Applying a Needs Analysis to promote Daughter Craft for year-round access to far-offshore wind turbines

A comparative assessment of the transfer phase

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SIEMENS Gamesa RENEWABLE ENERGY

Thesis to obtain the degree of MSc in Marine Technology in the specialisation of *Ship Design*

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By

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Performed at

Siemens Gamesa Renewable Energy

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Cover photo from STB 12 - the little offshore wind farm vessel I ESVAGT A/S (mynewsdesk.com)

Preface

With the apparent urgency to combat climate change, I am honoured to have contributed to a project that could promote the energy transition.

When I was looking for a graduation topic, the Covid-19 pandemic sure made me doubt whether I would be able to find a supervisor. So, first of all, I would like to thank my two daily supervisors. Austin Kana for offering me the topic and his time. I sincerely appreciated his guidance and feedback throughout this project. André Rinne for helping me better understand how the operations and maintenance of offshore wind farms are done. You were always willing to give more information than I bargained for. I would also like to thank Hans Hopman for being the chair of the thesis committee and for our interesting discussions during our meetings.

This project required extra hands on deck because the project involved quite some hydromechanics. That is why I would like to thank Henk de Koning Gans, Harleigh Seyffert and Jaap Gelling for their valuable insights.

I would also like to thank my colleagues at Siemens Gamesa. René Wigmans made me feel very welcome in his team and I sincerely appreciate his involvement during this project. Fernando Sanchez Santiago, Kenneth Coughlan and Jan Schroeter for their expertise and connections.

Last but not least, I'd like to thank those who were also closely involved on a personal level. My huisMantin for going through the graduation experience with me. Dad and Mirjam for keeping me sane. My friends, thanks for the laughs.

Sophia Brans
Rotterdam, March 2021

Summary

Offshore wind turbines need to be maintained to preserve their availability and to ensure continuous energy output. New wind farms are being installed relatively further away from shore to benefit from higher average and more stable wind forces and due to depleting locations nearshore. A disadvantage of these far-offshore locations is that they are characterised by adverse weather conditions. This challenges current maintenance strategies because, besides being further from shore, far-offshore wind turbines need more frequent maintenance and must be accessed in rougher weather conditions. Operations and maintenance operators have shifted from using refitted, multipurpose vessels to purpose-built Service Operation Vessels to carry out planned maintenance of far-offshore wind turbines, but they lack multitasking capabilities. Its daughter craft is a valuable asset for unplanned maintenance in the summer when it can operate safely, but it is often not deployable during the winter due to the rougher weather conditions.

The main goal of this thesis was to improve accessibility to (defective) far-offshore wind turbines. The main research question was: What are the deficiencies of current daughter craft, and how can these access vessels be modified to operate year-round at far-offshore wind farms?

It took a Systems Engineering approach to answer this question. This approach followed the steps of the Needs Analysis phase. Each daughter craft's seakeeping performance was analysed using Strip Theory.

The results show that the daughter craft's main deficiency lies in its current operational requirements; they do not match the conditions expected at the new operational areas. Performance in oblique waves is currently riskiest since that is when higher vertical accelerations can be expected, or a combination of vertical and lateral accelerations. Also, wave steepness has more effect on accelerations than wave height. However, there are refit solutions available for existing daughter craft to improve their seakeeping performance. Additionally, the daughter craft's relatively small size gives it a poor stability in a seaway. Future daughter craft designs should be focussed on stable seakeeping performance during transfers rather than during high-speed transits.

An analysis into the seakeeping performance of four prototype daughter craft showed that it is feasible to increase the transfer requirement from a significant wave height of $H_s \leq 1.5$ m to $2.0 \leq H_s \leq 2.5$ m. The analysis indicated that the catamaran type daughter craft have a high potential to realise year-round accessibility to far-offshore wind farms due to their improved performance in oblique waves conditions.

Lastly, it is believed that accessibility can be improved further if the wind turbine's access systems is modified to better facilitate the connection of the daughter craft during transfers. This solution is probably more suited for wind farms that are still in the development phase.

Contents

Abbreviations

ABC	Axe Bow Concept
B	Centre of Buoyancy
CoF	Centre of Flotation
CoG or G	Centre of Gravity
C1	Catamaran 1 (see section 6.4)
C2	Catamaran 2 (see section 6.4)
CTV	Crew Transfer Vessel
DC	Daughter Craft
ESC	Enlarged Ship Concept
FRC	Fast Rescue Craft
GA	General Arrangement
GHG	Greenhouse Gasses
GRP	Glass-reinforced Plastic
LCOE	Levelized Cost of Energy
M	Metacentre
MII	Motion Induced Interruptions
MSI	Motion Sickness Incidence
M1	Monohull 1 (see section 6.4)
M2	Monohull 2 (see section 6.4)
O&M	Operations and Maintenance
OPEX	Operational expenditures
RAO	Response Amplitude Operator
SATV	Service Accommodation and Transfer Vessel
SES	Surface Effect Ship
SOV	Service Operation Vessel
SWATH	Small Waterplane Area Twin Hull
DUT	Delft University of Technology
LCG	Longitudinal Centre of Gravity
VCG	Vertical Centre of Gravity
W2W	Walk-to-Work

List of symbols

b	Beam of demihull	[m]
c	Horizontal clearance between demihulls	[m]
d	Water depth	[m]
F_b	Bollard push force	[kN]
g	Gravity acceleration	[m/s^2]
GM	Metacentric height	[m]
GZ	Righting arm	[m]
H_s	Significant wave height	[m]
J_1	Normal force (in x-direction)	[kN]
J_3	Shear force (in z-direction)	[kN]
S (or κ)	Wave steepness	[-]
T	Draught	[m]
t	vertical clearance	[m]
T_p	(Peak) Period	[sec]
V	Ship speed	[knots] or [m/s]
z	Heave motion	[-]
α	Friction coefficient	[-]
Δ	Displacement	[tonnes]
ζ	Wave amplitude	[m]
θ	Pitch motion	[°]
λ	Wavelength	[m]
ν	Roll damping coefficient	[-]
ϕ	Roll motion	[°]
ω	Frequency	[rad/s]
ω_n	Natural frequency	[rad/s]
∇	Volume displacement	[m^3]

Glossary

Accessibility

The fraction of time in which safe access to wind turbines is achieved *(By Shafiee [1]).*

Angle of vanishing stability

The heeling angle when a righting arm diminishes to zero. After that point, the stability becomes negative and will cause a vessel to capsize.

Availability

The proportion of the time that a turbine, or the wind farm as a whole, is technically capable of producing electricity *(By Phillips et al. [2]).*

Bollard pull/push

The measure of a vessel's pulling power and is often associated with tugboats. In this case, interest lies in the ability to push onto the turbine's boat landing.

Broaching

The loss of directional control, which leads to an involuntary change in a ship's course.

Downtime

Antonym of *availability.*

Far-offshore wind farm

An offshore wind farm located at least 65 km from the coast and port. This term is used to distinguish offshore wind farms where offshore-based hubs are deemed the most economical (see section 4.1.1 for further elaboration).

Green water

A (large) quantity of water that is shipped onto a ship's deck as a result of large waves.

Golden hour

The period after an accident when medical treatment is critical and most likely to prevent death.

Habitability

The ship's ability to perform her mission with minimum discomfort to crew, passengers, and specialist staff *(By Stapersma et al.* [3]*).*

Heeling

When the ship is inclined by an external force, for example, by the action of waves and wind *(By Luhulima et al.[4]).*

Inaccessibility

Antonym of *accessibility.*

LCOE

The revenue required (from whatever source) to earn a rate of return on investment equal to the discount rate (also referred to as WACC) over the life of the wind farm *(By Hundleby & Freeman [5]).*

Nacelle

The housing for all of the power components at the top of the wind turbine.

Operability

The ship's ability to carry out her mission in all encountered weather conditions *(By Stapersma et al.* [3]*).*

Scheduled maintenance

Synonymous with calendar-based maintenance.

Survivability

The ship's ability to survive and stand extreme weather conditions, e.g. freak waves or ride of a storm and resulting dynamic loads *(By Stapersma et al.* [3]*).*

Troubleshooting

Synonymous with corrective maintenance and inspecting.

Weather window

The scope of weather conditions when (offshore) operations can be performed within acceptable limits.

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1 General introduction

Offshore wind energy is becoming a prominent contender for clean energy production. Since the technology is relatively new, it is prone to unforeseen problems, making maintenance a major factor of concern for wind farm operators. Although accessing and servicing offshore wind turbines is getting more complicated due to greater distances from the port and rougher weather conditions, these obstacles can be overcome by implementing specialised Operations and Maintenance (O&M) vessels. In short, this thesis aims to improve the design of these O&M vessels and their interfaces to overcome the rougher weather conditions observed at far-offshore wind farms.

This chapter provides relevant background information (section 1.1), the problem definition, goal and questions involved (section 1.2), the applied methodology (section 1.3), its relevance (section 1.4), the scope (section 1.5) and the report outline (section 1.6).

1.1 Background information

Wind turbines are a great alternative to clean energy production

With the known negative effects linked to the use of fossil fuels, it is becoming increasingly more important to switch to clean energy. Among many alternatives, wind farms are one of the most environmentally feasible solutions to reduce greenhouse gasses (GHG). According to a lifecycle assessment by Guezuraga et al. [6], this especially holds when the entire lifecycle of wind turbines is compared to other renewable energy sources. Figure 1-1 by Schlömer et al. [7] puts this into perspective.

Options	Direct emissions	Infrastructure & supply chain emissions	Biogenic CO_2 emissions and albedo effect	Methane emissions	Lifecycle emissions (incl. albedo effect)
	Min/Median/Max	Typical values			Min/Median/Max
Currently Commercially Available Technologies					
Coal—PC	670/760/870	*9.6*	*0*	*47*	**740/820/910**
Gas—Combined Cycle	350/370/490	*1.6*	*0*	*91*	**410/490/650**
Biomass—cofiring	n.a. [ii]	–	–	–	**620/740/890** [iii]
Biomass—dedicated	n.a. [ii]	*210*	*27*	*0*	**130/230/420** [iv]
Geothermal	0	*45*	*0*	*0*	**6.0/38/79**
Hydropower	0	*19*	*0*	*88*	**1.0/24/2200**
Nuclear	0	*18*	*0*	*0*	**3.7/12/110**
Concentrated Solar Power	0	*29*	*0*	*0*	**8.8/27/63**
Solar PV—rooftop	0	*42*	*0*	*0*	**26/41/60**
Solar PV—utility	0	*66*	*0*	*0*	**18/48/180**
Wind onshore	0	*15*	*0*	*0*	**7.0/11/56**
Wind offshore	0	*17*	*0*	*0*	**8.0/12/35**
Pre-commercial Technologies					
CCS—Coal—Oxyfuel	14/76/110	*17*	*0*	*67*	**100/160/200**
CCS—Coal—PC	95/120/140	*28*	*0*	*68*	**190/220/250**
CCS—Coal—IGCC	100/120/150	*9.9*	*0*	*62*	**170/200/230**
CCS—Gas—Combined Cycle	30/57/98	*8.9*	*0*	*110*	**94/170/340**
Ocean	0	*17*	*0*	*0*	**5.6/17/28**

Notes:

[i] For a comprehensive discussion of methodological issues and underlying literature sources see Annex II, Section A.II.9.3. Note that input data are included in normal font type, output data resulting from data conversions are bolded, and intermediate outputs are italicized.

Figure 1-1: Emissions of selected electricity supply technologies (gCO2eq/kWh) [i] [7]

A more recent study by Wang et al. [8] determined that onshore wind turbines produce less than half as much GHG than offshore wind turbines during their total lifecycle, see Figure 1-2. The greatest difference in GHG production is linked to the transport and installation of offshore wind turbines. Compared to onshore wind farms, those offshore emit 126% more GHG because their foundations require more material. That is also why the 'dismantling and disposal' of offshore wind turbines emit 140% more GHG than onshore wind turbines.

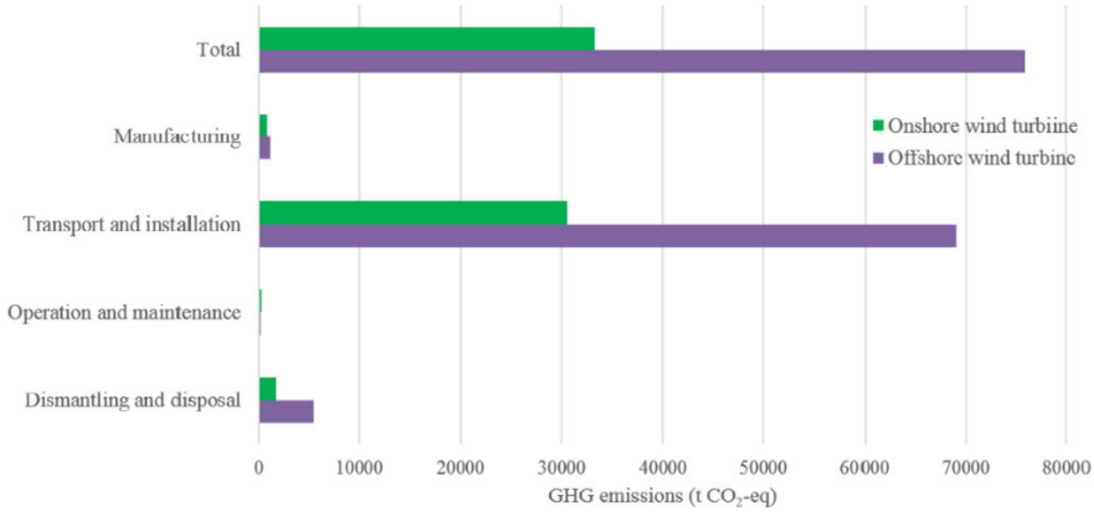

Figure 1-2: GHG emissions for onshore and offshore wind turbine [8]

In principle, wind farms located onshore are also cheaper than those offshore due to lower installation costs, cheaper foundations and less frequent maintenance. However, the advantage of offshore wind farms is that they generate a higher energy output due to more consistent and stronger winds. This gives them a higher potential to produce clean energy consistently. They also have limited visual pollution and economies of scale due to larger wind farm sizes [9].

Offshore turbines are moving farther from the shore

Walsh [10] reports that offshore wind farms in Europe are moving farther from shore, see Figure 1-3. It shows that the average distance to shore of offshore wind farms under construction in 2019 was 59 km, while in 2018, it was 35 km. This is because operators want to attain stronger and more stable wind resources and due to depleting locations nearshore.

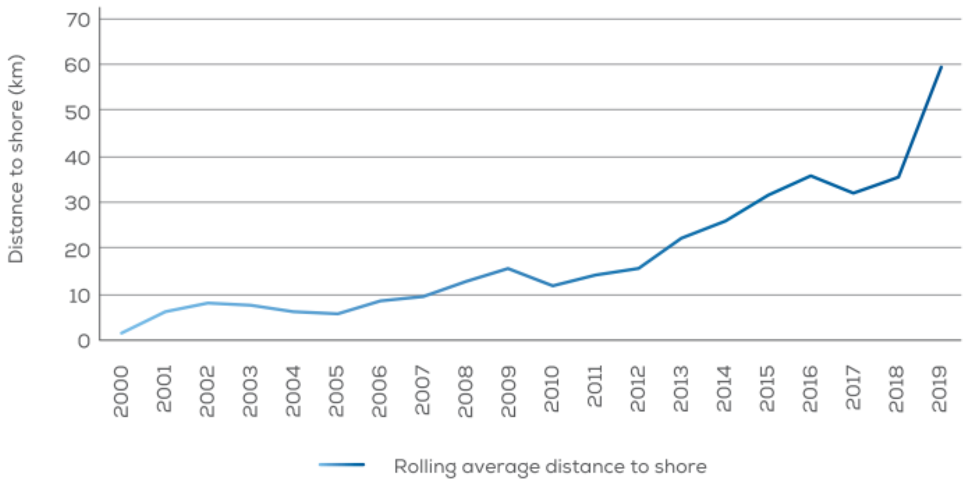

Figure 1-3: Rolling average distance to shore of online offshore wind farms in Europe [10]

Yet, this trend is making it more challenging and expensive for wind farm operators to provide continuous service. The harsh weather conditions that characterise these far-offshore locations require wind turbines to be maintained more frequently (than those situated onshore). But the weather and distance also makes accessing the turbine more complicated. As a result, Shafiee [11] describes that the availability of offshore wind farms is in the range of 60–70%, while for onshore wind farms, it is typically between 95% to 99%.

Maintenance costs can be minimised, provided that the operator has the right tools

A turbine must remain operational to generate revenue, which makes maintenance a crucial aspect to uphold. If not done properly, the downtime of a turbine will cause the wind farm owner to lose revenue, increasing the total costs of O&M. Figure 1-4 shows that excessive preventive maintenance can be expensive on its own, while insufficient preventive maintenance calls for more and expensive corrective maintenance. So, to keep maintenance costs low, operators must find the right balance between preventive (calendar-based) and corrective maintenance. Having the right equipment (e.g. O&M vessels) helps balance the costs and prevent (further) downtime.

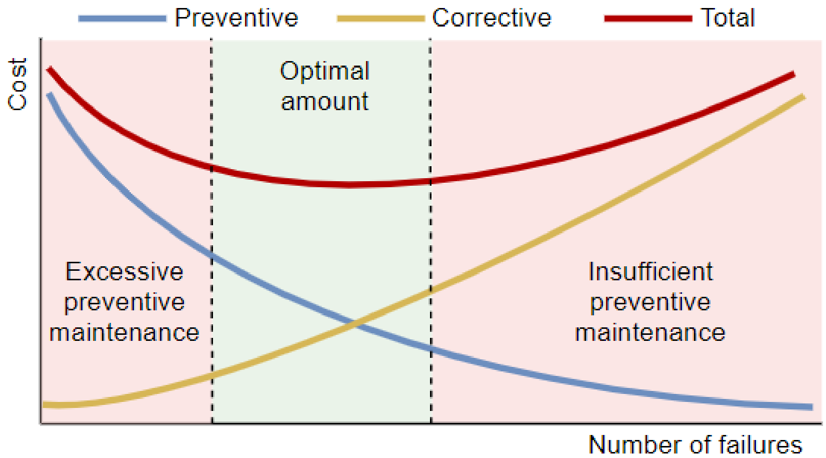

Figure 1-4: Balance between preventive and corrective maintenance (adapted from [12]*)*

1.2 Problem definition

The main adverse effect of the remoteness of far-offshore wind farms is the increased transit times from ports decreases the time available for maintenance tasks and causes fatigue in technicians. A common solution is to work from an offshore-based hub, such as a Service Operation Vessel (SOV). This vessel sails to and stays in the vicinity of the wind farm and can accommodate technicians overnight. This way, technicians are closer to the wind farm and can reach turbines within a smaller time frame, thus increasing turbine availability. However, SOVs are used primarily for calendar-based (preventive) maintenance. This minimises the need for unforeseen (corrective) maintenance but does not eliminate it. When an unforeseen event occurs, an SOV is often occupied and cannot reach the defective turbine fast enough. So, the problem is that **SOVs are not flexible enough to carry out corrective next to preventive maintenance, i.e. to service defective wind turbines next to scheduled turbines, which does not benefit wind farm availability**.

Other access vessels can assist in the event of unforeseen events by transporting technicians from the SOV or the shore. Examples include a daughter craft (DC) launched from an SOV, a Crew Transfer Vessel (CTV), and a helicopter. Yet, with farms moving farther from shore, each solution becomes impractical for reasons such as limited weather window, longer transit times and limited cargo capacity, making them less suitable to access defective far-offshore turbines. So, the second problem is that **the accessing capabilities of smaller vessels are insufficient for far-offshore wind farms**. If both problems persist, O&M operators will continuously not be able to repair a (sudden) turbine malfunction in time, leading to turbine downtime and revenue losses.

Concerning the ocean-going vessels, SOVs (and their gangways and cranes) and CTVs are continually upgraded to keep up with new developments in the offshore wind industry, while DCs are left behind and treated as an accessory. Thus, the hypothesis is that improving the DC's ability to access turbines shows great potential to maintain high wind turbine availability.

1.2.1 Goal

The overall goal of this study is to improve accessibility to (defective) far-offshore wind turbines. Based on the stated problems, (i) SOVs require new subsystems to increase their multitasking capability and (ii) the DC shows the most potential to do so. Hence, this study aims to confirm that the DC is the system-of-interest based on its capabilities and deficiencies and determine what is required to resolve them. The objectives are:

1. Confirm the need to improve turbine accessibility.
2. Understand how maintenance is currently carried out and how state-of-the-art vessels fit into the picture.
3. Describe the problems associated with wind farms situated farther offshore and establish which gaps need to be filled.
4. Link the problems to system features and establish how these can be improved.
5. Define designs and concepts that can potentially solve the defined problems.
6. Validate that the found solutions contribute to improving turbine accessibility.

1.2.2 Main question

This thesis's main question is **What are the deficiencies of current daughter craft, and how can these access vessels be modified to operate year-round at far-offshore wind farms?**

1.2.3 Sub-questions

The main question is solved by answering the sub-questions below, which correspond to the established objectives:

1. Why is there a need for offshore wind farms to move farther from shore, and who are the key stakeholders? (Chapter 2)
2. How are (other) state-of-the-art access vessels used in O&M of offshore wind farms? (Chapter 3)
3. What are the daughter craft's operational objectives when they are required to operate in areas farther from shore? (Chapter 4)
4. Which system functions are relevant to the desired objectives, and how do they perform in current and new environments? (Chapter 5)
5. How should these functions be modified or implemented in a new system considering system constraints? (Chapter 6)
6. How effective is a new system in improving access to far-offshore wind turbines? (Chapter 7)

1.3 Systems Engineering

This study takes a Systems Engineering approach by Kossiakoff et al. [13]. Specifically, the process of the *Needs Analysis* phase. It is the first of three phases during Concept Development, which is the first stage of the Systems Engineering lifecycle. This stage contains the necessary analysis and planning to establish the need for a new system, the feasibility of its realisation and the specific system architecture perceived to satisfy the user needs best [13]. Figure 1-5 displays all the stages and phases included in a system's engineering lifecycle. It also highlights the location of the applied stage and phase for this study. The two remaining phases within Concept Development are excluded because, as clients to vessel suppliers, O&M operators only need a set of operational requirements that properly fit their needs. The activities involved in the later stages are considered more relevant for the vessel supplier. Consequently, the two remaining stages are also excluded.

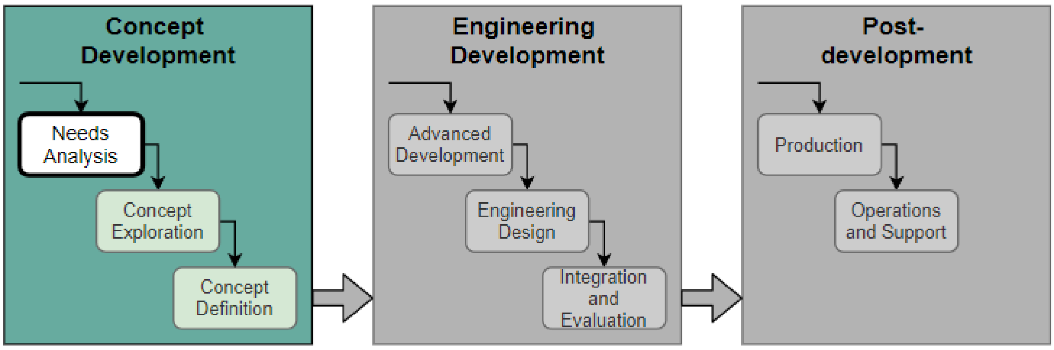

Figure 1-5: Systems engineering lifecycle model (Adapted from [13])

1.3.1 Needs Analysis phase

Figure 1-6 shows the four steps that constitute the Needs Analysis phase and several inputs and outputs that flow throughout. The first inputs indicate that the development of a system could be deficiency-driven or technology-driven. In this case, each existing system is deficiency-driven due to its lack of performance in new operational areas, discussed in section 4.2.4. The steps in the Needs Analysis phase are characterised as follows:

- Operations Analysis – Defines the deficiencies in current systems and operational objectives of the new system, which are the primary product of this phase. The objectives are decomposed into a set of primary and secondary objectives. This will clearly state the system's purpose and tasks.
- Functional Analysis – Translates operational objectives to determine the system's functional and performance requirements. Then it will be clear what type of system is needed to meet the objectives. In other words, this step aims to make a case for the feasibility of the system's development by relating it to elements of existing systems.
- Feasibility Definition – Addresses the physical implementation. This step uses the output from the previous activities to deliver the initial operational and physical requirements. So, it will describe the system's basic characteristics while considering any technical or cost constraints.
- Needs Validation – Examines the validity of the results from the previous activities. It ultimately delivers the operational validation criteria to determine the system's usefulness and feasibility in terms of cost and risk.

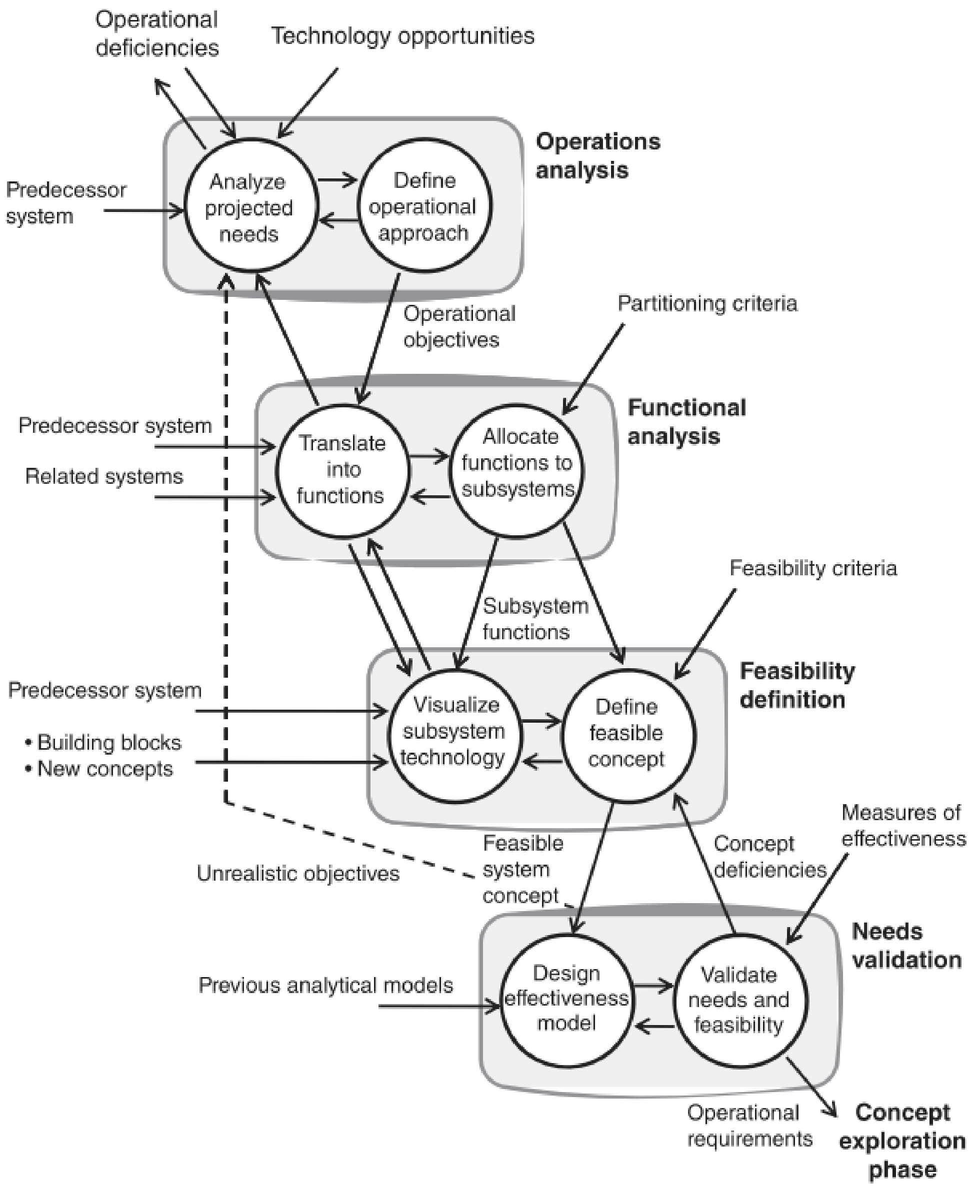

Figure 1-6: Division of the Needs analysis phase within the Systems Engineering approach [13]

1.4 The scientific and societal relevance

What makes this study unique is that it is the only report that focusses on the development of a DC and treats it as its own system within the system-of-systems (i.e. O&M and the SOV). It does so by applying Systems Engineering to determine the operational requirements at a high level of detail. At the end of the Needs Analysis phase, there are still many uncertainties, meaning that the program risk is still high. Nevertheless, it at least reduces the risk of embarking on the development of a system that does not address vital operational needs [13]. So, this study's results will present a solid basis for further development.

This study is also relevant to society since it promotes the transition to clean energy. This is because improving the DC's ability to access wind turbines will indirectly increase the turbine's availability. In turn, financial risks are reduced, and clean energy could become more affordable. On another note, it could also stimulate the use of hydrogen-powered machines since hydrogen can be produced (nearly) emission-free through renewable power rather than fossil fuels; this is currently being endeavoured by Ørsted [14].

1.5 Study scope

The scope of this study is bound to the following points:

- **Access to far-offshore wind turbines in the North Sea:** That is where most of the offshore wind turbines are currently located.
- **Wind farms in the O&M phase:** To demarcate the type of vessels being researched. Vessels necessary during wind farm development, commissioning and decommissioning are excluded.

1.6 Report outline

Chapter 2 covers the validity of the need to upgrade O&M vessels for far-offshore wind farms. First, it explains that wind farms are moving farther from shore because investors are pursuing stronger and more stable winds to run wind farms at a competitive price. The next section breaks down the costs involved in offshore wind farm O&M. The last section covers the industrial relevance of this study by discussing stakeholders' interests and conflicts.

Chapter 3 clarifies current methods and aspects in offshore O&M. Specifically, it explains fundamental terms and examines their characteristics and use, and previous research invested in state-of-the-art vessels applied for offshore wind farm O&M.

Chapter 4 discusses the operations analysis. The first section settles on the operational areas, representing real locations where the SOV and DC are applied. The second section then describes the influential weather conditions associated with those areas. The third section covers the deficiencies in current service vessels. The fourth section concludes by justifying why redesigning the daughter craft or redefining their requirements has the highest potential to improve access to wind turbines. Most importantly, it proposes the first set of high-level operational objectives. Finally, the last section contains comments about this chapter's conclusion.

Chapter 5 covers the functional analysis. It focuses on the system function (the hull) related to the key operational objective given in the previous chapter. First, key terminology for seakeeping is clarified. The second section analyses hulls applied to vessels that make use of the boat landing to gain insight into the operability. The following two sections address ship responses that are expected during transit and transfer. The fifth section describes the method used to analyse the seakeeping performance, and the sixth section discusses the results. The last section discusses the main observations from these results.

Chapter 6 explains the feasibility definition. It starts with system constraints: the first section covers the physical constraints, while the second section discusses the applicability of safety and comfort constraints. The third section discusses feasible solutions that improve seakeeping and fit within the set of constraints. In the end, the last section proposes concepts that integrate the solutions.

Chapter 7 contains the needs validation. The first section compares the new concepts to a parent hull, using the same method applied in chapter 5. It displays which concepts worked best for various conditions. The chapter ends with various high-level solutions which can further decrease responses during transfers.

Chapter 8 concludes the thesis by answering the research questions from this chapter and provides recommendations for further research.

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2 The need to upgrade O&M vessels for far-offshore applications

Before the new system can be developed further, there must be a valid need for a new system. This chapter argues for the case by supporting a prominent trend in the offshore wind market (section 2.1), providing information related to O&M costs (section 2.2) and who the stakeholders are (section 2.3).

2.1 Offshore wind farms are moving farther away from the shore

Section 1.1 states that wind farms are moving farther from shore to pursue stronger and more stable winds and due to depleting locations near the shore. The practicality is supported by an assessment of resources by Hundleby & Freeman [5], where they determined the economically attractive potential of European offshore zones at the end of 2030. It was determined using technical potential capacity that can generate energy at or below a reference levelized cost of energy (LCOE) [5]. The reference was based on the expected electricity cost from a typical large Combined Cycle Gas Turbine Plant. Additional costs to integrate the wind farm's energy into the grid were included as well, amounting to an estimated LCOE of €65 / MWh.

Figure 2-1 displays which areas in the European sea basins in the North Sea hold economically attractive potential. The upside scenario differs from the baseline scenario as it makes optimistic assumptions regarding technological and political developments. The upside scenario clearly shows that energy could be generated farther from shore at the same competitive price, which will be necessary when locations closer to shore are depleted. The LCOE is comprised of expected costs for, among others, operational expenditures (OPEX). The next section elaborates on how the OPEX is comprised.

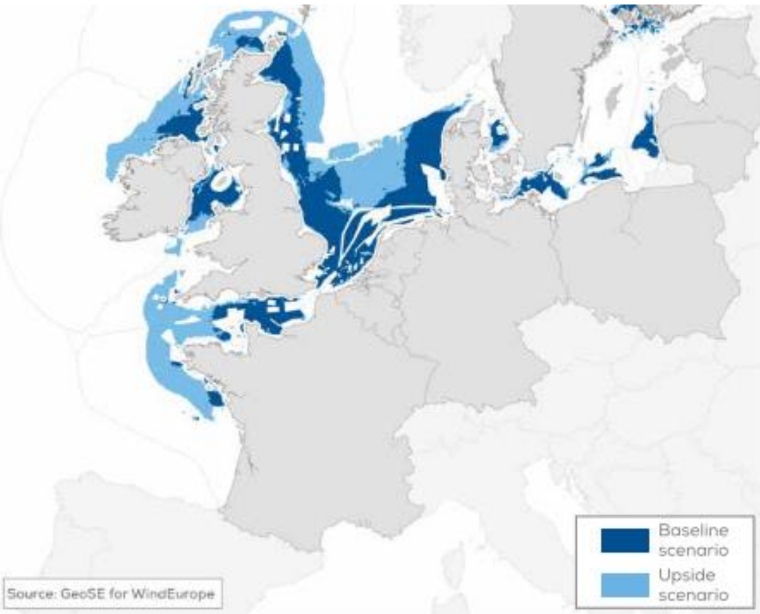

Figure 2-1: Wind farm areas delivering the economically attractive potential at or below an LCOE of €65/MWh under the baseline and upside scenarios at the end of 2030 [5]

2.2 Costs of Operations and Maintenance

Operations and Maintenance (O&M) of offshore wind currently accounts for at least 20% of the total lifecycle costs [15]. When looking at costs during operational expenditures (OPEX), O&M accounts for approximately 53% of the costs [16]; see Figure 2-2.

