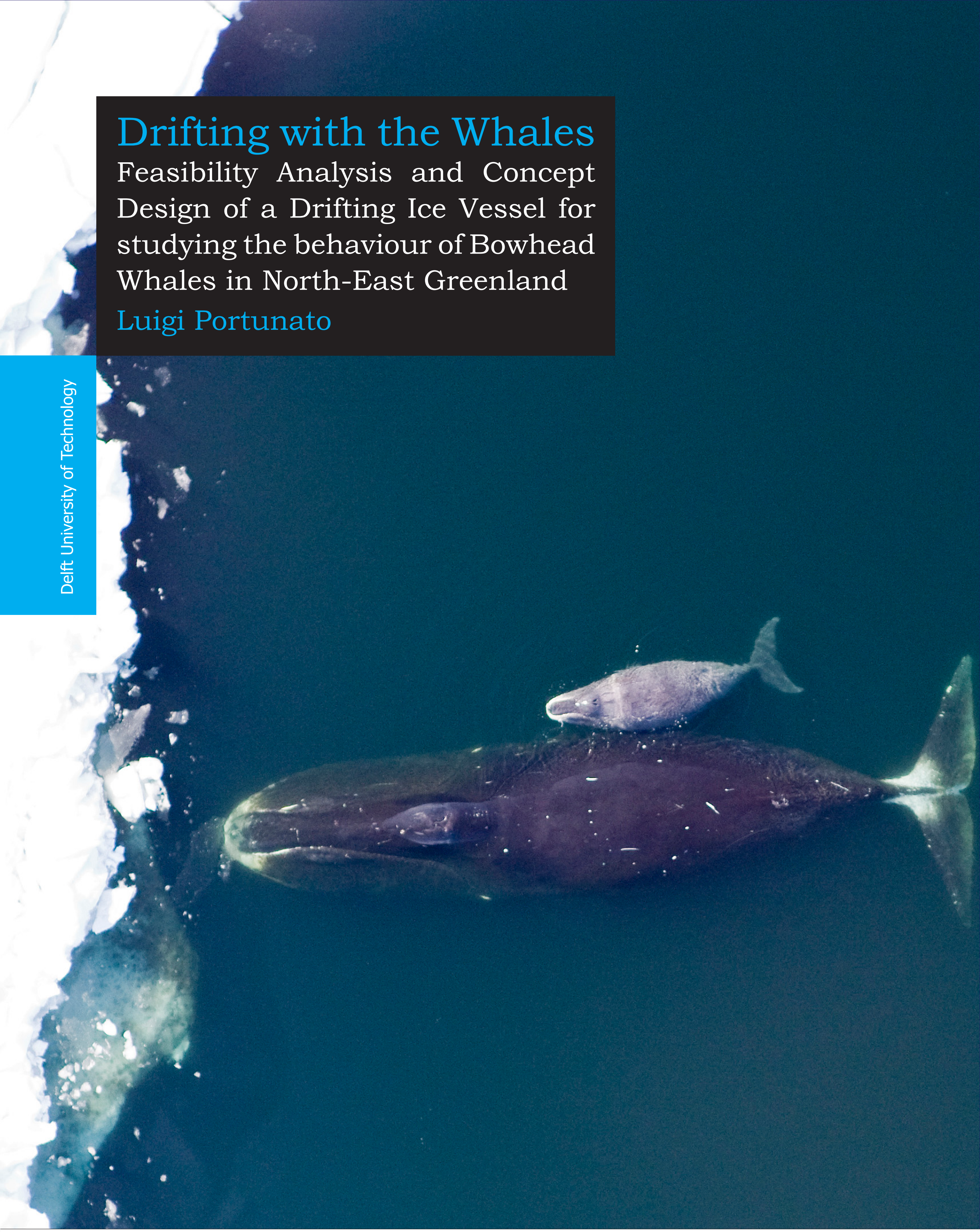
Drifting with the Whales

Feasibility Analysis and Concept Design of a Drifting Ice Vessel for studying the behaviour of Bowhead Whales in North-East Greenland

Luigi Portunato

Delft University of Technology



TU Delft Delft University of Technology

Challenge the future

Drifting with the Whales

Feasibility Analysis and Concept Design of a Drifting Ice Vessel for studying the behaviour of Bowhead Whales in North-East Greenland

by

Luigi Portunato

in partial fulfillment of the requirements for the degree of

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CONOSHIP INTERNATIONAL TU Delft Delft University of Technology Ice Whale Foundation

Preface

The bowhead whales suffered centuries of indiscriminate hunting, which almost extinguished their Svalbard subpopulation. Recently, it has been discovered that a lot of bowhead whales spend the whole winter every year under the ice around North-East Greenland coast, communicating through a broad range of vocalisations. The unknown origin of this behaviour was one of the reasons for the establishment of the Ice Whale Foundation that, thanks also to the funding of the Royal Netherlands Institute for Sea Research, has the goal to organise a series of six polar winter expeditions, starting from 2020, its main aim being the study of the Bowhead Whales in the Fram Strait. This context and the purpose to carry out the above-mentioned study originated the request for a small, compact and affordable research platform, which is the subject of my thesis.

The past nine months have been really intense and challenging: I met many people from which I learnt a lot and who gave me a great help in my work. For this reason I wish to thank first of all my TU Delft supervisors: Hans Hopman, for his wise guidance and the extremely interesting discussions he shared with me, and Jeroen Hoving, for all the knowledge about the ice and the passion about the Arctic that he transmitted to me during both his course and our progress meetings.

I am extremely grateful to all the Conoship people, in particular to Harald Rugebregt, Guus van der Bles and Joan van den Akker, for supporting and challenging me during the design of the vessel.

I wish also to thank the all the Ice Whale Foundation for the idea and the efforts that its members put in this project. Specifically, Herman Sips, the initiator of this work, who is putting an incredible willpower in his dream to realise this research vessel, and Dick Veen, for having hosted me in the period I spent in Groningen.

Special thanks also to Wim Jolles and Klaus Harving Krane for their help in the environmental analysis and for sharing their broad experience about the Polar environment and the Arctic navigation.

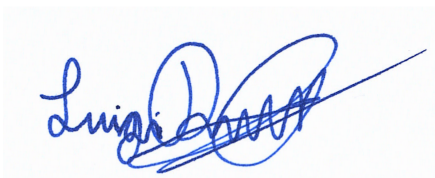
I also wish to express my gratitude to all the people, who collaborated with my work for different reasons: Grant Redvers, who shared his experience with the Tara Arctic expedition, Gerard Dijkstra, for describing and showing me some of the designs that he produced, and Kaj Riska, for guiding me through the naval architecture Polar topics.

Furthermore, I am deeply grateful to my mum, my dad, my brother and my granddad, which spent so much effort in supporting and helping me during this period in the Netherlands.

I wish also to thank all my friends in Genova and in Delft that always supported me in the past two years, in particular to Agnese that helped me a lot for the graphic design of this thesis and has always been a great support.

Finally, a special thanks also to Cortina, for hosting me and recharging me every year, and to Genoa, for making me suffering every Sunday afternoon.

Luigi Portunato
Delft, September 2018



Abstract

The subject of this research is the concept design of a compact and economically feasible platform for studying the behaviour of bowhead whales in the ice-infested water around the coast of North-East Greenland and particularly in the Fram Strait.

The study is focused on the capabilities of the vessel to operate in a dynamic ice-infested environment and on the strategies to be used for surviving in such a harsh area. An extensive part of the research consists in an environmental study of the ice and climatic conditions of the Fram Strait which are barely available in literature.

The design is carried out using a System Engineering approach in order to evaluate the mission and its requirements and to transform them into high-level concepts which are compared through the usage of an Analytic Hierarchy Process. The ice-breaking capabilities are evaluated using the Net Thrust Concept and the ice loads in compressive ice are calculated through a quasi-static approach with ISO19906 standard for Arctic offshore structures.

The final concept design proposes a vessel that can accommodate a crew of six people and that can perform the research activity also underwater through a moon pool. The vessel is able to reach the operational location autonomously and to drift following the ice movements towards South. Moreover, it is able to cope with compressive ice events thanks to a rounded hull that lifts the vessel up when compressed by ice.

Overall, the construction and operation of the Drifting Ice Vessel are judged to be feasible. However, the task is not without risks and further experiments, tests and trials are recommended, to verify more deeply and validate the ice-loads estimation and the lifting behaviour of the hull.

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List of Figures

Nomenclature

α	Inclination of the structure
α_{we}	Bow waterline entrance angle
λ	Largest eigenvalue
μ	Ice-structure static friction coefficient
μ_i	Ice-to-ice friction coefficient
∇	Underwater volume
ϕ	Bow stem angle
ϕ_r	Friction angle of the ice rubble
ψ	Bow flare angle
ρ_i	Ice density
ρ_w	Sea water density
σ_f	Flexural strength of the ice sheet
θ_r	Angle that the rubble makes with the horizontal
A_{wet}	Wetted area
B	Breadth
c	Cohesion of the ice rubble
C_R	Ice strength coefficient
CI	Consistency index
CR	Consistency ratio
D	Moulded depth
D_p	Propeller diameter
E	Ice Young's modulus
e	Porosity of the ice rubble
F_H	Total horizontal loads on the structure
F_V	Total vertical loads on the structure
g	Gravity acceleration
h^*	Reference thickness of 1,0 m
h_c	Height of the contact area
h_i	Ice thickness
H_B	Ice breaking load

H_L	Load component required to lift the ice rubble on top of the advancing ice sheet
H_P	Load component required to push the ice sheet through the ice rubble
H_R	Load component required to push the ice blocks up the slope through the ice rubble
h_r	Height of the ice rubble
K_E	Bollard pull quality factor
L_{bow}	Length of the foreship at the waterline
l_c	Length of the circumferential crack
L_{oa}	Lenght over all
L_{par}	Length of the parallel midbody at the waterline
L_{wl}	Lenght at the waterline
m	Ice feature mass
N	Number of criteria
nu	Ice Poisson's ratio
P	Maximum delivered power required
p_G	Global ice pressure
R_B	Ice bending resistance
R_C	Ice crushing resistance
R_S	Ice submersion resistance
R_i	Ice resistance
R_{ow}	Open water resistance
T	Draft
t	Thrust deduction factor
T_B	Bollard pull thrust
T_{NET}	Net thrust
v	Vessel speed
v_i	Ice feature speed
v_{ow}	Maximum open water speed
w	Projected length of the structure

1

Introduction

1.1. Background

The Bowhead Whale (fig. 1.1), also known by its scientific name *Balaena Mysticetus*, is one of the largest animals in the world and, differently from the rest of whale species, lives all of its life in the cold Arctic waters without migrating. Adults usually reach 19 meters in length and 80 tons of weight, while there are some records of specimina reaching 24 meters and 100 tons (George et al., 2018). They differ from the other species of whales by their dark colour, the lack of a dorsal fin and their particular mouth, with a small upper and really big lower jaw and extremely long baleens (up to 3 m). Moreover, they can easily live for over 150 years.
They live in different Arctic areas along the ice edge, covering a west to east area from the Okhotsk Sea and the Chukchi Sea until Franz Josef Land. They usually travel in groups of 5-6 elements and can remain underwater for up to one hour, even if usually the submersion time is limited to 10-20 minutes. Their swimming speed is also usually quite low, on average 1-3 knots.
Bowhead Whales are also particularly known for their very complex underwater communication through the use of low frequency (<1000 Hz) sounds. These frequencies, however, are relatively high if compared with other species of whales. This ability is particularly used during reproduction periods for finding mates, but also for navigation and socialisation (Finley, 2001).

Figure 1.1: Bowhead Whale photographed by Paul Nicklen in 2008 (© Paul Nicklen/National Geographic Creative).

Their conservation faced a really big risk because of human whaling activities which decimate their population. Since having forbidden to hunt them, their global population conservation status is no longer endangered. However, some subpopulations heavily suffered from the whale hunting period and are now in danger. In particular the East Greenland-Svalbard-Barents Sea Bowhead Whale subpopulation nowadays counts only a few elements in the order of 100-150. According to the IUCN Red List of Threatened Species, their conservation status just recently moved from "critically endangered" (Reilly et al., 2012) to "endangered" (Cooke and Reeves, 2018). In figure 1.2 a graph is presented from Allen and Keay (2006), showing how the Svalbard population declined due to the whale hunting from the 60000 whales of 1611 until the circa 100 of the 20^{th} Century.

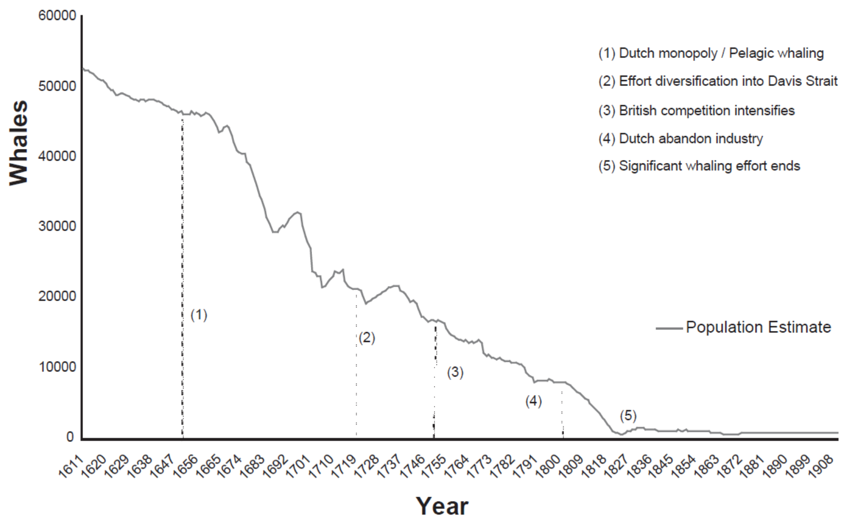


Figure 1.2: Decline of the East Greenland-Svalbard-Barents Sea Bowhead Whale subpopulation between 1611 and 1911 (Allen and Keay, 2006).

The information about the life and behaviour of the Bowhead Whales is still quite limited, however, during winter 2008-2009 a very interesting fact has been observed and reported by Stafford et al. (2012).

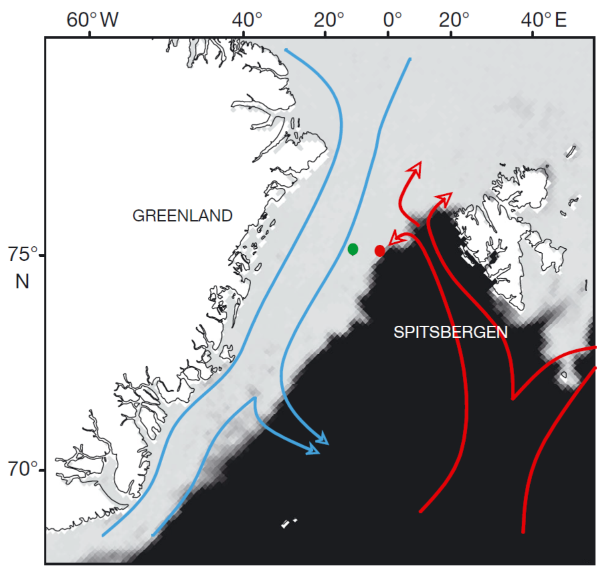


Figure 1.3: Position of the Hydrophones used for listening to the Bowhead Whales during winter 2008-2009 (Stafford et al., 2012).

Using two hydrophones, which have been moored in the Fram Strait (fig. 1.3) between November 2008 and March 2009, sounds of singing Bowhead Whales were recorded continuously. Especially around the position of the Western Hydrophones (79°N 5°W) the amount of whales recorded has been massive and, considering the small population of the area, it can be considered a very interesting phenomenon. Furthermore, the local conditions in that period are really harsh: the ice coverage percentage reaches values over 90%. Considering the already mentioned quite small underwater time of the Bowhead Whale, the choice of staying in an area with lack of open water areas at the surface is at least peculiar. In order to justify this behaviour, some hypotheses have been raised: it is possible that the whales reach this area during the mating period because the ice can help the sounds transmission keeping a quieter background. However, there is no sure answer yet and further studies have to be done in order to understand the reasons for this behaviour and elaborate on the complex ways of communications between these enormous mammals.

1.2. History of the project

In this context and to face these challenges, the Ice Whale Foundation was established in 2017. The main aims of this organisations are the assessment of the behaviour, the mating strategies and the vulnerability of the Bowhead Whales and the increment of the public visibility of this mammal in order to make it one of the symbols of the Arctic marine life protection against the sea ice extent reduction. Among the various initiatives planned, one of the main goals is the organisation of a series of six polar winter expeditions in subsequent years, starting from 2020, with as main aim the study of the Bowhead Whales in the Fram Strait. Thanks also to the funding and cooperation of the Royal Netherlands Institute for Sea Research, the project started in 2017.

Therefore, the first step in tackling the problem is the evaluation of the best way to do such a study with a restrained budget and without disturbing and damaging the living areas of the mammals. In order to produce a feasibility study and come up with the concept design of a vehicle which is able to reach the above-mentioned goals, the Dutch-based ship design company Conoship International has been involved. Conoship is a ship design and engineering office founded in 1952 in Groningen as the central design office for a group of Northern Dutch shipyards. It now develops a very wide range of ships, from general cargo vessels, tankers, dredgers, to ferries and offshore vessels. Moreover, a collaboration with the Delft University of Technology has been initiated with the aim of exploiting the university's experience in the Arctic technology field.

1.3. Initial requirements

The initial requirements from the Ice Whale Foundation for the vehicle will be listed in this section. The initial requirements were quite broad and sometimes decided already assuming design choices which may not be the best and should be analysed first. The main assumption is that the vehicle is going to be a regular vessel, however, this choice might not be the best possible and will be therefore subjected to a revision process. Due to these reasons the requirements during the process will be revised and refined following the environmental analysis and the system engineering process. In section 1.4 the method used will be more thoroughly described. The complete initial lists of Operational and Research Requirements can be found in appendix A.

The key requirements can be summarised as follows:

- Operating in the Marginal Ice Zone of the Fram Strait between 75°N and 82°N
- Silent navigation as much as possible
- Gross Tonnage under 500 GT
- Cost limited to 5 Millions of euros
- 150 days of autonomy between October and March
- Crew limited to 5-6 persons

1.4. Problem approach

Due to the uniqueness of the project and the great number of unknowns of the environment and research it is very important to approach the problem in a complete and logical way from the start.

The scheme of the process applied for this design is shown in figure 1.4.

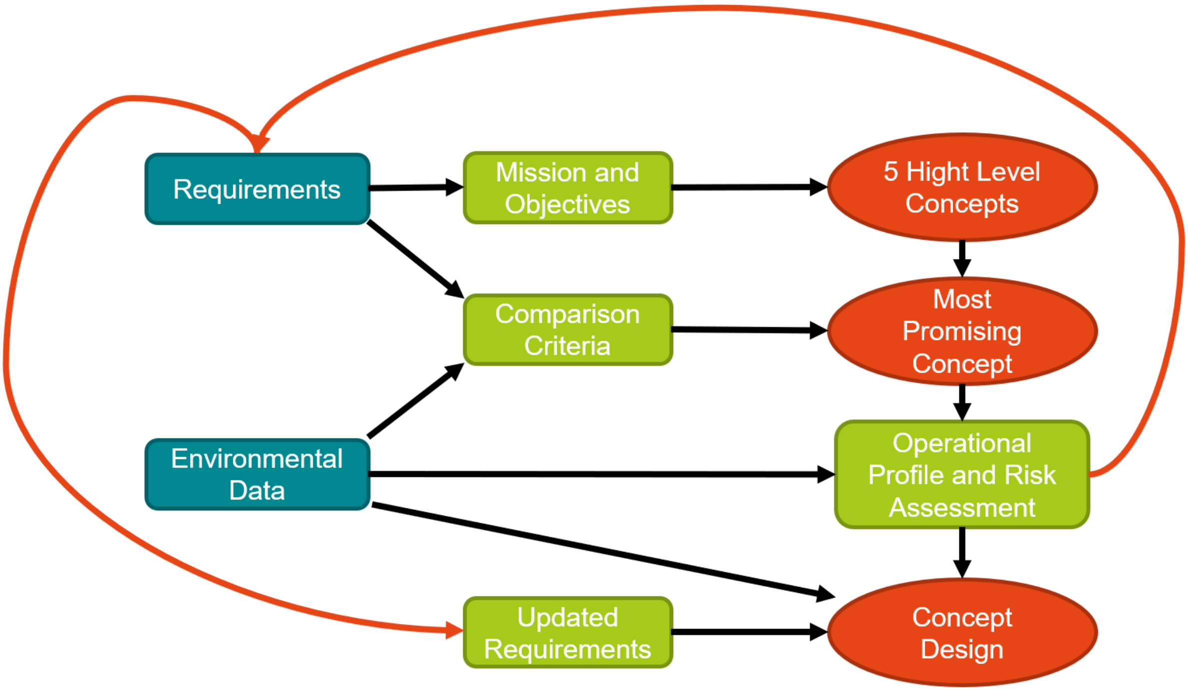


Figure 1.4: Scheme of the design process used for the development of the concept design.

The starting point are both the mission requirements provided by the Ice Whale Foundation and the environmental data collected, which are going to be elaborated upon and presented in chapter 2.

From those a step back has to be made and using a System Engineering process, which will be presented in section 4.2, the mission and the objectives of the expedition are extrapolated. Based on these objectives, five high-level suitable concepts will be proposed, presented and analysed. An interesting presentation of the System Engineering approach to the inter-relationships among the system design processes is presented by NASA (2007).

The next step will be the comparison between the high-level concepts. This will be done using an Analytic Hierarchy Process (AHP) which will be presented in section 4.4. The Comparison Criteria used in the Process are derived from the Ice Whale Foundation mission Requirements and the Environmental data produced. Following this comparison, a Most Promising Concept will be selected. This concept, however, will be still at a high-level stage and the design space will be still quite large.

Using the Environmental data an Operational Profile and the following Risk Assessment will be produced (chapter 5). During this process the evaluation of the risks is going to modify the definition of the Operational Profile, therefore these two passages are strictly related through a cyclic process of refinement.

The result is going to be a high-level concept with a planned operational profile and a related risk assessment, this will be used for refining the initial requirements, giving limitations and/or better defining the request of the Ice Whale Foundation. The Foundation itself has to play a very important role in this requirements updating phase, which has to be conducted in strict collaboration.

Finally, using the updated requirements, the environmental conditions and the chosen operational profile, the final concept design can be defined, optimising it and basing the design choices on the three above-mentioned elements. This last step, as will also be more deeply explained in section 6.1, is composed by a cyclical design. In fact, the final design results will cover topics which are not independent from one another. This cyclical process will be composed by a few iterations in order to define and optimise the final result.

1.5. Limitations and Objectives

One of the first things to fix are the objectives that are going to be reached and the subdivision of the work with Conoship International.

The final result of the thesis is going to be a concept design, which means that only the broad outlines of the design are going to be designed. Detail engineering and more precise calculations will be done in a later stage of the project. In particular, the main results that this thesis wants to reach are the selection of the most suitable vehicle for the fulfilment of the mission and the motivations behind this choice.

This selection process is strictly linked to the definition of a most suitable operational profile. The feasibility of the design is going to be shown through the design process itself. The final concept is going to be presented through a vehicle specification together with initial linesplan of the hull and renders of the vehicle itself.

The key elements of the thesis are going to be the choice of the concept and ice related features, in particular: the evaluation of the design environment, the comparison between suitable concepts, the choice of a most suitable design, the definition of the operational profile in order to complete the mission, the ice-hull interaction (ice loads, ice resistance, possible icebreaking capability), the propulsion power required and a broad analysis of the possible propulsion systems.

On the other hand, Conoship International will take care of the standard naval architecture parts: accommodations volume estimations, stability calculations, thickness of main section plates and stiffeners, water resistance calculations, propulsion selection, weight estimation and price estimation.

1.6. Regulations applying

Depending on the configuration of the vehicle some important regulations are also applying and giving design limits. In case the vehicle will be a vessel it will have to comply with the IMO regulations. Following the Ice Whale Foundation requirements, the Gross Tonnage of the vessel does not have to exceed 500, in this situation and navigating in international waters the vessel will have to comply with the MARPOL regulation (MARPOL-IMO, 1973), according to article 3 of the convention.

However, the vessel can be exempted from the SOLAS regulation (SOLAS-IMO, 1974). In fact, Regulation 3 of Part A of the above-mentioned convention states that *"the present regulations, unless expressly provided otherwise, do not apply to [...] cargo ships of less than 500 gross tonnage"*. Nevertheless, in this situation, the safety of the crew is covered and regulated by the flag authority, which in this case has been indicated in the Dutch flag.

Furthermore, due to the operation in an area which is considered by the International Maritime Organisation as Arctic Waters, the new International Code for Ships Operating in Polar Waters (commonly know as Polar code) will partially apply (Polar Code-IMO, 2016). In this case, again because of the GT under 500, the vessel is exempted of part of the convention and the situation will be similar to a fishing boat case. In fact, Part I of the code is applied only to vessels which also have to comply with SOLAS regulation (Part I-A, Section 1.1). This fact cuts off all the safety and structures requirements, which nevertheless can be still considered as a guideline. However, Part II of the Polar Code is still mandatory also for vessels under 500 GT. This part covers the environmental rules.

As of today (October 2018), the Netherlands signed the new Polar Code but they did not ratified it yet. This means that if the vessel was built at the present time, the whole regulation would not apply at all. However, the Netherlands are planning to ratify the convention soon and therefore, not knowing the construction starting date yet, the Polar Code has to be taken into account for this concept design.

Taking a closer look at the regulation, two parts can have a quite heavy influence on the design. The first regards the fuel oil tanks that *"shall be separated from the outer shell by a distance of not less than 0.76 m. This provision does not apply to small oil fuel tanks with a maximum individual capacity not greater than 30 m^3"* (Part II-A, Chapter 1, Section 1.2.1). The same rules apply also to *"all oil residue (sludge) tanks and oily bilge water holding tanks"* (Part II-A, Chapter 1, Section 1.2.4). These rules will require either placing the tanks away from the hull or making them all smaller than 30 m^3.

The second important rule is stated in Part II-A, Chapter 1, Section 5.2.1, here it is affirmed that discharge of untreated sewage and garbage is prohibited in all Arctic Waters and that treated sewage and garbage can only be discharged *"as far as practicable from areas of ice concentration exceeding 1/10, but in any case not less than 12 nautical miles from the nearest land, nearest ice-shelf, or nearest fast ice"*. The applicable definition of *fast ice*, according to Part II-A, Chapter 1, can be found in World Meteorological Organization (1970). This rule basically forces to maintain all the above-mentioned products on board for all the time of the mission spent in an area covered by ice.

2

Environmental Analysis

2.1. Introduction and Methodology

The understanding and the collection of information regarding the operational area of the vessel represented one of the biggest challenges for this design. The main reason for this is the almost total lack of direct information about the environmental and climatic conditions of the area. In fact, compared to other polar areas, this part of the Fram Strait has been almost unexplored mainly for two reasons: the lack of petroleum and gas extraction activities around the coasts of Greenland and the relatively low scientific research interest of the area. These conditions together with its remoteness and its extreme conditions make the Fram Strait almost totally lacking direct images and information. Therefore, the path chosen for this environmental analysis has been the collection and evaluation of indirect information, such as satellites data and images from various European and International mission. The elaboration of this data has two main goals: giving a global idea of the conditions that have to be faced, with the aim of producing an operational plan, and produce the main design data for the development of the vessel concept.
The data have been downloaded from public FTP servers in the format of NC files, they have been collected in matrices and elaborated using different Matlab codes and finally analysed and plotted to highlight the most important characteristics and extrapolate the required information. The target period chosen for all the data are the winters of the decade from 2008 until 2018.

2.2. Global Characteristics of the Fram Strait

The reference point of the hydrophone presented in the research of Stafford et al. (2012), 79° N 5°W, is the first target of the research but the locations that will be covered are going to span over an area from 75°N until 82,5°N. The first important consideration that has to be done is that at these latitudes the light during the winter months is almost always absent. In fact, as can be seen from figure 2.1, the Nautical Twilight, which represents the limit after which the human eye does not capture sunlight anymore, starts at the beginning of November and some visible light reappears only at the beginning of February. This gives three entire months without sunlight which is already a big challenge for both the operational point of view and the mental stress of the crew of the vessel.

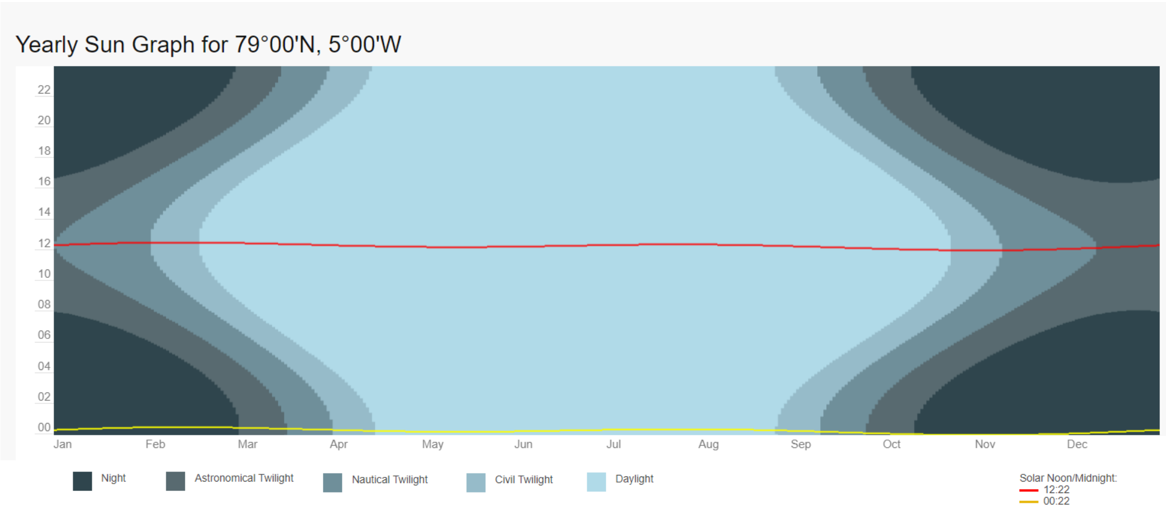


Figure 2.1: Sunlight duration in the Hydrophone location over the year (Image from: www.timeanddate.com)

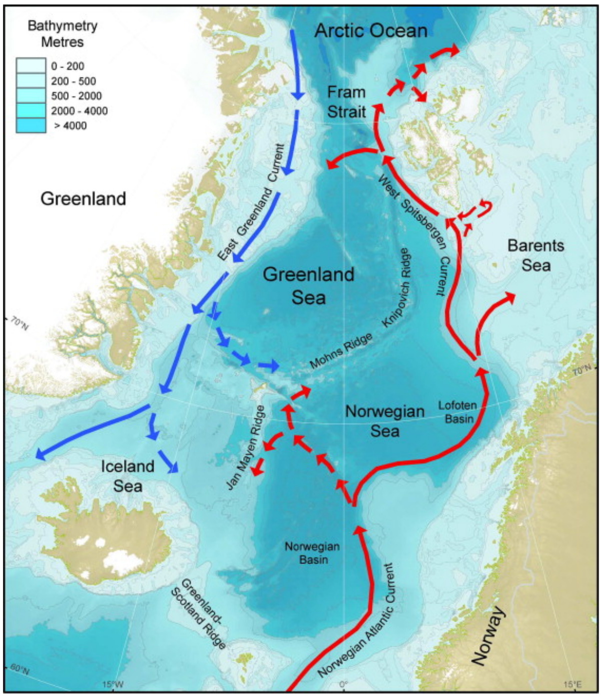


Figure 2.2: Main Currents paths and bathimetry around the area analysed, (Isachsen et al., 2014)

Regarding the geography of the Fram Strait, this has some salient characteristics that can be highlighted. The water flow is governed by two currents: the East Greenland Current, which is flowing toward South along the coast of Greenland, and the West Spitsbergen Current, which flows toward North along the coast of the Svalbard Archipelago (fig. 2.2). Another important feature of the Strait is that it represents the only deep connection between the Arctic Ocean and the rest of the Seas, (Klenke and Schenke, 2002). All these characteristics together lead to the fact that the Fram Strait is by far the most important place of ice export from the Arctic. In fact, more than 90% of the ice that flows out of Arctic passes through the Fram Strait, (Woodgate et al., 1999). A nice overview of this process is presented in figure 2.3. Here it can be seen that, due to the currents paths of the Arctic Ocean, most of the ice after some years is directed and expelled through the Fram Strait, this leads to the result that ice of all types and ages transits through this area. This fact has multiple implications for the design, which will be elaborated in section 2.4.2.

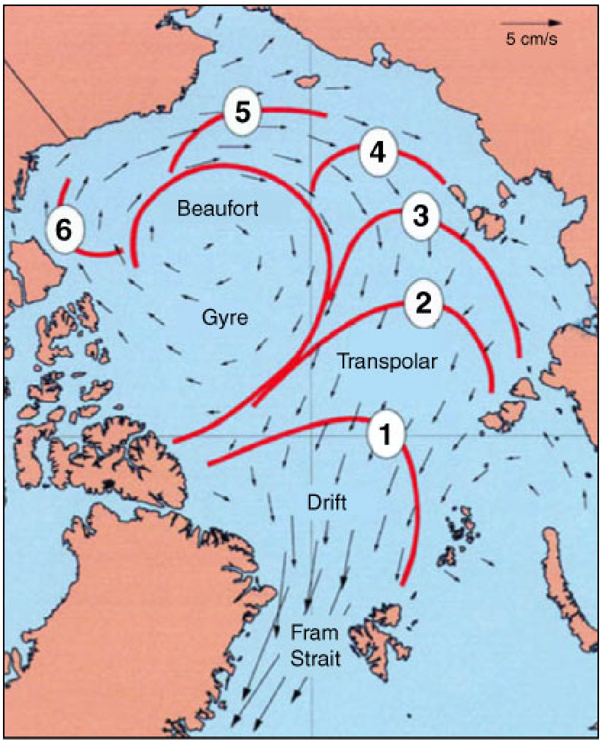


Figure 2.3: Ice patterns in the Arctic Ocean, the numbers on the red lines represent the average years spent inside the Arctic before being exported in the Fram Strait, (Backman et al., 2006)

2.3. Temperatures

The temperature data has been obtained from the ERA5 dataset of the European Centre for Medium-Range Weather Forecasts, (ECMRW, 2017). It provides the air temperature at an altitude of 2 m with a grid resolution of 31 km × 31 km. The data have been collected hourly for the last ten winters (September, October, November, December, January, February, March and April from 2007/2008 until 2017/2018).

There are three main utilities of the temperature data: to have an idea of the temperatures and their local variations, to estimate the ice growth during the winter and to design onboard machinery, insulation and winterization solutions.
Some of the results can be seen plotted in figures 2.4, 2.5 and 2.6. One of the main conclusions that can be drawn from figures 2.4 and 2.5 are that the freezing season starts on average at the end of September for the two southeast locations (76°N and 78°N) and at the end of October for the north-east one (81°N). Temperatures remain negative in all the location at least until the end of May and the coldest month are February and March. Minimum values can go under -20° C. As a matter of example in figure 2.6 the daily minimum, maximum and average temperature can be seen for the last 10 years in the northeast location, it can be seen that, even in the polar night months, the temperature differences over the day can vary a lot.

As already mentioned, the temperatures of the area can be used for calculating the ice thickness of the new ice refrozen in the leads and the polynyas of the Fram Strait. In fact, using the Freezing Degrees Days method it can be easily calculated that refrozen ice usually reaches values of 50 cm with rare peaks of 70 cm. These values are quite low looking at the harsh temperatures of the area. However, this happens due to the really dynamic characteristics of the Fram Strait which do not leave the open water undisturbed for long periods.

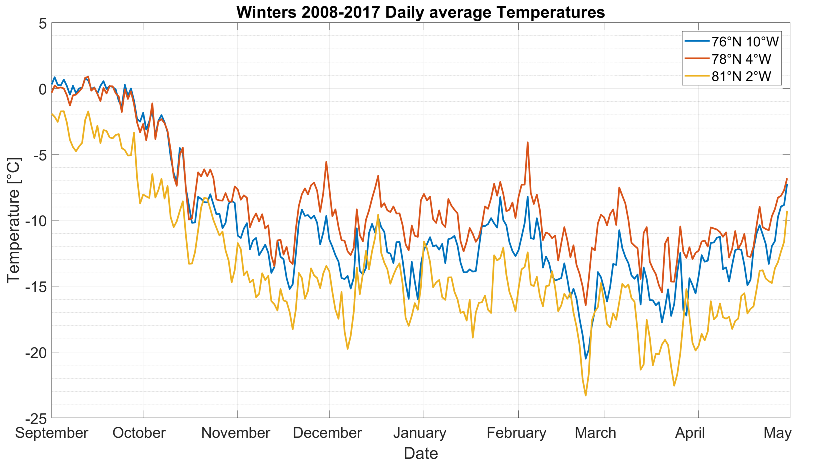


Figure 2.4: Daily average temperature variation in the decade 2008-2017 for three locations (data from ECMRW (2017)).

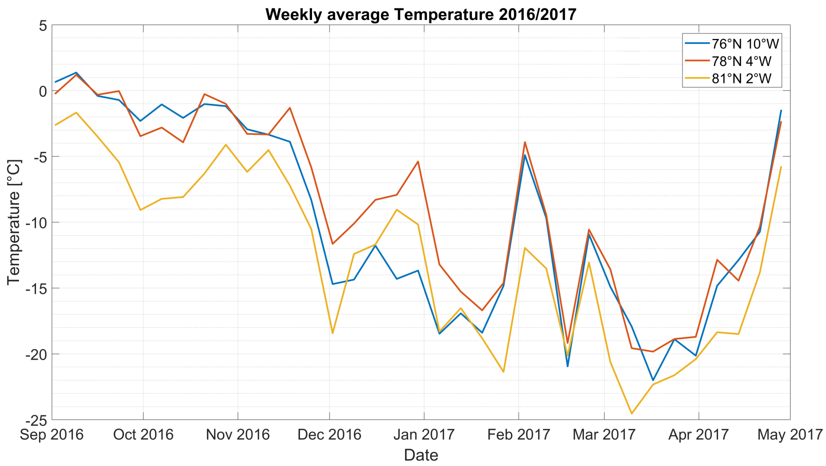


Figure 2.5: Weekly average temperature variation of winter 2016/2017 in three different locations (data from ECMRW (2017)).

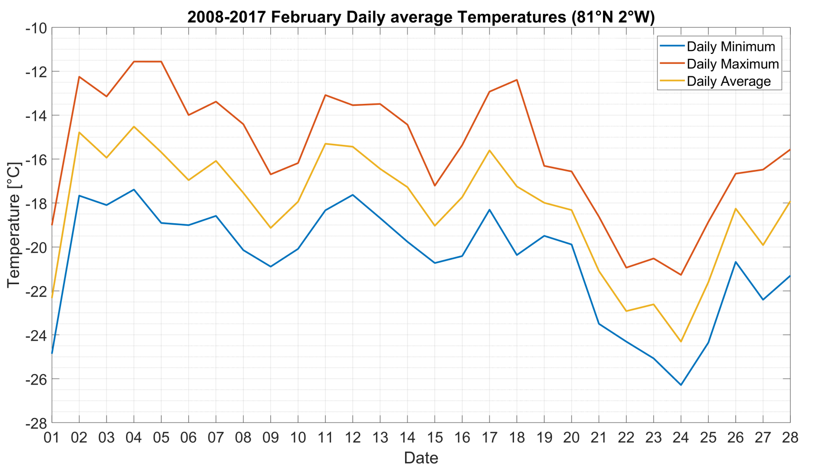


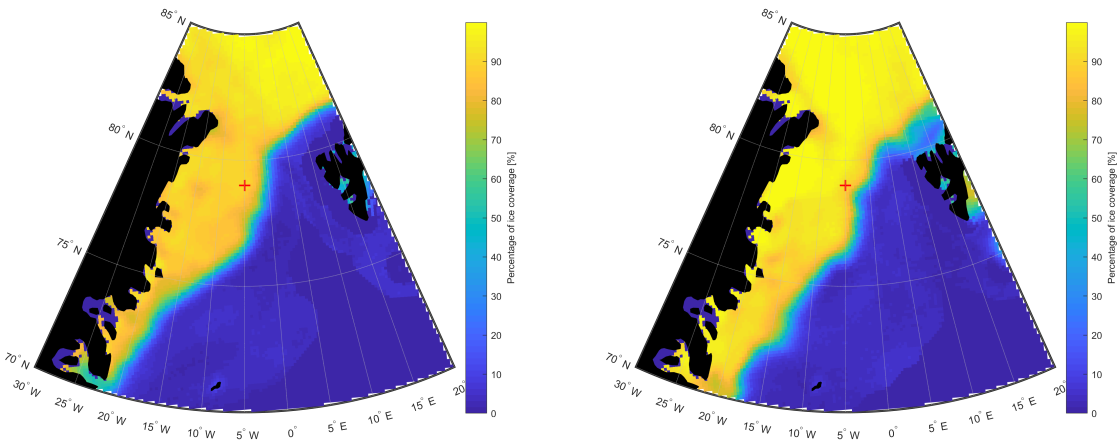
Figure 2.6: Daily minimum, maximum and average temperature in February at the location 81°N 2°W (data from ECMRW (2017)).

2.4. Ice Conditions

2.4.1. Ice Concentration

The ice concentration represents the percentage of water covered by the ice. According to the study of Stafford et al. (2012) the Bowhead Whales where recorded in areas with ice coverage of more than 90%. This, together with the fact that whales need some open water for emerging and breathing, shows the important influence that the ice concentration has on the operational side of the research.

The dataset has been collected from the sea ice concentration product of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (METNorway and DMI, 2017). It has a grid resolution of 25 km × 25 km and gives the percentage of ice covering on average the area. Data are available in monthly averages for the winters from 2012/2013 until 2016/2017 (Months of November, December, January, February, March and April).

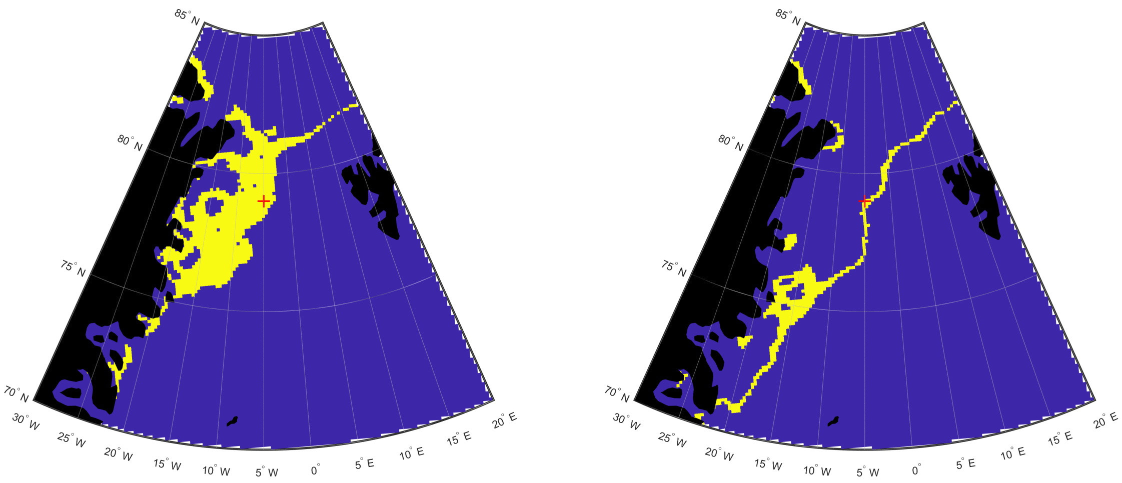


(a) November 2013 (b) April 2014

Figure 2.7: Ice concentration in the Fram Strait area (data from METNorway and DMI (2017))

As can be seen in fig. 2.7a (beginning of winter) and fig. 2.7b (end of winter) the increase of the ice shelf is not that strong in the area around where the whales have been spotted in the past (red cross), where it remains more or less constant over the winter.

