Aalto University School of Engineering
Department of Mechanical Engineering
Marine Technology
MEC-E1004 - Principles of Naval Architecture

Concept design of expedition cruise ship Frostisen

Final report

Submitted 11.12.2020

Tuomas Kohosalmi
Gonzalo Sanfeliu Moreno
Sarah Blackwell
Elisa Majamäki

Project team

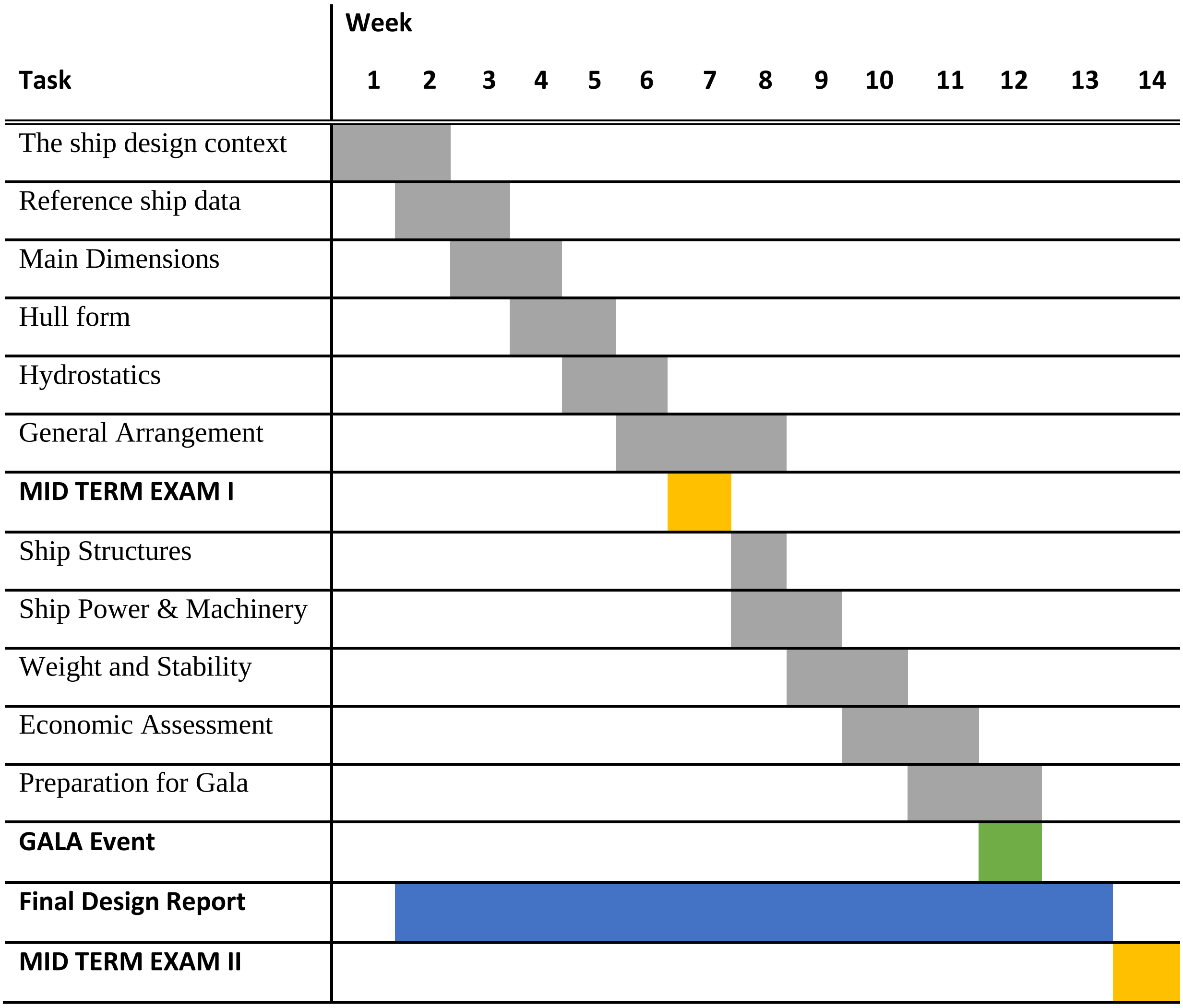
Tuomas Kohosalmi – Safety and Structural leader.
Currently studying both bachelor's level and masters level courses, focusing on completion of the requirements for his bachelor's degree, whilst advancing in his master's study path as much as possible. Worked in EVAC as a project assistant focusing on data collection and verification, which was his first touch on marine technology. Completed his bachelor's degree on the topic of "Composites and their fire safety in marine technology" and is interested in focusing on the topic in his master's level.

Gonzalo Sanfeliu Moreno – Ice and machinery leader.
Graduated in the Polytechnic University of Valencia with a bachelor's degree in mechanical engineering focused on machine design, where his competences lay. He worked in the mechanical maintenance team of a nuclear power plant helping to manage the worker teams and participating in the maintenance operations, what gave him an overall idea on how big mechanical systems work. His first touch with marine technology happened on the decision to study the Nordic master's in cold climate engineering and taking naval architecture as a minor. Currently interested in the effects of ice and frozen waters in ships while keeping the interest on ship machinery development. Being those two interests the ones that will be developed and used in this ship design project.

Sarah Blackwell – Design and Stability leader.
She has a bachelor's degree in naval architecture and marine engineering from the University of Michigan. Since graduating 2 years ago, she has been working in the industry at Foreship Oy in Helsinki. Here at Aalto she plans to pursue a structural engineering path within the marine technology program. At work, she has been doing safety engineering, including fire protection and evacuation plans for cruise ships. She has studied SOLAS requirements according to the work and has been to drydocks for the conversion of cruise ships. She has also developed GA's for cruise ships. She has performed lightweight surveys and inclining tests. Her strength and interest is in the cruise and ferry industry, in design, stability, and structural work. Her knowledge of the cruise industry will be employed for the concept of the ship and the overall design, keeping the project focused on marketability and passenger experience. She will also utilize her knowledge of safety requirements and stability. Her interest in structural engineering makes her the choice for the structural leader of this project.

Elisa Majamäki – Sustainability leader.
She has a bachelor's degree in energy and environmental technologies and a master's degree in water and environmental engineering. She has been working for one year as a researcher at the Finnish Meteorological Institute, where she also did her master's thesis on tracking the environmental pressures from recreational boating. Her doctoral studies and research focus on development of a global ship emission model. She can share her knowledge about environmental issues of ship traffic with other members of the design team and help the team to identify and assess the environmental impact of the ship. She also has experience in estimating the power needs of the vessel and is familiar with different marine engine technologies.

Project schedule



Contents

1 Design context and mission

1.1 Design mission and objectives

The design mission of Frostisen is to design an environmentally friendly luxury expedition cruise ship capable of operating in the arctic. The design of the ship will focus mainly on passenger experience, sustainability, and safety. The technical constraints of the ship will include requirements for ice class and clean design class, increased maneuverability, hull optimization for reduced fuel consumption, stability in harsh seas, stabilizers for passenger comfort, and size limitations in remote ports. The economic constraints will include construction and material costs balanced with the luxury cruise mission.

The name "Frostisen" comes from one of Norway's largest glaciers. We chose this name as a reflection of the mission. The ship will operate in and around Norway's coastline, and the cruise will feature opportunities to explore Norway's nature. The choice of a glacier to represent this ship also relates to the mission, as Frostisen represents something clean, arctic, and grand. Glaciers, like so much of the arctic environment, are also fragile. The aspect of fragility is also crucial to our design, as our mission and innovations will center around environmental sustainability. Frostisen will employ a new concept of a "clean cruise," which includes environmental technologies, environmental passenger features, and a focus on health and isolation of illness as a response to COVID-19.

The design objectives are centered around the mission: passenger experience, marketability, sustainability, and safety are all considered. Throughout the design spiral process, the overall goal will be considered. All regulations will be forefront as well. The design will consider all regulations, assuming DNV Passenger Ship class, and complying with IMO and SOLAS regulations. In our case, the environmental objectives are also important. The ship should meet IMO Tier III emission regulations and have high energy efficiency. Additional attention will be given for methane emission rates to decrease the greenhouse gas emissions of the ship. design objectives include a speed of around 15 knots, and a size small enough to reach remote ports, but large enough to maximize passenger capacity. Finally, economic design objectives will be related to the building cost, cost per cruise, maintenance costs, profitability, and payback period. Based on similar ships, Frostisen should cost around 150 million Euros, and the number of passengers and cost per cruise should balance out the cost of construction and operation. One economic objective is to keep the payback period under 20 years.

1.2 Design variables, innovations, and boundaries

The scope of this report will cover the concept design, or the first round of the design spiral. The main dimensions, weight, hull, and general arrangement of the ship will be defined. We will also choose main route the ship will travel and assess ship's power requirements accordingly. Power and resistance will be calculated, and machinery will be defined. As we aim for environmentally friendly and sustainable design, emissions will be estimated. Preliminary checks for hull strength will be done. As the aim is to design a passenger vessel, safety issues, such as fire safety and evacuation possibilities will be addressed. The current pandemic has shown the importance of hygiene and good ventilation on-board and we aim to take these aspects into account during the project. Finally, a preliminary estimation of the costs of the design will be provided. The key variables that make the designed ship unique are the ones related to the customer experience, operating the ship in arctic areas and the sustainability of the design.

In the cruise industry, there is pressure to innovate a ship to set apart from its competitors. Successful cruise ships have a "wow factor" to make it unique and marketable. However, it is difficult to create something new, unique, and different without compromising cost and creating technical difficulties. Instead of reinventing the cruise ship model widely used today, we will implement a series of small innovations that add up to create a modern ship. Our innovations will include clean technologies, a composite superstructure, and luxury architecture. The composite superstructure will be the biggest innovation in terms of technical innovation, as this has never been created on a cruise ship due to fire safety and cost. Our goal is to create an arrangement that implements composites into the superstructure without compromising the strength and keeping a reasonable construction cost. The structure will be designed in more detail in the second design spiral and may include a combination of composites and thin steel sandwich plates.

Other innovations include using batteries which can be used for zero emission cruising in fragile environments, electric engines, solar panel walkways built into the deck, and igloo cabins designed with glass walls and ceilings to view nature. In response to COVID-19, there will also be 3 "health zones" aligning with the fire zones, which can be isolated in case of an outbreak of virus, to prevent spread. There will be a medical center onboard as well. The health zones will also have separate air circulation from the other health zones, so the air will be isolated to prevent disease spread.

1.3 Design parameters

The design parameters we will consider can be divided in three categories, the environmental conditions, the economic conditions, and the operational costs. Even when all of them are unpredictable, especially when designing a ship going from the south to the north of Norway, the environmental conditions can be put in intervals based on earlier years data. This way, some minimums can be considered as a starting point. Some of the ones that affect in great measure to the ship we are designing are:

Wind, being able to reach an intensity of 12 in the Beaufort scale.

Waves, that can be of big dimensions due to the strong wind, therefore, great stabilization must be achieved to give the best possible passenger experience, and for that stabilizer fins and other stabilizing techniques will be used, thus, increasing costs.

Big range of temperatures depending on the season and the place, going from less than -20ºC in the north of Norway in winter to more than 35ºC in the south of Sweden in summer, and water temperatures ranging from below 0ºC in the Norwegian sea to over 20ºC in the Baltic sea. Since we will not be icebreaking, the operational area of the ship will be constrained depending on the season.

Another uncertainty that will need to be faced is the possible appearance of sea ice, and, even when this would be young ice as can be seen in the following Image 1, the ship will need to be prepared for that so Ice Class 1A* will need to be achieved, increasing the costs on structural requirements and power requirements among other systems.

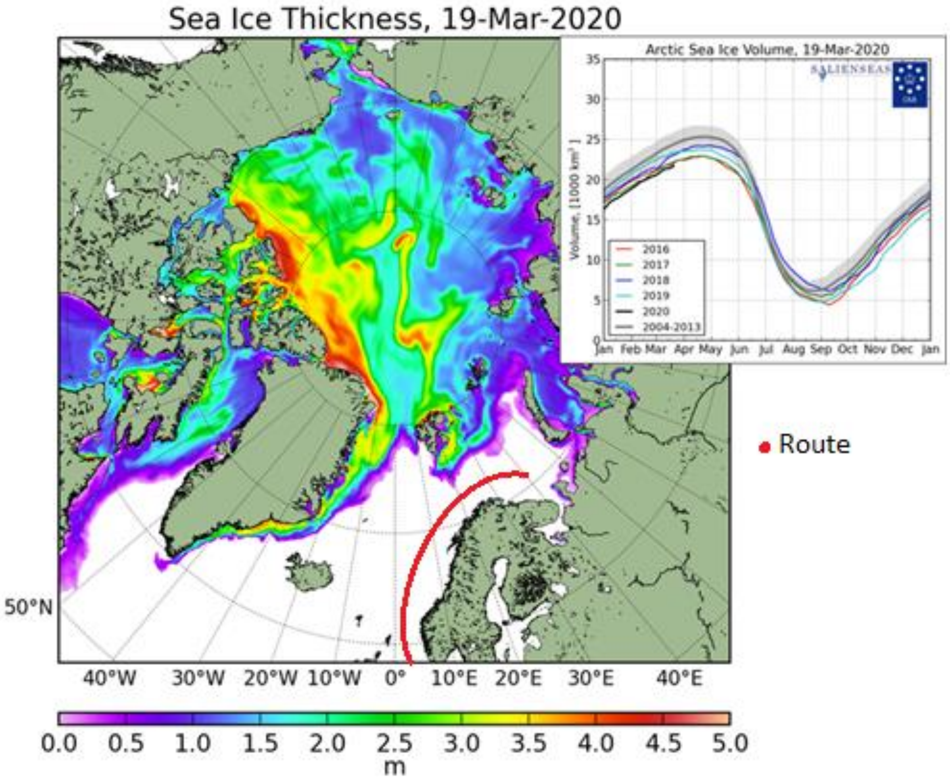


Figure 1. Sea Ice Thickness and Volume on 19-Mar-2020. [polarportal.dk]

Regarding the economic conditions and the operational costs, some of the ones that influence the most are the maintenance cost and the building costs, as well as the fuel price and the emission tariffs, but all of those are still completely uncertain because of the system that is wanted for this ship, being it a combination of LNG engines plus electric engines. Other operational costs to consider are the costs of ongoing maintenance and drydocks. Emission tariffs will also be uncertain and out of our control. However, we plan to go above and beyond the emission requirements for our design. One other important cost that will be hard to consider and uncontrollable is the cost of materials. The steel cost will be predictable, but the composite cost will be harder to predict as it is a new material. Composites are not widely used on ships, and very rarely on passenger ships. Thus, the cost and the response of these materials will be uncertain. The consideration of different types of composites will be a key in our design, as we must balance cost, strength, and fire protection.

1.4 Design constraints

The major constraints when designing a ship are the different regulations affecting the ship, and the legislation of the flag state and intended route. With the route known for the ship we can easily identify the different regulatory bodies, under whose authority our ship will fall under.

The International Maritime Organization (IMO) is an agency of the UN responsible for naval regulations. They have multiple different conventions affecting the design and construction of ships, with the major conventions, under which the smaller codes/regulations fall under, being:

- International Convention for the Safety of Life at Sea (SOLAS)
  - Excluding chapters VIII, X and XII
- International Convention for the Prevention of Pollution from Ships (MARPOL 73/78)
  - Annex I-VI and IMO 2020
- Ballast Water Management Convention (BWM)

The European Maritime Safety Agency (EMSA) bases their legislation on the regulations set by the IMO and act as the legal body enforcing legislation and regulation set by both agencies. Despite Norway and Iceland not being members of the EU, they are members of EMSA, setting our ship under the jurisdiction of EMSA.

The flag state should also be considered. Although the ship operates mostly in Norway, Norway has a very expense flag. The Bahamas is a common choice for cruise ships, including many of our reference ships. The flag state introduces standards unique to each state. If Frostisen is registered to the Bahamas, she will need to undergo the certifications, emission requirements, safety requirements, and procedures required by the state. The choice of flag state, like the choice of classification society, is based mainly on the cost of the requirements and integrity of the standards.

Frostisen will be classed by DNV as a passenger ship (RU-SHIP, 401-passenger ship), undergoing the requirements listed from the DNV class documentation. The choice of DNV was also partially based on similar ships, along with the fact that DNV is a Norwegian authority. Many of the regulatory bodies will have overlapping requirements. However, DNV will have their own set of interpretations and class specific requirements. Going forward, we will use DNV as a guide for our design.

Physical constraints affecting the ship design are the size restrictions of the intended ports, limitations on the route, and limitations of the available shipyard facilities. Other physical constraints become apparent during the design process, as certain design choices will limit the size pf the ship, and place technological constraints on the ships design. We researched the expected ports along our routes, and concluded that we can reach even remote ports with a draft below 6 meters.

2 Reference ship and data

2.1 Definition and description of ship type

The ship will be a cruise ship with a capacity of 355 passengers and 65 crew without Ro-Ro capability, as the focus of the ship is to make round trips, visiting locations on the way. Due to the arctic climate of our selected route, the ship will be an expedition type vessel, with hull reinforcements allowing traverse across icy waters. Also being an expedition type vessel, the ship will have the ability to carry several zodiac boats allowing for landings at locations without ports. Among the crew should also be expedition leaders knowledgeable in the areas visited and observation decks are available in current expedition cruise vessels.

Alongside all specialized equipment and designs for activities in the remote areas the cruise visits, onboard passenger satisfaction is a priority as the ship is still a cruise vessel. The common accommodations available in normal cruise vessels are also available in expedition cruises, though at a slightly smaller scale due to the space taken by the expedition equipment.

2.2 Reference ships

Our team has selected three reference ships that are similar to the one we are thinking on, and from which we could take some ideas on the systems that we could implement.

Figure 2.Le Commandant Charot

The first one is "Le Commandant Charcot", with the IMO number 9846249. It is an icebreaking cruise ship with French flag, owned by the French company "Compagnie du Ponant" and built by Vard in Romania and Norway, with a total cost of NOK 2,7 billion (about €242,6 million).

Some technical characteristics of this ship are her Polar Class 2 rating, a LOA of 150 m, draft of 10 m and a beam of 28 m. It has the capacity for 270 guests in 5 guest decks, and 190 crew members. It has a gross tonnage of 31757 and 42MW of installed power coming from diesel engines that can be run by both diesel and LNG, from which 34MW are used in the two ABB Azipod propulsion units that makes it reach 15 kn.

This makes this ship, that will start its service in 2021 and has been launched in March 2020, "the world's first luxury expedition icebreaker".

Figure 3.Quark Ultramarine

Our second reference is the "Quark Ultramarine", with the IMO number 9861017. It is a cruise ship registered in the Marshall Islands, owned by the German company "TUI Group", operated by "Quark Expeditions" and built by Brodosplit in Croatia, with a total cost of €134 million.

Some technical characteristics of this ship are his Ice Class 1 Super rating (equivalent to Polar Class 6), a LOA of 128 m, draft of 5,1 m and a beam of 22 m. It has the capacity for 199 guests in 5 guest decks, and 140 crew members. It has a gross tonnage of 13500 and is powered with diesel engines that can be run by both diesel and LNG, from which 12MW are used in the 4 electric propulsion units, 1,2MW on 2 bow thrusters and 0,8MW for a stern thruster, reaching 16kn and being able to use a Dynamic Positioning system that automatically maintains the ship's position by using the thrusters, eliminating the use of an anchor. This ship is still being built and will be launched in 2021.

Figure 4. L'Austral

Our final reference ship is “L’Austral”, with the IMO number 9502518. It is a Cruise ship built in 2010 in Fincantieri-Ancône-Italy and sails under the flag of Wallis and Futuna, owned by “Compagnie du Ponant”.

The ship has a LOA of 142 m, draft of 4.9 m, and a beam of 20 m, with a cruising speed of 14 knots and is Ice Class 1C. It has a guest capacity of 264 and crew capacity of 140, with a total of 6400 kW of installed power and the gross tonnage is 10944.

3 Hull form and hydrostatics

3.1 Main dimensions

To find our main dimensions, we used the statistical method and Normand's number. Normand's number is based on displacement and seems to be more useful when considering a ship which has displacement as an owner's requirement (cargo). As we do not have a good estimate for our displacement, or details of the outfitting weight and machinery weight of reference ships, the statistical method was preferable. This method uses empirical formulas from existing ships to estimate the main dimensions based on inputs that we can predict ourselves. We input the deadweight and speed based on our design needs and similar ships. The only known limitation to our ship was the draft limitation to stay below 6 meters of draft. Our first run at the dimensions gave a draft of 4.8 meters. We did have to increase it, but it still falls below 6 meters. The results of the statistical method are shown below.