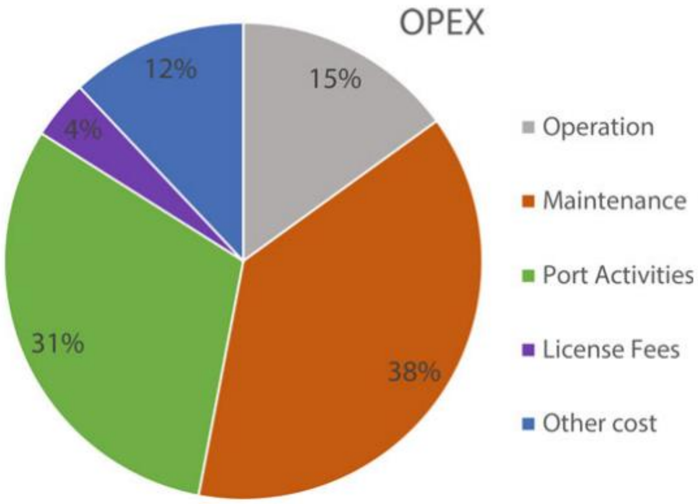

Figure 2-2: Breakdown of OPEX of an offshore wind farm [17]

Offshore operations are the daily activities concerned with managing the offshore wind farm, which includes but are not limited to asset monitoring, sales, marketing, administration ([2]), managing the supply chain, coordinating daily routines and setting up proper maintenance strategies. Operations account for 15% of OPEX, while the largest portion (38%) of OPEX is linked to maintenance. There is much research that focusses on minimising maintenance costs, such as improving maintenance logistics ([1], [18]), weather forecasting ([19], [20]), or optimising the maintenance fleet ([21], [22], [23]). While operators do implement these strategies, unforeseen corrective maintenance still contributes up to 90% of O&M costs [24]; 30% of that is due to downtime and the subsequent revenue losses [25][1]; see Figure 2-3.

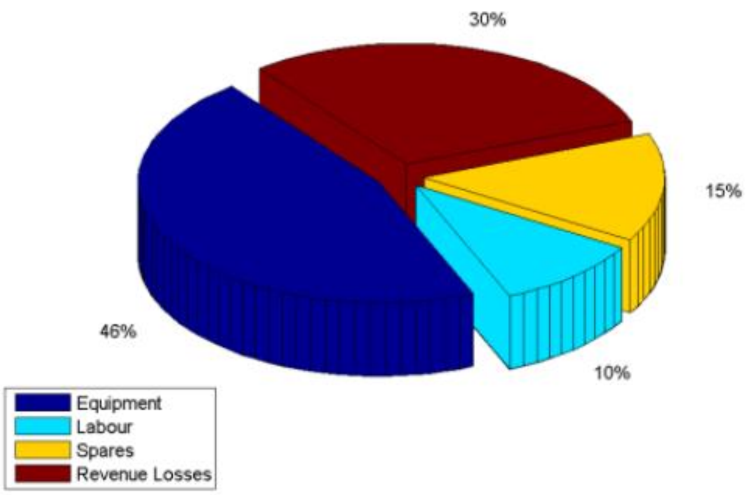

Figure 2-3: Breakdown of wind farm unplanned corrective maintenance costs [25]

[1] Based on a case study where a hypothetical wind farm was set up, located 120 km from the nearest port and consisting of 130 turbines

According to van de Pieterman et al. [25], the most substantial portions of unforeseen O&M costs are linked to equipment used for maintenance activities and revenue losses. Assets such as vessels (including cranes), helicopters, tools and safety gear all fall under equipment. Revenue losses are primarily due to turbine downtime as a result of unforeseen events and inaccessibility. Thus, enlarging the operating weather windows for accessing far offshore sites is a crucial driver for cost reductions in offshore wind [15]. However, new equipment may have higher charter rates due to potentially higher production costs and OPEX. However, the increased equipment costs must not outweigh the revenue gains.

2.3 Stakeholder interests and conflicts

Depending on their level of influence, stakeholders can play a significant role in establishing a valid need for a project. Ahsan et al. [26] mapped the stakeholders of O&M offshore wind farm operators and determined the extent of their power and interests. Specifically, they examined instrumental stakeholders who are described as "*key parties on whom a firm largely depends to run its business and who are influential as to whether the firm achieves its corporate goal".* In their case, the maintenance operator was considered as the "firm" since they are responsible for running the offshore wind farm. To analyse the influences of the operator's stakeholders, Ahsan et al. categorised each recognised party into the four groups shown in Figure 2-4; players, subjects, context setters and crowd. Players have high interest and high power to influence the project activities; subjects have high interest but low power; context setters have high power but low direct interest in the project; and the crowd consists of stakeholders with low interest and low power [26].

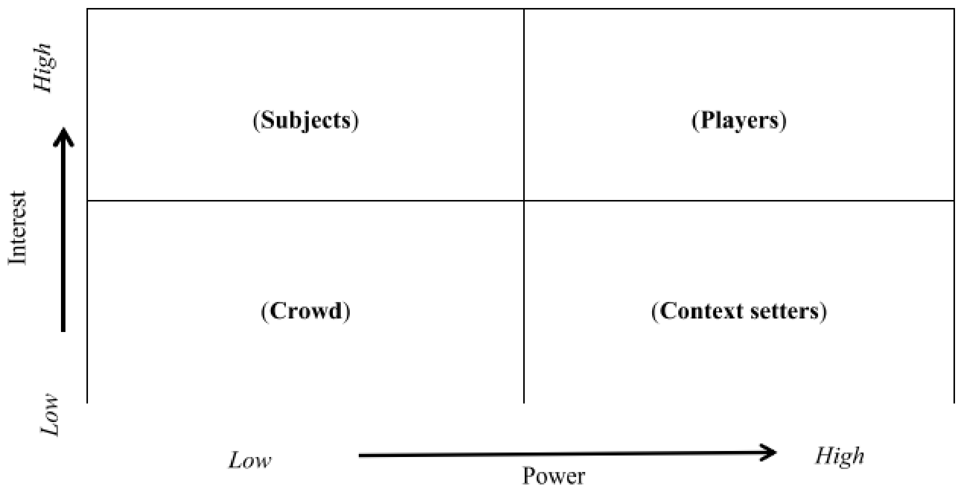

Figure 2-4: Stakeholder's power/interest matrix [26]

This section discusses the concerns and interests of the *players* Ahsan et al. recognised in O&M, displayed in Figure 2-5. Note that each stakeholder also has its own set of stakeholders but is not considered within scope. Moreover, Ahsan et al. identify the port facility as a player in offshore O&M. The reason is that operators must use port facilities to transfer turbine parts and technicians from onshore to offshore. The distance from the port to the offshore wind farm and the quality of facilities are key factors when selecting a port to ensure effective and efficient O&M activities [26]. However, it is not considered a stakeholder, in this case, because the DC is SOV-based and will hardly make use of port facilities. Admittedly, when an SOV goes back to port, they will use port facilities, and the port should be selected while considering the needs of the SOV rather than that of the DC.

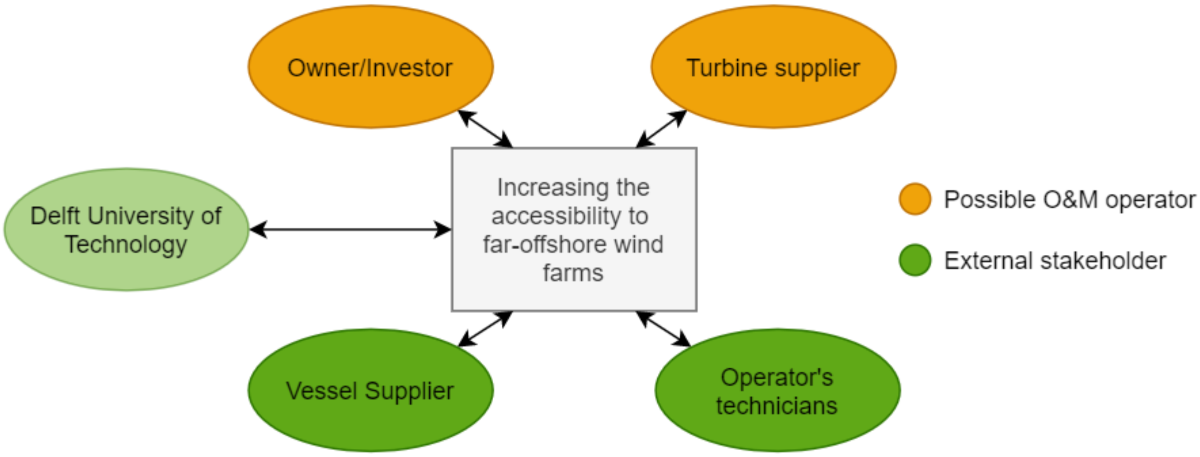

Figure 2-5: The stakeholders of increasing accessibility to far-offshore wind farms (adapted from [26]*)*

Figure 2-5 shows the relevant stakeholders for this project and the possible wind farm operators in orange. The O&M operator is not considered to be a stakeholder but an additional role that stakeholders may have, next to being a wind farm owner or the turbine supplier. The parties displayed in green are external stakeholders, which means they have interests other than O&M operators, some even conflicting. A more in-depth explanation of each stakeholder's involvement is given in the following sections. A summary of the interests and conflicts is given in Table 2-1 (section 2.3.7).

2.3.1 Wind farm owners and investors

Wind farm owners oversee all O&M strategies and drive offshore wind technology since they demand turbine suppliers to compete for turbines with the highest quality and output. After purchasing a new set of turbines, the owners can either carry out O&M independently or outsource it to the turbine supplier (typically offered in a warranty agreement) or another third-party company. When the owner intends to take over maintenance after the warranty period has ended, their technicians often perform maintenance alongside the turbine supplier's technicians to develop the required skills. In the event that O&M is outsourced, the owners are a key stakeholder of the hired O&M operator.

The interests of wind farm owners and investors lie in wanting to see high returns for their investments. It is presumed that, for example, based on reports showing the potential of wind far-offshore, they are contemplating the feasibility of such wind farms. As argued in section 2.2, the risk is that this type of wind farm requires more frequent maintenance, and it is relatively harder to provide that at offshore locations. If they do not have the right resources to provide the required maintenance, they will lose revenue. So, wind farm owners and investors will benefit from this study because it aims to find a tool that can help preserve the availability of far-offshore wind turbines, which minimises the risk of their investment.

With regards to ownership, an owner can choose to own a particular wind farm completely. It is also common for owners to invite investors to participate in an upcoming or ongoing project. The Dutch wind farm Gemini, for example, is now owned by Northland Power (60%), Siemens (20%), HVC (10%) (these companies were engaged since the development of the farm) and Alte Leipziger/Hallesche Investment Fund (10%) (acquired shares in 2018) [27].

2.3.2 Wind turbine suppliers

After an owner calls for the procurement of wind turbines for a new offshore wind farm, turbine suppliers compete with one another to win the contract. The contract terms typically include manufacturing, installation and O&M activities. The duration of the O&M's warranty is agreed upon by both parties, which could be for the farm's entire lifecycle or the first 3-5 years after installation. When the warranty period ends, and the turbine supplier is no longer the O&M operator, they become a key stakeholder of the subsequent O&M operator, which is then the wind farm owner. This is due to the exclusive experience and supply chain that the turbine supplier has.

It is also possible to split O&M activities among the owner and turbine supplier. Ørsted, an owner with the largest share of cumulative installed capacity (16%) at the end of 2019 [10], carries out their own O&M, but is sometimes supported by one of their turbine suppliers, such as Siemens Gamesa, for scheduled maintenance.

Research on key trends in offshore wind in Europe ([10]) reveals that Siemens Gamesa is currently the largest offshore wind turbine supplier with a share of 68.1% installed capacity. To put their performance into perspective, they are followed by MHI Vestas, who have a total installed capacity of 23.5%.

2.3.3 The additional role: O&M operator

The operator is the party that carries out O&M after the offshore wind turbines have been installed, making them (partly) financially responsible. Next to the manufacturing, turbines suppliers often include logistics and maintenance as service to a wind farm owner(s). They typically offer an O&M warranty for the first 3-5 years. In the case the wind farm owner accepts, the turbine supplier becomes the first operator. After the warranty expires, the turbine supplier can be rehired, or O&M is taken over by the owner's (third-party) technicians. In short, both the owner of a wind farm or a turbine supplier can be the O&M operator.

The owner and turbine supplier both have self-interests, which is minimising costs. As O&M operator, they become responsible for the O&M finances, for example, the cost of parts, technicians and vessel chartering. As shown in Figure 2-3, the two largest portions of the costs are associated with equipment and revenue losses, the latter of which is primarily due to turbine downtime caused by unforeseen events. Hence, additional interest is preserving turbine availability and ensuring the accessibility of defective wind turbines. They also seek suitable equipment to carry out maintenance for unforeseen events, which this study could provide. It is presumed that turbine operators currently take a conservative approach since the technology is relatively new. So, there is excessive preventive maintenance of the wind turbines. However, the untimely inability to reach turbines in time also causes the need for much corrective maintenance.

This study's solution could also reduce costs as it allows them to reduce the amount of preventive and corrective maintenance, see Figure 1-4. However, merely adding a new type of equipment to the operator's current armada is not a straightforward process. It must be integrated with external systems and be practical for technicians to use, for example. Also, while the increased capabilities of new/additional equipment may reduce revenue losses, the subsequent costs must not cancel out the gains.

2.3.4 Service technicians

An offshore wind farm owner may decide whether to carry out O&M themselves or have it outsourced to minimise costs. It also occurs that owners outsource specific tasks instead of total operational responsibility, such as major component changes or calendar-based maintenance. The alternatives include the turbine supplier or a third-party maintenance company. While the latter may not possess the same quality level as the turbine supplier, it could be a more cost-effective alternative. This does not imply that third-party companies are inferior since large turbine suppliers often hire third-party companies for specialised tasks.

In any case, the technicians are tasked with doing the necessary repairs and ultimately using the equipment. While an operator may wish to sail in all weather conditions, the technicians' safety and comfort must not be overlooked. Jupp et al. [28] state that the vessels must deliver high(er) levels of comfort in transit and zero-speed, along with improved safety during transfer operations. Therefore, there may be limitations concerning the practicality of vessel performance and capabilities. So, this project must consider how technicians will experience the vessel during operation.

2.3.5 Vessel suppliers

Wind farms placed offshore require vessels to carry out O&M. These vessels can be assigned with various tasks ranging from transportation of crew to storage of parts. Section 3.2 describes the different vessels applied for O&M of offshore wind farms.

Operators usually have no interest in owning a fleet because they wish to focus their attention on wind turbines and the maintenance required. So, vessels are often chartered from vessel suppliers. This reduces the cost as well since fleet maintenance is the responsibility of the vessel supplier. Well-known vessel suppliers include ESVAGT, Van Oord and Palfinger.

While the duration of charter contracts typically ranges between 3-5 years, vessel suppliers prefer more sustainable contracts for vessels with high investment costs such as SOVs [26]. Because of these long-term contracts, operators must charter the right vessel with the right capabilities for the right tasks. As a result, when large operators such as Ørsted or Siemens Gamesa request a type of vessel for any reason, it would be in a vessel supplier's best interest to provide them with the most suitable vessel. If a vessel supplier cannot deliver what the operators need, they will miss significant demand in the O&M market. Therefore, they must stay on top of what the needs of an O&M operator are with regard to far-offshore accessibility, which is what this study will provide.

2.3.6 Delft University of Technology

The Delft University of Technology (DUT) is included as an external stakeholder because there is an indirect interest in increasing the accessibility to far-offshore wind farms. The underlying interests are encouraging cleaner energy due to the depletion and adverse effects of fossil fuels. The DUT acknowledges and supports this need by supporting this study, which contributes by making defective far-offshore turbines more accessible and thus a more attractive and feasible venture for investors.

2.3.7 Summary of interests and conflicts

Table 2-1 shows an overview of the stakeholders' interests and conflicts. Note that there are more conflicts than what is given here, again since each stakeholder has their own set of stakeholders, which is out of scope.

Table 2-1: Overview of the stakeholders' interests and conflicts

Stakeholder	Primary interests	Conflicts with…
Owner/Investor	Moving farther offshore for higher output and returns, minimal risk	
Turbine supplier	Winning turbine contracts	
O&M Operator *(role may apply to owner/investor or turbine supplier)*	Preserving turbine availability, minimising costs, ensuring turbine accessibility	
Operator's technicians	Comfortable and safe working conditions	…operator: Lower and upper vessel performance is limited
Vessel supplier	Winning vessel chartering contracts	…operator: Engineering and building may come at a cost that operators are not willing to pay
Delft University of Technology	Encourage the transition to cleaner energy	

This report aims to improve the improve accessibility to (defective) far-offshore wind turbines. Since O&M operators are engaged with ensuring turbine accessibility, the remainder of this report will consider their interests, not forgetting the other stakeholders' conflicting interests. Mainly Siemens Gamesa's stance is considered because, as a turbine supplier, they have the largest installed capacity shares, making them a highly influential stakeholder in O&M.

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3 Current methods in offshore O&M

To quote Dalgic et al. [23]: *"As the number of turbines in offshore wind projects increases, and the wind farms are located further away from shore, there is a need to develop specialised new O&M vessels and transfer systems that will provide access to turbines throughout the year in rough sea conditions. New approaches may involve moving from port-based operations to ship-based strategies."*

To understand where the need for a new system comes from, it is first necessary to be familiar with current methods in offshore O&M. Since the ultimate goal involves increasing turbine accessibility, its definition and the operations involved are covered first (section 3.1). Then, the state-of-the-art access vessels currently available to do so are discussed (section 3.2). The chapter ends with the O&M strategies and where the access vessels fit in (section 3.3).

3.1 Accessibility

Accessibility is defined as the fraction of time in which safe access to wind turbines is achieved [1]. So, it depends on a vessel's capability to navigate to a turbine and allow technicians to access turbines safely. This factor is critical when a wind turbine has malfunctioned (or is about to) and during emergency rescue situations since the operator must be at that location within the golden hour. The process of accessing a turbine from offshore-based hubs, shown in Figure 3-1, consists of main phases: Launch and recovery, transit and transfer.

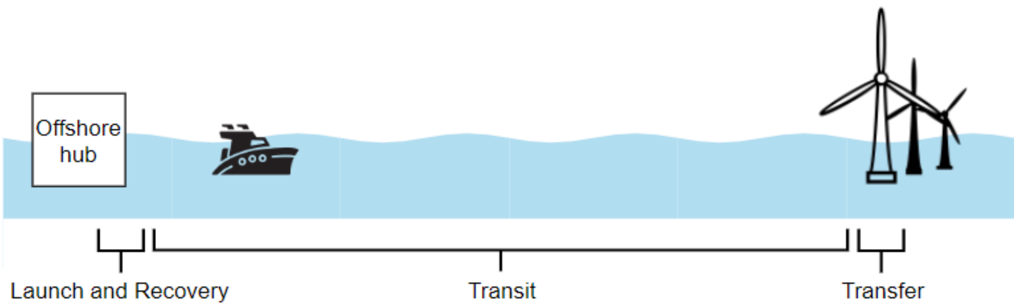


Figure 3-1: Access phases

Examples of offshore-based hubs include installing a fixed offshore platform or chartering an SOV that sails around the wind farm. Launch and recovery is the only phase where there is a dynamic interaction between the SOV and DC. For the remaining phases, the DC is independent of its mothership. Transit is the time needed to travel from the offshore-based hub to (the vicinity of) a particular wind turbine. The duration depends on ongoing weather conditions and the performance capabilities of the vessel. After transit, technicians and equipment can be transferred to wind turbines at several locations [15]:

- The boat landing at sea level from where vessels the technicians climb the ladder to reach the platform. The procedure is also known as "bump & jump".
- The platform located on top of the turbine's transition piece, where technicians can enter the tower directly using a walk to work gangway system.
- The helideck which provides direct access to the nacelle.

(a) The boat landing [29]

(b) The platform [30]

(c) The helideck [31]

Figure 3-2: Transfer locations of offshore wind turbines

Figure 3-2 displays the transfer locations and how the transfer is carried out. In transit, the vessels need the seakeeping performance to reach the turbines (quickly), while safe transfers require the motions to be near zero. The distribution between these phases differs per trip, as the time to travel between the SOV and the wind turbine is variable, while the time to transfer technicians is assumed to be relatively constant. But both phases are equally important to successfully access a wind turbine since one without the other makes the entire operation futile. Various configurations have been built to combine the needs of both phases [32], such as catamarans, (trimaran) SWATHs and SESs. These vessels are further discussed in the next section.

3.2 State-of-the-art access vessels

This section reviews several types of access vessels used to transfer technicians to offshore wind turbines. Table 3-1 offers a quick overview of the vessels' typical design characteristics that will be discussed.

Table 3-1: Typical design characteristics of offshore service vessels

Characteristic	SOV	DC	CTV	SATV	Helicopter
Length [m]	57 - 93	11 - 13 (<20)	12 - 34	36	NA
Beam [m]	14 - 20	4	4 - 10	11	NA
Speed [knots]	7.5 - 14	25 - 45	15 - 30 (<40)	16 - 20	> 65
Weight [tonnes]	NA	7 - 11	60 - 80 (<100)	83	NA
Accessibility [H_s] Transit & Transfer	< 3.0	< 1.2	< 1.5 - 2.5	< 2.0	NA
Cargo capacity [tonnes]	800 - 2300	1	1 - 30	75	< 0.1
Capacity [persons]	40 - 60	8 - 10	10 - 30 (<75)	12	6
Calls to port	(Bi)Monthly	NA	Daily	Weekly	Daily

3.2.1 Service Operation Vessel

A Service Operation Vessel (SOV) serves as a sailing warehouse and offshore-based hub for O&M activities[2]. SOVs are primarily used for preventive maintenance but are used for corrective maintenance if necessary. They include workshops and can accommodate 40-60 persons (15-20 crew and 25-40 technicians) onsite for up to a month, significantly reducing transit time to port and reaction time after a turbine malfunction. However, SOVs usually follow the same working pattern as technicians, which work on a rotation of two weeks. So, SOVs often make bimonthly trips back to port to change crew, reload cargo, and bunkering [15].

While many SOVs were retrofitted from the oil and gas industry [15], purpose-built SOVs are becoming popular due to their improved capacity to transfer technicians and cargo to wind turbines; Figure 3-3 shows one of the latest designs. This is because the inclusion of a hydraulic motion compensating (i.e. walk-to-work or W2W) gangway and cranes were considered during the design phase, giving an optimised arrangement. The W2W gangway, together with dynamic positioning systems, provide a safe and "ladder-less" approach to transferring technicians and cargo (<200 kg [15]) to wind turbine platforms. Furthermore, the SOV's better seakeeping behaviour causes less motion-induced fatigue for technicians and offers a large operational weather window for O&M activities (up to $H_s \leq 3.0$ m).

Figure 3-3: Mock-up of the Service Operation Vessel to be deployed by Ørsted [33]

Dewan and Asgarpour [24] set up a study to determine the best O&M strategies for five generic types of wind farms. These farms varied in terms of total wind farm capacity, individual turbine capacity, the number of turbines, the distance from the port and the water depth. Considering these parameters, along with O&M costs and turbine downtimes, they determined SOVs were the best fit for large wind farms (100-200 turbines of 8 MW) located 150 km from the coast.

Dalgic et al. [34] did a case study on the cost-benefit analysis of several offshore-hub concepts to a wind farm with 150 turbines, located 50 nautical miles from the O&M port. They determined that continuous chartering of an SOV (with onboard DCs) significantly increased the farm's availability, from 74%[3] to 92%, while decreasing total O&M costs by roughly 45%.

[2] SOVs can be used for installation and commissioning of offshore wind turbines as well.

[3] Base case where five port based CTVs are implemented. There is no mothership or fixed platform.

A fixed platform offered similar benefits, but whether it is also favourable for other wind farms ultimately depends on the climate, water depth, failure rates, turbine capacity and wind farm size [34]. One significant advantage that SOVs have over fixed platforms is that the SOVs themselves can also be used to access turbines. Though they are relatively expensive: charter rates can go for roughly €25.000 per day, excluding fuel and crew.

Also, SOVs have a low transit speed of 10-14 knots because they are primarily designed for dynamic positioning. When on-site, they are at a standstill 90% of the time. Furthermore, SOVs can only reach speeds of up to 6 knots before they need to approach the next turbine. Each turbine has a safety zone (roughly 500 m) where the ship must approach or leave the turbine in dynamic positioning mode. So, there is no need to increase the ship's transit speed. This is an acceptable trade-off considering the time it takes to sail back to port, which is done overnight so technicians can start working or be swapped in port the next day. Often even, these vessels sail slower during transit to or from port to save fuel.

However, this becomes a downside for wind farms increasing in area size (see section 4.1.2) because it will take SOVs longer to travel between turbines. Trouble arises when a turbine that needs troubleshooting is far from the SOV. This is especially inconvenient when it involves a simple restart, for example. The SOV often cannot travel to that turbine because they are restricted by safety regulations that state that the operator must reach a turbine within an hour when an emergency occurs, and technicians need rescuing or medical treatment. Therefore, to increase their multitasking capability for unforeseen events, SOVs are typically equipped with 1 – 3 DCs/FRCs, further discussed in the next section.

3.2.2 Daughter craft

Daughter craft (DC) are fast cruising boats that serve to access offshore wind turbines and can be launched from an SOV or fixed offshore hub when needed. An example is shown in Figure 3-4. They are included in the charter rate of SOVs (once requested) and are assumed to cost roughly €500 per day. DCs are primarily meant for urgent matters, especially for turbines located far from the SOV; most urgent tasks fall under corrective and condition-based maintenance. They are handy for small tasks such as a turbine reset. Also, DCs can be used even when the job concerns a large component because technicians can be sent ahead of the SOV's schedule to prepare the turbine.

Figure 3-4: Mare DC 12 WM [35]

The passenger capacity depends on the DC's size, but typical vessels can carry 8-10 technicians and two crew members. Moreover, with a range of 120 nautical miles, DCs can also be sent back to port for crew exchange or restock parts and food. In the water, DCs are quick to arrive at turbines with high transit speeds ranging from 25 – 45 knots. Once at the turbine's boat landing, the DC goes into bollard push condition to allow the technicians to approach and climb the turbine's ladder.

DCs are usually available for use since they are not included in any long-term maintenance schedules. However, even when a DC is available, whether or not the job can be carried out depends on the weather. Existing DCs have been designed to transfer at $H_s \leq 1.5$ m since that is predominantly observed in their current operational area, i.e. at wind farms situated closer to shore. Though some DC's are required to be capable of sailing in slightly higher waves to ensure recovery when the weather picks up unexpectedly. With offshore wind farms moving farther from the shore (section 2.1), rougher weather conditions and sea states are observed (section 4.2). This is restricting operators from utilising DCs because they lack in performance, especially during the winter season. Since the SOV is occupied with its own schedule, technicians must wait for a suitable weather window. This causes a delay which either leads to or extends a turbine's downtime.

Furthermore, few studies focus on the design or benefits of DCs as they are mostly included as accessories and not treated as a system on their own. Some only see it as an FRC, while others mistake it for a CTV, the latter of which is discussed in the next section.

3.2.3 Crew Transfer Vessel

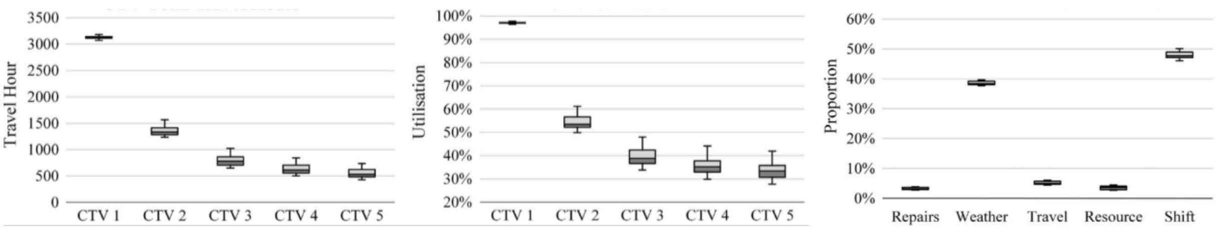
Crew Transfer Vessels (CTV) are multipurpose, high-speed vessels designed for wind farms relatively close to shore. So, there is enough range for a round-trip from the shore, but not enough to operate offshore for more than a day. In literature, they are occasionally mistaken for a DC. This study adheres to the following distinction: a CTV is an independent vessel that always heads back to port at the end of the day while a DC is dependent on its mothership, which launches, recovers and stores it. Thus, these vessels are used for daily port-based O&M but are still relevant to understand the deficiencies in current systems.

Figure 3-5: Crew Transfer Vessel with Turbine Access System [36]

CTVs have design speeds ranging from 15 – 30 knots and are more versatile in hull shape: they have been designed as monohulls, multihulls, (extreme semi) SWATHs and SESs; more on this is given in section 5.2.1. The majority of CTVs are aluminium catamarans due to the high speeds they can achieve, the good seakeeping behaviour in mild sea conditions and their improved stability when pushing against the boat landing of a wind turbine for offshore technician transfer [15]. Most CTVs can carry out transfers when waters are calm, which is approximately $H_s < 1.5$ m. When CTV's are equipped with a turbine access system (similar to a W2W gangway system), their ability to transfer increases to $H_s < 2.0$ m, see Figure 3-5. Note that these variants are larger to accommodate the W2W system. While adopting the latter gives a broader weather window and is also considered safer, vessels with or without a W2W gangway system are both generally good designs because near-shore wind farms ordinarily show these wave characteristics.

Costing approximately €4000 per day, CTVs are used for both corrective and preventive maintenance, which is feasible when the wind farm is situated relatively near shore. This is because the vessels, spare parts and technicians are more readily available within a reasonable timeframe.

Dewan and Asgarpour [23] determined that CTVs were best suited for smaller wind farms (50-100 turbines) located 30 km from the coast. Furthermore, Dalgic et al. [23] did a case study considering FINO 1, an offshore wind farm consisting of 150 turbines located 45 km off the coast of Germany. They examined the use of, among others, a fleet of five CTVs. They applied a methodology to utilise a CTV as much as possible. As a result, (a) and (b) of Figure 3-6 show that the first CTV has much more travel hours and a higher utilisation rate than the four remaining CTVs. They explain that this minimises the travel costs because allocating multiple CTVs to multiple failures instead of allocating a single CTV to multiple failures increases the cumulative travel time and fuel. Furthermore, when CTVs are used for 'manual resets' and 'minor' failures, Figure 3-6c displays the proportion of reasons contributing to the total turbine downtime. The highest portion is due to shift (48%) because failures during the night can only be amended in the following day shift. The second highest portion correlates to weather (38%), which is due to the applied CTV's limited operability ($H_s < 1.5$ m).



(a) CTV Total Travel hours (b) CTV utilisation (c) Distribution of downtime

Figure 3-6: Results of using five CTVs for FINO 1 [23]

Still, there is a highly competitive market for CTVs. With more wind farms being installed offshore, there is a greater demand for CTVs, and it has become more challenging to contract the right kind of CTV at the right time for specific locations [37]. Furthermore, since wind turbines are also becoming larger, see section 4.1.2, CTV's have been observed to be getting bigger to accommodate the larger spare parts. While seakeeping is still accounted for in larger designs, increased transit times are causing fatigue in technicians, decreasing their performance. Again, this can be solved by chartering an SOV to take over scheduled maintenance while CTVs cover unforeseen events. But a relatively new concept was developed for similar scenarios, which is discussed in the next section.

3.2.4 Service Accommodation and Transfer Vessel

Service Accommodation and Transfer Vessels (SATV) are a relatively new concept within offshore O&M. Its mission and functions are similar to those of an SOV, but it is a smaller variant that is better suited to cover scheduled maintenance of small wind farms far from shore. It also provides overnight accommodation for personnel and is capable of staying offshore for approximately a week. Typical concepts aim to carry 12 technicians, excluding crew members. Furthermore, they are made to reach speeds of 20 knots and transfer technicians by pushing against a turbine's boat landing.

There is currently only one SATV ("Ventus Formosa" in Figure 3-7) in operation at Formosa 1, a 128 MW (2x 4 MW and 20x 6 MW) offshore wind power station situated 6 km off the west coast of Taiwan that covers 11 km^2. It is considered a perfect fit for projects like this because a full 40-person SOV would be oversized for the relatively small wind farm, and a CTV that sails into port daily would be undersized [38]. In other words, it is meant for wind farms where going back to port every day is less efficient due to transit time. Hence, this vessel was designed to fill the gap between the capabilities of a CTV and an SOV.

Figure 3-7: Purpose-built Service Accommodation and Transfer Vessel deployed by Siemens Gamesa [39]

This particular vessel is equipped with an active fender system that reduces impact loads between the vessel and the turbine and ensures safe transfers. So, there is no need for a W2W gangway system, which saves time and costs.

3.2.5 Helicopter

All of the access vessels covered in the previous sections are seaborne and subject to metocean phenomena. SOVs are generally most capable of overcoming rough weather, although it is not the operator's first vessel of choice for urgent matters. When the smaller access vessels are inoperable, an operator may choose to deploy technicians using a helicopter. Figure 3-8 shows how technicians are hoisted to the heli-hoist platform. However, strong gusts can complicate these procedures. Also, unless the helicopter can land on the turbine or a platform nearby, its waiting time is restricted to less than 30 minutes [15].

Dewan and Asgarpour [24] state that the technical and economic feasibility of helicopters is based on weather conditions at the wind farm location, size of the wind farms and distance of the wind farm from shore. Another factor to consider is that it is not possible to transport many technicians (usually 3-6) and cargo (usually less than 100 kg) [15], especially large components which the seagoing vessels are capable of transporting. Moreover, it is relatively expensive to charter helicopters, approximately €100-200 per minute [15], but the turbines' preserved availability often compensates for this. Figure 3-6c shows the proportion of different reasons that contribute to the total turbine downtime and applies to helicopters too.

To conclude, helicopters are regarded as an operator's last resort and used for urgent corrective tasks which cannot be carried out by the operator's ocean-going fleet. It is then usually the most viable option because it can operate regardless of the sea state. Also, it is one of the fastest methods to transport technicians. Siemens Gamesa [40] specifies that a helicopter is 6x faster than a CTV and 12x faster than an SOV.