Figures 2.8a and 2.8b show the area with a coverage between 85% and 90%, which is the type of ice concentration found where the whales have been spotted in the past (Stafford et al., 2012). This clearly shows how, at the beginning of the winter, the area is much larger compared to the end of the winter, but still the strip around the past observations point remains constant. The graphs presented are from the winter 2013-2014, but this situation can be observed more or less in the same way every year.



(a) November 2013 (b) April 2014

Figure 2.8: Ice Concentration between 85% and 90% in the Fram Strait area (data from METNorway and DMI (2017))

2.4.2. Ice Type

Sea ice can mainly be divided into two types: multi-year (MY) and first-year (FY) sea ice. First-year ice is ice that had been generated in the last winter and did not face any summer in its lifetime. It can grow up until a thickness of 2 m. On the other hand, multi-year ice has faced at least one summer and due to snow accumulation and compression phenomena can reach thicknesses much bigger than 2 m. One other key fact that impacts a vessel design is the different strength between the two ice types. The ice strength, in fact, is strongly dependent on its salinity, which for a first-year ice layer is close to the sea water one, while for a multi-year ice flow this, due to the brine pocket drainage phenomenon, tends to zero. Therefore, a lower salinity means a more compacted and stronger ice and this characteristic will be very important for the hull design.
The data for the ice-type analysis have been collected from the SeaWinds on QuikSCAT scatterometer-derived Arctic sea ice classification dataset from NASA (Swan and Long, 2012). This dataset has a grid resolution of 4,45 km $\times$ 4,45 km and presents the ice type dividing it into areas with first-year prevalence and areas with multi-year ice prevalence. Data are available daily, but only a few selected periods have been analysed.

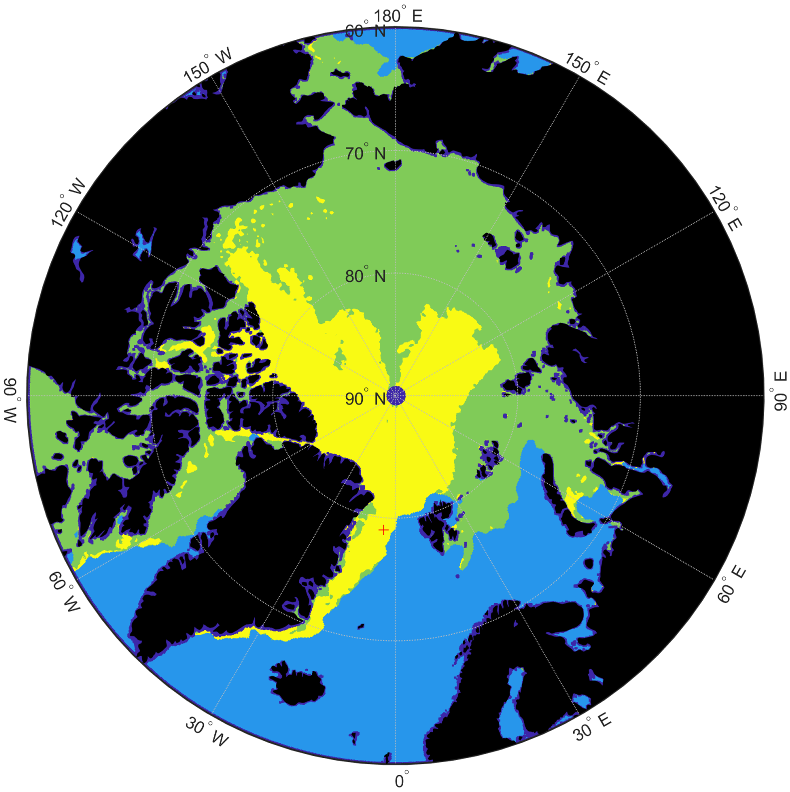


Figure 2.9: Ice type presence in the Arctic Ocean (January 2009) - Prevalence of first year ice in green, prevalence of multi-year ice in yellow (Data from Swan and Long (2012)).

As can be seen in figure 2.9 the currents already described in section 2.2 tend to transport all the ice of the Arctic Ocean through the Fram Strait and therefore the presence of multi-year ice floes is prevalent all over the area.

2.4.3. Ice Speed

The ice drifting speed data have been collected and elaborated using the low-resolution sea ice drift product of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) (Lavergne et al., 2010). It has a grid resolution of 62,5 km × 62,5 km and gives the average speed and direction of the ice measuring its position every 24 hours.
The second source of information are the results of the DAMOCLES ice-buoy campaigns between 2007–2009 presented by Haller et al. (2014). This was the scientific campaign to which Tara participated, one of the studies carried out was the analysis of the drifting speed, registering the speed of some buoys deployed in different positions in the Arctic Ocean. The results of the buoys that went through the Fram Strait are shown in figure 2.11.

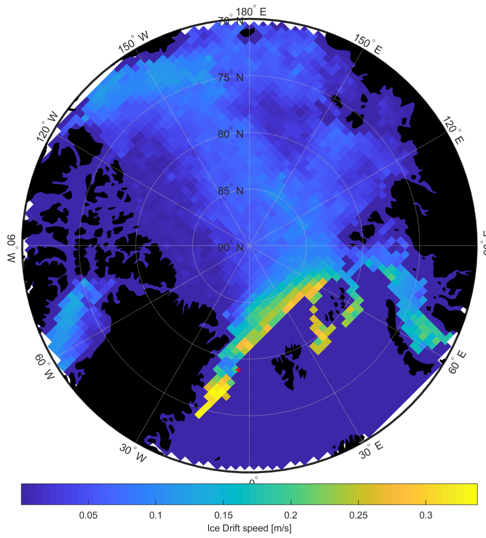


Figure 2.10: Ice drifting speed (January 2016) in the Arctic Ocean (Data from Lavergne et al. (2010)).

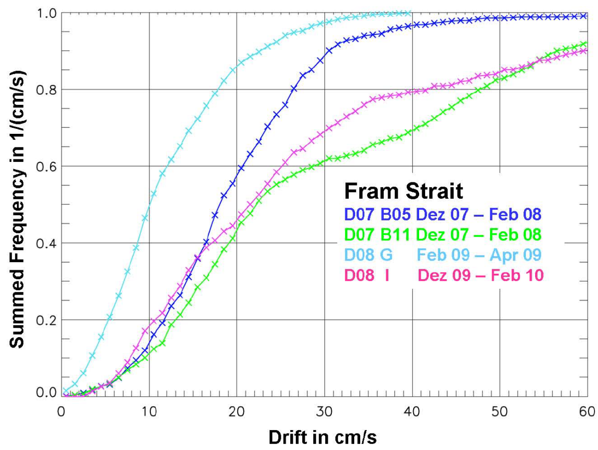


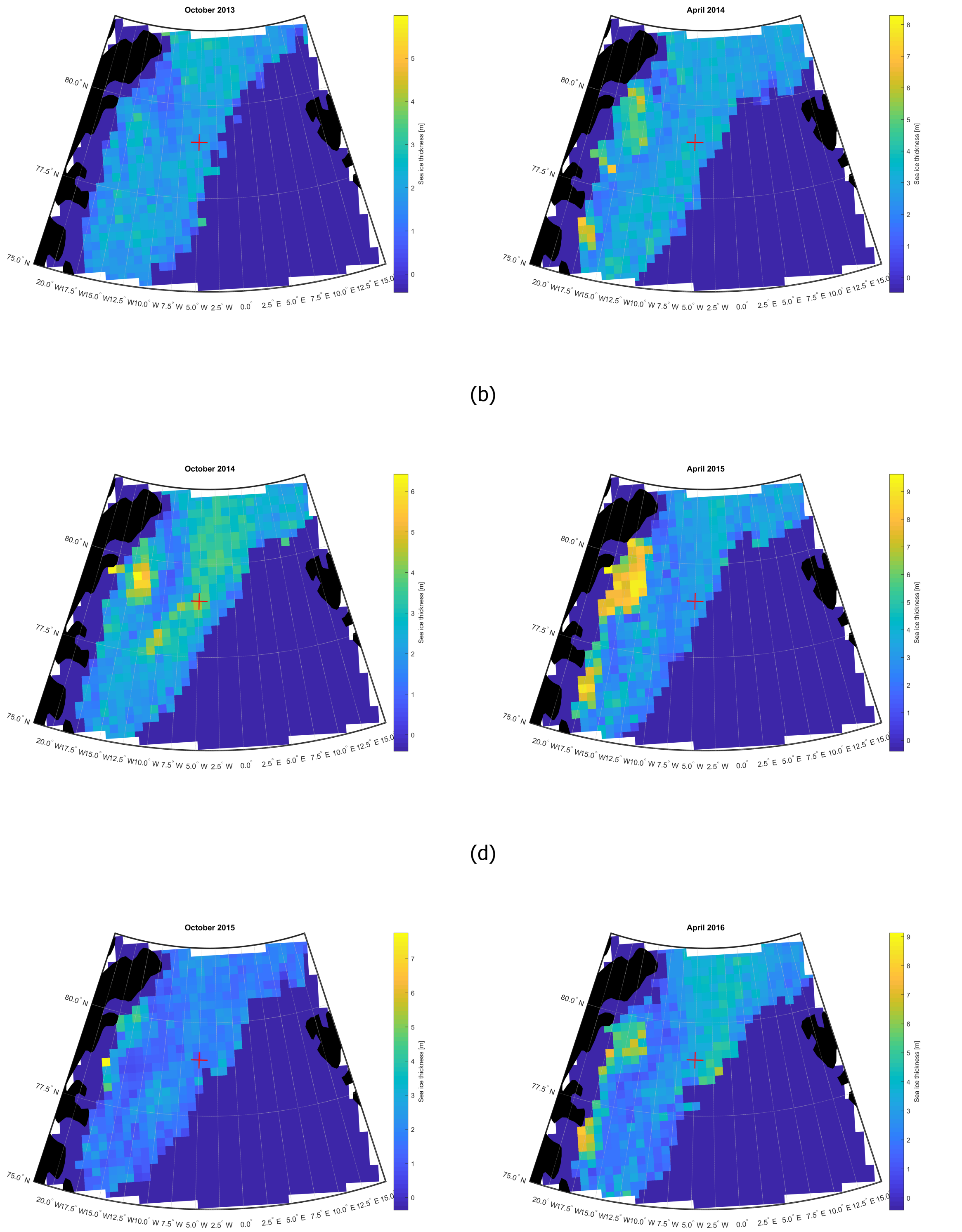
Figure 2.11: Measured drift velocity of the buoys deployed during the DAMOCLES ice-buoy campaigns 2007–2009 (Haller et al., 2014). The buoys drifted along different longitudes, The Western one was D08 G, followed by D07 B05, then D08 I and the Eastern one was D07 B11.

As can be seen in figure 2.10, the drifting speed of the ice in the Fram Strait is on average higher than in the rest of the Polar areas and always toward the south. This is due to the East Greenland current that transports the ice through the Fram Strait where is accelerated and then expelled in the Greenland Sea. The averages ice pack speed collected is around 0.15 m/s, which for an ice floe is a really high value.

Even more interesting are the data from the DAMOCLES campaign (fig. 2.11). Here it can be clearly seen, as also confirmed by Halvorsen et al. (2015), that the average drift speed is lower along the coast and increases going eastward. Furthermore, it can be seen how 50% of the measurements exceeded 0,1-0,2 m/s and 20% exceeded 0,2-0,6 cm/s.

2.4.4. Ice Thickness

The level sea ice thickness data collected are based on CryoSat-2 dataset (Grosfeld et al., 2006), have a resolution of 25 km × 25 km and they are available monthly. They represent the average thickness of the ice layer of the area.
Key data are shown in figure 2.12, these values are also confirmed by the High-resolution airborne laser scanner (ALS) measurements from Simonsen et al. (2015). It can be seen that average thickness values are around 2-3 meters with peaks of 6-7 m (fig. 2.12f). Furthermore, the presence of a big and really thick tabular multi-year ice floe near the coast of Greenland between 78°N and 80,5°N is also noticeable (very clear in fig. 2.12d) .



(a) (b)

(c) (d)

(e) (f)

Figure 2.12: Ice Thickness at ice minimum and maximum for winter 2013/2014, 2014/2015 and 2015/2016 (data from Grosfeld et al. (2006)).

2.4.5. Icebergs

Icebergs are floating remnants of glacial ice broken away from glaciers and ice shelves. Their size can vary from freeboards of 1,5m to more than 40 m and they can various and different shapes. After their detachment from the glacier ice shelf, they start floating and they drift moved by the wind and the current. When drifting toward south or when encountering obstacles or shallow areas they can start melting or breaking in smaller pieces. Besides their size, the other really dangerous feature of icebergs is their extremely high strength due to the total absence of salt and the millennial compression forces that they faced.
Unfortunately, there are no information or recorded observation in the area analysed, which means that they only source of information are satellite images and an analysis of the glaciers and the currents.

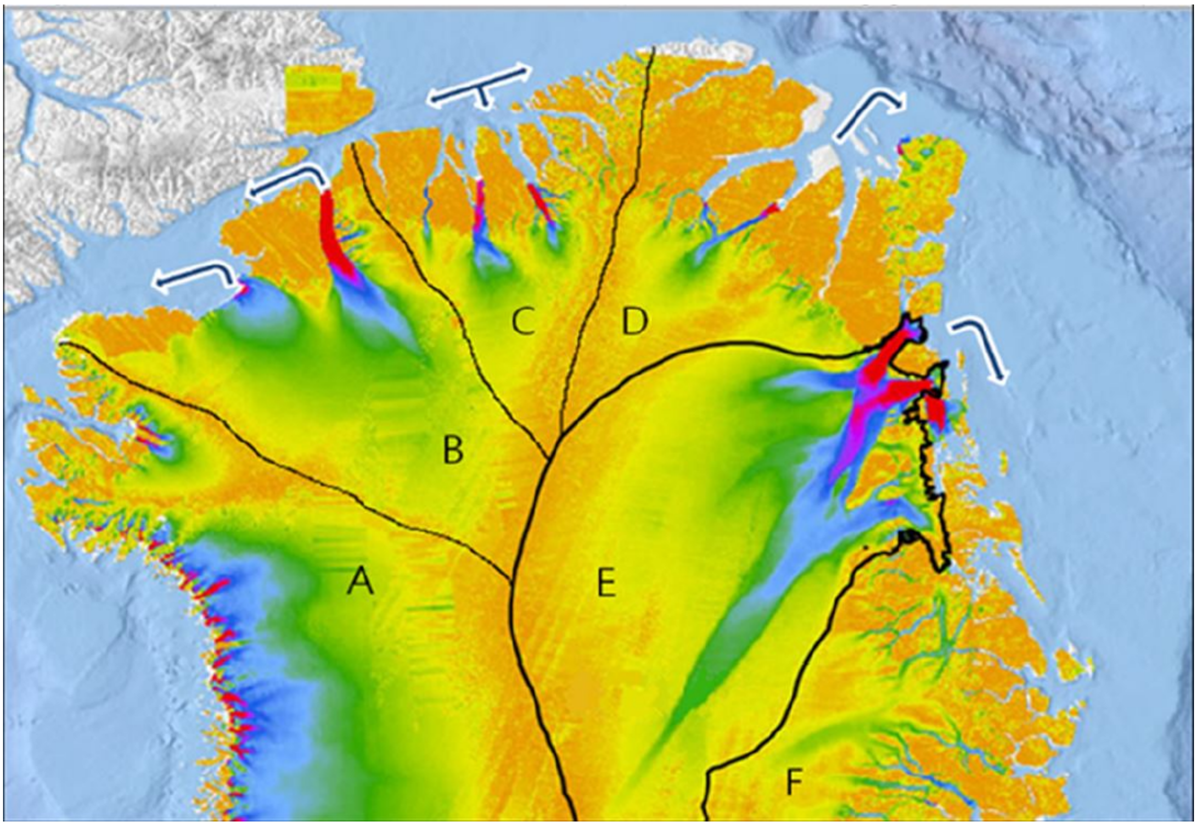


Figure 2.13: Drainage areas on the north coast of Greenland, speed of Greenland's ice sheet movements and main glaciers and icebergs directions, (Nissen et al., 2017)

Regarding local sources, the Northern part of Greenland has multiple glaciers basins that are an origin of icebergs (fig. 2.13). In particular, two of them are directing icebergs in the Fram Strait area: basin D and basin E. On the other hand, the icebergs, after the detachment, immediately face small islands and shallow waters that does not permit them to proceed unless broken in smaller pieces, (Nissen et al., 2017). Furthermore, the reference area for the vessel is also protected by the ice-covered areas along the Greenland coast. Therefore, rare and small icebergs are expected for this mission from the local sources.

A separate discussion has to be given for further sources. In fact, icebergs due to currents are able to travel really long distances. Therefore, it is important to analyse the main currents of the North Atlantic, which are presented in figure 2.14. Icebergs generated in the Greenland west coast can travel from the Baffin bay until the Labrador Sea and then, following the North Atlantic Current towards the north, reach the East Spitsbergen Current (fig. 2.2) and enter the research area.
However, such icebergs, besides being quite rare, will also be already heavily melted and broken. Moreover, coming from the open sea they are also easily detectable.

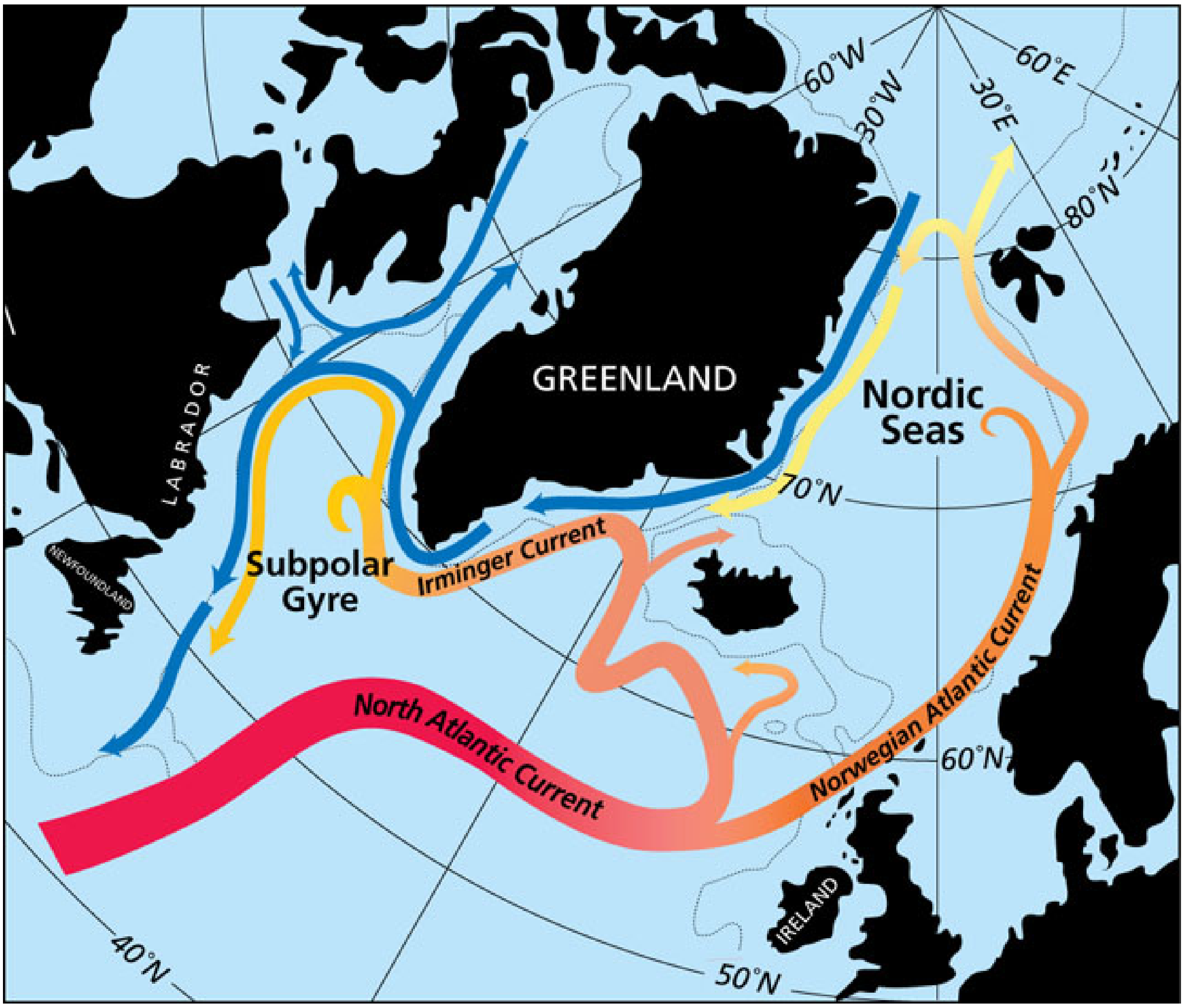


Figure 2.14: Main currents affecting icebergs in the North Atlantic, (Cook, 2010).

2.5. Wind

The wind data (speed and direction) have been obtained from two different sources: the Arctic System Reanalysis version 2 of the National Center for Atmospheric Research (UCAR/ENCAR, 2017) and the the ERA5 dataset of the European Centre for Medium-Range Weather Forecasts, (ECMRW, 2017). The Arctic System Reanalysis version 2 gives a grid resolution of 15 km × 15 km every 3 hours from 2009/2010 until 2011/2012, while the ERA5 provides a grid resolution of 31 km × 31 km with hourly records for the last ten winters from 2007/2008 until 2017/2018. For both of them have been analysed the months of September, October, November, December, January, February, March and April.
Even if the Arctic System Reanalysis version 2 has more than double the resolution, after a comparison it has been decided to present the ERA5 data because of their much longer duration and their higher frequency.

One of the biggest risks for a vessel navigating in ice along the North Greenland Coast is a so-called compression event. A compression event develops when the ice is pushed toward the east by the wind, in fact, in such a situation the coast on the West side of the ice acts as a barrier that restrains the movement of the ice. This phenomenon leads to a great compression in the ice with all the water leads closing. Such an event can be very dangerous for a structure floating surrounded by the ice and therefore has been the main aim of the wind analysis.
For evaluating the occurrence, frequency and severity of this phenomenon it has been decided to study the wind data at six different latitudes on the ice edge. As the ice edge varies over the winter, also the six points in order to remain on the border have to move. Therefore the winter has been split into three different periods in which the average ice edge remains in the same position. This leads to a total of 18 locations studied, their latitudes and longitudes are listed in table 2.1 and plotted in figure 2.15.

Latitudes [°N] \ Longitudes per Month [°E]	September, October, November	December, January, February	March, April
76	-9	-8	-7
77	-5	-4	-5
78	-3	-2	-4
79	0	0	0
80	2	1	5
81	5	5	12

Table 2.1: Wind roses locations.

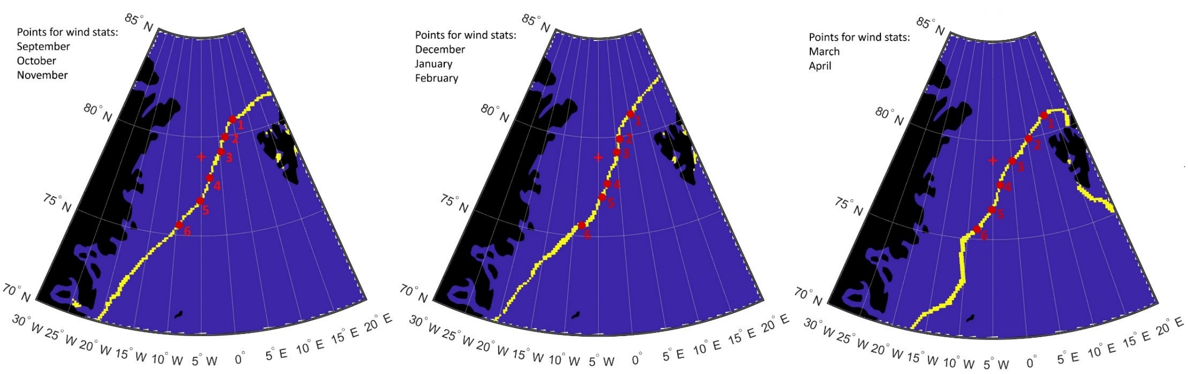
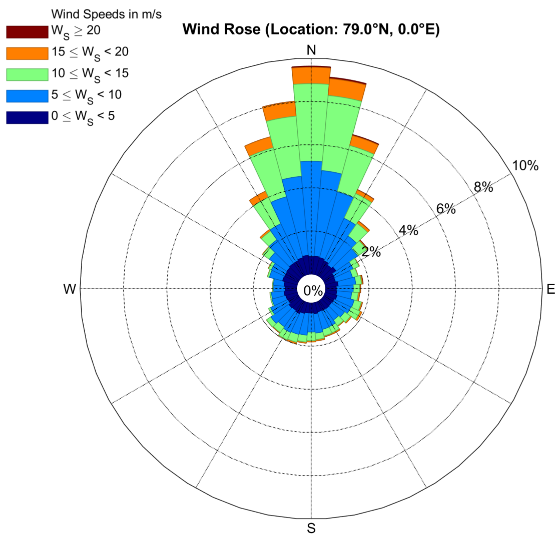
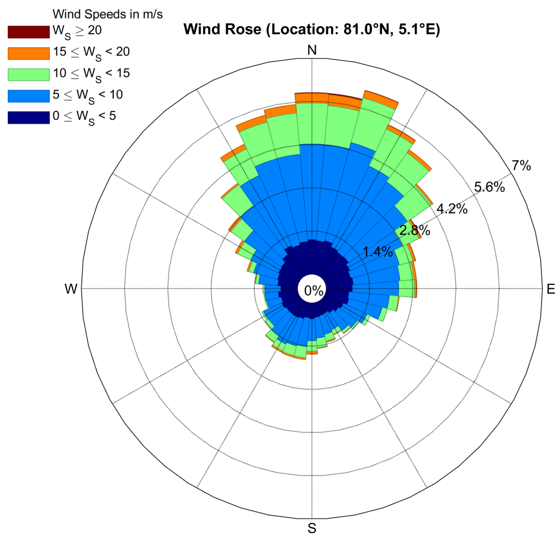


Figure 2.15: Wind roses at locations of table 2.1.

In these locations the data have been plotted in Wind Roses, two of them with a yearly average are presented in figure 2.16, while the complete monthly overview of all of them can be seen in appendix B. The wind rose in figure 2.16a is representative for the majority of the points analysed, here can be clearly seen how the wind is extremely northerly prevalent with some speed peaks that exceed 20 m/s, but mostly with speed lower than 10 m/s. Winds causing compression events (strong easterly and south-easterly) are quite rare. The situation slightly changes in figure 2.16b, where the wind rose is plotted for the Northeast latitude (81°N). Here, now lacking the coverage from the Svalbard Archipelago, there is a relevant presence of north-easterly winds, but the easterly and south-easterly ones are still on the same frequency of the southern points.



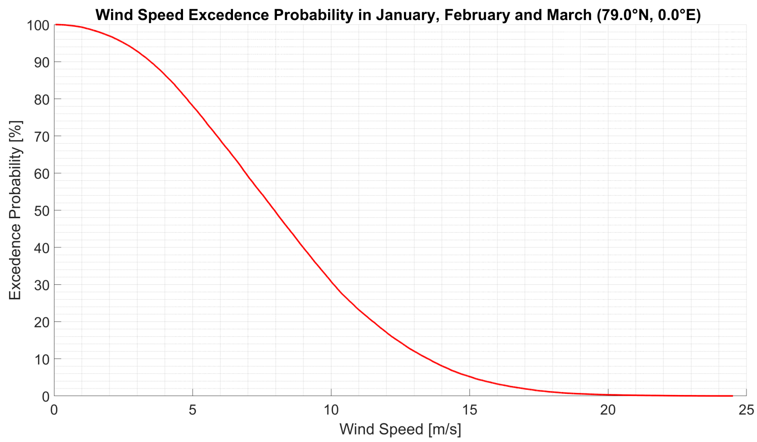
(a)



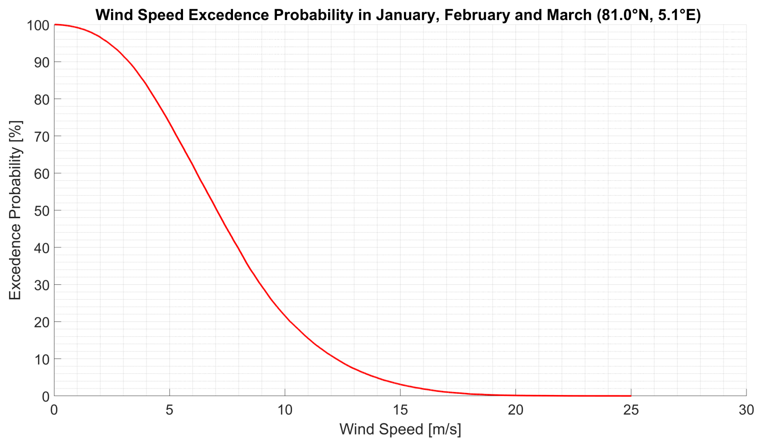
(b)

Figure 2.16: Selected Wind Roses (data from ECMRW (2017)).

To give an idea of the probability of each wind speed to occur, in figure 2.17 are shown the wind speed probability exceedance plots in the same points of the wind roses of figure 2.16. It can be clearly seen how winds are relatively slow, especially in the Northern latitude where the probability of exceeding 10 m/s is around 20% (fig. 2.17b) versus the 30% of 79°N (fig. 2.17a).



(a)



(b)

Figure 2.17: Selected Wind speed exceedance plots (data from ECMRW (2017)).

For a better overview of the frequency, intensity and characteristics of these events, it is important now to define and isolate them between the enormous amount of data available. The strategy used is to select the periods in which the wind is blowing from the east in three different locations at the same time (77°N 7°W, 79°N 5°W and 81°N 3°W). The reason for using as a criterion the contemporary presence of the above-mentioned conditions in three locations is to leave out the possibility of capturing local wind phenomena which are not creating any pressure events. As an example, the results for the year 2014/2015 are plotted in figure 2.18, where every single point plotted is 1 hour of contemporary easterly wind in all the three locations. The points are plotted over the time showing the wind speed. In such a way it is possible to have an idea of the yearly total amount of events (the number of points column), their intensity (the vertical position of the column) and their duration (the amount of points inside the column). The results for all the years analysed are available in appendix C.

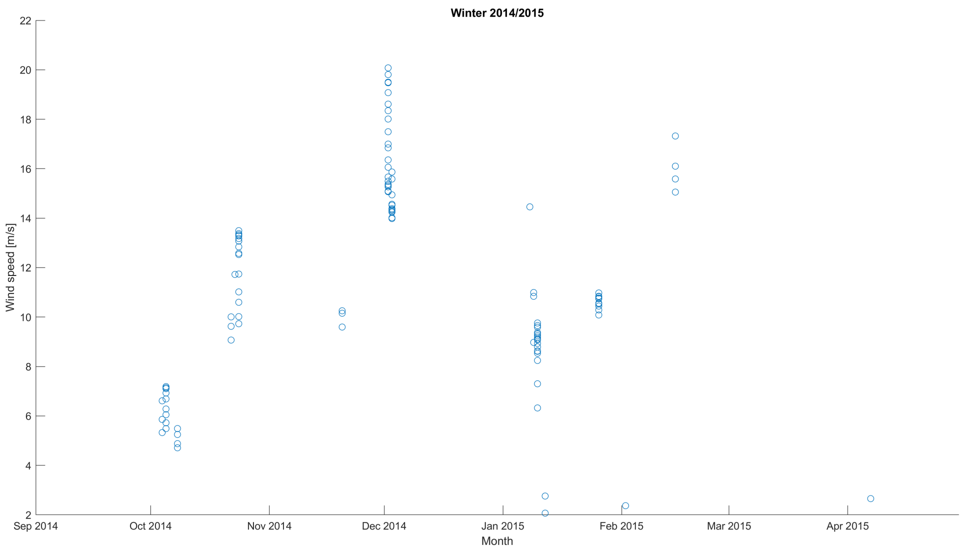


Figure 2.18: Wind Events recorded in 2014/2015. Each point is one hour of wind event duration (data from ECMRW (2017)).

The total amount of strong events, as already expected looking at the wind roses, is quite low, but it is still possible to see some of them probably strong and long enough to create pressure in the ice. In particular two of them have been analysed and plotted in figure 2.19 and 2.20. Here, wind speed and direction of the events of the 8^{th} of January 2015 (fig. 2.19) and of the 1^{st} of December 2014 (fig. 2.20) are plotted.

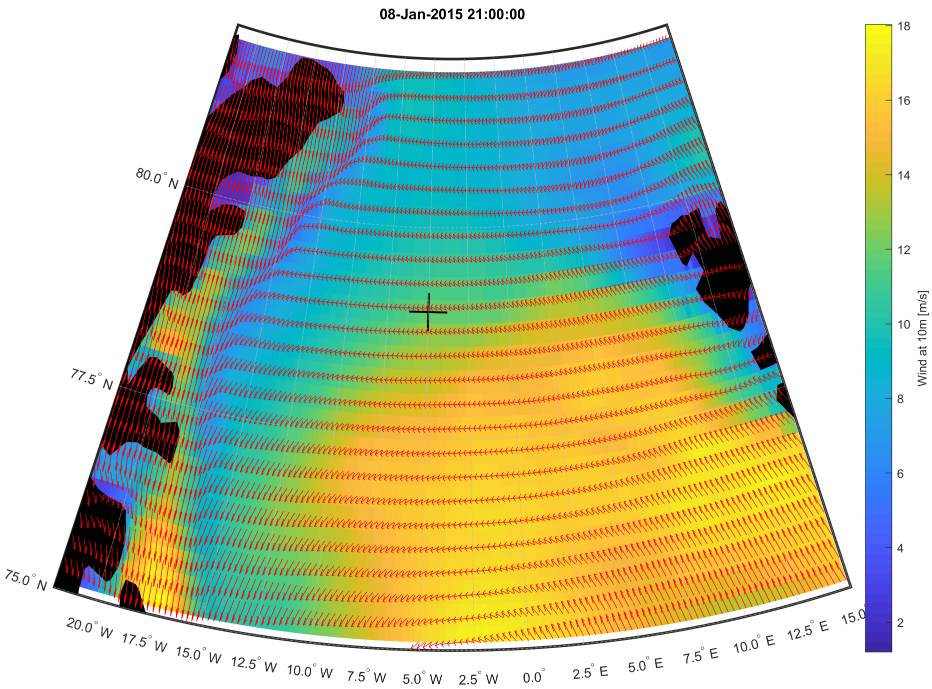


Figure 2.19: Wind plot of wind event of 8^{th} of January 2015 (data from ECMRW (2017)).

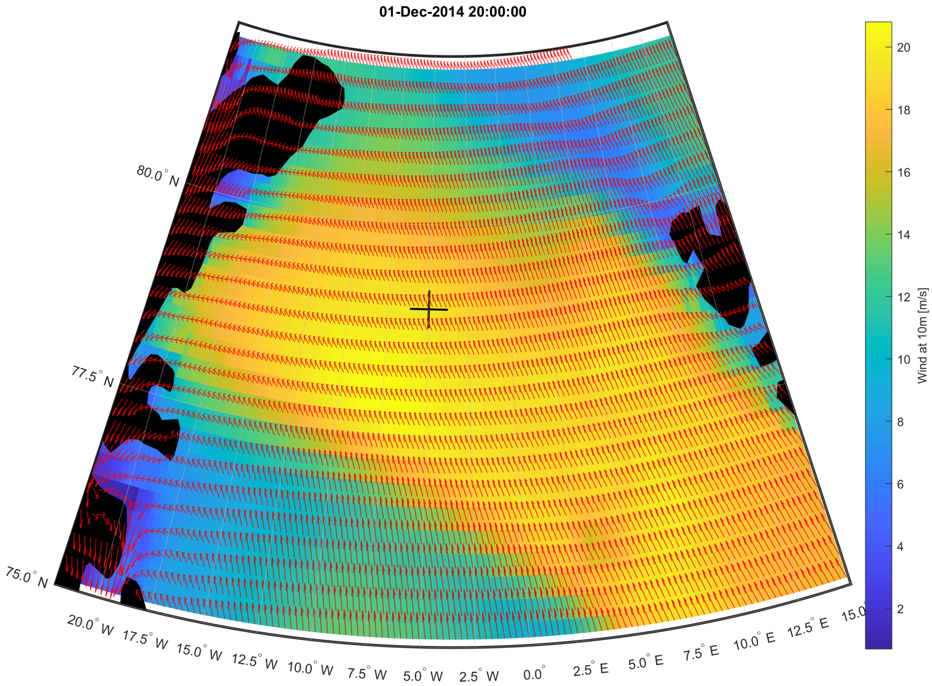


Figure 2.20: Wind plot of wind event of 1^{st} of December 2014 (data from ECMRW (2017)).

Moreover, the results of the wind event of the 8^{th} of January 2015 can be appreciated in figure 2.21. This shows a satellite view of the area before and after the wind event occurred.

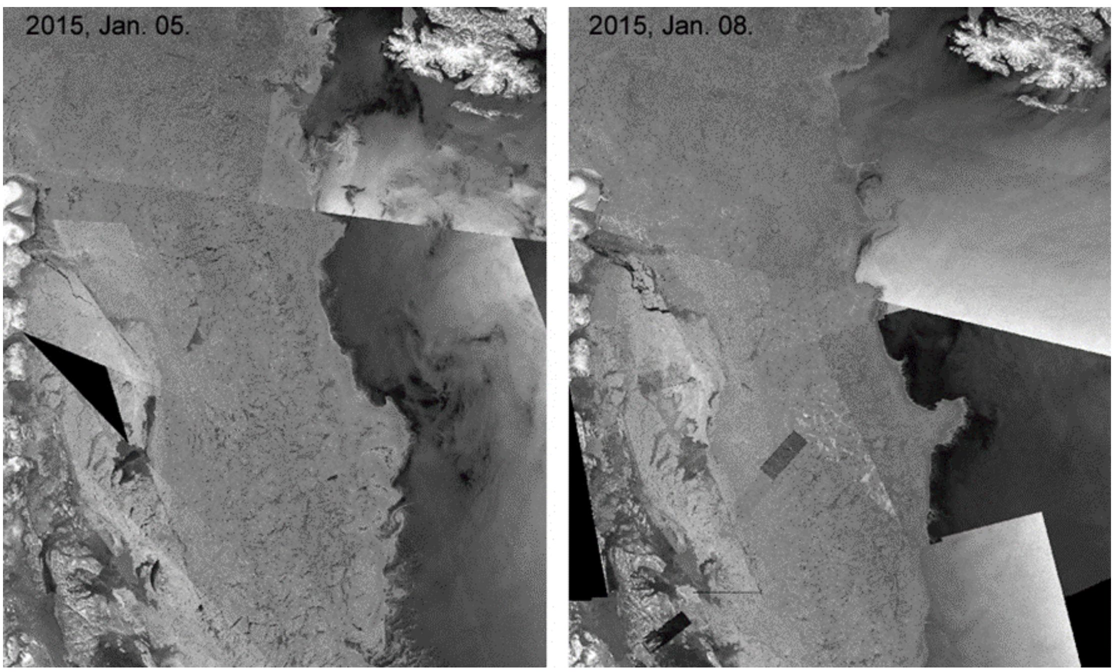


Figure 2.21: Satellite image of the area before and after the wind event of the 8^{th} of January 2015. Images from Sentinel 1A and 1B, 1 km resolution and 3-day mosaic (Krane and Jolles, 2018).

Here it can be seen how the ice on the 5^{th} of January presents a lot of leads and open water, while three days later it is strongly compacted and ridged and the leads are not present anymore.

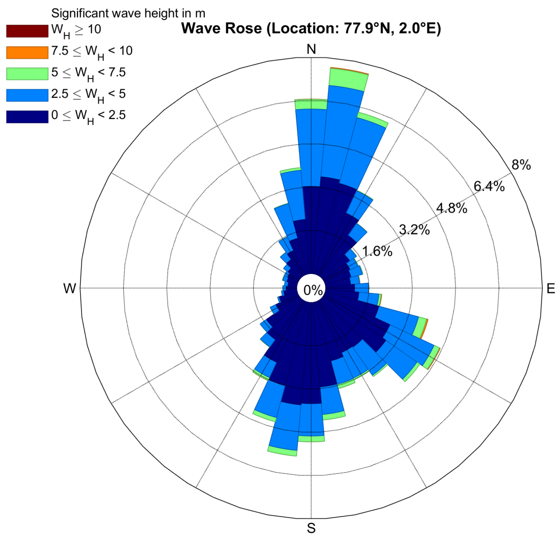
2.6. Waves

For the waves a similar approach has been used. The data of the height of wind waves, height of combined wind waves and swell and wave direction have been downloaded again from the ERA5 dataset of the European Centre for Medium-Range Weather Forecasts (ECMRW, 2017) with a grid resolution of 31 km × 31 km with hourly records for the last ten winters from 2007/2008 until 2017/2018.
Regarding the waves, the main interest is their intensity along the Marginal Ice Zone and their behaviour during the compression events previously analysed. As for the wind also in this case some wave roses have been generated. This time the locations, due to the necessity of open water, are 20 nautical miles South-East of the same point used for the wind roses, an overview is presented in table 2.2.

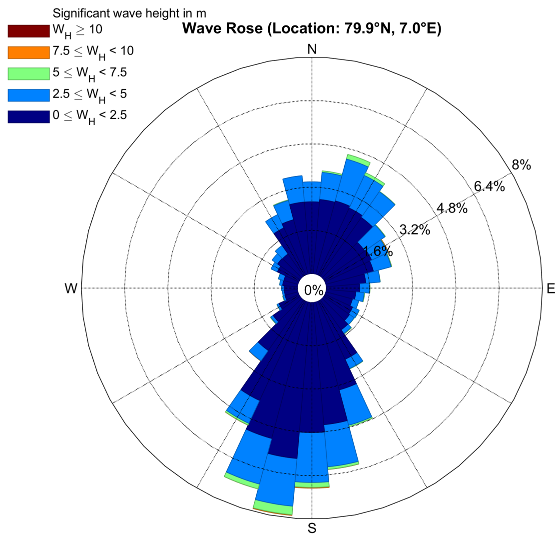
Latitudes [°N] / Longitudes per Month [°E]	September, October, November	December, January, February	March, April
75,75	-7	-6	-5
76,75	-3	-2	-3
77,75	-1	0	-2
78,75	2	2	2
79,75	4	3	7
80,75	7	7	14

Table 2.2: Wave roses locations.

The complete set of wave roses is presented in appendix D, while in figure 2.22 the yearly average ones 20 miles southeast of the locations of the wind roses of figure 2.16 can be seen. It is noticeable that the waves are mainly directed parallel to the ice edge. Furthermore, in figure 2.23 the correspondent wave exceedance plots are shown.