Table 1. Output of the statistical method

Δ	10000.00
LPP (m)	135.82
B (m)	20.90
T (m)	4.81
D (m)	12.35
C_B	0.714
C_M	0.987
C_P	0.723
C_{WP}	0.804

Later, after developing our hull based on these dimensions, and after iterations based on weights and machinery, a more detailed set of main dimensions were taken:

Table 2. Final main dimensions

Loa (m)	158.08
LPP (m)	135.80
Δ (tons)	9353
B (m)	20.90
T (m)	5.5
D (m)	12.35
C_B	0.584
C_M	0.861
C_P	0.679
C_{WP}	0.804

Additionally to using the statistical method based on historical data, we collected a database of 26 reference ships to compare with our chosen dimensions. The chosen ships are mostly expedition cruise vessels, and a few small luxury cruise vessels with similar mission and capacity. Dimensions, powering and machinery, ice class, and passenger capacity were all collected for the ships. The dimensions were chosen based on the statistical method using deadweight and draft as the input. These input values were also estimated from reference ships. We took averages from the database and chose values closer to the ships that are most similar to our desired outcome.

The quality of the statistics is fairly good. The statistics were all taken from their respective classification society databases, so they are accurate. We chose the references carefully, so that each ship is similar not only in size but also in the mission. We also focused on reference ships that had LNG and/or batteries, as the machinery comparison is only relevant to those. It is difficult to choose ships that are completely matching our goals, however, especially as we plan innovations such as lightweight superstructure and alternative fuels. Some reference ships must also be older, and the deadweight may not match our ship as they will use different fuel. Some of the newer ships also might not be completely comparable, such as the National Geographic Endurance, which has an XBow, and generally a modern and alternative shape. It is difficult to consider the comparison of ships, as the older ships are more plentiful and reliable but outdated, but the newer ones have more innovations. Le Commandant Charcot also has an unusually high draft for its size. We searched multiple resources to make sure it was accurate. We cannot explain why the draft is so much higher, but we can assume that there is some design element that requires a larger draft, so in this case it is also hard to compare our ship.

In Figures 4 below, the principal dimensions are compared as ratios between different parameters. Figure 1 shows the beam of each ship for its length. Our ship is aligned well with the reference ships, right along the average. This comparison is an easy one since there are not really outliers, and it is clear that the ratio is on target. The relevance of the length to beam is that the larger the beam is per length, the more "full" the ship is. If we decreased the beam, this would lead to less resistance and more speed, but compromises the capacity. As a passenger ship, it is important to maximize the space to fit more passengers comfortably. This ratio must be considered and optimized for our design goals. It is important to note for each of these figures that our length is on the large end of the reference ships, so much of the comparison will be based on the trend. It would be useful if there were more reference ships between the range of 150-200 meters. Figure 5 shows speed per length. Our ship is right on trend here as well.

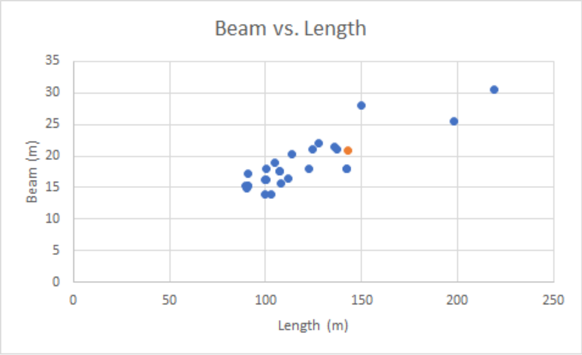


Figure 5. Beam vs. length for the reference ships (blue)

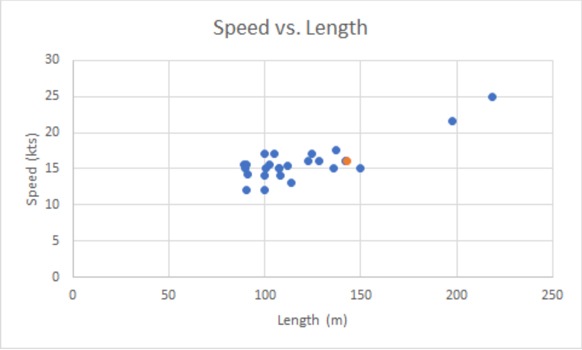


Figure 6.Speed vs. length for the reference ships (blue)

Based on the first iteration of the main dimensions, our draft was quite low compared to other ships. In estimating the weight later on in the course, we realized that we needed to increase the displacement of our hull. This was done simply by increasing the draft from 4.8 meters to 5.5 meters. The draft now matches our reference data much better.

The reason for the discrepancies between our ship and the reference ship could be explained by the methods used to determine our principal dimensions. The statistical method was utilized, which uses empirical formulas that were built from historical data. This data mainly consists of cargo ships, and the input values of the method are also geared towards cargo ships. Our input was only estimated from similar ships, as we do not have any clear idea of the deadweight. Deadweight is not an owner's requirement of cruise ships. The deadweight to displacement ratio was also estimated from historical data and was only based on the estimated length of our ship. This ratio, found in the course materials, only had estimated values for passenger ships between 50-120 meters of length and 200 to 360 meters. Unfortunately, our ship falls between these values so the estimate was even rougher.

3.2 Hull form

Drawing the hull lines was based on main dimensions defined in the previous step of the ship design project.

Available drawings and images of references ships were used to modify the hull form to be suitable for an expedition cruise ship. Main example used was L'Austral as it has similar features as the ship we aim to design.

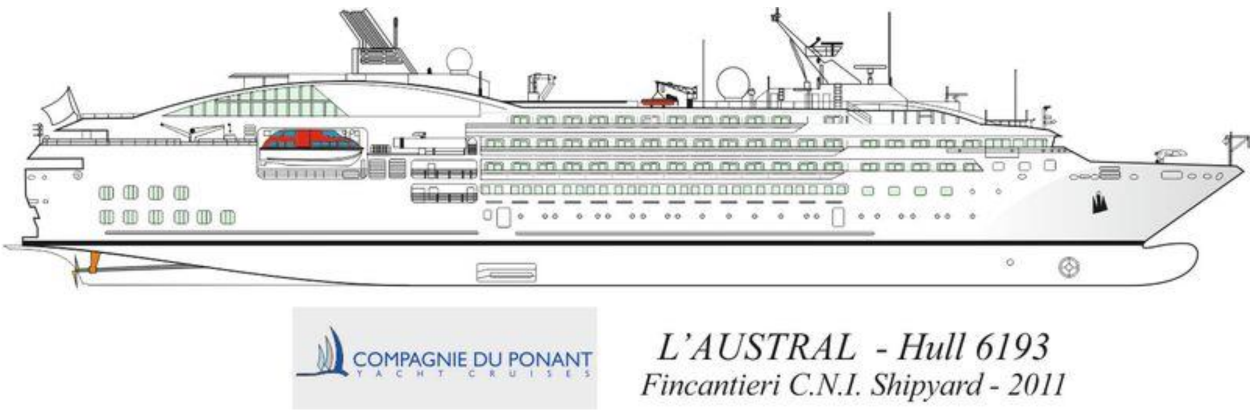


Figure 7.Hull of the reference ship L'Austral (source: navim.com)

Values in offset-table were changed to create a form similar to L'Austral and to achieve a fair form of the section area curve. Offset values chosen after iteration process are shown in table 3.

Table 3. Offset Values

						Water Line Data (Non-Dimensional)											
		Stern-profile (transom)		CL-	Fr 0	Fr 1	Fr 2	Fr 3	Fr 4	Fr 5	Fr 6	Fr 7	Fr 8	Fr 9	Fr 10	Bow-profile	
	z	x	y	buttock	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	x	y
Upper Dk	2.57	-0.040	0.950		0.98	0.99	1	1	1	1	1	1	0.87	0.79	0.45	1.100	0.2
WL 8	2.18	-0.038	0.940		0.97	0.98	0.99	1	1	1	1	0.98	0.85	0.73	0.35	1.080	0.12
WL 7	1.79	-0.035	0.910		0.94	0.95	0.96	0.99	1	1	0.99	0.97	0.83	0.64	0.22	1.060	0.06
WL 6	1.39	-0.030	0.750		0.825	0.9	0.93	0.97	0.99	0.99	0.97	0.94	0.8	0.53	0.15	1.040	0.02
CWL	1.00	-0.015	0.000	-0.015	0.4	0.8	0.88	0.95	0.98	0.98	0.95	0.89	0.74	0.39	0.12	1.015	0
WL 4	0.80	0.060	0.000	0.06	-0.4	0.65	0.84	0.935	0.965	0.965	0.935	0.86	0.677	0.31	0.105	1.000	0
WL 3	0.60	0.120	0.000	0.12	-1	0.2	0.75	0.9	0.94	0.94	0.91	0.815	0.585	0.23	0.09	1.020	0.04
WL 2	0.40	0.150	0.000	0.15	-2	-0.2	0.58	0.85	0.9	0.9	0.86	0.76	0.46	0.15	0.075	1.030	0.055
WL 1	0.20	0.180	0.000	0.18	-2	-0.5	0.33	0.78	0.85	0.85	0.77	0.65	0.31	0.08	0.06	1.025	0.045
WL 1/2	0.10	0.210	0.000	0.21	-2	-0.7	0.13	0.735	0.81	0.81	0.7	0.55	0.22	0.05	0.04	1.015	0.03
WL 1/10	0.01	0.240	0.000	0.24	-2	-1	-0.15	0.66	0.75	0.75	0.55	0.36	0.12	0.015	0.01	1.000	0.001
Flat Bottom	0.00	0.260	0.000	0.26	-2	-1	-0.2	0.6	0.73	0.73	0.53	0.35	0.1	0.01	0	0.980	0
CL	0.00									0							0

Table 4 and 5 show computed ship dimensions and hull coefficients. We compared the coefficients with values given in related literature and all of them are within reasonable ranges for a passenger ship.

Table 4.Main data output

Loa [m]	154.8
Lwl [m]	141.2
Displacement [m3]	9265
Displacement [ton]	9496
Froude Nr. (Fn)	0.22

Table 5.Hull form coefficients

L / B	6.50
L / D	11.00
B / T	3.8
Slenderness ratio:	6.72
Block coefficient (CB)	0.594
Midship area (Am) [m2]	104
Midship area coefficients (CM)	0.906
Prismatic coefficient (CP)	0.655
Waterplane area (Aw) [m2]	2249
Waterplane area coefficients (CW)	0.793
LCB	-1.5%
KB	3.07
BM	6.44
KM	9.51

Hull side profile based on offset-table (table 2).

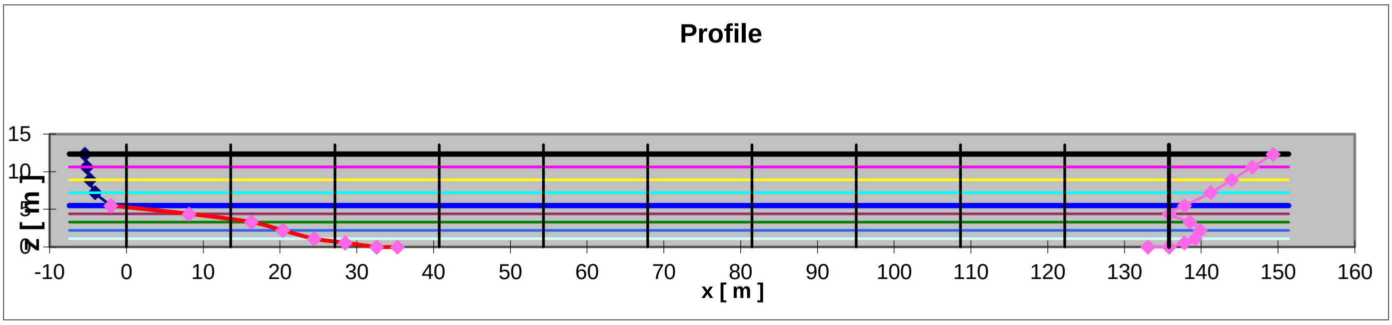


Figure 8.Hull side profile

Figures 3 and 4 show the half breadths of the ship and different frame sections. The goal was to have inclined sides on the ship as it will be an ice class ship, and the frame sections were faired to the best of our ability.

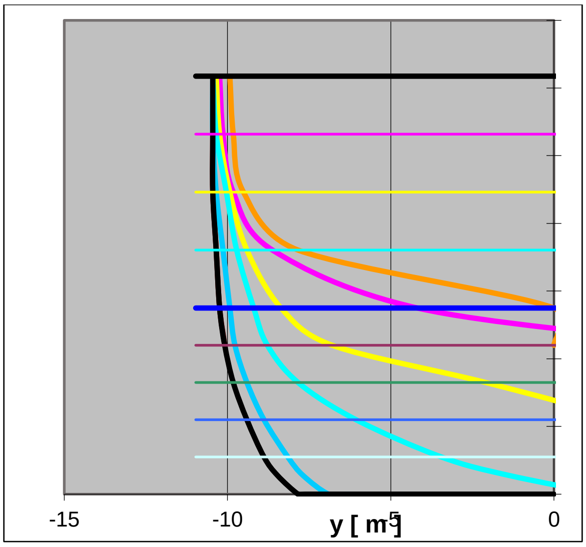


Figure 9.Frame section at the stern

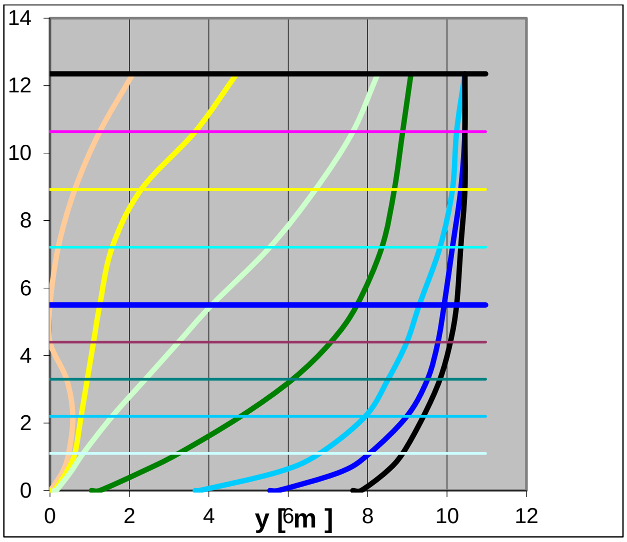


Figure 10.Frame section at the bow

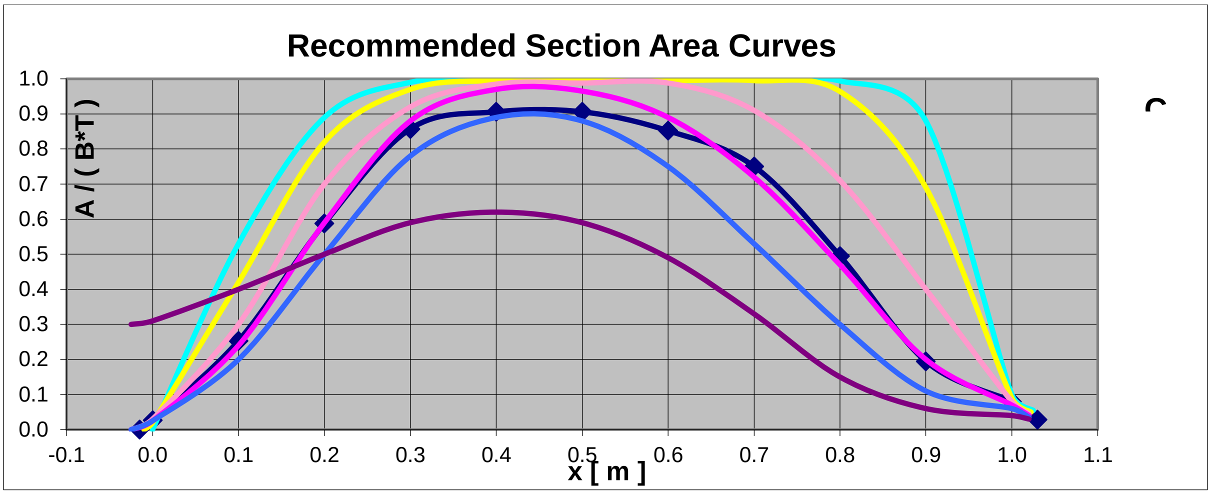


Figure 11. Recommended section area curves

The frame sections were adjusted to make the SAC of our ship follow the recommended SAC curves, but due to the inclined sides, we were unable to get the curves to match completely.

3.2.1 Delftship

The ship modeling program Delftship was used to create a 3D model of our hull form. The purpose of creating a Delftship model is to visually see how the hull lines form surfaces and to further fair the lines to create a smoother hull. This hull form can also be used to develop our design later in this course. In the next course we will use NAPA, but for this preliminary level this version suffices. Delftship is very useful at this point, not only for looking at the curves of the hull, but for generating design hydrostatics. We have not reached the hydrostatics section of this course yet, but the hydrostatics tables include a lot of useful information about the hull form and its preliminary stability.

To create a hull form, the Excel sheet was used. Control points were created from the offset table. The process of manually modeling the hull is also very useful to understand how to relate the different lines and tables from the Excel. The offset table is used literally to offset the control points to their correct locations along the hull surface. The surface is then modeled along the points and evaluated. The following hull was created from these offset points, and then the surface was faired. Specifically, the area aft of midships was faired a bit so that there was not the weird dip in the lines as shown in the excel.

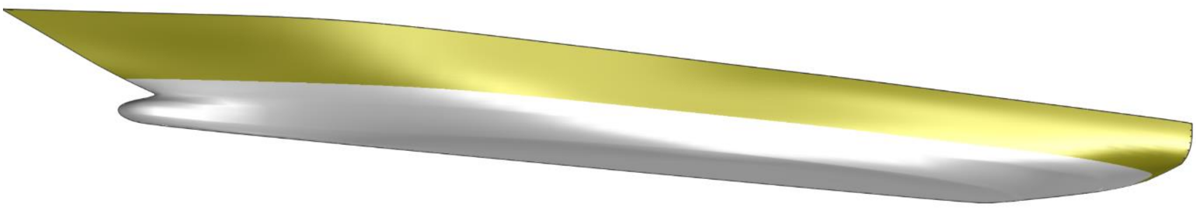


Figure 12. Frostisen hull created in Delftship

The displacement is 9343 tons, compared to 9496 tons of the excel hull design. The waterline length is 140.95 m. The LCB is slightly aft of midships, at -0.788% compared to -1.5%. The block coefficient is also smaller at 0.5846 compared to 0.594. The other coefficients are also quite similar. Considering the Azipods, this hull version has a bit over 4 meters of clearance at the aft perpendicular, which should be enough to fit the Azipods.

Table 6. Volume properties of Delftship hull

Volume properties	
Moulded volume	9125.3 (m^3)
Total displaced volume	9125.3 (m^3)
Displacement	9353.4 (tonnes)
Block coefficient	0.5846
Prismatic coefficient	0.6788
Vert. prismatic coefficient	0.7275
Wetted surface area	3018.0 (m^2)
Longitudinal center of buoyancy	66.790 (m)
Longitudinal center of buoyancy	-0.788 %
Vertical center of buoyancy	3.169 (m)

Table 7. Waterplane properties of Delftship hull

Waterplane properties	
Length on waterline	140.95 (m)
Beam on waterline	20.224 (m)
Entrance angle	17.951 (Degr.)
Waterplane area	2280.6 (m^2)
Waterplane coefficient	0.8035
Waterplane center of floatation	62.646 (m)
Transverse moment of inertia	61902 (m^4)
Longitudinal moment of inertia	2814048 (m^4)

Table 8. Midship properties of Delftship hull

Midship properties	
Midship section area	99.0 (m^2)
Midship coefficient	0.8612

The sectional area curve is shown in Figure 7. Considering the sectional area curve of this hull form compared to the previous one, this hull carries area more evenly and the curve is smooth. The curve is skewed slightly aft, meaning that the midship section is aft of the midpoint between perpendiculars, and there is more volume towards the aft. The fore part of the ship gradually becomes fuller and sharply becomes slimmer aft.

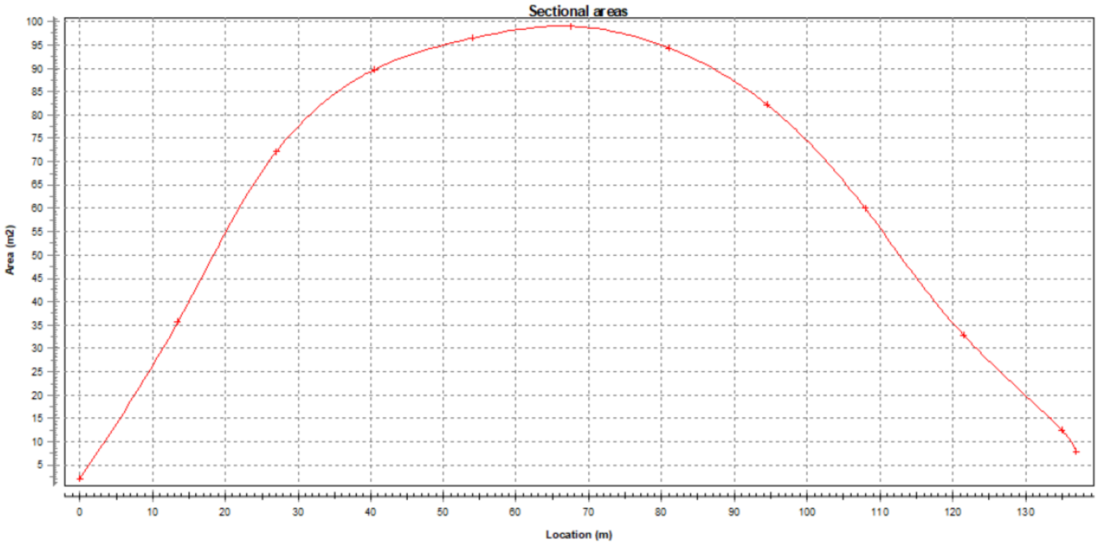


Figure 13. SAC of Delftship hull

3.3 Hydrostatics

For this assignment, an estimation of the hull volume was taken from DelftShip, and its correctness was checked using the Simpson integration method with the provided Excel file.