Figure 3-8: Helicopter transferring a technician to the heli-hoist platform [41]

3.3 Maintenance strategies

Maintenance is carried out to preserve the availability of wind turbines; to ensure energy output and revenue. The first maintenance check may take place approximately 500 hours or a month after a turbine has been made fit for purpose. According to Krause and Stead [17], individual turbines can then require around five visits per year: one annual maintenance visit and three to four when there is a (minor) malfunction. Yang et al. [42] state that about 75% of onshore wind turbine failures are related to the minor errors occurring in the turbines' electrical and power electronic control systems, and there is no doubt that the offshore environment worsens the situation. For some of the largest offshore wind farms (such as the Hornsea One with 176 turbines), that could amount to roughly 900 visits per year.

In principle, there are several reasons why and how maintenance is carried out, which are divided into the reactive or proactive approach; see Figure 3-9 for an overview. A reactive/corrective response concerns unforeseen events, while a proactive/preventive approach aims to prevent failures. Table 3-2 shows an overview of which vessels are primarily used for the different strategies. This section describes which strategies the access vessels from section 3.2 are used for. However, only the vessels use concerning far-offshore applications will be discussed, namely the SOV (mothership) and DC, since there is a somewhat greater distinction between their tasks. In contrast, both CTVs and SATVs are suitable to carry out all maintenance strategies for wind farms located near the shore. In case of an emergency, operators can always request additional (airborne) vessels from the shore. Furthermore, O&M vessels can also work in combinations. For example, SOVs assigned to wind farms relatively close to port are sometimes aided by CTVs for particular tasks.

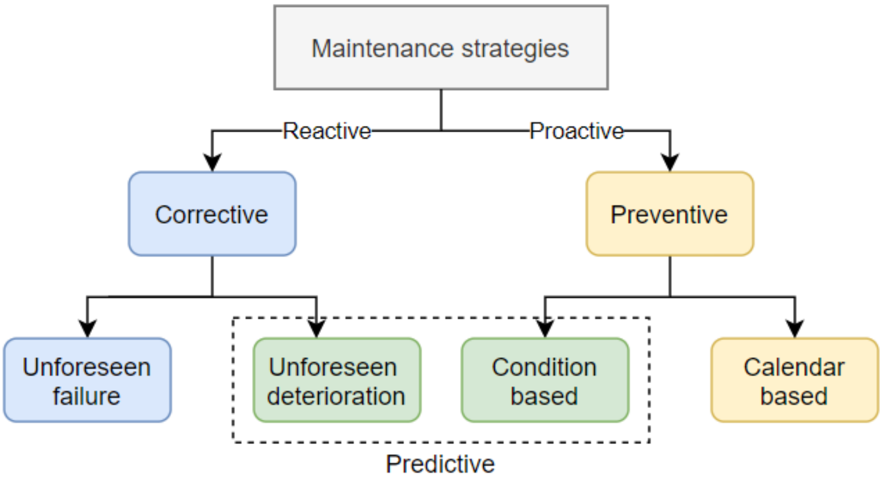


Figure 3-9: Overview of maintenance strategies (Adapted from [43]*)*

Table 3-2: Overview of vessel use

Maintenance strategy	*Far-offshore*		*Near-shore*		*Urgent*
	SOV	DC	CTV	SATV	Heli
Unforeseen failure		X	X	X	X
Unforeseen deterioration		X	X	X	
Condition-based	X	X	X	X	
Calendar-based	X		X	X	

3.3.1 Corrective maintenance

Corrective maintenance is a reactive response for repairing or replacing components after unforeseen failure or deterioration. There is more flexibility for the operator to carry out this type of maintenance when the wind farm is located closer to the shore because resources such as equipment, spare parts, or technicians are more readily available within a reasonable timeframe. The same cannot be said for wind farms located far offshore where transit time is extended, leading to lower response time and causes fatigue in technicians and therefore decreases their performance. Then the operator has to rely on resources that are more within reach and available on short notice. These types of jobs can be both unplanned and planned, despite their sudden nature.

3.3.1.1 Unplanned corrective maintenance: Unforeseen failure

Unplanned corrective maintenance could be as simple as restarting the turbine or as complex as replacing a whole component. Either way, this may interfere with equipment scheduling, consequently causing a turbine's (extended) downtime and revenue losses. The latter makes unplanned corrective maintenance the largest contributors to O&M costs, as discussed in section 2.2.

If the component is small enough, an operator will send the fastest craft the component fits on: an SOV's DC, if the sea state allows, or a helicopter. But urgent malfunctions concerning large components, for example, could force the operator to temporarily disrupt the SOV's schedule to solve the problem.

3.3.1.2 Planned corrective maintenance: Unforeseen deterioration

Planned corrective maintenance occurs when the state of a turbine's component has unexpectedly worsened but has not failed yet. While it has a corrective nature, this type of maintenance also falls under the term predictive maintenance. In this case, the condition of the turbine was remotely monitored using sensors. Because the condition was picked up before the turbine broke down, an operator has sufficient time to gather equipment and plan the job. This could also call for 'batch-wise' ([2]) maintenance if the same problem is spotted at multiple turbines within the same farm.

In this case, an SOV and its DC can be used for planned corrective maintenance. In the case the wind farm is far offshore, the DC is sent beforehand to allow technicians to examine the extent of the problem and correct onsite if possible. If it turns out that an SOV is needed, the task will be scheduled.

3.3.2 Preventive maintenance

Preventive maintenance is carried out to reduce the probability of unforeseen failures. In principle, it is known that a specific component will fail, but it is uncertain when that would occur. There are two methods to implement preventive maintenance.

3.3.2.1 Condition-based maintenance

The first is condition-based maintenance which is initiated after sensor data shows a familiar trend of deterioration. The trigger gives the operator enough time to them respond. This could be applied, for example, after a component has previously failed without warning. Other identical components could then be monitored to avoid a turbine shutting down. This mainly occurs after a turbine has been in service for several years. This falls under the term predictive maintenance as well.

Again, DCs are the primary vessels used to carry out condition-based maintenance if the weather window is sufficient, and the required components are transportable. Large components that are expected to need maintenance shortly are usually be incorporated in a turbine's calendar-based maintenance, so there is no need to alter the SOV's original schedule.

3.3.2.2 Calendar-based maintenance

The second type of preventive maintenance is calendar-based. This implies that the turbines are inspected and serviced regularly, perhaps annually or bi-annually. It is usually based on known failure rates, giving operators ample time to schedule when service is needed.

For far-offshore maintenance, this type of maintenance is carried out primarily using the SOV. The main reason is that SOVs are less sensitive to varying weather conditions, allowing the operator to remain on schedule. Also, it could occur during an inspection that technicians discover a component that needs replacing or repairing. So, it is convenient to have the SOV nearby to obtain the required parts and tools. In fact, some components are so large that they can only safely be transferred by the SOV using its onboard equipment. Even in these cases, DCs are occasionally sent in advance so technicians can prepare the turbine for when the SOV eventually arrives.

4 Operations analysis

This chapter represents the first step of the *Needs Analysis* phase within *Concept Development*. The access systems covered in section 3.2 were designed with specific operational requirements in mind. To understand their shortcomings in new environments, it is first necessary to establish their new operational areas (section 4.1). By defining the associated operating conditions (section 4.2), it will be possible to express the deficiencies in current systems (section 4.2.4) and determine the new system's operational objectives (section 4.4) that will set it apart from current systems. Section 4.5 offers concluding insights.

4.1 Operational area

This study is limited to wind farms located in the North Sea because most are currently located there. This section covers the criteria used to establish which wind farms represent the operational areas where offshore-based hubs are considered useful, but accessibility has become an issue. The focus lies on these hubs because they can overcome the observed weather conditions, but they are either occupied or not fast enough to take care of unplanned events. So, their operational area represents the operational area of the DC.

4.1.1 Distance from shore

Walsh [10] confirms that the average distance from shore is increasing, see Figure 1-3. Note that these distances do not directly indicate transit times since the distance to shore does not always represent the distance to port. Still, if an operator wishes to reach these wind farms and operate efficiently, they must have vessels with enough range. Therefore, distance plays a significant role when choosing a suitable vessel.

Phillips et al. [2] estimated the most cost-effective distances to implement various O&M vessels, see Figure 4-1. While O&M vessels have improved since 2013, the figure still gives a decent indication of where the transition points may lie. Accordingly, only wind farms situated roughly 35 nautical miles (65 km) from the port are considered relevant for this study because then offshore-based hubs, i.e. SOVs, are deemed the most economical.

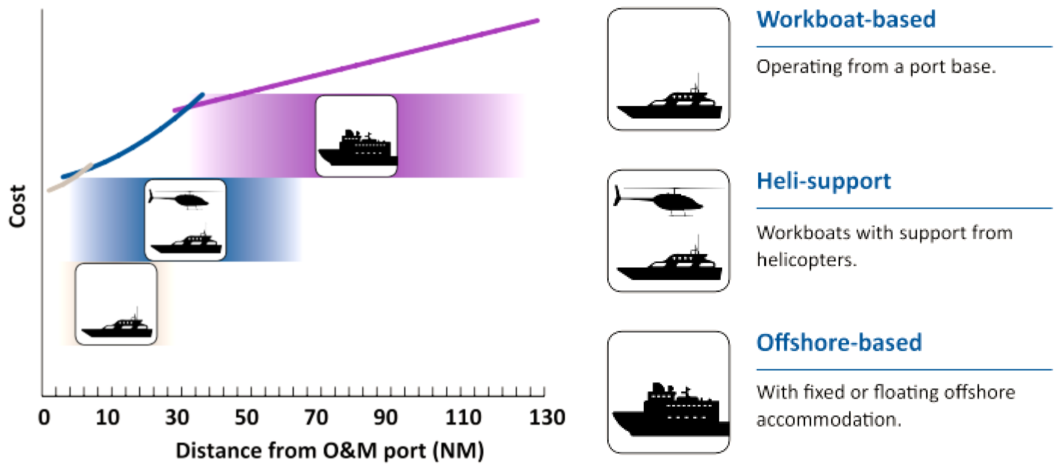


Figure 4-1: Lowest cost O&M strategy as a function of distance from O&M port [2]

4.1.2 Wind farm size

The farm size and area are also essential aspects to consider with regards to accessibility. The offshore wind industry is observing an increase in average turbine size ([44]) and capacity, see Figure 4-2. This makes it possible to harness the greater wind potential found at far-offshore locations. However, the spacing between wind turbines then increases too because, as a rule of thumb, the distance between turbines is roughly six to nine times the rotor diameter [5]. The greater distance between each turbine means fewer turbines can be accessed each day, which lowers productivity and makes daily trips back to port more impractical and. So, SOVs are still the access vessel of choice but note that the more extensive the park, the more it needs to travel between scheduled turbines.

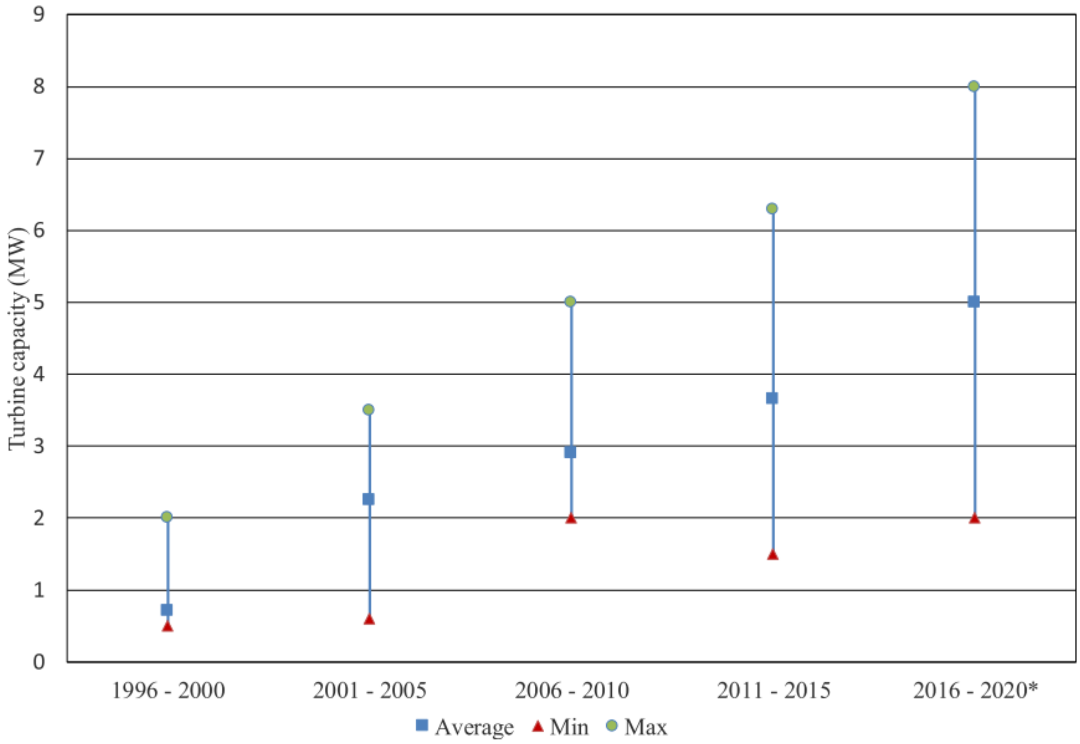


Figure 4-2: Evolution of offshore wind turbines based on the commissioning period. The last period involves the projects in pre/under construction. [44]

Considering the distance, an SOV can visit approximately six scheduled turbines per day[4]. With a yearly weather window of 90% [40], an SOV can then be scheduled to service nearly 2000 turbines per year. Krause and Stead [17] estimated that offshore wind turbines need to be visited 15 times[5] per year for both scheduled service and troubleshooting. In that case, wind farms with at least 120 turbines are expected to properly occupy an SOV, which will be this study's benchmark.

It is acknowledged that SOVs are currently also being used for wind farms with as low as 80 turbines [15]. The wind farms are then occasionally finished prematurely, which leaves the SOV idle until the next job starts. Since the vessel was chartered, its unproductivity means the operator is not using the vessel efficiently, but this is currently still feasible for some wind farms due to subsidies.

[4] Implies there are at least 12 approaches per day, depending on the team size and shift pattern.
[5] Value is based on a wind farm with 200 turbines of 5 MW each, needing 3000 offshore visits per year.

4.1.3 Reference wind farms

The two previous sections established which type of wind farms will represent the operational areas where SOVs are considered useful. In brief, those where the distance to shore is greater than 65 km and have at least 120 turbines. Figure 4-3 illustrates the location of various wind farms in the North Sea and which of those meet both criteria. Ultimately, there are five (sets of) wind farms that match the requirements for this study.

However, Dogger Bank and IJmuiden Ver are two sets of wind farms that are still in development, so there are still many unknowns. These clustered wind farms may end up having different owners who decide to carry out turbine O&M independently, leaving fewer turbines per SOV. But as a whole, these two sets of wind farms will properly occupy an SOV. So, their locations are still considered relevant for this study. Above all, those farms pose as future markets that can benefit from an access vessel designed for their operational area.

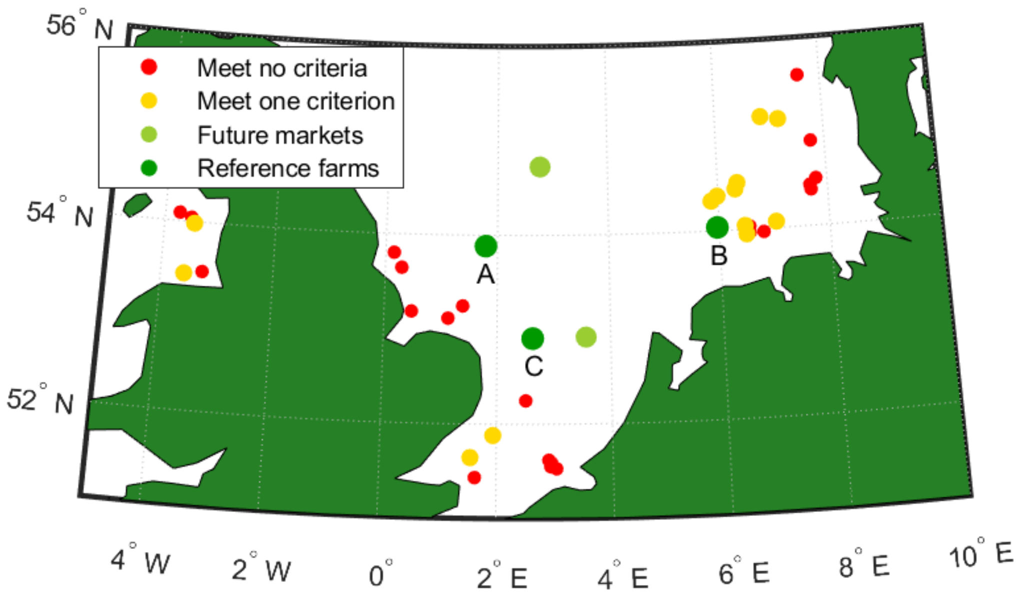


Figure 4-3: Locations of offshore wind farms in the North Sea

The three remaining wind farms will be used as references to analyse turbine accessibility. The first is Hornsea One, indicated by ‘A’ in Figure 4-3. It currently has the largest capacity and is the farthest wind farm from shore. The second is Gemini, indicated by ‘B’ in Figure 4-3. It has a relatively low total capacity compared to the other reference wind farms, but this is because each turbine has a lower capacity. Lastly, there is East Anglia Three, indicated by ‘C’ in Figure 4-3. It is currently under construction but will soon be among those with the largest capacity, and it is relatively close to the port for a far-offshore farm.

Table 4-1 gives an overview of their characteristics. Notice how the site area significantly varies between all three wind farms. This has to do with the broader spacing required for the larger turbines of Hornsea One and East Anglia Three.

Table 4-1: Characteristics of selected offshore wind farms

Characteristic	A: Hornsea One [45]	B: Gemini [27]	C: East Anglia Three [46]
Capacity [MW]	1218	600	1400
Distance to shore [km]	120	85	70
Site area [km²]	407	2 x 34	305
Number of turbines [-]	174	150	172

4.2 Operating conditions

Whether a turbine is accessible depends on the access vessel's ability to navigate in the ongoing weather conditions. Specifically, wind speed, significant wave height and wave steepness predominantly affect vessel seakeeping [47]. It should be noted that the performance of a majority of vessels is characterised by significant wave height. However, since these phenomena all interact and influence each other, it is doubtful whether a vessel's operability can be determined using a single parameter [47]. Because of the interaction, experience shows that vessels occasionally still fail during conditions they were designed to handle. Focus is laid on the weather conditions present at the reference wind farms. Since all wind farms show similar weather conditions, only the data from Hornsea One will be shown here for conciseness. Data from the remaining wind farms are located in appendix A. Also, the most common wave directions and effect of monopile wake are briefly discussed.

4.2.1 Wind speed

Wind speed has both direct and indirect influence on a vessel's performance, in the form of wind resistance and waves, respectively. The magnitude of wind resistance essentially depends on the vessel's area above the waterline (e.g. sails, freeboard and superstructure), wind velocity and wind direction relative to the ship's direction [48]. Moreover, the effects on manoeuvrability depend on the draught as well: wind loads are less effective on vessels with a relatively large wetted surface. For example, light winds on a vessel in light condition have a similar effect as stronger winds on a fully loaded vessel. Figure 4-4 shows the absolute and relative amount of wind speeds measured over 21 years at Hornsea One, 10 m above the free surface. Looking at the measured wind speeds, the vessel's total resistance can (but rarely will) be increased up to 25-30% [49]. In any case, high wind speeds more often affect the crew's performance rather than the vessel, but the observed winds are hardly expected to limit the crew's ability to work.

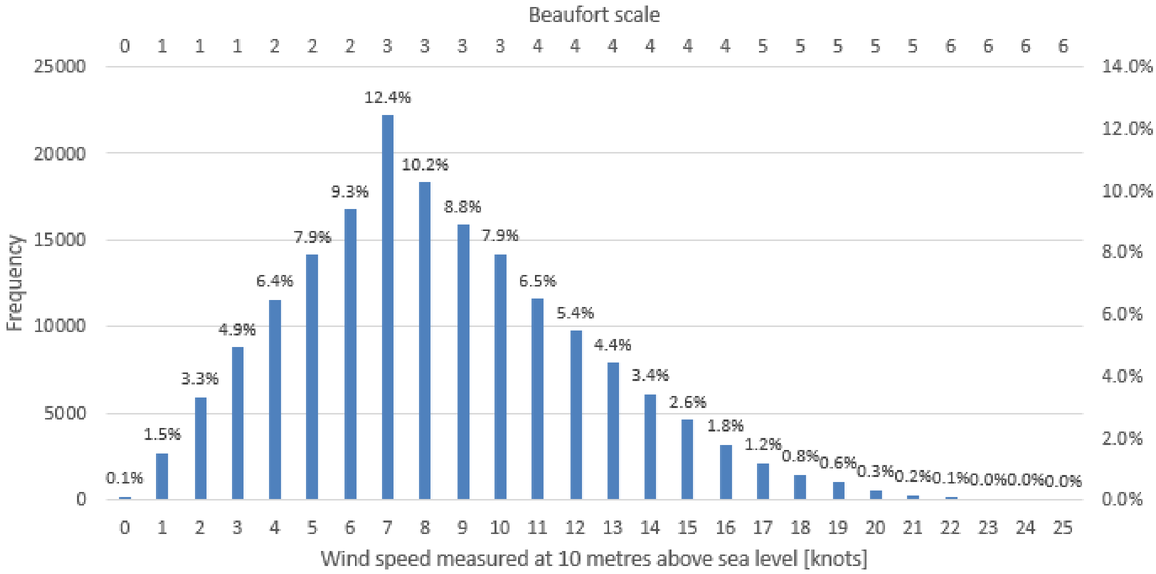


Figure 4-4: Histogram of occurring wind speeds at Hornsea One

Note that there is a difference between wind resistance and air resistance, the latter being the resistance caused by the flow of air over the ship with no wind present [49]. Air resistance alone depends on how streamlined the vessel is and typically contributes to the lowest portion (4-8%) in a vessel's total resistance [49]; see Figure 4-5.

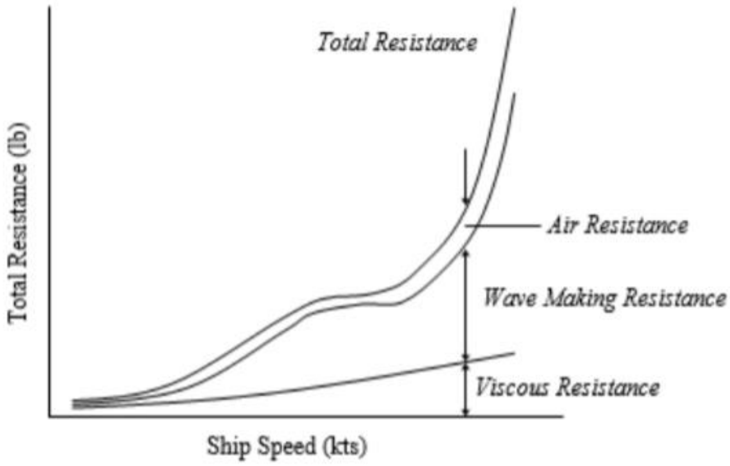


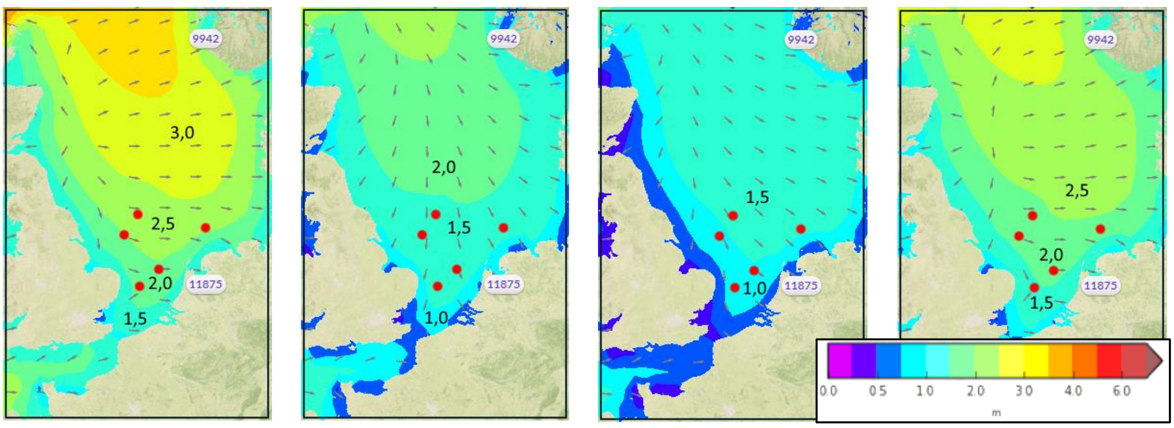
Figure 4-5: Components of hull resistance [49]

Besides being a force on its own, wind can generate surface wind waves and swell, two phenomena that influence a vessel's performance. The difference between the two is that wind waves are generated locally, causing an irregular sea surface while a swell is formed due to wind elsewhere and grows as it travels. The magnitude of wind waves depends on wind speed, the distance over which the wind has blown (also known as fetch), the time the wind has been blowing over the fetch, the water depth and the relative direction of tidal stream and current to the wind [47].

Although easy to determine, wind speed alone is not a reliable indicator of likely conditions to be experienced ([47]) because of its effects on the ocean and subsequent effects on a vessel. Due to its minimal and indirect influence on the vessel and crew, wind speed has been acknowledged but will not be considered a design criterion.

4.2.2 Significant wave height

Significant wave height (H_s) is defined as the mean height of the highest one-third of waves and is a popular design criterion to determine a vessel's operational limit [47]. Figure 4-6 displays the mean H_s for different seasons. At the reference wind farms' locations, illustrated by red dots, it can be seen that waves with H_s = 1.5 m are typical for the summer period while $H_s \geq 2.5$ m occurs during the winter. While these figures show the variation of the mean significant wave height over a year, they do not show how often these occur.



(a) January *(b) April* *(c) July* *(d) October*

Figure 4-6: Seasonal mean significant wave height [m] in the North Sea using MetOcean View Hindcast [50]

Figure 4-7 shows the *cumulative* occurrence of various significant wave heights measured over 21 years at Hornsea One. It shows that waves up to H_s = 6.5 m were observed but waves this high are relatively scarce compared to the lower wave heights. In fact, this wind farm observed $H_s \leq 2.5$ m for 90% of the time annually. Furthermore, these wave occurrences differ throughout the seasons: 90% of waves in the summer are $H_s \leq 2.0$ m, while this increases to $H_s \leq 3.0$ m in the winter. Overall, this graph gives a good initial impression of how often a *range* of significant wave heights is likely to occur. It will ultimately be used to determine the weather window theoretically.

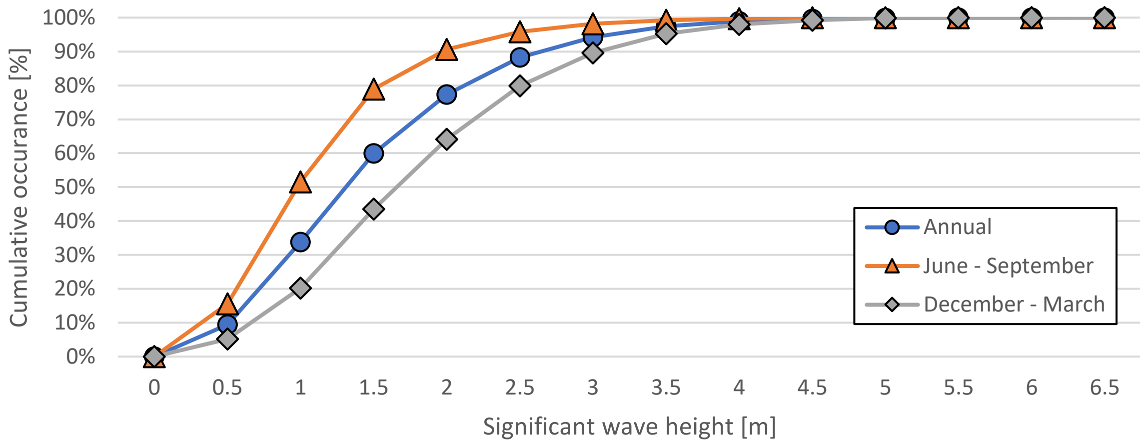


Figure 4-7: Measured wave data at Hornsea One (adapted from [51])

It should be noted that different data providers may show variance in metocean characteristics. The difference is most considerable if daily observations are compared. Monthly, the results are comparable. Yearly, the results are similar to one another.

4.2.3 Wave steepness

A report by MaTSU [47] considers wave steepness to be the most crucial aspect considered by the crew during launch/recovery and manoeuvring of rescue craft. Hence, while significant wave height is a more popular parameter to determine a vessel's operational limit, MaTSU [47] considers wave steepness to be a better indicator because it determines the force upon a fixed or floating structure, how it will behave and when waves are likely to break. Like significant wave height, wave steepness is linked to its location. Furthermore, it steepens when there is an opposition between wind and current directions. Table 4-2 is a wave scatter diagram of the sea states measured at Hornsea One. In essence, it indicates how many waves correspond to a specific combination of significant wave heights and wave periods. Where there is no data implies that waves will break due to steepness.

Wave steepness (S) is defined as the ratio between significant wave height (H_s) and wavelength (λ). However, neither wavelengths nor wave speeds[6] were included in the used weather database. According to Antão and Soares [52], the wavelength can be calculated from the dispersion relation, given in equation 1.

$$\lambda = \frac{gT^2}{2\pi} \tanh \frac{2\pi d}{\lambda} \tag{1}$$

[6] Wavelength is the ratio between wave speed and frequency

Table 4-2: Scatter diagram of sea states at Hornsea One (adapted from [20]*)*

Hornsea 1		Significant wave height (Hs)														
		0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	Sum
Peak period (Tp)	0.0	73	21													94
	0.5	21	24													45
	1.0	18	27													45
	1.5	13	40						No data here because waves break due to steepness							53
	2.0	25	40													65
	2.5	25	86	1												112
	3.0	93	718	10												821
	3.5	478	2885	203												3566
	4.0	1026	5677	3910	9											10622
	4.5	553	3624	9684	569											14430
	5.0	340	3345	9069	6245	84	1									19084
	5.5	372	2852	4963	9668	2379	33									20267
	6.0	180	2149	3690	5111	7415	1115	13								19673
	6.5	203	1867	3368	3847	4671	4040	422	1							18419
	7.0	150	1466	2871	3038	2923	2596	1847	91							14982
	7.5	136	934	2114	2235	2120	2136	1526	860	104						12165
	8.0	155	954	2307	1749	1792	2157	1610	702	315	69	2				11812
	8.5	138	894	2223	1531	1025	921	1408	619	151	66	36				9012
	9.0	134	501	982	882	601	471	654	732	236	44	17				5254
	9.5	180	726	1381	1278	632	310	330	534	390	159	29	2			5951
	10.0	127	358	717	576	331	137	189	233	276	104	33	2			3083
	10.5	151	510	1095	907	506	245	101	97	182	166	65	22	1		4048
	11.0	55	183	340	342	233	145	45	39	74	109	48	12	1		1626
	11.5	80	229	496	621	299	145	80	36	52	35	44	12	4		2133
	12.0	35	86	154	124	104	50	22	18	12	17	19	7	2		650
	12.5	46	75	188	204	189	103	41	18	15	25	21	4			929
	13.0	13	61	66	60	30	26	4	3	1	7	2	4			277
	13.5	3	28	35	45	37	27	20	6	2	3	1	1			208
	14.0	8	32	20	24	44	28	2				3	3			164
	14.5	2	11	6	8	6	5	3								41
	15.0		6	5	1	3	11	12	2							40
	Sum	4833	30409	49898	39074	25424	14702	8329	3991	1810	804	320	69	8	0	179671

Where g is the gravity acceleration, T is the wave period, and d is the water depth. Deepwater assumptions are applied since the ratio between wave heights, and water depth is large, i.e. $\frac{2\pi d}{\lambda} \gg 1$ [53]. As a result, equation 1 simplifies to:

$$\lambda = \frac{gT^2}{2\pi} \tag{2}$$

Inserting equation 2 the definition for wave steepness gives equation 3.

$$S = \frac{H_s}{\lambda} = \frac{2\pi H_s}{gT^2} \tag{3}$$

Table 4-3 is similar to Table 4-2 but it shows the corresponding values for wave steepness. The values corresponding to H_s = 0 m and T = 0 s have been excluded in here because they are considered to be infinitely short and small waves with negligible steepness. Furthermore, it shows that waves will break when S ≥ 0.05 and the majority of waves have S = 0.03.

On another note, Hong et al. [54] point out that the relative motions between ship and waves could be largest when the wavelength is close to the ship length, also known as the pitch-forcing period. This must be considered when designing the forecastle deck height and green water protector.

Table 4-3: Wave steepness at Hornsea One

Wave frequency (rad/s)	Peak period (Tp) / Steepness (S)	Significant wave height (Hs) 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
12.6	0.5	1.28												
6.3	1.0	0.32												
4.2	1.5	0.14												
3.1	2.0	0.08												
2.5	2.5	0.05	0.10											
2.1	3.0	0.04	0.07											
1.8	3.5	0.03	0.05											
1.6	4.0	0.02	0.04	0.06										
1.4	4.5	0.02	0.03	0.05										
1.3	5.0	0.01	0.03	0.04	0.05	0.06								
1.1	5.5	0.01	0.02	0.03	0.04	0.05								
1.0	6.0	0.01	0.02	0.03	0.04	0.04	0.05							
1.0	6.5	0.01	0.02	0.02	0.03	0.04	0.05	0.05						
0.9	7.0	0.01	0.01	0.02	0.03	0.03	0.04	0.05						
0.8	7.5	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05					
0.8	8.0	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05			
0.7	8.5	0.00	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.04			
0.7	9.0	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04			
0.7	9.5	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04		
0.6	10.0	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04		
0.6	10.5	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	
0.6	11.0	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.03	
0.5	11.5	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	
0.5	12.0	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03	
0.5	12.5	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02		
0.5	13.0	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02		
0.5	13.5	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02		
0.4	14.0	0.00	0.00	0.00	0.01	0.01	0.01				0.02	0.02		
0.4	14.5	0.00	0.00	0.00	0.01	0.01	0.01							
0.4	15.0	0.00	0.00	0.00	0.01	0.01	0.01	0.01						

$$S = \frac{2\pi H_s}{gT^2}$$

Shows at what steepness waves will break

4.2.4 Prominent wave directions

The wind turbines of the reference farms have the boat loading oriented such that vessels encounter head waves the most. This is because head waves are generally considered to induce the lowest responses. This is also beneficial because the chance of large roll motions is then minimised. Figure 4-8 and the graphs in appendix A.3 show which other incoming waves are then also encountered most frequently. As a result, the subsequent waves are of particular importance at the reference farms:

- Hornsea One: Head, beam and following waves
- Gemini: Head and beam waves
- East Anglia Three: Head, stern-quartering and following waves

Section 5.1.1 elaborates the terms used to describe wave directions. Figure 4-9 shows how often the different incoming wave angles are observed over 20 years at Hornsea One. Note that the graphs only show wave directions from 0° to 180° due to vessel symmetry. This is why waves at 179° occur twice as much as waves at 180°. The same applies to waves arriving from 0°. At Hornsea One, it can be seen that head waves are only 30% more likely to occur compared to following waves and three times more likely than oblique waves. This holds as well if only the waves during working hours and specific ranges of wave heights are considered. Due to the small variance in occurrences, the design of DCs should not be solely be focussed on performance in head waves but also in other wave directions.