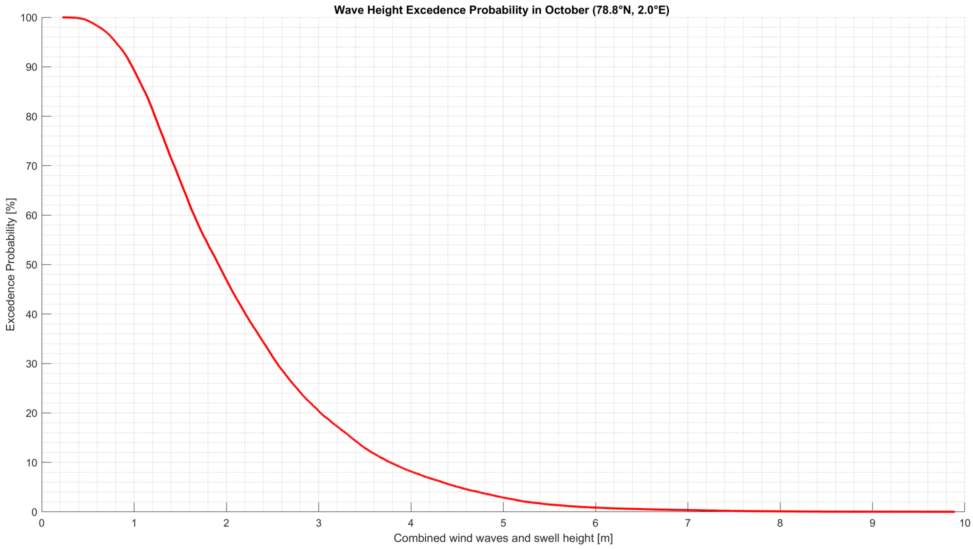
(a)



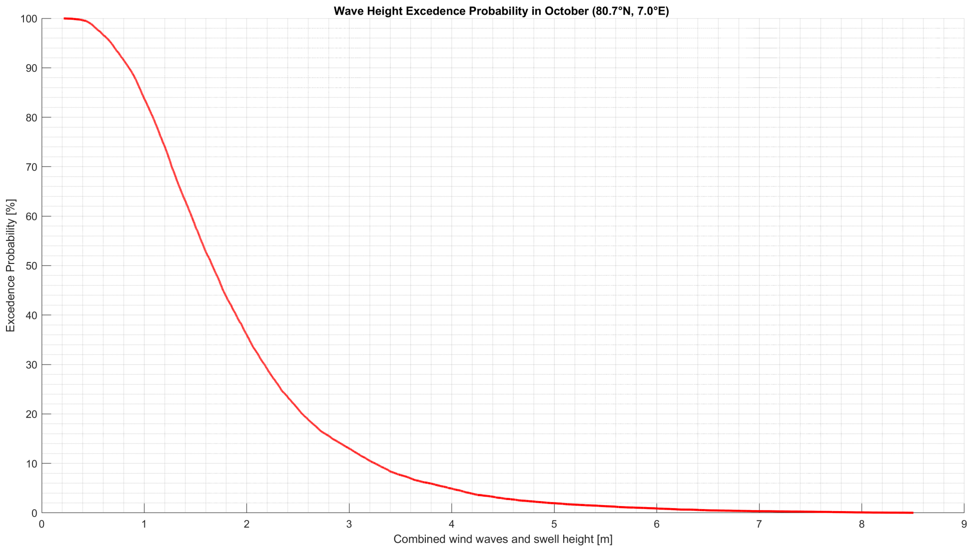
(b)

Figure 2.22: Selected roses of combined wind and swell waves (data from ECMRW (2017)).

Finally, in figure 2.24 and 2.25 the height and direction of the waves are plotted for the same pressure events selected in 2.6. Both with only the height of wind waves and one with the height of combined wind waves and swell and wave.

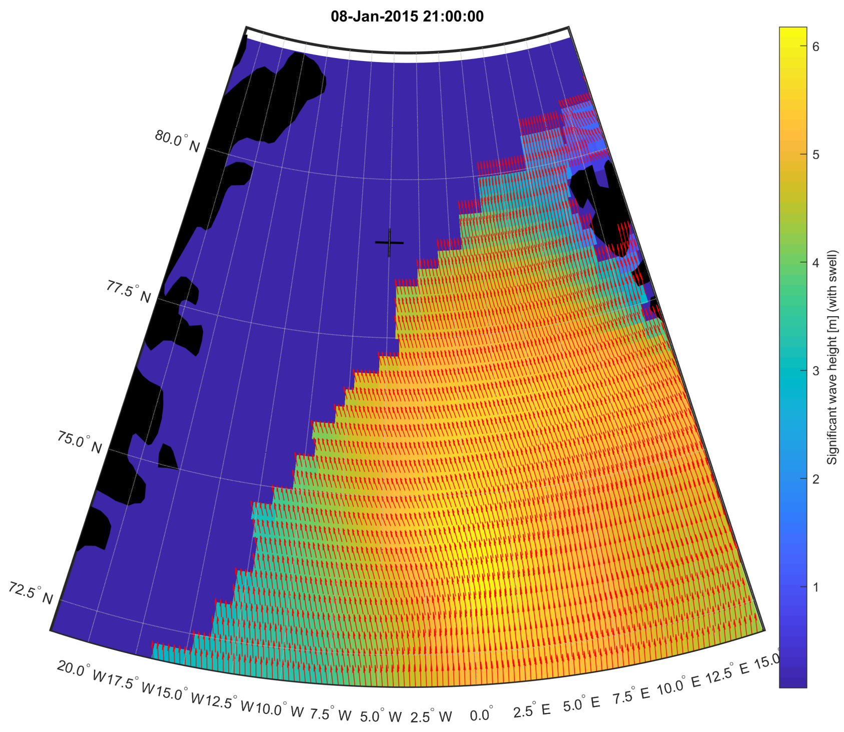


(a)

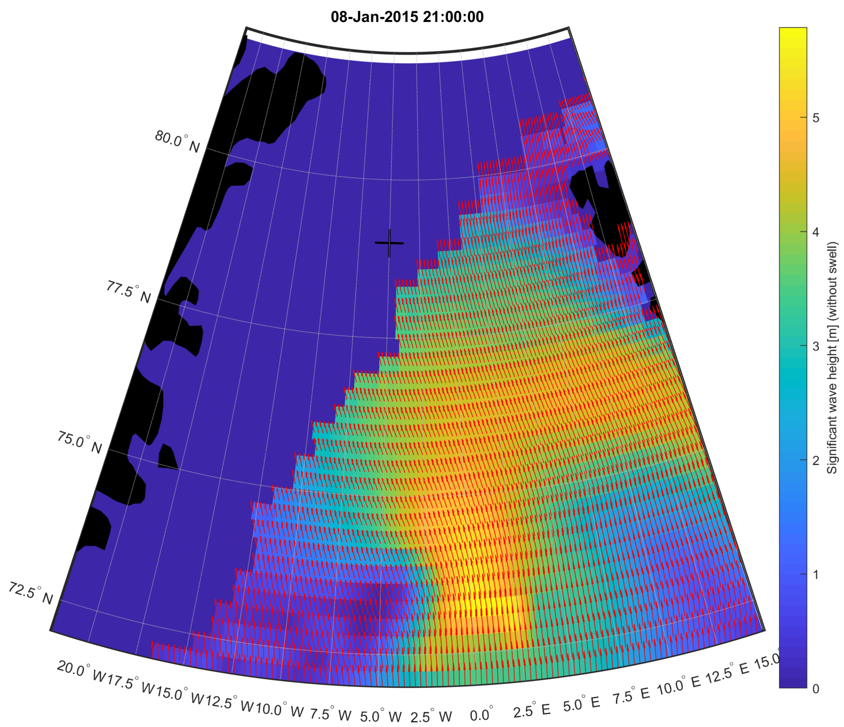


(b)

Figure 2.23: Selected wave height exceedance plots (data from ECMRW (2017)).

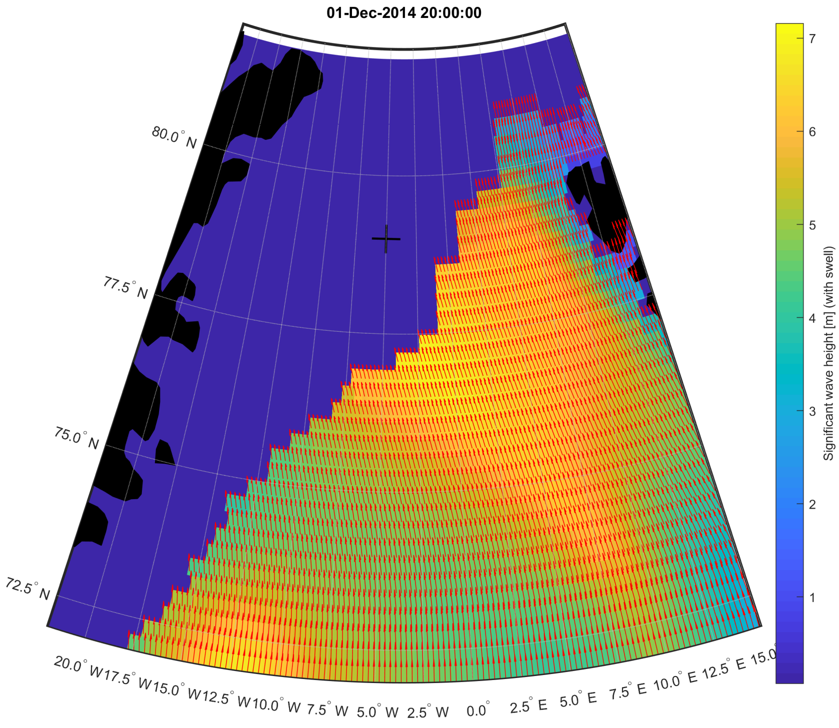


(a) Combined wind waves and swell height

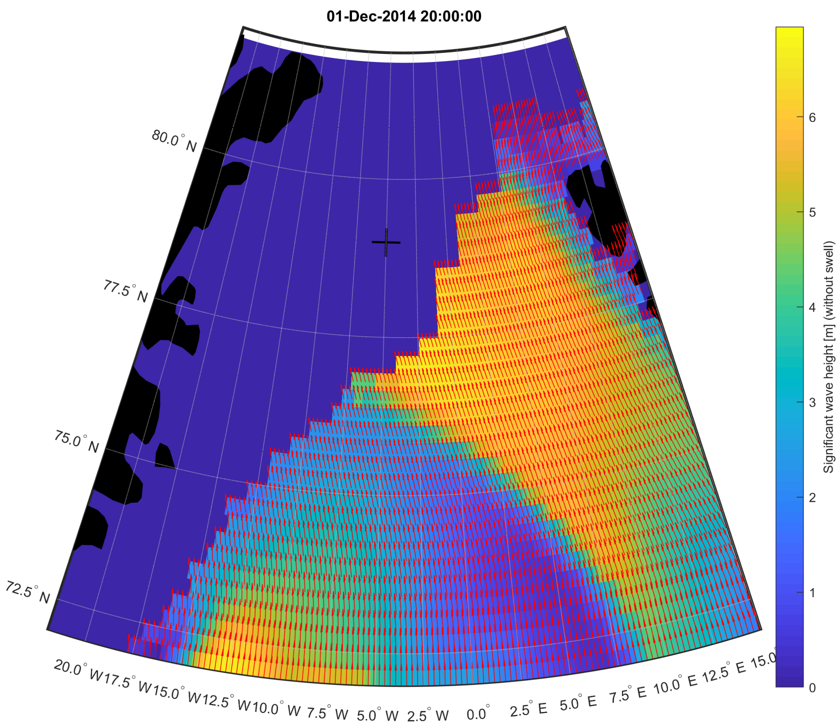


(b) Wind waves height

Figure 2.24: Wave plots of wind event of 1^{st} of December 2014 (data from ECMRW (2017)).



(a) Combined wind waves and swell height



(b) Wind waves height

Figure 2.25: Wave plots of wind event of 8^{th} of January 2015 (data from ECMRW (2017)).

2.7. Global Overview and Main Conclusions

The environmental analysis carried out helped a lot to give a picture of the main characteristics and risks present in North-East Greenland and in particular the Fram Strait. This area presents an extremely dynamic environment and a really various range of Ice Types. The study of the currents and the geographical characteristics of the area, together with the ice type and speed analysis, helped to highlight and prove this dynamic situation and will be extremely important for the structure dimensioning. The peculiarity of the Fram Strait as main discharge point of the Arctic Ocean ice permits the contemporary presence of ice of multiple ages and structures. The temperatures analysis has been used for defining the refrozen ice thickness and will be useful for the insulation and heating systems sizing.

The evaluation of ice concentration over the winters of the last ten years, matched with the Bowhead Whales behaviour, helped to understand the key target areas for the research and their size. The collection and elaboration of data regarding the average ice thickness and its variation over the winter will be later an input for the hull freeboard and main dimensions and helped for defining the most dangerous situations that the mission will have to face. The definition of the compression events and the description of their characteristics through images and ice data will define the main strategies and the overall characteristics of the vessel and, in particular, of its hull shape. Furthermore, the study of the wind and waves through roses and exceedance plots gave an idea of the frequency and occurrence of the wind events.

The provided environmental analysis is, however, sufficient only for a concept design. For further design steps a more deep study is recommended, with a more extended evaluation of the compression events, analysing a bigger number of cases. A more deep study will be even more important for operational purposes. In this case the collection and the purchase of much more detailed satellite images will play a fundamental role in order to precisely define a series of strategies depending on the occurrence and variation of different environmental situations.

3

Similar Missions Evaluation

In the first stages of the design a lot of effort has been put into the research and study of similar missions that can be used as inspiration or comparison for this design. The really particular profile mission and the unexplored chosen area makes indeed difficult to find a comparable project, but three missions captured the attention and will be used for different reasons in the development of the final concept design.

The three designs presented are the schooner Tara, the sailing yacht POLAR and the Icebreaking Emergency Evacuation Vessel (IBEEV). In the next sections their main features will be briefly described.

3.1. Tara

Figure 3.1: Tara boat, (Tara Expedition Foundation, 2016)

Tara (fig. 3.1) is a 36 m sailing boat designed in 1987 by the naval architects Oliver Petit and Luc Bouvet (Redvers, 2010). After having been built, it passed by different owners among which the most famous is the New Zealander sailor and American's Cup winner Sir Peter Blake, which also died on Tara shot by pirates while sailing on the Amazon river. It is now owned by the Tara Expedition Foundation which uses it for scientific expeditions around the World. It has also a twin vessel called Paratii II owned by the Brazilian explorer Amyr Klink (Klink, 2014). Tara's main characteristics are shown in table 3.1.

The hull has a particular very rounded shape that, together with the very light aluminium hull, gives to the vessel the possibility of being easily pushed up by the ice when pressed on the sides.

Characteristics	Value
$WaterlineLenght$	36 m
$Beam$	10 m
$Draft$	1,5 m
$Weight$	120 t
$PropulsionPower$	2 x 260 kW
$HullMaterial$	Aluminium

Table 3.1: Main characteristics of the vessel Tara (source: taraexpeditions.org)

Furthermore, a retractable keel is installed in order to protect it by the ice. Moreover, the rudders can be manually uninstalled and the propellers are protected by a particular hull shape. The aluminium hull is reinforced at the keel and at the water line through an ice belt, reaching thicknesses of 25 mm. Among the various expeditions completed by Tara, one in particular is of great interest for this design. In fact, in 2006-2008 Tara travelled along the North Pole for 2 years while drifting (Tara Expedition Foundation, 2016) and during the last winter the expedition also crossed the Fram Strait following a route really close to the area of interest for the Ice Whale Foundation (fig. 3.2). The expedition was lead by Grant Redvers and had been used for collecting scientific data for different research fields. Thanks to the information provided by Grant Redvers via a video-conference, it has been possible to learn about the problems faced and the strength and weakness of the design.

Figure 3.2: Tara route of Tara Arctic expedition 2006-2008, (Tara Expedition Foundation, 2016)

The vessel entered the pack ice on the 4^{th} of September 2006 with the help of an ice breaker which opened a space for the vessel inside of an ice floe. Here the vessel waited berthed to the ice until, due to the ice pressure, it has been pushed up. Tara travelled on the ice for two years, receiving provisions and supplies via aeroplanes or icebreakers. It finally went out of the ice on the 21^{st} of January 2008. According to Redvers description, the lifting up of the vessel happened in multiple occasions and always really fast and without problems. Problems of inclinations and misalignments happened when the ice floes were not pushing perpendicularly to the sides. Besides these misalignments the main issue faced was the mounting and dismounting of the rudders, which was taking too much time and due to the rapid movements of the ice, especially in the Fram Strait, could lead to dangerous situations. Moreover, the not retractable propellers were difficult to protect from the ice. The hull did not suffer any damages from ice pressure, even if, during compression events, the sound of the ice force on the hull was really strong. Some trenches around the hull had been dug to avoid ice riding up to the deck. Lastly, the navigation in the ice channels was quite difficult and the route was mainly decided depending on their conformation and direction. One of the main issues was their very rapid and sudden closure and disclosure. Furthermore, in these conditions it was almost impossible to use the sails as propulsion and therefore the diesel propulsion was by far the most used.

3.2. Dykstra Polar Yacht

Figure 3.3: POLAR sailing yacht by Dykstra Naval Architects (Yachtemoceans, 2017)

Characteristics	Value
Waterline Lenght	21,25 m
Beam	7,26 m
Draft	1,5 m
Weight	85 t
Propulsion Power	2 x 118 kW
HullMaterial	Aluminium

Table 3.2: Main characteristics of the sailing boat POLAR (Yachtemoceans, 2017)

The second design is the future Polar Yacht from Dykstra Naval Architects with the project name POLAR (fig. 3.3). Data are not fully public yet but, thanks to the courtesy of Gerard Dijkstra, lots of knowledge has been gained during a meeting at the main office of Dykstra Naval Architects in Amsterdam. Information about the main characteristics has been collected, especially on the hull structure, on the winterisation methods and on the safety facilities adopted. In table 3.2 the main characteristics of the vessel can be found.

Among the various information collected, particularly interesting are the hull characteristics: the hull is inspired by the Schooner Tara and also presents a very rounded aluminium hull with a 25mm belt on the waterline (ice belt), on the keel and at the bow. Another interesting feature is the design of the living areas as a survival module that can float independently. The vessel has a very redundant heating system and, for keeping them ice free, the exhaust gasses are discharged passing through the masts, which also contain heated bearings. The vessel is equipped with various vehicles both for evacuation and pleasure purposes, such as a 6 m tender, a sleight and a kayak. Both keel and rudders are retractable. The vessel presents two rotatable carbon masts without stays (wing rig) and the main propulsion system is powered by two diesel engines which transmit power with a direct shaft connection to the propellers, which are also retractable using an innovative system. The auxiliary power can be also generated by a wind turbine and solar panels.

3.3. Icebreaking Emergency Evacuation Vessel (IBEEV)

The last design presented is the Icebreaking Emergency Evacuation Vessel (fig. 3.4). This vessel has been designed for the evacuation of the personnel of the Kashagan field in the North Caspian Sea, Kazakhstan (Arctic Climate Change Economy and Society, 2013). Its characteristics are shown in table 3.3.

Figure 3.4: Icebreaking Emergency Evacuation Vessel (IBEEV) (Arctic Climate Change Economy and Society, 2013).

Characteristics	Value
Waterline Length	42,34 m
Beam	8 m
Draft	2,1 m
Weight	508 t
Propulsion Power	2 x 550 kW
HullMaterial	Steel

Table 3.3: Main characteristics of the Icebreaking Emergency Evacuation Vessel (IBEEV) (Data from appendix I and from Arctic Climate Change Economy and Society (2013)).

The vessel has to face the level ice conditions of the Caspian see during winter and the very shallow waters of the area. It has the capability to accommodate up to 340 people and can break up to 60 cm of ice. Furthermore it has been designed for passing through anoxic environments and pools of burning oil. Each of the passengers has a personal carbon dioxide scrubber and rebreather and combustion air for the engines is provided by high-pressure bottles. The hull is in steel and the propulsion is given by two diesel engines which power two ice-classed azimuthal thrusters produced by Schottel (App. I).

4

Selection Process

4.1. Approach

In this section, a first concepts analysis and selection will be carried out. First, a System Engineering approach will be used to evaluate the mission and the requirements and to transform them into some physical high-level concepts and some related concept of operations. Moreover, the proposed concepts will be compared using some criteria derived from the mission requirements and the environmental condition previously evaluated and presented. The output of this selection process will be a concept of operation connected to a high level most promising concept. This concept will still be with a lot of design space and variables, but it will already have some defined characteristics and a clear method to follow in order to fulfil the mission.

4.2. System Engineering Process

According to US Air Force (1974), System Engineering can be defined as a "logical sequence of activities and decisions that transforms an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation".
System Engineering is very useful in a design like this, where the research requirements are not fully defined and the mission does not have predecessors or previous similar projects which can be analysed and evaluated. Analysing the mission and the requirements while splitting them in really high-level and abstract concepts and then assigning them to a physical structure helps also the designer to have a clear view of the problem, avoiding preconceptions and not excluding less obvious solutions. Moreover, System Engineering "focuses on defining customer needs and required functionality early in the development cycle [...] while considering the complete problem" (Haskins et al., 2006).

4.2.1. Missions

The first part of the process is the definition of the mission of the vehicle that has to be designed. To do this, it is really important to deeply understand the real research goals requested by the future owner. In order to give a proper definition, it is also important to keep a high-level description.
Based on the initial Ice Whale Foundation requirements previously presented in chapter 1 the research goals have been split in a primary mission and in a secondary mission. They have been defined as follow:

- **Primary mission:** Detect and identify Bowhead Whales in the Marginal Ice Zone of the Fram Strait and assess their characteristics and behaviour
- **Secondary mission:** Analyse water and environment for supporting different studies.

The primary mission has to be considered the main goal of the whole study. The secondary mission is of less relevant importance and can be considered just as an added value to the fulfilment of the primary one. Therefore, the System Engineering concept presented here will focus only on the primary mission, while the secondary one will be used only as an evaluation criterion for the Analytic Hierarchy Process of section 4.4.

Furthermore, the primary mission can be contextualised with the environmental conditions (High Arctic, polar night, very low temperatures and the situation depicted in chapter 2) and the operational time frame (150 days of mission, winter period).
In the above-mentioned conditions the primary mission objectives can be also defined, these are:

- **Searching the whales**
  The physical patrolling of the area by the designed vehicle looking for the mission target.
- **Detecting the whales**
  The physical detection of a target and the process of collecting initial information.
- **Identifying the whales and collecting the data**
  The identification of the detected target as the searched one and its tracking and observation for storing the raw data required by the final research purposes.
- **Analysing and transferring the information**
  The analysis of the collected data and their transport to the mainland.

4.2.2. First Level Synthesis

From the functions required for carrying out the primary mission objectives follow the functions necessary for completing the mission. The important step is now to allocate these functions into the physical solutions and their own carriers. This can be done by following a logic synthesis process that first assigns to each function a principle that performs it through a principle solution and then for each of them defines the solution carrier.

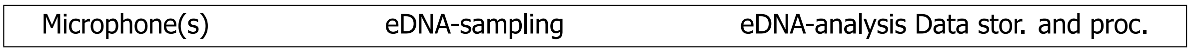
This process, called First Level Synthesis, applied to the vessel design is schematised in table 4.1. Here it can be seen that, for each function derived from the primary mission objectives, are first assigned one or two principles and for each of them are following a principle solution and a solution carrier. The application of one principle does not exclude the possibility of using another one at the same time. So, for example, for the detect function the main principle used is going to be the sounds research, but the visual help through infrared cameras can be really important. The same applies for the identification which is going to be carried out as a combination of sound analysis and environmental DNA sampling (Ficetola et al., 2008). On the other hand, for the search function the visual research through satellite images has been turned out to be unfeasible and therefore the chosen principle is the sound research.

Function	Principle	Principle Solution	Solution Carrier
Search	Visual Sounds	Camera Microphone	Satellite / UAVs / ... -Passive: buoys -Active: (A or U)UVs, (U)SVs
Detect	Visual Sounds	Camera Microphone	Satellite / UAVs / ... Buoys / (A or U)UVs, (U)SVs
Identify	Sounds Sampling	Sound analysis eDNA in water	Computer Water samples + DNA-analysis from/on (A or U)UVs, SV
Collect Data	Digital	On/Off-line memory	Local disk or cloud based
Analyse	Digital	Computer assisted Data Processing	Human + computer (on SV or Onshore)

Table 4.1: First Level Synthesis: for the Search function only the sounds principle has resulted to be feasible. For Detecting and Identifying both principles are going to be used.

After having assigned at least one solution to each of the required functions, they now have to be merged and collected in a single system. The possible logical combinations are four:

- **Principle Systems option A**

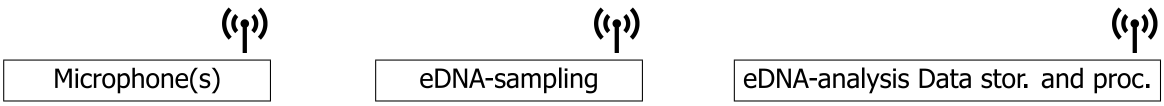


This solution collects all the solution carriers in one single physical platform which consists of one manned active research vessel with active hydrophones and active eDNA water sampling and storage.

- **Principle Systems option B**

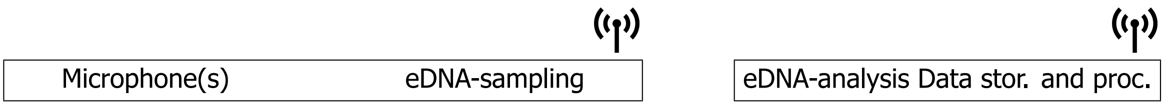
System B combines eDNA sampling and analysis with data storage and processing in one manned (semi)active research vessel. On contrary, hydrophones are placed on passive drifting buoys with microphones and transmitters positioned in a grid by active unmanned or autonomous underwater drones (UAV/UUV) or directly on the drones.

- **Principle Systems option C**



This option splits the three solutions in separates platforms: active unmanned or autonomous underwater drones (UAV/UUV) with microphones and transmitters, active unmanned or autonomous underwater drones (UAV/UUV) for eDNA water sampling and data storage and processing and eDNA Analysis in a manned platform/vessel or at an onshore control.

- **Principle Systems option D**



The last option, like the one before, presents data storage and processing and DNA Analysis in a manned platform/vessel or at an onshore control, but differently has only one type of active unmanned or autonomous underwater drones (UAV/UUV) with microphones, transmitters and for eDNA sampling ability.

4.3. High level concepts

In this section, five high-level concepts will be presented. Each concept can accommodate one or more of the System solutions presented in the previous section. Each concept has different ability and faces the risk of the area in different ways, in the following scheme the five concepts are presented dividing them in how they behave in ice and how they are free to operate in this environment.

Operational Freedom ↓ / Ice Behaviour →			
	Regular Open Water Vessel	Towed Unpropelled Platform	
		Hybrid Propelled Platform	
		Autonomous Underwater Vessel	Regular Icebreaker

In the following sections, each concept will be briefly described including some examples and its concept of operation will be presented.

4.3.1. Regular Open Water Vessel

Figure 4.1: Side view of "Sea Bridge One" from Sea Mercy (source: seamercy.org).

- **Applicable Principle Systems**
  System C, System D.
- **Description and example**
  This first concept is a regular research vessel for navigating in open water, without any capability of neither ice-breaking, neither ice navigation. The vessel has to be able to face the harsh temperature condition and it needs good survivability and seakeeping.
  The example presented is the "Sea Bridge One" from Sea Mercy (fig. 4.1), which is a research vessel designed by Dykstra Naval Architects for humanitarian aids for remote islands in the Southern Pacific Ocean.
- **Concept of Operation**
  This concept should remain out of the Marginal Ice Zone (MIZ) in open water returning to Longyearbyen when bad weather occurs. The whales search and detect is going to be done through hydrophones moved by/on UAV/AUV/UUV, the vessel is going to be the main control platform for the drones and the main location for data collection and eDNA storage and analysis.

4.3.2. Towed Unpropelled Platform

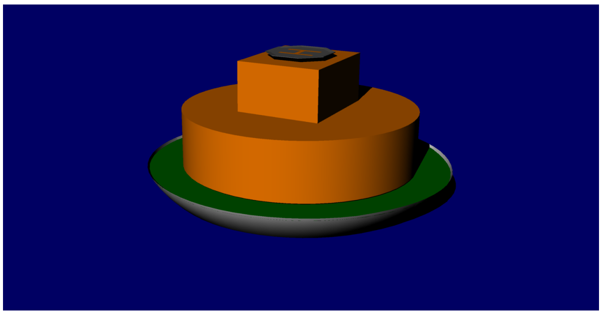


Figure 4.2: Render of a possible Towed Unpropelled Platform.

- **Applicable Principle Systems**
  System A, System B, System C, System D.

- **Description and example**
  This concept is a research platform without propulsion able to resists to the ice loads and to be lifted by the ice during high-pressure events. It has the possibility of installing a moon pool in the central bottom of the structure. A rounded shape helps to have the same ice facing ability on all sides. In open water is towed by a vessel. No similar example concepts exist for such a platform. A possible render is presented in figure 4.2.

- **Concept of Operation**
  The platform is towed into the ice to the starting location by an icebreaker. Then it starts drifting southwards in the ice pack. Exiting from the ice drifting zone the platform is picked up again by the icebreaker. Exactly as in the previous concept, the whales search and detect is through hydrophones moved by/on UAV/AUV/UUV, the platform is the main control station for the drones and the main location for data collection and eDNA storage and analysis. Possibly multiple loops can be done with the help of the icebreaker for each loop.

4.3.3. Self-Propelled Platform

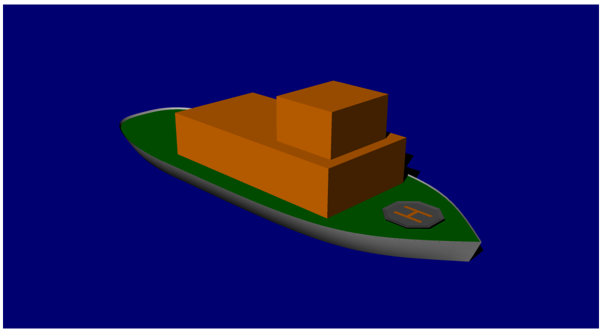


Figure 4.3: Render of a possible Self-Propelled Platform.

- **Applicable Principle Systems**
  System A, System B, System C, System D.

- **Description and example**
  This is a propelled platform that can be ship-shaped or not depending on the level of ice or open water ability required. Both ice and water navigation have to be performed autonomously. A moon pool can be located at the bottom. Again no similar example concepts are available and in figure 4.3 a possible render is shown.

- **Concept of Operation**
  The platform will reach the location in the ice pack autonomously and it will drift and navigate towards the south with the possibility of doing multiple loops. Search and detect whales can be done through hydrophones moved by or on UAV/AUV/UUV and on board. The crew on board collects the data and store the eDNA analysis.

4.3.4. Autonomous Underwater Vehicle

Figure 4.4: Sideview of the Seaglider C2 from Kongsberg (source: km.kongsberg.com).

- **Applicable Principle Systems**
  System C, System D.

- **Description and example**
  In this concept the research is performed by multiple underwater gliders which are a type of autonomous underwater vehicle (AUV) that, by slightly varying their buoyancy, they can move up and down and transform vertical motions in horizontal (Meyer, 2016; Wood, 2009), this gives the possibility of having really a large range and endurance. The example presented (fig. 4.4) is the Seaglider C2 produced by Kongsberg, which is one of the best underwater gliders available on the market.

- **Concept of Operation**
  This concept needs 3-4 AUVs controlled from shore that navigate autonomously in a selected area following the whales by themselves. They can operate autonomously in loops of 4/6 weeks (Barker, 2012), collecting eDNA and listening with their hydrophones, and then return to shore where the data and the eDNA collected can be extracted, stored and analysed.

4.3.5. Regular Icebreaker

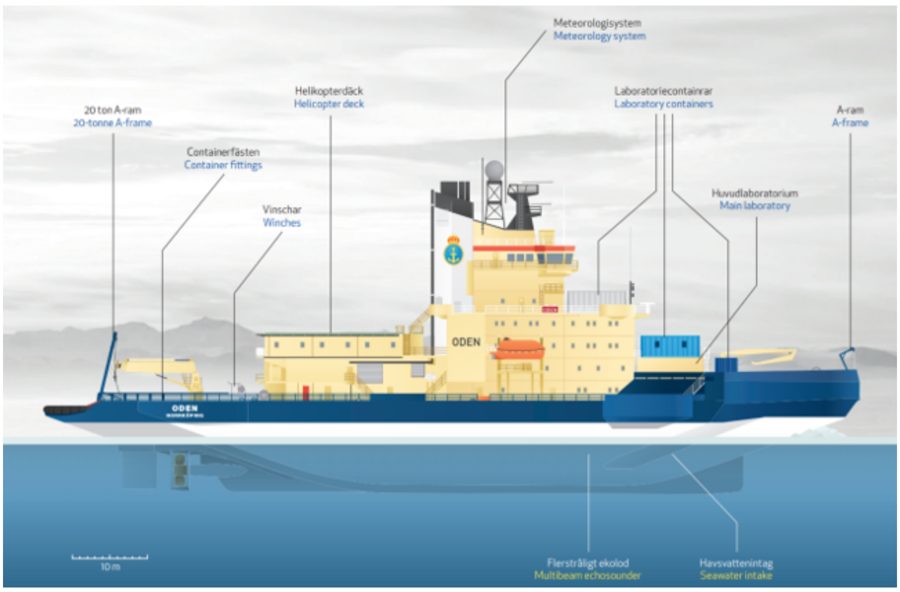


Figure 4.5: Side view of Icebreaker “Oden” from the Swedish Polar Research Secretariat (source: polar.se).

- **Applicable Principle Systems**
  System A, System B, System C, System D.

- **Description and example**
  The last concept is just a regular ice-breaking vessel for research purposes. There are a lot of existing ships like this, of different size and capabilities, but all with much bigger size than the previously presented concepts. The example showed in figure 4.5 is the Oden from the Swedish Polar Research Secretariat.

- **Concept of Operation**
  In this case, due to the very high operational freedom of the vessel, the concept of operation can vary a lot. In general, the main idea is that, after having reached the location autonomously, the vessel can patrol the area navigating where necessary. The search and detect function is carried out by hydrophones moved by/on UAV/AUV/UUV and on board together with the eDNA sampling. The elaboration, storing and analysis, due to the size of the vessel can also be done directly on board by the crew.

4.3.6. Concept of Operation Physical Allocation

	Phisical Architecture																		
	Towed Unpropelled Platform				Ice Breaker			Open Water Vessel			Hybrid Vessel				Autonomous Underwater Vehicle		
Functional Architecture	Towing Vessel	Env. Forces	Drones/ Buoys Hydr.	Crew	Prop. Engine	Drones/ Buoys Hydr.	Crew	Prop. Engine	Drones/ Buoys Hydr.	Crew	Prop. Engine	Env. Forces	Drones/ Buoys Hydr.	Crew	Prop. Engine	Onboard Hydr.	Onshore Personal
Searching	X	X			X			X			X	X			X		
Detecting			X			X			X				X			X	
Identifing				X			X			X				X			X
Analysing and Tranfering data	X			X	X		X	X		X	X			X	X		X

Figure 4.6: Physical functional allocation on the five high level concept.

For the purpose of summarising, in figure 4.6 is schematised the physical allocation of the functions previously presented into the five high-level concepts.

4.4. High Level Concepts comparison

4.4.1. Analytic Hierarchy Process

The tool used for comparing the criteria is the Analytic Hierarchy Process (AHP), which has been elaborated and presented in Saaty (1984). The Analytic Hierarchy Process is a multiple attributes decision-making tool that, using pair-wise comparisons and weighted criteria, gives a selection from fixed alternatives through a formal mathematical approach. During the process, each criterion is first compared pair-wisely (i.e. it is always a 1 vs 1 comparison) giving a value from 1/9 until 9 in order to weight them. Then, alternatives are compared, again pair-wisely, once per criterion. So at the end of the process, the result is going to be one criteria ranking and one ranking for each criterion, showing the scores obtained by each alternative in that particular criterion. These results combined are going to give as result the final ranking with the absolute scores of each alternative. The process can be schematised with a decision three (fig. 4.7).

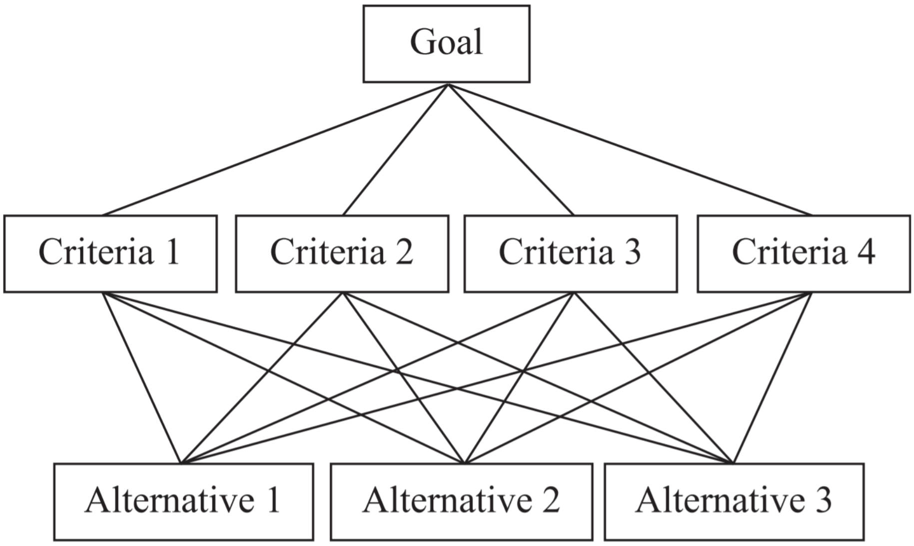


Figure 4.7: Analytic Hierarchy Process decision tree concept (Wu and Kou, 2016).

To give more strength to the scores of the alternatives it has been decided to let different people and experts involved in the project do the comparison and then average their results. Their experience in different fields and their different involvement in the project gives a more disinterested and valuable result. The list of the expert asked can be found in appendix E.

The survey has been carried out by sending a booklet containing general information about the Analytic Hierarchy Process, the descriptions of the five concepts compared, the descriptions of the criteria used, the instructions for the compilation and the empty matrices to be compiled. In this stage one of the biggest challenges has been to give to all the experts the same and correct idea of the concepts and the criteria used. For these reasons the production of this booklet played a very important role for a good result of the AHP.

It is also important to point out that the AHP is a really useful tool for helping in decision-making, however strongly dependent on the input values and therefore does not have to be trusted as a mathematical result, but it has just to be used as a helping tool for supporting the final decision.

4.4.2. Criteria

In this section the criteria definitions used for the AHP selection are presented.

- **Primary mission Performance**
  The ability of the vehicle to perform primary mission-related studies: how easy is it, how frequently can data get collected and analysed, maximum data limit, quality of collected data, level of disturbance on the elements analysed, quality of the instruments installable...
- **Secondary mission Performance**
  The ability of the vehicle to perform secondary mission-related studies: how easy it is, how frequently can data get collected and analysed, maximum data limit, level of disturbance on the elements analysed, quality of the instruments installable, number of simultaneously studies possible, quality of collected data...
- **Flexibility in operations**
  Ability to face and deal with drawbacks and unexpected phenomena (both of the vehicle, of the targets and of the environment): route changes, adverse environmental conditions, lack of targets, change of planning...
- **Availability**
  Uptime of the vehicle: percentage of total time (150 days) in which it is available to perform the primary mission: operative time, environmental limitations, reliability of the vehicle, how easy is maintenance, proven concept, ability to intervene on damages and problems...
- **Public visibility**
  Visibility of the project to both the scientific and non-scientific community: type of research possible, innovation of the design, "green potential", power of the image...
- **Potential for future uses**
  Possibility of usage again over the years, possibility of adapting the design to different researches, impact of multi-use programs on size and crew of vessel...

Some important criteria such as cost and safety have intentionally not been taken into account into the AHP comparison. Regarding the cost, the reason is that the differences in price between the concepts and especially its dependence on the final concept of operation make really difficult to include it in the AHP. Therefore, it has been decided to take it into account separately together with the AHP results. Similarly, the crew safety is strongly dependent on the operational profile and therefore it will also be considered separately during the design. In fact, all the presented concepts have a minimum level of safety and the final concept of operation will just have to be chosen in a way to maximise the crew safety. Also the technical readiness of the technology has to be evaluated in a later stage of the design and is going to be one of the results of the feasibility study.

4.4.3. AHP application

In this section, the Analytic Hierarchy Process is presented step by step. The first step is to evaluate the importance of each criterion, the matrix presented is the result of the evaluation of the experts. Each entry represents the importance of the left column criterion (A) over the top row one (B). The scale is presented in table 4.2

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

Table 4.2: Grade scale for criteria comparison. A is the criterion in the left column and B the one in the top line. If B is more important than A the score is the reciprocal (i.e. 1/grade).

After collecting the results from the experts the following matrix is obtained from their geometric average:

	Primary Mission Performance	*Secondary Mission Performance*	*Flexibility in Operations*	*Availability*	*Public Visibility*	*Potential for Future Uses*
Primary Mission Performance	1	4,217	5,000	3,915	3,271	4,380
Secondary Mission Performance	0,237	1	1,710	1,587	1,613	2,154
Flexibility in Operations	0,200	0,585	1	0,550	1,000	2,080
Availability	0,255	0,630	1,817	1	1,442	2,080
Public Visibility	0,306	0,620	1,000	0,693	1	2,924
Potential for Future Use	0,228	0,464	0,481	0,481	0,342	1

The criteria ranking can extrapolated calculating the matrix principal eigenvector, which is:

Criterion Weight	
0,863	*Primary Mission Performance*
0,300	*Secondary Mission Performance*
0,186	*Flexibility in Operations*
0,256	*Availability*
0,226	*Public Visibility*
0,121	*Potential for Future Use*

The last step is to verify the matrix consistency, this can be done using the matrix largest eigenvalue which is 6,178. From this the consistency index can be calculated:

$$CI = \frac{\lambda - N}{N - 1} = \frac{6,178 - 6}{6 - 1} = 0,036 \tag{4.1}$$

Where λ is the largest eigenvalue and N is the number of criteria.

And for verifying if the matrix is cardinally consistent the consistency ratio has to be minor than 0,1:

$$CR = \frac{CI}{1,240} = 0,029 < 0,1 \Rightarrow CardinallyConsistent \tag{4.2}$$

The same procedure has been applied to the alternatives comparison, but using the scale of table 4.3.

Grade	Intensity
1	A and B perform equally well on the criterion
3	A performs weakly better than B on the criterion
5	A performs better than B on the criterion
7	A performs strongly better than B on the criterion
9	A performs extremely or absolutely better than B on the criterion

Table 4.3: Grade scale for alternatives comparison. A is the concept in the left column and B the one in the top line. If B performs better than A the score is the reciprocal (i.e. 1/grade).

The resultant matrices were all cardinally consistent and are now presented.