The hull volume, displacement, Vertical Center of Buoyancy (KB), and Longitudinal Center of Buoyancy (LCB) position estimation by DelftShip are the following:

Table 9. Delftship data

Volume (m^3)	9125
Displacement (t)	9353
LCB from fr0 (m)	66.79
KB (m)	3.169

Then we manually calculated the Sectional Areas using the offset points from our 3D model. This method will check the calculations using Simpson's integration, based on the excel calculations for the sectional areas. The method inputs only the intersections between half breadth and waterlines, to create the shape of the hull at each station. As opposed to the method built in to Delftship, this method only uses 10 points. In class, we discussed that sometimes integrating more points does not necessarily produce better results. In this case, the results were quite similar but slightly lower than the Delftship estimate. Table 5 shows a sample of the CSA integration. Table 6 shows the resulting areas and LCB. The CSA curves are shown in the appendix.

Table 10.Excel CSA calculations using offset points for Station 9.

WL	Z-coordinate	1/2 ordinates	SM	Product for area	Lever @ Frame 0	moment of area	
		y_n	k_n	$y_n * k_n$	R_n	$y_n * k_n*R_n$	
[-]		[m]	[-]	[m^2]	[m]	[m^3]	
0	0	0	1	0.0	0	0.0	
1	0.55	0.794	4	3.2	1	3.2	
2	1.1	1.282	2	2.6	2	5.1	
3	1.65	1.641	4	6.6	3	19.7	
4	2.2	1.965	2	3.9	4	15.7	
5	2.75	2.262	4	9.0	5	45.2	
6	3.3	2.502	2	5.0	6	30.0	
7	3.85	2.76	4	11.0	7	77.3	
8	4.4	3.084	2	6.2	8	49.3	
9	4.95	3.368	4	13.5	9	121.2	
10	5.5	3.64	1	3.6	10	36.4	
			Σ	64.6	m^2	403.3	m^3

Table 11.Excel CSA results using Excel CSA method

Volume	9081	m3
Density of water	1.025	t/m3
Displacement	9307.89175	t
LCB from fr0	66.792	m

The results can be seen as correct as the deviation is 0.48%. The above method is the Simpson's method using the integration of cross-sectional areas. There is a second method available which integrates the waterplane areas instead. It is an analogous but opposite method that uses the waterplane areas along each waterline as input. We took a total of 10 areas along the waterlines from 0 to our design waterline of 5.5 meters.

Table 12 shows an example of the calculation of a waterplane area, where the offset y (half breadth) areas were input from our hull model. The waterplane curves are found in the appendix.

Table 12. Example Calculation of the Waterplane Area (WL . 3.84m)

x-coordinate	1/2 ordinates	SM	Product for area	Lever @ Frame 0	moment of area	
	y_n	k_n	$y_n * k_n$	R_n	$y_n * k_n*R_n$	
	[m]	[-]	[m^2]	[m]	[m^3]	
0	0.0	1	0.0	0	0.0	
13.771	6.3	4	25.3	1	25.3	
27.542	8.7	2	17.4	2	34.7	
41.313	9.2	4	36.6	3	109.9	
55.084	9.5	2	19.0	4	76.0	
68.855	9.7	4	38.7	5	193.6	
82.626	9.3	2	18.6	6	111.8	
96.397	8.5	4	34.1	7	238.5	
110.168	6.4	2	12.8	8	102.4	
123.939	3.4	4	13.6	9	122.6	
137.71	0.0	1	0.0	10	0.0	
		Σ	216	m^2	1015	m^3

The resulting waterplane areas were input to the Excel sheet using Simpson's integration of waterplane areas. The waterplane areas from 0 to 5.5 meters are shown in Table 9, with the coordinating waterplane elevations, and Simpson's integration values. Table 10 shows the resulting volume and KB.

Table 13.Excel WPA calculations using offset points.

WL	Z-coordinate	WPA	SM	Product for volume	Lever @ keel	moment of volume	
[-]		y_n [m^2]	k_n [-]	$y_n * k_n$ [m^3]	R_n [m]	$y_n * k_n * R_n$ [m^4]	
0	0	0.0	1	0.0	0	0.0	
1	0.55	1076	4	4304.0	1	4304.0	
2	1.1	1309	2	2618.0	2	5236.0	
3	1.65	1437	4	5748.0	3	17244.0	
4	2.2	1545	2	3090.0	4	12360.0	
5	2.75	1711	4	6844.0	5	34220.0	
6	3.3	1870	2	3740.0	6	22440.0	
7	3.85	2009	4	8036.0	7	56252.0	
8	4.4	2102	2	4204.0	8	33632.0	
9	4.95	2170	4	8680.0	9	78120.0	
10	5.5	2273	1	2273.0	10	22730.0	
			Σ	49537.0	m^3	286538.0	m^4

Table 14.Volume and KB from WPA method.

Volume	9081.8	m3	
KB	3.181	m	above keel

As expected, the volume using this method is the same as the volume found using the CSA method (CSA method using offset values). This result further solidifies the calculations. The KB estimated by Delftship is 3.167 m, while the Excel method produced a KB of 3.181 m. The difference between the values is 0.44%. It is clear that the Simpson's integration method using 10 points produces accurate results compared to the Delftship method.

In comparison with the DelftShip software results, a very small difference can be noted in each method:

Table 15.Comparison of results between DelftShip and Excel CSA calculations.

	DelftShip	Simpson Excel (WPA)	Difference	Simpson Excel (CSA)	Difference
Volume (m^3)	9125	9081	14.1 (0.48%)	9081	14.1 (0.48%)
Displacement (t)	9353	9308	45 (0.48%)	9308	45 (0.48%)
LCB from fr0 (m)	66.79			66.79	0.00 (0.00%)
KB (m) from BL	3.169	3.181	0.012 (0.38%)		

A sectional area curve was also produced from the Simpson's integration results. The sectional area curve is shown in Figure 1.

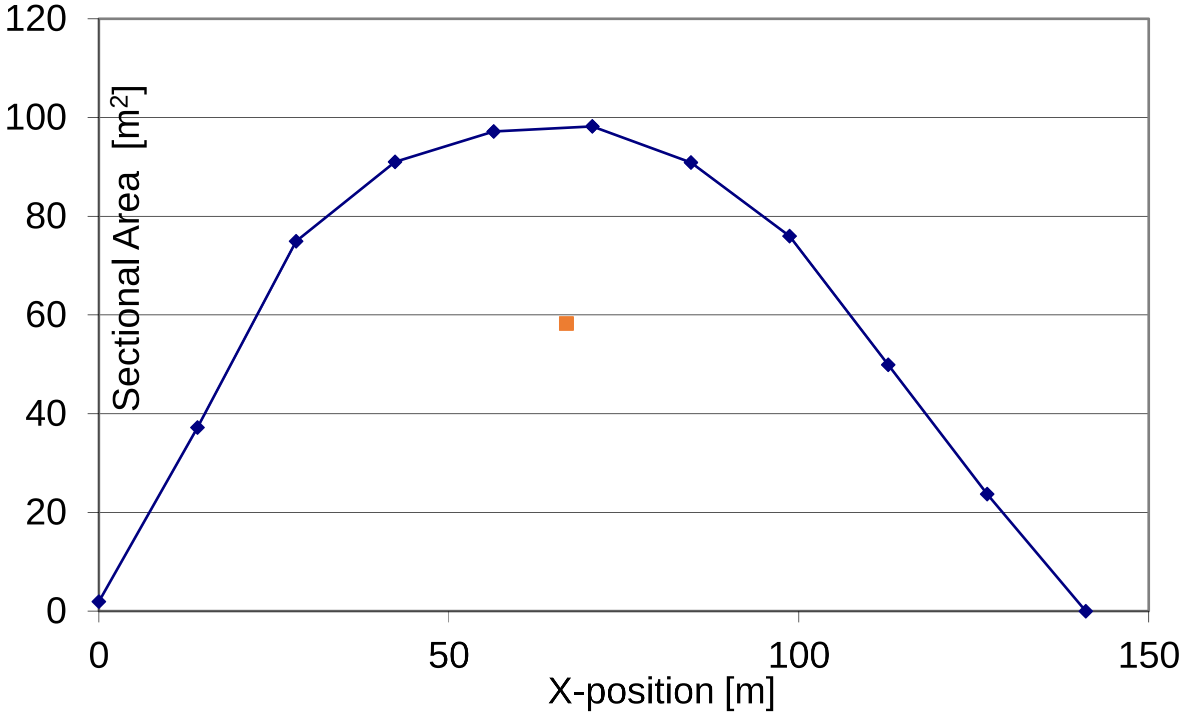


Figure 14. SAC

4 General arrangement (GA)

4.1 GA definition

The General Arrangement (GA) of a ship defines the basic layout of the ship. This layout includes everything from the ship's deck areas for each deck, the layout of all of the spaces in the ship, and the location of the frames and bulkheads. The GA details the layout, generally showing the flow of the spaces, and detailing the locations. The GA can be used onboard a ship as a map and is an important tool in the design process to see practically how the spaces are designed. The GA is also used later in the design as a background for safety plans, tank plans, structural plans, etc. The GA defines the number of decks, fire zones, watertight bulkheads, frame spacing, and double bottom. Non-technical aspects are also very important in cruise ships, so the mission and aesthetics of our design are also considered at this point.

To output the AutoCAD from the Delftship model, the deck spacing must first be known. To get the deck spacing, we looked at requirements. The requirements for deck spacing comes from DNV. The escape area must include a vertical height of 2 meters, so the total height must be equal to 2 meters plus overhead area. The requirements for the double bottom height are stated in SOLAS chapter II-2, Part B-2, Regulation 9, and the DNV GL regulations are based on SOLAS. The double bottom height rules are as follows:

"*Where a double bottom is required to be fitted the inner bottom shall be continued out to the ship's sides in such a manner as to protect the bottom to the turn of the bilge. Such protection will be deemed satisfactory if the inner bottom is not lower at any part than a plane parallel with the keel line and which is located not less than a vertical distance h measured from the keel line, as calculated by the formula:*
h = B/20. However, in no case is the value of h to be less than 760 mm, and need not be taken as more than 2,000 mm."

Based on this information the height of the double bottom for Frostisen should be a minimum of 1045mm.

Then, the deck heights are determined. The deck heights were chosen to be 2.7 meters, based on requirements and reference ships. Some heights needed to be irregular to better fit the design. To begin with the AutoCAD drawing of the GA, the deck heights in the hull are determined. The double bottom height and subsequent decks inside the hull were added to the intersections of waterlines in Delftship, and the lines were exported to AutoCAD. The waterlines at the given heights were taken from the lines plan and shown in different plan view areas, outlining the deck areas at each height. Using the shape of the top of the hull, the superstructure decks were then added.

The freeboard requirement was considered at this stage. Our minimum freeboard is 2.21 meters. Our actual freeboard is 6.76 meters. The freeboard is calculated using the following equation:

$f = -587 + 23L - 0.0188L2$ where f is the freeboard in mm

The design for the superstructure decks were mainly generated using reference ships. Before adding each deck, the profile view was created. The profile view of the GA used the profile of the hull. The hull deck lines were added to the view, and then horizontal lines were generated at each height of the superstructure decks. The next part of the design comes from using reference ships to create a modern and functional design. The overall height must be low enough not to ruin the stability. Based on our reference ships with similar lengths, the ship will have about 5 decks of superstructure. Our deck has 5 decks above the hull, including the top deck which is basically the ceiling of the functional top deck.

Since the height of the structure will add a lot of weight distribution to the top of the ship, the stability may be compromised. Our ship will use a superstructure made of a combination of composites and steel, or thin steel sandwich panels, which will decrease the weight of the superstructure. This will contribute to overall reduction in fuel and will also help the stability.

The resulting deck heights and descriptions are as follows. The decks of crew spaces are labeled with letters, while the decks of public spaces are labeled with numbers. The area below deck A is the double bottom, which includes ballast tanks and voids. The height of the bridge deck (deck 4) complies with the requirement for bridge visibility (SOLAS). The requirement states that the view must not be obstructed by more than 2 times the length. Our ship's bridge visibility is 40.8 meters forward, which is more than sufficient.

Table 16.Decks with height and descriptions.

Deck	Height (m above BL)	Description
A	1.05	Double bottom, machinery, tank top
B	3.75	Tanks and machinery, crew cabins, laundry
C	6.45	Crew space, provisions , provisions loading
0	9.35	Crew space, mooring stations, and entrance/passenger gangways, medical center
1	12.26	Reception area, forward cabins, open deck walkway with lifeboats, and aft lounge area with infinity jacuzzi
2	14.96	Cabins, including "igloo" suites in aft, lifeboat equipment/cranes
3	17.66	Cabins, including "igloo" suites in aft
4	20.36	Public areas, dining and restaurants, bridge, galley
5	23.06	Spa and gym, pool deck with solar walkways, bar
6	25.76	Roof, funnel.

The next step after each deck height and general shape were determined is to determine the frame spacing and locations of watertight bulkheads. The frames were estimated based on reference ships. We chose a frame spacing of 600 mm, which leads to a total of 264 frames ranging from frame -7 to frame 256. The watertight bulkhead spacing was generated using regulations. Both SOLAS requirements and DNV GL rules related to the general arrangement were checked. DNV GL rules state that there should be a minimum of 7 watertight transverse bulkheads for our ship length, a collision bulkhead and an aft peak bulkhead. We chose to have 8 watertight transverse bulkheads in the ship. The acceptable range for the length of the collision bulkhead has been provided and for our ship, the distance of the forepeak bulkhead aft of the forward perpendicular shall be 6.9m - 9.995m. Length of the collision head of Frostisen is 9.0m. Both engine room and the generator room must be enclosed by watertight bulkheads. The engine rooms are the main engine room and the battery room which holds additional machinery. Location of the aft peak bulkhead depends on the position of the engine room and the shaft as it should be located so that the stern tube and rudder trunk are enclosed in a watertight compartment.

After the watertight bulkheads spacing was designed, the main staircases were added to the above waterline areas. The machinery space may require more complex staircase and ladder systems. The passenger areas, from deck 0-5, will have 2 main staircases that correspond to 3 main fire zones in the superstructure. A fourth main fire zone is added to the hull decks, as the length of the hull requires another fire zone (length must be under 48 meters as per SOLAS requirements). The main fire zones are shown in the below figure as the vertical red lines with the "MFZ" label. Additionally, there are 4 main crew staircases. The figure shows Frostisen's profile, detailing the vertical positions of the areas. The most notable things in this figure are the fire zones, watertight bulkheads, deck levels, and staircases.

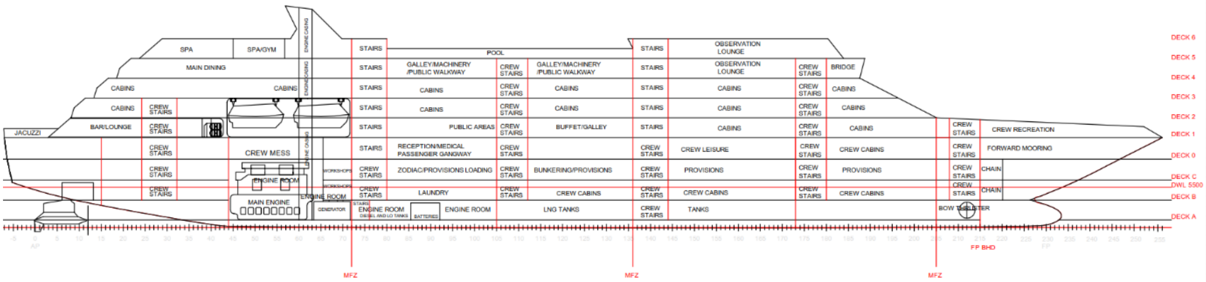


Figure 15. Ship profile

After the fire zone spacing was determined, the main flow of the ship is designed. The watertight bulkheads determine the spacing inside the hull, especially framing the machinery space and the continuous sections of the lower decks. Above the main deck, the spacing and flow of the ship is only determined by the MFZ spacing. The MFZs and the staircases are the only continuous factors between the upper decks. The safety and escape requirements determine the need for safe passage to the main staircases in case of emergency, and the MFZs split the ship into firesafe sections. The number of passengers is important to consider here, as the staircase requirements depend on the number of passengers expected to escape from different zones of the ship. There are staircases accessible from each fire zone, and plenty of room to include the required width and landing areas. The muster stations will be next to the lifeboats on deck 1.

From this point in the GA design process, we filled the details of each deck. The machinery was determined first, as the machinery determines the location of the aft peak bulkhead, and there are watertight bulkheads also required at the other end of the engine room. The exhaust trunk was also placed, which leads to a vertical trunk that goes through every deck. These elements were added and the GA was adjusted. The following figure shows the machinery deck, Deck A. Below this deck is the double bottom, which has a height of 1050 mm and contains tanks and voids. The main components of this deck are the main engines and generators, batteries and additional machinery space, LNG tanks, and other tanks (arrangement to be determined). There is also a bow thruster aft of the fore peak bulkhead.

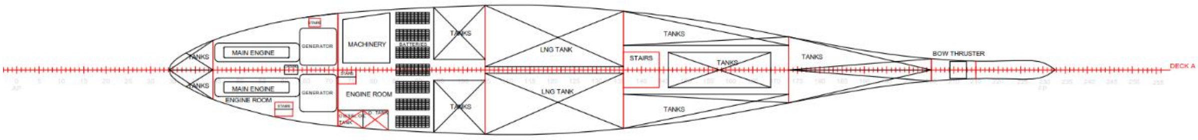


Figure 16. Deck A

Decks B and C contain the second level of machinery, the azipod room, and crew spaces. The azipods extend from the hull on Deck B, although there was a problem with the spacing such that the azipods extend on a slope based on the shape of the hull, and do not sit flat inside the room. There is enough space for the machinery in the aft part of the hull as shown, but in the second design spiral the hull will be adjusted to better fit the azipods. Directly above them on Deck C is the steering gear room. The crew spaces include cabins, mess, galley, and provisions. The crew area is designed to have easy transportation of goods from provisions to the main galley above. There is also a loading area on deck C for loading provisions and offloading waste. Decks B and C are shown below.

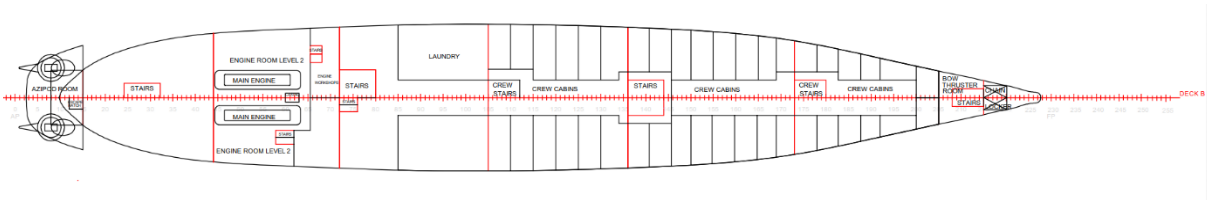


Figure 17. Deck B

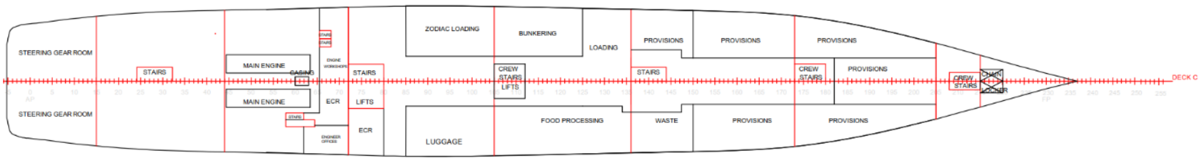


Figure 18. Deck C

Deck 0 is the first deck that allows passengers. This deck includes the passenger gangway and reception, and a medical center, but the rest of the deck is confined to crew areas. Many areas have still not been determined at this early design stage. This deck also includes the forward and aft mooring stations. The mooring stations need to be checked for adequate area requirements but look viable based on reference ship arrangements. Deck 0 is shown below.