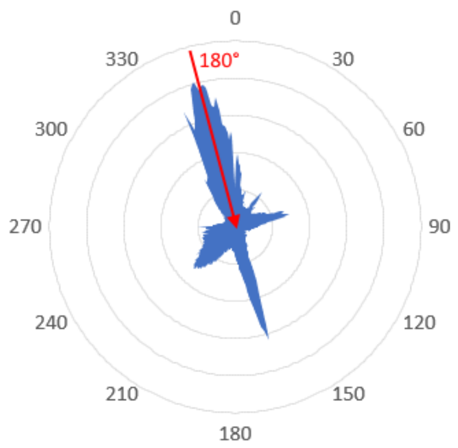


Figure 4-8: Dominant wave directions at Hornsea One

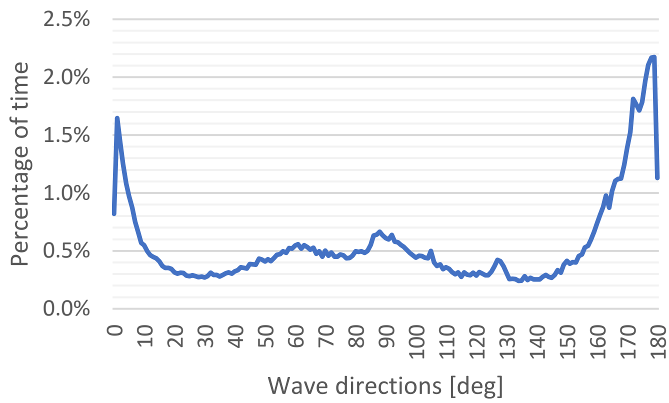


Figure 4-9: Division of incoming wave angles at Hornsea One

4.2.5 Monopile wake

As stated in the previous section, the boat landing of the modern wind turbines is positioned such that vessels, which transfer via their bow, mostly encounter head waves. When there are indeed mainly head waves during the transfer, a large monopile structure, with a diameter of 4-6 metres, in front of the vessel meets the waves first. However, based on experience, the monopiles are not expected to “block” waves due to the vast energy in the rest of the sea.

This is confirmed using results from Tang et al. [55], who investigated the effects of various types of breaking and spilling waves on offshore monopiles. Figure 4-10 shows two snaps of the vertical displacement of a spilling wave breaking on an offshore monopile. In their case, the water depth was 1.2 metres, wave height was 0.6 metres, and the period was 1.4 seconds. The left photo shows that the wave does first “block” the wave, but the right photo shows that the water almost immediately surges back and forms a ridge where the DC would be. Thus, it seems that monopile wake could increase heave effects on the DC during transfers. Studying the effects of monopile wake on a vessel would require a multibody analysis. However, this project takes a simplified approach by only looking at the DC floating in waves. Due to the lack of interaction, fender type or material will also not be discussed.

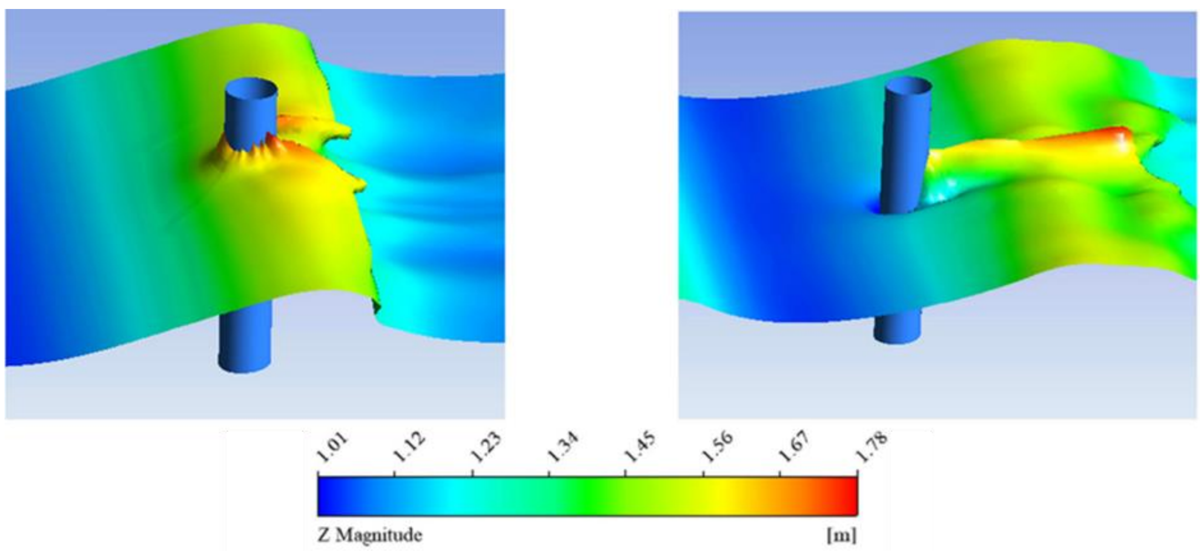


Figure 4-10: Breaking wave flow around the monopile foundation [55]

4.3 Deficiencies in current systems

The need to maintain the reference offshore wind farms can partly be fulfilled by the vessels discussed in section 3.2. This implies that they are not entirely suitable for the job. So, there are deficiencies that must be addressed. As stated in section 1.2, the problem is that SOVs are not flexible enough to also carry out preventive and corrective maintenance, i.e. to service defective wind turbines and scheduled wind turbines, which lowers turbine availability. This section discusses the SOV related deficiencies and why other O&M vessels are not suitable for the (new) operating conditions, which were established in the previous section.

4.3.1 SOVs are more suited for preventive maintenance

Purpose-built SOVs currently have a weather window for operations of 90% due to good seakeeping behaviour. Along with the W2W gangway system, SOVs are highly capable of accessing turbines and are rarely constrained by ongoing weather conditions. This makes it perfect for scheduled maintenance. However, Krause and Stead [17] estimated that offshore wind turbines need to be visited 15 times per year for both scheduled and unforeseen events. The latter interrupts the operator's scheduling. In theory, the SOV could operate fulltime to maintain the availability of the wind farms' turbines, but in practice, this is not considered a feasible method to operate. As a result, the SOV's primary deficiency is its capacity to provide maintenance for unforeseen events due to its low response time.

4.3.1.1 No need for additional technicians

As mentioned throughout this report, SOVs resolve an operator's problem concerning lengthy transits from the port. By allowing 25-40 technicians to stay in the vicinity of the turbines overnight, roughly 6-12 turbines can be maintained considering team sizes. There is no benefit to adding more technicians because an SOV cannot visit more turbines due to safety restrictions. Notice the difference in the number of turbines in Table 4-1. There is a higher chance of unplanned events for wind farms as large as Hornsea One and East Anglia Three. When an alarm goes off elsewhere in such a farm, the SOV is often restricted from going there since it will otherwise be too far and slow when an emergency occurs and technicians need rescuing. So, the additional technicians would be left idle.

4.3.1.2 Chartering two SOVs is expensive and excessive

Placing two (smaller) SOVs in a wind farm is not a solution to increase the response time. The main reason is that it is deemed too expensive, and there would be overcapacity for wind farms similar to the reference farms from section 4.1.3. First, a smaller variant of the SOV is presumed to be roughly €20.000 per day, which is not significantly less than the initial rate of €25.000 per day: the single ship will cost at least € 9 million per year while having two smaller SOVs would cost € 15 million per year, both excluding fuel and crew.

Second, following the procedure from section 4.1.2, having two SOVs would mean that at least 12 scheduled turbines could be visited each day. Turbines could then be serviced more than 30 times per year, which is excessive because 20 visits per year are considered conservative. Having two SOVs does reduce the time needed for scheduled service, but there is no need for this because there are not (yet) many other wind farms that need servicing. In other words, there is not enough demand which would leave many ships idle.

In contrast, a study by Scheu et al. [56] determined that the availability of a wind park consisting of 500 turbines is highest if it is serviced by three ships. Moreover, they determined that using more ships was only useful up to a certain wave height. However, this study cannot be applied here because the vessels had a capacity of 4 technicians each.

4.3.1.3 Downsizing the SOV is impractical

On another note, simply using one smaller SOV to save costs is not practical either for wind farms as large as the reference farms because this goes at the cost of accommodation and storage space; fewer parts means fewer resources readily available.

Furthermore, having the minimum amount (25) or fewer technicians is impractical due to the following. Technicians will work in teams of at least two, meaning up to 12 turbines can be serviced per day if unplanned events are 'neglected'. However, unplanned events are inevitable. So, depending on the number of events, fewer technicians will be available for scheduled service. Take the conservative amount of 20 troubleshooting events per turbine per year. In a farm with 120 turbines, there will be 2400 troubleshooting events per year. With an expected availability of 90%, seven turbines are expected to need troubleshooting per day which leaves enough technicians for scheduled service of only five turbines per day. When a farm has more than 120 turbines, such as Gemini, having 25 technicians is not enough, especially if larger teams are formed. Note that SATVs are technically a smaller variant of SOVs but are used for significantly smaller wind farms than the reference farms from section 4.1.3.

4.3.2 Smaller access vessels are inadequate in their current form

When maintaining defective far-offshore turbines, the previous section argues that the problem is not the SOV's design but its multitasking capability. So, other vessels could be implemented alongside the SOV to increase this. The vessels covered in section 3.2 are all suited for offshore maintenance but become impractical for far-offshore wind farms in their current state for the following reasons:

- Existing DCs were designed to meet the criteria of transferring at $H_s \leq 1.5$ m and achieving 25 knots in $H_s \leq 2.5$ m. This is acceptable for wind farms near shore but less so for far-offshore wind farms where the conditions at the reference farms are regularly observed to be $H_s > 1.5$ m during the winter (see section 4.2.2).
- CTVs have better access performance than DCs and are faster than SOVs. But since they operate from the port, the vast distances make them ill-suited for far-offshore applications. Simply fitting an existing CTV onto an SOV is not possible because of its relatively large size. First of all, most of these vessels will not fit in or on the space made available on the SOV. Second, CTVs typically weigh 60-80 tonnes which is more than the onboard davits can handle. Stronger davits are more expensive, require more space, and possibly a (total) redesign of the SOVs arrangement. Lastly, CTVs were likely not made to be carried by their superstructure, as is done with DCs. This would require a new method for launch and recovery.
- SATVs are similar to CTVs in size, so the same size restrictions mentioned above apply. Furthermore, these vessels also provide accommodation, which is not necessary since the SOV already fulfils this task.
- Helicopters cannot transport large cargo needed for large wind turbines.

4.4 The daughter craft should be improved

In essence, SOVs in their current state are deemed fit for purpose. However, troubleshooting turbines can happen anywhere at the farm, and it would be inefficient to send an SOV to these 'arbitrary' locations. Operators are also restricted in doing so due to safety regulations that state that the operator must reach a turbine within an hour when an emergency occurs, and technicians that they dropped off need rescuing. So, to increase turbine availability, solutions should be sought in increasing the SOV's multitasking capability. This could be achieved by improving one of the SOV's subsystems, and the system-of-interest is the DC because:

- DCs are already useful in the summer when weather conditions are relatively calm.
- DCs have a relatively cheap day rate compared to SOVs (about €500, which is included in the SOV's charter rate of roughly €25.000 per day), so they are more accessible for a redesign.
- Since DCs are included in the charter rate, it is more convenient and efficient to use the already paid vessels instead of hiring another access vessel.
- Altering a CTV (or any other craft) to fit on and work from an SOV technically classifies it as a daughter craft.
- Even at lower speeds, the DC will reach the turbine faster than a CTV at top speed; the next section elaborates this.

4.4.1 Time saved by using a DC

For far-offshore wind farms, trips by CTV will have longer transit times than DCs due to the larger travel distances. Figure 4-11 demonstrates this. For each reference farm, the left set of figures shows the transit times for DCs and CTVs, and the right set shows how much time is won by using a DC instead of a CTV. The distance used for the DC is the largest distance within a wind farm. There are two distances for a CTV: the shortest route is from the port to the nearest wind turbine, and the longest route is the distance between the port and the farthest wind turbine. Lastly, a speed of 25 knots was taken as a reference point to compare travel times. As a result, a DC sailing 15 knots, for example, over the largest distance within Hornsea One, will be 45-60% faster than a CTV. Accordingly, increasing the DC speed will increase the time won back. Therefore, DCs are a valuable asset to offshore wind farm O&M. With regards to response time, DCs are always closer to the destination and should not have to sail as fast as CTVs. As a result, high speed should no longer be a requirement but a feature. Therefore, it will not explicitly be defined in the operational objectives.

4.4.2 High-level operational objectives

Figure 4-12 displays an overview of the DC's operational objectives. They focus on what the new vessel will accomplish by clearly stating the DC's purpose and tasks. Here, the objectives are used to clarify which deficiencies in current systems must be overcome to justify the development of a new DC.

Most of the objectives are already fulfilled by existing DCs, indicated in green as *fundamental objectives*. Together they distinguish the DC from other access vessels. The objective, which became a critical deficiency due to a changing operational environment, is indicated in blue

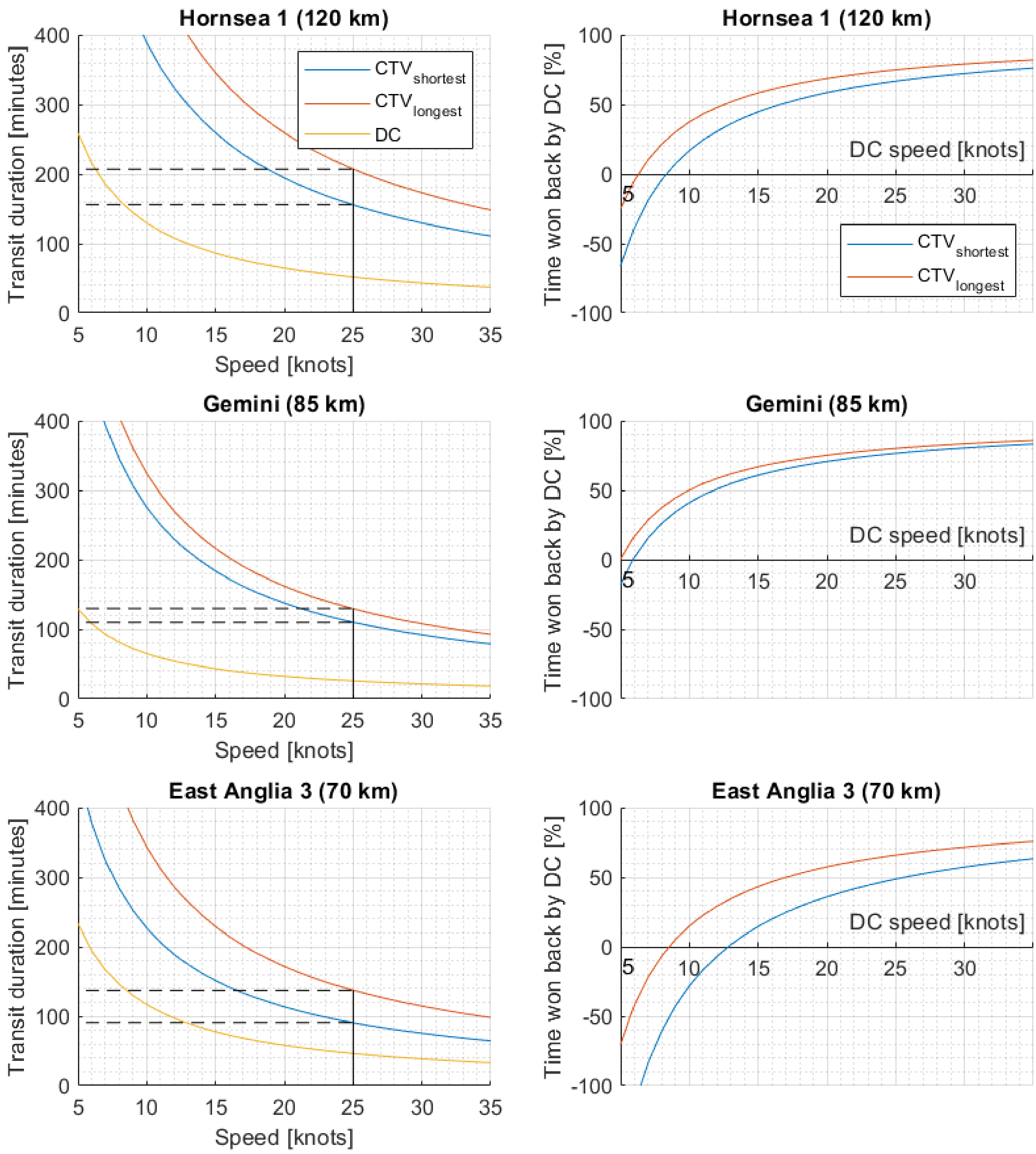


Figure 4-11: Comparison of transit duration for DC and CTV

and is characterised as the *enhanced objective*. Note that 'sufficient range to go to port' is technically an objective that is affected by the changed operational environment as well, but it is presumed to be a matter of merely increasing the fuel capacity. This is deemed less crucial to improve the operability at far offshore wind farms.

Some objectives represent boundaries that must be considered, namely those linked to storage and safety/comfort. The latter ensures that the DC is not overpowered, making it impractical for technicians to use. In fact, avoiding injuries during transfer will be emphasised in this study since turbine access is not possible without acceptable transferring conditions.

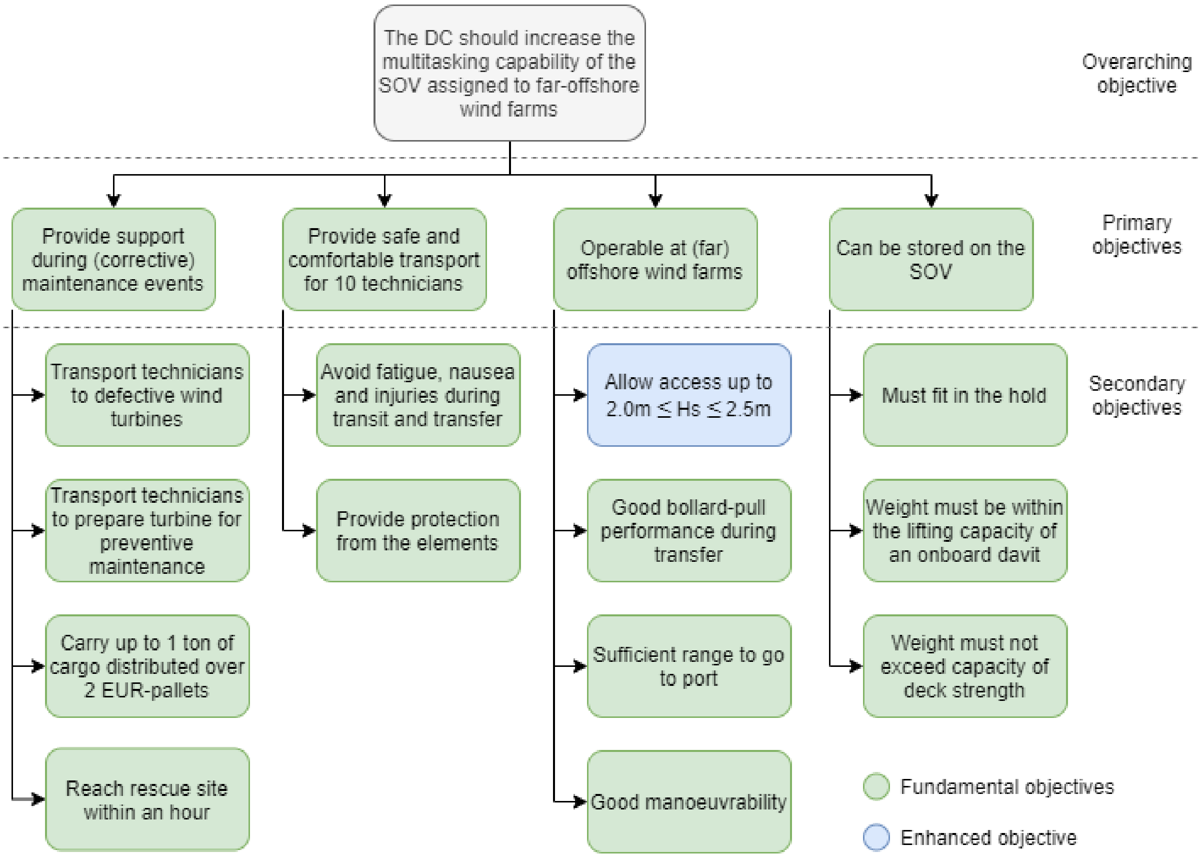


Figure 4-12: Objectives tree of the daughter craft

4.4.2.1 Match the significant wave height threshold to the new operational area

Current DCs are designed to transit at $H_s \leq 2.5$ m and transfer at $H_s \leq 1.5$ m, although transfers only take place when $H_s \leq 1.2$m. Based on Figure 4-7, the *practical* threshold gives DCs a relatively small weather window: an average accessibility rate of 45%. In the summer, this increases to 65% but decreases to a low 30% in the winter. O&M operators are aware of this difference and currently accept it as a risk in their maintenance strategy. Still, Brussel and Bierbooms [57] found that access systems should have an accessibility of at least 82% if operators wish to maintain a wind farm availability of over 90%. Therefore, to increase accessibility to offshore wind turbines, **the requirement for transfer using DCs should be increased from $H_s \leq 1.5$ m to a range of 2.0 m < $H_s \leq 2.5$ m** to be capable of operating in the conditions frequently observed at far-offshore wind farms.

Though it is seasonal, Figure 4-6 shows that $H_s \leq 2.5$ m appear annually at the locations of the reference farms. According to the data from Figure 4-7, increasing the DC's threshold from $H_s \leq 1.5$ m to a range of $2.0 \leq H_s \leq 2.5$ m could, in theory, increase the accessibility to wind turbines by an annual average of 32-43%. This would give the DC a similar level of average accessibility (77-88% for Hornsea One) as the SOV. Figure 4-13 offers a different perspective as it shows the operability per month. It also shows how much could theoretically be gained when a vessel is designed for higher significant wave heights. Most importantly, this graph confirms that most of the accessibility can be gained during the winter. Note that this graph was made considering hourly measurements. Appendix A4 provides information on how the weather data was processed.

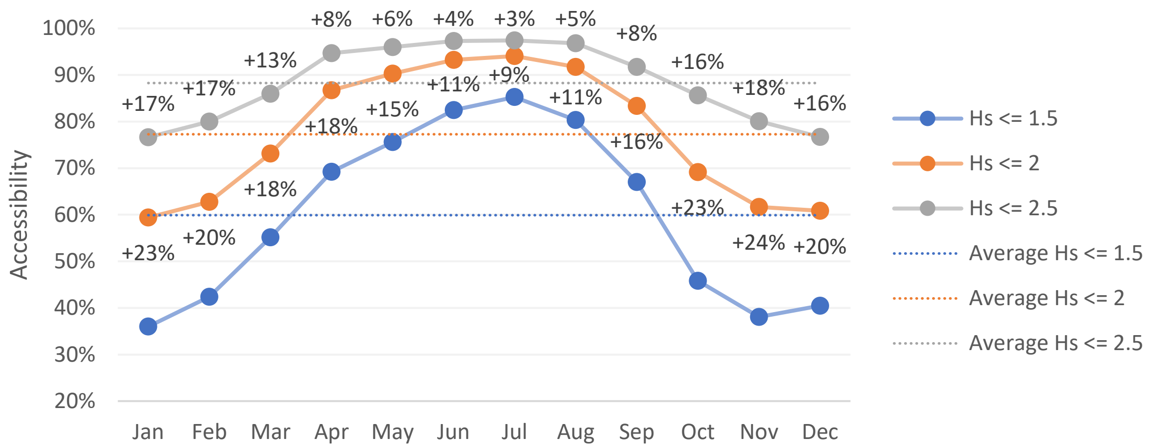
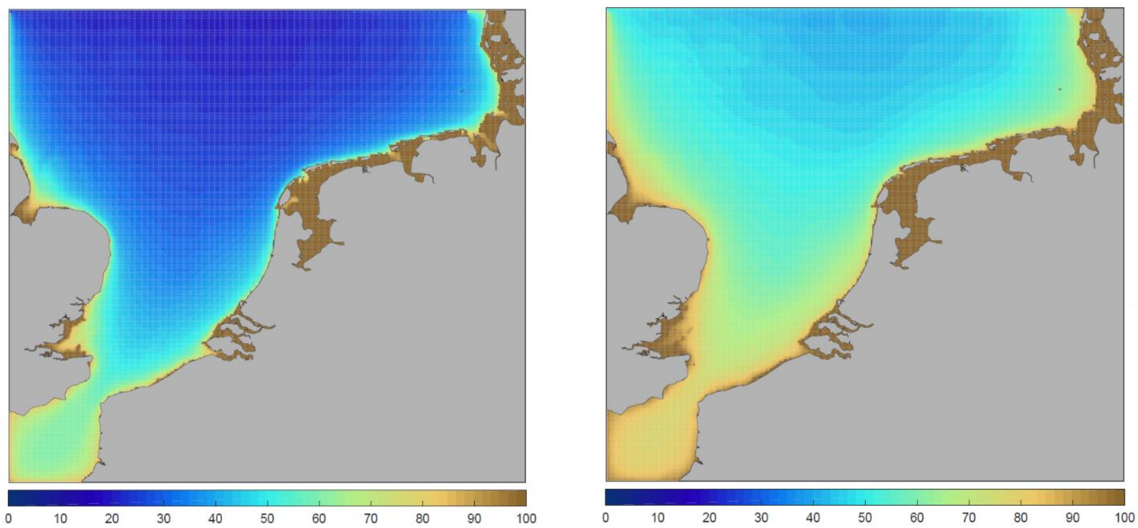


Figure 4-13: Theoretical accessibility per month at Hornsea One

This theory is supported by the results of Lavidas and Polinder [19]. Figure 4-14 demonstrates how the wind turbine accessibility increases by 20-35% when vessels can operate in $H_s \leq 1.5$ m versus $H_s \leq 1.0$ m. This is all because the vessel is no longer limited by a higher range of high waves, giving it a larger weather window.



(a) $H_s \leq 1.0$ m *(b) $H_s \leq 1.5$ m*

Figure 4-14: Accessibility in percentage of time, based on different thresholds [19]

4.4.2.2 Inclusion of wave steepness in the design process

Literature commonly refers to the significant wave height to describe an O&M vessel's performance. However, this parameter alone is not enough as a design guideline because of the interaction between the three phenomena [47], given in section 4.2. Therefore, this study will include the wave steepness in the process. Table 4-2 shows how many waves correspond to a specific combination of significant wave heights and wave periods. Table 4-3 shows the corresponding values for wave steepness.

Based on those two tables, it is clear that $0.05 \leq S \leq 0.06$ is the highest wave steepness to consider. However, it is on the conservative side since $S = 0.03$ is what predominantly occurs. Although $S \geq 0.10$ also appears, Table 4-2 shows that only 1 in the 35064 waves showed this characteristic. Therefore, it is deemed negligible. The same judgement is applied to the notably higher values corresponding to $H_s = 0.5$ m, which have less than a 0.03% chance of occurring. It is also presumed that these relatively small waves will have minimal impact.

4.5 Concluding insights

This chapter established that DCs have the most potential to allow O&M operators to carry out corrective maintenance from an SOV. A brief analysis of DC transit times shows that DCs can sail slower than CTVs and would still reach their destination earlier. So, 25 knots should no longer be required as a design speed but become the desired top speed. Then, rescue operations can still be carried out using the DCs if it is not possible to use the Fast Rescue Crafts. Furthermore, this new objective could change certain design aspects. For example, since high speeds are no longer a necessity, hard-chines could become obsolete. However, the optimal design speed is unknown, which is why it was not explicitly specified in the secondary objectives.

Lastly, of all the operational objectives, only the access objective was enhanced to address the greatest deficiency of current DCs: low accessibility (during the winter) at far-offshore wind farms. This objective applies to both the transit and transfer phase, although current DCs were already designed to transit in $H_s \leq 2.5$ m. So, it is mainly the original transfer requirement that is enhanced here. Furthermore, the crew can always rely on adjusting its course and speed during transit. But during transfers with zero-speed, the DC must have adequate stability to allow safe transfers to take place. Furthermore, the (optimal) design speed for transit is now unknown because the current requirement of 25 knots is no longer considered necessary. Based on those three reasons, this thesis will primarily focus on the transfer phase.

5 Functional analysis

This chapter is the second step in the *Needs Analysis* phase within *Concept Development*. It establishes whether there is a feasible and technical approach to design a system that could meet the operational objectives stated in section 4.4.2.

The DC's enhanced objective is essentially about improving seakeeping. Beukelman [58] states that a ship's behaviour in a seaway primarily depends on its speed, main dimensions, and proportions. The second point of interest is the underwater hull form parameters and the weight distribution, especially for fast semi-planing ships. Tan [59] adds that the relationship of the ship length to significant wave length and the ship's course also play a vital role. A majority of these points can be traced back to the DC's hull, which makes that the system's function-of-interest.

Section 5.1 clarifies key terminology in seakeeping by describing basic terms and ship stability. Then, the performance of different hull types is covered in section 5.2. Specifically, it discusses the hull types of current DCs and CTVs because they also make use of the boat landing, and the latter generally have better accessibility. The next two sections cover the ship motions involved during both transit (section 5.3) and transfer (section 5.4). Note that transit is still covered because access is not possible without it. Then, the method to analyse the responses of existing DCs in various (rougher) wave spectra are given in section 5.5, and the results which give insight into their seakeeping performance is covered in section 5.6. Lastly, section 5.7 concludes the chapter by discussing the main observations.

5.1 Key terminology in seakeeping

5.1.1 Incoming wave angles and ship motions

Ships respond to waves that can come from any angle (μ). In this report, distinct incoming waves are labelled according to terms shown in Figure 5-1.

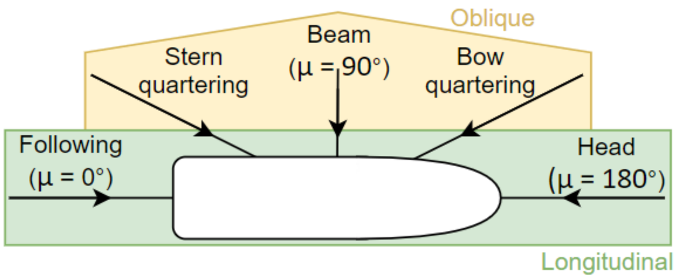


Figure 5-1: Incoming wave labels

How ships respond depends on their seakeeping performance and stability. Speed also plays a role, so both access phases are characterised by different responses from DCs. A majority of studies (e.g. Ref. [60], [59] and [61]) agree that vertical and horizontal accelerations on board are generally the most limiting parameters. Figure 5-2 shows the six degrees of freedom, three of which are translational, and three are rotational motions. But only heave, roll, and pitch have hydrostatic restoring forces and therefore possess natural response periods [62]. Yang et al. [42] identify these three motions as critical to the safety of transfer. So, this project will only focus on these three motions. So, the vertical acceleration is caused by heave and pitch, and the roll motion induces the lateral acceleration.

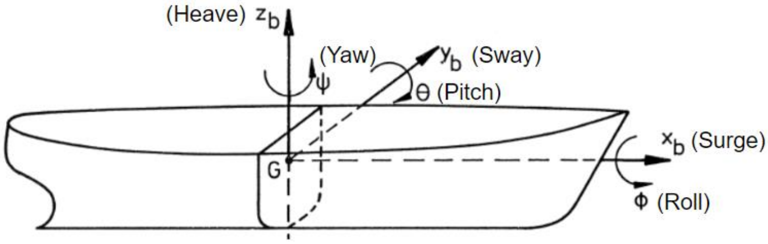


Figure 5-2: Ship motions (Adapted from [63]*)*

5.1.2 Ship stability

Stability is the capacity for a vessel to return to a stable state after a disturbance. A vessel with good initial stability can make it easier to limit accelerations, but excessive stability could result in motion sickness. After a disturbance, only the motions for heave, roll, and pitch will restore a vessel to its stable state due to the presence of restoring forces. However, with regards to rotational stability, only roll and pitch are of concern. These are referred to as transverse and longitudinal stability, respectively. Furthermore, ships are inherently more stable in the longitudinal direction since there is relatively more buoyancy reserve.

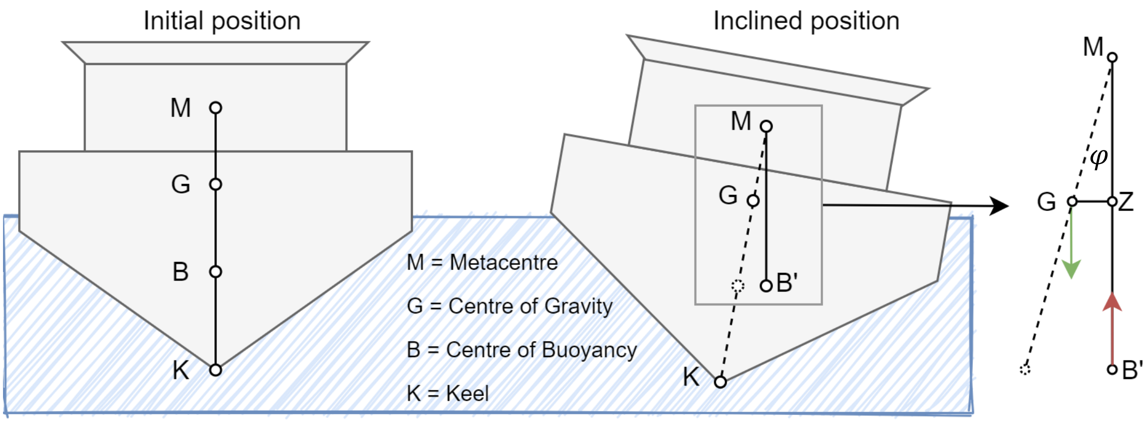


Figure 5-3: Ship transverse stability

Ship stability is commonly expressed using the stiffness parameter: the metacentric height (GM), which is the vertical distance between the vessel's centre of gravity (G or CoG) and metacentre (M). The latter is the intersection of vertical lines through the original and shifted centres of buoyancy (B) in the initial and slightly inclined positions [4]. In simplified cases, M is assumed not to shift for small heeling angles ($0° < \varphi < 10°$). Figure 5-3 illustrates how B shifts off the centreline when the submerged geometry changes, while G remains. This offset creates a distance, called the righting arm (GZ), between the equal forces that act in opposite directions. If the arm is positive, a rotation is produced until the vessel rolls back to its initial (upright) position. Figure 5-4 shows the righting arms of several types of vessels.