- **Primary mission performance**

	Towed Unpropelled Platform	Ice Breaker	Open Water Vessel	Hybrid Vessel	Autonomous Underwater Vessel
Towed Unpropelled Platform	1	0,362	3,826	0,630	2,080
Ice Breaker	2,759	1	5,241	2,884	4,762
Open Water Vessel	0,261	0,191	1	0,217	0,909
Self-Propelled Platform	1,587	0,347	4,610	1	5,013
Autonomous Underwater Vehicle	0,481	0,210	1,101	0,199	1

Whose principal eigenvector is:

Criterion Score	
0,307	*Towed Unpropelled Platform*
0,814	*Ice Breaker*
0,109	*Open Water Vessel*
0,463	*Self-Propelled Platform*
0,128	*Autonomous Underwater Vehicle*

- **Secondary mission performance**

	Towed Unpropelled Platform	Ice Breaker	Open Water Vessel	Hybrid Vessel	Autonomous Underwater Vessel
Towed Unpropelled Platform	1	0,306	1,310	0,405	1,357
Ice Breaker	3,271	1	3,780	1,587	3,557
Open Water Vessel	0,763	0,265	1	0,281	1,442
Self-Propelled Platform	2,466	0,630	3,557	1	3,684
Autonomous Underwater Vehicle	0,737	0,281	0,693	0,271	1

Whose principal eigenvector is:

Criterion Score	
0,232	*Towed Unpropelled Platform*
0,741	*Ice Breaker*
0,192	*Open Water Vessel*
0,577	*Self-Propelled Platform*
0,167	*Autonomous Underwater Vehicle*

- **Flexibility in operations**

	Towed Unpropelled Platform	Ice Breaker	Open Water Vessel	Hybrid Vessel	Autonomous Underwater Vessel
Towed Unpropelled Platform	1	0,131	1,077	0,200	0,563
Ice Breaker	7,612	1	5,739	2,621	3,780
Open Water Vessel	0,928	0,174	1	0,223	0,855
Self-Propelled Platform	5,000	0,382	4,481	1	1,913
Autonomous Underwater Vehicle	1,776	0,265	1,170	0,523	1

Whose principal eigenvector is:

Criterion Score	
0,110	*Towed Unpropelled Platform*
0,856	*Ice Breaker*
0,127	*Open Water Vessel*
0,448	*Self-Propelled Platform*
0,197	*Autonomous Underwater Vehicle*

- **Availability**

	Towed Unpropelled Platform	*Ice Breaker*	*Open Water Vessel*	*Hybrid Vessel*	*Autonomous Underwater Vessel*
Towed Unpropelled Platform	1	0,179	0,630	0,342	0,212
Ice Breaker	5,593	1	4,380	2,154	2,621
Open Water Vessel	1,587	0,228	1	0,794	0,511
Self-Propelled Platform	2,924	0,464	1,260	1	0,693
Autonomous Underwater Vehicle	4,718	0,382	1,957	1,442	1

Whose principal eigenvector is:

Criterion Score	
0,116	*Towed Unpropelled Platform*
0,818	*Ice Breaker*
0,205	*Open Water Vessel*
0,312	*Self-Propelled Platform*
0,421	*Autonomous Underwater Vehicle*

- **Public visibility**

	Towed Unpropelled Platform	*Ice Breaker*	*Open Water Vessel*	*Hybrid Vessel*	*Autonomous Underwater Vessel*
Towed Unpropelled Platform	1	1,442	2,080	0,405	2,080
Ice Breaker	0,693	1	0,693	0,342	1,613
Open Water Vessel	0,481	1,442	1	0,303	1,842
Self-Propelled Platform	2,466	2,924	3,302	1	3,659
Autonomous Underwater Vehicle	0,481	0,620	0,543	0,273	1

Whose principal eigenvector is:

Criterion Score	
0,404	*Towed Unpropelled Platform*
0,255	*Ice Breaker*
0,279	*Open Water Vessel*
0,813	*Self-Propelled Platform*
0,178	*Autonomous Underwater Vehicle*

- **Potential for future uses**

	Towed Unpropelled Platform	*Ice Breaker*	*Open Water Vessel*	*Hybrid Vessel*	*Autonomous Underwater Vessel*
Towed Unpropelled Platform	1	0,441	0,747	0,511	1,310
Ice Breaker	2,268	1	3,000	1,442	2,759
Open Water Vessel	1,339	0,333	1	0,437	1,186
Self-Propelled Platform	1,957	0,693	2,289	1	3,107
Autonomous Underwater Vehicle	0,763	0,362	0,843	0,322	1

Whose principal eigenvector was:

Criterion Score	
0,267	*Towed Unpropelled Platform*
0,697	*Ice Breaker*
0,270	*Open Water Vessel*
0,567	*Self-Propelled Platform*
0,214	*Autonomous Underwater Vehicle*

Once all the matrices are calculated it is possible to collect all the alternatives resultant eigenvectors in one matrix and vectorially multiply it with the criteria eigenvector. The resultant vector is the final concepts ranking:

	Primary Mission Performance	*Secondary Mission Performance*	*Flexibility in Operations*	*Availability*	*Public Visibility*	*Potential for Future Uses*
Towed Unpropelled Platform	0,307	0,232	0,110	0,116	0,404	0,267
Ice Breaker	0,814	0,741	0,856	0,818	0,255	0,699
Open Water Vessel	0,109	0,192	0,127	0,205	0,279	0,270
Self-Propelled Platform	0,463	0,577	0,448	0,312	0,814	0,567
Autonomous Underwater Vehicle	0,128	0,166	0,197	0,421	0,178	0,214

×

Weight	
0,863	*Primary Mission Performance*
0,300	*Secondary Mission Performance*
0,186	*Flexibility in Operations*
0,256	*Availability*
0,225	*Public Visibility*
0,121	*Potential for Future Use*

=

Score	
0,509	*Towed Unpropelled Platform*
1,435	*Ice Breaker*
0,324	*Open Water Vessel*
0,988	*Self-Propelled Platform*
0,371	*Autonomous Underwater Vehicle*

4.4.4. Results and choice

The results give a slight preference to the Ice Breaker (1,4), immediately followed by the Self-Propelled Platform (1,0) and then all the others quite left behind with scores which are at least half of the concept in the second position. The final choice is then between the Ice Breaker and the Self-Propelled Platform, here comes in the importance of the cost.

In order to compare the building cost of the proposed high-level concepts, their building cost has been estimated and then compared. Depending on the concept, the cost estimation is based on similar previously built vehicles (Ice Breaker and Towed Unpropelled Platform), vehicles available on the market (AUV) or educated guesses based on size and complexity of the vehicles (Self-Propelled Platform and

Towed Unpropelled Platform). It is important to highlight that the resultant costs only reflect the order of magnitude of the vehicles price and cannot be considered as precise price estimation for each concept. In fact, the design space is still too big and sizes and complexity of each vehicle can still vary a lot.

The results are plotted in figure 4.8. Here the Final AHP Score for each concept is plotted over the concept Cost expressed in its price normalised with the total price of the AUV concept.

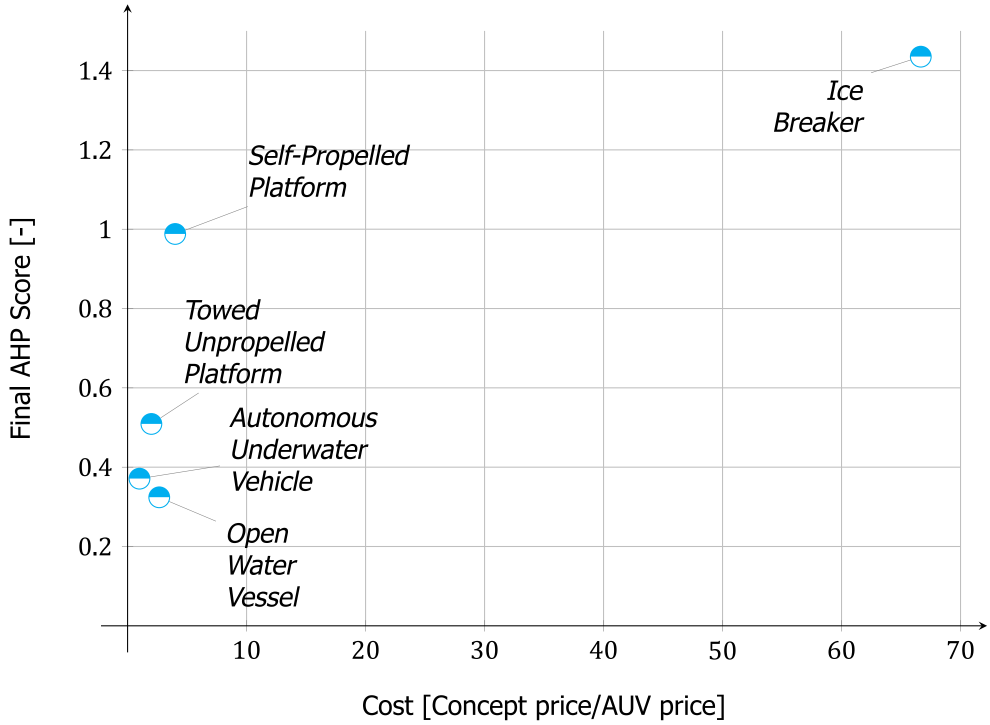


Figure 4.8: Final AHP score versus concept cost normalised with AUV price.

The above graph clearly shows how the Ice Breaker cost is extremely higher than all the other four concepts. In particular, the Ice Breaker cost is more than 65 times the cheapest solution cost (the AUV) and around 25 times the Self-Propelled Platform cost. The building cost of a regular ice breaker is, therefore, not considered as feasible for this project. Moreover, the difference in final score between the Ice breaker and the Self-Propelled Platform is not large: for these reasons the final choice is on the Self-Propelled Platform.

4.5. Most Promising Concepts

4.5.1. Philosophy and Design space

The selected concept still leaves a very broad design space, the self-propelled platform can be designed focusing more on ice or open water. The choice of the design type will depend on the final concept of operation and operational profile that will be presented in chapter 5.3. The design space is given by the possibility of "playing" with the hull parts (bow, sides and stern as in figure 4.9) and the propulsion arrangement. Depending on the choices done on these parts the ice or open water navigation ability can change significantly.

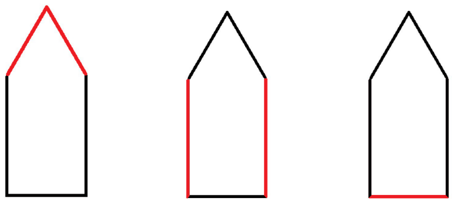


Figure 4.9: Hull design space.

For example, the bow can be designed with or without a bulb and could have some small icebreaking ability or not, the stern can also have some icebreaking capability and can present retractable azimuthal thrusters or azipods. Also, the sides can be rounded and incline following the Tara concept or can be fully vertical.

4.5.2. Examples

In order to show the above-mentioned possibilities, some design examples are presented in figure 4.10.

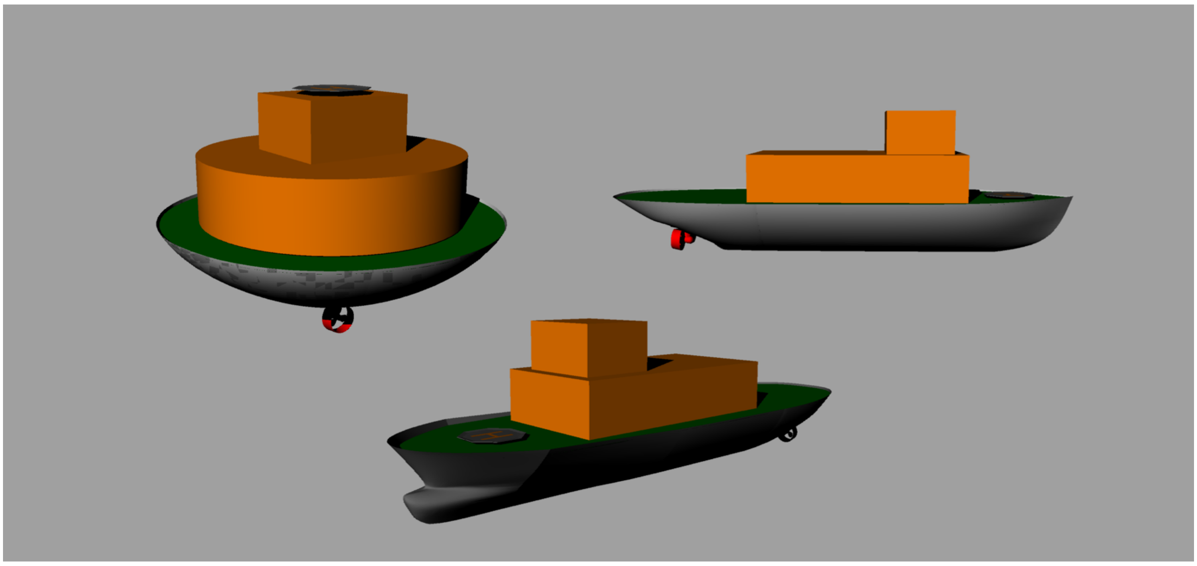


Figure 4.10: Three example design for the selected concept.

The first one on the left is fully focused on resisting to ice and has a really bad open water resistance, moreover the propulsion with a retractable thruster is mainly focused on moving in ice. The concept on the right is more in the middle between an ice focused design and an open water one: the pointy bow can break and crack the ice and the sides are almost vertical. Lastly, the concept at the bottom is definitely much more focused on open water navigation, with a bulb and non-azimuthal thrusters.

5
Operational Profile and Risk Assessment

5.1. Mission Operations Overview

After the selection of the concept, for evaluating the best design choices it is now important to define the operational profile and the mission description. In this chapter the mission profile of the vessel will be described using the environmental data and information presented in chapter 2 and with the help of some satellite images. In appendix F on two satellite images of the area of the 18th March 2008 a possible route through the ice is plotted, from the entrance into the ice until a final location.

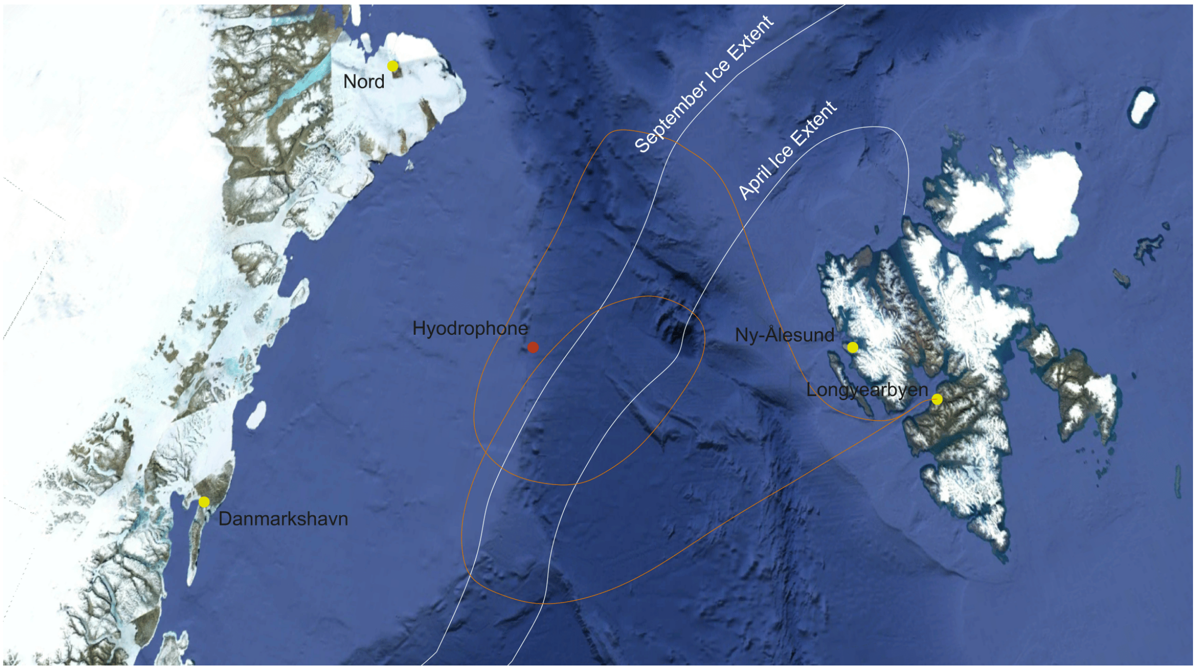


Figure 5.1: Fram Strait satellite view with the Hydrophone position and the main settlements indicated, in orange the route of a possible two loops mission. Satellite image courtesy of USGS (Sentinel-2A)

First of all, it is important to give an overview of the logistic possibilities in the area. As can be observed in figure 5.1, the main settlements of the area are Danmarkshavn and Nord, on the Greenland coast, and Longyearbyen and Ny-Ålesund, in the Svalbard Archipelago. The two Danish settlements are a weather station and a military base respectively and they are both with less than 10 people stable over the year and both inaccessible during winter by normal vessels and hardly reachable even by Icebreakers. However, the two villages on the Svalbard coast are ice-free all year round. Ny-Ålesund

is a research station with a population between 30 and 120 people, depending by the season, and Longyearbyen is a proper village with more than 2000 inhabitants. The latter one, in particular, has really good logistic structures, with a port and one international airport.
Because of these characteristics, Longyearbyen is the best option as the main logistic centre and departure port for the mission. After leaving Longyearbyen, for better covering the research area (Marginal Ice Zone between 75^{th} and 82^{nd} parallels north), the strategy chosen is to do multiple loops entering the ice from the north, drifting with it towards the south and then going out again in open water. This loop can be repeated multiple times entering and exiting in different locations depending on where the whales have been spotted and choosing the target area time by time.

In figure 5.1 a possible combination of 2 loops is presented in orange, the first one for studying a northern area at the beginning of the winter and the second one more southern during the end of the winter. During every loop, a grid of buoys with hydrophones can be deployed in order to constantly map the presence of whales in the area. This can be done directly from the vessel or with the help of drones such as Unmanned Aerial or Underwater Vehicles. The more precise measurements and observations will be done using the hydrophones present on board and through the ones mounted on the Unmanned Underwater Vehicles.

5.2. Strategies and Risk Assessment

In this section, the main strategies available for each step of the mission will be analysed. Moreover, a description of the main risks to be faced and will be given and the related solutions and mitigation strategies assessed.

5.2.1. Entrance in the pack ice

The first important step is to find a good weather window for approaching the Marginal Ice Zone navigating in the ice-free area of the Fram Strait. After the regular open water navigation, the first crucial part is the entrance in the ice. The location cannot only be decided based on the area that wants to be studied, but also and especially on the characteristics of the Marginal Ice Zone. In fact, as can be seen in the graphs 2.7a and 2.7b of section 2.4.1, the ice concentration goes over 90% almost immediately and with such an ice coverage the presence of leads and channels is essential. Therefore, a live study of the satellite images is really important to find the water path leading to the desired location.

5.2.2. Leads Navigation

The navigation in leads can be difficult and presents many dangers. The leads, due to the movement of the ice floes around, open and close frequently and often suddenly. Moreover, the surrounding ice can be very thick and full of multi-year ice intrusions and possibly small glacial ice blocks. Therefore, it is really important for the protection of the vessel to try to navigate as much as possible surrounded by level ice to which the vessel is able to resist in case of lead closing.
In the satellite image of figure F.2 multiple leads can be seen, if analysed more carefully it can be noticed that some of them are dark blue and some of them are light grey. In fact, while the dark blue ones are with open water, the grey ones present a layer of refrozen ice. This ice grew in loco and is relatively young compared to ice in its surroundings. Due to the very dynamic characteristics of the leads, this ice does not have the time to grow more than a certain thickness. Due to movements of the surroundings, however, those refrozen leads can be compressed, thereby significantly increasing the thickness of their ice. The situation showed in image F.1 and image F.2 is very common after the freezing period starts and in the worst periods open water leads might be very hard to find. Therefore, it is important that the vessel is able to break those thin layers of ice. A more thorough description will be given in chapter 7.
During this phase, it is already possible to deploy the buoys from the vessel which are going to form the observation grid.

5.2.3. Drifting Strategies

The strategy for starting a safe drift is probably the key point of the mission. Few examples of such operation are available besides the Tara voyage, and even in that situation, this operation has been done only a couple of times (Redvers, 2010). Therefore, due to all of these unknowns, it is really important to keep the safety of the crew in the first place avoiding all the risk as much as possible.

The strategy adopted is to berth the vessel along a sufficiently big young ice floe with some important features. This has to be very straight to follow the side of the vessel as much as possible in a way that in case of closing lead the vessel will be loaded uniformly. Moreover, the thickness and the freeboard have to be sustainable by the hull of the vessel in case of compression. One other important point is the type of ice floes standing on the other side of the lead, it is really important the absence of big multi-year ice blocks or even small icebergs: a compression with this kind of ice, even if only on one side, can be really dangerous.
Then, when trapped or lifted by the ice, the situation is relatively safe and the main danger is represented by ice riding up on the sides which, in a worst-case scenario, can ride up until the deck. For keeping the ship safe it is important to design the vessel sides with a vertical or slightly downward inclined structure to protect the deck from this phenomenon.
This silent phase is the most important one for the research and is the one in which the UAVs and UUVs are used.

5.2.4. Compression Events and Storms

In case of big compression events, when navigating in leads or when berthed, as already explained, it is vital to avoid the presence of big ice features around. Due to the rapidity of these events, it is also primordial to have a sufficient manoeuvring ability to align the sides of the vessel with the surrounding ice floes. Also in this situation having some icebreaking capability in more than one direction can be helpful to find a safe position. Storms creating compression events are anyway predictable with some advance, it is evident the importance of preventing and anticipate these phenomena with a constant meteorological forecast control.

During a compression event, the wrong lead can be a really dangerous place, but the area of the marginal ice zone along the open water where the ice concentration is lower is probably even more unsafe. The waves directed against the ice pack are in fact not immediately dispersed, but they take some time to be dissolved. Thus, due to the possibility of finding big waves moving strong ice blocks into the vessel, these areas during storms have to be avoided.

Therefore in this situation, the best strategy is to go toward East where the ice is more dense, searching for a location surrounded by safe ice.

5.2.5. Evacuation

The scenario of an evacuation is, of course, something to be considered as very last option. In such a harsh and dynamic environment the vessel is by far the safest place to stay. A prevention plan for such a case is therefore really important.
Rescue can be really difficult and slow due to the remoteness of the area. Evacuation by helicopter is not an option in this area: the location is too far from the heliports onshore and the conditions of full darkness are not affordable for such a vehicle. In case of evacuation, usually from this location the fastest rescue are the Russian icebreaker working in the Arctic Ocean, but they take at least one week to reach the Fram Strait. One other option can be represented by a vessel with an helicopter on board that, leaving from Longyearbyen, reaches the outside of the marginal ice zone and let the aircraft fly until the rescue area. However, again this solution takes time and is strongly dependent by the environmental conditions. Therefore, it is vital to have flexibility and enough survival capability. Different type of life raft vehicle might be considered, such as regular lifeboats, snowmobiles or hovercraft. The aim has to be to reach a safe ice floe where is possible to safely wait for the rescue to come. An interesting overview of the technology available for rescue and evacuations system in Polar waters is presented in the report by Arctic Climate Change Economy and Society (2013).

5.3. Navigation Mode Definition and Operational Profile

To be able to calculate the loads on the hull it is very important to define and analyse the scenarios in which the vessel will be navigating. This can be done by merging the environmental data previously reported, the operational requirements from the owner and the strategies elaborated in this chapter. As just described in section 5.2, the vessel voyage can be subdivided from the point of view of the navigation in three different modes: open water navigation, ice navigation and passive ice drifting. For evaluating the ice loads and the propulsion, the interesting scenarios are the latter two and therefore the focus will be on them. In section 6.2 this subdivision will be developed and followed for the definition of the physical models. The loads during the drifting mode will be evaluated in chapter 6, while the study of the ice breaking mode will be done in chapter 7.
All the elements for defining the operational profile are now available. This is shown in figure 5.2.

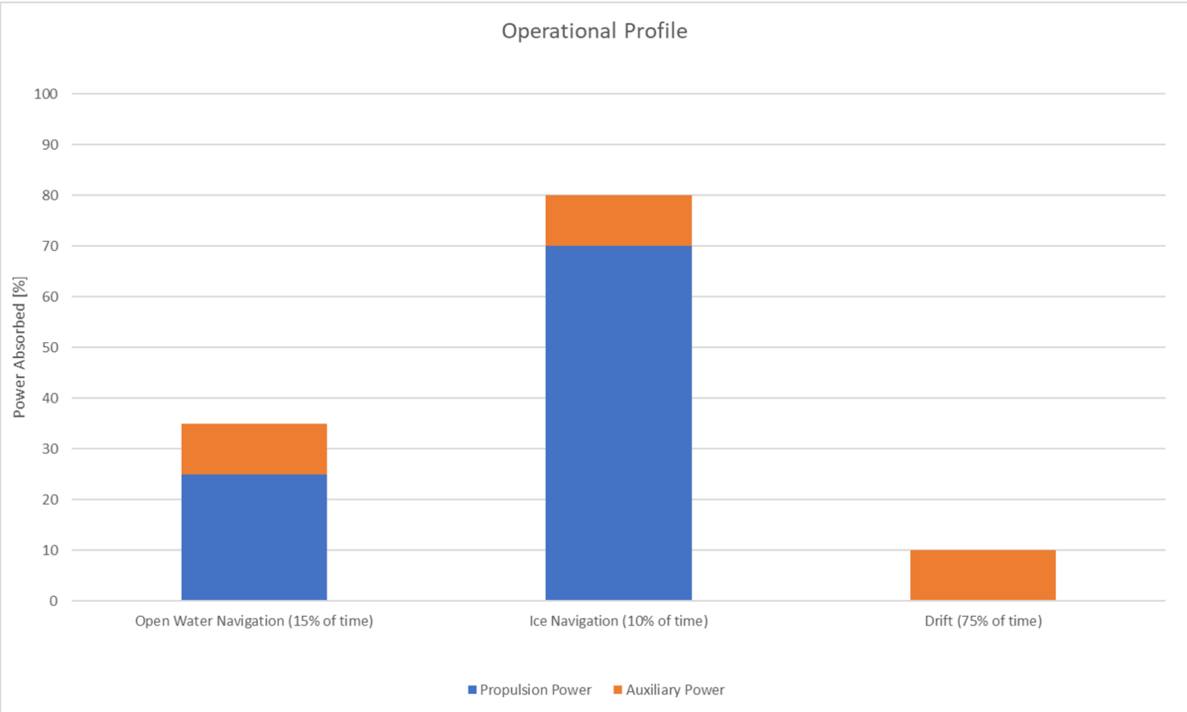


Figure 5.2: Operational profile of the vessel during its mission divided in the three navigation modes.

The estimation of the power consumption of the three modes is provided in the above figure. Regarding the open water navigation, the power has been calculated using the resistance calculation provided by Conoship (Appendix J), which also estimated the hotel power consumption in all the three modes. For the ice navigation, the estimation of the power will be described later in chapter 7.

In figure 5.3 and figure 5.4 are shown the power and the speed variation over one single loop of 30 days.

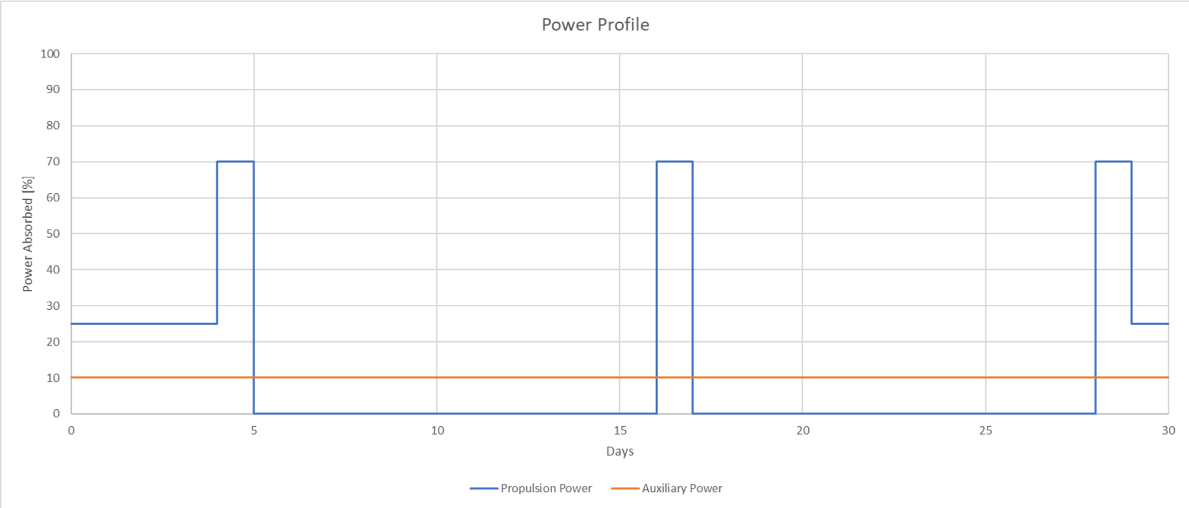


Figure 5.3: Propulsion and Auxiliary Power variation over one loop of 30 days. Three peaks can be distinguished, which correspond to: the entrance in the ice, one re-positioning and the exit from the ice respectively.

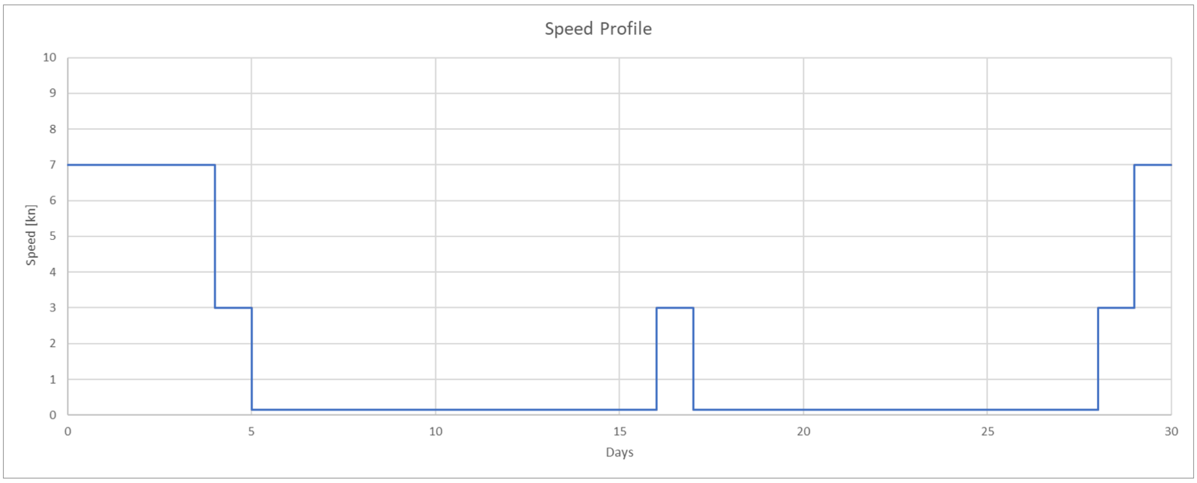


Figure 5.4: Speed variation over one loop of 30 days.

5.4. Design Driving Principles and Reviewed Requirements

After having analysed the strategy adopted and the related risk, the design driving principles can be now defined. Because of the fact that the major risks happen during the ice channel navigation and the drift start, the choice is to focus the concept design on these situations. The goal is to give to the hull the ability for surviving in the previously described conditions. Therefore, the water navigation ability will be a secondary point and limited by the other two modes. The concept will be more ice focused, putting particular attention into making the ice drifting safe, to be able to be protected by the ice in all situations and with enough flexibility and manoeuvring ability.

Furthermore, after the definition of the operational profile, the operational requirements of the vessel can be modified and refined together with the Ice Whale Foundation.

Those can be summarised as the following:

- Operating in the Marginal Ice Zone of the Fram Strait between 75°N and 82°N
- Silent Navigation as much as possible
- Gross Tonnage under 500 GT
- Cost limited to 5 Millions of euros
- 100 days of autonomy between October and March
- Crew limited to 5-6 persons
- Space for research containers on board
- Moon pool for divers and equipment deployment

The first big difference with the initial requirements (section 1.3) is the relaxation of the autonomy requirement from 150 days to 100 days. This is due to the fact that such a long autonomy would have meant an amount of supply and fuel hardly feasible for such a small vessel. Furthermore, the stress for the crew and the risk would have increased a lot without a real gain. In fact, using the loop strategy described in section 5.1, one stop in Longyearbyen during the mission does not signify a big loss.

The second requirement inserted is the possibility of transporting of containers for scientific equipment. This will give the vessel the possibly of easily performing different expeditions, which strongly increases the attractivity of the platform to possible investors and sponsors.

The last new requirement is the moon pool. This request was actually already in the initial ideas of the Ice Whale Foundation, but, with the definition of the most suitable concept and the concept of operation previously described in this chapter, it is now of very high importance for the success of the expedition. Moreover, it also increases the value and the attractivity of the vessel as well.

6

Concept Development and Ice Load Evaluation

6.1. Final Concept Development Process

At this point the proper design process of the final concept can start. As already shown in figure 1.4, the necessary input data (reviewed requirements, environmental conditions and operational profile and risk assessment of the selected high-level concept) is now complete and can be used for proceeding. The development that will be described in the following chapters is a cyclic process that is going to collapse in the final refined design. In the following two sections will be addressed the ice load evaluation approach and the propulsion power estimation approach.

In the subsequent section the main dimension and the final design of the vessel will be presented. However, all these design topics are not independent, but extremely closely related. The power and the ice loads definition are also going to determine the choice of the hull size and form. But on the other hand loads and power are strongly dependent on the vessel size.

Therefore, during the design process these elements have been changed and refined multiple times. However in this thesis, in order to have a more clear presentation, each single topic has been analysed separately in a linear order.

6.2. Load Evaluation Philosophy

From the three navigational modes described in section 5.3, the main focus and hull design drivers are the ice channel navigation and the ice drifting. These are the most interesting scenarios for the ice loads evaluation as already concluded at the end of chapter 5. The ice channel navigation can be seen as an active way of facing the ice, while on the other hand the ice drifting can be seen as a passive measure. This implies that a very different approach has to be used to analyse them and consequently to evaluate the related loads and the hull design. The choice was made to study the vessel while in its channel navigation through a dynamic model of a vessel navigating in ice infested water. On the other hand, while passively facing the ice loads, a quasi-static model was chosen. In fact, the passive ice facing condition happens only when the vessel is trapped between two features which are pushing the vessel and loading its hull. In this condition, the relative speed between the vessel and the surrounding ice floes can be considered as quasi-static. Another choice done at this design stage has been also to "specialise" each side of the vessel for one or two of the three navigation modes described in section 5.3. The result is what can be called a "triple acting hull": vessel port and starboard sides designed for passively facing ice loads, bow thought for open water navigation and icebreaking of refrozen channels and stern focused on breaking ice astern for manoeuvring purposes. This design approach is schematised in figure 6.1. Nevertheless, due to the already highlighted rapidity of channel closing events, it has also been decided to give some ability to passively face the loads also to bow and stern.

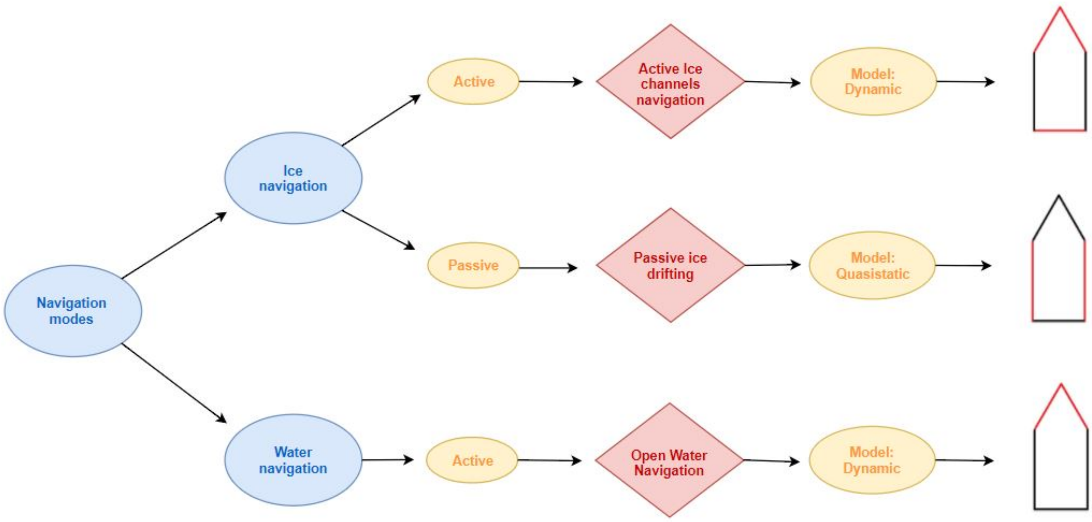


Figure 6.1: Flow graph of design philosophy, subdivision of the ice navigation modes and graphical representation of the "triple acting hull" principle.

This chapter will focus on the loads generated during the Ice Drifting mode, the active navigation will be later analysed in chapter 7.

6.3. Main scenarios evaluated

From the environmental analysis of chapter 2 the conclusion that can be drawn is that the main characteristics of the area can be summed up as a variegated and highly dense mix of first-year and multi-year level ice features with maximum thickness up to 7 m with occasional presence of very big and thick multi-year blocks and small icebergs with thickness around 15 m, but that can reach values of 25m. Because of these reasons, three main dangerous scenarios of passive vessel-ice interactions can be distinguished:

- Case 1: Vessel compressed by two level ice floes
- Case 2: Vessel compressed by one level ice floe and one big multi-year ice feature/small icebergs
- Case 3: Vessel compressed by two big multi-year ice features/small icebergs

The three scenarios are represented in figure 6.2. From now on for the passive ice load approach description, two cases will be distinguished: hull side loaded by a level ice floe and hull side loaded by a multi-year ice features/small icebergs.

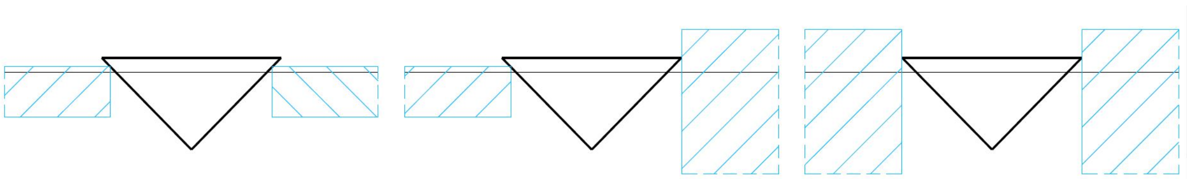


Figure 6.2: Schematic representation of (from left to right): vessel compressed by two level ice floes (Case 1), vessel compressed by one level ice floe and one big multi-year ice feature/small iceberg (Case 2), vessel compressed by two big multi-year ice features/small icebergs (Case 3).

6.4. Level ice Loads

6.4.1. Approach and problems

As already previously explained, due to the zero relative speed between the ice and the structure, in this case, the vessel can be considered as static and thus can be approximated as a fixed structure. The choice is now how to face the ice loads.

Regarding the situation of the vessel loaded by a level ice floe, the solution found is inspired by the "Tara" schooner design. Instead of forcing the relatively small hull with very big ice loads, the solution adopted is to build the hull with a downward inclination angle in a way that, when the ice is pressing from the sides, also a vertical component is generated that push up the structures freeing it from the loads. Furthermore, the hypothesis of static behaviour gives the possibility to use the formulas and methods of the ISO19906 concerning offshore fixed structures, (ISO, 2010). Therefore, it is possible to calculate the vertical and horizontal components of the force acting on the hull and define as the maximum compressing action that the hull has to face the horizontal force generated when the vertical components equal the weight of the vessel.

The ice loads are here described as an increasing load that either become constant, reaching the value of the force moving the ice, either return to zero if the ice breaks (Løset et al., 2006). This formulation by hypothesis is taking in account a quasi-static situation and does not say anything about the dynamic of the vessel lifting. This can leads to an underestimation of the loads because of some effects such as the force overshoot, dependent on the loading speed, or the effect of the loss of buoyancy during the event. A first approach to study and evaluate the relevance of this dynamic behaviour has been done conducting a time-domain simulation of the event (fig. 6.3).

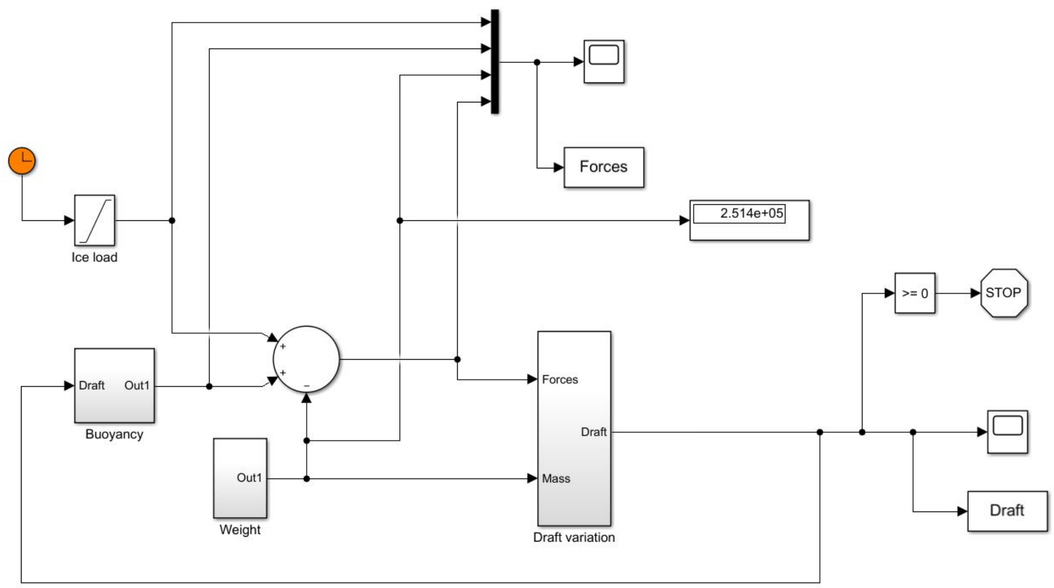


Figure 6.3: Simulink blocks scheme for time-domain simulation of ice impact event and the consequent lift up of the vessel.

The results show that for certain ice loading conditions, even if for a few seconds the hull can suffer vertical loads higher than its weight (fig. 6.4). However, such a way of analysing the problem through time-domain simulations is too much dependent by the final shape of the hull and by the way in which ice is impacting the structure and thus really hard and difficult to analyse.

Therefore it has been decided to follow another approach and study the ice loads transit phase as an impact and the steady-state phase as the quasi-static situation previously described.

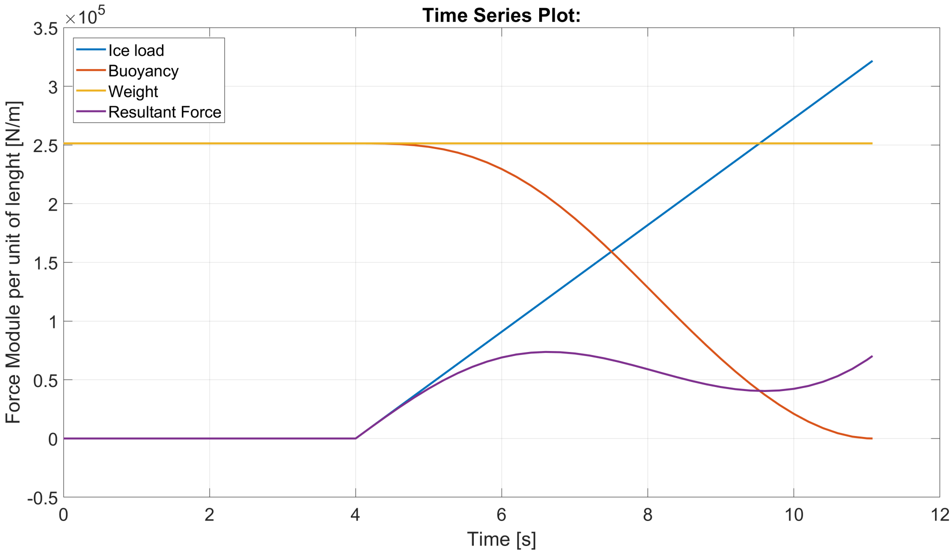


Figure 6.4: Example of the time variation of the vertical forces acting on an hull section after an ice impact event.

6.4.2. Model

Taking into account all the previous reasoning the model can be now defined. For simplifying the situation the problem is modelled as shown in figure 6.5: the hull is simplified with a triangular shape with the sides inclined by a constant angle α. The structure is loaded by constant thick ice layers on both sides. Also, the ice characteristics are considered as constant.