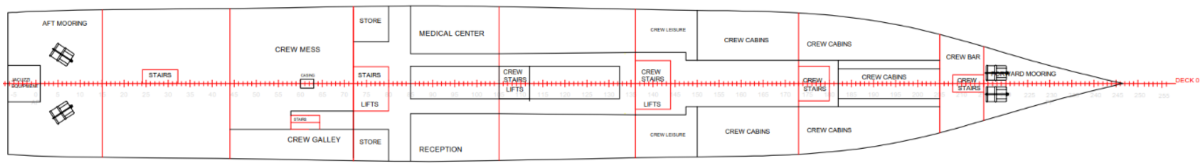


Figure 19. Deck 0

Deck 1 is the main deck, the first deck above the hull, which is unrestricted by watertight bulkheads. This deck includes passenger areas. The fore area is passenger cabins, and the aft is a bar and an outdoor deck that includes the lifeboats, liferafts, lifejacket boxes, and additional lifesaving machinery to launch the applicances. The public area and bar/lounge next to the open deck will be the muster stations. This aft deck also includes a luxury infinity jacuzzi.

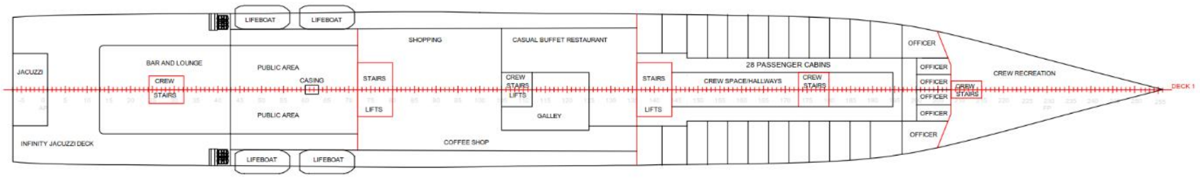


Figure 20. Deck 1

Customer cabins are located on decks 2 and 3. As the goal is to provide a luxurious experience for all passengers, the ship has only sea facing cabins. The majority of the cabins are 16.8m2, but there are some larger (up to 25m2) cabins available at the aft and front of the ship. Larger suites at the front of the ship are targeted for customers who want more space and comfort during the trip. “Igloo suites” at the aft of the ship are the most luxurious ones as they have wide windows that partly continue to the roof of the cabin. These windows enable better view and also an opportunity to see the sky from the cabin. Top part of the window must be transparent only from inside of the cabin to ensure privacy of the passengers. In total there are 176 passenger cabins, which leads to a total passenger capacity of 355.

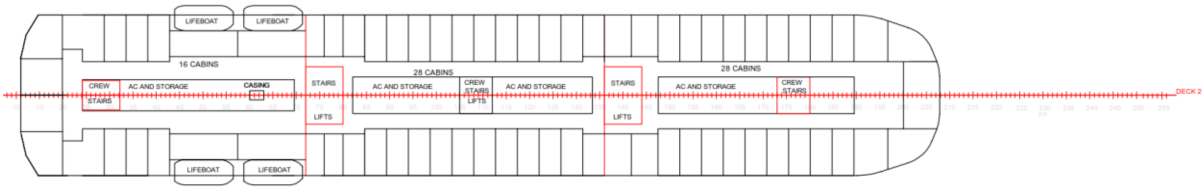


Figure 21. Deck 2

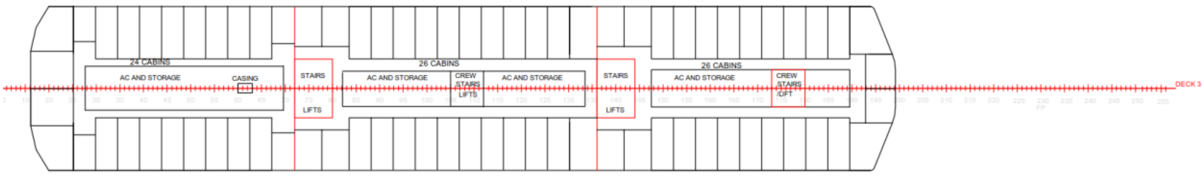


Figure 22. Deck 3

Decks 4 and 5 include some of the more luxurious aspects of the cruise. They include a spa and gym, a main restaurant and galley, an observation lounge on top of the bridge, pool deck, and a solar panel walkway that will include lights and motion activation. These decks also have a few technical requirements, like the bridge and the emergency generator room. The crew areas such as the galley, pool machinery room, and emergency generator room have been designed so the provisions can be easily transported directly from Deck C food preparation area, and so that the space is maximized for passengers (window areas unobstructed). Decks 4, 5, and 6 are shown below.

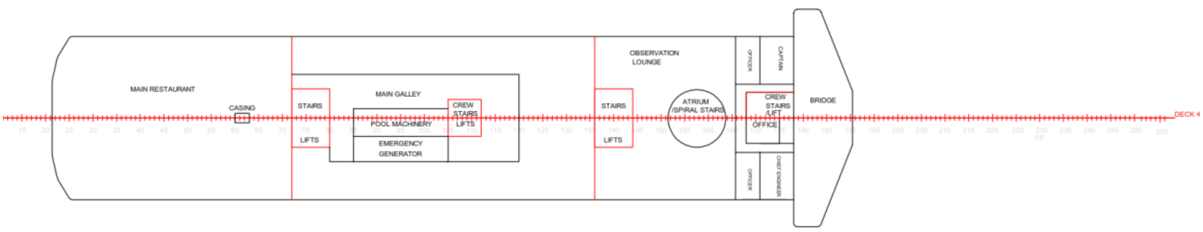


Figure 23. Deck 4

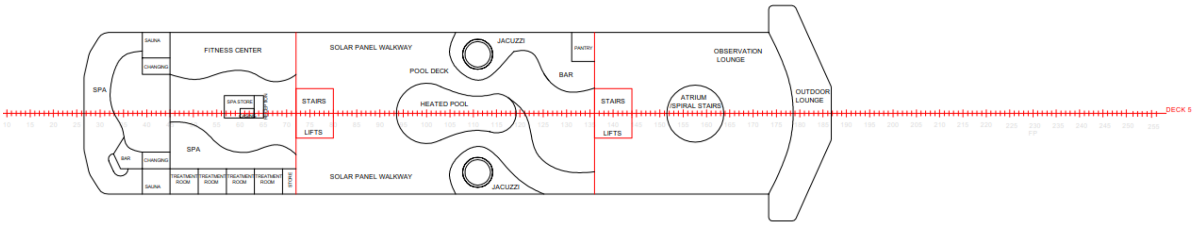


Figure 24. Deck 5

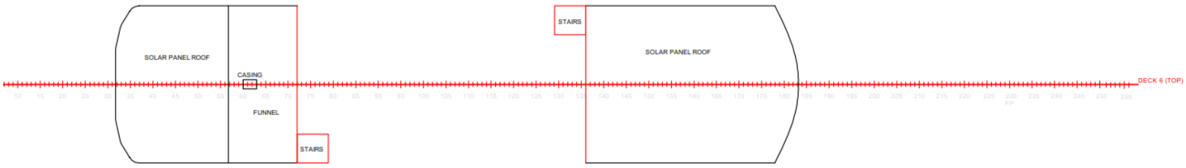


Figure 25. Deck 6

5 Structure

5.1 Structural requirements

The structural requirements for longitudinal bending strength, shear strength, hull girder ultimate strength and structural continuity of the vessel are defined by the DNV GL in the “DNV GL rules for classification: Ships (RU-SHIPS) Part 3 Hull”. Longitudinal bending strength, shear strength and hull girder ultimate strength are defined in Chapter 5, and the requirements of structural continuity is defined in chapter 3.

The longitudinal bending strength is determined in “DNVGL RU Ships, July 2020, Part 3, Chapter 5, Sec 2, 1 Vertical hull girder bending strength”, and it is determined that the continuous longitudinal strength is based on the section modulus and moment of inertia minimum requirements set within the section. When all requirements for the section modulus and moment of inertia are met, the vessel fulfills the DNV GL regulation requirements for longitudinal strength. The shear strength requirements are given in “DNVGL RU Ships, July 2020, Part 3, Chapter 5, Sec 2, 2 Vertical hull girder shear strength” where the different permissible shear forces are defined based on sea conditions and the hull girder shear capacity is calculated based on those. The hull girder ultimate strength is presented in “DNVGL RU Ships, July 2020, Part 3, Chapter 5, Sec 4 Hull Girder Ultimate Strength Check” and is determined as the vertical hull girder ultimate bending capacity, which is to be checked under hogging and sagging conditions separately.

The structural continuity of the vessel is defined in “DNVGL RU Ships, July 2020, Part 3, Chapter 3, Section 5, 2.1 Structural continuity” and states that the continuity of the ships structure must be maintained, and that attention is to be paid in areas where there are changes in the structure, and the locations of connections between primary supporting members or stiffeners. It is separately mentioned that the longitudinal members of the structure are to be arranged so that continuity of strength is maintained.

The specific structural requirements for our ship comes from the structural requirements of our particular design. One problem might be in the viability of sharp angles found in the stern section of the ship (the forward end is now curved instead). A principle of structural design is to avoid corners. Almost every structural component of a ship has curved edges. The sharp corners of our design are in our “igloo cabins,” suites designed after igloo hotels. To fit this design idea, the connections between the windows need to be angular and geometric. The analysis of this structure is not traditional, as it includes glass, and the connections have not been specified yet. It is too complex to perform at this early stage, but is something to consider in later analyses. Another structural challenge specific to our ship is that we have an ice class, so higher structural requirements need to be met.

5.2 Steel general arrangement

Frostisen is designed to operate in arctic region but only during autumn and summer seasons and there is no need for the ship to be able to operate in thick ice independently. The aimed ice class is PC 6 that allows operation in thin first-year ice. Operation in ice and low temperatures must be considered when choosing the building material of the ship. DNV GL rules for classification were used as guidance for choosing suitable hull material.

Table 17.Steel grades for weather exposed plating (DNV GL 2020)

Thickness t [mm]	Material class I				Material class II				Material class III					
	PC(1) through **(5)**		**PC(6)** and **(7)**		**PC(1)** through **(5)**		**PC(6)** and **(7)**		**PC(1)** through **(3)**		**PC(4)** and **(5)**		**PC(6)** and **(7)**	
	MS	HT	MS	HT	MS	HT	MS	HT	MS	HT	MS	HT	MS	HT
$t \le 10$	B	AH	B	AH	B	AH	B	AH	E	EH	E	EH	B	AH
$10 < t \le 15$	B	AH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
$15 < t \le 20$	D	DH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
$20 < t \le 25$	D	DH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
$25 < t \le 30$	D	DH	B	AH	E	EH [2)]	D	DH	E	EH	E	EH	E	EH
$30 < t \le 35$	D	DH	B	AH	E	EH	D	DH	E	EH	E	EH	E	EH
$35 < t \le 40$	D	DH	D	DH	E	EH	D	DH	F	FH	E	EH	E	EH
$40 < t \le 45$	E	EH	D	DH	E	EH	D	DH	F	FH	E	EH	E	EH
$45 < t \le 50$	E	EH	D	DH	E	EH	D	DH	F	FH	F	FH	E	EH

Table 17 shows the steel grade requirements for different ice classes, plate thicknesses and material classes. For aimed ice class PC 6, B/AH steel is sufficient for all material classes from 1 to 3. AH36 steel is commonly used and cost efficient and therefore, this material was chosen for the ship's hull.

5.3 Superstructure

Ship's superstructure is not in continuous contact with the seawater and therefore the loads on the structure are smaller than on the hull. When choosing the material for the superstructure the aim was to decrease the weight of the ship by using materials with lighter weight, such as composites or aluminum. Decrease in weight of the ship would increase the energy efficiency of the ship as the power needed for the propulsion is lower. Main challenges of aluminum and FRP composites are related to fire safety. Aluminum deforms when exposed to fire for a long time and composites have poor fire resistance and noxious gases might be released when the material is combusted. According to SOLAS II-2/17 it is possible to use FRP composite materials in ship, but the level of safety should be equivalent to the safety of a ship made of steel.

We searched for examples of how composites could be used in passenger ship superstructure. A concept design of using lightweight structures in a SOLAS vessel was done as a part of LASS-C project. Upper decks of an existing vessel M/S Norwegian Gem (LOA=294m, 2400 passengers) were designed to be made of FRP composite instead of steel. The material used was a sandwich construction with a lightweight core (PVC foam or balsa wood) separating two laminates of FRP. Thermal insulation was used on interior surfaces to achieve fire protection of 60 minutes. (Evegren 2015) Another example is the COMPASS project that showed how an existing RoPax vessel, Prinsesse Benedikte (LOA=142m) could be retrofitted to use composite materials on the upper deck superstructures. Sandwich faces of the material were glass fibers impregnated in Prime 20LV epoxy and the core was Divinycell P10 which has good fire and high temperature performance. (Karatzas 2016)

It is possible to use composite materials and meet the requirement of 60 minutes fire protection. However, Karatzas (2016) discusses documented accidents where fire has been burning longer and evacuation of passenger and crew has taken several hours. This is major concern that has to be considered in the design. We will continue doing research on this topic and perhaps a combination of steel and composite could be used to achieve higher level of safety during possible fire.

Cross section drawings

The cross-sectional drawings were composed using our hull and deck designs, and reference ships/course notes to estimate the parts, framing system, and sizes of stiffeners needed. These cross-sectional areas are analyzed in the next section. The following figure shows the midship section and engine section.

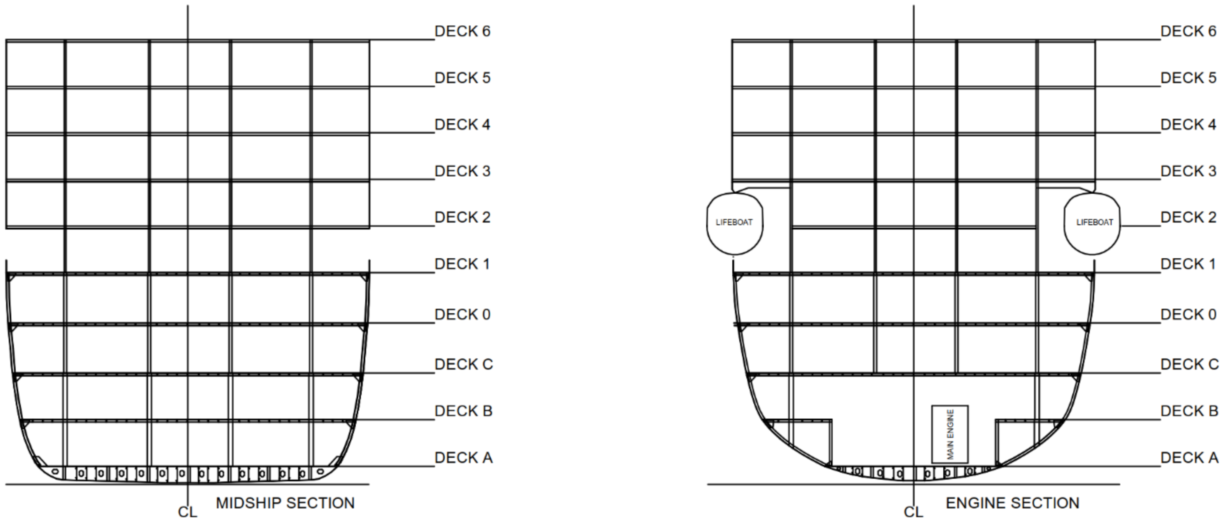


Figure 26. The midship- and engine sections of the ship

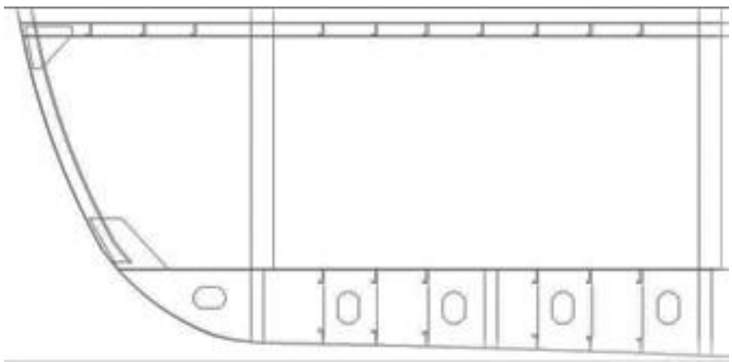


Figure 27. Detail of the midship section structure

Our ship is longitudinally framed. This means that there are longitudinal stiffeners running fore to aft throughout the ship's structural design. These stiffeners have thickness as described in the following table. The longitudinals are shown in the zoomed figure. The double bottom floor will be placed every 3 frames. Clearly, there is transverse framing as well, but the longitudinal frames are more frequent. This is typical for long passenger ships. The superstructure design is incomplete at this point, as it is made of composites. The composite design needs further research. The required thickness of the different decks and shell elements are also shown in the table. These were calculated using DNV rules.

Table 18. Coefficients and calculated values of minimum deck thickness based on DNV GL

Element		a	b	k	t_min (mm)
Shell	Keel	5	.05	.72	10.85
	Bottom/bilge	4.5	.035	.72	8.60
	Side	4	.035	.72	8.10
Deck	Weather deck	4.5	.02	.72	6.85
	Ballast tanks	4.5	.015	.72	6.30
	Other decks	4.5	.01	.72	5.70
Bulkheads	Ballast	4.5	.015	.72	6.30
	Peak	4.5	.015	.72	6.30
	Watertight	4.5	.01	.72	5.70
	Nontight tanks	5	.005	.72	5.60
	Other nontight	5	0	NA	5
	Accomodation	4.5	0	NA	4.5

Table 19. Stiffness and bracket calculated thickness based on DNV GL

Stiffener and attached end brackets	Tank boundary, single strength deck and shell up to freeboard deck	5.9
	Structures in deckhouse and superstructure and decks for vessel with more than 2 continuous decks above 0.7 D from baseline	4.0
	Other structure	5.2
Tripping brackets		5.9

Section modulus

Using the measurements from the Autocad cross-section drawing, the dimensions of items were filled in table 18 and moments were calculated.

Table 20.Measurements and calculations from the Excel.

Item	Nr. of parts	Breadth	Depth	Height	Area	1. Moment	2nd Moment @ centroid	2nd moment @BL
	n	b	d	h_j	A=n*b*d	$S=A*h_j$	$i=n*b*d^3/12$	$I_S=A*h_j^2$
[-]	[-]	[m]	[m]	[m]	[m^2]	[m^3]	[m^4]	[m^4]
Tank Bottom	1	14,240	0,011	0,005	0,155	0,001	1,52E-06	4,55E-06
Tank top	1	15,268	0,006	0,947	0,087	0,082	2,36E-07	7,81E-02
Deck	1	20,981	0,007	12,156	0,148	1,798	6,13E-07	2,19E+01
Outer shell	2	0,008	12,160	6,080	0,197	1,198	2,43E+00	7,28E+00
Inner shell	2	0,019	12,160	6,080	0,450	2,736	5,54E+00	1,66E+01
Long. bulkhead	1	0,208	12,160	6,080	2,532	15,397	3,12E+01	9,36E+01
				∑	3,569	21,211	39,175	139,462

From there, the required values to calculate the stress were calculated and these results are shown in table 3.

Table 21.Calculations from the Excel.

Total cross-section		
Ship Depth D	12,16	m
Neutral axis	5,94	m from BL
Elements, $i_{,tot}$	39,17	m^4
Elements, $I_{S,tot}$	139,46	m^4
I_{BL}	178,64	m^4
I	52,56	m^4
Z_{deck}	8,456	m^3
Z_{bottom}	8,844	m^3

For calculating the stresses at the deck and the bottom of the ship, the bending moment must be defined. This has been done based on DNV GL rules Part 3 Chapter 4 on ship loads. Computed bending moments for hogging and sagging are:

Hogging = 577898.4 kNm

Sagging = -491213.7 kNm

Value for hogging is used for calculations as it is larger.

And finally, using the bending moment, stresses were calculated and the results are shown in table 20.

Table 22.Load and response as in section modulus excel

Load and response		
Moment	5.80E+08	Nm
σ_{deck}	68.59	MPa
σ_{bottom}	65.58	MPa

6 Power and machinery

6.1 Operating profile

Frostisen will not have a fixed route and schedule, but those will vary depending on the season and market demand. An example route was created based on routes of reference ships with similar mission. The route is from Oslo to Longyearbyen with two stops at Bronnoysund and Tromso. Total cruising time is 5 days and 4 hours, and both stops are 4 hours long and the total distance is 1830 nautical miles. Length of the cruise can be easily modified by adding or removing stops.

Figure 28.Example route of the ship

The power need of the ship depends mainly on the ship speed. Frostisen is assumed to travel with a speed of 3 knots in difficult locations, such as archipelago and port areas, 16 knots near areas where speed might have to be decreased and 18 knots in open sea. Estimation of the propulsion power at different speeds has been described in the following chapters. Auxiliary power needs are assumed to stay constant during the cruise except for the bow thruster that is assumed to be used only when the ship is manoeuvring (at speed of 3 knots or less). Power load in comparison to the total power production capacity of the ship is shown in the figure below.