A vessel with a small GM is more prone to capsizing after rough weather conditions cause it to heel due to the small GZ it creates [64]. This leads to a long roll period, i.e. it takes longer to roll back to the initial position. On the other hand, a large GM will lead to a short roll period, making the ship stiffer since it rolls back to the initial position faster. The same theory applies to longitudinal stability.

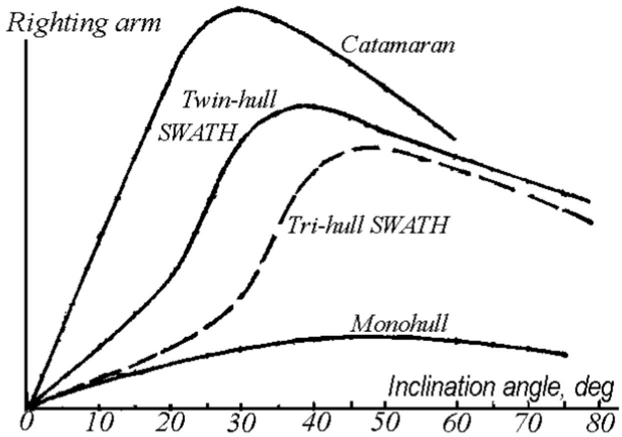


Figure 5-4: Transverse stability comparison of some multihulls and monohull [65]

5.2 Existing hull types for small access vessels

Only the hulls of DCs and CTVs are studied here since these vessels use the boat landing to transfer technicians to a wind turbine. The other access vessels from section 3.2 are not included because they were designed to transfer using other or additional system functions.

5.2.1 Daughter craft

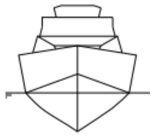
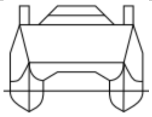
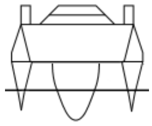
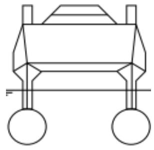
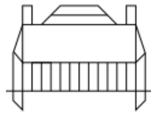
There are many commercially available DCs for O&M operators to use. Most are monohulls with a hard chine, which means that the (straight) hull has a "knuckle". At speeds of $Fr \geq 0.7$, this design feature hydrodynamically lifts part of the vessel out of the water, also known as planing. The reduced wetted surface and resistance promotes speed-power performance. This is what enables existing DCs to reach top speeds of 35-45 knots. The following section elaborates on the performance of monohulls and compares it to hull types.

5.2.2 Hull types applied to CTVs

Hu et al. [15] made an overview of commercially available access vessels for offshore wind farms, see Table 5-1. These (advanced) vessel types are described using definitions given by Stapersma et al. [3]:

- Monohull: A single hull vessel, and in this case, with such an underwater configuration that at high speed, a hydrodynamic (lift) force is generated which acts on the ship's bottom and thereby lifts the ship partly (semi-planing) or almost fully (planing) above the water surface.
- Multihull: A vessel consisting of two or more hulls (such as a catamaran or trimaran) which may show, more or less, similar lift behaviour as monohulls at high speeds. It was developed to provide larger deck areas and more stable platforms against roll.
- Small Waterplane Area Twin Hull (SWATH): A vessel derived from catamarans and has relatively deeply submerged cylindrical hulls. The small volume and waterline area of the surface piercing struts give the SWATH superior behaviour, especially in head waves.
- Surface Effect Ship (SES): A vessel that rests partly on an air-cushion (static air pressure) which is generated by fans and retained by a construction of fixed and/or flexible sidewalls ("skirts").

Table 5-1: Typical characteristics of CTV types [15]

		Monohull	Catamaran	Trimaran	SWATH	SES
Length	[m]	12 – 25	15 – 27	19 – 27	20 – 34	26 – 28
Transit speed	[knots]	15 – 25	18 – 27	18 – 22	18 – 23	35 – 39
Passengers	[-]	12	12	12	12/24	12/24
Cargo	[tons]	5 – 10	10 – 15	1 – 5	2 – 10	3 – 5
H_s	[m]	1 – 1.2	1.2 – 1.5	1.5 – 1.7	1.7 – 2	1.8 – 2.2
Sketched shape		 [66]	 [66]	 Adapted from [67]	 [66]	 [66]

These different and advanced designs were created to minimise the resistance by minimising the displacement volume and wetted surface, or both [68]. Table 5-1 also shows how operability (H_s) varies with the different hull types. The advantages and disadvantages of each vessel type, according to Hu et al. [15], is given in Table 5-2.

Table 5-2: Advantages and disadvantages of the CTV types (Adapted from [15]*)*

	Advantages	Disadvantages
Monohull	• Low cost • Scalable	• Can only operate up to sea states of 1 m < H_s < 1.2 m due to their low stability while transferring offshore technicians onto the monopile
Multihull	• Can achieve high speeds • Good seakeeping in medium sea conditions • Improved stability when pushing against the boat landing	• Relatively higher costs compared to monohulls
SWATH	• Greater stability by minimising the hull cross-section at the sea's surface	• High costs • Lower speed compared to catamarans
SES	• High stability leading to high speeds • Less fuel consumption • Good seakeeping behaviour	• Complex designs • High costs

5.2.2.1 Extreme semi-SWATH

Jupp et al. [28] reported on BMT's extreme semi-SWATH (XSS), see Figure 5-5, which combines the characteristics of catamarans and SWATHs. The aim was to develop a wind farm support vessel with the technical benefits of a SWATH without the associated cost and complexity. It is considered an improvement compared to semi-SWATHs, which were developed for the commercial fast ferry market and have always been constrained by the increased fuel consumption tolerated by the industry [28]. Furthermore, the XSS bridges the gap in technical ability between a SWATH and a semi-SWATH, with only a limited commercial performance reduction. However, it will have a higher power requirement than a catamaran.

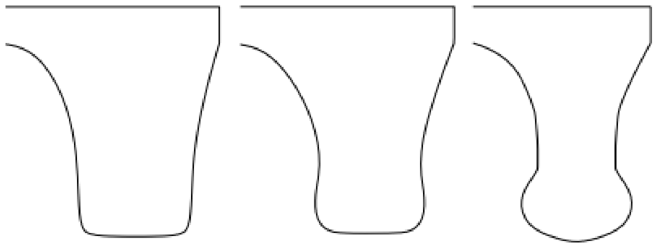


Figure 5-5: Comparative sections – Left to right; Conventional Catamaran, ModCat, XSS [28]

They carried out seakeeping tests using a (physical) model to measure the heave, pitch and vertical accelerations during transit. The actual results were not presented in the paper, but in combination with an active ride control system, initial predictions indicated that the motions and accelerations could be reduced by 80%. As a result, Turbine Transfers built two 24-metre XSS as a CTV, see Figure 5-6.

Figure 5-6: 24 m XSS Wind farm Support Vessel [69]

5.3 Ship response parameters during transit

Transit quality depends on the weather conditions and a vessel's seakeeping performance. The latter is evaluated against seakeeping criteria, expressed as some limiting values of ship motion response to wave action [3].

Various thresholds for acceptable motions during transit have been established, and seem to depend on vessel size, speed, trip duration, encounter frequency, onboard location and level of required human effectiveness (e.g. Ref. [3], [61] and [68]). For example, long transit times expose passengers to long periods of induced motions, which leads to motion sickness. Experienced passengers such as O&M technicians are generally resistant to this. But rough weather can cause excessive and extreme accelerated motions, which may cause discomfort or harm and reduce their ability to perform at the wind turbine. According to Journée and Massie [70], the vertical acceleration limits are higher for small craft because the crew can tolerate higher vertical acceleration when the oscillation frequency is high. Section 4.4.1 displayed how much time is saved by using DCs instead of CTVs. These shorter travel times make rougher transit conditions slightly more acceptable.

So, seakeeping criteria are mission-dependent, though they are often still exceeded due to rough weather conditions. A study by de Jong [66] aimed to qualify the characteristics of the seakeeping behaviour of fast ships. This was done by re-examining previously obtained experimental material (e.g. by Keuning and van Walree [68]), both at full- and model-scale. The events that are defined as limiting factors for safe operation in waves are elaborated in the following sections.

5.3.1 Slamming, (voluntary) speed reduction and bow diving

Keuning and van Walree [68] determined that the crews on high-speed craft typically impose a voluntary speed reduction to avoid high peaks in the vertical acceleration. They add that the occurrence of such a “one big peak” is generally what provoked a speed reduction by all the crews to “prevent it from happening again” [68].

These high peaks can lead to slamming, which jeopardises crew safety and the vessel’s structure. These levels are highest in head waves ([60]) and often bow-quartering waves [70]. Changing the vessel’s heading can reduce the risk of slamming, but practical course headings are sometimes limited. Phillips et al. [61] state that stern-quartering and following seas can cause a sailing vessel to accelerate down a wavefront and bury its bow into the back of the wave in front and potentially lead to broaching and capsizing.

5.3.2 Green water and deck wetness

Another transit event is green water shipping or spray; it is not ideal, but it is tolerated. ESVAGT’s DC (STB12), for example, experiences green water shipping in $H_s \geq 1.2$m and but it mostly depends on the wind and wave pattern. The crew and passengers are protected in the weather-tight cabin. But cargo stored outside could be damaged or even thrown overboard if the green water quantity is vast. So, cargo is always securely fastened and covered with watertight material. Green water will also lead to deck wetness, which increases the risk of technicians slipping. However, decks can also become wet due to rain. Therefore, decks are generally covered with a non-slip coating.

5.4 Ship response parameters during transfer

Transferring technicians to a turbine is the riskier phase of the two because some passengers will move around the vessel and have to “jump” onto the turbine’s ladder. Also, green water could cause the technicians to fall or be injured by hurled cargo. Lastly, extreme motions during transfers and large pushing forces can also severely damage the wind turbine’s boat landing [42]. This is what vessels push onto to allow technicians to jump across.

Figure 5-7 shows how the DC’s fender interacts with the boat landing, and these transfers can take place in one of two ways: when pushing onto the boat landing, there is either a fixed contact point, or the fender slides up and down the boat landing.

Figure 5-7: A top view of a fender interacting with the wind turbine’s boat landing [71]

5.4.1 Push-on transfer

A push-on transfer is a landing operation where the friction force between the vessel-fixed fender and the boat landing keeps the relative motion (close to) zero [71]. This is the preferred transfer method among O&M operators because slip is then minimised.

5.4.1.1 Fender slip and propulsor ventilation

According to Wu [71], slip is thought not to occur if the shear force (J_3) that is caused by waves is smaller than a factor of the combined bollard push (F_b) and normal force (J_1):

$$|J_3| < \alpha[F_b + J_1] \quad (4)$$

With α being the friction coefficient, which depends on the material of the fender. The frequency of slip should be minimised because a wrongly timed jump could have harmful or fatal consequences. This could be done by providing the DC's with the appropriate propulsion system (which includes engine and propulsor) and designing a suitable fender. But slip can also be the consequence of propulsor ventilation. Assuming that the transfers take place at the bow, Phillips et al. [61] explain that short steep waves located near amidships can pitch the vessel stern-up, which will cause the propulsor to (approach or) emerge from the water surface, see Figure 5-8. The propulsor could then suck in air which reduces thrust. As a result, F_b is lowered, and slip is more likely to occur.

Figure 5-8: Sketched propulsor ventilation (Vessel: ProZero DCW 15 m Transfer Vessel, taken from [72])

5.4.1.2 No-slip confidence level

The same study by Phillips et al. [61] reveals a current[7] no-slip confidence level as low as 70%. This is based on conditions where the zero-crossing wave period is six seconds, which leads to 30 slips per ten minutes. The industry currently works around this by only putting the vessels to use during calm weather conditions. However, they propose that the industry increases this threshold to one slip every ten minutes to obtain a confidence level of 99%.

5.4.2 Sliding transfer

The sliding transfer is similar to push-on transfer, except that the vessel is allowed to move vertically and thus follows the swell/wave pattern. So, slip is accepted within the process, contrary to the preference that slip is minimised. The underlying principle is that safety during transfers is improved by making the risk visible instead of hiding it [73]. Vessels such as the DC have relatively less inertia and power to push onto the boat landing and hold its position. Considering equation 4 from section 5.4.1.1, the wave forces are more likely to cause slip. Therefore, sliding access is deemed more applicable to these small access vessels.

[7] Statement was published in 2015.

Regarding propulsor ventilation, it is assumed that a wave capable of lifting the stern, when it is situated midship, will sooner push the small vessel off the turbine rather than cause the propulsor the ventilate.

5.5 Seakeeping performance analysis method

Seakeeping can be studied using a broad range of techniques, both digitally and through (scaled) experiments. It would be best to do digital simulations in the early design stage of a vessel rather than perform scaled model tests since these are more suited for iterated and established designs. So, simulations are made to gain insight into how different the DCs' motions are in several wave spectra and headings.

The analysis method is shown in Figure 5-9 and is similar to the approach by Tan [59]. However, in this case, operational criteria will not be used to make a design assessment. That is, as stated by Phillips et al. [61], because there is seemingly far less experience and consensus with respect to the limits of vessel motion for transfer mode. They also suggest a threshold given in section 6.2.2, but it is unclear how feasible those values are for DCs. The two-dimensional Strip Theory (within MAXSURF Motions) is expected to overestimate the resulting motions because it neglects the effects of three-dimensional flow, viscosity and nonlinearities [74]. So, it is presumed that these criteria will often be exceeded. Strip Theory and its applicability are further elaborated in section 5.5.2.

Therefore, this report aims to compare the DCs to each other based on priorities in ship performance rather than operational criteria. As a result, the operator guidance segment will not include operability plots but rather demonstrate which DC works best, given the set of responses to certain conditions. Also, this chapter analyses existing DCs. So, the feedback obtained from the design assessment, which addresses the deficiencies, will be applied in chapter 6, where a reflection on the original DCs will lead to the design of new DCs. These new DCs are then analysed using the same method in chapter 7. Figure 5-9 also illustrates in which chapters each step of the method is taken.

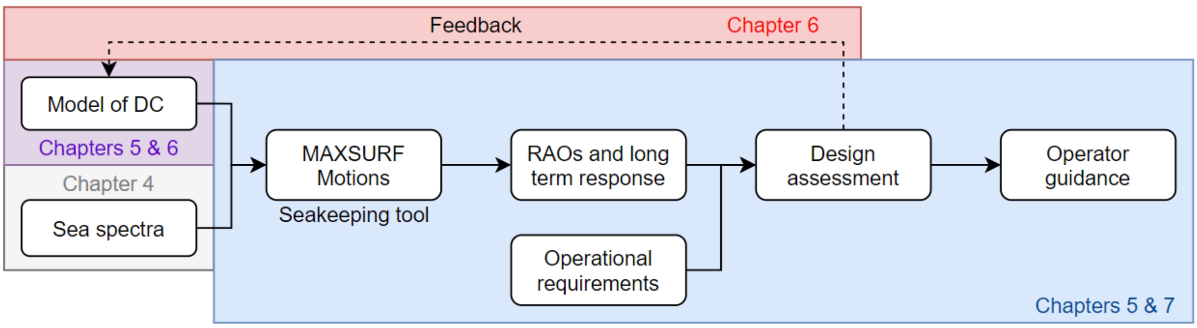


Figure 5-9: Seakeeping performance analysis method (Adapted from [59])

5.5.1 DC hull models and their development

Mock-ups of a small, medium and large existing DC were created with lengths of 10, 13 and 16 metres, respectively. These three were chosen to gain an insight into the capabilities of a range of DCs currently available.Other specifics and model line plans are given in Appendix B. Public information about the reference DCs are provided as well.

5.5.1.1 Hull generation

The DC models were created using MAXSURF Modeler. First, a draft of the hard chine monohull was created by letting the “quick start” module create a workboat with the desired primary hull parameters, see Figure 5-10. The hard chine is the line that splits the red and grey surfaces. The figure also shows the control points which change the hull shape when shifted and the waterline. Then, several detailed views of the reference vessels were inserted as background images to be traced. However, these drawings are confidential. So, while these were used alongside public photos to replicate the DCs, this report will not demonstrate how the tracing was done, but it will explain the general approach.

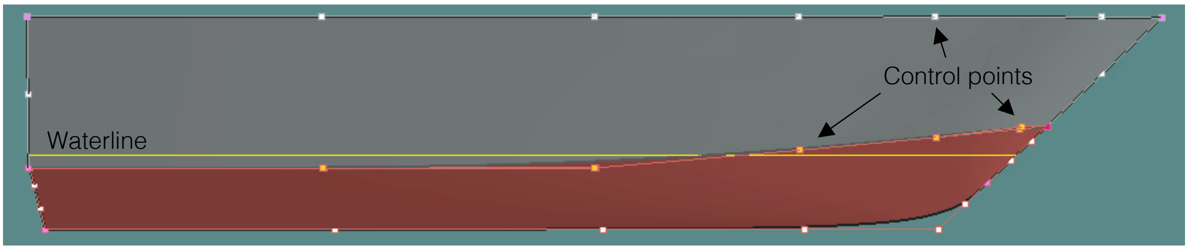


Figure 5-10: Default hull shape of workboat by MAXSURF Modeler

The five major changes that were required to give all DCs the required shape are as follows:

1. The outline of each vessel was replicated to establish the outer shapes. It was mainly the depth and bow shape that needed adjusting. Specifically, its profile had to be “less sharp”; see the difference between Figure 5-10 and Figure 5-11.
2. The slope of the hard chine was different, especially for the small and large reference DC. Mostly the height at the bow had to be adjusted using the control points; see the difference between Figure 5-10 and Figure 5-11.

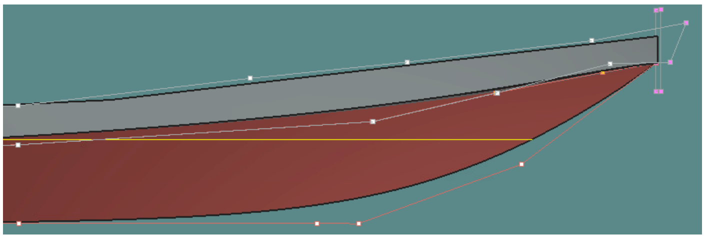
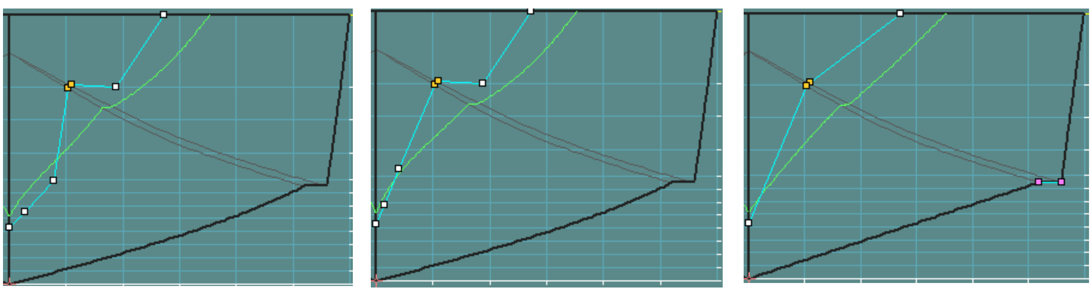


Figure 5-11: Profile view of altered bow shape and hard chine height

3. After the hard chine was altered, the topside and bottom (i.e. grey and red part of the hull in Figure 5-10) surfaces were no longer straight (Figure 5-12a), which is necessary for planing; even after straightening the control points (Figure 5-12b). Therefore, the intermediate control points were deleted, and these surfaces were made linearly stiff in the transverse direction (Figure 5-12c).



(a) (b) (c)

Figure 5-12: Hull made linearly stiff to obtain “flat” plates

4. The small and large DC also had spray rails. However, they were not modelled in the mock-ups because they would distort the Lewis mapping, see section 5.5.3.1. Instead, they were implemented as a roll damping factor, see section 5.5.3.2.
5. The transfer platform was shaped. But it will not affect the results because Strip Theory does not distinguish between alternative above water hull forms [75].

5.5.1.2 Resulting DC mock-ups to be tested

The resulting DC models are shown in Figure 5-13. Note that the shown images are not to scale. These models were inspected visually and deemed to have a good resemblance to the confidential line plans. Still, the results may deviate slightly from the actual motions of these vessels since these mock-ups were not optimised through iterations. This is acceptable as these models serve to study (hard chine) monohull behaviour in high waves.

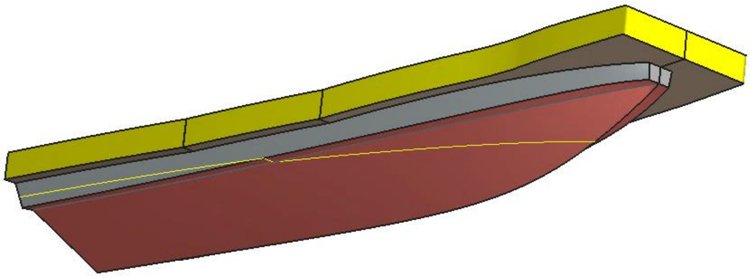
5.5.1.3 Hull fairing

The hull shapes were also evaluated for good fairness, which is important for hydrodynamics because water particles flow over the hull surface, and their motion is governed by the derivatives of the curves on the hull surface [76]. This was assessed for all hulls by checking the longitudinal curvature gradient: the colours should evenly graduate along the hull. Changes from blue to red indicate that there are inflections. Transverse curvature is not assessed because the hulls are relatively flat in the transverse direction. Figure 5-14 shows an acceptable longitudinal curvature for all three DCs, even with the inflection at the aft of the medium-sized DC caused by the heightened stern. Also, the larger DC shows a minor inflection by the hard chine at the bow. But it is not expected to disturb the flow drastically because it is situated above the waterline. Overall, the vessels are established to be fair.

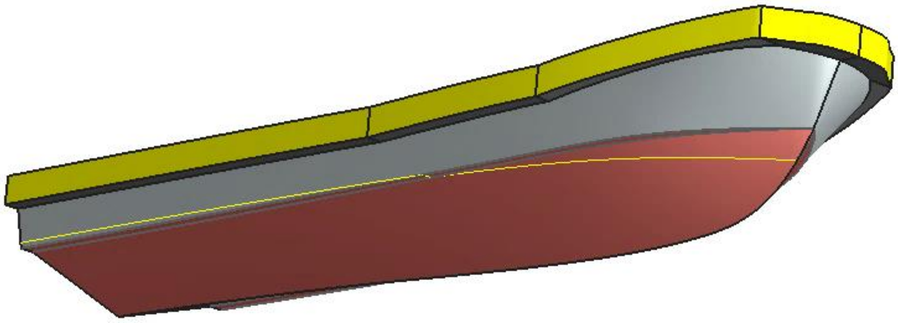
5.5.2 Strip Theory and its applicability

The seakeeping analysis was done using Strip Theory, which is a linear, frequency domain approach to study seakeeping. In essence, it converts the three-dimensional underwater hull into two-dimensional sections or strips, each of which has associated local hydrodynamic properties (added mass, damping and stiffness), which contribute to the coefficients for the complete hull [77]. This is not the only way to study seakeeping, but it is a practical method to determine ship motions without resorting to (scaled) experiments. It also requires significantly less computation time to produce seakeeping predictions compared to 3D methods. It is especially useful for including seakeeping in the early design analysis of alternatives and calculating mission operability [78]. Note that the reference DCs are not in an early design stage, but the method is deemed valid for this thesis as it uses mock-ups that will later be compared. According to Lloyd [77], there are several approaches to this theory, but all apply the same assumptions. The following list specifies these assumptions, which are elaborated to discuss the applicability to this case.

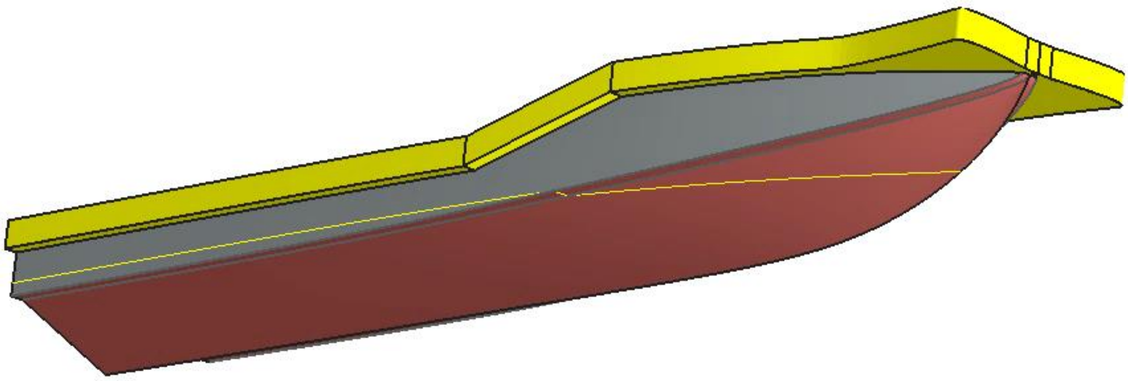
- The ship is slender: The predictions are effective for ships with $L/B \geq 2.5$ m [79]. The three mock-ups have an L/B-ratio of approximately 2.8 m, 3.3 m and 4.10 m.
- The ship hull sections are wall sided: The hydrostatic properties should not change as the ship rolls [78]. The non-linear effects caused by the DC's wedge-like hull shape (or flare) will not be captured by linear Strip Theory, which will lead to inaccuracies.



a) Small DC (10 metres)



b) Medium DC (13 metres)



c) Large DC (16 metres)

Figure 5-13: Mock-ups (Images are not to scale)

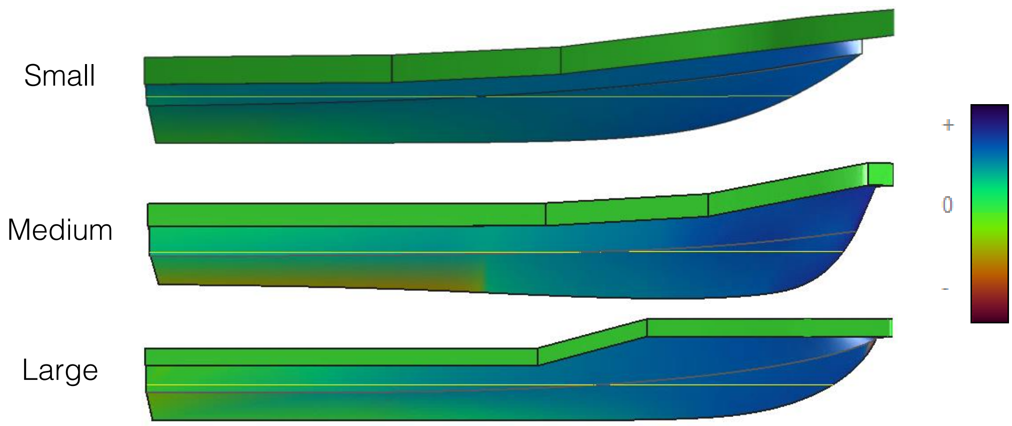


Figure 5-14: Hull fairness (Images are not to scale)

- The motions are small: Then, the submerged geometry (used to calculate radiation, diffraction and incident wave forces) can be considered constant [78]. But this is not the case since the relatively large waves are expected to induce large motions on the DCs. As a result, non-linear effects due to emergence or submergence will be lost.
- The hull's presence does not affect the waves: The DCs' inertias are relatively small, meaning waves are more likely to affect the DC than vice versa.
- The hull is rigid so that no flexure of the structure occurs: The hull is indeed stiff.
- The speed is moderate, so there is no appreciable planing lift: The DCs are capable of planing at speed, but the analysis is done at zero-speed.
- The water depth is much greater than the wavelength, so that deepwater wave approximations may be applied: Which is the case according to section 4.2.3.

So, the Strip Theory will not give entirely accurate results due to non-linear behaviours. However, as argued by Keuning and Pinkster [60], the linear approach may be justified for the sake of comparison. Lastly, Strip Theory only delivers the results for heave, roll and pitch. But this is acceptable since these were the motions of interest, as stated in section 5.1.1.

5.5.3 Input parameters for MAXSURF Motions

For conciseness, only the large DC is shown in the following figures as the figures for the other DCs were similar. Figure 5-15 shows the large DC with the applied settings. Specifically, they show which locations are of interest, how many Strip Theory sections are placed and how they were shaped. The following paragraphs explain the process to achieve this. Note that corrections for the transom stern are neglected because these terms have no effect at zero-speed [80].

5.5.3.1 Measure hull

Strip Theory requires the hull to be divided into multiple 2D-sections to carry out the analysis. Furthermore, the accuracy of the seakeeping analysis is controlled by the amount of mapped sections and the number of mapping terms. They are displayed as green lines in Figure 5-15. For proper predictions, the number of sections, equally spaced between the aft (AP) and forward perpendicular (FP), was set to the maximum number where the mapping still correctly followed the DC's shape. Ultimately, each DC was given a different number of sections since it varied when the mapped section would be distorted. The medium DC was given a low number of sections (15) because a higher amount would always cause at least one section to distort.

Furthermore, Lewis sections are used to map the vessel's sections and are required to compute the hydrodynamic properties. MAXSURF Motions chooses the best Lewis sections that should fit the actual hull sections, but they are not exact replicas, see Figure 5-16. For example, angular sections, such as hard chines, are rounded off. Also, the mapped section is always horizontal, where it crosses the vertical axis and vice versa. Furthermore, it is generally up to the designer to determine what number of mappings is truly compatible. In this case, low numbers of mapping terms failed to replicate the straight hull while the maximum of 15 improperly mapped the hard chine sections. Here, the number of mapping terms varied per vessel. The large DC has 11 terms, and Figure 5-16 shows how this setting gives an acceptable balance between mapping the hull and the hard chine.

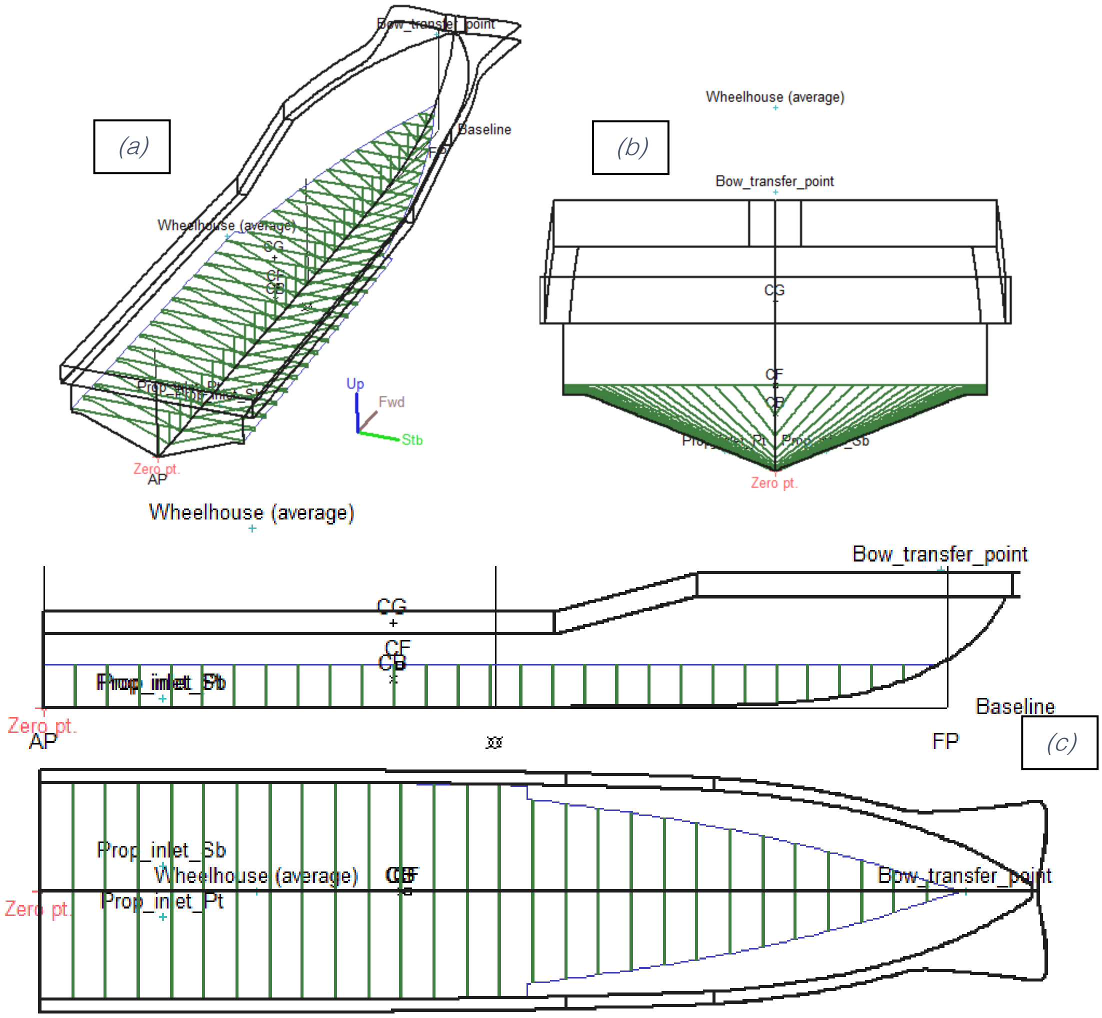


Figure 5-15: (a) Perspective, (b) section, (c) profile and (d) bottom view of large DC with input parameters

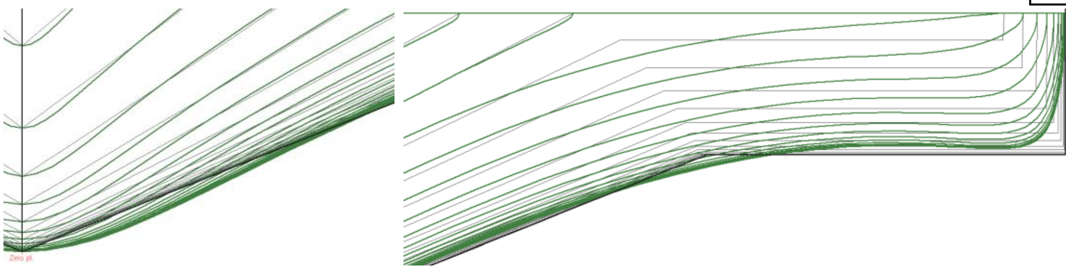


Figure 5-16: Mapped sections of the hull in green, compared to the original sections in white

5.5.3.2 Mass distribution

After the sections were established, the radii of gyration were specified for roll, pitch and yaw. These are often estimated as a percentage of the beam and length. The default settings in MAXSURF Motions correspond to widely accepted values, namely 0.35B, 0.25L and 0.25L ([70]), respectively. These values were left unchanged since the real values were unknown.