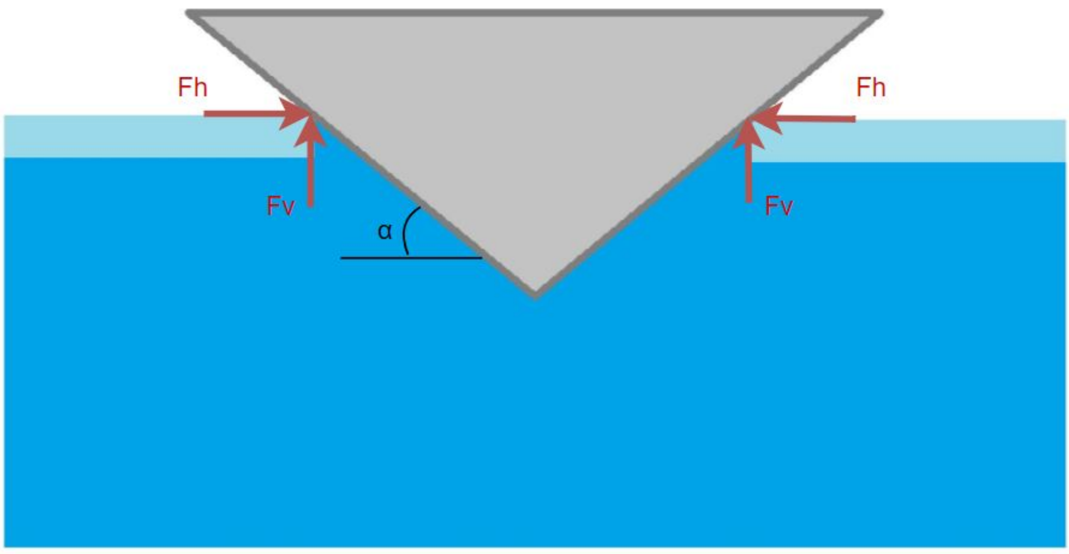
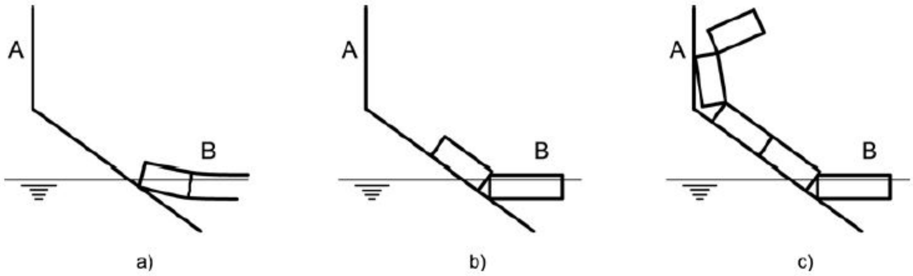


Figure 6.5: Modellization of the vessel pushed up by the ice as quasi-static.

The first part of the analysis is the impact moment: the ice layer is approaching the structure with a constant speed and, after the collision, it starts penetrating the hull until it stops completely. This situation can be easily studied by a matter of analysing the kinetic energy loss of the ice floe (Løset et al., 2006), using the work-energy theorem (equation 6.1).

$$\int F(x)dx = \frac{1}{2}mv_{i,beg}^2 - \frac{1}{2}mv_{i,end}^2 \tag{6.1}$$

Then, for the steady state situation, as already stated, the ISO19906 formulation for downward sloping structures can be used (ISO, 2010). It describes the loading event as a cycle that is described in figure 6.6 (the description is for an upward conical structure, but is valid in the same way in the downward case).



Key

a) ice sheet approaches structure

b) ice begins to fail and ride up face of structure

c) ice blocks ride up face of structure and are turned back at vertical face

A sloping structure

B encroaching ice sheet

Figure 6.6: Schematic description of the ice load cycle on a upward conical structure, (ISO, 2010)

This allows the horizontal loads on the structure to be calculated through the evaluation of a few components (equation 6.2).

$$F_H = \frac{H_B + H_P + H_R + H_L}{1 - \frac{H_B}{\sigma_f l_c h_i}} \tag{6.2}$$

Where σ_f is the flexural strength of the ice sheet, l_c is the total length of the circumferential crack, h_i is the is the thickness, H_B is the breaking load, H_P is the load component required to push the ice sheet through the ice rubble, H_R is the load required to push the ice blocks up the slope through the ice rubble and H_L is the load required to lift the ice rubble on top of the advancing ice sheet prior to breaking it. However, in our case the hypothesis is that the ice is not breaking and then the components H_P, H_R and H_L can be neglected, leading to equation 6.3.

$$F_H = \frac{H_B}{1 - \frac{H_B}{\sigma_f l_c h_i}} \tag{6.3}$$

The formulae for calculating all the loads components can be found in appendix G.

Again following the ISO document, also the vertical load component can be found:

$$F_V = F_H \frac{\cos\alpha - \mu \sin\alpha}{\sin\alpha + \mu\cos\alpha} \tag{6.4}$$

Where α is the inclination of the structure and μ is the ice-structure static friction coefficient. The effects of different angles on the structure can be analysed using these formulae and the load upper limit after which the vessel starts to be lifted up can be determined.

6.4.3. Validation

For verifying the validity of the ISO formulae they have been compared with the results of full-scale measurements on the Kulluk vessel, (Wright et al., 1999; Wright, 2007). This vessel (fig.6.7) was a drilling unit designed for ice conditions with thickness up to 1.2 m. It had a waterline diameter of 70 m and downward structure with an angle α of 23° (Løset et al., 2006).

Figure 6.7: Kulluk drilling unit (Wright, 2007).

Because of the above-mentioned characteristics it does quite good fit in the ISO formulation hypothesis. Therefore, using the characteristics of the Kulluk, the loads were calculated using the complete formulation provided from the ISO for breaking the ice (eq. 6.2 and 6.4). In the same graph were plotted the full-scale peak loads measured and normalised by Wright et al. (1999) and the loads calculated using the formulation with no breaking ice (eq. 6.3 and 6.4). The results can be seen in figure 6.8. The big variations of the measured loads were expected due to the great amount of variables that can influence the ice strength. It can be seen that the full equation curve fits the full-scale measurements quite well and that in neglecting the other terms the difference is not that accentuated. In fact, while at low ice thicknesses the calculated loads are lower than the measured ones, at higher values (the more interesting ones for this design) the differences are much smaller. Moreover, these minor differences can be overcome with adequate safety coefficients.

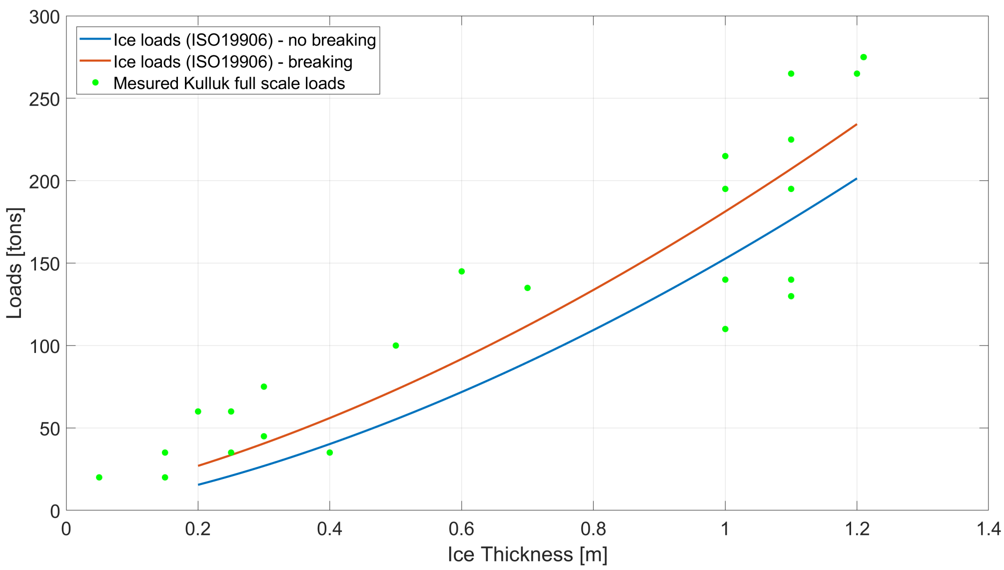


Figure 6.8: Comparison between loads calculated with ISO19906 (ISO, 2010) and measured Kulluk full scale ice loads (Wright et al., 1999)

6.5. Multi-year ice features/Small icebergs Loads

6.5.1. Approach and problems

The main problems in case of big multi-year ice features or small icebergs are two: their really high strength and their freeboard. Especially the freeboard can go far over the vessel inclined sides. The solution proposed for this situation is to build a strengthened vertical ice belt around the vessel to protect it from these ice blocks (fig. 6.9). The aim is to dissipate the loads on this vertical structure. Using the same hypothesis of section 6.4.1 is again possible to apply the ISO19906 (ISO, 2010), this time the limit state is the breaking in crushing.

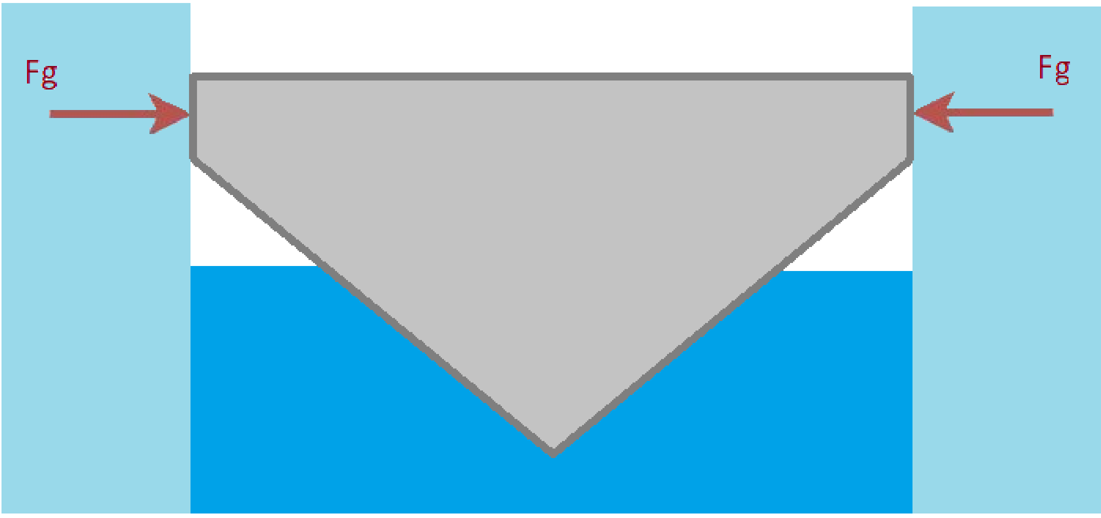


Figure 6.9: Scheme of the ice belt protecting the hull from multi-year ice features/Small icebergs.

6.5.2. Model

The model for the crushing ice loads is presented in figure 6.9 and for calculating the global ice action F_G the formulation presented by the ISO19906 is used for global actions on vertical structures due to ice crushing. This formulation models the process as shown in figure 6.10.

The model of structure presented in the ISO19906 document is a vertical wall. This is slightly different from the structure presented in this thesis, which is vertical only in the top part. However, in order to consider this difference, as also suggested by the ISO19906, the contact area vertical size is going to be selected as the height of the vertical belt instead of the thickness of the ice.

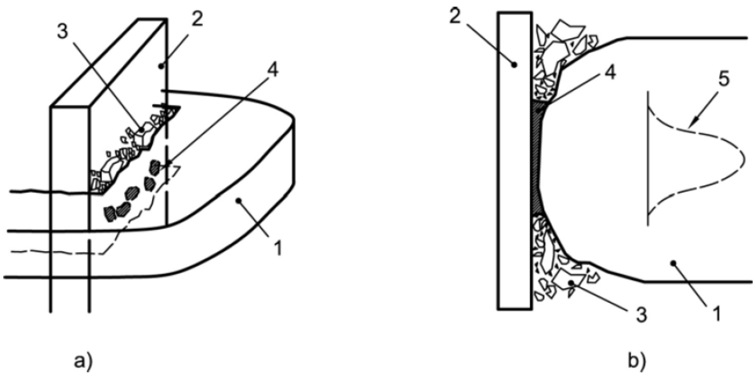
The process for evaluating the ice actions is quite straightforward, first the global pressure is evaluated using equation 6.5:

$$p_G = C_R \left(\frac{h_c}{h^*}\right)^{n_{cr}} \left(\frac{w}{h_c}\right)^{m_{cr}} \tag{6.5}$$

Where C_R is the ice strength coefficient, which for Arctic areas can be assumed as C_R=2,8 MPa (ISO, 2010), h_c is the height of the contact area, h^* is a reference thickness of 1,0 m and m_{cr} and n_{cr} are empirical coefficients.

For finding the value of the global ice action F_G the global pressure p_G simply needs to be multiplied by the interaction area (eq. 6.6), which in the vessel case is the height of ice belt h_c times the projected length of the structure w.

$$F_G = p_G h_c w \tag{6.6}$$



Key

a) ice sheet interaction with the flat surface of a narrow vertical structure

b) profile of ice sheet interaction with vertical structure

1 ice sheet

2 structure

3 spalls and extrusion

4 high pressure zones in a), layer of crushed ice of high pressure zone in b)

5 pressure distribution over the contact surface

Figure 6.10: Schematic ice crushing failure mode against a structure and location of compressive actions during the interaction (ISO, 2010).

6.6. Results

This section presents the results of the calculation that will be used to define the hull design in chapter 8.

The relevant main dimensions of the structure are presented and explained later in section 8.3, all the ice characteristics have been defined using values available in literature for the Fram Strait (Ji et al., 2011; Ettema and Urroz, 1989; Wallen Russell and Lishman, 2016; Marmo et al., 2005).

6.6.1. Inclined sides

In figure 6.11 the resultant forces on the structure are given in function of the hull angle at the waterline and for a thickness of 2 meters, which is going to be the minimum required to lift the vessel. As can be seen, the vertical components are not affected by changing the angle because the vertical force is limited by the bending breaking load of the ice sheet which is a function of its flexural strength. What does change is the horizontal component of the force that augments with the increasing of the angle. This is due to the fact that with small angle most of the force of the ice floe is contributing to bend the ice layer, while for big angles this contribution is much less.
After having estimated the weight of the vessel, the force required to lift the vessel can be determined as well as the relative ice thickness. Then depending on the loads, the hull angle can be chosen. Looking at the graph it seems logical to choose the angle as small as possible aiming for the smallest global load possible. However, small angles mean a very wide hull which is not ideal and limiting the range of feasible angles. The choice of the angle will be presented and justified in chapter 8.

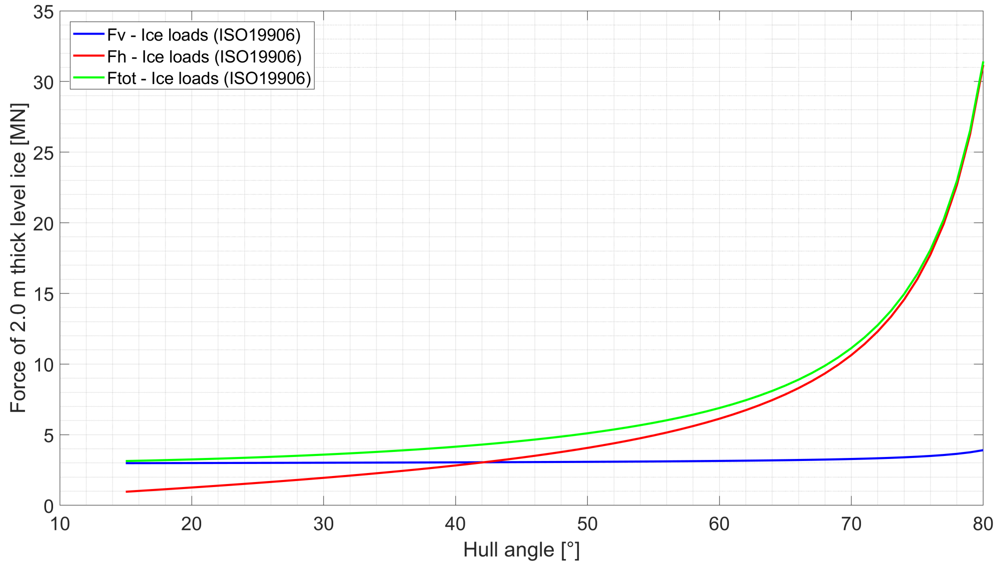


Figure 6.11: Forces on the structure due to limit stress of ice breaking in bending over hull angle at the waterline.

Then in figure 6.12 the resultant forces on the structure are presented in function of the ice thickness for the final hull inclined at 70°. After choosing the angle, by looking at this graph, it is possible to use the thickness that is going to exert enough force to lift the vessel to determine the total load on the hull.

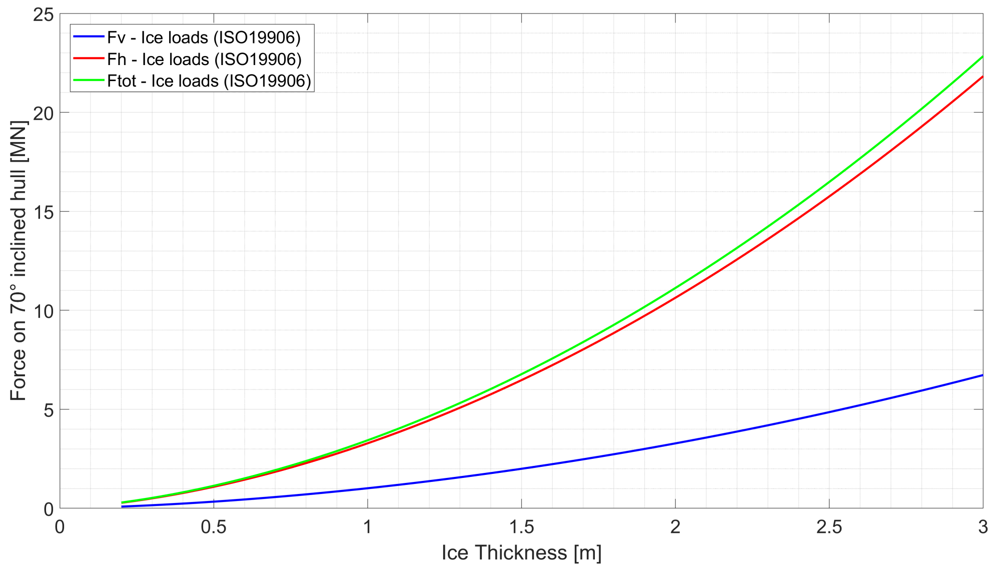


Figure 6.12: Forces on the structure due to limit stress of ice breaking in bending over ice thickness.

6.6.2. Vertical sides

For the vertical sides, in figure 6.13 the resultant pressure is given in function of the ice belt height. It can be observed how a small belt is going to face bigger pressure, this result, even if it may seem illogical for a normal material, is normal for ice due to size and scale effects, according to Weiss et al. (2014) and Bažant (1999).

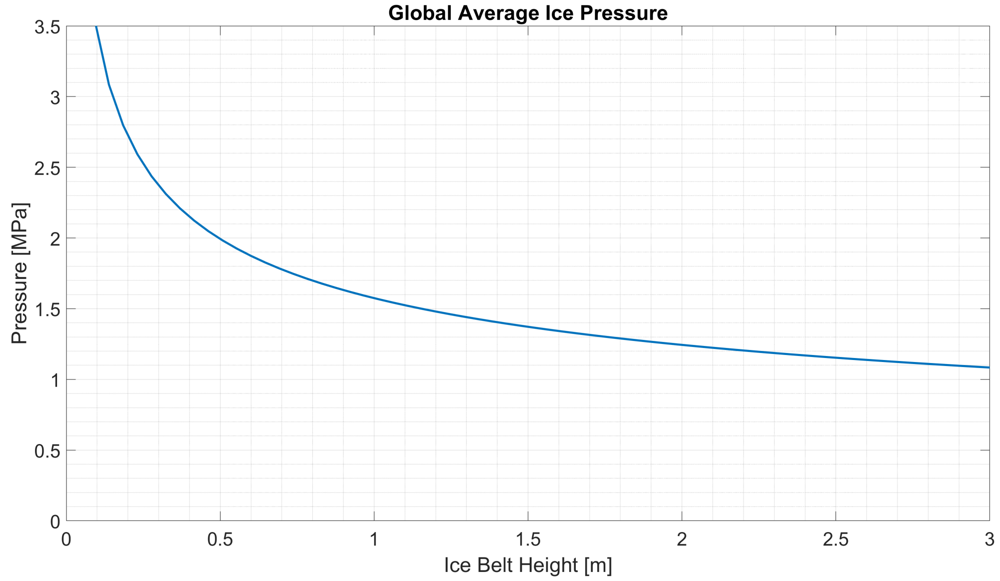


Figure 6.13: Pressure on the structure due to limit stress of ice breaking in crushing over ice belt height.

On the other hand, as can be taken from figure 6.14, the global force on the structure is still increasing with a bigger ice belt. Therefore the size has to be a compromise depending on the two above variables. Again the choice of this dimension will be made and justified in chapter 8.

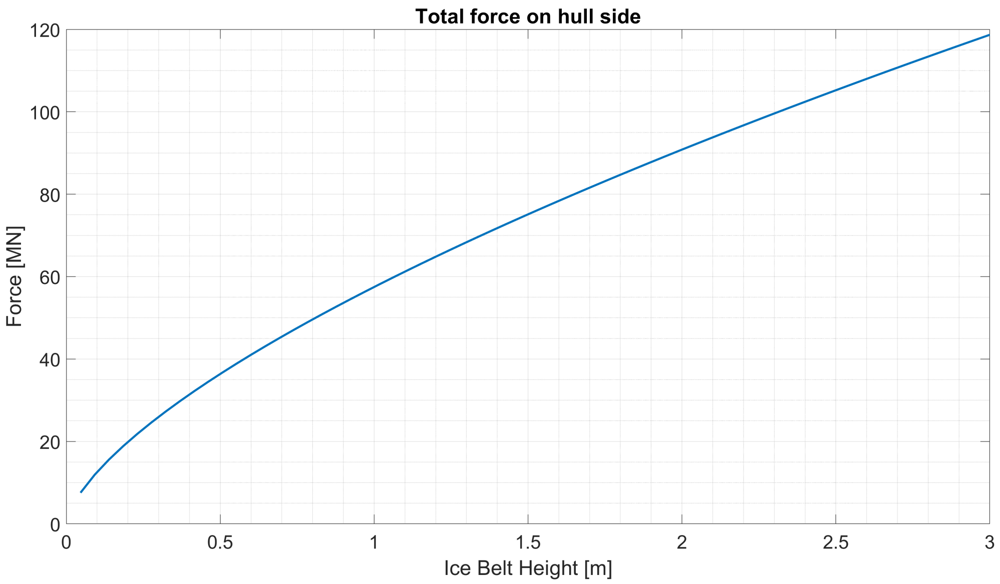


Figure 6.14: Forces on the structure due to limit stress of ice breaking in crushing over ice belt height.

6.6.3. Final Overview and Main Conclusions

The choice of good strategies for facing the ice loads is a really crucial phase of the design and will strongly influence the result of the design. The main choices for the hull structures that are affected by the ice loads and that will be presented in chapter 8 are the hull side inclination of 70° and an ice-belt of 0,75 m. Regarding the first choice, this value leads to a maximum global load on the vessel side of 11,2 MN with 2 m of ice. This value is considered affordable by the hull structure. The same consideration can be made about the ice belt maximum global load on the vessel which results in 47 MN. These results are lower than the design loads recommended by the Ice Class notation (Russian Maritime Register of Shipping, 2002). In fact, the Ice Class notations are thought for Ice Breaking vessels in different ice loads situations. For these vessels the loads are higher due to the dynamic situation governed mainly by impacts, which lead to a limit energy case. Therefore, the ice loads estimation proposed in this thesis provides a new calculations method that gives a more specific result for the situation analysed. This, if accepted by the classification society, can avoid the over-dimensioning of the hull structure that would follow to the use of an Ice Class notation for the hull structure design.

However, it is recommended to improve and verify the load estimation presented through the use of model tests in ice tank and full-scale measurements on inclined floating structures in ice compression conditions. In particular, it is recommended to analyse the effect that the rubble ice presence has between the structure and the level ice on the vertical force acting on the hull. Furthermore, it is also recommended to verify at which angle the failure mode of the ice starts to be fully in bending without crushing occurring.

7

Propulsion and Icebreaking

7.1. Approach

The main aims of this chapter are to evaluate the optimal hull forms and features for most suitable icebreaking capability and the relative propulsion power required. Moreover, also the propulsion arrangement options will be briefly discussed. While, according to the design principle presented in section 5, the vessel will be able to break some ice also with the stern, the main navigation mode in the refrozen leads is forward icebreaking. Therefore this chapter is focused on this feature. The final hull dimensions will be presented in chapter 8, while the propulsion results for the selected hull shape are available in section 7.5.

7.2. Ice Resistance Evaluation

For analysing the performance of different hulls and for determining the required power the first step is to determine the ice resistance. For this purpose, some semi-empirical regression methods are available from the literature. It is important to point out that most of them are developed for vessels of bigger sizes and characteristics, however, a couple of these methods can be applied for this first conceptual design phase (Hu and Zhou, 2015).

For this design, the choice has been to apply two of them and compare the results. The two methods chosen are Lindqvist (1989) and Riska et al. (1997), their process and description can be found in appendix H.

7.3. Power Estimation

The following step, after having evaluated the resistance, is the estimation of the power required for the ice navigation. For this purpose, a very useful tool is the concept of net thrust T_{NET} (Juva and Riska, 2002). This is defined as "the thrust available to overcome the ice resistance after the thrust used to overcome the open water resistance is taken into account" (Juva and Riska, 2002).

Therefore, knowing that at the self-propulsion point the total thrust available to overcome the total resistance is given by the propeller thrust deducted by the thrust deduction factor t (eq. 7.1).

$$T \cdot (1 - t) = R_{ow} + R_i \tag{7.1}$$

It is possible to define the net thrust T_{NET} as:

$$T_{NET} = T \cdot (1 - t) - R_{ow} = R_i \tag{7.2}$$

Moreover, at a conceptual phase, the variation of the T_{NET} over the speed can be well approximated by a quadratic curve (Riska et al., 1997). Therefore, knowing that at zero speed the net thrust available is equal to the bollard pull thrust T_B and that at maximum open water speed v_{ow} the net thrust available is zero, the T_{NET} can also be expressed as:

$$T_{NET}(v) = \left[1 - \frac{1}{3}\frac{v}{v_{ow}} - \frac{2}{3}\left(\frac{v}{v_{ow}}\right)^2\right] \cdot T_B \tag{7.3}$$

Then, expressing the bollard pull thrust with the bollard pull quality factor K_E as in equation 7.4.

$$T_B = K_E \left(P \cdot D_P\right)^{2/3} \tag{7.4}$$

Where D_P is the propeller diameter and P the power required.

The T_{NET} can finally be expressed as:

$$T_{NET}(v) = \left[1 - \frac{1}{3}\frac{v}{v_{ow}} - \frac{2}{3}\left(\frac{v}{v_{ow}}\right)^2\right] \cdot K_E \left(P \cdot D_P\right)^{2/3} = R_i(v) \tag{7.5}$$

Here, using the ice resistance calculated at a design speed and a design ice thickness, the estimated maximum open water speed, the estimated propeller diameter and the bollard pull quality factor (which depends by the propulsion system configuration selected, reference values are presented by Juva and Riska (2002)), it is possible to estimate the power required for in the design conditions.

Furthermore, using equation 7.5 the overall ice performance of the vessel can be plotted in function of the speed.

7.4. Validation

Both Riska et al. (1997) and Lindqvist (1989) have been thought for much bigger vessels with different hull shapes, therefore in order to verify the applicability of these methods to a vessel with such a small scale, it has been decided to test them first with a known existing vessel with similar dimensions and then compare the resulting estimated power with the real installed value. For this purpose the chosen ship is the Icebreaking Emergency Evacuation Vessel (IBEEV). This vessel has already been described in chapter 3 and its main data are available from the Schottel specification which can be found in appendix I and from RINA (2007).

Data	Value
L_{wl}	42,3 m
B	8 m
T	2 m
L_{bow}	6,75 m
L_{par}	30 m
ϕ	16°
h_i	60 cm
v	3 kn
v_{ow}	11 kn
K_E	0,98
D_P	1,4 m

Table 7.1: Data used for resistance calculation and power estimation for the IBEEV. Data collected from Schottel brochure (App. I).

Using the input data summarised in table 7.1, the resistance has initially been estimated using for simplicity Riska et al. (1997). Using the resistance value at the design point of 3 knots and 60cm of ice the power has also been estimated. The results are available in table 7.2.

	R [kN]	P [kW]
Riska ($h_i = 60cm, v = 3kn$)	122,6	1104,0

Table 7.2: Results of the power estimations and resistance calculations for the IBEEV using Riska et al. (1997).

The power estimation of 1104,0 kW is extremely close to the maximum delivered power of the installed thruster (1100 kW). These results show the solidity of the methods chosen.

7.5. Results

7.5.1. Input data and design points

In this section the calculations results for the vessel will be presented. The design conditions can be derived from section 2, where for the ice channel navigation the refrozen ice usually reaches values of 50 cm with rare peaks of 70 cm. These two values have been chosen as design points. Regarding the correspondent design speeds it has been decided of choosing 3 knots for breaking the common 50 cm ice and 1 knot for the rare 70 cm one. These values are relatively low, but high speed in ice channel navigation is not important and keeping these design speeds permits to save a lot of power.

As already explained, the hull characteristics used in the calculations are the final ones that will be presented in chapter 8 and which have been optimised using the ice resistance calculations methods presented in this chapter. The ice characteristics are the same used for the ice load evaluation (Ji et al., 2011; Ettema and Urroz, 1989; Wallen Russell and Lishman, 2016; Marmo et al., 2005).

7.5.2. Resistance

Having two design points, the resistance has to be calculated with two different thicknesses (50cm and 70cm).

A summary of the data used is presented in table 7.3.

Data	Value
σ_b	500 kPa
ρ_i	912 kg/m^3
L	36,5 m
B	10 m
T	2,8 m
L_{bow}	8,5 m
L_{par}	20 m
ϕ	25°
α	51°
ψ	31°
μ	0,05
g	9,81 m/s^2
ρ_w	1025 kg/m^3

Table 7.3: Data used for the resistance calculations.

As previously anticipated, the resistance has been evaluated both with Lindqvist (1989) and with Riska et al. (1997), the results can be apreciated in figure 7.1 and 7.2, for 50 cm and 70 cm respectively.

As can also be seen from table 7.4, the results of the two methods are similar, especially at the design points.

	R [kN] $h_i = 50cm, v$=3kn	R [kN] $h_i = 70cm, v = 1kn$
Riska	122,0	124.2
Lindqvist	101.4	118,5

Table 7.4: Comparison of the Resistances at the design points calculated with Riska et al. (1997) and with Lindqvist (1989).

Figure 7.1: Resistance curve in 50cm level ice according to Lindqvist (1989) and Riska et al. (1997).

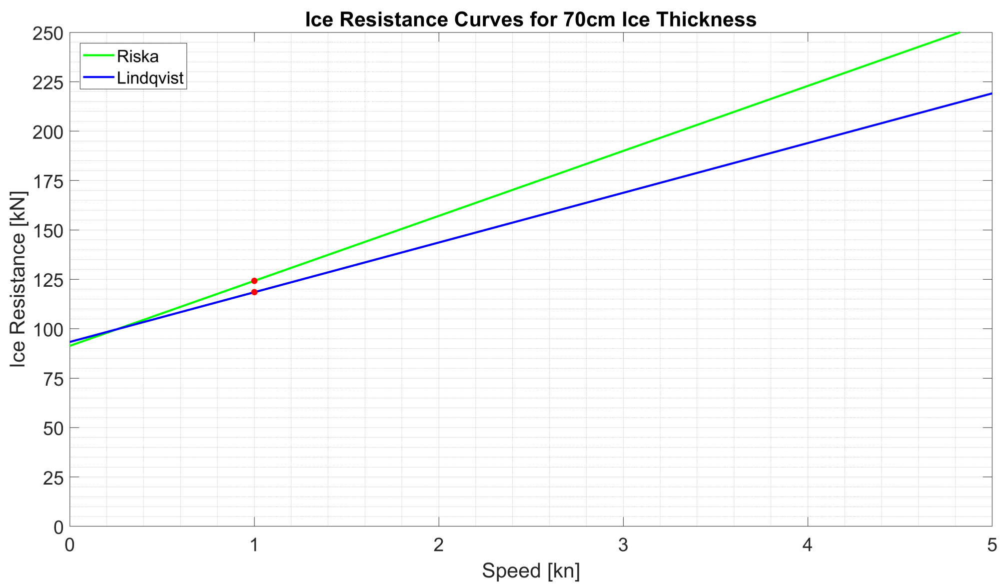


Figure 7.2: Resistance curve in 70cm level ice according to Lindqvist (1989) and Riska et al. (1997).

The chosen method for estimating the power is Lindqvist (1989). The reason is that this method is more generalised and better suited for the size of this vessel, while on the other hand Riska et al. (1997) is more focused on commercial vessels which have dimensions and characteristics too different from this case.

7.5.3. Propulsion Power

Having the two different design points, the first step to take is to compare the respective required power to define which of the two design conditions is the limiting one.
A summary of the data used is presented in table 7.5.

Data	Value
v_{ow}	10 kn
K_E	0,98
D_P	1,5 m

Table 7.5: Data used for the power estimation calculations.

Applying the procedure explained in section 7.3 the results found are presented in table 7.6. The propeller diameter D_P as first approximation is taken as the IBEEV one (appendix I), the open water maximum speed v_{ow} has been calculated by Conoship (appendix J) and the bollard pull quality factor K_E can be chosen from Juva and Riska (2002).

	P [kW] $h_i = 50cm, v$=3kn	P [kW] $h_i = 70cm, v = 1kn$
Lindqvist	900,6	943,6

Table 7.6: Comparison of the Propulsion at the design points calculated with T_{NET} concept using the resistance evaluated with Lindqvist (1989).

The power required for breaking 70 cm of ice at 1 knot is more and therefore the power selected is 950kW.

The net thrust is plotted over the speed for this power in figure 7.3. In the same graph are plotted also the resistance of various ice thicknesses. From this plot it is possible to evaluate the global performance of the vessel in ice.

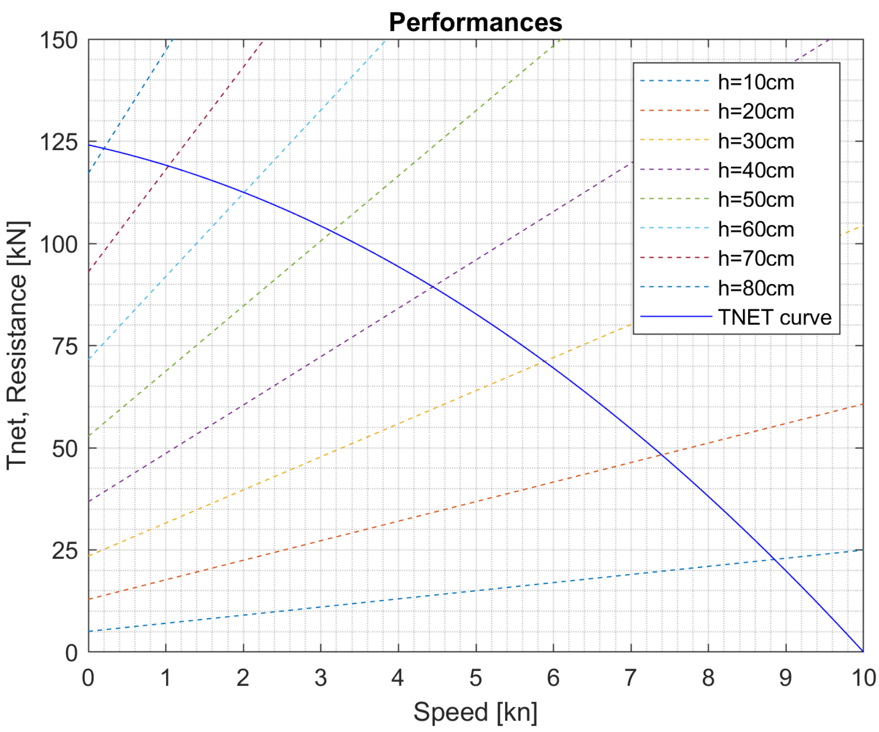


Figure 7.3: The T_{NET} curve (Juva and Riska, 2002) at 950 kW plotted with the resistance curves at various thicknesses according to Lindqvist (1989).

The performances can be also plotted showing the breakable ice thicknesses at different speeds (fig. 7.4).

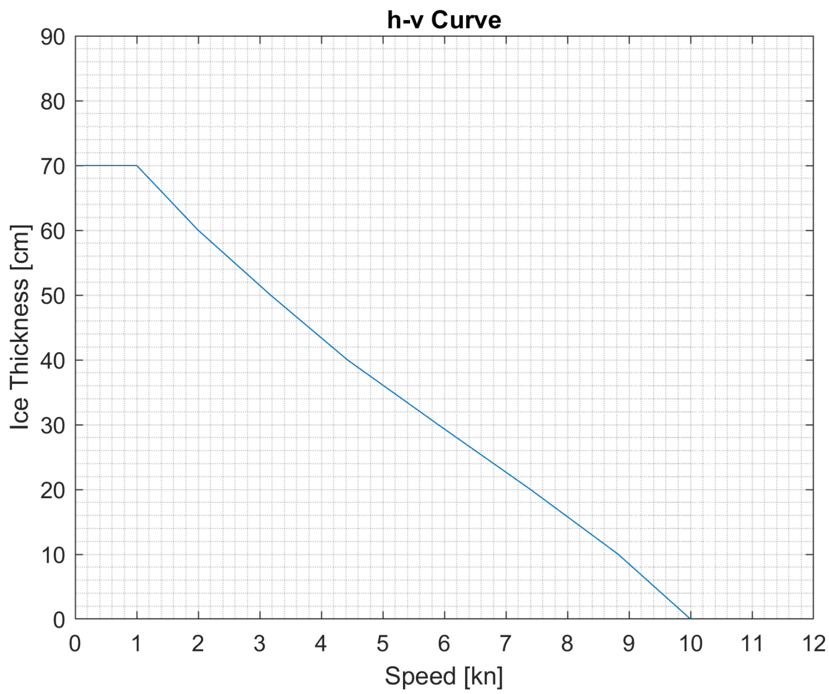


Figure 7.4: Vessel Ice-Breaking performances: speed versus thickness.

7.6. Propulsion System Layout

As already explained in section 1.5, the definition of the propulsion system and of the power generation system is not a goal of this thesis. However, a broad analysis and initial selection of the most suitable propulsion system is necessary in order to complete the mission strategy, the operational profile and give a complete overview of the ice-breaking capability.

On the other hand, the choice of the power generation system type has been delegated in its entirety to Conoship International. Their final choice has been a classical diesel engine. This choice has been made with the aim of using a well-proven concept for maintaining a very high level of reliability for the power generation, which is of vital importance for the safety of the expedition. A diesel engine, in the maritime field, is a reliable and proven concept that best suits this case. Some other more innovative options have been analysed, such as hydrogen propulsion, but this technology at the moment is not yet broadly used and it would have added an ulterior factor of uncertainty to the project. Such a technology, however, can be taken into consideration for future vessels of this type.

Regarding the power transmission, for an icebreaking vessel the best choices, in order to have good torque performance at all engine revolutions, are either a diesel-electric propulsion or a direct drive propulsion, but with the installation of a controllable pitch propeller (Riska, 2011). In fact, the torque capability of direct drive transmission to a fixed pitch propeller is not optimal for this situation. The first option gives also advantages for spacing and reliability and has been therefore chosen for this design. One more advantage of this choice is given by the possibility of installing batteries. The batteries can be charged and then used when completely silent operation is required.

The last part to define is the propulsion system. In this case the ideal choice would be a couple of retractable azimuthal thrusters. In fact, using this combination is possible to have the manoeuvring and icebreaking advantages during propulsion and be able to retract them and fully protect them when the vessel is lifted up by the ice. However, after having contacted a few companies, it came out that such a system is not available on the market and the only way to have it would be to design it in purpose for this project. This is possible, but it is also an expensive choice which is not feasible with the budget available. Furthermore, reinforcing such a system for ice-loads in such a small propulsion, can lead to the risk of a too big and heavy structure. The alternative available is then to install two Z-Drive azimuthal thrusters with a sufficient ice class capability for resisting to the ice and design the hull in a way that protects them when the vessel is lifted on the ice. For this purpose the use of a skeg and a nozzle can be really useful. Furthermore, the nozzle can also help in ice breaking when the speeds are close to zero and the conditions are similar to bollard pull. On the other hand, the downside of this choice is that such appendices on the hull disturb the popping-up process, especially when the forces are not completely from the sides. Moreover, when the vessel is sitting on the ice there is the risk of ruining the propellers and their transmission systems.

8

Hull Concept

8.1. Design Philosophy and Environment

The design of a hull, especially in this very particular case, is done based on the environment that has to face during his life. The area covered by the vessel is mostly unknown and only few information and direct images and descriptions are available, especially during winter time. This is due to the fact that, besides the few cases previously mentioned in chapter 3, no vessel has travelled in this area in such a period. Therefore, the only information on which the design can be based are the environmental data gained by the satellites. This leads to the fact that, due to the difficulties of describing common scenarios, the really harsh environment and the very few evacuations options for the crew, the design of the hull will be mainly done with the aim of protecting the vessel and the people on board from the outside environment. Moreover, the high variability of the environment of the area creates a really diverse list of worst-case scenarios, which will be analysed in the next section. Designing a hull that has to face so many different situations in a safe way has the downside that it will not be "optimised" for relatively safer scenarios (e.g. open water navigation).

8.2. Hull design features and characteristics

8.3. Main dimensions

The hull shape has been first developed nondimensionally with only the ice-related measures fixed. The main ratios (L/B, B/T and B/T) and coefficients were in fact chosen following some trade-off. The three ratios are depending on each other and therefore the resultant values are a compromise. Furthermore, B and T have some limitations given by the influence that they exert on the stability of the vessel on ice. These relations will be further explained in section 8.3.1.
L/B has been chosen to be around 3,5: having a small ratio increase the manoeuvring ability in ice of the vessel (Quinton et al., 2006), but on the other hand, looking at the formula of chapter 7, an even smaller L/B would have decreased a lot the icebreaking capabilities (Hu and Zhou, 2015), with as results a too big installed propulsion power. Contrarily, the effect on the manoeuvrability by L/T is the opposite: big values are increasing the ability of the vessel (Quinton et al., 2006), therefore a value around 14 has been chosen. Regarding B/T, which has been chosen as around 4, it has been decided in order to have a better stability when lifted on the ice and a good inclination of the hull sides, more details are going to be given in section 8.3.1.

The final dimensions and volumes followed some limitations which are influencing the hull size. The first limitation given is the request by the Ice Whale Foundation to remain under 500 t of Gross Tonnage. The reasons for this limitation are the desire of remaining with a small vessel in order to limit the costs and, more important, the smaller amount of regulations with which is necessary to comply. In fact, as already presented in section 1.6, the SOLAS convention (SOLAS-IMO, 1974) and part of the Polar Code (Polar Code-IMO, 2016) are not applicable for a vessel with such tonnage, the safety of the crew is regulated by the Flag authority instead. On the small side, the minimum size of the vessel has been limited by the minimum requirements for the living space, working space and equipment and especially fuel and consumable for the minimum requested autonomy of 100 days (sec. 5.4). Based on these boundaries a first estimation of volumes required has been done by Conoship, with this value the final numerical main dimensions of the hull have been fixed.

8.3.1. Main section

The main section of the hull can be seen in figure 8.1, this can basically be vertically divided into two different parts. The first one goes from the keel line until 0.75 m over the waterline.