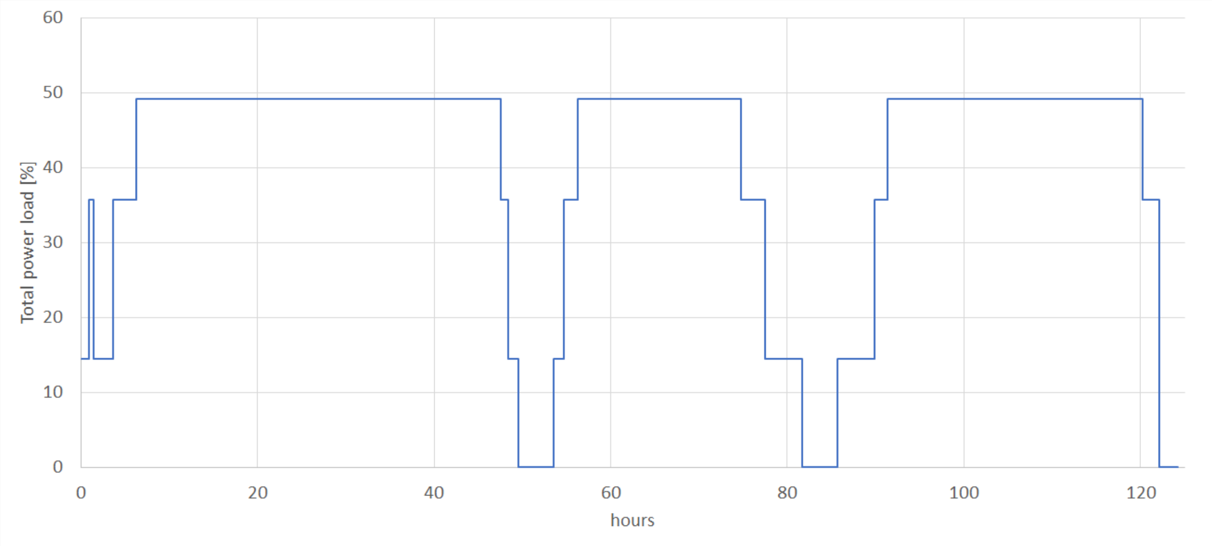


Figure 29.Power load of the ship during the example route

This graph only shows the estimation of the power consumption. The ship is designed to have a battery system and therefore, the main engine of the ship can be operated at the optimal load most of the time and additional power need can be covered with the battery system. This will improve the flexibility and efficiency of the ship.

6.2 Resistance and propulsion power

Propulsion power of the ship is calculated with method proposed by Holltrop and Mennen (1982). Input values of our ship are taken from Autocad drawings and the Delftship model.

Table 23.Principal particulars

LBP [m]	135.8
B [m]	20.9
T [m]	5.5
lcb [%]	-0.782
Cp	0.679
Cb	0.584
Cms	0.861
Cwp	0.804
Abt [m2]	3.5
Cstern	0
Tf [m]	5.5
Ta [m]	5.5
hb [m]	3.741
At [m2]	0
S [m2]	3016.8

After few iterations, an ABB Azipod DO1600P was chosen for the ship's propulsion and the propulsion particulars used in calculations were defined based on the product manual. The method used for resistance calculations is based on more traditional propulsion systems and therefore, using Azipod might increase the uncertainties of the resistance estimation.

Table 24. Propulsion particulars

Number of blades	Z	5
Pitch of the propeller	P (m)	3.00
Diameter of the propeller	D (m)	4.0
High of the shaft from keel line	Hp (m)	1.5
Single-screw or twin-screw	K	0.1
Open water efficiency	eta0	0.63

Different appendage particulars also affect the ship resistance. Used method lists different items that should be considered and the only particular on the designed ship is the bow thruster. Diameter of the bow thruster is 2.2 meters.

Method by Holltrop and Mennen (1982) estimates the ship's resistance in calm water and without biofouling on the hull. The actual resistance will be larger due to the impact of weather and sea conditions and biofouling. IMO (2014) proposes typical sea margin of 10 – 30 % power addition due the weather. We used a sea margin of 15 % to estimate the average power need of the ship's propulsion and 30 % margin to estimate the maximum power need in more difficult weather conditions. IMO (2014) also uses an addition of 9 % power need due to hull biofouling. This value is very conservative and with proper maintenance it can be kept lower. However, for the design we use the 9 % increase in power due to hull fouling to ensure the capacity of the ship's power plant and propulsion.

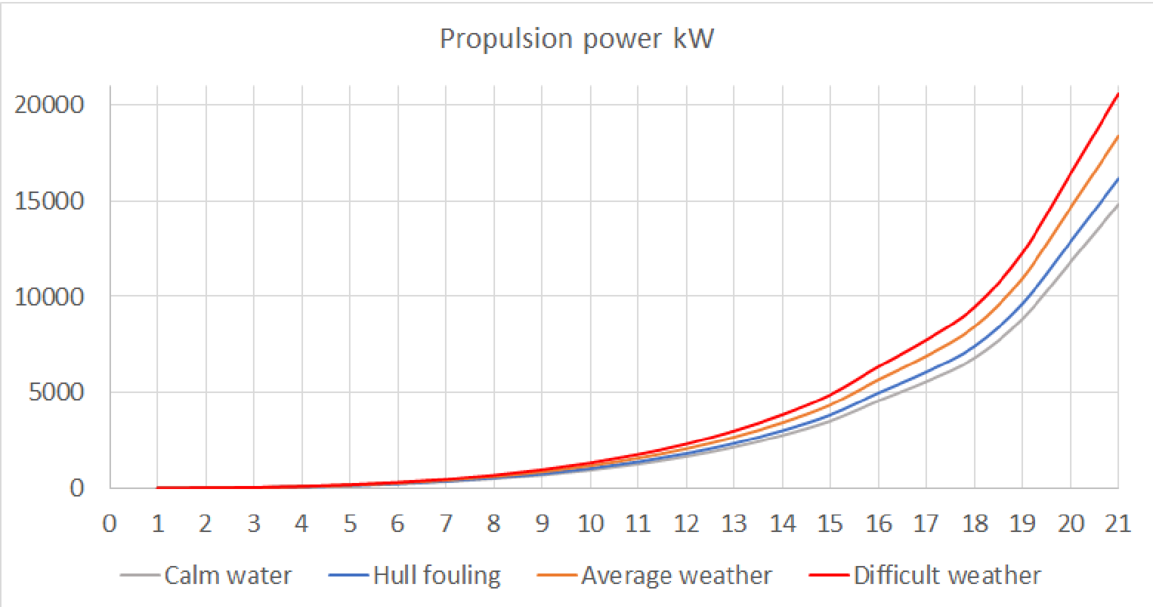


Figure 30.Propulsion power need in calm water without hull fouling (grey line) and with maximum hull fouling (blue line) and in average weather conditions (orange line) and difficult weather conditions (red line). Both weather scenarios include estimation of the

The design speed of the ship is 16 knots, and this speed should be achieved in most of the weather and sea conditions. The maximum speed of Frostisen is 21 knots and this can be achieved with propulsion power of 14800 kW in calm water conditions. This value is used for choosing the propulsion machinery of the ship.

6.3 Total power demand

Hoteling load of a cruise ship can be significant and therefore, some estimation of the accommodation power needs must be done at the early stage of the design process. The power need of the vessel can be estimated by assuming that each passenger requires 3 kW power for accommodation and services on-board (CMP and the City of Copenhagen 2015). With passenger capacity of 355 and 55 crew members, the hoteling load of Frostisen is 1230 kW.

For sizing the bow thruster, Wärtsilä recommends 0.6-0.8 kW per m2 of wind area. Using an average value of 0.7 kW/m2, the required bow thruster power is estimated to be approximately 1800 kW. Additional 500 kW is reserved for other auxiliaries, such as engine and fuel auxiliaries.

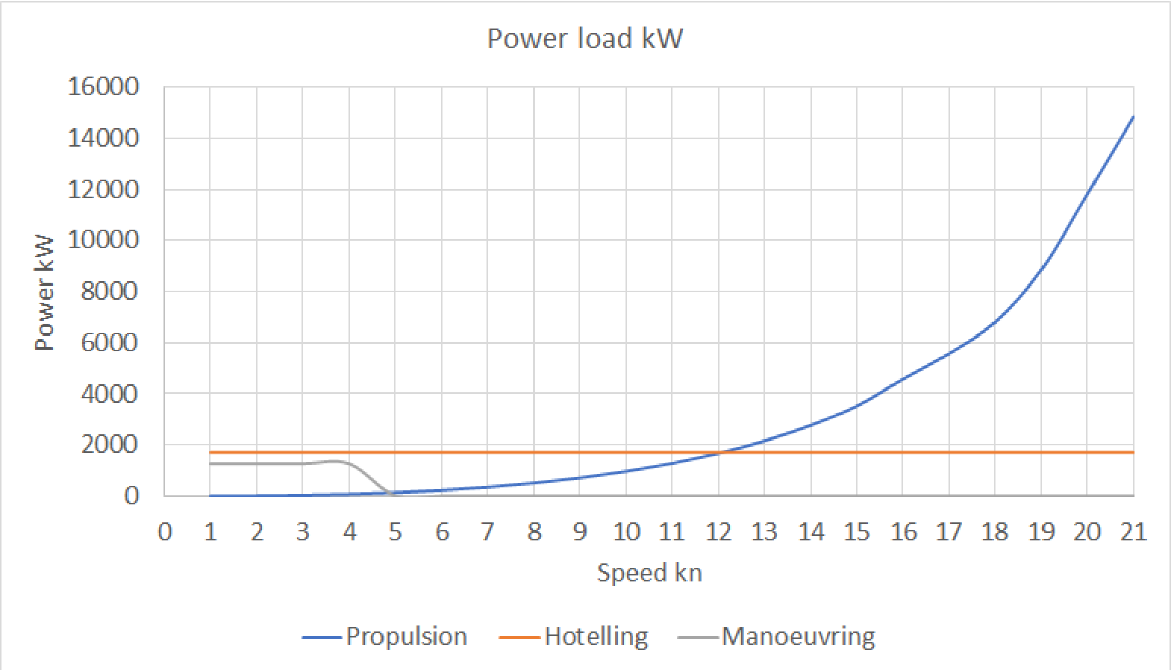


Figure 31. Power need of the ship as a function of ship speed

Maximum auxiliary power need is estimated to be 3530 kW. Combining this with the maximum propulsion power, the maximum power need of the ship is 18500 kW. There are large uncertainties especially considering the estimation of auxiliary power need of the ship as most auxiliary systems will not be defined at the concept design phase. The estimation will be more precise as there are more details in the design.

6.4 Machinery

In the case of the propulsion system, a couple of ABB Azipod DO1600P with a power of 7.5 MW each using 4 meters diameter propellers with 3 meters of pitch.

Regarding the energy source chosen, the Frostisen will use mainly LNG with a minimal amount of diesel to keep the engine working. The engine chosen will be a dual fuel engine two strokes.

This dual fuel engine type was used due to its low emissions of unburned methane. Methane is a greenhouse gas that has a higher warming potential than carbon dioxide and therefore, methane emissions can quickly make the GHG reductions of LNG irrelevant. Frostisen is a luxury ship that targets customers that want to experience arctic nature without damaging it. Reducing the GHG emissions of the ship plays an important role in the sustainability of the ship, but also in the marketing possibilities.

The engines chosen are a couple of 2-stroke MAN B&W 6G50ME-C9.6-GI-LPSCR that will be used in the Dual-fuel mode to meet the Tier III regulations. This engine model has a power of 10,320kW with a fuel consumption of 141,2 g/kWh of gas plus 5,1 g/kWh of diesel using an exhaust gas bypass for work in cold temperatures.

These engines will be coupled with two MAN TCA66 turbochargers and two Siemens 1DT1142-1XE04-07A2 generators capable of generating 13,240 kW each, and with an efficiency of 97,98%.

The total maximum power than the ship can produce without solar power is 20,223 e-kW.

The electricity produced will be sent to the batteries and from there to all the systems of the ship. Using the batteries will help to combine several different energy sources as solar panels will also be installed on the ship. Battery system will also increase the efficiency and flexibility of the ship power production.

The battery system in Frostisen has a capacity of 18 MWh occupying around 150 m^3 and is connected to all the ship through an AC line.

Solar panels

The use of solar panels to supply a portion of the power requirement of the vessel would reduce the overall emissions. Due to the routing of the vessel, and the seasons during which it would be in certain parts of the world (winter months in the Antarctic and summer months in the Arctic), the length of day would be at its highest, even reaching 24h sunlight when beyond the polar circle during mid-summer. This would allow for continuous power generation with solar panels, but due to inclination of the earth, the insolation of the polar regions is weaker than between the tropics and the polar circles. Due to the low angle of the sun, it is best to use sun tracking with the panels as keeping the cells pointing directly at the sun allows for the largest amount of solar radiation to reach them.

As found in Solar cell efficiency tables, using multi-junction solar cells, it is possible to reach efficiencies around 40%, with a more common efficiency of approximately 35%. Comparing this to single-junction solar cells, which are the most common type of commercial cell, that can achieve an efficiency of 23% and are generally heavier than multi-junction cells, it is apparent that the use of multi-junction cells is optimal. The losses imparted on multi-junction cells are also less than with single-junction cells, and due to the lower temperatures in the polar regions, the thermal losses of the cells should be lessened.

A slightly simplified calculation for power output of solar cells follows as:

$$E = A * r * H * PR$$

Where A is the area of the panel in m2, r is the efficiency of the panel, H is the average irradiation at the angle of the panel over an area, over a time period, and PR is the performance ratio of the cell which is calculated from the losses, with a default value of 0.75. Using a mapping of monthly average daily irradiation of Norway as reference, the irradiation can be estimated as 4000 Wh/m2/day. Using an estimation of 0.8 performance ratio, to account for lower thermal losses, and 35% as the efficiency of the panel, we get an approximation of 1117 Wh/m2 as the energy output from the panels. If using the highest efficiency cells with 40% efficiency, we get 1277 Wh/m2 as the energy output.

Depending on the area of solar panels able to be placed on the vessel, it is possible to produce a portion of the hoteling load of Frostisen with solar panels. It needs to be noted that the solar tracking of the panels will require a portion of the power produced and that the value of daily irradiation is a monthly average, meaning there will be variation from day to day.

6.5 Emissions

One of our design targets is to ensure sustainability of the ship to protect the arctic environment and to attract customers. Expedition cruises are often marketed for people who are interested in environment and therefore, it is important to be able to convince customers that the ship is more ecological than competing expedition cruise ships.

Exhaust gases from the engine are one important factor defining the environmental impact of the ship. We have estimated average emission rates of some major pollutants generated by the ship engine and these rates are shown in the table below.

Table 25. Estimated average emission rates

Pollutant	**g/kWh**	**source**
NOx	2.8	Engine manufacturer
CH4	0.2	ICCT (2020)
CO2	440	SINTEF (2017)
PM	0.02	VTT (2019)

Engine uses LNG as the main fuel which decreases many emissions, such as sulfur oxides, black carbon and particulate matter, in comparison to conventional marine fuels. Frostisen also has a Selective catalytic reduction (SCR) system that controls NOx emissions. One major issue with LNG engines is the emissions of unburned methane as CH_4 has higher global warming potential than carbon dioxide. Study by ICCT (2020) shows, that high pressure two-stroke engines have significantly lower CH_4 emissions than other dual-fuel marine engine types.

Actual emission rates depend on the operation of the engine. Battery system makes it possible to optimize the engine operation so that the fuel consumption can be minimized. This will not only decrease the emissions but will also lower the fuel costs of the ship operation. Battery system allows ship to be operated while the main engines are shut down. When only battery power is used, the ship will be in zero-emission mode and will also be more silent. This operation mode can be used in areas with sensitive environment or in the night, to provide additional comfort for the passengers.

7 Outfitting

7.1 Main equipment

Besides the main machinery, powering, and propulsion equipment, the ship needs much more machinery and equipment to run. The most important systems in terms of the ship's operation include the anchoring, mooring, and life saving systems. Anchoring and mooring are crucial to the operation of any vessel, and life saving equipment is especially important for passenger ships.

The anchoring system will be a traditional two stockless bow anchors. The requirements for our anchoring system came from the International Association of Classification Societies guidelines. These guidelines provided an equation that was evaluated to decide on the anchor weights and chain lengths and diameters. The following equation was used to find the equipment number (EN):

$$EN = \Delta^{\frac{2}{3}} + 2.0\,(hB + S_{fun}) + \frac{A}{10}$$

The displacement and beam are known, but the between the waterline and top of superstructure h, and the wind area A were calculated using our GA. The EN for our ship is 1700, which results in two anchors each with a weight of 5240 kg, and two anchor chains each with a length of 577.5 meters and a diameter of 73 mm if using mild steel grade. The information about the anchor and chain will be useful in further developing the GA and weight analysis.

The mooring system is on Deck 0. Our ship will have two mooring stations, one forward and one aft. The mooring stations will be below the passenger decks, 1 deck below the main deck. There will be openings for the mooring lines. This way no space is taken away from the passenger experience which will make the ship more profitable and more aesthetically pleasing to customers.

The life saving equipment was chosen in accordance with SOLAS requirements. The SOLAS requirements are such that 50% of total persons onboard must fit into the lifeboats on each side of the ship. In the case that we have extra life rafts, we can fit 75% of total persons on board, and an additional 50% on life rafts, totaling to the capacity of 125% of persons onboard. To figure out the exact equipment needed, we first chose the capacity of passengers and crew. Based on the number of cabins and the reference ships for the crew members, we chose a maximum passenger capacity of 355 and a maximum crew capacity of 65. The total persons on board is 420 maximum.

To better fit the lifeboats and conserve space, we chose to have 4 lifeboats of 80 persons capacity and 6 liferafts of 35 person capacity. The total capacity of lifeboats is 320, which matches the requirement. The total capacity of liferafts is 210. The total liferaft capacity must be at least 210 (25% for total persons on board, and 25% additional). The lifeboats we chose are the Viking NORSAFE JYN-85. This boat has dimensions of 8.56 x 3.15 x 3.30 m, and were placed on the GA accordingly. The hook for this boat was chosen also from this company. Two lifeboats will be placed on each side of the ship, and the liferafts are placed just aft of them. The liferafts are 35 person liferafts, and the launching system is also drawn on the GA. These lifrafts are stacked and have a crane that will slide the liferafts and launch in case of emergency. The additional equipment for liferafts and lifeboats are not specified, but the systems used here are standard and meet requirements. The muster stations will be in the outdoor deck space next to this equipment, and inside the adjacent bar if needed.

8 Weight and stability

8.1 Lightweight and centre of gravity

Main components and systems of Frostisen have been classified according to the SFI group system and relevant groups are shown in the table below. As the design project is at the concept phase, it is not yet possible to determine weight of all components.

Table 26. SFI grouping system

1	**Ship General**		**Item**	**Weight ton**
	10	Specification, estimating, drawing,		
	11	Insurance, fees, certificates		
	12	Quality assurance, general work, models		
	13	Provisional rigging		
	14	Work on ways, launching, docking		
	15	Quality control		
	16	Guarantee/mending work		
	17	Ship repair, special services		
	19	Consumption articles		
2	**Hull**			
	20	Hull materials, general hull work		3746.4
	21	Afterbody		
	22	Engine area		
	23	Cargo area		
	24	Forebody		
	25	Deckhouses and superstructure		354.19
	26	Hull outfitting		2440.9
	27	Material protection, external		
	28	Material protection, internal		
3	**Cargo Equipment**			
	30	Hatches, ports		
4	**Ship Equipment**			
	40	Anchoring Equipment		
	41	Mooring Equipment		
	42	Manoeuvring Equipment		
	43	Communication Equipment		
	44	Navigation Equipment		
5	**Passenger and Crew Equipment**			
	50	Lifesaving Appliances, Medical Equipment		
	51	Furniture, Entertainment, Inventory		
	52	Galley/Restaurant, Provisions, Laundry		
	53	Sanitary Systems		
	54	Pool Equipment		

	55	Transport Equipment		
	56	Ventilation		
	57	Cabins		
	58	Ladders, Stairs, Lifts, Deck Coverings, Railings		
6	**Machinery Main Components**			
	60	Main engine	2x MAN B&W 6G50ME-C9.6-GI-LPSCR (250t)	700
	62	Thruster	Wartsila WTT-18	12.25
	63	Azipod	2x ABB Azipod DO1600P (100t)	200
	64	Economizer		
	65	Generator	2x Siemens 1DT1142-1XE04-07A2 (25t)	50
7	**Systems for Machinery Main Components**			
	70	Fuel systems		518
	71	Lube oil systems		16
	72	Cooling systems		
	73	Compressed air systems		
	74	Exhaust systems & air intakes		
	75	Steam, condensate & feed water		
	79	Automation systems for machinery		
8	**Ship Common Systems**			
	81	Firefighting and Emergency Alarm		
	85	Electricity transformer		
	86	Battery	5040x 12V300Ah (43.kg)	217.22
	87	Electric Cable installation		

Lightweight calculations of the ship were done based on a method by Watson and Gilfillan. One special feature of Frostisen is the composite superstructure and some additional calculations are needed to estimate the structural weight of the ship. The method for defining the composite weight is explained in more details later in the report.