The vertical centre of gravity can also be altered here. This parameter depends on, among others, the location of the installed machinery, equipment, fuel and number of passengers. Based on existing data, the vertical centre of gravity averaged around 1.4 metres for all DCs.

5.5.3.3 Damping factors for roll

Motion damping occurs because the oscillating hull radiates energy away from the ship in the form of waves [77]. For most motions, Strip Theory makes a decent estimation of the damping factors based on (potential) wave damping while neglecting the minimal viscous effects [70]. However, viscous effects dominate the roll motion, while wave making is only a small portion of the total roll damping coefficient. Figure 5-17 gives a breakdown of the roll damping coefficient (ν) for various speeds.

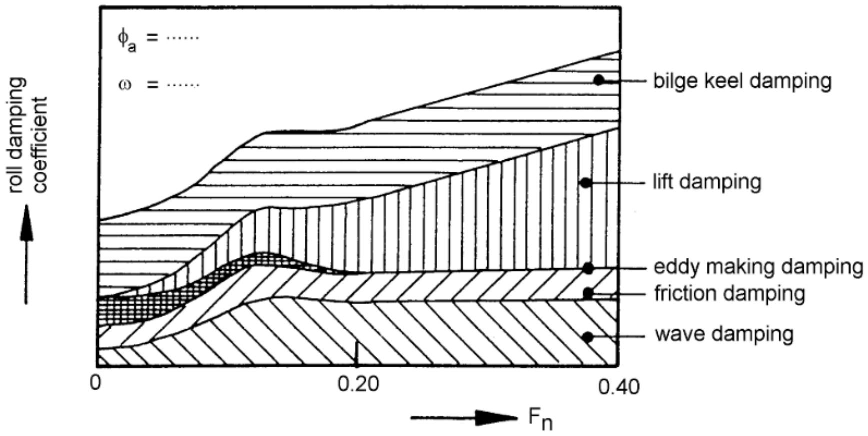


Figure 5-17: Example of roll damping components [70]

The subdivision is not entirely accurate due to hydrodynamic interaction, but it is convenient [81]. During transfers, the DC has zero-speed. Then, the lift component of roll damping is equal to zero and is therefore excluded. The remaining components that make up viscous roll damping here are skin friction, eddies, and appendage forces, see Figure 5-18, all of which have nonlinear contributions.

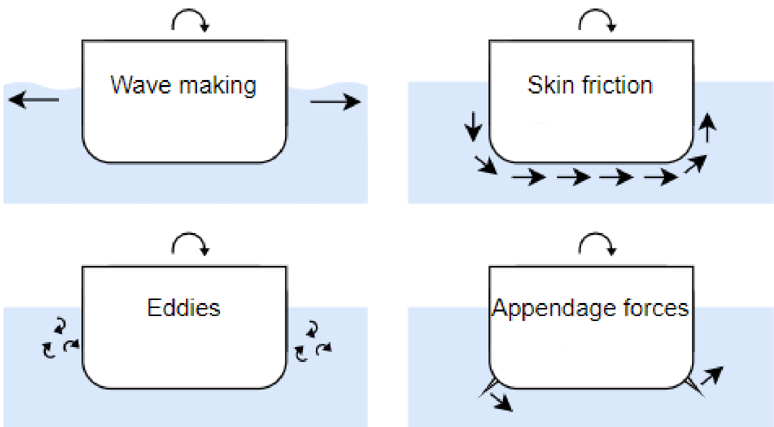


Figure 5-18: Illustration of viscous roll damping sources at zero-speed (adapted from [77]*)*

In MAXSURF Motions, the user can specify the total damping factor to include these viscous effects. The total roll damping can be determined by performing free-roll decay experiments with model tests, but physical models of these DCs are unavailable. On the other hand, there are various approaches to calculate the contribution of each component numerically (the most popular and well-examined being Ikeda's method [82]) which works satisfactorily for conventional ships. Also, the procedure given by the International Towing Tank Conference (ITTC) [83] is based on Ikeda's method and includes corrections for hard chine hulls. With this approach, the roll damping coefficient varies as it depends on roll amplitude and frequency. But many scientific works assumed a constant coefficient [84].

Krata and Wawrzynski [84] did a comparative study between linear (constant) and nonlinear models to assess their influence on roll damping modelling. In the end, both models were deemed applicable in their case. Assuming that their (general cargo) vessel does not influence the results, this project will use a constant total roll damping coefficient based on literature, although there is limited information.

The presence of a hard chine is expected to result in a relatively high roll damping coefficient due to separated vortices from the hard chine [83]. In a study by Graham [85], the total roll damping of a sailing warship with a round bilge and hard chine was 0.096 and 0.176, respectively, which is an increase of 80%. Based on Figure 5-17, the total roll damping coefficient is lower at zero-speed. Still, the DCs were tested with a roll damping coefficient of both 0.15 and 0.20. These represent the “worst” and “best” case, respectively.

5.5.3.4 Damping factors for heave and pitch

In MAXSURF motions, the damping factor for heave and pitch can be set as well. Usually, the heave and pitch damping should be left at zero because Strip Theory is capable enough to determine the RAOs of these motions. However, in sliding transfers, there is frictional contact between the DC’s fender and boat landing. Specifically, the friction is bound to affect the DC’s bow motions. The idea is that when the wave forces are low, a fraction of the combined forces F_b and J_1 (from equation 4) will hold the bow in place. As soon as the wave forces are higher, then the bow will slip. However, it was determined that a damping factor for heave and pitch would not simulate the frictional effect because it is a function of time; damping will only occur for faster heave and pitch motions. In other words, the faster the movement, the more force is applied. Thus, a damping term for these motions is more suitable for time-domain simulations.

5.5.3.5 Locations of interest

On the vessel, there were three locations of interest, namely:

- The platform at the bow where technicians wait to jump on the turbine: To see what type of motions can be expected when transfers take place.
- The “middle” of the wheelhouse: To see what type of motions can be expected in the cabin when technicians are moving around and preparing for a transfer.
- The top of propulsor inlets at port and starboard: To look for propeller emergence, which will cause thrust reduction and create a gap between the DC and boat landing.

5.5.3.6 Vessel speed

It is possible to study the motions at any (low) speed. Since transfers are being studied, the DCs are given zero-speed.

5.5.3.7 Wave directions

In MAXSURF Motions, incoming waves can be set to any angle. However, running each individual angle is excessive, so they were grouped into the five headings named in Figure 5-1. Explicitly, stern- and bow-quartering waves were set at 45° and 135°, respectively. The grouping is still expected to give a complete impression of the resulting motions.

5.5.3.8 Wave spectra

Lastly, the JONSWAP spectrum was used to specify the wave spectra needed to simulate various (irregular) sea states of the North Sea. Seven wave spectra were set up, see Table 5-3, which are based on current requirements and the weather conditions found at the reference farms.

The first spectrum (noted by 10-3) resembles common calm weather conditions; when it is generally safe to use DCs. In addition, there are essentially three pairs of spectra, each with a different significant wave height:

- H_s = 1.5 m: the current transfer requirement for DCs.
- H_s = 2.0 m: the lower boundary of the increased threshold.
- H_s = 2.5 m: the upper boundary of the increased threshold.

Of those pairs, the first spectrum represents the steepest condition for that wave height, and the second represents the most common steepness for that wave height.

Table 5-3: Simulated wave spectra and their labels

Spectrum label	10-3	15-6	15-3	20-5	20-3	25-5	25-3
Significant wave height [m]	1.0	1.5	1.5	2.0	2.0	2.5	2.5
Peak wave period [s]	4.5	4	5.5	5	6.5	5.5	7
Steepness [m]	0.03	0.06	0.03	0.05	0.03	0.05	0.03

5.6 Seakeeping performance assessment of reference DCs

With two roll damping coefficients, four locations, one speed, five wave directions and seven wave spectra, a total of 280 conditions were simulated per vessel. This section discusses the resulting motions and accelerations that can be expected from the DCs. This is given in the form of Response Amplitude Operators (RAOs) and long-term responses to (wind) waves. Furthermore, section 4.2.4 explained that the boat loadings are positioned such that head waves are encountered most, which should induce the lowest responses. So, although the dominant wave direction varies over time, mainly the responses in head waves are considered for the DC rankings.

5.6.1 Response Amplitude Operators

Typically, the first step is assessing the ship's responses to regular waves for a range of headings in the frequency domain [74]. The results are displayed in the form of RAOs. These are transfer functions that show how the vessels are likely to respond to waves at sea. Each motion has its own graph due to different mass, damping and stiffness coefficients [86]. They are also independent of the significant wave height ([66]) because the heave RAOs were made non-dimensional against wave height, and the roll and pitch RAOs against wave slope.

Here, the encounter frequency is the same as the wave frequency due to zero-speed. The lower frequencies are dominated by the restoring terms. The vessel motions will then (partly) follow the waves' height or slope, like a cork, depending on the incoming direction. The mid frequencies are dominated by damping terms. This is usually where resonance peaks are found because the encountered waves match the vessel's natural period. The mass terms (vessel inertia) dominate the higher frequencies. Then, the progressively shorter waves continuously have less effect on the ship's length until it is nought.

5.6.1.1 Relevant encounter frequencies

The RAO graphs also include an overlay, similar to the histogram in Figure 5-19, to provide additional information. This is not a wave spectrum used to determine the response spectra. It represents the occurring wave frequencies accumulated at all three reference farms. It is divided into four sets because, due to wave breaking, there is an upper frequency limit when certain wave heights will no longer occur. For example, waves larger than 1.5 metres will not occur when $\omega \geq 1.6$ rad/s while 2.5-metre waves will not occur when $\omega \geq 1.1$ rad/s. It is based on the data from tables that show the wave steepness at the reference farms, e.g. Table 4-3. Note that these limits depend on how the weather data sets are organised. In essence, the distribution helps to show which frequencies are (most) common, while the division will show in which range of wave heights the resonance peaks will occur.

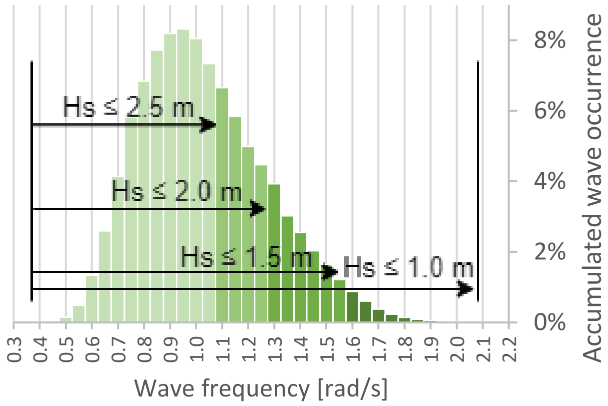


Figure 5-19: Distribution of accumulated wave occurrences

5.6.1.2 Heave RAOs

MAXSURF Motions gave incorrect heave RAOs for the specified locations because the motions for low frequencies started at zero rather than at unity. This meant that the vessel's motion would not follow the waves. The heave RAOs at the CoG did show this characteristic and thus seemed more plausible. Therefore, it was decided to use the heave RAOs of the CoG and transform them manually to the specified locations. Appendix C contains the script used to achieve these RAOs.

The resulting heave RAOs at both the bow transfer point and wheelhouse are shown in Figure 5-20. These monohulls now do show expected behaviour in all wave directions and start at unity at low frequencies, which means that they will follow the wave patterns. The differences between both locations (per vessel) are minimal and mainly occur at the lower frequencies.

Overall, this set of DCs has a good heave performance. There is peak resonance in beam waves, but all of the DCs' natural frequencies are situated outside the range of common encounter frequencies. So, the chance that DCs will experience resonance in beams during transfers is insignificant. In the event that there are beam waves travelling with $\omega \approx 2.5$ rad/s, the large DC will experience the highest responses. Also, only for the small DC is there a slight peak resonance at the wheelhouse for stern-quartering waves, but it is deemed negligible. Lastly, there is a relatively tiny peak at roughly $\omega = 11$ rad/s, which is not visible in the graphs, but the resulting response is also negligible since it does not exceed 0.2 m/ζ.

5.6.1.3 Roll RAOs

The roll RAOs are shown in Figure 5-21. Note that there is only one graph for both the bow transfer point and the wheelhouse because the responses are "angular". Also, the results for following and head waves are absent due to ship symmetry. Lastly, the response induced by stern-quartering waves is similar (in this case, the same) to the bow-quartering waves due to zero-speed. So, only the bow-quartering are visible.

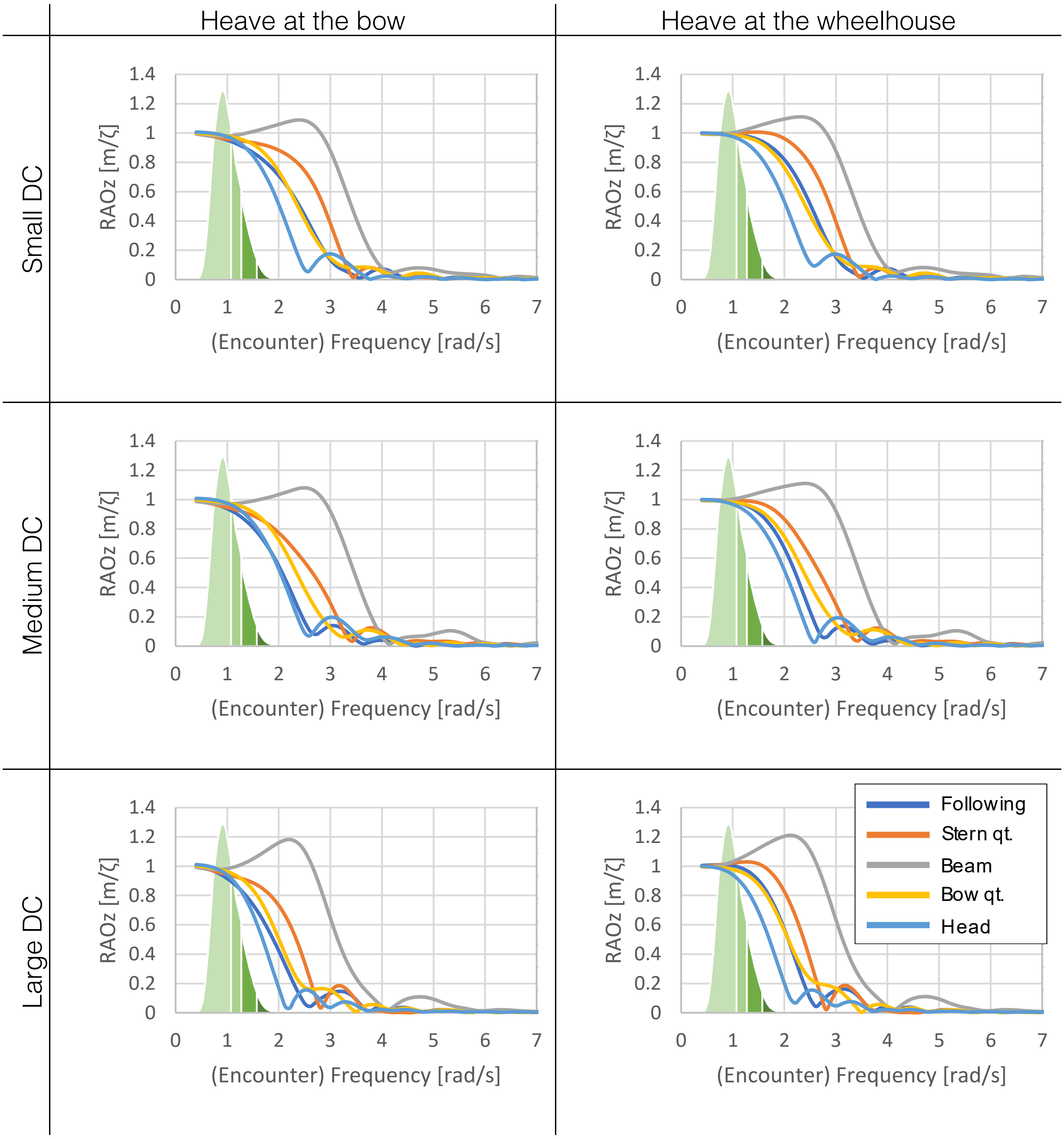


Figure 5-20: Heave RAOs at the bow transfer point and the wheelhouse

The graphs show that the natural roll frequency is approximately ω_n = 1.7 rad/s for the small DC. This is just within the range of the common wave frequencies, but the chance these waves will occur is meagre. With ω_n = 2.1 rad/s and ω_n = 2.4 rad/s, the medium and large DC, respectively, have less chance to experience resonance. Still, these DCs should not be deployed in the event that beam waves with (predominantly) the frequencies mentioned above are present. Furthermore, the quartering waves induce lower responses from the DCs. So, these conditions are safer but still can induce large motions.

Also, the response amplitudes of each DC are similar to one another; i.e. their maximum response is more or less equal. This is logical since all three DCs were given the same roll damping coefficients. Most importantly, the graphs show how υ = 0.20 leads to lower responses, which would be beneficial during transfers.

5.6.1.4 Pitch RAOs

Figure 5-21 also displays the pitch RAOs. Again, there is only one graph for both the bow transfer point and the wheelhouse because the responses are “angular”. Here, following waves will induce the largest pitch rotations. This is because the flatter stern is less suited to pierce waves compared to the bow. Also, all resonance peaks are located within the range of expected encounter frequencies. But those of the medium and large DCs are closer to the frequently observed wave frequencies. So, although the small DC has the highest response, the natural frequencies of the medium and large DC are unfavourable.

Section 4.2.3 mentioned the influence of the pitch-forcing period. For these DCs with lengths 10.6, 13 and 16 metres, the pitch-forcing periods are approximately 2.6, 2.9 and 3.2 seconds, respectively. Since these frequencies are uncommon at the relevant locations, the forecastle deck height and green water protector are not prioritised in the DCs design.

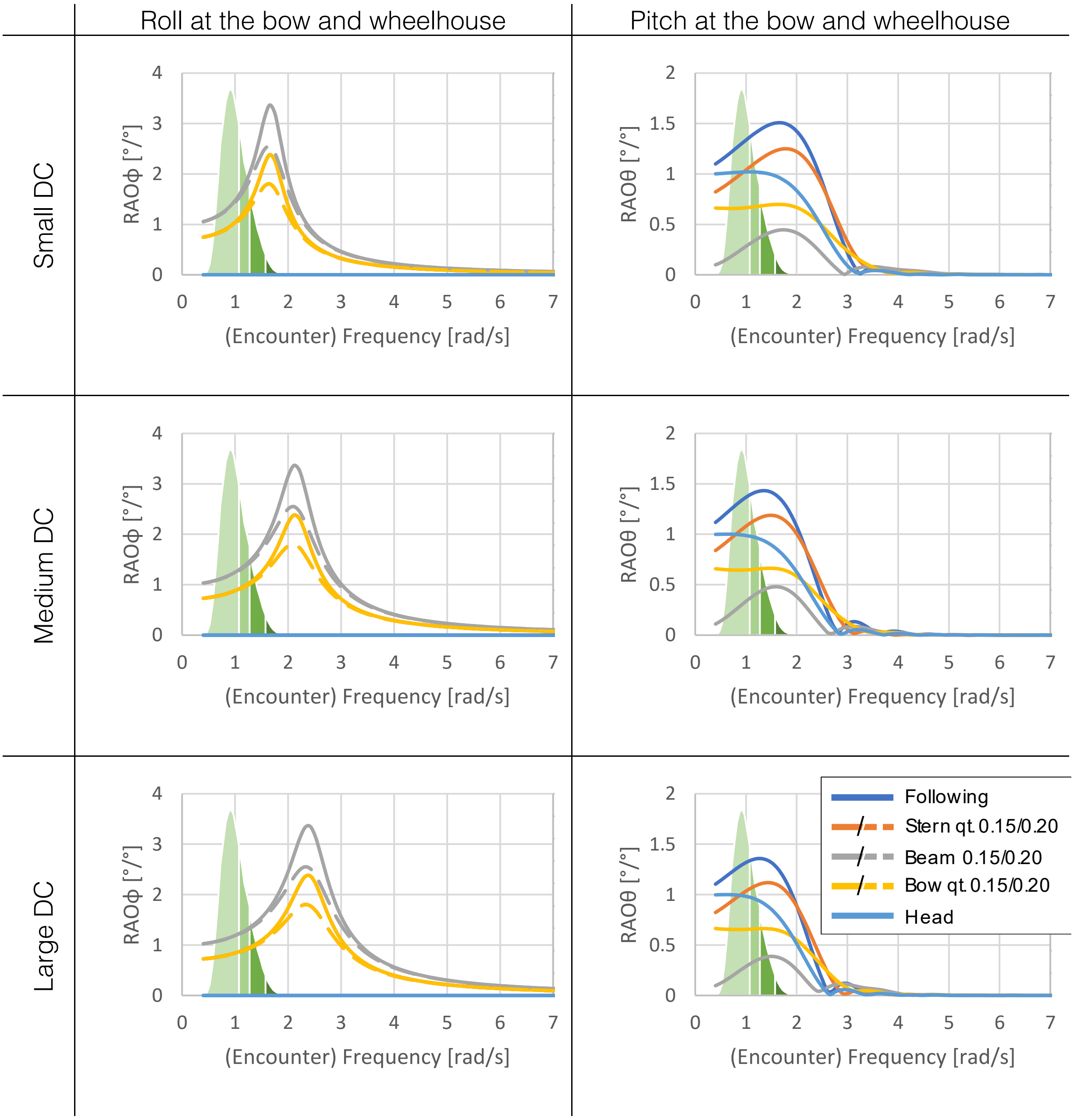


Figure 5-21: Roll and pitch RAOs

5.6.1.5 DC ranking

Table 5-4 gives an overview of the DCs ranked according to the response of the bow and wheelhouse in waves, with the best being at the top. Earlier, it was made clear that mainly head waves were considered for ranking the DCs. This is because the large DC has the lowest heave response in head waves but the highest in beam waves. The medium DC has a slightly higher response in head waves and a lower response in beam waves. All DCs had similar responses for the roll motion, but the natural frequency of the large DC was farthest from the common wave frequencies. Lastly, there is no clear winner for pitch motions: although the small DC has the highest response, the medium and large DC have a natural frequency that is closer to common wave frequencies.

Table 5-4: Overview of the DCs ranked according to their RAOs in head waves

Ranking	Heave	Roll	Pitch
1	Large and medium	Large	No clear "winner."
2		Medium	
3	Small	Small	

5.6.2 Long-term responses to waves

This section's results are comprised of multiple short-term responses; each corresponds to DCs with $\upsilon = 0.15$ since the results for $\upsilon = 0.20$ were similar. Section 5.5.3.8 specified which spectra were entered, and the same labels are used here. Together, the results show how the DCs respond to wave conditions that are observed throughout the year. As stated in section 5.1.1, vertical and horizontal accelerations on board are seen as the most limiting factors for comfort and safety. According to König et al. [87], it is crucial to limit the *relative* motion between the ship and the boat landing to ensure that the servicing staff can disembark from the ship safely during the transfer manoeuvre. This is certainly the case for floating wind turbines but less so for monopiles fixed in the ground. In that case, it is possible to use the *absolute* acceleration at the bow. However, the relative motions will be used to assess if propeller emergence and bow diving will occur. Lastly, multiple teams can also be dispatched to various wind turbines per trip. During each intermediate transfer, the technicians waiting in the wheelhouse could experience motion sickness. So, the last section briefly analyses the comfort levels.

The polar graphs display the absolute motions and accelerations at the bow and wheelhouse for all wave directions and spectra. Only half of the polar plot is shown because the DCs are symmetrical in the xz-plane.

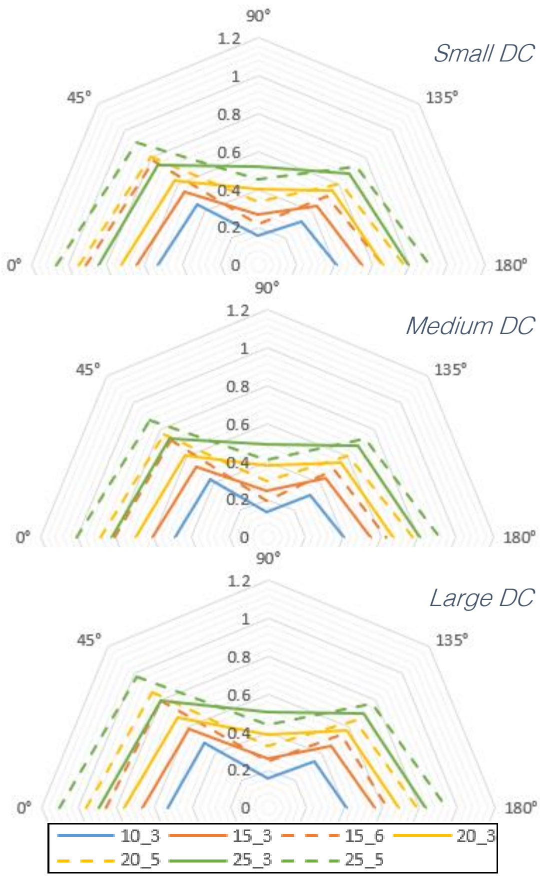


Figure 5-22: RMS absolute vertical motions [m] of the bow transfer platform

5.6.2.1 Absolute motions and accelerations of the bow and wheelhouse

The absolute vertical motions at the bow, see Figure 5-22, show how much the bow moves. It includes all (three) motions and depends on the wave spectrum and angle. The highest motions are induced by head and following waves. For example, in common conditions, the small DC's bow can shift with a significant amplitude of up to (2 x 0.82) 1.64 metres in following waves. Furthermore, higher wave heights increase the motion, while wave steepness increases the motion further. There is little difference between the three DCs.

Figure 5-23 shows that the highest vertical accelerations at the bow are caused by following and stern-quartering waves. Furthermore, steeper waves will increase the accelerations, while a varying wave height seems to have relatively less effect. In addition, the results for the highest" steepness give an impression for the maximum observable accelerations. This is because steeper waves do not exist due to wave breaking. Thus, accelerations are not expected to exceed this limit either. When the motions are compared between DCs, they are reduced for the medium and large DC. But the medium DC achieves the lowest accelerations in beam waves.

Figure 5-23: RMS absolute vertical accelerations [m/s²] at the bow transfer point

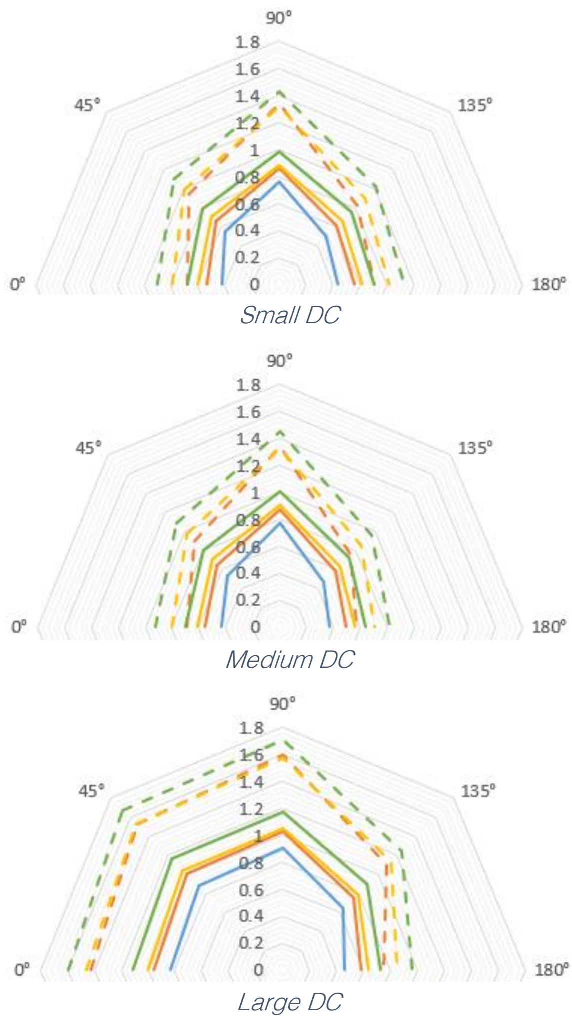


Figure 5-24: RMS absolute vertical accelerations [m/s²] at the wheelhouse

At the wheelhouse, Figure 5-24 shows that beam waves cause the highest vertical accelerations and not longitudinal waves. Note the smaller y-axis compared to Figure 5-23: the *absolute* response at the wheelhouse is not significantly higher than at the bow. Furthermore, steeper waves increase the accelerations, but this is more pronounced for beam waves as the difference decreases for the other wave directions. For example, the steepest 1.5-metre waves will induce roughly the same response as common 2.5-metre waves when they come from the longitudinal direction. A comparison between DCs shows that the small and medium DC have similar responses, with a slight reduction from the latter in head waves. Only the large DC has increased responses, especially for following waves. This could be because the wheelhouse is placed relatively farther from the LCB.

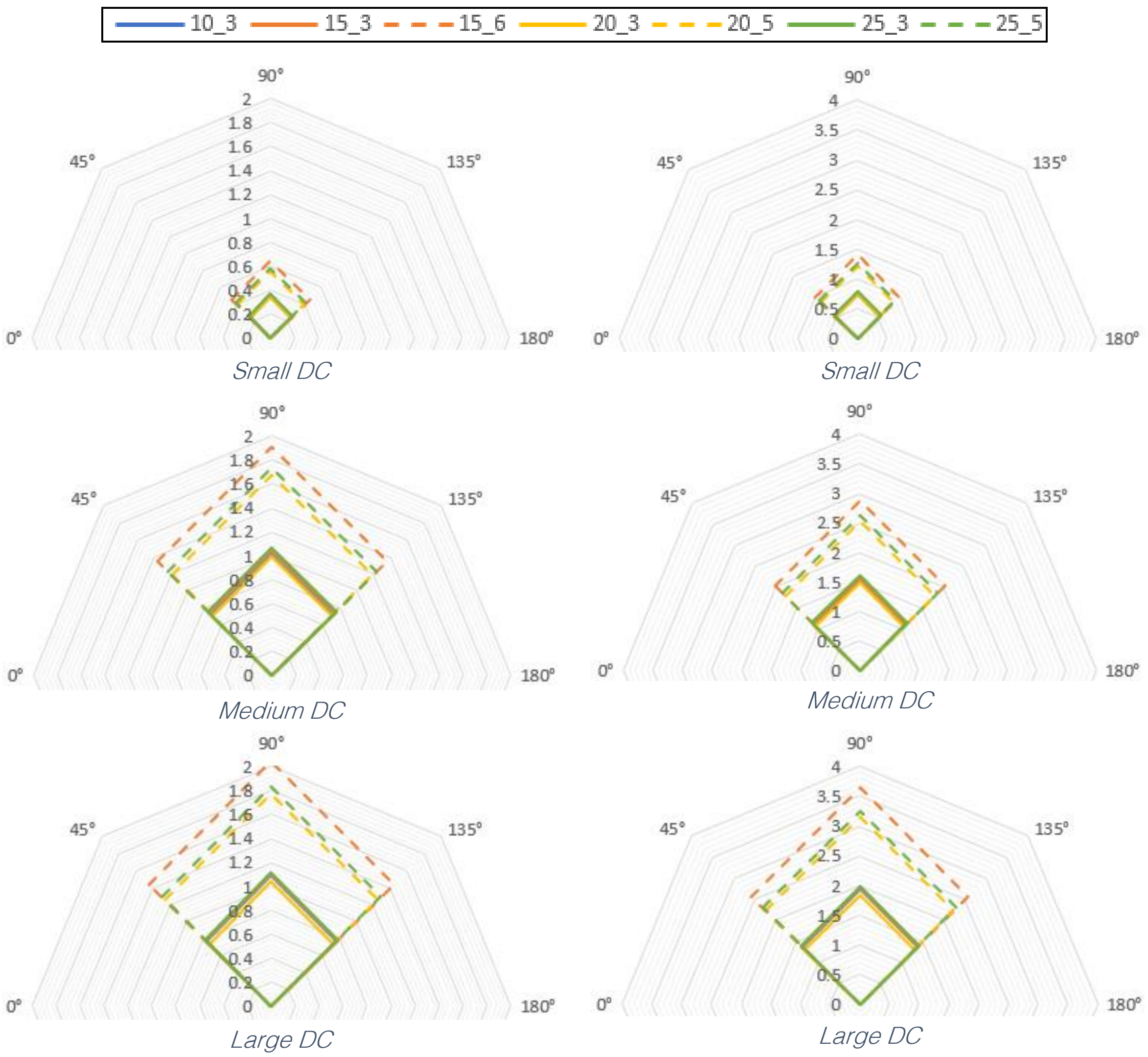


Figure 5-25: RMS absolute lateral acceleration [m/s²] due to roll at the bow transfer point

Figure 5-26: RMS absolute lateral acceleration [m/s²] due to roll at the wheelhouse

Figure 5-25 and Figure 5-26 show the absolute lateral accelerations at the bow transfer point and wheelhouse, respectively. The graphs show that the medium and large DC comparable lateral accelerations in all wave directions, but the accelerations at the wheelhouse are larger for the large DC. Again, steeper waves will increase the accelerations, while a varying wave height has relatively less effect. Furthermore, lateral accelerations are more intense at the wheelhouse than at the bow, presumably due to the higher beam at that location.

5.6.2.2 Relative motions to the water surface

Relative motions can predict phenomena such as bow diving, slamming and propeller racing [59]. Since the simulations were not done in the time-domain, it is only possible to determine *if* these events will occur and not precisely *when*. This is because the impacts that cause the accelerations will occur at each regular cycle or not at all [66].

Only slamming will not be assessed. After all, it is assumed to be more of a hazard during transit and not during transfers because it is typically avoided by reducing speed. Furthermore, the effect of different roll damping coefficients was slightly more apparent than in the previous section but is still excluded in this analysis since the difference between vessels is more important to understand. The graphs also include a boundary which helps determine if the event would occur.

Bow diving occurs if the relative vertical bow motion exceeds the DCs freeboard [86]. It was decided to use the bow transfer point for this assessment rather than assign a new location and increase the total simulation time. According to Figure 5-28, the bows of all three DCs are not likely to submerge for any combination of wave direction and spectra. Wave steepness does slightly increase the motions, but even the steepest waves will not cause the bows to dive. So, the raised deck at the bow is very effective to avoid deck wetness.