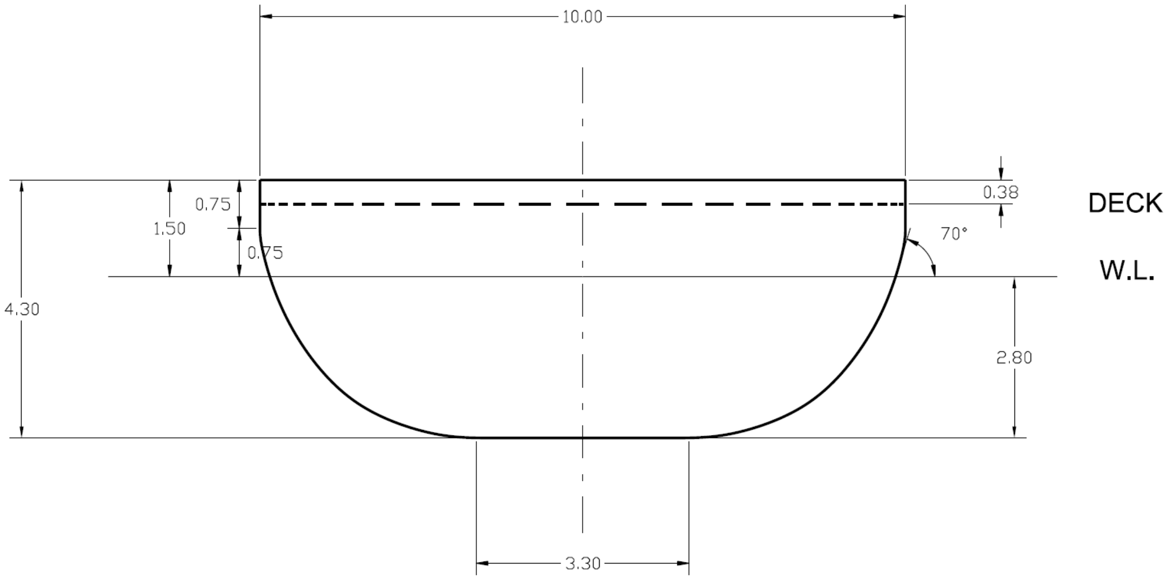


Figure 8.1: Hull Main Section.

This part has been designed thinking about the scenarios in which the hull is compressed by level ice from the sides (See Case 1 and Case 2 of section 6.3). In this case, when the loads will be high enough, the vessel will be pushed up by the ice, sitting on it. For completing this process some design features have been implemented. First of all, the inclination of the hull at the waterline can be adjusted to find a good compromise for minimising the horizontal loads without having a too wide vessel. Looking at the graphs in figures 6.12 and 6.11 of section 6.6.1, the choice for a good compromise between low loads, a not too wide hull and a not easy hull lifting has a good result in an angle of 70°. For coming up with this value it has been really useful the graph presented in figure 8.2.

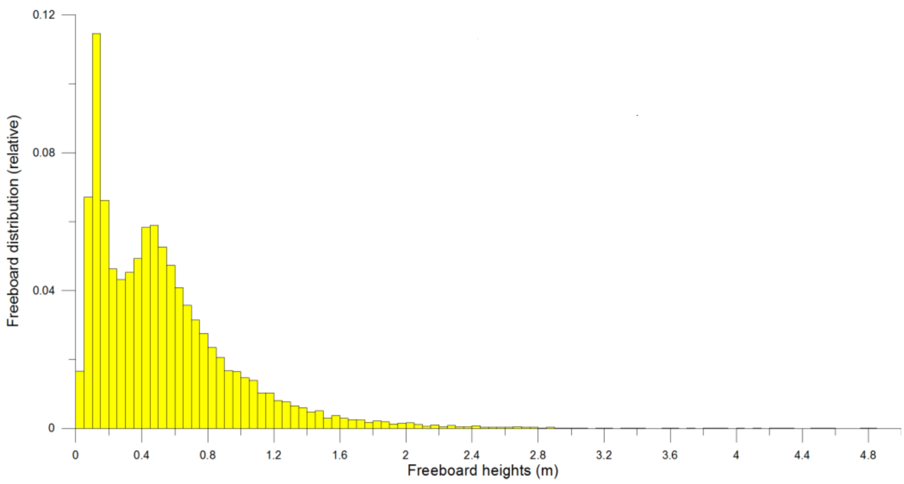


Figure 8.2: Freeboard distribution from High resolution airborne laser scanner (ALS) measurements. Horizontal East-West overflight on the Fram Strait at 79,5°N, Spring 2016 (Simonsen et al. (2015) as cited by Nissen et al. (2017)).

Here it can be observed the freeboard distribution of the ice in the area. In this graph two peaks can be seen: the first one, at 0,15 m, represents the first year ice frozen in loco, while the second one, at around 0,5 m, is due to the multi-year ice floes. Now, again using the graph in figure 6.12, and knowing that from as a first estimate the vessel is going to weight around 640 t (Conoship estimate can be found in appendix K), it is possible to determine which ice thickness is going to result in the 3,2 MN per side necessary to completely lift up the vessel with a 70° inclined side. This ice thickness is around 2 m and, knowing that the thickness-freeboard ratio in the Fram Strait is on average around 5,5 (Nissen et al., 2017), it can be seen that the hull is going to be lifted by all the multi-year ice features with a freeboard over 0,36 m and not by the first year ice (fig. 8.2).

Furthermore, the bottom part of the vessel is flat to avoid excessive inclinations of the vessel when is sitting on the ice, this is helped also by the smooth connections between the flat part and the inclined sides. In fact, if, due to unbalanced forces from starboard and port side, the vessel is going to be inclined during the process, these parts of the hull with a very small inclinations, together with the central centre of gravity of the structure, are going to make the hull rolling toward a straight position when the process is completed.

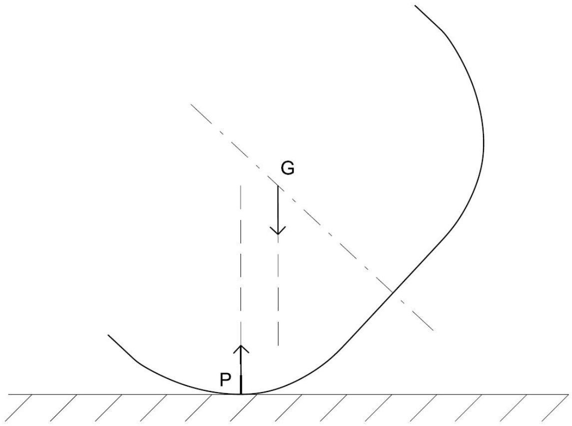


Figure 8.3: Forces acting on the hull inclined.

This flat bottom is 1/3 of the total vessel breadth, this number is the results of some trade-off. In fact, when the vessel is transversely inclined it will tend to come back to the right position only if the centre of gravity vertical is internal to the contact vertical (fig. 8.3). Otherwise, the vessel is going to capsize. To ensure that this is going to happen for all the inclinations, has to be checked the position of the centre of gravity with respect to the evolute curve of the sides shape (fig. 8.4). The barycenter has to be under the evolute curve to ensure that for all the inclinations on the boat will act the correct moment. Furthermore, the more the centre of gravity is distant from the curve the more the bigger the moment acting on the ship. Increasing the flat bottom will give a more stable ice-sitting position, but increasing it too much will lead to really vertical sides and to a much less smooth connection between these two elements. The result is going to be a much lower evolute (fig. 8.5), with the already explained bad influence on the stability. On the other hand, a much smaller flat bottom when the vessel is on the ice will decrease the transverse stability because the boat is loaded on a much smaller surface.

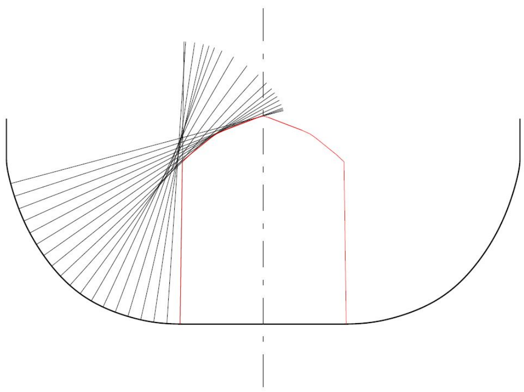


Figure 8.4: Evolute of the hull shape (red line) and possible positions of the center of gravity.

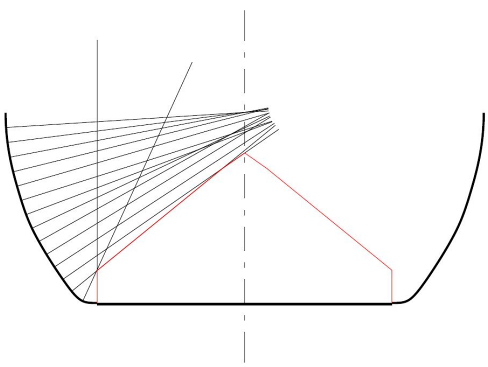


Figure 8.5: Influence of a large bottom on the evolute curve of the sides.

Looking over the waterline it can be seen that the inclined part of the hull finishes at 0.75m above

the waterline, this value has been chosen looking of the maximum thickness of the level ice found in the area. In fact, again using figure 8.2, it can be observed that more than 80% of the ice features have a lower freeboard, so this value will be enough for facing the majority of the cases.
Above the inclined sides a vertical reinforced ice-belt goes all around a vessel. This has been designed for protecting the hull from the big multi-year ice feature and small icebergs and dissipate their loads on the main deck of the vessel (which finishes at half of their height). The choice of a vertical structure has been done because of the fact that these big ice features are of really different shapes and dimensions (which leads to asymmetrical forces on the hull) and therefore an inclined structure (upward or downward) can lead to rolling events that can easily capsize the vessel. This creates the necessity of breaking the ice in crushing instead of bending, which leads to loads 5-6 time bigger. But, due to the small size of the belt, the reinforced part does not have to be too big, with a positive influence on the vessel weight. The value of 0,75 m of height has been chosen to stand up to almost all the freeboards present in the area (fig. 8.2). Bigger values are rare and represent icebergs that are easy to avoid. Furthermore, such an ice belt thickness, as can be seen from figure 6.13 of chapter 6, gives a pressure value which is already out of the initial peak.

8.3.2. Longitudinal section

The longitudinal section has been designed following exactly the same principles as the main one, but taking into account the necessity of ice breaking with the bow and the presence of the propulsion system in the stern.

Looking first at the bow, this has been designed following the principle of the "Spoon Bow" (Yamaguchi et al., 1997), which improves the ice-breaking abilities and has a good behaviour when the vessel is compressed not from the sides. Initially, the first idea was to give to the vessel a more pointy bow, in order to "crack" the ice, which for first-year ice is a better solution, but the bad behaviour of such a hull form in non-transverse compressive ice led to the choice of the "Spoon Bow" 8fig. 8.6. This bow type, in fact, can decrease the horizontal component of the loads uniformly from all sides.

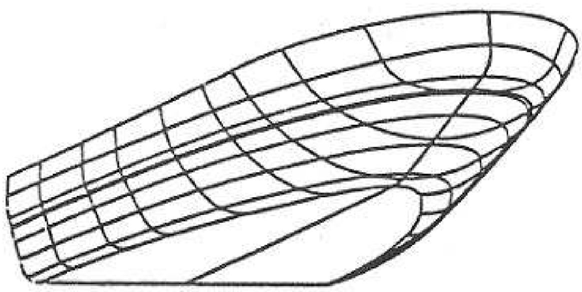


Figure 8.6: The "Spoon Bow Concept" (Quinton et al., 2006).

The bow inclination at the waterline in the centerline has been chosen of 25° (fig. 8.7), this value has been found using the methods presented in chapter 7 for optimise the ice-breaking ability without decreasing too much the open water behaviour. On the bow side values of angle have been chosen with the help of the rules for icebreaker of Russian Classification Society (Russian Maritime Register of Shipping, 2002). Moreover, the ice belt above the waterline is exactly constructed with the same characteristics as on the sides.

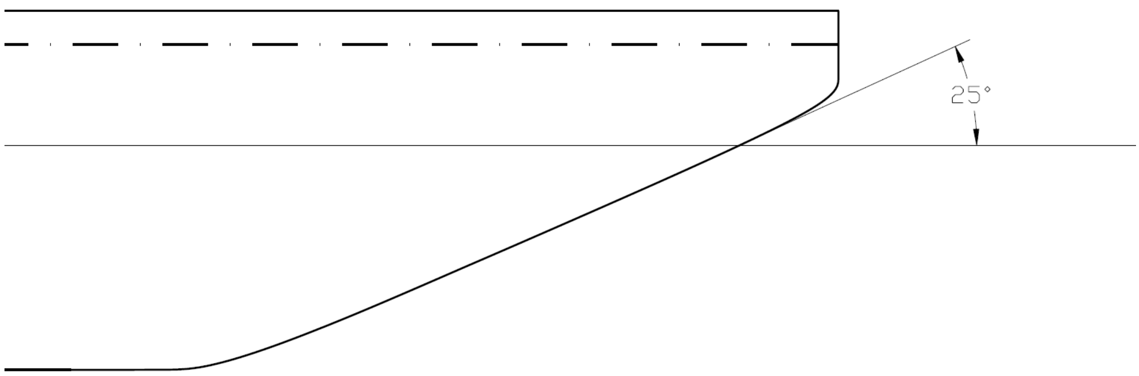


Figure 8.7: Longitudinal Section at the bow.

The situation becomes harder in the stern where the presence of the propellers has to be taken into account. The idea here is to have an inclination at the waterline equal to the inclination at the bow (fig. 8.8), trying to have the ice forces as much symmetrical as possible and in order to give some icebreaking capability also going astern during manoeuvring. Then, going deeper, the inclination suddenly decreases going almost to zero. This less inclined area gives the space to install two retractable azimuthal propellers (more detailed described in section 7.6).

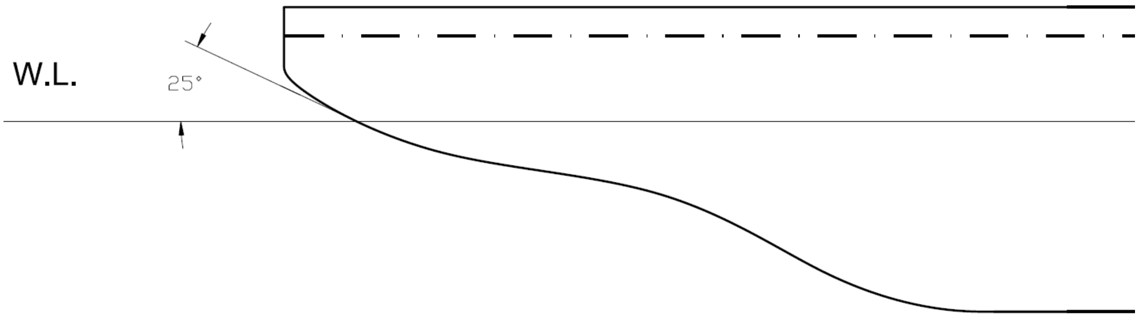


Figure 8.8: Longitudinal Section at the stern.

A 3D render of the final hull shape concept is presented in figure 8.9, while the main dimensions and characteristics are summarised in table 8.1.

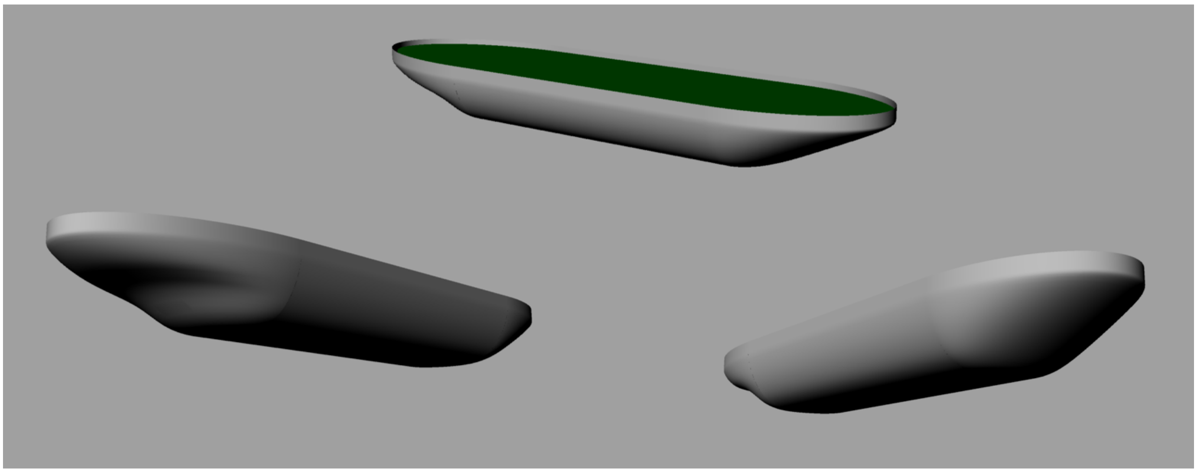


Figure 8.9: 3D render of the hull shape.

Data	Value
L_{oa}	38,5 m
L_{wl}	36,5 m
B	10 m
D	4,3 m
T	2,8 m
∇	620 m^3
A_{wet}	400 m^2

Table 8.1: Main dimension of the hull.

9

Final Concept and Conclusion

In this chapter, the final concept with its key features is going to be presented. Some renders of the concept can be seen in figure 9.1, the linesplan of the hull is in appendix L and the general arrangement in appendix M.

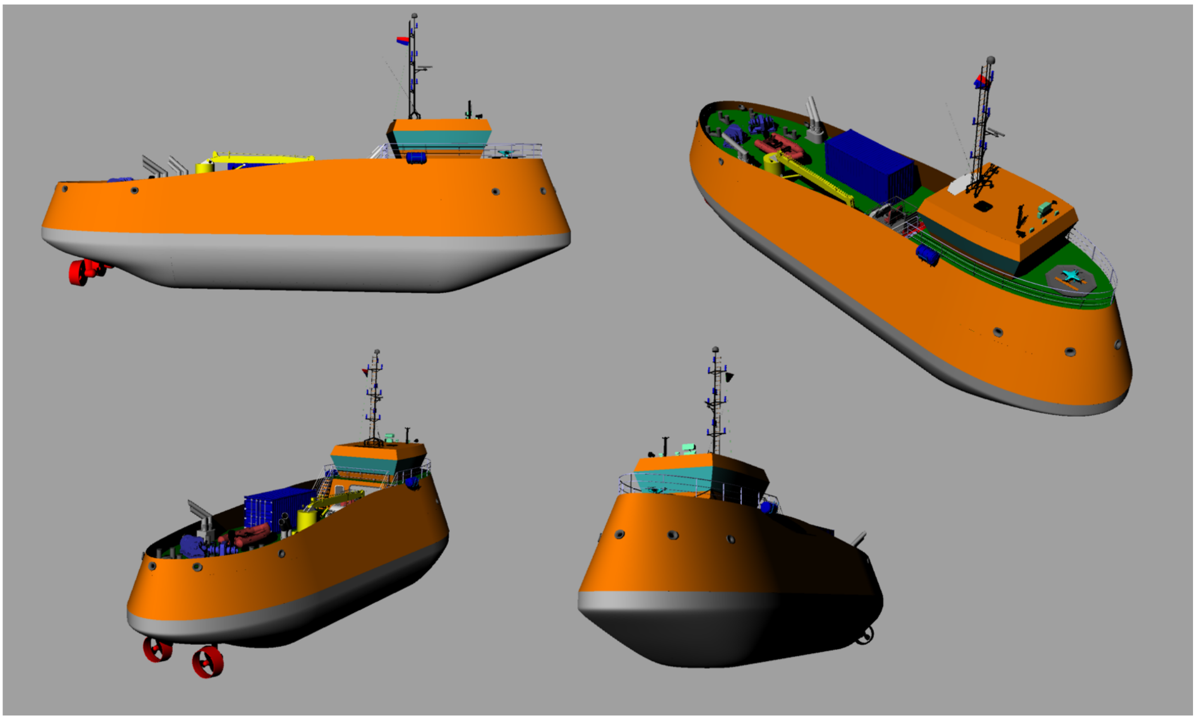


Figure 9.1: 3D render of the final concept of the vessel.

9.1. Final Concept Design Description

As can be seen from the General Arrangement of appendix M the vessel is divided into four decks. The double bottom and the double sides contain mostly fuel tanks, which, being directly in contact with the outer shell, according to the Polar Code have to be smaller than 30 m^3 (Polar Code-IMO, 2016).

Just above the tank top the first deck is located, containing the dry lab with the sampling storage room and the workshop. On the same deck, at the stern, there are the engine rooms and the thruster rooms. Both of them are split in two longitudinally in order to keep a good level of redundancy.

On the second deck all the living spaces are located: rooms for the crew (limited to six people), lavatories, daily room, fitness room, medical room and galley. Moreover, the space for boarding scientific containers inside the vessel is present and this is the deck where at midships around the Wet Lab is situated around the moon pool. Here all the research related to sampling and diving is performed. Furthermore, the UUV/AUV can be deployed from here. The moon pool is also accessible from the third deck, through a vertical passage.

The third deck is mainly open: starting from the stern one finds the space for mooring, the area for placing two more containers with scientific equipment, a crane on the starboard side, and the space for storing various types of vehicles. The bow section is not fully open but has open sides in order to not be considered for the Gross Tonnage volume. In this semi-open area the bow mooring area is situated, along with the emergency diesel generator room, a possible space for a liferaft and another free area which can be used for storing scientific equipment. The only fully closed-off area are the stairs leading from the third deck up to the bridge.

The upper deck is fully occupied by the bridge, which is also used as sound analysis lab. The bridge has been designed to offer a nearly 360° view.

Looking at the outside of the vessel, the hull part has been already described in chapter 8, the superstructures have been designed with an upward inclination, in order to keep the ice-belt described in chapter 8 as the most external part of the vessel for protecting the superstructure. For protecting from ice ride-up the second deck contains no windows and openings. The open deck in the stern is protected at the sides by two walls that permit to work outside with some protection from the wind.

9.2. Conoship International Concept Design comparison

During the development of the project, some modifications have been requested by the Ice Whale Foundation to the final design which changed neither the strategy to face the ice nor the key design features of the concept (fig. 9.2). However, some main dimensions change significantly.

Figure 9.2: 3D render of the Conoship vessel (Image produced by Conoship International).

In particular, the main request was to increase the draft of the vessel to 3,8 m. The motivation of the request is to have a deep draft and be able to have the moon pool free from the ice when the floes are trapping the vessel. However, these motivations have not be considered valid enough for modifying the concept design result of this thesis. In fact, having a deeper draft does make the process of being lifted up by the ice longer and harder, giving a smaller level of safety. Furthermore, also the advantages given by this choice are not considered sufficiently useful, because, according to the calculations presented in chapter 6, ice floes over 1,9 m are going to lift up the vessel and therefore an increase of the draft would not give any improvements. The only advantage given by this choice is that, to maintain the same displaced volume and the same gross tonnage, the length of the vessel has to be decreased, decreasing the L/B and therefore improving the manoeuvring in ice (see section 8.3). However, looking also at the results presented by Quinton et al. (2006), the manoeuvring ability in ice of the concept design presented is considered already good enough for the mission.

The general arrangement of the Conoship final concept is presented in Appendix N.

9.3. Effects of modifications of minimum requirements on the final result

At the end of the design process, it is now interesting to analyse the effect that the modification of the requirements has on the dimensions and cost of the final result.

First of all, one of the stronger requirements was the autonomy time. An increase of the 100 days of autonomy is not considered feasible because of the limitation of the 500 GT, a decrease is however possible. Due to the fact that the majority of the fuel is contained in the double bottom and at the sides, the volume gain would however not be significant and also the cost would therefore not decrease. In fact, most of the volume is occupied by scientific equipment and working spaces.

Especially the moon pool and the wet lab are covering a big space. In order to decrease the vessel size in a significant way, the best way is to remove the requirement of the moon pool and the surrounding facilities. This would lead to a quite big space reduction and savings in structural elements. On the other hand, the moon pool is one of the key elements for a good result of the expedition and therefore such a choice has to be much more deeply evaluated and the economic gain has to be significant.

In order to decrease the cost, a good choice would be to downgrade the icebreaking capability and the propulsion system. In fact, the diesel generators are one of the most expensive parts of the vessel and the very high power output is necessary for fulfilling the ice breaking requirements. On the other hand, this choice is going to affect also the safety of the vessel. Therefore, again, it has to be studied and analysed accurately and may be taken into account only for a future second vessel.

One other choice that would decrease the costs is choosing a direct driven linear shaft instead of the Z-Drive transmission chosen. This would save some money with a downgraded manoeuvring ability which again decreases the safety of the vessel.

9.4. Feasibility and Conclusion

The final results is a strong and compact platform (fig. 9.3) with the ability to face different and harsh conditions using different strategies. The costs have been estimated by Conoship International also consulting some shipyards and it does not exceed the limit of 5 millions of euro imposed by the Ice Whale Foundation. The vessel is able to fulfil the revised requirements and the expedition is considered feasible. This feasibility has been verified during the design itself and no obstacle that would have stopped the project has been found.

However, it is important to point out that the expedition is of course not fully free of risks. A lot of care and caution has to be used, especially during the initial loops. The onshore control and meteorological station will play a fundamental role in helping and directing the expedition.

Furthermore, the crew has to be thoroughly trained for surviving in such a small and harsh environment for such a long time. It is strongly advised to train the crew through proper sea and ice trial, possibly in loco and with an initial support from one other vessel.

Moreover, it would be really useful, in order to keep the mental stress of the crew always at a good level, to stop at least one time between the loops in Longyearbyen to rest and check the physical and psychological status of the people on board.

9.5. Recommendation for future Design Development

In this final section, for the future design steps, some recommendations are provided.

The first improvement to further investigate is the possibility and the costs of building ice classed retractable azimuthal thrusters, this solution would improve a lot the safety and the ability of the vessel. Otherwise, the strength of non-retractable azimuthal thrusters in compressive ice has to be further analysed.

As already mentioned in chapter 7 and especially for other future versions of this vessel, different power generation and propulsion methods could be considered. More environmental friendly and autonomy-oriented solutions can be evaluated.

Regarding the hull shape, a more detailed study of the propeller-hull interaction has to be carried out. The hull form at the stern can be improved in order to increase the efficiency of the thrusters. Also some improvements to the hydrodynamic of the hull can be further evaluated. However, in this case attention has to be paid in order to avoid a downgrade of the ice-related ability of the hull. Ice tank model and full-scale tests, as already mentioned in 6, are going to be really important in order to validate the methods and the results presented.

Regarding the operations, besides the suggestions already given in section 9.4, a broader analysis of the ice conditions in different years and conditions is recommended to be carried out. Especially during the entrance and exit of the ice-infested water, different strategies can be evaluated and defined using detailed satellite images.

Lastly, due to the extremely harsh environment of the Fram Strait during the drift toward South, it is strongly recommended to try to be lifted on the ice as fast as possible and remain there for the most part of the drift. The moon pool operations can be performed by digging a hole through the ice. Remaining in the water with ice that continuously and strongly compresses the vessel is a risky situation that gives almost no advantages and needs to be avoided as much as possible.

Figure 9.3: Top-view render of the final concept toghether with some Bowhead whales. Background image from Mocklin et al. (2012).

A

Initial Operational and Research Requirements

The Operational and Research Requirements presented in this appendix have been produced by the Ice Whale Foundation.

Concept IWF-180223

Ice Whale Foundation

OPERATIONAL REQUIREMENTS MARVEL (MODULAR ARCTIC RESEARCH VESSEL)

1 Starting Points

- Compact, robust and save research platform.
- Operating within the drift-ice zone of the Fram Strait.
- Operating during the polar winter-polar night.
- Autonomous for five months.
- The main research mode is passive drift along with the surrounding ice.
- Gross tonnage will be less than 500 GT.
- Construction will not exceed 5 M€.

2 Operating area

- The operating area is limited by latitudes 82.5° and 75°N.
- MARVEL operates in dynamic drift-ice with 50 - 95% coverage.
- Position 79°N - 5°W is a reference point (proven Ice whale wintering area by fixed hydrophone)

3 MARVEL routing

3,1 Navigation in the Fram Starit

- The start of the expeditions is around mid-October, when the ice area is close to its mid-September minimum extent and there is still some daylight.
- Expeditions end in the first half of March.
- The duration of the expeditions is about 150 days.
- The basic research mode for MARVEL is passive drift.
- In passive drift mode, the operating area (from around 82.5° to 75°N) will be crossed in about 45 days. To stay in the research area during 5 months, MARVEL should actively navigate at least 1000 Nm in a northward direction during the expedition period.
- North bound displacement of MARVEL should be executed at intervals, leaving the dense drift-ice zone and re-entering at a more northern latitudes.
- During the expedition at least 4-5 're-entering loops' should be performed
- Within the drift-ice zone slow navigation is required to get close to leads with whales are presumed to gather and mate.

3,2 Transfers

- Preferably MARVEL should navigate on its own power to and from the rearch area. (NL - Spitsbergen: 1800 Nm / Spitsbergen - starting point: 350 Nm). Refuelling is possible in Longyearbyen during ice free months.

4 Expedition Control

- MARVEL applies the ISS (International Space Station) organzation structure, where an autonomous, remote station will be intensively supported by a Ground Control Station.
- The Ground Control Station supports: Routing - Ice and meteo data - Technical and medical support - Research methods and data - Safety and SAR-operations. MARVEL's captain always bears ulimate responsibility, according to national and international law.

5 Crew

- MARVEL has a limited crew of 5-6 persons. The crew combines functions as: captain, expedition leader, navigator, engineer, scientist, household and cooking.

6 Research facilities

- A moonpool midships give access from a sheltered wetlab to the seawater under the ice cover for ROV's, Scuba diving, visual an acoustic observation and sampling. The moonpool opening measures at least 1.2 m across. The exit/entrance at the keel should be kept ice-free (e.g. de-icing by air screen through the moonpool)
- Winches of different sizes should be applied in the wetlab with pulleys directy above the moonpool to lower research equipment. Anchoring from ther interior through the moonpool when mooring might be considered as a simple and elegant solution, thereby avoiding unnecessary exterior protruding parts.
- A UAV-deck to launch and land UAV's (drones) as much obstacle free as possible (rigging, masts). The posibility to outstretch a UAV landing-net should be considered.
- The wetlab should be combined with the location of the moonpool.
- The dry lab (mainly sensitive electronic equipment) could be combined with the navigation and communication room, i.e. the bridge
- Placement of one or two sea-containers, transformed to dedicated sresearch-laboratories, should be considered, depending on the requirements of polar scientsits (Inventory yet to be made).

7 Accomodation and rooms

- 6 single crew cabins measuring 2 x 2 m
- longroom and galley could be combined.
- cabin: anitation-shower-hot tub.
- cabin: washing, drying clothes
- cabin: first-aid, fitness and day-light therapy
- storage room food and supplies
- bridge/communication/navigation
- wetlab/moonpool
- engine room, powerbank, heating, freshwater, spares and tools
- storage room food and supplies

8 Navigational aids

- gps, (ice-)radar, sonar, ais, infrared cameras, night vision image intensifier, flood and beam lights.

9 Communicational aids

- broadband satellite (Iridium), VHF radio, shortwave radio.

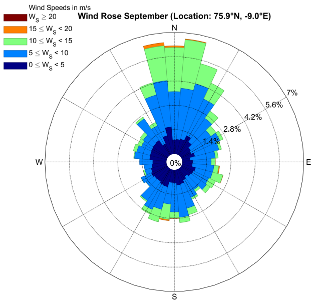
Research requirements

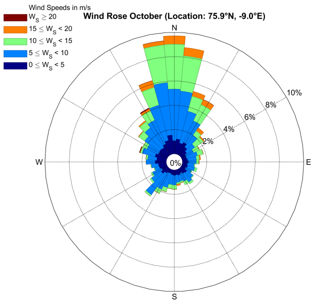
	Research objective	Research method	Required/Optional?	Requirements on vessel
1	Acoustically locate and track ice whales present in an X km radius around	1. Directional hydrophone, lowered from protected environment inside the ship	Required	Moonpool, minimum width 1.2m Winch & pulley, capacity xxx tonne Storage space for directional hydrophone (approx. lxbxh)
		2. 'Buoy' hydrophones, brought out	Required	UAV landing deck UAV landing net UAV storage space, close to landing deck, lxbxh approx. 2x2x2m UAV fuel tanks, capacity approx. xxx litres/m3 Repair workshop Storage space for (x number of) buoys with dimensions lxbxh
2	Visual observation of the waters below the drift ice	1. Scuba diving	Required	Moonpool, minimum width xxx m Changing room located close to moonpool Diving gear storage, approx. xxx m2 Air compressor charging rate xxx litres/min or brand xx type xx 2-bottle filling station
		2. ROV	Optional	Moonpool, minimum width xxx m Winch, capacity xxx tonne ROV control room ROV storage and workshop
3	Take water samples	1. Take water samples through	Required	Moonpool Pulley Storage space for sampling equipment (approx. xx m3)
		2. Take water samples with UAV	Optional	See 1.2 for requirements for UAV Storage space for sampling equipment, located near UAV space
4	eDNA analysis	1. Onboard analysis of water	Required	Storage for sampling kits Wet lab for sample analysis (approx. x m2) Dry lab for results analysis (room for x desktop computers) Fridge for sample storage (xxx m3)
5	Take atmospheric	1. Measurements onboard vessel	Required	Anemometer Thermometer Barometer
6	Enable other institutions to conduct their research	1. Provide space for stand-alone research modules	Optional	Space for two 40 ft high-cube lab containers with electricic connection

B

Wind Roses

The wind roses presented in this appendix have been produced using the ERA5 dataset of the European Centre for Medium-Range Weather Forecasts, (ECMRW, 2017).


Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose September (Location: 75.9°N, -9.0°E)
N
E
S
W
0%
1.4%
2.8%
4.2%
5.6%
7%


Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose October (Location: 75.9°N, -9.0°E)
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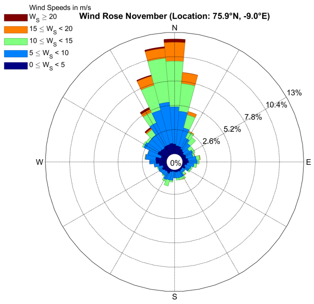
8%
10%


Wind Speeds in m/s
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$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose November (Location: 75.9°N, -9.0°E)
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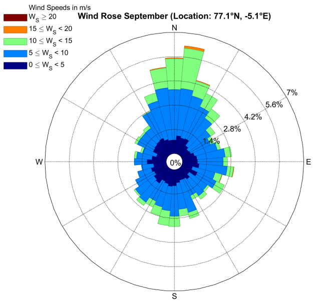
7.8%
10.4%
13%


Wind Speeds in m/s
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$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose September (Location: 77.1°N, -5.1°E)
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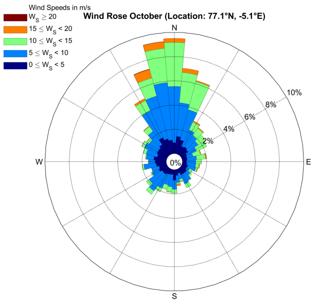
0%
1.4%
2.8%
4.2%
5.6%
7%


Wind Speeds in m/s
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$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose October (Location: 77.1°N, -5.1°E)
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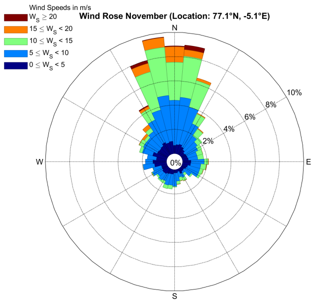
Wind Speeds in m/s
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$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose November (Location: 77.1°N, -5.1°E)
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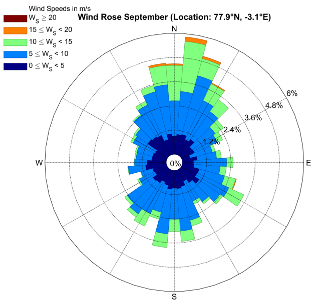
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$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose September (Location: 77.9°N, -3.1°E)
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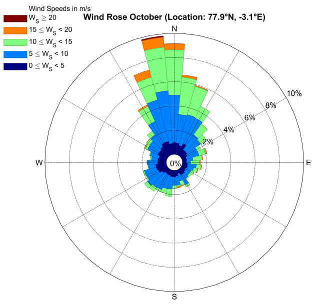
2.4%
3.6%
4.8%
6%


Wind Speeds in m/s
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$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose October (Location: 77.9°N, -3.1°E)
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8%
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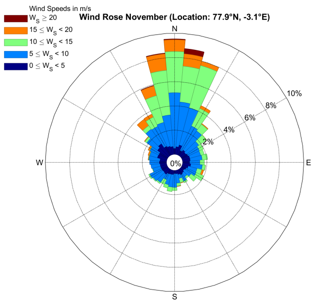
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$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose November (Location: 77.9°N, -3.1°E)
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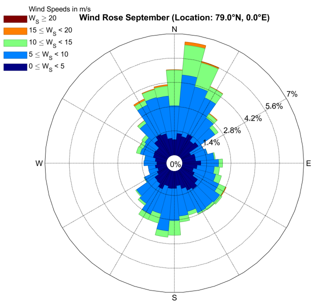
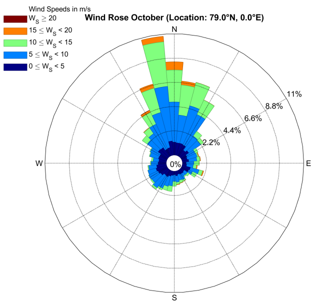
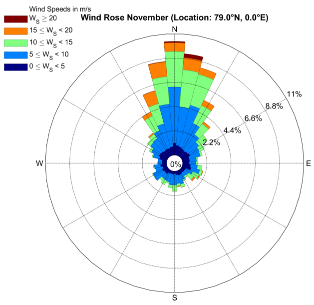
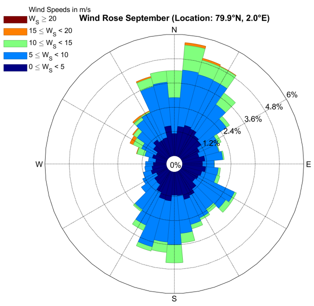
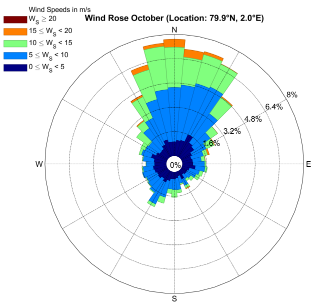
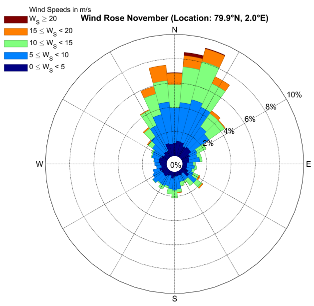

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose September (Location: 79.0°N, 0.0°E)
N
E
S
W
0%
1.4%
2.8%
4.2%
5.6%
7%

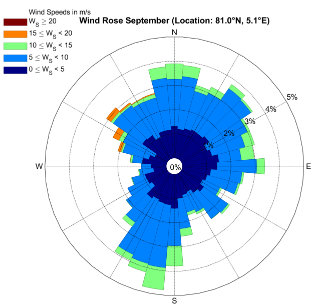

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose October (Location: 79.0°N, 0.0°E)
N
E
S
W
0%
2.2%
4.4%
6.6%
8.8%
11%

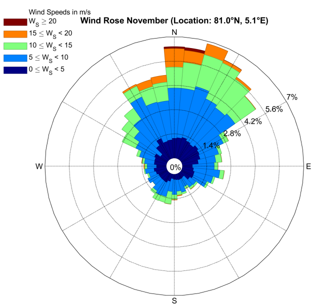

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose November (Location: 79.0°N, 0.0°E)
N
E
S
W
0%
2.2%
4.4%
6.6%
8.8%
11%

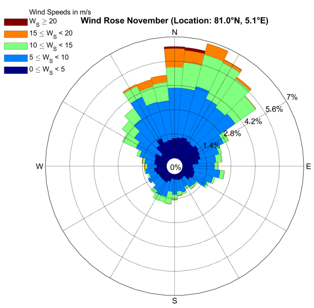

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose September (Location: 79.9°N, 2.0°E)
N
E
S
W
0%
1.2%
2.4%
3.6%
4.8%
6%

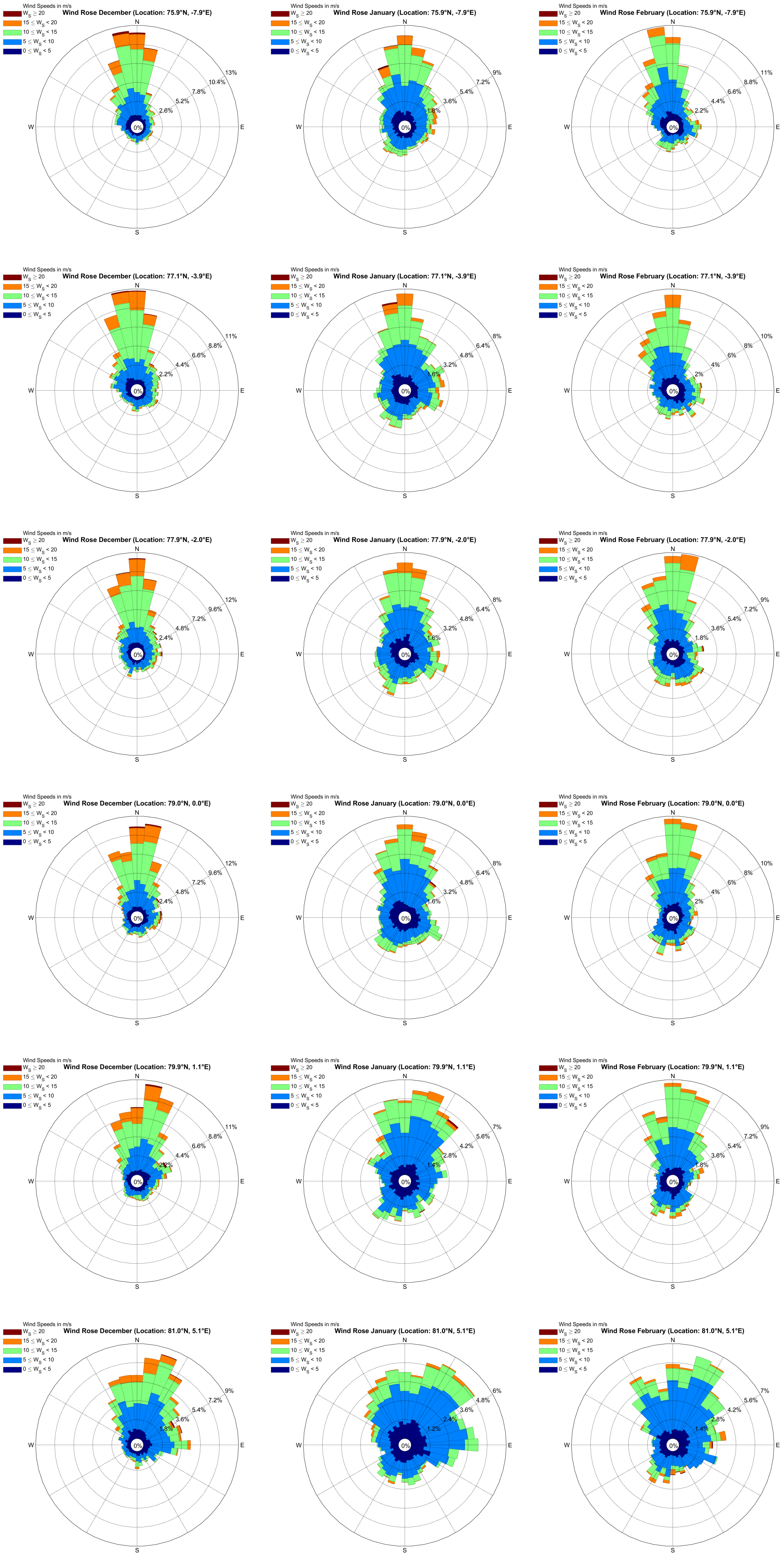

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose October (Location: 79.9°N, 2.0°E)
N
E
S
W
0%
1.6%
3.2%
4.8%
6.4%
8%

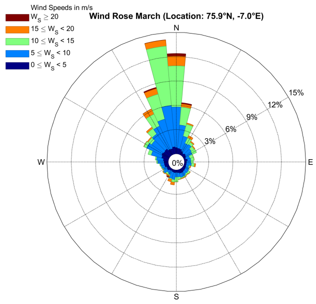

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose November (Location: 79.9°N, 2.0°E)
N
E
S
W
0%
2%
4%
6%
8%
10%