Table 27. Structural weight

Length of superstructure (m)	109.8
Height of superstructure (m)	24.5
Length of deckhouse (m)	0
Height of deckhouse (m)	0
E	6679.72
K	0.038
WS Steel superstructure	1949.97
WS Hull	3746.40
KGhull (m)	**6.27**
LCGhull (m)	**67.41**
WS Composite superstructure ton	354.19
WS Composite structure + Hull ton	**4100.58**
WS Steel structure + Hull ton	5696.36

Table 28. Machinery weight

MCR (KW)	10320
N (rpm)	100
type of plant	Diesel electric
No of engines	2
cm	0.83
W_M (tonne)	**972.753**
Height of engine room (m)	9.35
Height of double bottom (m)	1.05
KG_M (m)	**3.955**

Table 29.Outfitting weight

Outfit coefficient (Co)	0,86
Outfitting weight (Wo) ton	**2440,9**
KG_O (m)	**13.86**

Table 30.Ship's main characteristics

L (m)	135.8
B (m)	20.9
T (m)	5.5
D (m)	12.5
CB	0.5844
LCB (m) @AP (m)	67.556
Lightship weight (with composite) ton	**7514.21**
Lightship weight (without composite) ton	9109.98
KGLight	**8.44**

8.1.1 Composite weight calculation

In the case of our vessel, the weight estimation of the superstructure, if built from a composite, was done with the assessment of the critical property of the structure. The structure made from composite may be membrane or bending critical. That is:

Membrane, e.g. topmost decks, and bottom plating far from hull girder neutral axis,

Critical stiffness: $EA = E * b * t$

Critical strength: $\sigma_{critical,memb} = F/(b * t)$

Bending, plating participating mainly on local pressures due to cargo, hydrostatics,

Critical stiffness: $EI = E * b * \frac{t^3}{12}$

Critical strength: $\sigma_{critical,bend} = 6 * \frac{M}{t^2}$

The critical bending strength (Flexural strength), and -membrane strength (Yield strength) are known for different materials, so it is required to calculate the critical force and moment to exceed these values. Granta Edupack was used for acquiring the material properties and plotting Ashby diagrams for material selection, which are presented in Appendix B.

Table 31. Refrence steel for weight calculation

Reference material	ASTM992
Young's modulus E (GPa)	200
Yield strength (MPa)	345
Flexural Strength (MPa)	291
Density (kg/m^3)	7800

For the calculations, the properties of the refence material were defined, with ASTM 992 structural steel used as a base, since it is, according to different steel manufacturers, an equivalent to ABS AH36 steel, which is used in our vessel. AH36 itself was not used as the necessary properties could not be acquired.

Table 32. Deck lengths and thicknesses

Deck	Deck length (m)	Deck thickness (m)
5	96.1432	0.00685
4	101.4785	0.0057
3	109.8302	0.0057
2	118.1529	0.0057

The length and thickness of each deck in the superstructure were defined, and with these values the calculations could be done.

Table 33. Critical membrane- and bending stiffness, and -strength for the decks

	Membrane		Bending	
Deck	Stiffness (N)	$F(N) = \sigma_{critical,memb}(b * t)$	Stiffness (Nm^2)	$M(Nm/m) = t^2 * \frac{\sigma_{critical,bend}}{6}$
5	1.31716E+11	227210417.4	515037.7203	2275.74125
4	1.15685E+11	199557470.3	313218.4642	1575.765
3	1.25206E+11	215981088.3	338996.4038	1575.765
2	1.34694E+11	232347677.9	364684.8335	1575.765

After calculating the critical values, the thickness of the composite required to exceed these values can be calculated. The values for the composite used in the calculations are presented below and the choice of composite was dictated by Ashby diagrams of Young's modulus, Yield strength and Flexural strength as functions of density, and all composites were restricted to be classified as non-flammable. The composite chosen is a Cyanate ester/HM carbon fibre composite as it has the highest mechanical properties of the available composites and has a low density.

Table 34. Composite material properties

Composite option:	Cyanate ester/HM carbon fiber, UD prepreg, UD lay-up
Young's modulus (GPa)	299
Yield strength (MPa)	1890
Flexural Strength (MPa)	1890
Density (kg/m^3)	1620

Table 35. Calculated composite thickness based on critical strength and -stiffness

	Composite thickness in **(m)** based on:				
Deck	Membrane Stiffness	Membrane Strength	Bending Stiffness	Bending Strength	T_{min}:
5	0.00458194	0.001250397	0.00599069	0.002687857	**0.00599069**
4	0.003812709	0.001040476	0.004984954	0.002236611	**0.004984954**
3	0.003812709	0.001040476	0.004984954	0.002236611	**0.004984954**
2	0.003812709	0.001040476	0.004984954	0.002236611	**0.004984954**

The minimum thickness for each deck is based on whether the deck structure is membrane or bending critical. With the values of the composite thickness known, the mass per area of both the steel and the composite can be calculated, and the ratio between the two can be attained.

Table 36. Steel and composite weight per area and the ratio of these values

Ref.Mat. (kg/m^2)	Composite (kg/m^2)	Weight ratio between Ref. to composite
53.43	**9.704917663**	**0.181637987**

The weight estimation for the composite structure can be done by calculating the steel superstructure weight using the Watson and Gilfillan approach, and then multiplying it with the weight ratio. This gives us a steel superstructure weight of 1949.97 tons and composite superstructure weight of 354.19 tons, leading to an approximate 82% weight reduction.

8.2 Deadweight

As a cruise ship, Frostisen is not carrying cargo, but the weight of passengers must be included in the deadweight. Each passenger is assumed to weight 90 kg with their belongings. With average passenger capacity of 355, the weight of passengers is 31.95 tons.

Size of the freshwater tank can be estimated by using a design value of 0.17 tons/person of water per day. With 400 people on ship and recommendation of 10 days storage, the weight of the water tank is 680 tons. As most of the cruise ships, also Frostisen would most likely have a distillation onboard. Weight of the crew and their effects is estimated to be 0.17 tons/person. Frostisen has 55 crew members so the weight is 9.35 tons. Weight of provisions is estimated to be 0.01 tons/(person*day). For one week and 400 people, the weight is 28 tons. Weight of the fuel that should be carried can be estimated as:

W(fuel) = SFR * MCR * range/speed *margin

The ship has two 6G50ME-C9.6-GI engines and the maximum continuous rate is 20640 kW. These engines are dual fuel and therefore, two separate calculations are done for LNG and diesel fuels. Fuel consumption rates according to the engine manufacturer are 141,2 g/kWh of methane and 5,1 g/kWh of diesel. Design speed of the ship is 16 knots and the distance we want the ship to be able to travel with one tank is 2500 nautical miles. Design margin of 10% is used. Based on these, fuel weights are 500 ton of LNG and 18 ton of diesel. These estimations are very conservative as the actual power consumption of the ship travelling with a speed of 16 knots is only 35% of the maximum power.

Amount of lube oil needed on-board is calculated based on recommendations of the engine manufacturer. The recommended tank size is 17m3 and the weight of the full tank would be approximately 16 tons.

Table 37.Items in deadweight calculations in tons

Cargo	31.95
Fuel (LNG)	500.907
Fuel (MDO)	18.09225
Lube Oil	16.02
Fresh Water	680
Crew	9.35
Ballast	0
Provisions	28
TOTAL DWT	1284.3

8.3 Displacement

After both lightweight and deadweight of the ship are known, the displacement can be calculated. Summary of the ship weight and main coefficients related to weight are listed in the table below.

Table 38. Weight of Frostisen

Lightweight	7514.21
Deadweight	1284.32
Displacement	8849.33
Displacement (Delftship)	9353
Lightweight / Displacement	0.85
DWT / Displacement	0.15

Displacement from calculations is compared to the displacement based on the Delftship model and there is a margin of 555.5 tons between these weights. The margin is 7.4 % of the ship's lightweight while the recommended margin at concept design phase is 15 %. Low margin should be considered in the next design steps especially, because the ship has a low DWT/displacement ratio and therefore, the weight estimation more sensitive for errors in the calculations. Regardless the margin being still lower than recommended, there has been significant improvements in it during the design process. After first weight calculations, the calculated displacement was 25 % larger than the displacement of the Delftship model. The displacement was increased by changing the ship's draft.

9 Costs, price, and contract

9.1 Building costs

For the building cost estimation, similar basic ships were checked, and a percentage of cost for each part of the ship was used.

From reference ships we could get an average part cost as can be seen in the following table:

Table 39. Split cost in similar ships

Hull	Machinery and Propulsion	Cargo containment and handling	Common system/Assembly and system integration	Hotel and accommodation
25	21	12	20	22

With this information and using the hull price, we were able to estimate each part cost, but as we have several special systems due to the luxury nature of the ship, we took the out to add them afterwards.

For the basic hull plus superstructure made of steel, we calculated the weight of the metal used and the building costs with 500 operators working for 1 year as follows:

Table 40. Hull and metal superstructure cost

Piece	Tonnes	€/kg	Total price (€)
Hull	3746	0.736	2 757 056
Superstructure	1950	0.736	1 435 200
Build cost	500 workers / 12 months	16€/h	16 700 436
Total			20 892 692

By using the previously obtained percentages, we could get the price of a ship with the main characteristics of ours but without the extra equipment that the Frostisen has (as batteries, solar panels, the composite superstructure and the extra cost in machinery and systems due to the dual fuel).

Table 41. Split cost

Hull	Machinery and Propulsion	Cargo containment and handling	Common system/Assembly and system integration	Hotel and accommodation
20 892 692€	17 549 861.28€	10 028 492.16€	16 714 153.60€	18 385 568.96€

This “total” price is 83 570 768.00€ to which we added a 7% (5 849 953.76€) in financial costs (assumed as unexpected material need, problem fixings, etc), getting a basic ship total cost of 89 420 721.76€.

For the extra systems in our ship, a 10% (8 357 076.80€) was added in concept of extra for machinery due to our use of Azipods plus dual fuel generators and all the subsystems that these include, a 5% (4 178 538.40€) was added in concept of extra systems mainly for the use of the huge battery system that will need to be refrigerated, the converters, power managers, etc..., and the extra cost of the composite superstructure (354 tonnes at 188€/kg (66 587 720.00€) minus the price of the precalculated steel superstructure (1 435 200.00€) totalling 65 152 520.00€), batteries (15 250 000€) and solar panels (with a calculated price of 86.21€/m^2 for 1400m^2, and a total of 120 689.66€) to get a final estimated price of **182 479 546.62€**

The SFI system developed in last week's assignment is a categorization system for equipment onboard the ship. The SFI system is used in this case to check the cost estimation developed by the coefficient method. Each category is examined for its key components, checking against the calculations above. The calculation for the building costs includes hull, machinery and propulsion, ship common systems/system integration, outfitting, hotel and accommodation. Our SFI groups level 1 is ship general, hull, cargo equipment, ship equipment, passenger and crew equipment, machinery, machinery systems, and ship common systems. The analysis of these categories alongside the categories of the cost estimation are shown below.

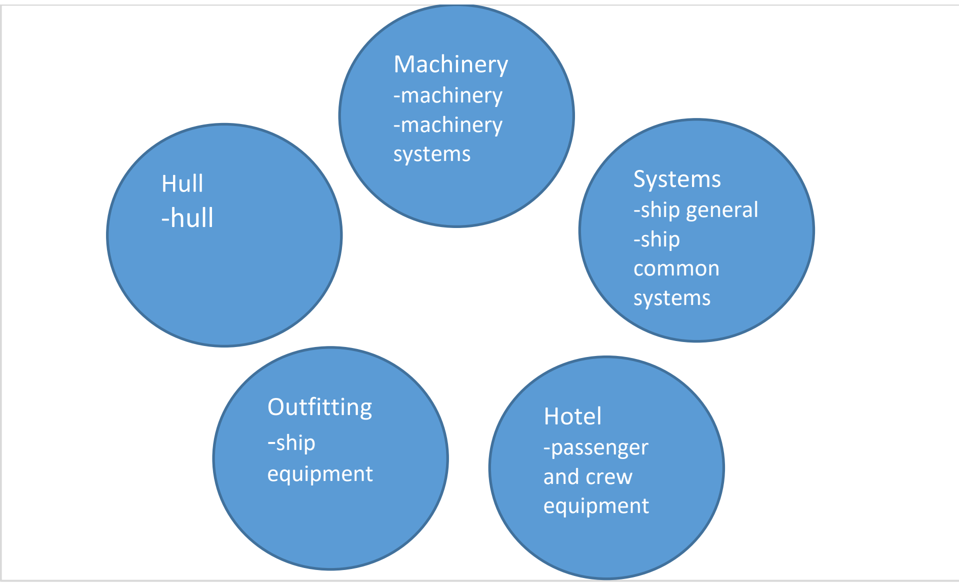


Figure 32. Cost Estimation Parameters with SFI Categories in Each Parameter

To check the building cost, we also compared our estimation with reference ships. Publicly available building cost information is a bit hard to find, but we were able to find some articles containing building costs from the shipyards. The table below shows the reference ships' building costs, comparing to Frostisen.

Table 42. Building cost comparison

Ship	Cost	Length OA (m)	# of PAX
Frostisen	€183 M	158	355
National Geographic Endurance	€113 M	124	126
National Geographic Unnamed Sister Ship	€126 M	124	126
Quark Ultramarine	€134 M	128	200
Ponant Le Laperouse	€125 M	131	270
Scenic Eclipse	€190 M	168	228
Seabourne Sojourn	€200 M	198	450
Crystal Endeavor	€180 M	183	200

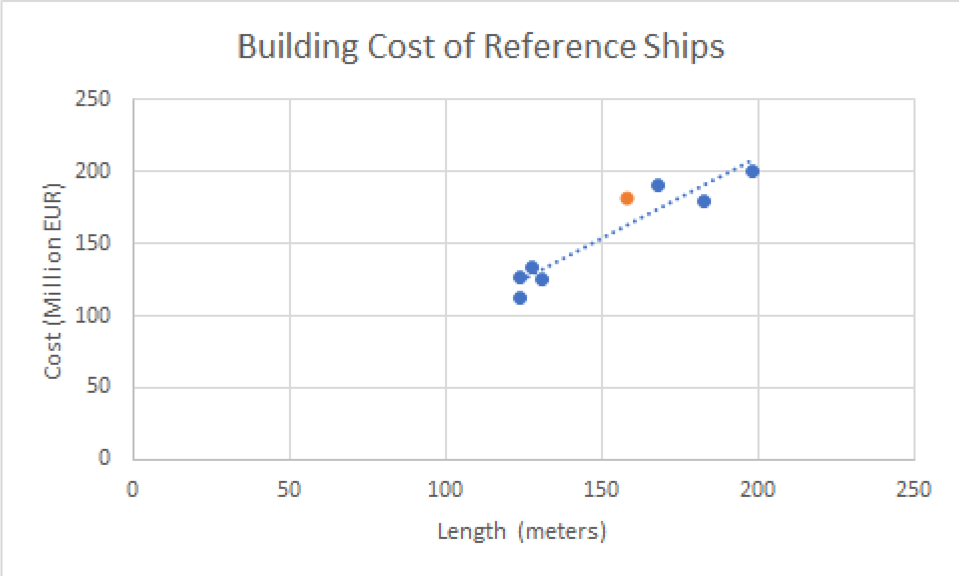


Figure 33.Building Cost of Reference Ships (Blue) and Frostisen (Orange).

It is difficult to make a direct comparison between our ship and our reference ships because there are so many factors that affect the cost. Figure 2 compares the cost per length of each reference ship with Frostisen (shown in orange). Clearly, the building cost of Frostisen fits the trend with the reference ships.

The initial cost of Frostisen's machinery is higher than many references as azipods, batteries, electric machinery, and solar panels all have high initial cost. Frostisen's concept is based on having a clean cruise, reducing emissions, creating a passenger experience that centers around the environment and Frostisen's relation to it. The initial high cost of these experiences leads to a payback in attracting the right customers who will pay more for an environmentally clean cruise. Expedition cruise ships are already niche and designing a ship to be even more niche is a strategy to set it apart from the competitors. Ponant is a good comparison to Frostisen in this regard, because Ponant cruises are also niche, high luxury, with similar machinery and mission. The building cost of Le Laperouse is the best comparison to Frostisen, in size, luxury, machinery, and mission. Seabourne Sojourn is also a good comparison. Though it is more of a traditional cruise ship, Seabourne Sojourn is closer in size and passenger capacity to Frostisen. It fits, then, that Frostisen is between these two costs, with Le Laperouse costing €125 M and Seabourne Sojourn costing €200 M.

One other key difference between Frostisen and the reference ships is the high cost of composites. Composites in our design represent a 400% increase in cost as compared to steel. This only affects the superstructure, which will be made partially by composite material in combination with thin steel plates. The composite design will again be attractive to customers, set Frostisen as a technically innovative ship, and most importantly for the cost analysis, will reduce fuel consumption. The composites and machinery, while having a high initial cost will provide a lower operational cost. The payback period for the composites and different machinery components may extend further than the lifetime of the ship but are still a good choice in terms of marketability, future emission regulations, and care for the environment.

10 Evaluation

10.1 KPIs

Net present value (NPV) of the ship was calculated to ensure the profitability of the design project. To estimate the NPV for each year and the payback period, costs and incomes must be estimated. The ship is assumed to be 240 days in operation per year.

Income

Main source of income for the cruising company is the ticket sales. Additionally, each passenger will use some money on-board for shopping, beverages or services that are not included in the ticket price. Luxurious expedition cruises have higher pricing than traditional cruises and prices of several expedition cruise companies (such as Poseidon, GAdventures and Quark expeditions) were compared to gain understanding of reasonable ticket prices. Prices varied from 230 euros to 1350 euros per day per passenger. Maximum passenger capacity and ticket prices per person per day of different cabins in Frostisen are listen in the table below.

Table 43. Passenger capacity and ticket price per passenger per day

Cabin	**Passengers**	**EUR**
Standard suite (2 persons)	292	700
Family suite (3-4)	31	800
Deluxe suite (2 persons)	16	900
Igloo suite (2 persons)	16	1300

The additional spending of each passenger is estimated to be 25–75 euros per day based on the cabin; Passengers in more expensive cabins are assumed to spend more. Most of the cruise lines report occupancy rate of over 100%. However, to obtain more conservative estimation of the income, occupancy rate of 90% is used. Total incomes of the ship are estimated to be 59M euros per year.

Costs

Fuel costs of Frostisen are estimated by assuming that the ship would be travelling at the design speed of 16 knots for 20 hours on each operation day. Price of LNG is estimated to be 250 EUR/ton and MDO 300 EUR/ton. Crew expenses are estimated to be 125 euros per crew member per day. Each passenger is on-board estimated to cause additional cost of 100 euros per day. This value is lower than for some large cruise lines, but Frostisen is relatively small cruise ship and aims for luxury which explains higher costs per passenger. Véronneau and Roy (2012) analyzed the market and economics of passenger vessels by using data from different cruise companies. They listed expenses of cruise lines and these statistics were used to estimate the additional operational costs of the ship. Additional 500000 euros is reserved for maintenance per year.

Table 44. Annual costs of the ship

	EUR
Fuel	1 290 523
Crew	1 650 000
Passenger needs	8 520 000
Commissions, transportations etc	4 865 907
Other operational	5 712 152
maintenance	500 000
TOTAL	**22538 582**

Input values needed for the NPV analysis are given in table below. Initial investment is the building costs of the ship. Incomes and costs are calculated as explained in previous chapters and lead to annual revenue of 36.3M. Interest rate of 12% is used.

Table 45. Input values for the NPV analysis of the ship

Initial investment	182 479 546.6	EUR
Operating days	240	days/year
Income	58 859 040	EUR
Annual costs	22 538 582	EUR
Annual revenues	36 320 458	EUR
Interest rate	0.12	%

Table 46. Net present value of the ship

Year	NPV, annual cash flow	NPV
0	-182 479 547 €	-182 479 547 €
1	32 428 980 €	-150 050 566 €
2	28 954 447 €	-121 096 119 €
6	18 401 074 €	-102 695 045 €
7	16 429 531 €	-86 265 514 €
8	14 669 224 €	-71 596 291 €
9	13 097 521 €	-58 498 769 €
10	11 694 215 €	-46 804 554 €
11	10 441 264 €	-36 363 290 €
12	9 322 557 €	-27 040 733 €
13	8 323 712 €	-18 717 022 €
14	7 431 885 €	-11 285 136 €
15	6 635 612 €	-4 649 525 €
16	5 924 653 €	1 275 129 €
17	5 289 869 €	6 564 998 €
18	4 723 097 €	11 288 096 €
19	4 217 051 €	15 505 147 €
20	3 765 224 €	19 270 371 €
21	3 361 807 €	22 632 179 €
22	3 001 614 €	25 633 793 €
23	2 680 012 €	28 313 805 €
24	2 392 868 €	30 706 673 €
25	2 136 489 €	32 843 163 €

Payback period of 15 years is acceptable, but not optimal. For shorter payback time, for example closer to 10 years, the annual costs should be decreased, or income increased. Increasing ticket prices might decrease the sales and therefore, decreasing the costs should be preferred. However, ticket prices are based on current market and analysis of longer period should be done especially as the COVID-19 pandemic is affecting cruise prices. Also decreasing the initial costs of the ship would decrease the payback period. To optimize operational costs, more detailed information is needed of the actual operational costs, such as drydocking and port costs that are currently based on statistics of other ships.