Propulsor emergence, and thus loss of thrust, occurs if the relative vertical motion of the propulsor exceeds the depth of the propulsor [86]. Figure 5-27 illustrates how the depth between the water surface and propulsor is determined; the depth is the offset between the water surface and the propulsor's highest point. In addition, the small and medium DCs are fitted with a propeller and the large DC with a waterjet.

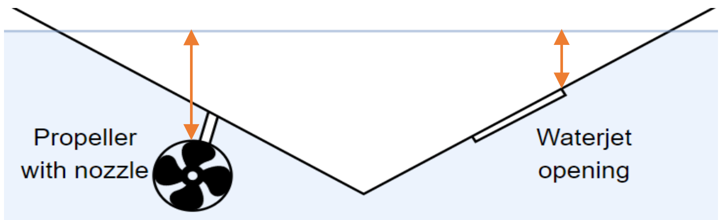
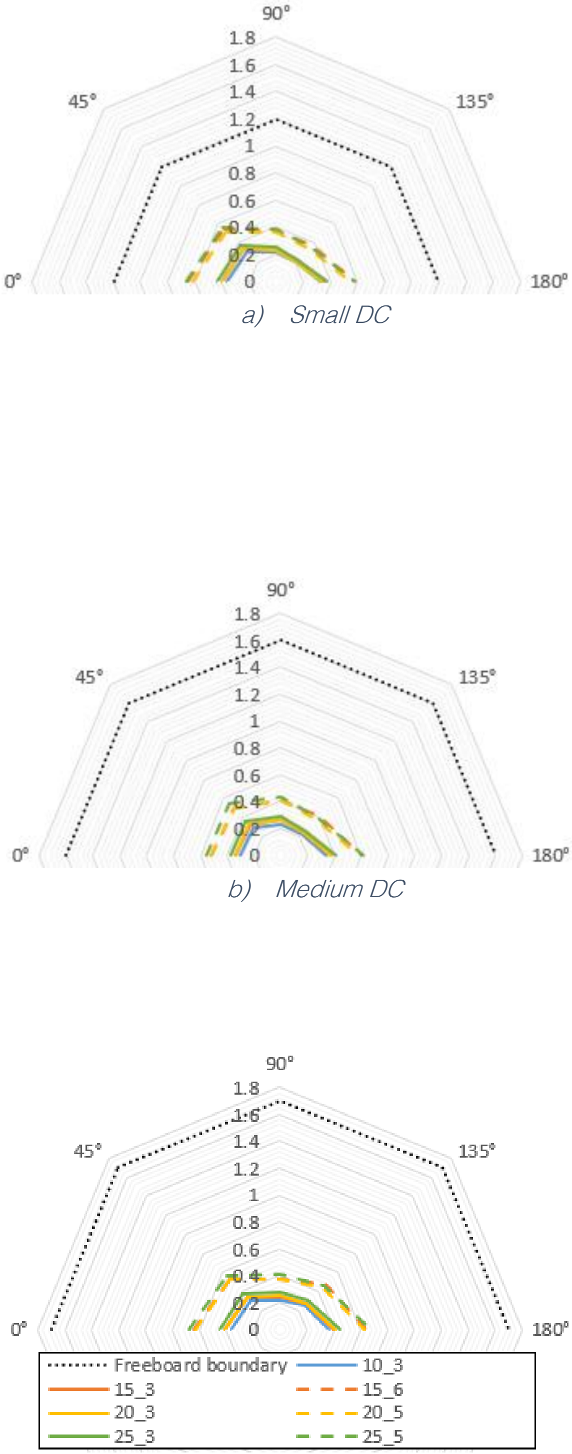


Figure 5-27: Propulsors and the depth to their inlet

Figure 5-29 shows the relative motions between the propulsor inlets (on both sides of the vessel) and the water surface for all wave directions and spectra. The values for longitudinal waves are equal for both propulsors, but waves from oblique directions induce slightly different responses from the two propulsors. Therefore, the figures show the entire polar plot, but the upper half belongs to the propulsor at the port-side and the lower half to the starboard-side. The propulsors of the small and large DC manage to stay submerged in all wave spectra and directions. But the risk is much larger for the medium DC. For that vessel, even the common wave spectra can cause propulsor emergence. But the inlets also have the smallest depth from the water surface. Suppose the propulsors were placed lower (this goes for the large DC as well, then there would be more leeway before they start to ventilate. However, due to the hull shape, this will put them closer to each other laterally, which may affect transit performance.

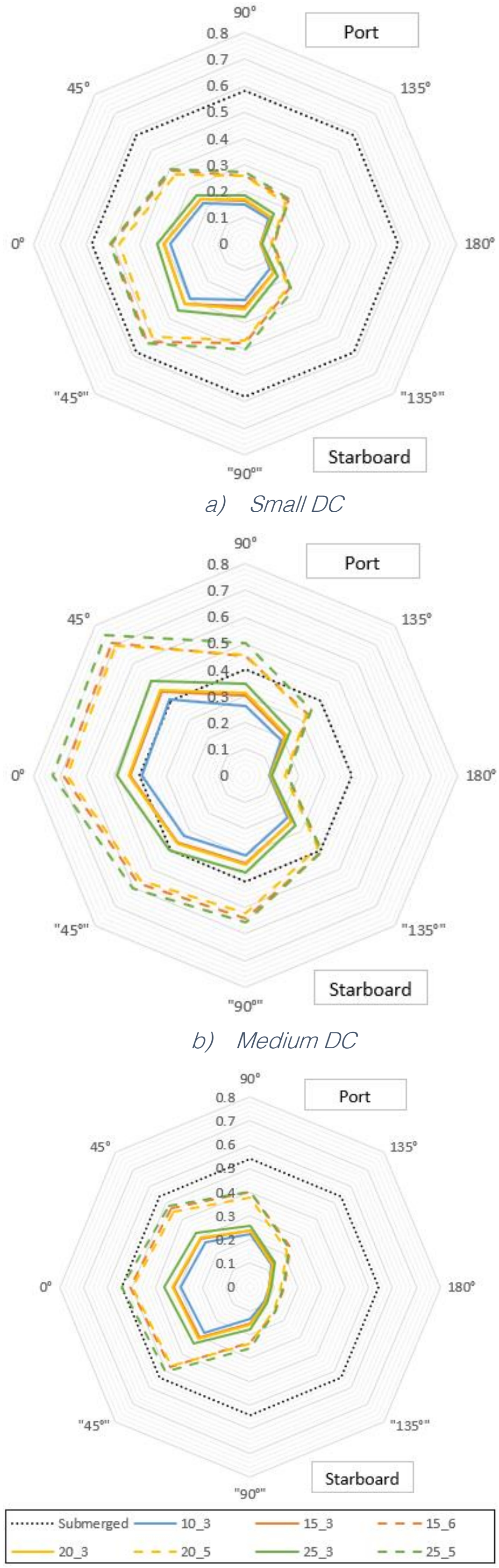


a) Small DC

b) Medium DC

c) Large DC

Figure 5-28: RMS relative motions [m] of the bow transfer point



a) Small DC

b) Medium DC

c) Large DC

Figure 5-29: RMS relative motions [m] of the propulsor inlets

5.6.2.3 DC ranking

Table 5-5 gives an overview of the DCs ranked according to their response in irregular waves, with the best being at the top. Low responses to head waves are still considered most valuable in the ranking, but each DC more or less matched in that regard. So, the ranking is based on overall performance instead. Also, the motions at the bow are considered most important because that is where the transfers take place. In that case, the medium DC performed the best since it has the lowest motions and accelerations.

At first, it seemed to be outperformed by the small DC in the lateral accelerations. But since its vertical motions and accelerations were higher, it is presumed that the lateral accelerations are lower due to a too low GM, which is known to give "tender" responses. So, a brief analysis of the righting arms was carried out. The heeling angle was determined for each wave spectrum, and the corresponding GZ values were compared; some examples are shown in Appendix D. It was determined that the small DC indeed always had the lowest GZ. So, although the slope of the small and large DCs are similar for $0° < \varphi < 20°$, it is the momentary heeling angle that determines the response. Furthermore, the small DC will also capsize at a much lower heeling angle than the other DCs. Based on this alone, it always scored lowest in the ranking in the categories regarding absolute responses.

Furthermore, the medium DC performs the worst in terms of propulsor ventilation. With that said, propulsor ventilation is considered important to minimise because then the transfers operations are safer. Since the small DC has an unacceptably low GZ, the large DC is the winner there.

Table 5-5: Overview of the DCs ranked according to their long-term response

Ranking	Vertical bow motions and accelerations	Lateral bow accelerations	Combined wheelhouse accelerations	Bow diving	Propulsor ventilation
1	Medium	Medium	Medium	No clear "winner."	Large
2	Large	Large	Large		Small
3	Small	Small	Small		Medium

5.7 Main observations

Ship designers often select hull forms based on calm water performance, even though the sea is mostly not calm [59]. It is uncertain to what extent this applies to the reference DCs, but it is clear that they were designed to achieve high speeds due to the presence of hard chines. Furthermore, head seas are generally known to defy safety and comfort restrictions during transit [60]. This is why the crew often impose a voluntary speed reduction and change the course heading. Also, aggressive heave motions can cause objects or people to be lifted from the deck, and excessive pitching can lead to slamming or submerge the bow [60].

5.7.1 Performance at zero-speed

When their performance is studied at zero-speed, it is clear that following, stern-quartering and beam waves induce the largest accelerations. This partly agrees with de Jong [62]: the limiting behaviour of stern-quartering and following seas is important for the operability of these types of vessels. But his argument is related to the risk of bow diving and the occurrence of broaching possibly followed by capsizing. The former does not seem to be a risk during transfers, and broaching was not investigated. In contrast to the studies on vessels with a forward speed, the RAOs and long-term responses show that head waves seem to cause the least or relatively fewer excitations when all (three) motions are considered. Thus, it is smart to position the wind turbine's boat landing to ensure these vessels encounter head waves the most. But as discussed in section 4.2.4, waves from other directions are not significantly less likely to occur.

According to the RAOs, the roll motions pose a larger threat to safety than heave and pitch motions when the waves do not travel longitudinally; even more so when the wave frequency approaches the natural roll frequency of the DCs. Fortunately, the natural roll frequency is one that seldomly occurs and only when $H_s \approx 1$ m, see Table 4-3. Nonetheless, the DCs must maintain a high roll damping coefficient to limit the roll response. Regarding long-term response, beam waves will induce the lowest vertical accelerations but the highest lateral accelerations. In head waves, there are (virtually) only vertical accelerations which make transfers less risky, even though the absolute response is higher.

5.7.2 Effect of wave parameters

The wave steepness seems to increase the DC responses more than higher wave heights. This makes sense looking at the rotational RAOs in Figure 5-21, which are made non-dimensional against wave slope and is a function of wave frequency, which is directly related to wave period. So, the higher the slope, the higher the response of the DC. This is also logical considering the opposite: a very/infinitely long wave with any wave height will give very slow pressure changes and thus low accelerations. Therefore, the combination of wave period (the relation to steepness is given in section 4.2.3) and wave height should be considered, rather than wave height alone when deciding whether it is safe to deploy DCs.

5.7.3 Motions to be improved

All in all, the results indicate what happens when existing DCs are used for rougher sea conditions. These results can thus be used to determine which conditions to avoid. Based on the RAOs of these reference DCs, the roll motion shall be prioritised for improvement since it is the riskiest motion when there are oblique waves. Because then, looking at the long-term responses, there are sometimes low vertical accelerations, but lateral accelerations are high. After that, the pitch motion is prioritised due to its performance in waves from the aft. Heave will be looked into last. So, modifications will be made based on the prioritised motions. For example, if a modification to improve the heave motion will undermine the roll response, it will not be implemented.

6 Feasibility definition

This chapter is the third step in the *Needs Analysis* phase within *Concept Development*. A system's feasibility is defined by how compatible it is with its interfaces, which can impose constraints. The constraints that the relevant interfaces impose will deliver initial operational and physical requirements. So, this chapter discusses the physical implementation.

The objectives from section 4.4.2 say that the DC must be stored on the SOV. Although minimal changes are considered allowed, the general arrangement of any SOV imposes limits to size and weight (section 6.1) and will be heavily included to guide the DCs design. Furthermore, how acceptable seakeeping is, depends on the safety of the technicians. So, the constraints that habitability impose are discussed in section 6.2. Technically, the wind turbine is also an important interface. But it is not considered here because it has more to do with fender type and material, which section 4.2.5 states are excluded from this study.

Furthermore, a system's feasibility can also be defined by finding examples of similar functional units in existing systems so that the feasibility of applying the same type of technology to the new system may be assessed [13]. With that said, many solutions have emerged from extensive research in the field to improve seakeeping performance. Those which have the reasonable potential to improve DC seakeeping include:

- Modifying the hull dimensions and proportions (Ref. [59], [60], [88] and [89])
- Applying a more suitable hull type or bow shape (Ref. [28], [90], [91] and [92])
- Implementing stabilisation devices (as appendages) (Ref. [42] and[59])

To summarise, seakeeping can be improved by increasing hull size, changing the hull type, and adding appendages to the hull. This was briefly discussed in section 5.2, but this chapter will focus on the applicability of these solutions. So, section 6.3 discusses feasible hull solutions from the aforementioned groups of solutions to increase seakeeping at rougher sea states. However, it excludes stabilisation devices because analysing their influence requires other and higher fidelity methods. In the end, section 6.4 proposes concept DCs that integrate the solutions. Note that no attempt is made to seek optimum designs in this step because the aim is establishing the feasibility to meet the set of operational objectives [13].

6.1 Size and weight constraints

A DC can either passively or actively interact with its mothership, although it is always via the onboard davit, which often includes a cradle, see Figure 6-1. The interaction is passive when the DC is not in use, i.e. being stored on the SOV, and then rests in a cradle. This implies that there must be an area available on the SOV's deck, which is regarded as a space constraint. There is active interaction when the DC is being launched or recovered. In that case, the davit lifts the DC by its hook. This means two things for the DC: (1) it must have the structural integrity to be lifted by its hook, and (2) its total weight must be within the davit's lifting capacity. Both points are related to the weight constraint. The next sections explain how these two constraints were quantified.

Figure 6-1: Davit with cradle carrying a workboat [93]

6.1.1 Reference SOV

Vessel suppliers often indicate that they are open to tailoring an SOV to the O&M operator's needs. But not all SOVs were designed with space for a DC in mind. Thus, it is necessary to establish a reference SOV that can serve as a mothership. At first, the idea was to select an SOV currently used to maintain any of the reference farms from section 4.1.3. Only East Anglia Three is not yet operational. So, no SOV has been assigned to it yet. Also, wind farms are occasionally supported by O&M support vessels, which are chartered in addition to the SOVs. However, these are not included in this study because these vessels are used temporarily.

With that said, Hornsea One is maintained from the Edda Mistral, and Gemini is maintained from the Windea la Cour. Both SOVs store their DC on the weather deck. However, looking at their general arrangements (GA), the DC seems to be partly enclosed by the vessel's walls and upper decks. Thus, there is little room for modifications, e.g. enlargement.

Therefore, it was decided to look at other existing SOVs whose GA offer more freedom for modifications. Granted, it is possible to alter a vessel's GA to store a larger DC elsewhere. But this will most likely require the entire deck arrangement to change since the storage containers and cranes will need to move to make room for the DC. Ultimately, these large changes could significantly affect the SOV's overall stability more than varying the weight of a DC at a (reasonably) fixed position on deck. Moreover, in Systems Engineering, it is more valuable to consider the constraints of current interfaces. So, changing the (entire) deck arrangement was avoided. That way, future implementation becomes more accessible.

In the end, the ESVAGT Faraday was chosen as the reference SOV for this study; its top view is shown in Figure 6-2. It is assumed feasible for the far-offshore wind farms because its size is similar to the Edda Mistral and Windea la Cour. Specifically, it can also accommodate 60 passengers and a similar amount of cargo.

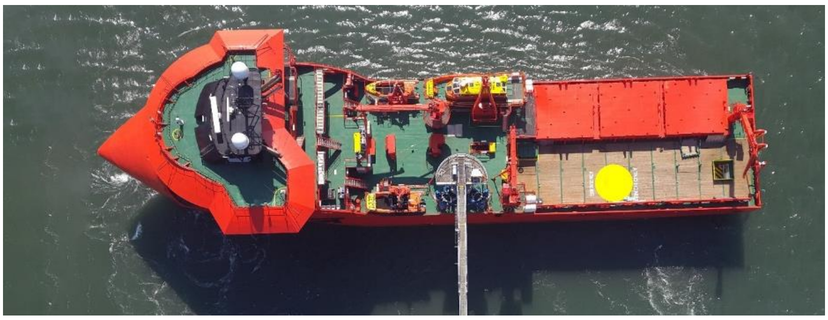


Figure 6-2: Top view of ESVAGT FARADAY [94]

6.1.2 Available deck area

The available deck area for a new DC is quantified while considering the current location of the DC. Figure 6-3 is a sketch of the surrounding area and includes notable systems. There is one staircase that is fixed, which allows the crew to reach the lower deck. The other staircase is used to enter the DC and is movable. Furthermore, there are two vessels: a DC (STB 12) and a fast rescue craft (FRC). The SOV's GA also indicated that there is space for a spare vessel. Lastly, there are several cranes. Two are the davits needed to launch and recover the two vessels. The larger deck-crane is generally used to transfer cargo from the SOV to the wind turbine's transfer platform. All three cranes are movable as well.

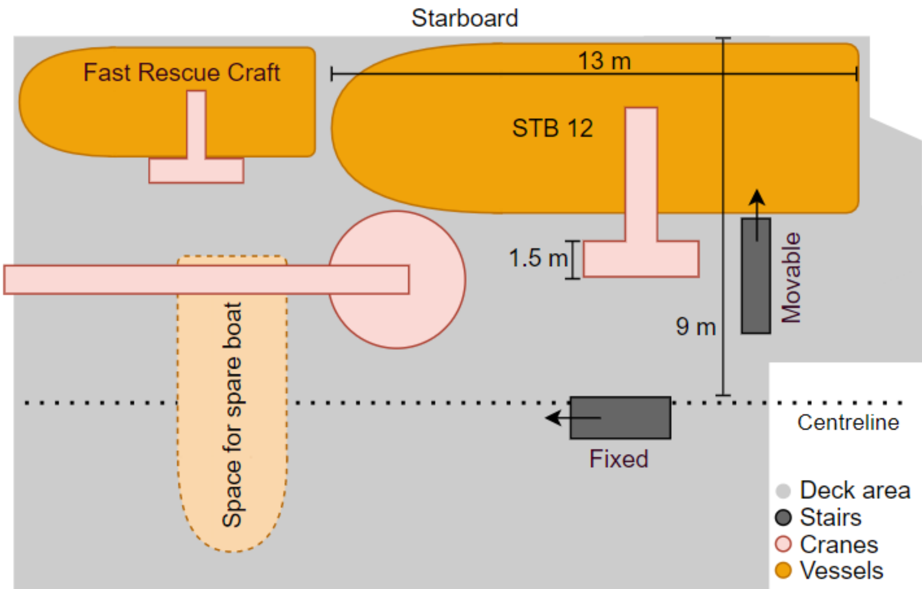


Figure 6-3: Sketch of available deck space on ESVAGT FARADAY

On this deck, there is more room for a DC to expand in width rather than length. The length of 13 metres is limited because of the FRC. It cannot be placed on the other side of the deck since there are another FRC and the W2W gangway system, see Figure 6-2. There will be room in the width if the deck-crane and DC's davit are moved towards to centreline. Deducting the space needed for the DC's davit leaves roughly 7.5 metres available in the width. This means that a catamaran with the same length, for example, may fit on the deck. Note that the davit also has a minimum required service area around it of approximately 1 metre. So, the movable stairs cannot be placed too close to the davit.

All the suggested deck modifications are assumed not significantly to affect the overall stability. Especially if the large crane is moved towards the centreline, it will cause less roll when carrying loads due to a smaller moment arm, and it can be used for both sides of the SOV. However, having it off-centre gives it a more extended outreach, which would be lost if the crane is moved farther from the edge.

6.1.3 Vessel material and davit capacity

The ESAVGT FARADAY is equipped with the davit shown in Figure 6-1 and has a safe working load (SWL) of 14 tonnes [93]. Davits are often chosen after the DC, but here the davit is an existing interface whose lifting capacity will be regarded as a constraint on the DC's weight. The latter can be divided into lightweight, which is fixed, and deadweight, which depends on how the vessel is equipped and loaded.

Lightweight is the weight of a ship alone, excluding its systems, cargo, fuel, and passengers. One influential parameter is the vessel's size since a larger vessel requires more material. But weight is not only determined by size but by material type as well. DCs are typically made of aluminium, while some have a superstructure made of glass-reinforced plastic (GRP). The use of these materials is mainly to achieve a low weight, which is beneficial for reaching high speeds, e.g. 30 knots. But a low structural weight is also valuable for economic and payload considerations [3]: the lighter your vessel, the more cargo you can carry per trip. Deadweight is the difference between a (fully) loaded condition and the ship's lightweight. It consists of "added" systems such as machinery, seats, cargo, fuel and passengers. In its heaviest condition, the DC's total weight should be within the davit's lifting capacity.

6.2 Habitability as a constraint on seakeeping performance

Seakeeping performance is evaluated against seakeeping criteria, expressed as some limiting values of ship motion response to wave action [3]. In general, these criteria address vessel habitability, operability and survivability. The quality of all three aspects lies in the hands of the vessel supplier, and an O&M operator will select a vessel considering their performance in these aspects.

Based on the enhanced objectives, this study's primary focus is improving the operability of DCs during transfers. Ideally, this aspect would be maximised to allow DCs to reach wind turbines during all weather conditions. But this goal is challenged by habitability. For example, one of the DC's main tasks is to arrive and stay at a wind turbine to allow technicians and equipment to transfer to the turbine. An operable DC will be able to reach the turbine and stay there, but a habitable vessel will have limited excitations to allow the transfers to take place safely. If a vessel is mainly operable, the motions are within an acceptable range for the vessel itself, but a wrongly timed move could cause injury to the technicians. So, because human comfort and safety have a crucial role in a DC's accessibility, habitability will define the limits as to how a vessel should respond to waves.

Sections 5.3 and 5.4 briefly discussed the ship response parameters during transit and transfer, respectively. This section expands that discussion by elaborating on thresholds that have been suggested. Although the transit phase is not simulated in this study, it is still included here as it is referred to in the discussion on transfer thresholds. These are given in terms of accelerations since that is generally deemed the most limiting factor during transfers for comfort and safety on board and thus operability.

6.2.1 Seakeeping criteria for transit

Keuning and Walree [68] conducted full-scale measurements to define the limiting criteria for the safe operation of fast ships in irregular waves. They concluded that the occurrence of peaks in the vertical accelerations was the most crucial criterion for safe operations. As stated in section 5.2, all crews voluntarily reduced the sailing speed, not because of the motions' amplitude but instead due to the occurrence of peaks in the vertical acceleration. This reaction is acknowledged as basic human nature and is why any criteria of the seakeeping should be based on setting limits to the *occurrence* of maxima in the vertical acceleration levels. They argue that the analysis for transit should, therefore, be done in the time-domain.

As a result, it was found that the occurrence of (very) high peaks at the *bow* of larger vessels (20+ metres) and the resulting vibrations was the cause to reduce speed. For smaller vessels, the occurrence of peaks at the *wheelhouse* proved to be far more important during transit. In the end, they proposed thresholds for vessels smaller than 20 metres in length, such as DCs: max 13 m/s^2 at the wheelhouse and 25 m/s^2 at the bow.

6.2.2 Seakeeping criteria for transfer

Accessing the turbine is the more difficult phase during access operations. Phillips et al. [61] state that there is far less experience and consensus with respect to the limits of vessel motion for transfer mode but point out that the vertical and horizontal acceleration limits should at least be lower than the values for transit. Specifically, they suggest that the thresholds at the wheelhouse should be 0.5 m/s^2 for vertical acceleration, 0.4 m/s^2 for horizontal acceleration and predominantly zero at the transfer point. These thresholds are based on significant values and not extremes as is done for the transit of high-speed vessels.

The values suggested for transfer are not only lower than the values applied for transit, but they seem to stem from an idealistic assessment. It is uncertain how feasible these values are in practice, especially for the relatively small DCs that cannot guarantee a low frequency of slip in high waves. Looking at Figure 5-26, the current DCs exceed these thresholds for the wheelhouse in most conditions. The criterium for the transfer point (at the bow) is deemed more probable if the vessel can execute push-on transfers; a procedure that effectively minimises slip. Therefore, this study will not consider the proposed thresholds for transfer as a hard constraint but as a goal.

6.3 Feasible (hull) modifications to improve seakeeping during the transfer phase

The notion is that the DC's operability can be increased by redesigning the vessel with the objectives from section 4.4.2 in mind by considering habitability. Several design guidelines, e.g. alteration of (primary and secondary) hull form parameters and equipping motion control devices, are known to reduce specific motions. Researchers have also presented new solutions, such as the Axe Bow concept by Keuning and Pinkster [88], [92] & [95]. However, a majority of these studies were conducted for larger ships (L > 40 m), and it is unclear how much the findings apply to smaller vessels, such as DCs.

Furthermore, most of these studies were focussed on reducing the accelerations experienced during transit, while there is little or no information or guideline for operations with zero-speed. Still, these design solutions are included to determine how well they perform when applied to improve transfers. This section only covers solutions that can be implemented to the hull using MAXSURF Modeler; the solutions which require a different or more elaborate analysis are excluded.

6.3.1 General design guidelines to reduce heave and pitch motions

Beukelman and Huijser [96] carried out a parametric study to determine the effect of varying parameters on seakeeping performance (of monohulls). The vessels were larger than 60 metres and had forward speeds ranging between Fr = 0.15 to 0.25. The lowest test speed is considered low enough for the conclusions to be useful in this thesis.

Based on their results, they ranked which design parameters have the greatest influence on vertical movements:

1. Ship length: Larger vessels decrease the motions, accelerations, and slamming.
2. Ship speed: Heave increases strongly with speed, while pitch appears to be almost indifferent to speed.
3. Forebody section shape: V-shaped forebody sections (so a lower prismatic coefficient) reduce heave, accelerations, slamming and relative motions. Its influence on pitch is very small.
4. Block-coefficient: An increase of block-coefficient causes a rather strong reduction of motions, accelerations, relative motions and slamming.
5. Centre of buoyancy in length (LCB) and the radius of inertia: These are of minor importance in terms of influence and can only shift if the block-coefficient is large. Moving the LCB towards the fore slightly reduces pitch, accelerations, relative motions and slamming. An increased radius of inertia raises the heaving motion, while acceleration and relative motion are almost indifferent.
6. Wave period: All motions, acceleration and relative bow motions increase significantly with the wave period.

6.3.2 Primary parameters to vary to reduce roll motions (at zero-speed)

Gutsch et al. [97] studied the influence of design parameters to identify and benchmark mission-oriented seakeeping performance of monohulls. Although their scope considered vessel lengths ranging between 80 – 160 metres, which is significantly larger than DCs, these results are still relevant because they were done at zero-speed and include the differences caused by seasons. The designs of the parent hulls were derived from realistic ratios. Vessel operability was tested against limiting roll angles of 0.5°, 1.0° and 2.0° RMS (based on lifting operations) and only bow-quartering waves (μ = 150°) were considered in their analysis.

They presented their results as the operability performance (percOP) and Operability Robustness Index (ORI). The latter is a new method to express the global performance of a ship for a selected motion criterion [97]. It makes it easier to compare vessels when their percOP converges to 100% and is less dependent on the choice of the maximum allowable limitation value [97]. So, the results based on OPI will "weigh heavier" than the percOP.

In their results, the vessels always have higher operability during the summer, which is why only results for the winter will be discussed here. As is well known, longer vessels (with beams that typically correspond to that length) showed an improved roll performance. The remaining conclusions are summarised, with an emphasis on the results for their smallest vessel. First, notice how the figures also show that varying the parameters of smaller vessels has more influence on their performance. The DCs, which are at least five times smaller, are expected to amplify this trend, but this cannot be confirmed in this thesis and must be left to further research.

6.3.2.1 Beam

Varying the beam (and consequently the VCG, moment of inertia for roll and displacement) with respect to the parent hull mostly improved the operability. For the strict roll criterion of 0.5° RMS, a wider vessel will give a higher percOP and OPI, see Figure 6-4. However, when the roll criterion is increased to 2.0° RMS, the highest percOP is achieved with a narrower vessel. The OPI is then similar to that of a wider vessel. So, in that case, both a narrow and wide vessel would be suitable.

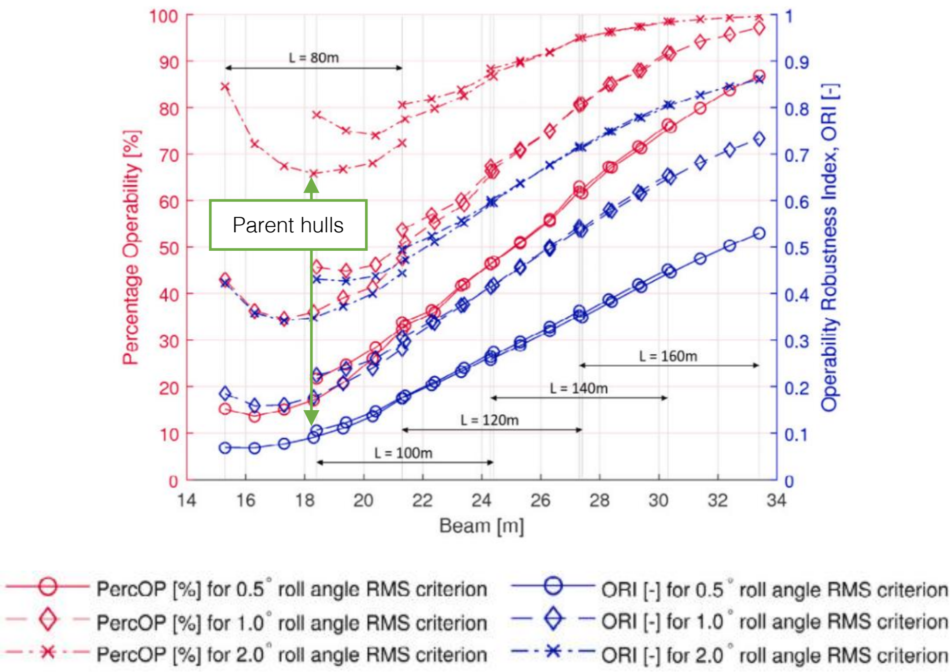


Figure 6-4: Effect of beam variation in the winter season in the North Sea (Adapted from [97]*)*

6.3.2.2 Draught

In the case of the 80-metre vessel, decreasing the draught (and consequently the VCG and displacement) slightly improved the percOP and OPI, see Figure 6-5. But it depends on what limiting roll angle is selected: The strict criterion shows there is no use for varying the draught, while the effects on performance are amplified as the limiting roll angle increases. Gutsch et al. [97] add that the variation of draught could influence roll damping due to minor viscous and more added mass effects, e.g. a larger draught would increase these effects.

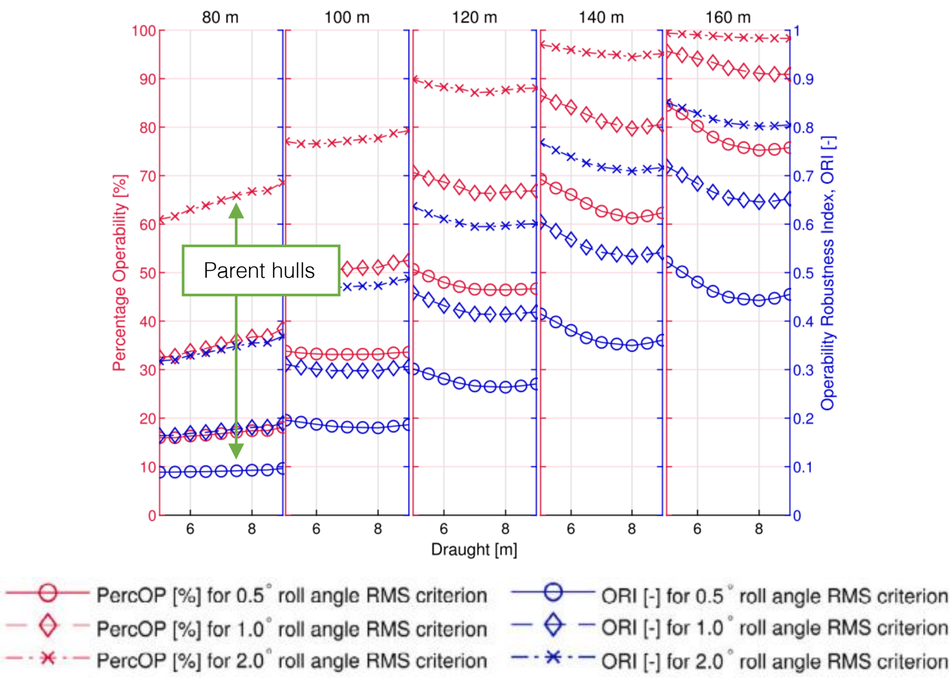


Figure 6-5: Effect of draught variation in the winter season in the North Sea (Adapted from [97]*)*

6.3.2.3 Metacentric height

Figure 6-6 shows that the percOP and OPI vary significantly as the GM_t varies (and consequently the VCG). Gutsch et al. [97] concluded that small vessels should have large GM_t to obtain high operational performance. However, they were considering lifting operations where the limiting roll criterion may be higher. In this case, the motions should be minimal. Then, the highest percOP and OPI is obtained through a relatively smaller GM_t.