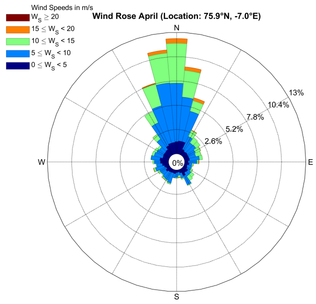

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose September (Location: 81.0°N, 5.1°E)
N
E
S
W
0%
2%
3%
4%
5%

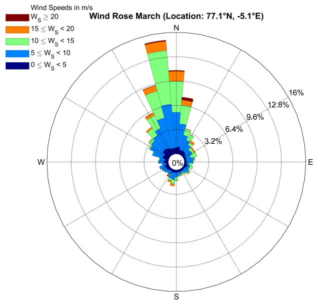

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose November (Location: 81.0°N, 5.1°E)
N
E
S
W
0%
1.4%
2.8%
4.2%
5.6%
7%

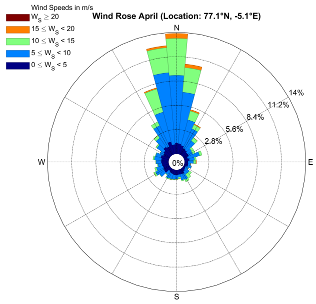

Wind Speeds in m/s
$W_s \geq 20$
$15 \leq W_s < 20$
$10 \leq W_s < 15$
$5 \leq W_s < 10$
$0 \leq W_s < 5$
Wind Rose November (Location: 81.0°N, 5.1°E)
N
E
S
W
0%
1.4%
2.8%
4.2%
5.6%
7%

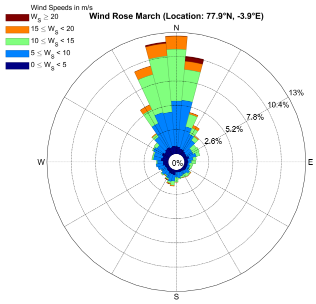

Wind Speeds in m/s
Wind Rose December (Location: 75.9°N, -7.9°E)
Wind Rose January (Location: 75.9°N, -7.9°E)
Wind Rose February (Location: 75.9°N, -7.9°E)
Wind Rose December (Location: 77.1°N, -3.9°E)
Wind Rose January (Location: 77.1°N, -3.9°E)
Wind Rose February (Location: 77.1°N, -3.9°E)
Wind Rose December (Location: 77.9°N, -2.0°E)
Wind Rose January (Location: 77.9°N, -2.0°E)
Wind Rose February (Location: 77.9°N, -2.0°E)
Wind Rose December (Location: 79.0°N, 0.0°E)
Wind Rose January (Location: 79.0°N, 0.0°E)
Wind Rose February (Location: 79.0°N, 0.0°E)
Wind Rose December (Location: 79.9°N, 1.1°E)
Wind Rose January (Location: 79.9°N, 1.1°E)
Wind Rose February (Location: 79.9°N, 1.1°E)
Wind Rose December (Location: 81.0°N, 5.1°E)
Wind Rose January (Location: 81.0°N, 5.1°E)
Wind Rose February (Location: 81.0°N, 5.1°E)
N
E
S
W

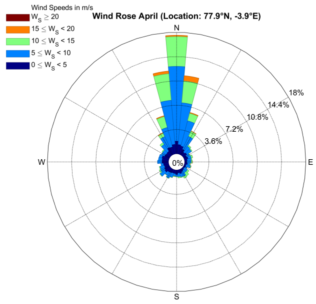

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose March (Location: 75.9°N, -7.0°E)
N
E
S
W
0%
3%
6%
9%
12%
15%

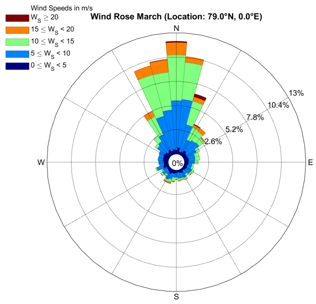

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose April (Location: 75.9°N, -7.0°E)
N
E
S
W
0%
2.6%
5.2%
7.8%
10.4%
13%

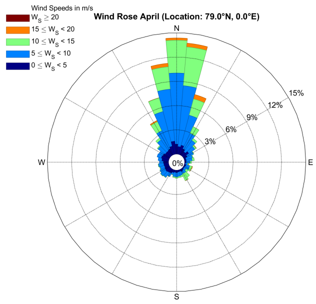

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose March (Location: 77.1°N, -5.1°E)
N
E
S
W
0%
3.2%
6.4%
9.6%
12.8%
16%

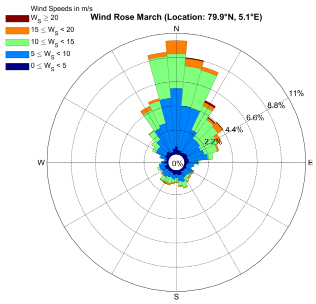

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose April (Location: 77.1°N, -5.1°E)
N
E
S
W
0%
2.8%
5.6%
8.4%
11.2%
14%

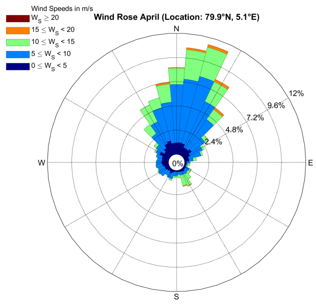

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose March (Location: 77.9°N, -3.9°E)
N
E
S
W
0%
2.6%
5.2%
7.8%
10.4%
13%

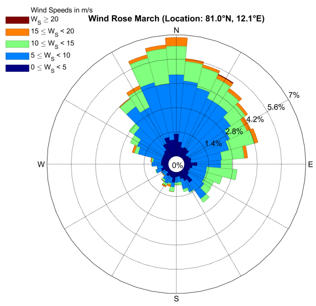

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose April (Location: 77.9°N, -3.9°E)
N
E
S
W
0%
3.6%
7.2%
10.8%
14.4%
18%

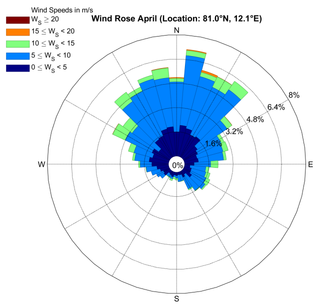

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose March (Location: 79.0°N, 0.0°E)
N
E
S
W
0%
2.6%
5.2%
7.8%
10.4%
13%


Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose April (Location: 79.0°N, 0.0°E)
N
E
S
W
0%
3%
6%
9%
12%
15%


Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose March (Location: 79.9°N, 5.1°E)
N
E
S
W
0%
2.2%
4.4%
6.6%
8.8%
11%

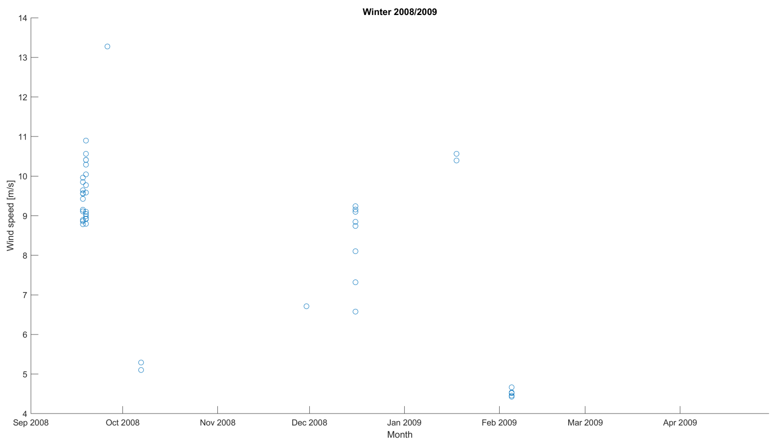

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose April (Location: 79.9°N, 5.1°E)
N
E
S
W
0%
2.4%
4.8%
7.2%
9.6%
12%

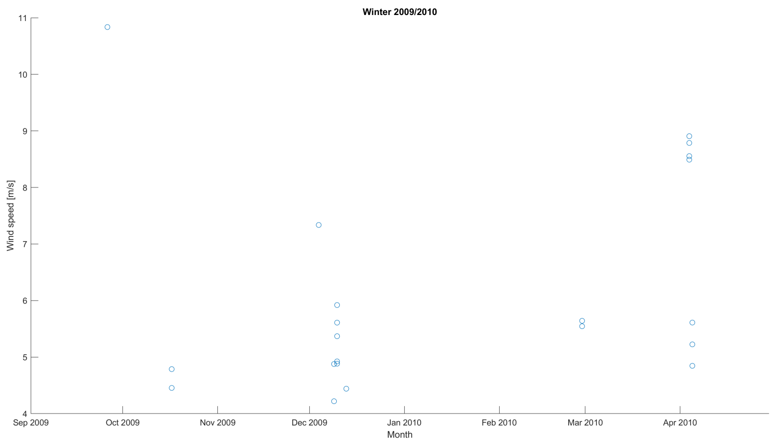

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose March (Location: 81.0°N, 12.1°E)
N
E
S
W
0%
1.4%
2.8%
4.2%
5.6%
7%

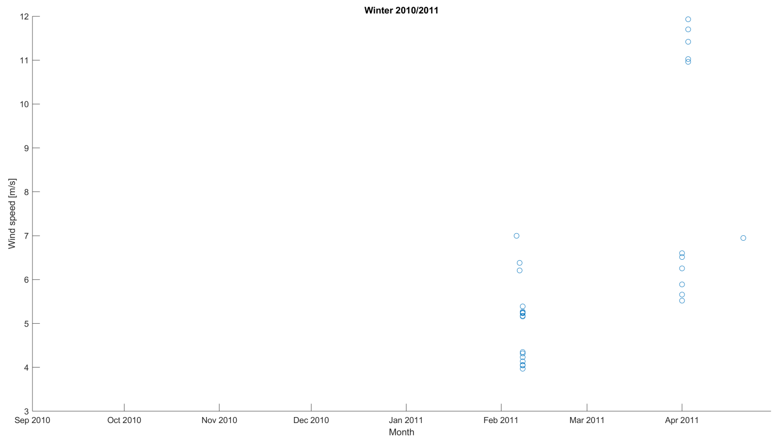

Wind Speeds in m/s
$W_S \geq 20$
$15 \leq W_S < 20$
$10 \leq W_S < 15$
$5 \leq W_S < 10$
$0 \leq W_S < 5$
Wind Rose April (Location: 81.0°N, 12.1°E)
N
E
S
W
0%
1.6%
3.2%
4.8%
6.4%
8%

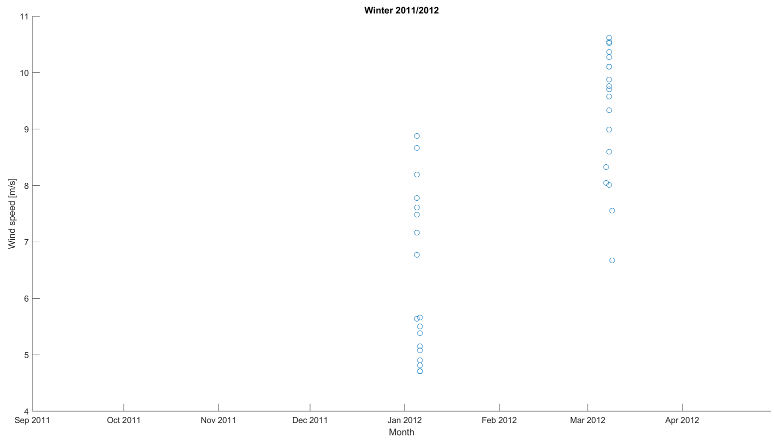
C
Wind Events

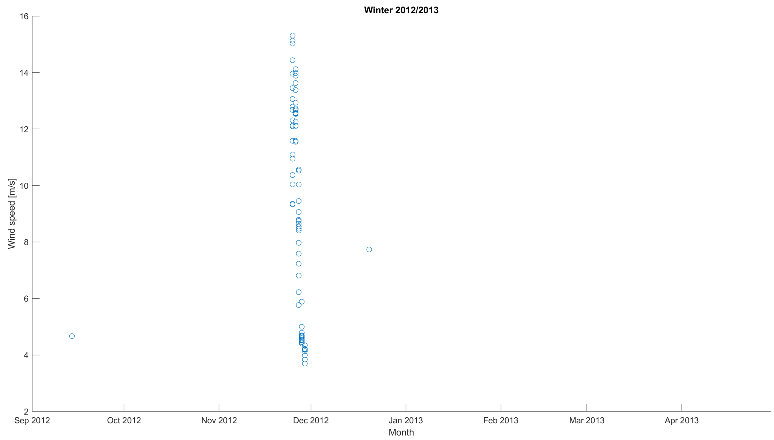
In this appendix are showed the wind events found in the last decade. Each point is one hour of wind event duration, the plots have been produced using the ERA5 dataset of the European Centre for Medium-Range Weather Forecasts, (ECMRW, 2017).

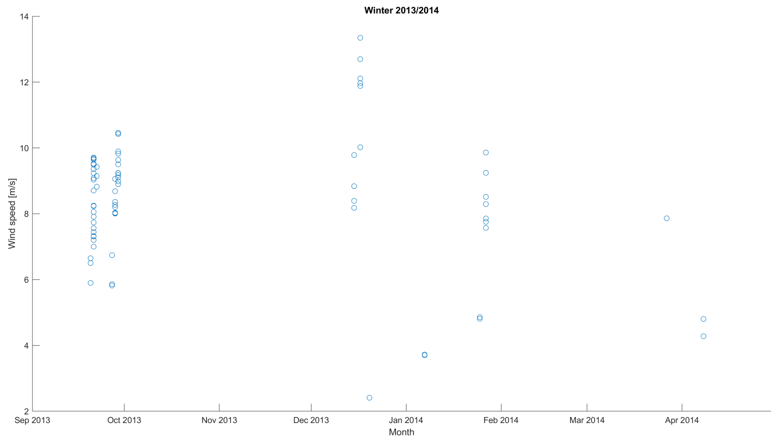


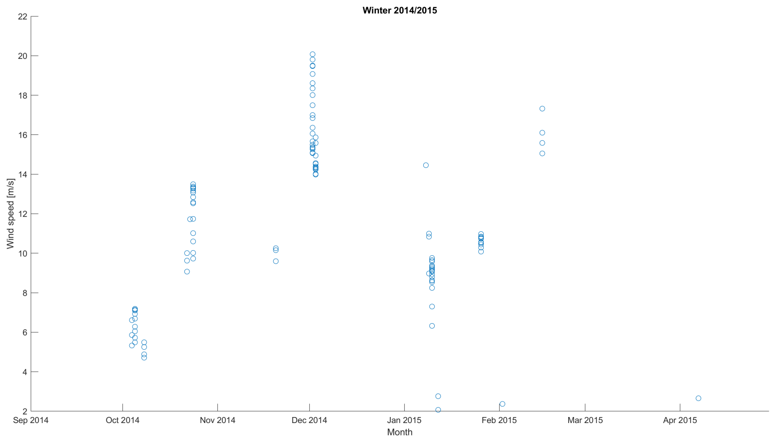


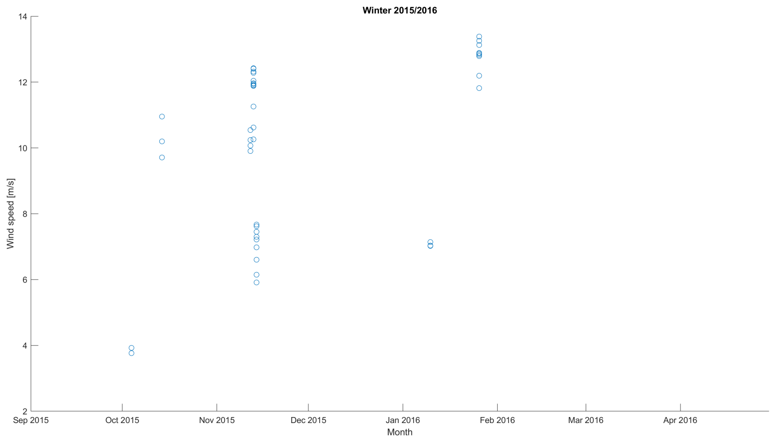

Winter 2010/2011
Wind speed [m/s]
Month
Sep 2010
Oct 2010
Nov 2010
Dec 2010
Jan 2011
Feb 2011
Mar 2011
Apr 2011

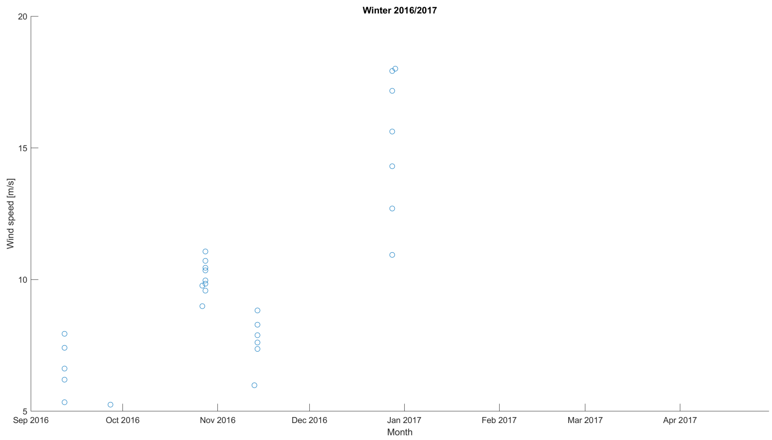

Winter 2011/2012
Wind speed [m/s]
Month
Sep 2011
Oct 2011
Nov 2011
Dec 2011
Jan 2012
Feb 2012
Mar 2012
Apr 2012

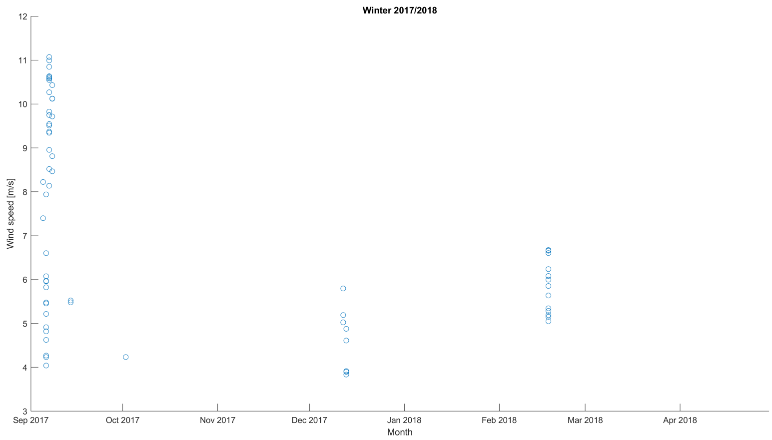

Winter 2012/2013
Wind speed [m/s]
Month
Sep 2012
Oct 2012
Nov 2012
Dec 2012
Jan 2013
Feb 2013
Mar 2013
Apr 2013


Winter 2013/2014
Wind speed [m/s]
Month
Sep 2013
Oct 2013
Nov 2013
Dec 2013
Jan 2014
Feb 2014
Mar 2014
Apr 2014


Winter 2014/2015
Wind speed [m/s]
Month
Sep 2014
Oct 2014
Nov 2014
Dec 2014
Jan 2015
Feb 2015
Mar 2015
Apr 2015


Winter 2015/2016
Wind speed [m/s]
Month
Sep 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016

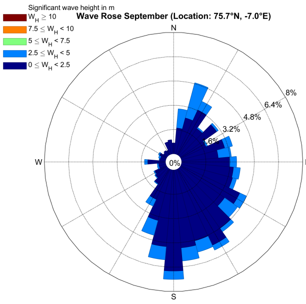

Winter 2016/2017
Wind speed [m/s]
Month
Sep 2016
Oct 2016
Nov 2016
Dec 2016
Jan 2017
Feb 2017
Mar 2017
Apr 2017

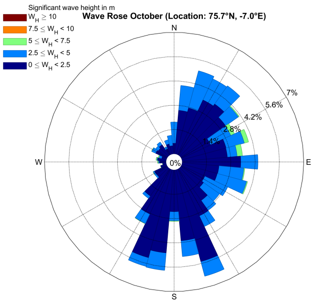

Winter 2017/2018
Wind speed [m/s]
Month
Sep 2017
Oct 2017
Nov 2017
Dec 2017
Jan 2018
Feb 2018
Mar 2018
Apr 2018

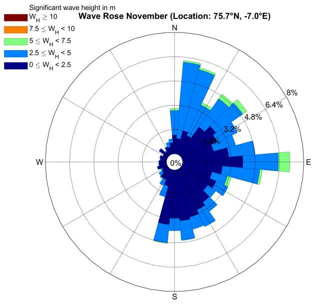
D

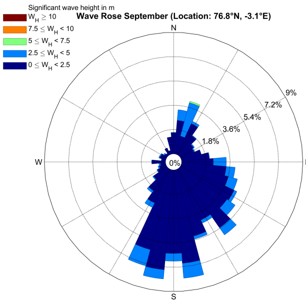
Waves Roses

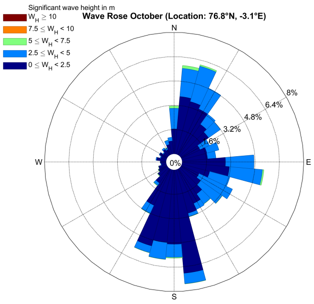
The wave roses presented in this appendix have been produced using the ERA5 dataset of the European Centre for Medium-Range Weather Forecasts, (ECMRW, 2017). They show the height of combined wind waves and swell.

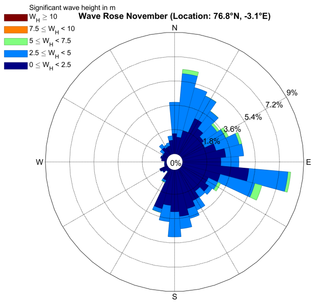

Significant wave height in m
Wave Rose September (Location: 75.7°N, -7.0°E)

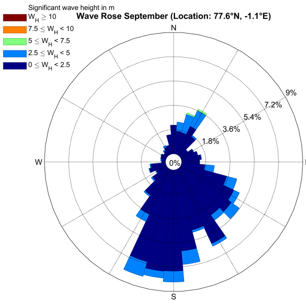

Significant wave height in m
Wave Rose October (Location: 75.7°N, -7.0°E)

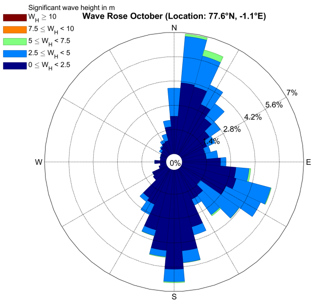

Significant wave height in m
Wave Rose November (Location: 75.7°N, -7.0°E)

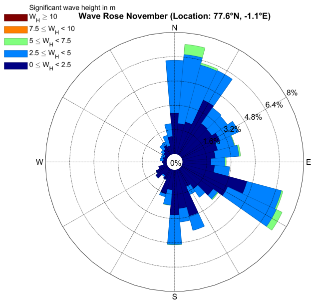

Significant wave height in m
Wave Rose September (Location: 76.8°N, -3.1°E)

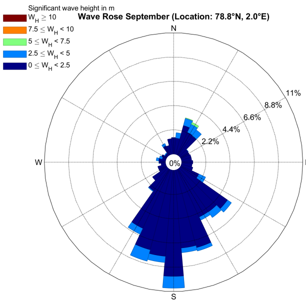

Significant wave height in m
Wave Rose October (Location: 76.8°N, -3.1°E)

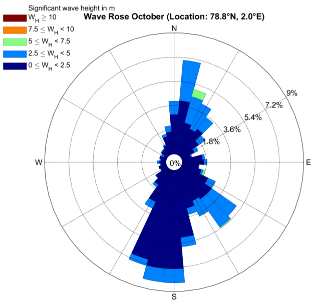

Significant wave height in m
Wave Rose November (Location: 76.8°N, -3.1°E)

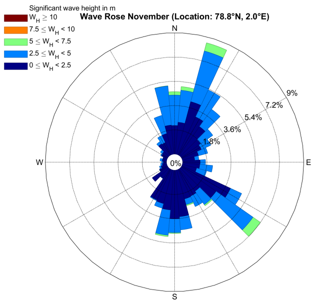

Significant wave height in m
Wave Rose September (Location: 77.6°N, -1.1°E)

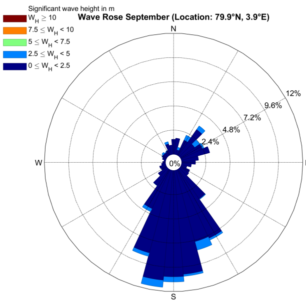

Significant wave height in m
Wave Rose October (Location: 77.6°N, -1.1°E)

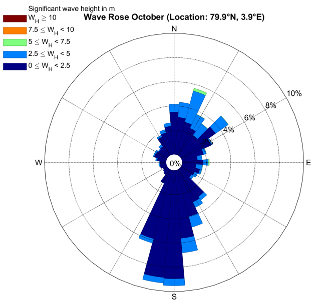

Significant wave height in m
Wave Rose November (Location: 77.6°N, -1.1°E)

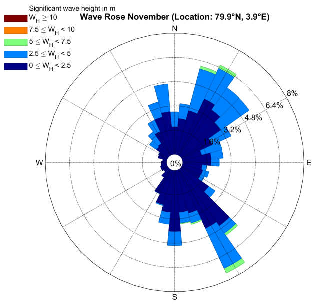

Significant wave height in m
Wave Rose September (Location: 78.8°N, 2.0°E)

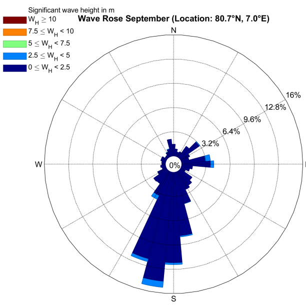

Significant wave height in m
Wave Rose October (Location: 78.8°N, 2.0°E)

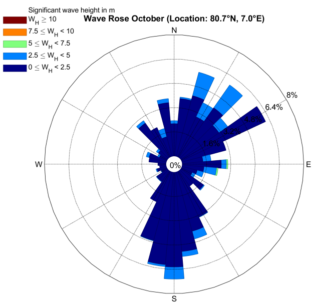

Significant wave height in m
Wave Rose November (Location: 78.8°N, 2.0°E)


Significant wave height in m
Wave Rose September (Location: 79.9°N, 3.9°E)


Significant wave height in m
Wave Rose October (Location: 79.9°N, 3.9°E)


Significant wave height in m
Wave Rose November (Location: 79.9°N, 3.9°E)


Significant wave height in m
Wave Rose September (Location: 80.7°N, 7.0°E)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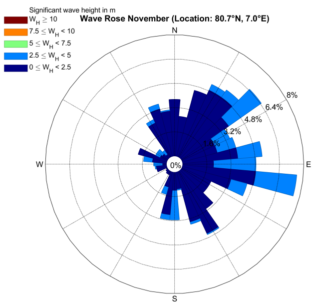
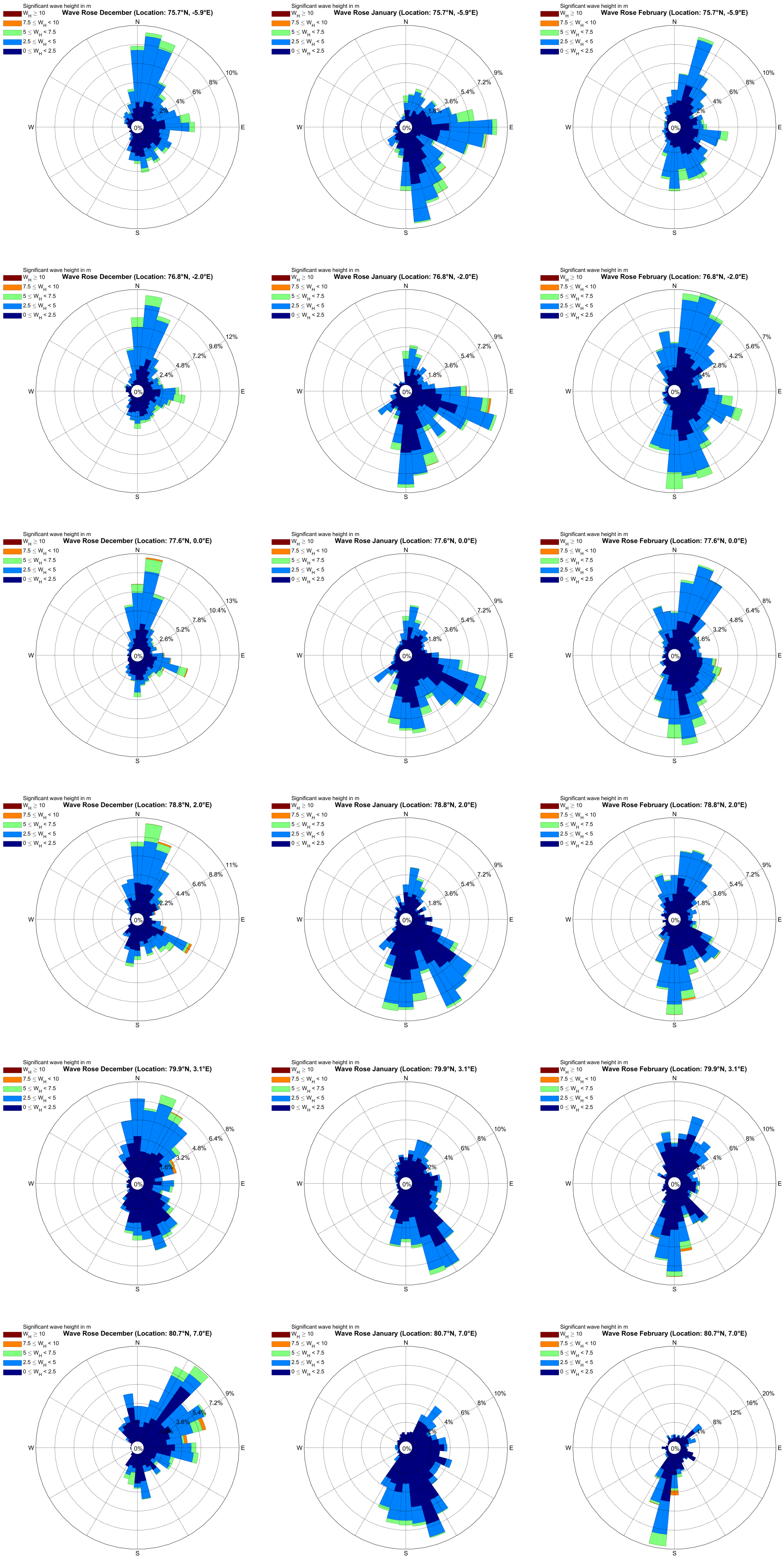
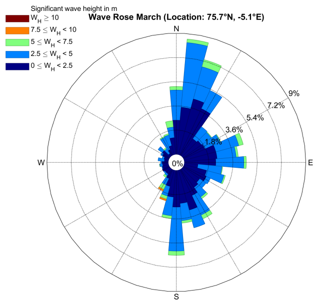
Wave Rose October (Location: 80.7°N, 7.0°E)


Significant wave height in m
Wave Rose November (Location: 80.7°N, 7.0°E)


Significant wave height in m
W_H ≥ 10
7.5 ≤ W_H < 10
5 ≤ W_H < 7.5
2.5 ≤ W_H < 5
0 ≤ W_H < 2.5
Wave Rose December (Location: 75.7°N, -5.9°E)
Wave Rose January (Location: 75.7°N, -5.9°E)
Wave Rose February (Location: 75.7°N, -5.9°E)
Wave Rose December (Location: 76.8°N, -2.0°E)
Wave Rose January (Location: 76.8°N, -2.0°E)
Wave Rose February (Location: 76.8°N, -2.0°E)
Wave Rose December (Location: 77.6°N, 0.0°E)
Wave Rose January (Location: 77.6°N, 0.0°E)
Wave Rose February (Location: 77.6°N, 0.0°E)
Wave Rose December (Location: 78.8°N, 2.0°E)
Wave Rose January (Location: 78.8°N, 2.0°E)
Wave Rose February (Location: 78.8°N, 2.0°E)
Wave Rose December (Location: 79.9°N, 3.1°E)
Wave Rose January (Location: 79.9°N, 3.1°E)
Wave Rose February (Location: 79.9°N, 3.1°E)
Wave Rose December (Location: 80.7°N, 7.0°E)
Wave Rose January (Location: 80.7°N, 7.0°E)
Wave Rose February (Location: 80.7°N, 7.0°E)
N
E
S
W


Significant wave height in m
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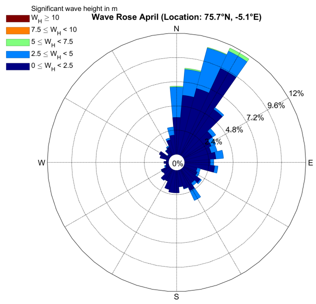
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose March (Location: 75.7°N, -5.1°E)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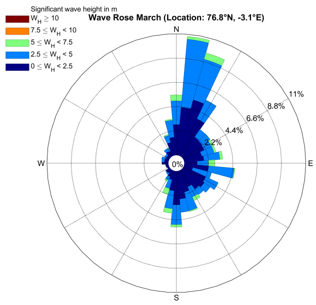
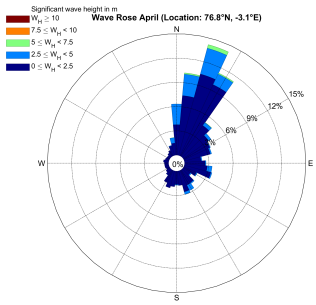
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose April (Location: 75.7°N, -5.1°E)


Significant wave height in m
$W_H \geq 10$
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose March (Location: 76.8°N, -3.1°E)


Significant wave height in m
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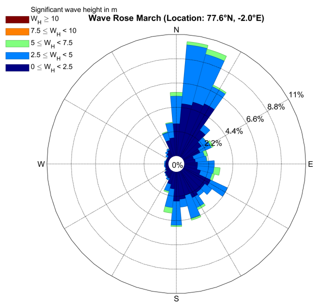
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose April (Location: 76.8°N, -3.1°E)


Significant wave height in m
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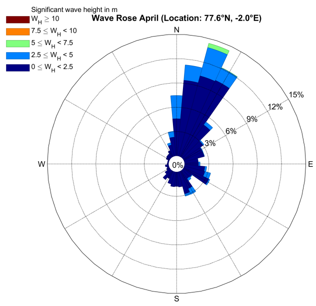
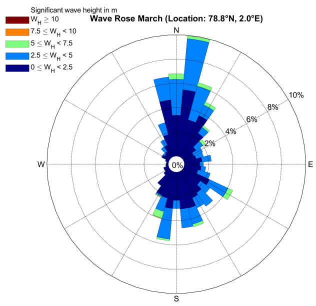
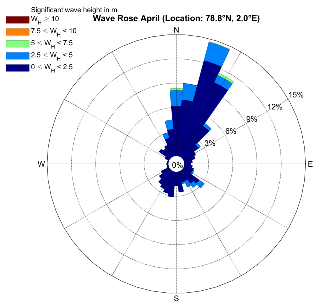
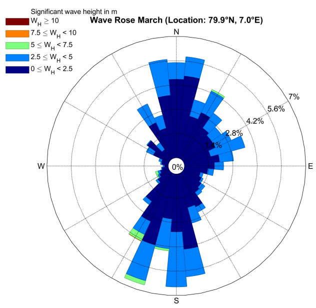
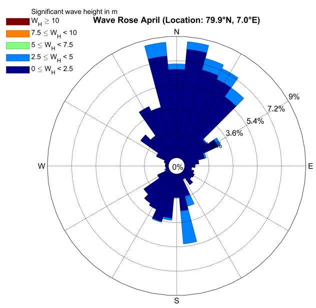
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose March (Location: 77.6°N, -2.0°E)

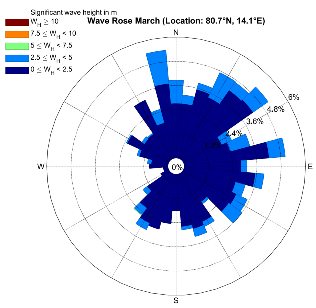

Significant wave height in m
$W_H \geq 10$
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose April (Location: 77.6°N, -2.0°E)

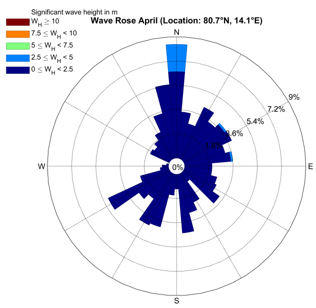

Significant wave height in m
$W_H \geq 10$
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose March (Location: 78.8°N, 2.0°E)


Significant wave height in m
$W_H \geq 10$
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose April (Location: 78.8°N, 2.0°E)


Significant wave height in m
$W_H \geq 10$
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose March (Location: 79.9°N, 7.0°E)


Significant wave height in m
$W_H \geq 10$
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose April (Location: 79.9°N, 7.0°E)


Significant wave height in m
$W_H \geq 10$
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose March (Location: 80.7°N, 14.1°E)


Significant wave height in m
$W_H \geq 10$
$7.5 \leq W_H < 10$
$5 \leq W_H < 7.5$
$2.5 \leq W_H < 5$
$0 \leq W_H < 2.5$
Wave Rose April (Location: 80.7°N, 14.1°E)

E

AHP experts list

During the Analytic Hierarchy Process the following people have participated to the survey in order to compare the different hight level concepts proposed:

- **Kaj Antero Riska** - Naval architect with very broad expertise in Ice and Arctic Technology
- **Jeroen Honvig** - Researcher in the fields of Offshore Engineering, Arctic Technology and Wave Mechanics
- **Herman Sips** - Chairmen of the Ice Whale Foundation and initiator of the project
- **Harald Rugebregt** - Project Manager of this design for Conoship
- **Joan van den Akker** - Naval Architect working on this design for Conoship
- **Wim Jolles** - Naval Architect with field experience in Ice Management and consultant for Arctic Technology Projects

F

Satellite Route

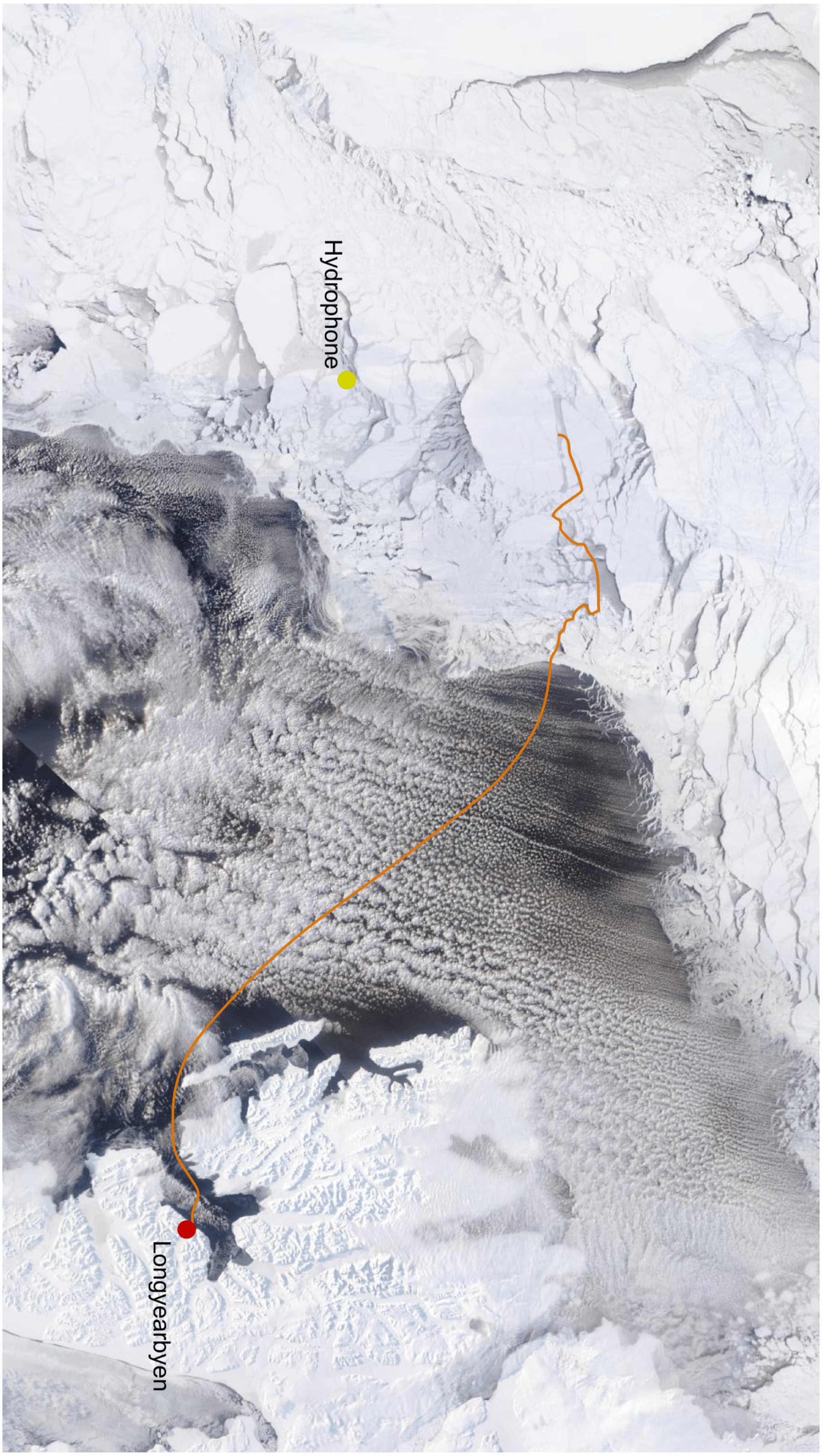


Figure F.1: A possible route to reach a berthing at an ice floe in the research location starting from the port of Longyearbyen. To give an idea of the distances the North-South size of the reached ice floe is around 40 km. Satellite image courtesy of the NASA Moderate-resolution Imaging Spectroradiometer (MODIS).)

Figure F.2: Same image of figure F.1, but zoomed on the ice channel navigation sector. To give an idea of the distances the North-South size of the reached ice floe is around 40 km. Satellite image courtesy of the NASA Moderate-resolution Imaging Spectroradiometer (MODIS).

G

ISO19906 Loading Components

In this appendix are presented the formulae for calculating all the loads components presented in chapter 6. All of them have been collected from ISO19906 (ISO, 2010).

The breaking load H_B can be found as:

$$H_B = 0,68\xi\sigma_f\left(\frac{\rho_w g h_i^5}{E}\right)^{0,25} \cdot \left(w + \frac{\pi^2 L_c}{4}\right) \tag{G.1}$$

Where L_c is:

$$L_c = \left(\frac{E h_i^3}{12\rho_w g\,(1 - \nu^2)}\right)^{1/4} \tag{G.2}$$

H_P, the load component required to push the ice sheet through the ice rubble, can be calculated as:

$$H_P = w h_r^2 \mu_i \rho_i g\,(1 - e)\left(1 - \frac{\tan\theta_r}{\tan\alpha}\right)^2 \cdot \frac{1}{2\tan\theta_r} \tag{G.3}$$

The load to push the ice blocks up the slope through the ice rubble H_R is:

$$H_R = wP\frac{1}{\cos\alpha - \mu\sin\alpha} \tag{G.4}$$

Where P is:

$$\begin{aligned} P = {} & 0,5\mu_i(\mu_i + \mu)\rho_i g\,(1 - e)\,h_r^2\sin\alpha \cdot \left(\frac{1}{\tan\theta_r} - \frac{1}{\tan\alpha}\right)\left(1 - \frac{\tan\theta_r}{\tan\alpha}\right) + \\ & + 0,5(\mu_i + \mu)\rho_i g(1 - e)h_r^2\frac{\cos\alpha}{\tan\alpha}\left(1 - \frac{\tan\theta_r}{\tan\alpha}\right) + h_r h_i \rho_i g\frac{\sin\alpha + \mu\cos\alpha}{\sin\alpha} \end{aligned} \tag{G.5}$$

Lastly, the load H_L required to lift the ice rubble on top of the advancing ice sheet prior to breaking it can be calculated as:

$$\begin{aligned} H_L = {} & 0,5wh_r^2\rho_i g\,(1 - e)\,\xi\left(\frac{1}{\tan\theta_r} - \frac{1}{\tan\alpha}\right)\left(1 - \frac{\tan\theta_r}{\tan\alpha}\right) + \\ & + 0,5wh_r^2\rho_i g\,(1 - e)\,\xi\tan\phi_r\left(1 - \frac{\tan\theta_r}{\tan\alpha}\right)^2 + \xi c w h_r\left(1 - \frac{\tan\theta_r}{\tan\alpha}\right) \end{aligned} \tag{G.6}$$

H

Ice Resistance Calculation Methods

H.1. Lindqvist

The first method applied is Lindqvist (1989). This formulation is a linear regression based full scale tests in the Bay of Bothnia. The method divides the ice resistance in three components: crushing resistance R_C, bending resistance R_B and resistance due to submersion R_S.