10.2 SWOT

Strengths

The expedition cruise sector, referred to as the sector hereafter, is a small niche in the overall cruise industry according to the Cruise Industry News 2018-2019 Annual Report, meaning there is less competition in the sector, especially with the ships themselves. This means there is a smaller group of ships Frostisen needs to differentiate from to be appealing to the customer.

Due to the size of our vessel, it fills a space in the sector where larger ships are unable to access all the ports it can access, and the ports she cannot access are generally only accessible by fishing vessels or smaller boats, leading to these ports being accessible via Zodiac by the cruise vessels. Another appeal of Frostisen is the emphasis on environmentally friendly operation of the vessel, using a dual-fuel engine and battery combination for low emissions operation and using solar panels to cover a portion of the hoteling load.

Weaknesses

Aside from niche markets indicating lesser competition in the sector, it also means that the sector is more susceptible to market fluctuations making the profit estimations less reliable in the long run. Also, with Compagnie du Ponant set to launch the first icebreaker expedition cruise ship Le Commandant Charot in 2021, it is possible that the capability to access ice covered sections of the ocean becomes an expected feature in the future, leading to Frostisen being a less desirable option for customers.

Opportunities

Due to the niche of the sector, there is a limited amount of cruise routes that are being sailed, and there are opportunities to plot new routes for to be sailed, providing variety to the market, allowing for Frostisen to be the only vessel traveling the route. If the routes are planned well and there is interest among the customers for travelling the route, there would be a period when there would be no competition. Alongside this, the customer experience of the cruise can be adapted based on feedback received from customers, and the adaptation can be directed towards positive distinction from the other cruises available.

Threats

Based on the article New Expedition and Adventure Ships On Order there are 26 new expedition cruise vessels being launched between 2020 and 2022, significantly increasing competition in the sector. With many of these ships differentiating themselves from the competition with various means, it becomes increasingly difficult to remain individual in a variety market. Another potential threat that needs to be considered is the possibility of new regulations being adopted to the polar regions, which Frostisen may not be compliant with, leading to the restriction of the possible areas of travel.

11 Discussion and conclusions

11.1 Ship project

Overall, the design project of Frostisen has been successful and the design product is in line with the mission that was defined during the first week of the course. Small size and ice class allow ship to operate in areas that larger cruise ships are not able to visit. Limited passenger number, spacious sea-facing cabins, luxurious igloo suites and public areas make the ship competitive with existing vessels on the expedition cruise market. Additionally, dual-fuel engine, battery system and SCR make the ship energy efficient and low-emission, making it easier to meet environmental legislation in the future and to convince customers that travelling on Frostisen is a sustainable choice.

Expedition cruise ship market is not large, but the search for reference vessel shows that there are several new vessels being launched at this moment. Additionally, during the course, Helsinki Shipyard announced that they have received an order for a new expedition cruise ship with diesel-electric propulsion and a battery system. This shows us that the ship we have designed has a market demand and chosen technologies are new, but ready to be commercially used.

Probably the youngest technology in Frostisen is the composite superstructure as the use of composite materials in ships has been limited by strict fire-safety regulations. There are fire-safe composite materials on the market, but the options are limited, and these products have high costs. During the concept design phase, the number of different composite materials considered and evaluated had to be limited to meet the deadlines. During the next round of the design spiral, more detailed analysis could be done to find the best option for the superstructure material, finding optimal balance between weight savings and material costs. Also, more advanced structural analysis should be done to ensure the strength of the superstructure and its connections with steel parts.

First weight calculations resulted in higher displacement than expected when the hull form and the draft was chosen. Design displacement was increased by increasing the draft and currently the displacement from weight calculations and the displacement given by Delftship model are in line. However, in the concept design phase it is recommended to have a larger weight margin than the current design has. This will impact future work as additional attention must be paid on the weight calculations.

Stability will also need to be considered in depth in the next design spiral. The initial draft as well as the increased draft were not analysed for stability impact, nor were the watertight sections analysed for damage stability. Next design spiral will go into detail in terms of stability. Another important next consideration is on the strength analysis which similarly did not go into detail to test the viability of our design. At this point, Frostisen is set up for the next design spiral in good shape to make adjustments as needed.

Sustainability of the design was one of the major parts of our design concept. During the concept design, the focus was on main components of the ship and therefore, the environmental impact has been mainly discussed in the design of the machinery, resistance, and weight of the ship. As more details are added in the design, sustainability can be also be improved for example by choosing energy efficient systems and designing the waste management systems on-board. These smaller details might be very visible for the customers and provide opportunities for marketing the cruise.

The performed economical assessment is preliminary and much more time could have been used for estimating the building and operational costs and annual incomes. Covid-19 pandemic has shown how quickly the situation in the cruise market can change. Future regulations might even lead to changes in fuel, for example LNG might be replaced with biogas during the lifetime of the ship. Analysis of the development of fuel and expedition cruise ticket prices for a longer time period might give us a better understanding of the future trends in the industry.

11.2 Learning process

Sarah Blackwell:

I came to this project with a different background than my teammates. Although many of them have a naval background, I am the only one with a degree in naval architecture. However, I have been out of school and working in the industry for a few years and have found this course to be very valuable in pushing my abilities and knowledge of what it means to be a naval architect. I learned a lot about the process of design. Although this is technically my 3rd time around the design spiral as a student, it is different every time. Specifically, the team members have been great this time. I found that I have had a lot more confidence resulting from this course and I learned about leadership and cooperation as much as technical information. In terms of the technical knowledge, I have learned some new methods, including Normand's method for main dimensions, new cost analysis methods, and the SFI system. It has been great for me to also see my group members learn about the naval architecture design process so quickly. For the most part, we had a great balance of people with different interests, and we each had our role. For example, I am interested in structural design, stability, and the overall naval architect's role of integrating the parts to a whole. My weakness is machinery, which was luckily the strong point of a few of the others. I am pleased with how the project developed and with the cooperation and sharing of the workload. I am excited to get further into detailed design next term.

Elisa Majamäki:

I chose PNA course as the first course of my PhD studies as I thought it would give a good base for following courses related to marine technology. I think the course succeeded to in terms of giving an introduction to design methods and tools in naval architecture. After this course, I have better understanding how naval architects work and feel more confident in using related terminology and notations. Our group members have different backgrounds, and this was a challenge for us, but also an opportunity to learn from each other. A least I felt that I learned a lot from other team members and also felt that it was easy to ask for help when needed. Current pandemic limited the working methods we could use, and I was sceptical about working fully remotely in the beginning of the course. I was happy to see that working via teams was successful, but what I missed from face-to-face meetings is brainstorming that is not as easy during online meetings. Overall, I've been very satisfied with the process and the final outcome of our design work.

Tuomas Kohosalmi:

As I was interested in studying some field in Naval architecture but was uncertain which field would be the most interesting, PNA was a good point to begin, since it is required in almost all the different naval study paths. With my prior knowledge of naval architecture coming from research for my bachelor's thesis, it was beneficial to go over the different topics at a surface level to give an inkling as to what may interest me. Working in a group to complete a preliminary design of a ship displayed the process well, and with the members of our group having different backgrounds, I feel everyone had to work outside their comfort zone at some point and everyone learned from each other. I feel that I learned quite a lot during the course and that I have a better definition of what interests me.

Gonzalo Sanfeliu Moreno:

After finishing my bachelor's degree in mechanical engineering focusing on machine design and working in a company in the automotive field, I realized that I did not like that, so I started exploring master's degree options. I got accepted in Cold Climate engineering in the sea track and having all the master's degree related with the sea, PNA looked like an obvious election for my minor. In this course I learnt the basics of Naval architecture and discovered which parts of the ship design I liked the most, to be able to focus more on the following courses. My background knowledge in machines helped me quickly understand the machinery systems in the ship, part in which I focused the most during this course. Thanks to this course, and because of the Coronavirus pandemic I have also "learnt" to work with a team online, what will surely be beneficial for my future. Overall, I think this course makes a lot of sense as a introduction to Naval Architecture everyone, either with or without a background in this field.

References

Aakko-Saksa, P., & Lehtoranta, K. 2019. Ship emissions in the future - review. VTT Technical Research Centreof Finland. VTT Research Report No. VTT-R-00335-19.

CMP and the City of Copenhagen. 2015. Options for establishing shore power for cruise ships in port of Copenhagen Nordhavn. Available: https://www.danskehavne.dk/wp-content/uploads/2015/12/GP-CMP-Shoreside-Report.pdf

ICCT. 2020. The climate implications of using LNG as a marine fuel. International council on clean transportation. Working paper 2020-02.

DNV GL. 2020. Rules for classification: Ships — DNVGL-RU-SHIP Pt.6 Ch.6. Edition July 2020

Franz Evegren. 2015. Engineering analysis report - Norwegian Future. ISBN 978-91-88001-29-0. ISSN 0284-5172.

IMO. 2014. Third IMO Greenhouse Gas Study 2014. Executive Summary and Final Report. International maritime organization.

Stenersen & Thonstad,. 2017. GHG and NOx emissions from gas fuelled engines. SINTEF. Report OC2017 F-108.

Véronneau, Simon & Roy, Jacques. (2012). The Blackwell Companion to Maritime Economics, Chapter: 8 Cruise lines and passengers.

Vasileios Karatzas. 2016. COMPASS – COMposite superstructures for large PASsenger Ships. Technical report. Available: https://brandogsikring.dk/files/Pdf/FogU/COMPASS%20Report.pdf

Cruise Industry News 2020 Annual Report. (2020). Cruise Industry News, Annual Report 33rd Edition.

New Expedition and AdventureShips On Order. (2020). Cruisecritic.com.Referenced 26.11.2020. https://www.cruisecritic.com/articles.cfm?ID=3014