These can be calculated using equations H.1, H.2 and H.3, respectively.

$$R_C = 0,5\sigma_f h_i^2 \frac{\tan\phi + \mu\frac{\cos\phi}{\cos\psi}}{1 - \mu\frac{\sin\phi}{\cos\psi}} \tag{H.1}$$

$$R_B = 0,003\sigma_f B h_i^{3/2} \frac{\tan\psi + \mu\frac{\cos\phi}{\sin\alpha_{we}\cos\psi}}{1 + \frac{1}{\cos\psi}} \tag{H.2}$$

$$R_S = (\rho_w - \rho_i)\, g h_i B \left\{ T\frac{B+T}{B+2T} + \mu\left[\left(0,7L_{wl} - \frac{T}{\tan\phi} - \frac{B}{4\tan\alpha_{we}}\right) + T\cos\phi\cos\psi\sqrt{\frac{1}{\sin\phi^2} + \frac{1}{\tan\alpha_{we}{}^2}}\right]\right\} \tag{H.3}$$

Where the ice characteristics are represented by h_i, σ_b and ρ_i, which are thickness, strength in bending and density respectively. The vessel hull characteristics are L_{wl}, B, T, ϕ, α_{we}, ψ and they represent waterline length, breadth, draught, stem angle, waterline entrance angle and flare angle. Furthermore, g is the gravity acceleration, ρ_w is the water density, μ is the hull-ice friction coefficient and v is the ship speed.
Then the total ice resistance can be determined using equation H.4.

$$R_i = (R_C + R_B)\cdot\left(1 + \frac{1,4v}{\sqrt{gh_i}}\right) + R_S\left(1 + \frac{9,4v}{\sqrt{gL_{wl}}}\right) \tag{H.4}$$

H.2. Riska

The second method applied is Riska et al. (1997). It is a modified version of Lindqvist (1989) and it uses empirical coefficients, which are based on full-scale tests with level ice in the Baltic Sea.
The total ice resistance R_i is a linear function of the speed v depending by the coefficients C_1 and C_2 (eq. H.5).

$$R_i = C_1 + C_2 v \tag{H.5}$$

Where the coefficients C_1 and C_2 can be determined using equations H.6 and H.7.

$$C_1 = f_i h_i B L_{par} \frac{1}{\frac{2T}{B} + 1} + (1 + 0,021\phi) \cdot \left(f_2 B h_i^2 + f_3 L_{bow} h_i^2 + f_4 L_{bow} h_i\right) \tag{H.6}$$

$$C_2 = (1 + 0,063\phi) \cdot \left(g_1 h_i^{3/2} + g_2 B h_i\right) + g_3 h_i \left(1 + 1,2\frac{T}{B}\right) \frac{B^2}{\sqrt{L}} \tag{H.7}$$

Where:

$f_1 = 0,23 kN/m^3$ $g_1 = 18,9 kN/(m/s \cdot m^{1,5})$

$f_2 = 4,58 kN/m^3$ $g_2 = 0,67 kN/m^3$

$f_3 = 1,47 kN/m^3$ $g_3 = 1,55 kN/m^3$

$f_4 = 0,29 kN/m^3$

And L_{par} and L_{bow} are the length of the parallel midbody at the waterline and the length of the foreship at the waterline.

I

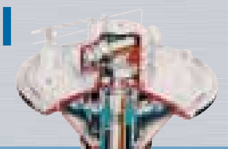
IBEEV Specification

In this Appendix is presented the brochure of the IBEEV, Icebreaking Emergency Evacuation Vessel. (source: schottel.de)

SCHOTTEL for the Shipping World

Ice Breaking Emergency Evacuation Vessel

IBEEV 1-4



Technical Data

Owner:	AGIP KCO, Kazakhstan
Designer:	Naval Engineering & Design Ltd., Poland
Shipyard:	Gdansk Shiprepair Yard Remontowa SA, Poland
Commissioned:	2 vessels in September 2006, 2 in March 2007
Power:	diesel-electric, 2 x 800 kW / 1500 r.p.m. each
Main propulsion:	2 x SCHOTTEL Rudderpropeller type SRP 550, 550 kW / 1500 r.p.m. each
Propeller diameter:	1400 mm
Steering:	SCHOTTEL Steering System type SST 900
Bollard pull:	11.5 t
Special features:	pull-propeller
Classification:	Det Norske Veritas ✠ 1A1 Ice-1B DAT (-30 °C)
Operation area:	Caspian Sea

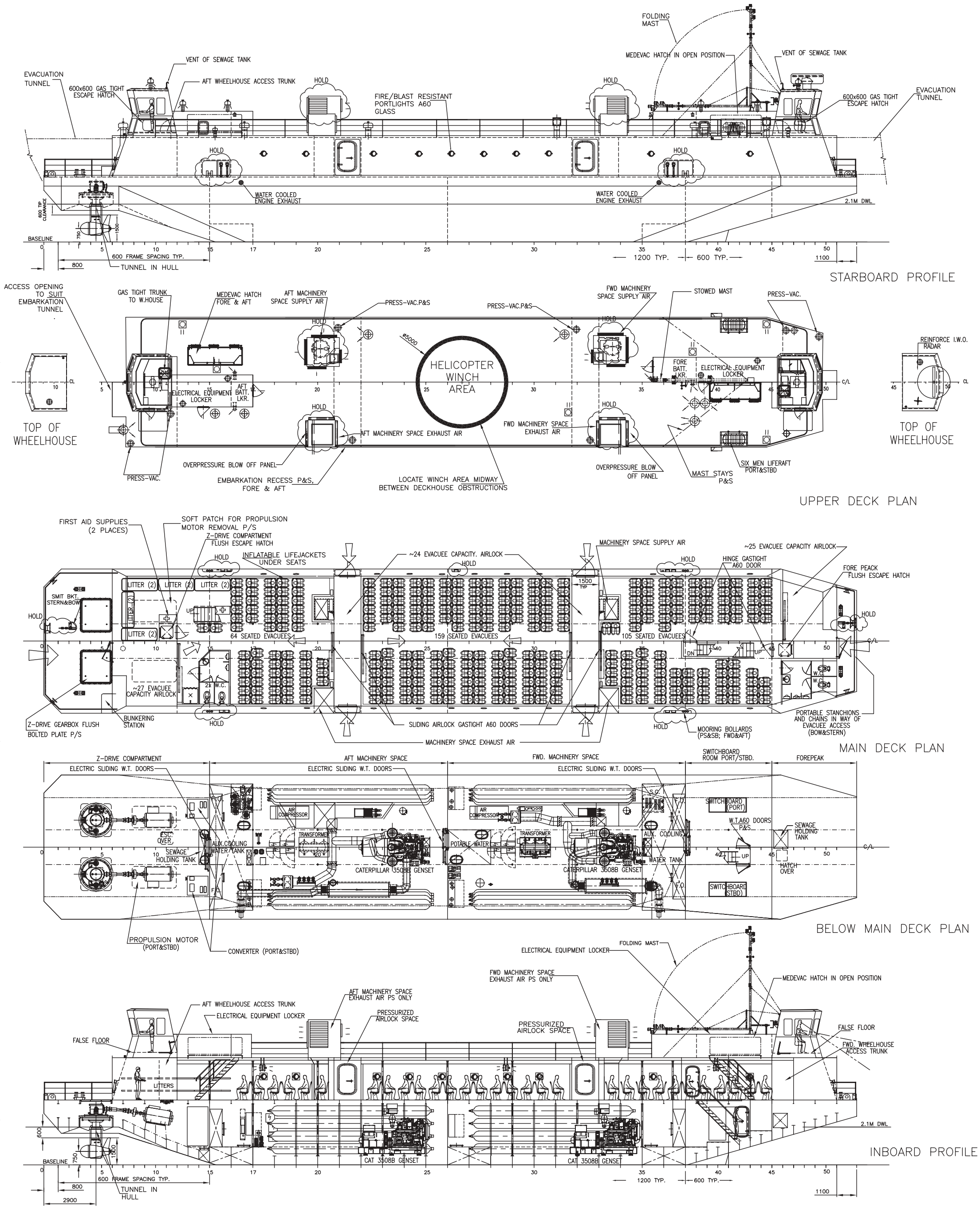
SCHOTTEL

Innovators in propulsion technology

Ice Breaking Emergency Evacuation Vessel
IBEEV 1-4

Main dimensions

Length overall:	45.10 m
Length pp:	42.34 m
Breadth overall:	8.00 m
Designed draught:	2.00 m



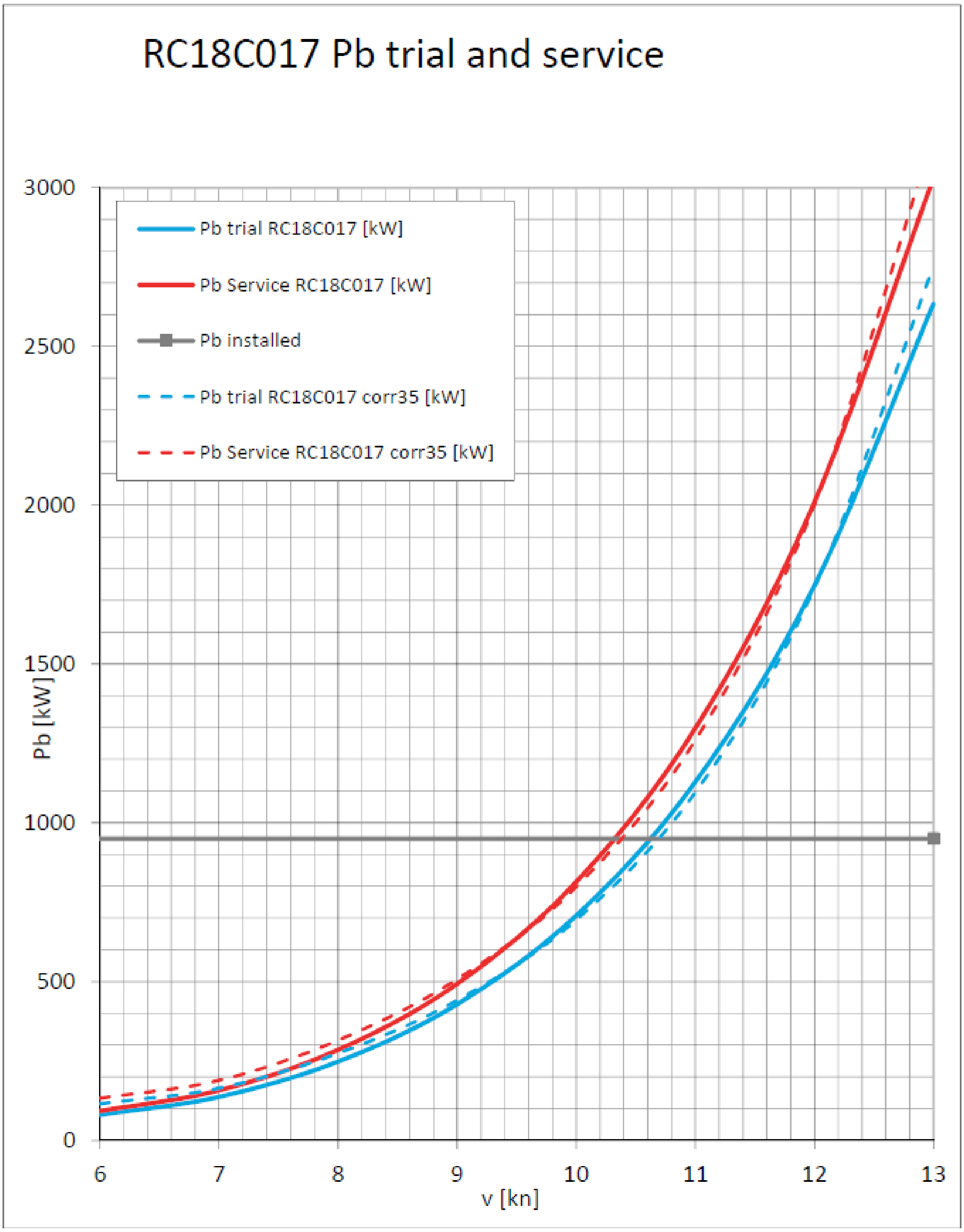
SCHOTTEL GmbH & Co. KG · Mainzer Str. 99 · D-56322 Spay/Germany
Tel.: + 49 (0) 26 28 / 6 10 · Fax: + 49 (0) 26 28 / 6 13 00 · eMail: info@schottel.de · www.schottel.de

J

Open Water Resistance

In this appendix is presented the brake power curve at trial and service conditions resultant from the Conoship open water resistance calculation. All graphs and calculations are produced by Conoship International.

The result used in the thesis is the maximum open water speed deliverable.


RC18C017 Pb trial and service
Pb trial RC18C017 [kW]
Pb Service RC18C017 [kW]
Pb installed
Pb trial RC18C017 corr35 [kW]
Pb Service RC18C017 corr35 [kW]
Pb [kW]
3000
2500
2000
1500
1000
500
0
6
7
8
9
10
11
12
13
v [kn]

K

Conoship Weight Estimation

The Weight Estimation presented in this appendix has been produced by Conoship International.

Subject: Light ship weight and stability

1.1 LSW

See table below.

Description	-	Total weight (incl. margin)
HULL AND SUPERSTRUCTURE (CONSTRUCTION)		292666.5kg
HULL AND SUPERSTRUCTURE (OUTFITTING & FOUNDATIONS)		23110.5kg
HULL AND SUPERSTRUCTURE (EQUIPMENT)		1050.0kg
PROPULSION AND MANOEUVRING SYSTEM		20697.6kg
SHIP SYSTEMS		20384.7kg
ELECTRICAL SYSTEM		18322.5kg
DECK MACHINERY, LIFESAVING AND FIRE PROTECTION		19724.25kg
RESEARCH SYSTEMS		0.0kg
ACCOMMODATION		35883.75kg
NAUTICAL, NAVIGATION AND COMMUNICATION EQUIPMENT		3150.0kg
	TOTAL	**434989.8**

Research systems is zero (not part of Light Ship weight). Our assumptions regarding the research equipment is a total of 30 tonnes distributed as follows:

Description	Part	Supplier	Quantity	Weight	Total weight
Accumulated weight guess			1	10000.0kg	10000.0kg
Lab containers (20 ft)			2	10000.0kg	20000.0kg

Other weights, when at maximum displacement (640 tonnes, T = 2.8 m):

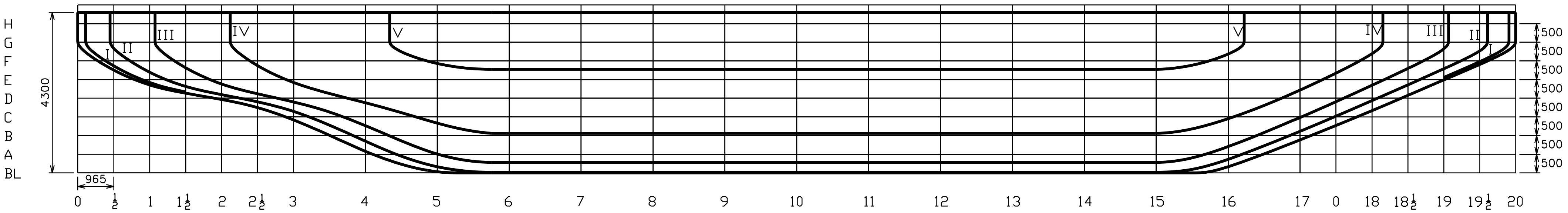
- Abt. 115 tonnes of fuel
- Abt. 25 tonnes of fresh water (max)
- Abt. 10 tonnes miscellaneous fluids (lube oil, bilge water etc.)
- Abt 25 tonnes of other weights (provisions, crew etc. as well as margin for an alternative research systems)

L

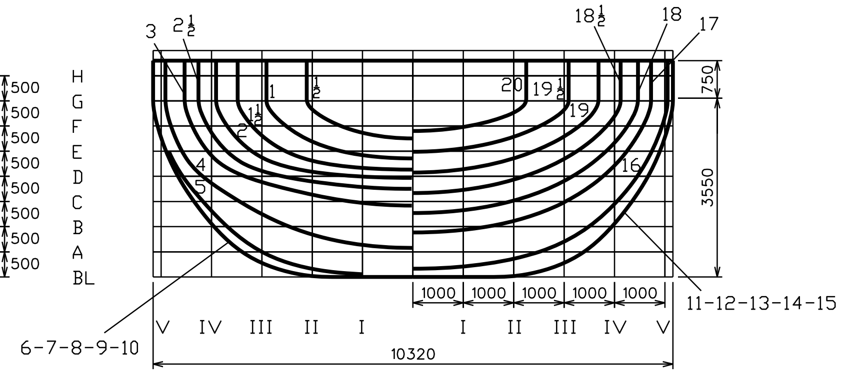
Linesplan

The Linesplan presented in this section has the main aim of showing the forms of the hull presented in this thesis. However, further studies regarding the hydrodynamic and the hull-propeller interaction effects are strongly recommended.

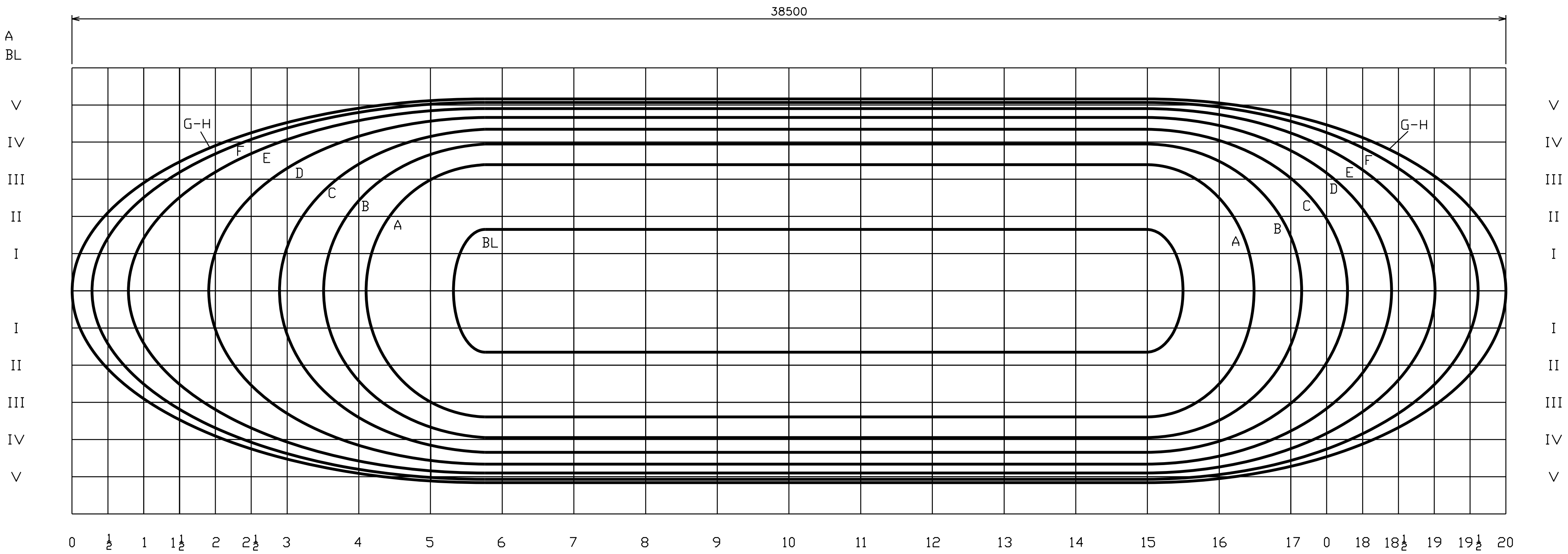
BUTTOCKS



STATIONS



WATERLINES



MAIN DIMENSIONS
L_{OA} = 38,5 m
L_{WL} = 36,5 m
B = 10 m
T = 2,8 m

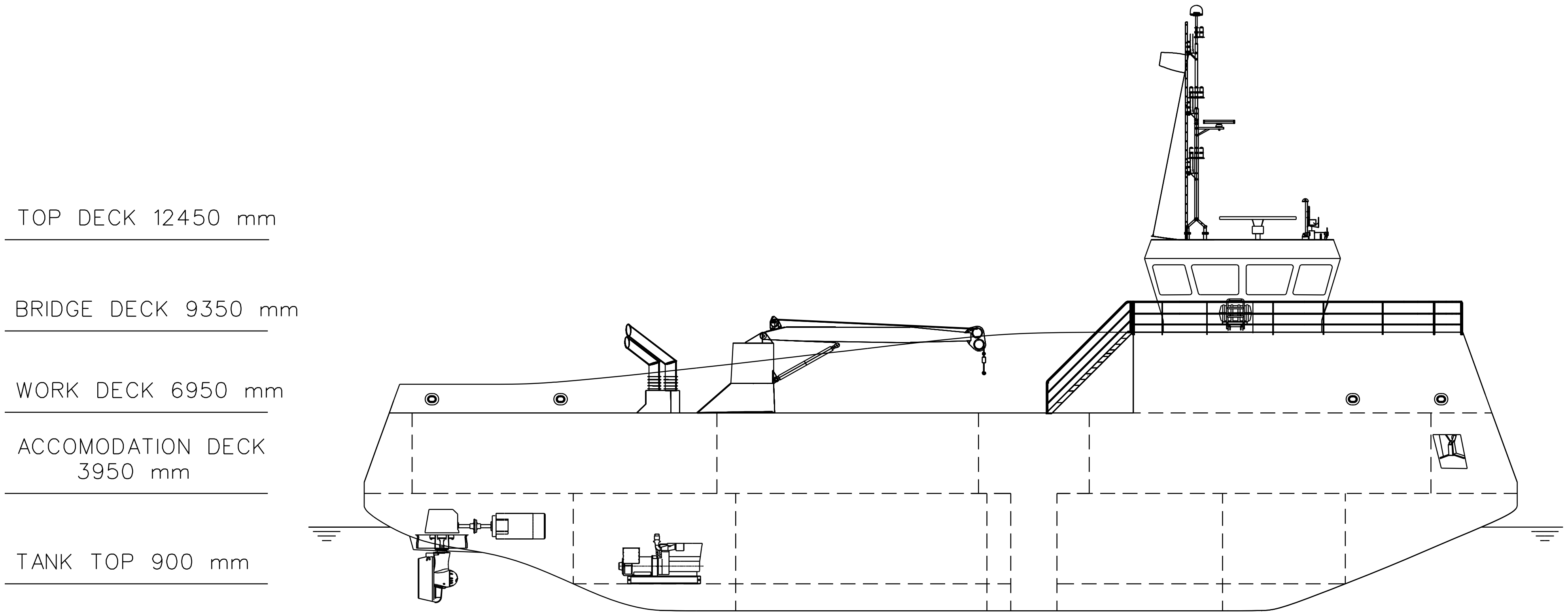
LINESPLAN

DELFT UNIVERSITY OF TECHNOLOGY	
MASTER THESIS MARINE TECHNOLOGY	
DRAWING LINESPLAN	
STUDENT LUIGI PORTUNATO	SCALE 1:150

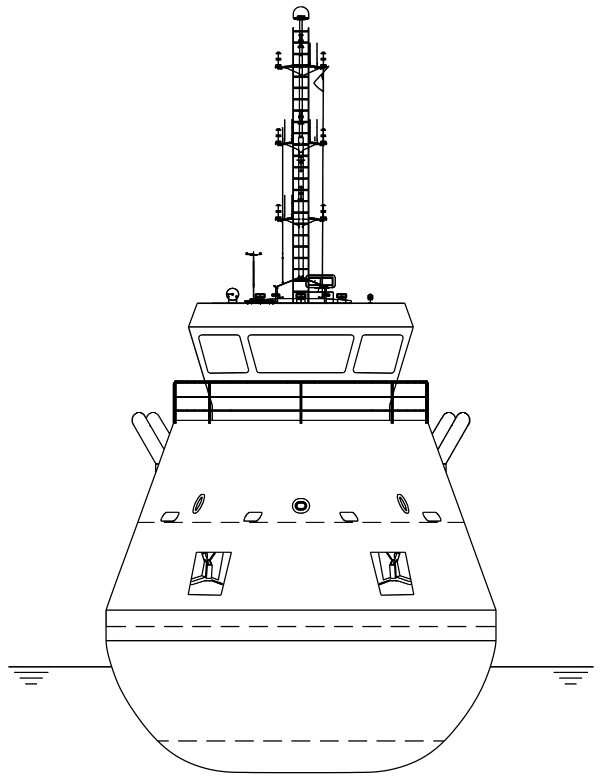
M

General Arrangement

In this appendix the General Arrangement of the vessel is presented. It is important to highlight that the main aim of this General Arrangement is to show a possible subdivision of the spaces in order to fulfil the Ice Whale Foundation requirements. However, not being one of the goals of this thesis, at this design stage it is not optimised yet and it is advised to further improve it in the future stages of this vessel design.



LONGITUDINAL VIEW



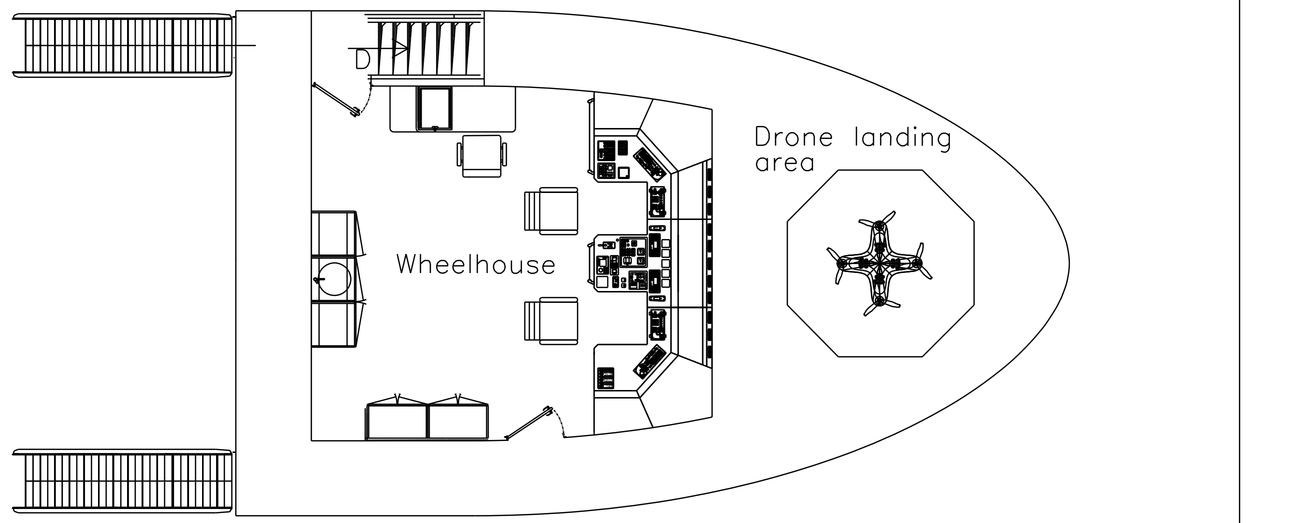
TRANSVERSAL VIEW

MAIN DIMENSIONS
L_{OA} = 38,5 m
L_{WL} = 36,5 m
B = 10 m
T = 2,8 m

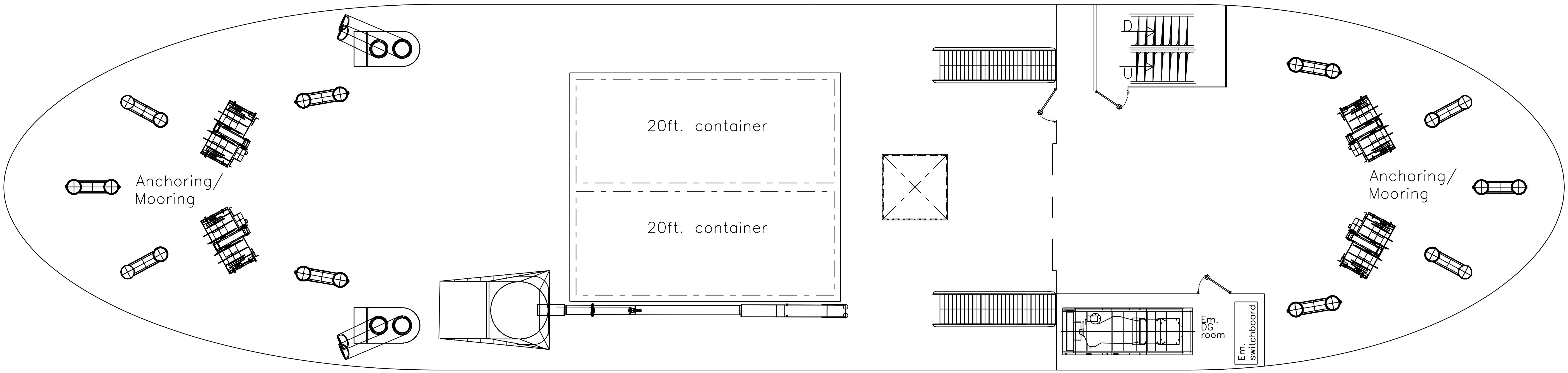
GENERAL ARRANGEMENT

LONGITUDINAL VIEW
TRANSVERSAL VIEW

DELFT UNIVERSITY OF TECHNOLOGY	
MASTER THESIS MARINE TECHNOLOGY	
DRAWING: GENERAL ARRANGEMENT	
STUDENT: LUIGI PORTUNATO	SCALE: 1:200



BRIDGE DECK



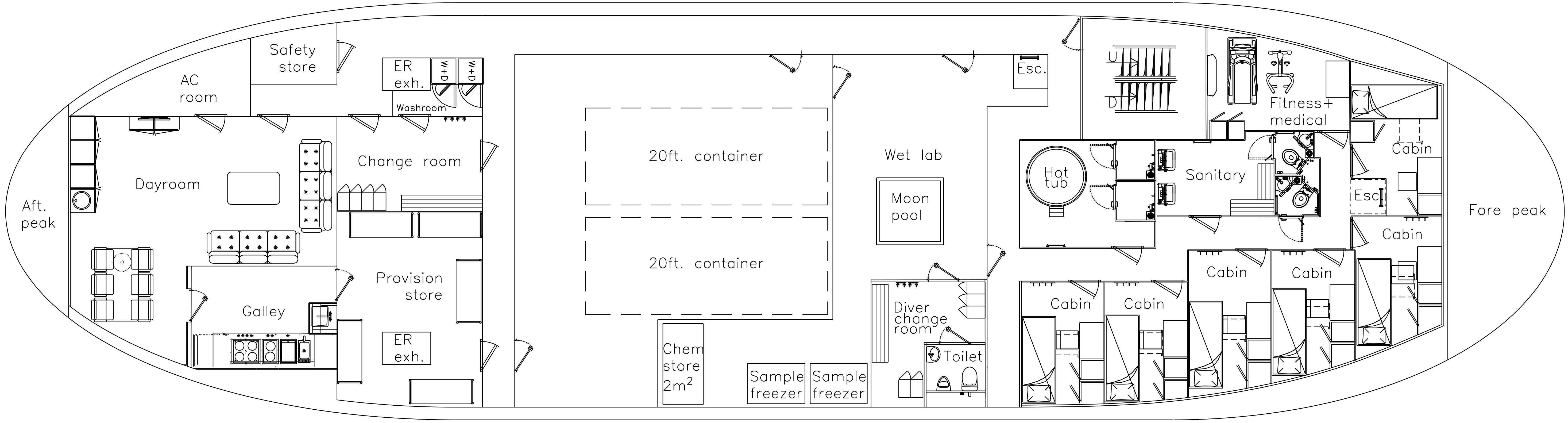
WORK DECK

MAIN DIMENSIONS
L_{OA} = 38,5 m
L_{WL} = 36,5 m
B = 10 m
T = 2,8 m

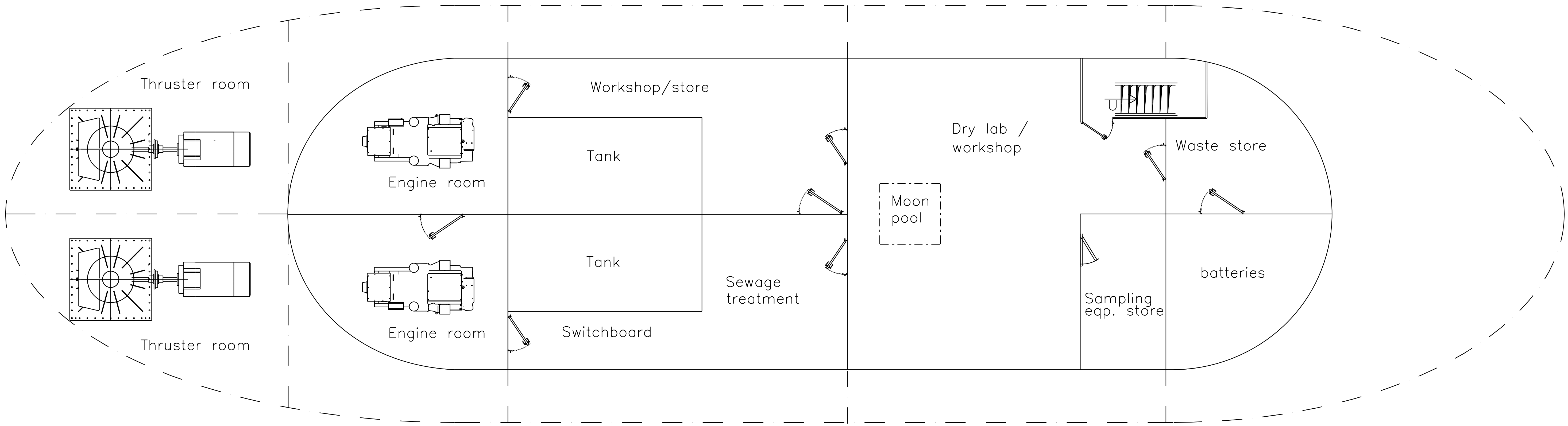
GENERAL ARRANGEMENT

BRIDGE DECK
WORK DECK

DELFT UNIVERSITY OF TECHNOLOGY	
MASTER THESIS MARINE TECHNOLOGY	
DRAWING GENERAL ARRANGEMENT	
STUDENT LUIGI PORTUNATO	SCALE 1:100



ACCOMODATION DECK



TANK TOP

MAIN DIMENSIONS
L_{OA} = 38,5 m
L_{WL} = 36,5 m
B = 10 m
T = 2,8 m

GENERAL ARRANGEMENT

ACCOMODATION DECK
TANK TOP

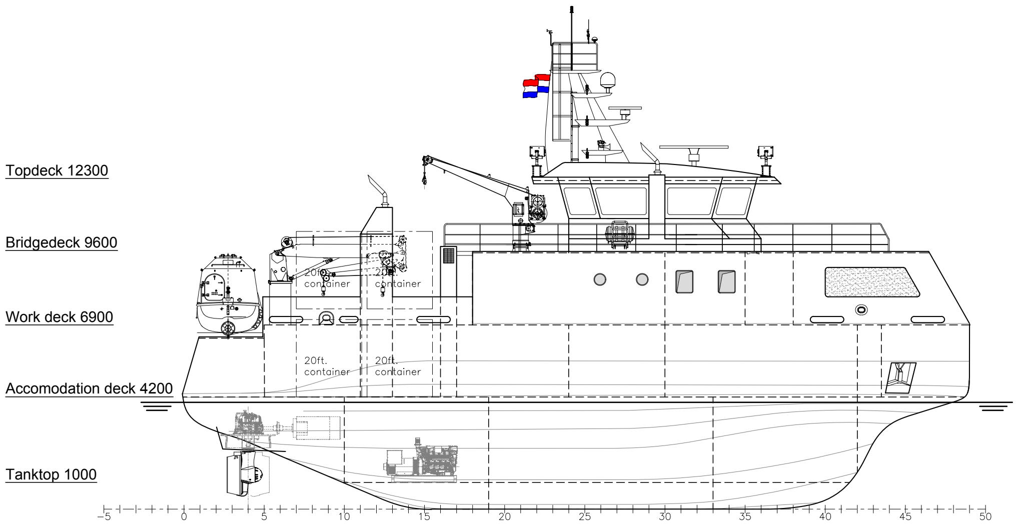
DELFT UNIVERSITY OF TECHNOLOGY	
MASTER THESIS MARINE TECHNOLOGY	
DRAWING: GENERAL ARRANGEMENT	
STUDENT: LUIGI PORTUNATO	SCALE: 1:100

N

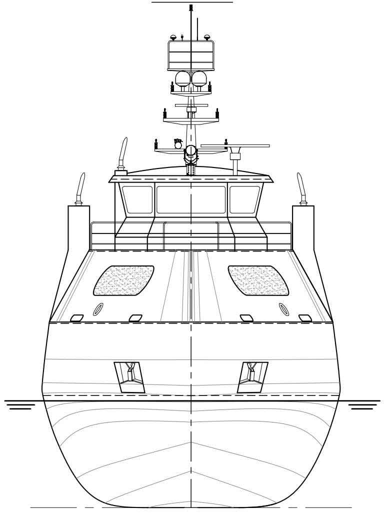
Conoship Vessel General Arrangement

The General Arrangement presented in this appendix has been produced by Conoship International.

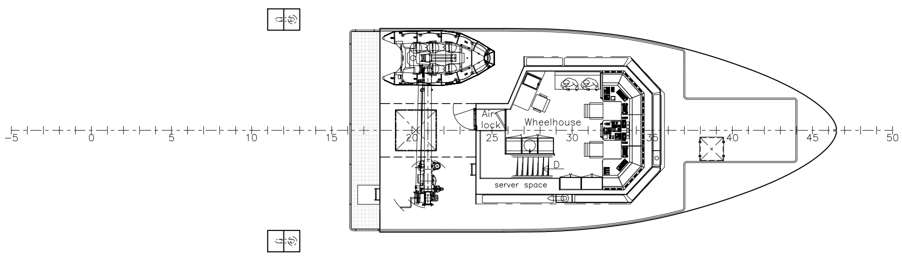
Profile



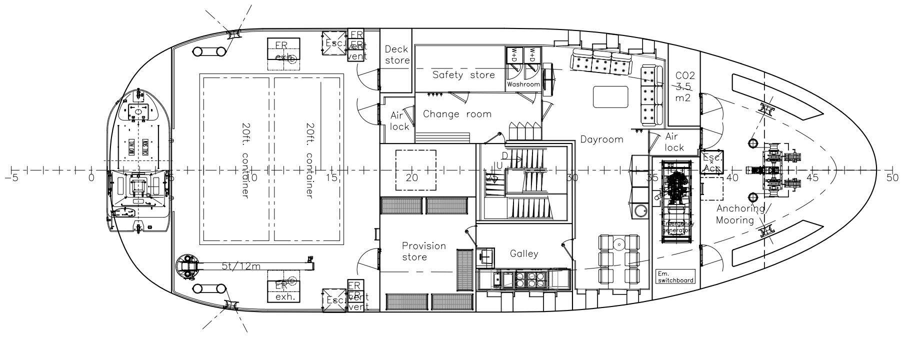
Frontview



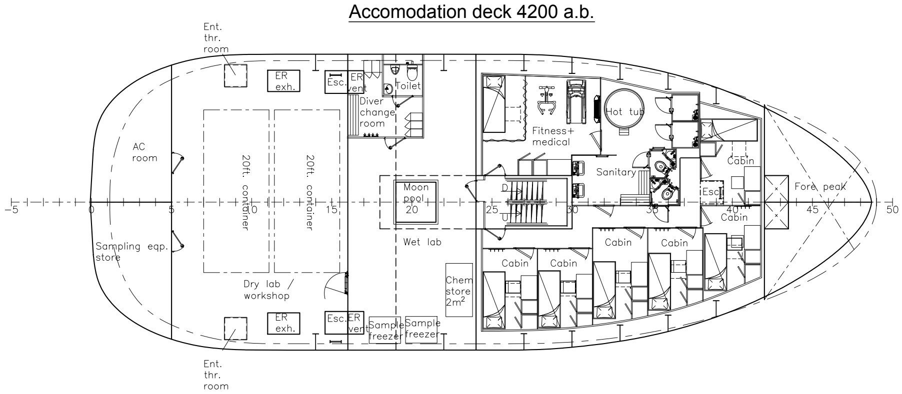
Bridgedeck 9600 a.b.



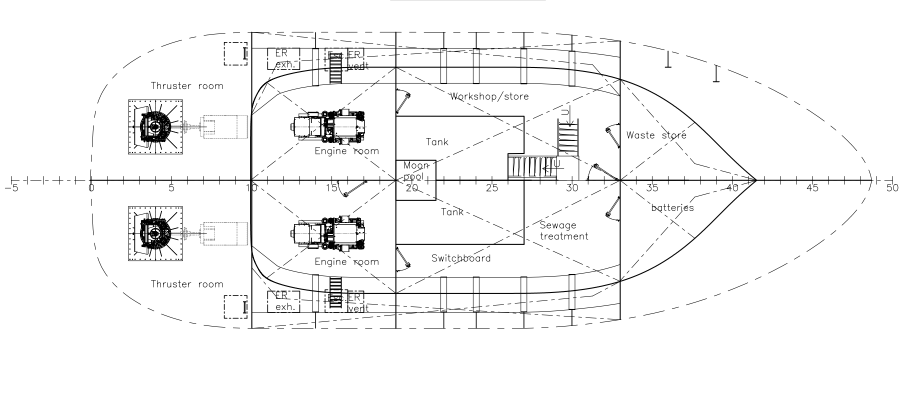
Workdeck 6900 a.b.



Accomodation deck 4200 a.b.



Tank top 1000 a.b.



MAIN PARTICULARS

Length over all	abt.	29.46 m
Length waterline	abt.	28.07 m
Length between perpendiculars		28.07 m
Breadth moulded		11.15 m
Depth moulded to maindeck		4.00 m
Draught	max.	3.80 m
GT	abt.	499 -

Ice Whale Foundation

NIOZ Sea Research

CONOSHIP INTERNATIONAL

DRAWING NO. RC18C017-001

DESCRIPTION: Concept General Arrangement

SCALE	SIZE:	YARD NO.	VERSION:	SHEET:
1:100	A1		00	1-1
DRAWN BY: HR	DATE: 06-08-2018	APPROVED BY:	DATE:	

O

Vessel Specification

Dimensions

Length Over All	28,5 m
Length at the Waterline	26,5 m
Draught	4,3 m
Breadth at Midship	2,8 m
Deck Area	250 m²

Propulsion System

Main Engines	Diesel-Electric
Propulsion Power	2x 600 kW
Azimuthing Thruster	2 x 475 kW FPP

Facilities

Crew	6
Moonpool	
Wet Lab	
Dry Lab	
Scientific Containers	2x (+2x on deck)
Drone Landing Deck	
Vehicles Garage	

Performances

OW Maximum Speed	10 kn
Ice Breaking (3kn)	50 cm
Ice Breaking (1kn)	70 cm
Endurance	110 days

CONOSHIP INTERNATIONAL TU Delft Delft University of Technology Ice Whale Foundation

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