Appendices

Appendix A

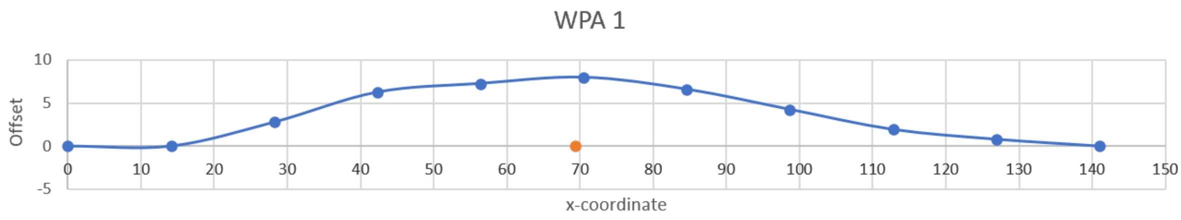


Figure 34. Waterplane area at waterline 1

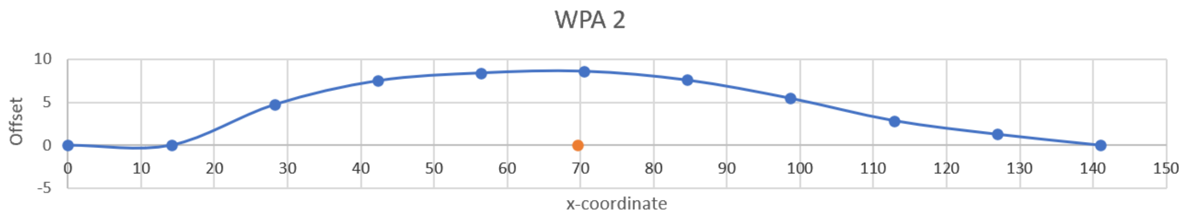


Figure 35. Waterplane area at waterline 2

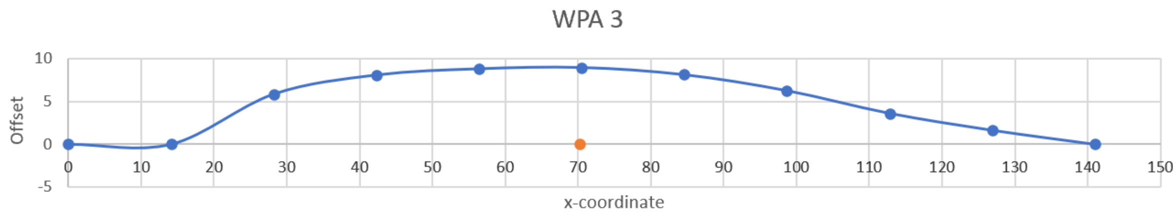


Figure 36. Waterplane area at waterline 3

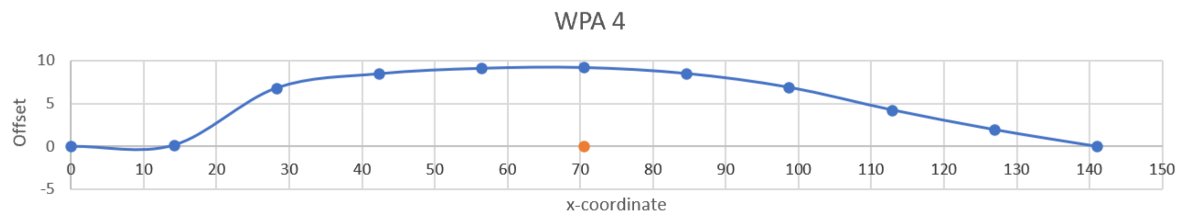


Figure 37. Waterplane area at waterline 4

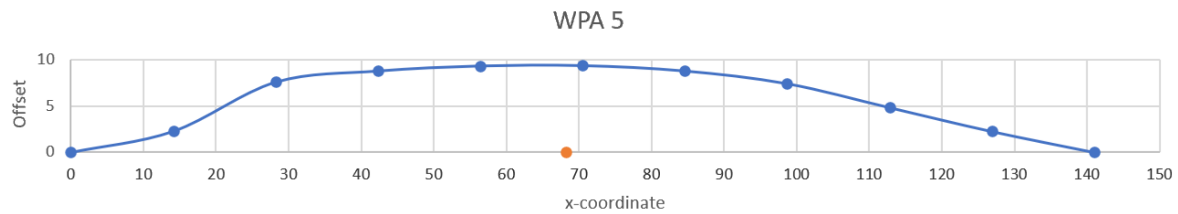


Figure 38. Waterplane area at waterline 5

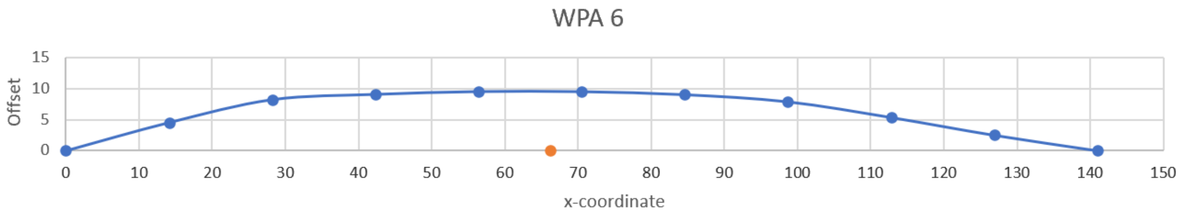


Figure 39. Waterplane area at waterline 6

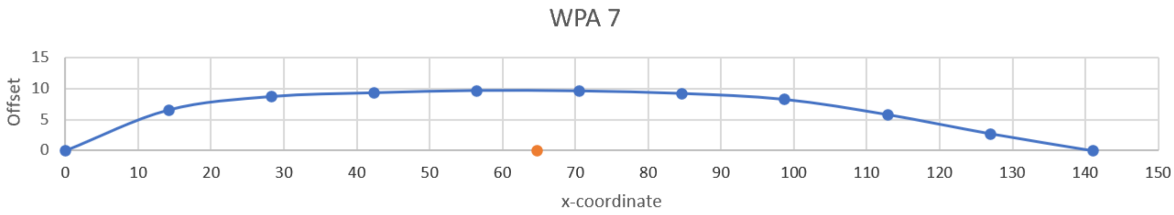


Figure 40. Waterplane area at waterline 7

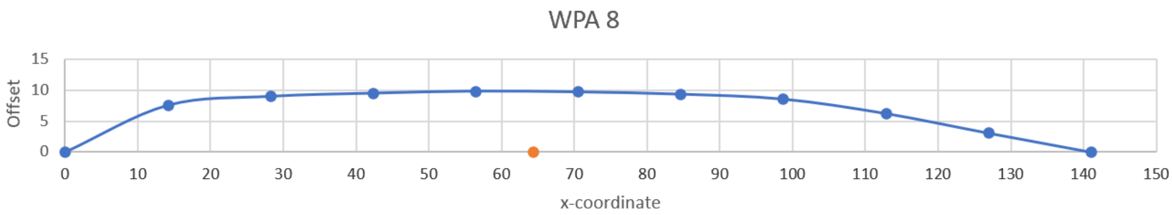


Figure 41. Waterplane area at waterline 8

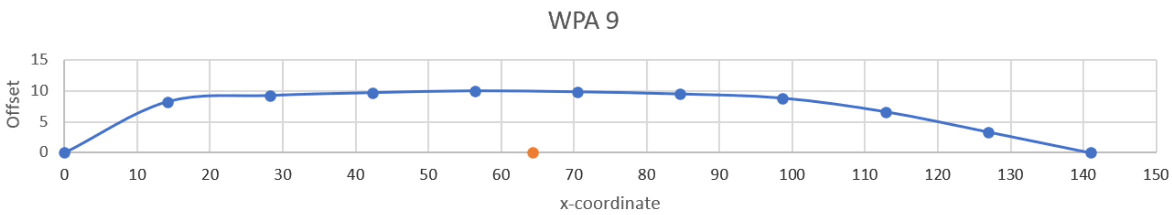


Figure 42. Waterplane area at waterline 9

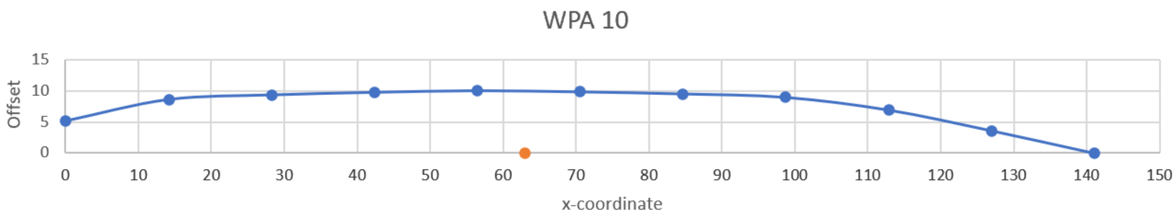


Figure 43. Waterplane area at waterline 10

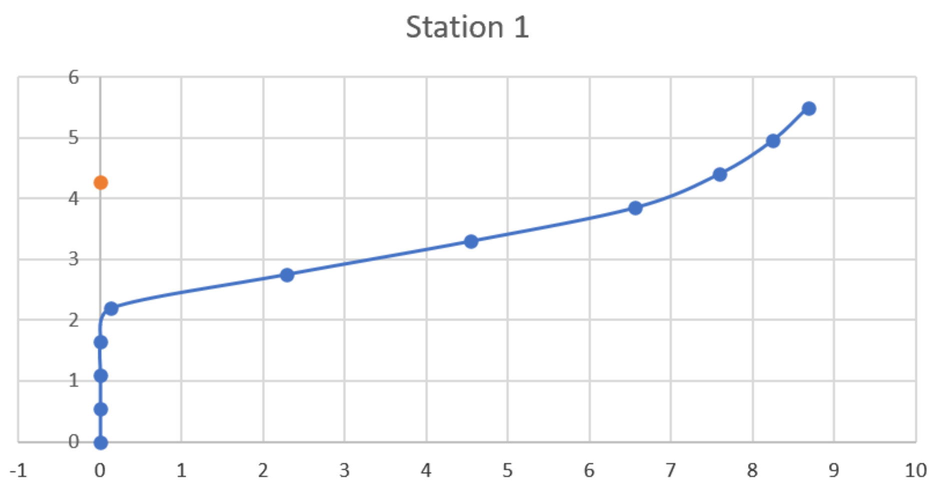


Figure 44.Station 1

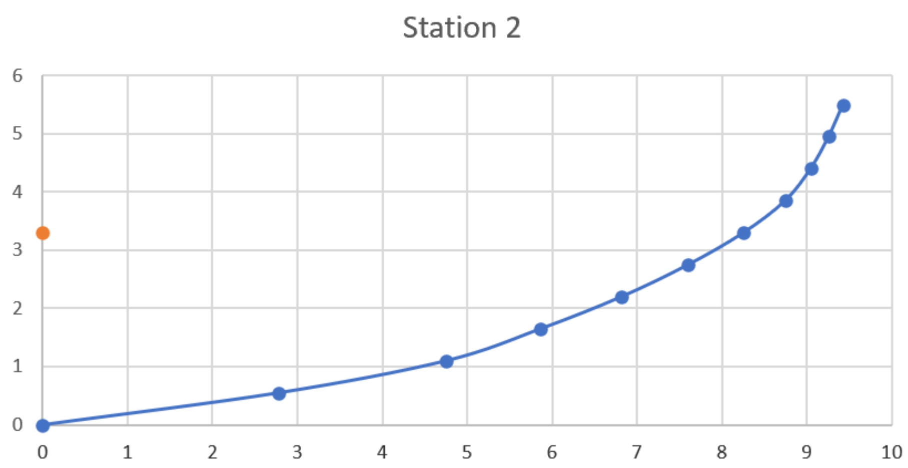


Figure 45.Station 2

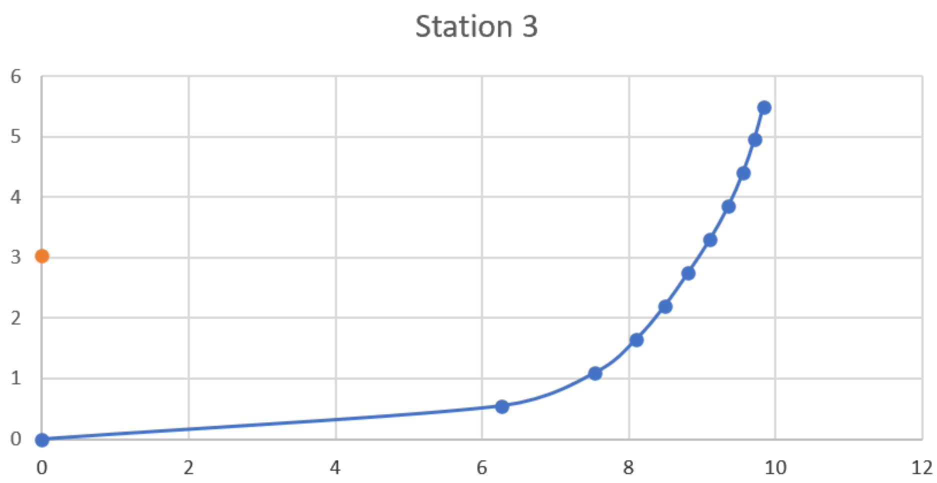


Figure 46.Station 3

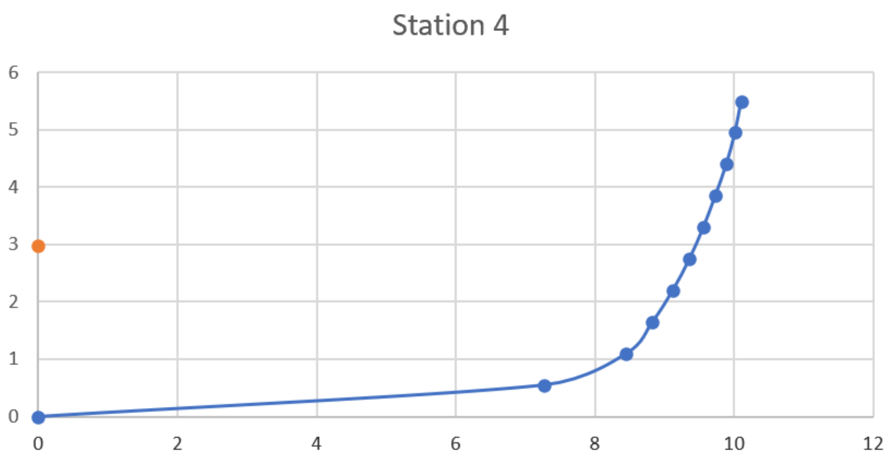


Figure 47. Station 4

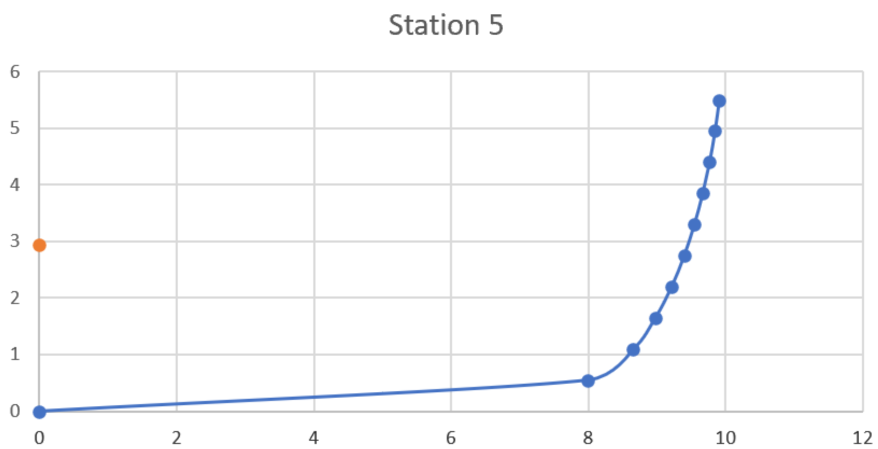


Figure 48. Station 5

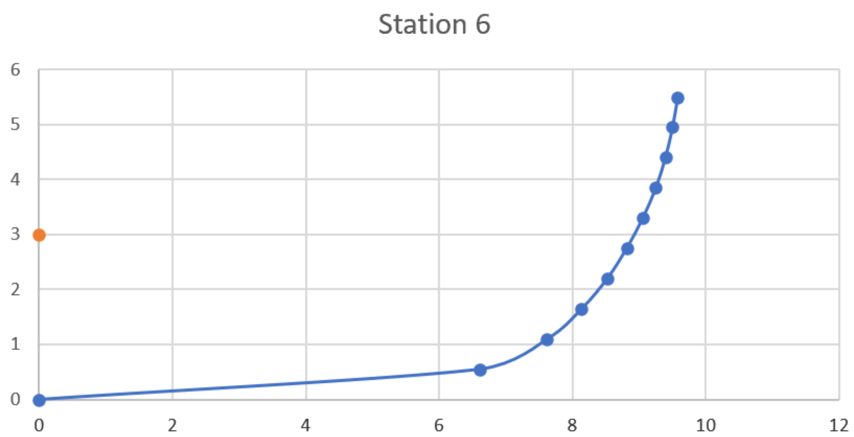


Figure 49. Station 6

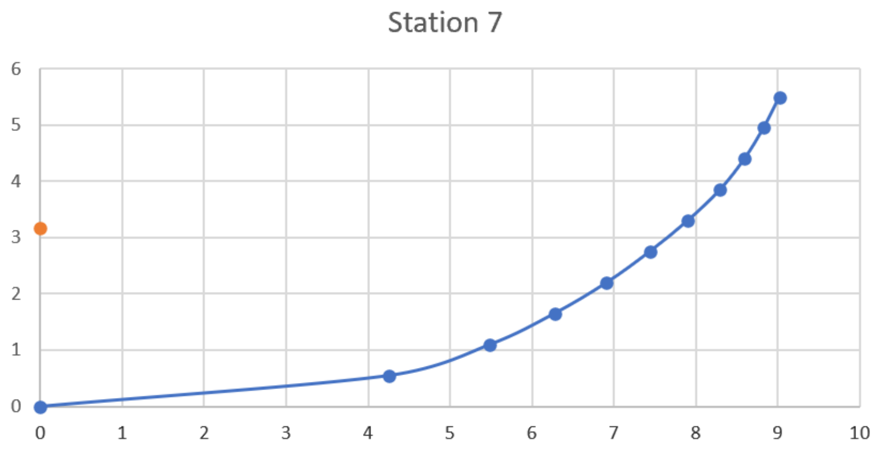


Figure 50. Station 7

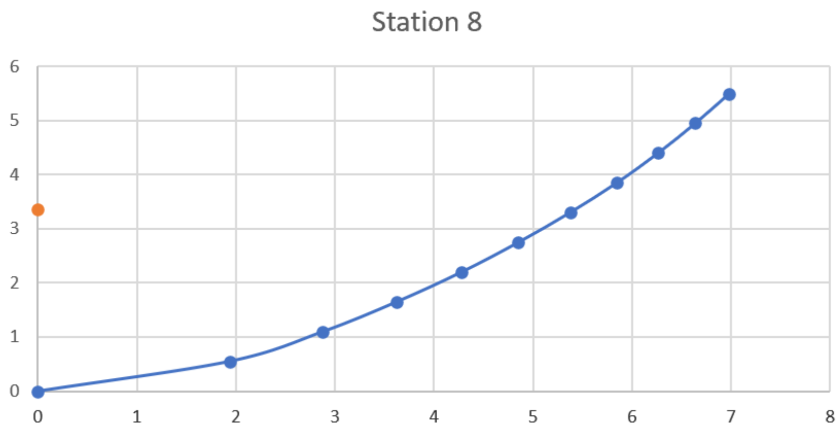


Figure 51. Station 8

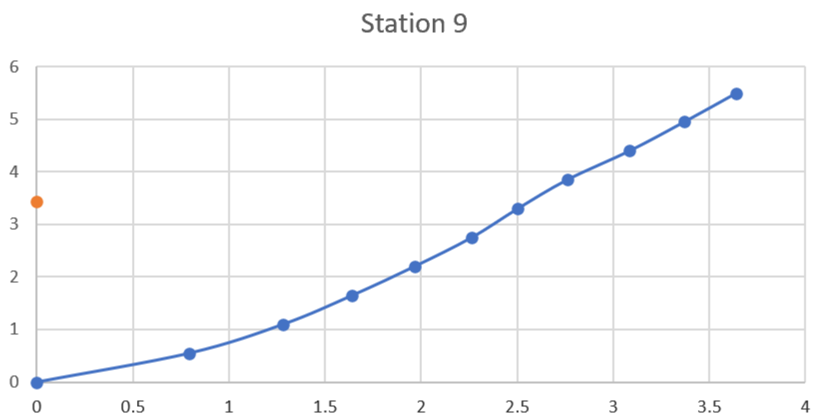


Figure 52. Station 9

Appendix B

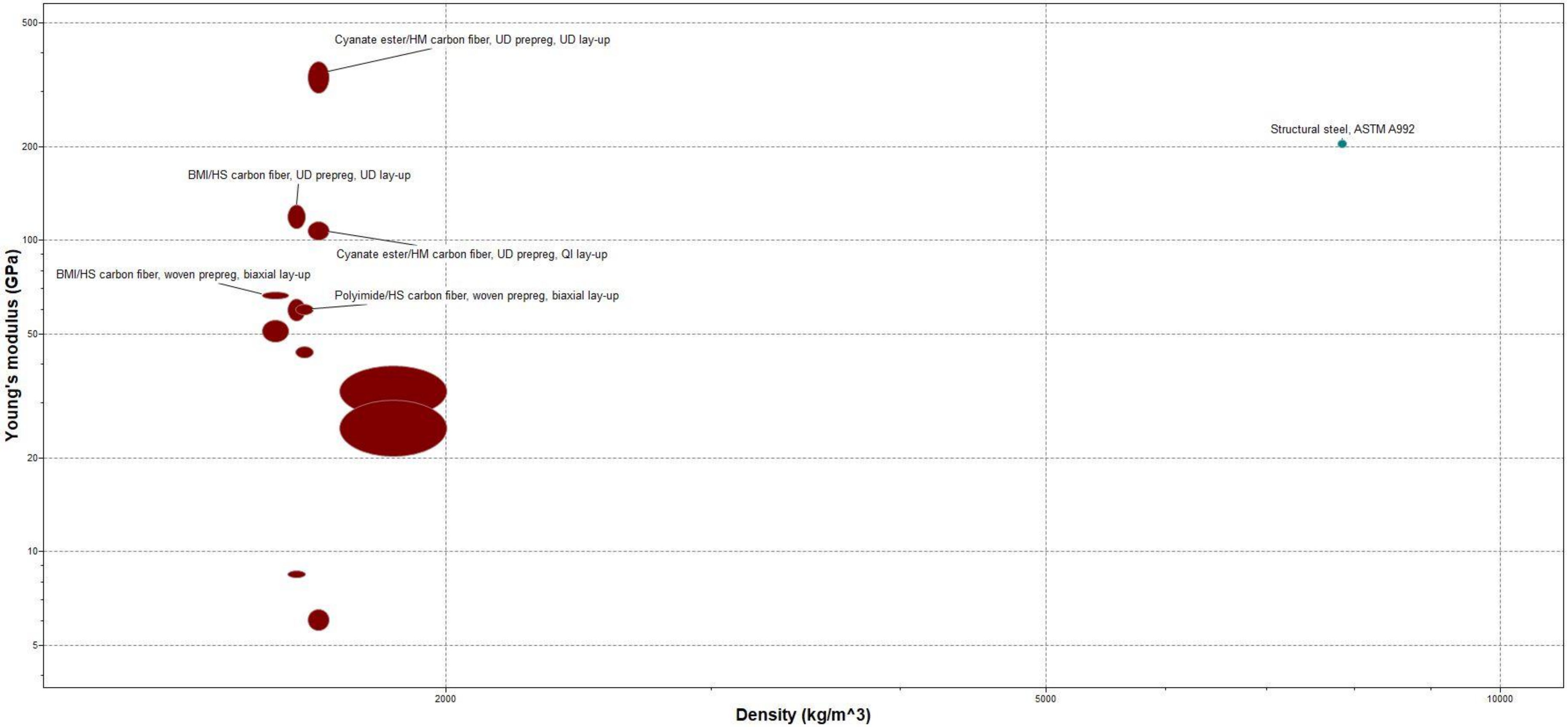


Figure 53. Ashby Diagram of Young's modulus [E] to Density [ρ]

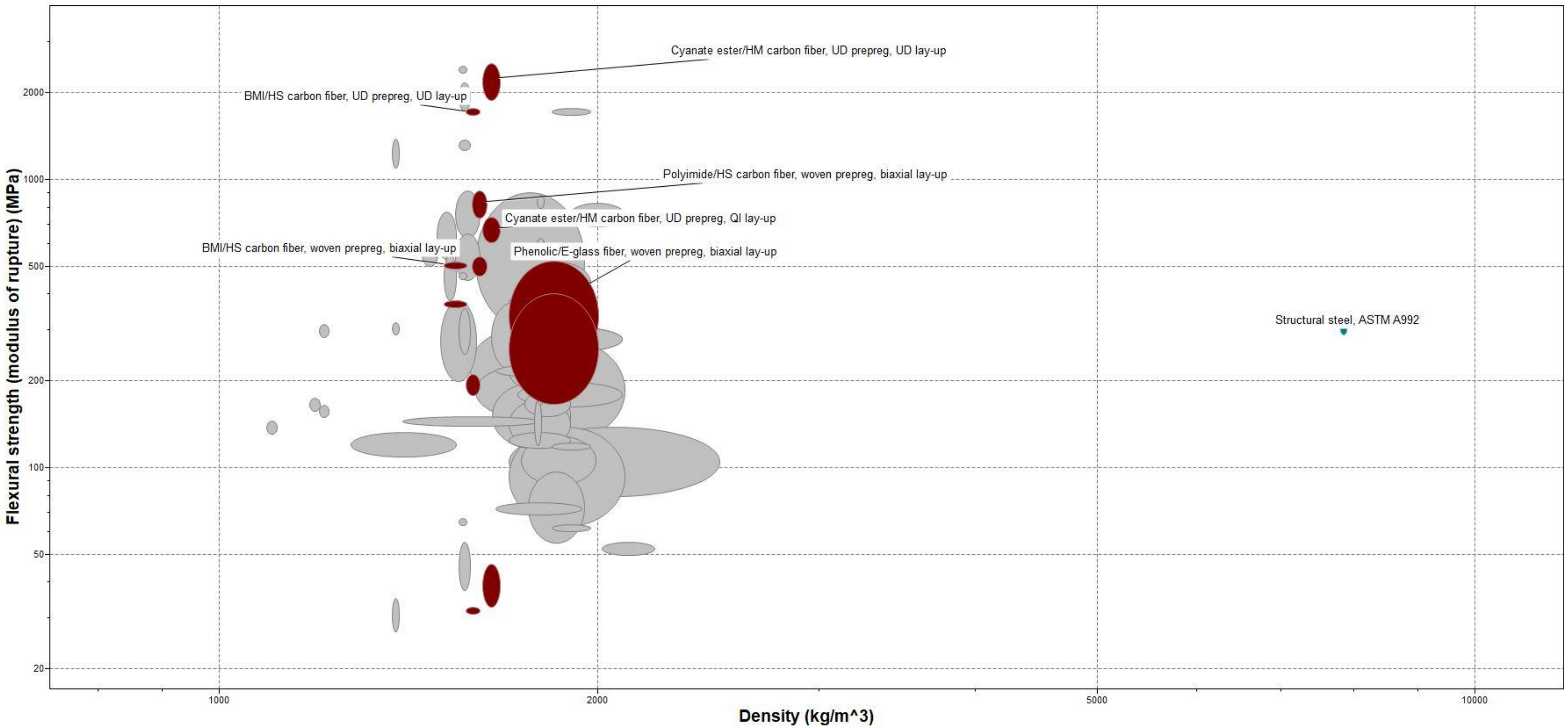


Figure 54.Ashby Diagram of Flexural strength [σ_f] to Density [ρ]

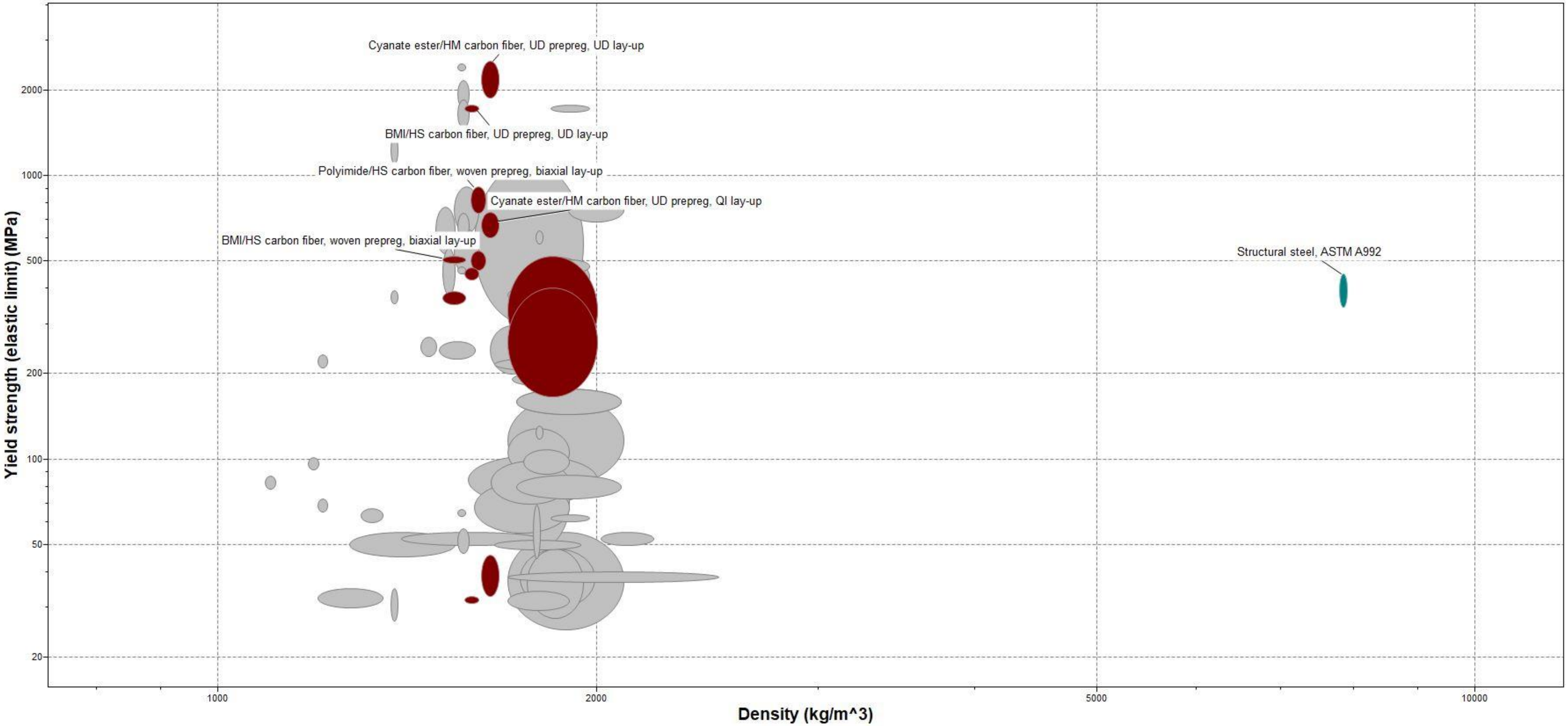


Figure 55. Ashby Diagram of Flexural strength [σ_y] to Density [ρ]