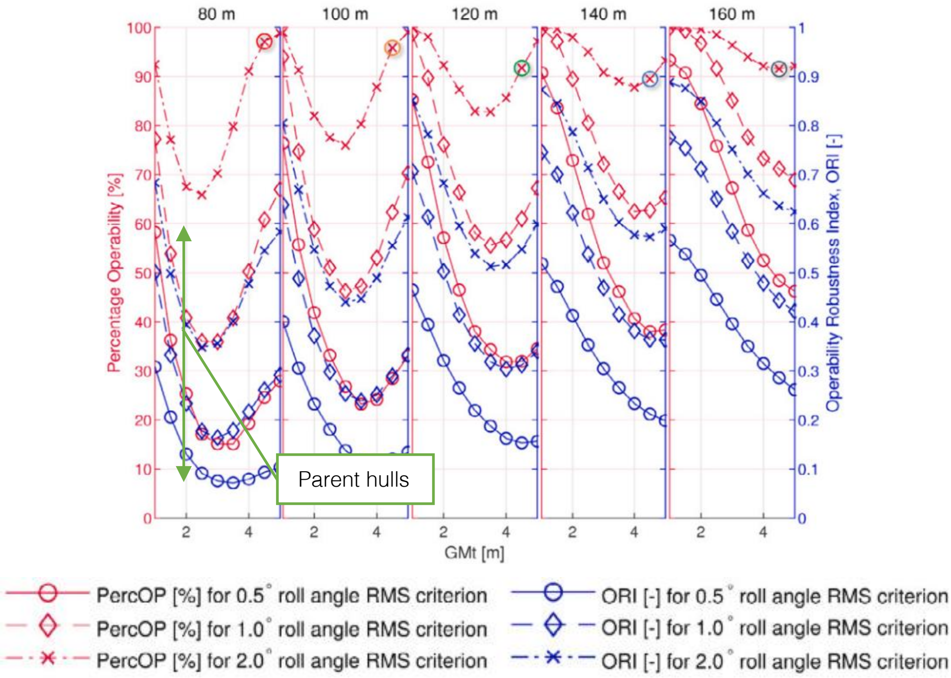


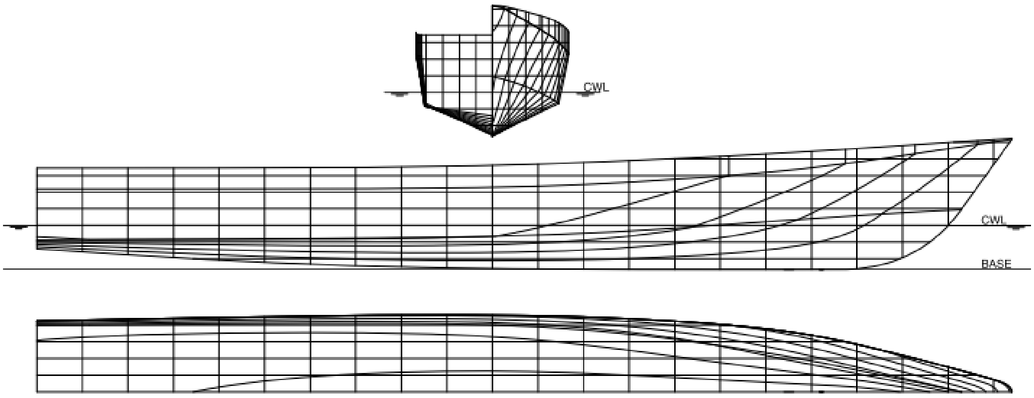
Figure 6-6: Effect of GM_t variation in the winter season in the North Sea (Adapted from [97])

6.3.3 Implement Axe Bow Concept to reduce heave and pitch motions

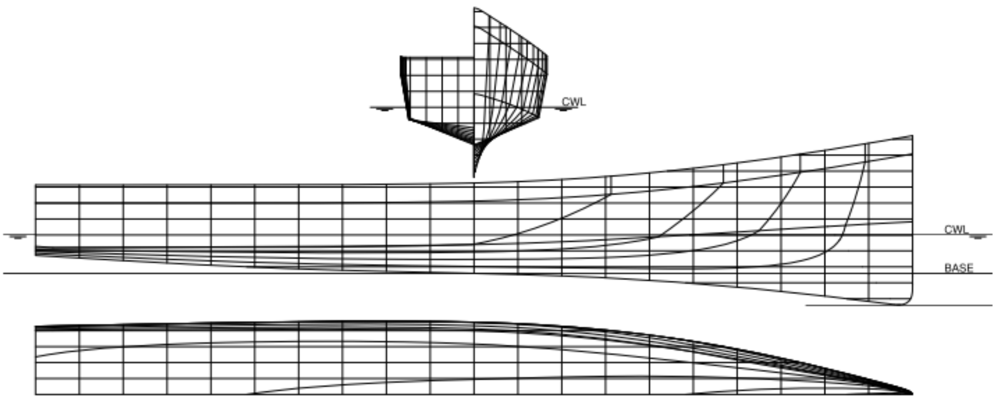
After the Enlarged Ship Concept (ESC) was introduced, Keuning and Pinkster [88] presented their study on a modified bow shape to reduce the non-linear behaviour in head seas caused by dynamic lift forces and the build-up of exciting wave forces. It was essentially an extension of their previous study on ESC performance since they used the 'void' space that the ESC made at the fore of the vessel to modify the bow. They determined the vertical accelerations using model tests and nonlinear methods besides the linear approach. This was the first of a series of studies that eventually led to the Axe Bow Concept (ABC) [92]. Note that the following results were obtained for vessels with a high forward speed. This concept is still discussed because it shows great promise for transit is thus worth investigating for transfers. Figure 6-7 shows the differences between the parent hull (ESC) and the ABC. They summarised the radical changes in hull shape with respect to the parent hull as follows:

- The flare is reduced to almost zero to minimise the change in momentaneous added mass and submerged volume while the fore ship carries out relatively large motions with respect to the waves.
- The stem is almost vertical. It should be noted that Figure 6-7 illustrates vessels with the same waterline length. But when the sheer extends downwards from the parent hull's overall length, the regained displacement volume would move the vessel's centre of gravity more forward.

- The sheer forward is significantly increased to minimise the risk of green water and guarantee sufficient reserve buoyancy.
- The centreline of the hull has a downwards slope towards to bow to minimise the risk of slamming, which occurs after hull emergence when sailing in waves.



(a) Parent hull with a conventional bow



(b) Axe Bow Concept

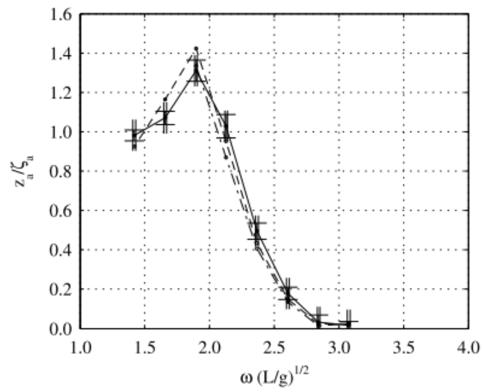
Figure 6-7: Line plans of conceptual designs [66]

6.3.3.1 Heave and pitch assessment in regular head waves

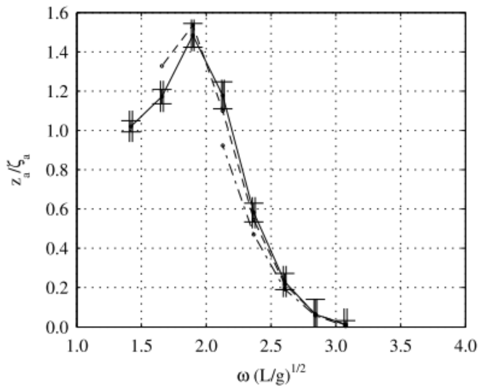
De Jong [66] compared the RAOs of the ESC and the ABC in head waves and with a varying wave steepness, indicated by kappa (κ). Figure 6-8 displays the resulting heave and pitch motions with a forward speed of 25 knots. It shows that the ABC's heave response is slightly larger than that of the ESC at the resonance frequency. So, the ABC possibly has less damping than the ESC. In contrast, the pitch response of the ESC is slightly larger than the ABC, which is perhaps due to its flare. Furthermore, the response to regular waves mildly depends on the wave steepness, but the influence is minimal.

6.3.3.2 Vertical accelerations

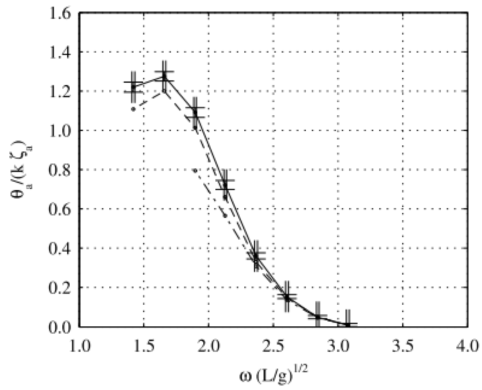
The improvement is more apparent when the vertical accelerations are considered. Figure 6-9 displays the RAOs of the vertical accelerations and includes the positive and negative peak values. The vertical accelerations at the CoG of the ABC are larger than those of the parent hull, which corresponds to the larger heave motions observed in Figure 6-8. It should be noted that the ships' CoGs were located at slightly different locations. It is presumed that this could also contribute to the difference in vertical accelerations.



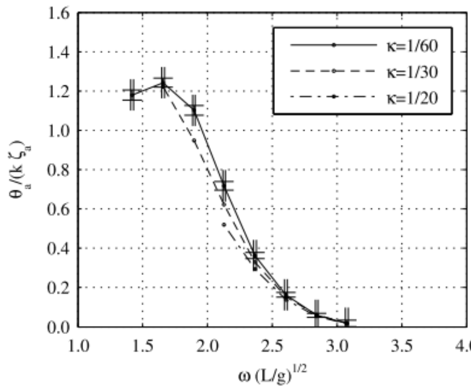
(a) *Heave motion of the ESC*



(b) *Heave motion of the ABC*

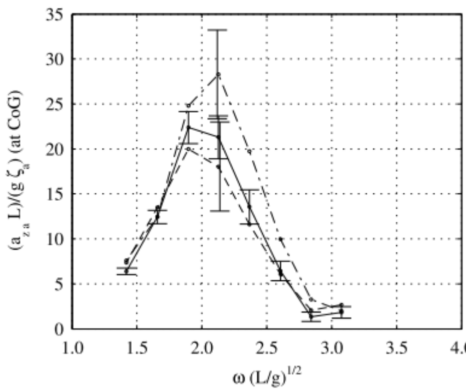


(c) *Pitch motion of the ESC*

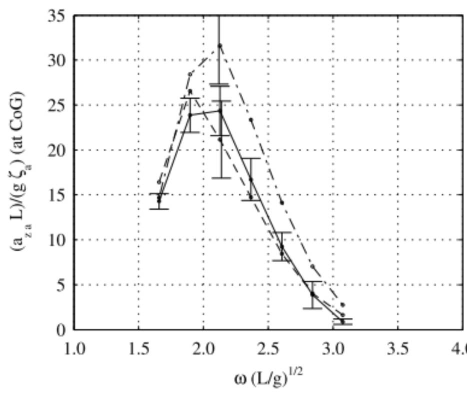


(d) *Pitch motion of the ABC*

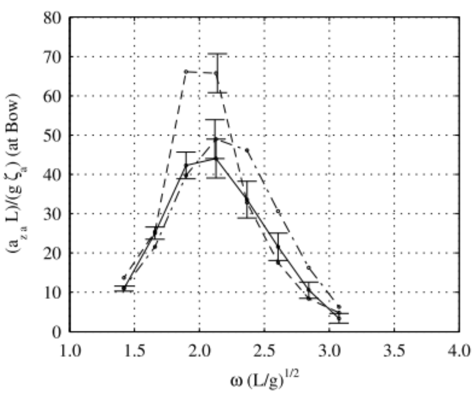
Figure 6-8: Comparison of the RAOs and their dependence on the wave steepness, V = 25 knots [66]



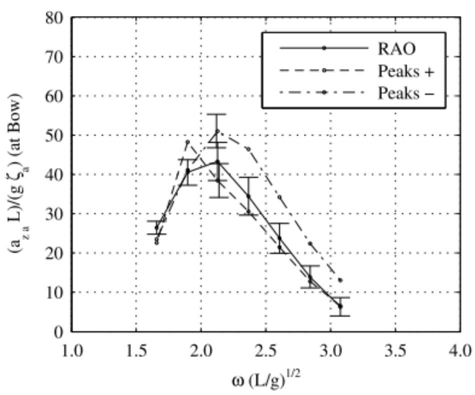
(a) *At the CoG of the ESC*



(b) *At the CoG of the ABC*



(c) *At the bow of the ESC*



(d) *At the bow of the ABC*

Figure 6-9: Comparison of the vertical acceleration RAOs and peaks, V = 25 knots, κ=1/30 [66]

The (linear) RAOs are similar for both designs at the bow, but the ESC experiences larger positive peaks than the ABC. This behaviour is also visible when the time traces of the vertical accelerations are compared, see Figure 6-10. The ABC shows a more linear behaviour compared to the ESC. These results allows de Jong [66] to conclude that modifying the bow of the ESC to the ABC successfully minimises the occurrence of extreme peaks, which improves safety and ride comfort during transit.

However, de Jong [66] insists that RAOs are not a valid tool to describe the entire motion response of fast ships in head waves. This is especially so for vertical accelerations because there is no clear indication as to how often these peaks will occur, only that they will occur. This is because, in a regular wave cycle, the impact which causes the accelerations will either occur at each cycle or not at all, such as in Figure 6-10. Therefore, the motions and responses were also studied in irregular waves. These results and the discussion thereof can be found in Appendix E. The next section summaries the study by de Jong [66] with an overview of the resulting operability.

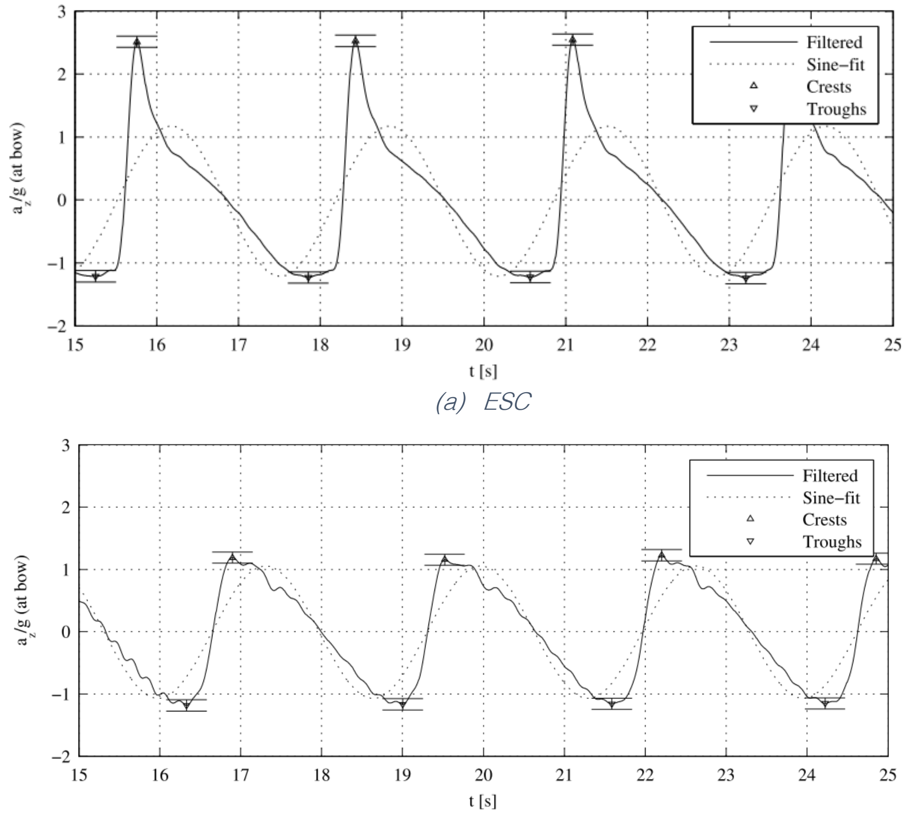


Figure 6-10: Time trace of the vertical acceleration level measured at the bow

6.3.3.3 Operability assessment in irregular waves

All in all, Table 6-1 shows that the ABC is deemed to be operable at more speeds and sea states than the ESC. This overview was initially established by Keuning and Walree [68], who conducted full-scale measurements to define the limiting criteria for the safe operation of (large) fast ships in irregular waves. Those same criteria (8 m/s² at the wheelhouse and 20 m/s² at the bow) were used to test the operability of the ESC and ABC. The criteria established for vessels smaller than 20 metres was given in section 6.2.1. To conclude, the ABC showed an improvement in operability of 40-50% compared to the ESC [66].

Table 6-1: Operability in tested wave conditions using developed criteria [68]

	ESC					ABC				
H_s / V	2.0	2.5	3.0	3.5	4.0	2.0	2.5	3.0	3.5	4.0
25	✓	✓	×	×	×	✓	✓	✓	✓	×
35	✓	×	×	×	-	✓	✓	✓	×	-
50	×	×	×	×	×	✓	✓	✓	✓	✓

6.3.4 Applicability for DC hull types operating at far-offshore locations

At far-offshore wind farms, the DCs are expected to operate in sea states characterised by harsh conditions (quantified in section 4.2). Section 5.2.2 showed that several hull types can operate at a higher range of waves than (hard chine) monohulls, but they are more costly solutions. The following sections discuss the applicability of the aforementioned CTV hull types as DCs. Note that the collection of CTVs by Hu et al. [14] may be comprised of old and refitted multi-purpose vessels designed with other design criteria in mind rather than stability during transfers.

6.3.4.1 SESs and SWATHs

Most of the vessels from Table 5-1 do not meet the desired seakeeping performance in terms of significant wave height (established in section 4.4.2). The only vessel types that approach this objective are the complex SWATHs and SESs. But their large size (20+ metres) are problematic for storage on an SOV; size limitations were discussed in section 6.1.

There is one relatively small SES suitable for use as a DC or CTV, namely the Sea Puffin 1, see Figure 6-11. With a length of just 16 metres, it is the smallest SES to date and is said to be light enough to be lifted by a standard onboard davit. While this vessel offers benefits such as lower fuel consumption and dampened motions during transfer, this vessel is merely operable when H_s < 1.75 m. At rougher sea states, it would be harder, if not impossible, to maintain the air-cushion. So, the Sea Puffin 1 is an improvement compared to traditional monohull DCs, but it does not entirely meet the objectives set for a DC working at the reference far-offshore wind farms. Therefore, it is not considered suitable to provide year-round access to far-offshore wind farms. De Jong [66] adds that the motion of SESs in waves is also not ideal since seakeeping was not the main drive behind their development. In any case, SESs are relatively complex designs due to the air-cushion technology.

Figure 6-11: Sea Puffin 1 [98]

SWATHs feature an improved ride quality in especially head waves, but they also rely heavily on control surfaces to limit their motions as they suffer from longitudinal or pitch instability

[66]. Furthermore, SWATHs are incredibly sensitive to additional deadweight due to their slender struts, which offer limited buoyancy reserve. Considering the size range of DCs, cargo of even one tonne is expected to affect the draft significantly. As a result, a SWATH DC would presumably need a very high tunnel height to avoid excessive wet deck slamming.

All in all, the large SESs and SWATHs meet the operational requirements in terms of significant wave height, but they are considered unfeasible to use as DCs due to their large size and need for complex technology. The seakeeping of these two vessel types in high waves depends on the technology's capacity rather than on “robust structures”. These advanced systems also have higher construction and operational costs, which is why many branches (including the offshore industry) tend to favour the fast monohull because it is simpler and has proven to work [66]. Furthermore, simulating the performance of SESs and SWATHs requires a higher fidelity method due to the flexible skirts and rapidly changing submerged geometries. Therefore, the applicability of these two hull types as DCs will not be simulated here.

6.3.4.2 Comparing monohulls and multihulls

Monohulls and multihulls are relatively cheaper and simpler hull types than SESs and SWATHs. Therefore, their applicability will be studied from here on. Luhulima et al. [4] made a comparison of these vessels based on stability and seakeeping criteria. They tested a monohull, catamaran and trimaran at sea state 5, a Froude number of 0.3 and different incoming wave angles using both MAXSURF Seakeepers[8] and ANSYS AQWA. ANSYS mostly gave lower results than MAXSURF because it makes use of more three-dimensional methods, but the results are as follows:

- For heave, the trimaran generally had the most excessive motions in head waves. As the wave angles varied, the monohull started to show the most excessive motions. Overall, both methods showed that the catamaran produced the least heave motions.
- For pitch, the trimaran again had extremely high values in head waves. At this point, the monohull seems to be the winner as it exhibits the lowest motions. Once the incoming wave angle varied, the catamaran had similar or lower motions compared to the other two vessels.
- For roll, head and following waves do not affect the vessels due to symmetry. However, monohulls had the highest roll motions in beam waves. Its results were a factor 2 and 8 times higher than a catamaran and trimaran, respectively.

Based on these results, the trimaran has the least potential to be applied as a DC. The following two sections elaborate on the applicability of monohulls and catamarans.

6.3.4.3 Monohulls

Most DCs are monohulls, and Table 5-1 shows that they can only operate up to $H_s < 1.2$ m due to their low stability while transferring offshore technicians onto the monopile. The low stability is attributed to the large roll motions when it encounters oblique waves. This was also seen in the seakeeping analysis of three mock-up DCs in section 5.6.

[8] Now known as MAXSURF Motions, which is also used for this project’s analyses.

Increasing a vessel's length generally improves its behaviour in waves, but this modification cannot be applied here; section 6.1.2 explains why. Furthermore, their poor transverse stability could be improved by implementing the previously named modifications to the monohull. It is not expected to improve so much that access in H_s = 2.5 m can be achieved safely. But these simple modifications will still be applied to investigate exactly how much there is to gain and what the effects are at zero-speed.

Another way to improve a monohull's transverse stability is to add stabilisation devices, but the effects of these devices also cannot be analysed using the same method described in section 5.5. For example, the estimation of roll damping of a ship due to bilge keel requires three-dimensional calculations [99]. So, how these devices would improve seakeeping performance is discussed as high-level solutions in section 7.2

6.3.4.4 Catamarans

Most CTVs are catamarans to benefit from their initial transverse stability and larger deck areas. The former is because catamarans have a larger GMt compared to monohulls (up to two to four times), and the mass moment of inertia of a catamaran may be smaller than that of a monohull (up to 15–20% lower) due to the mass distribution being more centralized than the buoyancy, so the catamaran's roll period is shorter [32]. Furthermore, the separated demihulls cause higher roll damping. All in all, these two features mean catamarans are stiffer in terms of roll. The larger deck area makes it possible to transport more technicians, equipment and cargo per trip. That way, the DC can perhaps make fewer trips from the mothership, which is better for its utilisation rate.

Thus, it is worth investigating the performance of a DC as a catamaran. Granted, monohulls are generally known to have better longitudinal stability. But according to Nazarov [100], factors of a catamaran's isolated hull shape are similar to those used for monohulls. That means that the previously named hull modifications can also be applied to catamarans, e.g. the axe bow. In fact, Damen's recent catamarans meant to operate as CTVs for the offshore industry are fitted with an Axe Bow, see Figure 6-12. Smaller catamarans by Albatross Marine Design also show hulls with a maximised waterline, e.g. the 12-metre catamaran in Figure 6-13. Other design parameters such as the block coefficient and the LCB will also be considered to improve heave and pitch. However, catamaran hull parameters cannot always directly be compared to those of monohulls since they are different hull types. So, recommendations for secondary hull parameters by Yun et al. [32] and Nazarov [100] will be prioritised for the catamaran DCs.

Figure 6-12: Damen Fast Crew Supplier 2710 [101]

Figure 6-13: CPCK1200 12-metre research catamaran [102]

6.4 Physical characteristics of DC prototypes

This section describes how the solutions were combined into several DC prototypes while considering the constraints from sections 6.1 and 6.2. These variations are believed to have improved seakeeping performance at far-offshore locations.

Two different hull types will be tested, namely a monohull and a catamaran. Furthermore, two versions of those two hull types were generated to understand the effects of changing certain parameters, especially since most of the modifications are based on results obtained for (much) larger vessels. The new DCs and their characteristics are summarised in Table 6-2.

These will be tested against a parent hull: the medium-sized DC, i.e. the STB 12 from ESVAGT. This DC is also currently used on the ESVAGT FARADAY. The comparison will provide insight into which modifications notably improve DC seakeeping performance.

Table 6-2: Physical characteristics of DC models

Design parameter	Parent hull (STB 12)	Monohull 1 (M1)	Monohull 2 (M2)	Catamaran 1 (C1)	Catamaran 2 (C2)
Main change(s)	N.A.	Smaller GM	Larger beam	Different hull type	Decreased clearance
Overall length [m]	13	13	13	13	13
Bow shape	Sharp bow	Axe bow	Axe bow	Axe bow	Axe bow
Waterline length [m]	12.39	13	13	13	13
Waterline beam [m]	3.68	3.67	4.27	7.10	4.70
Demihull width [m]	N.A.	N.A.	N.A.	1.60	1.60
Draught [m]	0.85	1.22	1.22	1.41	1.41
Metacentric height [m]	1.92	0.80	1.90	11.83	3.38
LCB [m]	5.58	5.49	5.69	6.248	6.248
Weight [tonnes]	13.49	12.60	15.43	20.36	20.36

6.4.1 Overall length

As stated by Stapersma et al. [3], the behaviour in waves of conventional ships can often (depending on ratio vessel length to wavelength, i.e. L_{wl}/λ) only be notably improved by increasing the size, e.g. by increasing the vessels length. This corresponds to what was explained in section 6.3.1.

Keuning and Pinkster [60] studied the effect of extending the area forward of a vessel's accommodation while making no changes to other parameters such as its layout, interior or passenger and cargo capacity. Their Enlarged Ship Concept proved to have immense potential to increase a vessel's operability, as it reduced resistance for all speeds and the responses in terms of heave and pitch motions and vertical accelerations.

However, there is a limit to how long the DC can be due to available deck space. In this case, there is no room for a longer DC on the reference SOV; see section 6.1.2. Future SOVs that are still in the engineering stage are relatively more flexible for implementing modifications. But based on the comparison of the three DCs from chapter 5, a higher length does not significantly improve the transfer conditions. Therefore, other solutions must be considered.

6.4.2 Bow shape and waterline length

Keuning and Pinkster [60] mention that seakeeping behaviour can be further optimised by bringing the best design length forward and redesigning the bow section. That is why the to be tested DC will have a bow that resembles the ABC. This way, the waterline length is increased without increasing the overall length of the vessel. The analysis will also aim to provide insight into the contribution of the ABC at zero-speed.

6.4.3 Monohulls

Section 6.3.4 covered the applicability of monohulls. It was established that current monohulls are can only operate up to $H_s < 1.2$ m and that the suggested modifications are not expected to improve seakeeping so much that access in $H_s = 2.5$ m can be achieved safely. Still, the monohull is included to investigate exactly how much there is to gain, what the effects are at zero-speed and because of the constraints imposed by the davit. The davit's cradle, shown in Figure 6-1, is meant for monohulls (and not catamarans). Although the davit could be altered to accommodate a catamaran, the current cradle is seen as a constraint since a cradle for catamarans is not commercially available in the O&M industry.

In short, the heave and pitch motions were addressed by applying the Axe bow, which makes the forebody section into a more pronounced V-shape. This decreased the prismatic coefficient and shifted the LCB slightly. However, the block coefficient decreased as well, which should be increased to improve the motions, according to Beukelman and Huijser [96]. But this is accepted since lowering the prismatic coefficient was deemed a more influential factor than increasing the block coefficient, see the ranking in section 6.3.1. The roll motions were addressed by testing a monohull with a smaller GM_t and a larger beam.

6.4.3.1 Metacentric height

Looking at the results by Gutsch [97], discussed in section 6.3.2, the largest increase in operability was attained by lowering the GM_t, when the strict criterion of 0.5° RMS is considered while keeping the remaining parameters the same. The trend in Figure 6-6 shows that a smaller GM_t should further increase the percOP and OPI, but this cannot be made infinitely small, or the vessel will no longer have a sufficiently large righting arm to counteract and prevent capsizing.

Furthermore, the increments applied by Gutsch et al. [97] are too large for the DC. So, this thesis will adjust the terms using equivalent percentages. The variant with $GM_t = 1$ m had the highest ORI. This is a decrease of 60% from the original $GM_t = 2.5$ m. As a result, the GMt of M1 was decreased from 1.92 to 0.8 metres. This was achieved by increasing the VCG. The resulting righting arm is discussed in section 6.4.6.

6.4.3.2 Beam

The beam of M2 is also chosen based on research by Gutsch et al. [97]. Specifically, the results related to the strict criterion of 0.5° RMS because the motions should be minimal to allow for safe transfers. Looking at the trend from Figure 6-4, increasing the beam is expected to increase the operability (which was only based on the roll motion). However, the beam cannot be increased indefinitely because the vessel will otherwise start to represent a barge while it must still have proper seakeeping performance during transit. The best performing beam variance was an increase of three metres compared to the original beam, which was adapted to represent realistic L/B ratios. Again, three meters is a relatively large increase for small vessels such as DCs. Thus, the same approach from the previous section is taken. Since a three-metre increase on the original 18.3-metre beam is equal to an increase of around 16%, the DC's beam will also be increased by 16%. This leads to a new beam of roughly 4.4 metres, which is well within the bounds of available deck space on the reference SOV. Furthermore, the altered beam changed the GM_t, so the VCG was increased to give M2 the same GM_t as the parent hull.

6.4.3.3 Draught

Gutsch et al. [97] explain that draught variation does not influence the vessel's natural roll period. This is especially so considering the strict criterion of 0.5° RMS. Therefore, the draught was not (actively) altered. The absolute draught of M1 and M2 is only higher than the parent hull because the axe bow extends further down.

6.4.3.4 Weight

In the multiple studies which compare the ABC to a parent hull form (e.g. Ref. [91] & [95]), the displacement volume merely increased by 0.3%. Therefore, it was believed that applying the ABC to a DC would not significantly increase the lightweight of the vessel, meaning the DC would remain within the lifting capacity of the onboard davit.

In this case, although the only significant difference between M1 and the parent hull is the inclusion of what resembles an Axe bow, the displacement was slightly lower than that of the parent hull. This is illogical since more material (of the Axe bow) should increase the weight. However, this is possibly because the overall hull shape must have been altered slightly during modelling. This contradiction is still acceptable since the DC is in the early conceptual stage. Furthermore, M2 has a larger beam and thus a higher weight. Both DCs are still within the lifting capacity of the onboard davit.

6.4.4 Catamarans

As stated in section 6.4.3, the davit's cradle is not meant for catamarans. So, (part of) the davit would have to be replaced if a catamaran DC would be needed. However, the potential for higher transverse stability and a larger deck area may make the replacement worthwhile.

According to Nazarov [100], the most substantial catamaran design points are the tunnel shape, vertical clearance and horizontal clearance between the demihulls. Only tunnel shape and vertical clearance will not be discussed because Strip Theory (described in section 5.5) does not analyse alternative above water hull forms. So, it cannot determine the effect of the waves on the catamaran above the waterline. The bow transfer point's height was assumed to be roughly 2.5 metres. The remaining hull parameters were verified using statistical data on principal particulars by Bondarenko [103] and were deemed realistic.

6.4.4.1 Demihull beam

The demihull beam (b) is the beam of a single hull; see Figure 6-14. It was determined by referring to Yun et al. [32]. For small utility craft, common L/b ratios are between 8 and 10. Considering the conclusion by Gutsch et al. [97] that wider is better, it was chosen to design the catamarans with L/b ≈ 8, which gives b = 1.6 m since L = 13 m.

6.4.4.2 Horizontal clearance

Horizontal clearance (c) is the distance between the inner sides of the demihulls, illustrated in Figure 6-14. Small-sized displacement (slow-speed) catamarans tend to be wider for optimised resistance compared to planing craft [32]. For vessels with zero-speed, a graph by Nazarov [100] recommends c/L = 0.3 to 0.45. Thus, the catamaran DC should have c = 3.9 m to 5.85 m since L = 13 m, see Figure 6-15a. However, section 6.1.2 states that there is only space for a vessel with B_{max} = 7.5 m, which leads to c_{max} = 4.3 m. This was applied to C1, which eventually had c = 4.0 m.

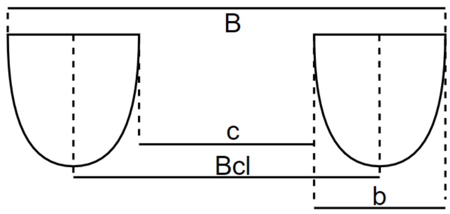
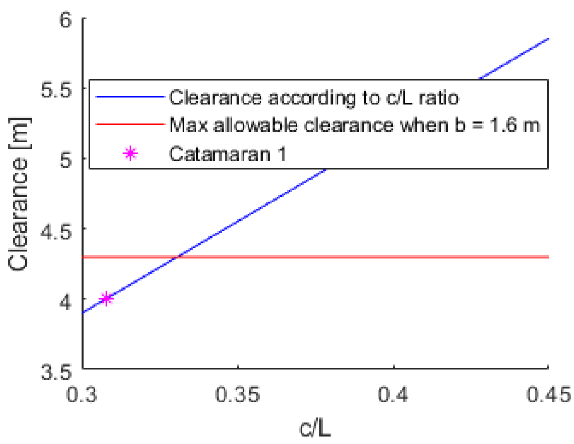
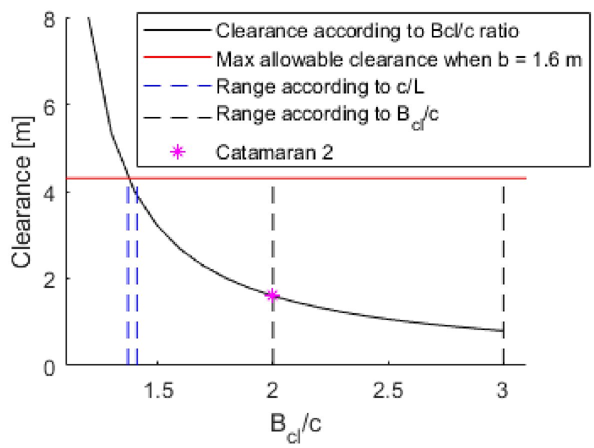


Figure 6-14: Catamaran hull annotations

A more recent source, by Yun et al. [32], states that lower speed (catamaran) designs by Nazarov's have B_{cl}/c = 2 to 3, with B_{cl} being the beam between the demihull centrelines. Figure 6-15b shows how the clearance varies within that B_{cl}/c ratio range. However, the resulting clearance is not in the same range that Nazarov proposed in Ref [100]. This recommendation would make the catamaran narrower, which is more applicable to planing vessels. Nevertheless, C2 adopts this smaller clearance c = 1.6 m, which the catamaran from Figure 6-13 has as well, to see the effects on roll motions (and not resistance) at zero-speed.



a) Clearance according to c/L ratio



b) Clearance according to Bcl/c ratio

Figure 6-15: Contradicting clearance recommendations

6.4.4.3 Hull shape

The catamarans were not modelled with the same hard chine as the monohulls because the focus lies on the transfer phase and not (high-speed) transit. At zero-speed, hard chines further dampen the roll motion [32], but this deemed unnecessary (for now) because the demihull separation will already provide that. Furthermore, section mapping (see section 5.5.3.1) becomes more complicated if hard chines are part of the submerged geometry. So, they were also excluded to make the modelling slightly easier. The hulls were given a wedge-like stern rather than a round one to ease the stern's re-entry; a rounder bilge has a flatter surface that slams when it impacts the water surface and a sharper bilge would pierce through more easily.

6.4.4.4 Weight

Catamarans are generally heavier than monohulls. This is presumably due to the structures which need to provide sufficient global transverse strength, e.g. the wet deck structure and the deck girder. The catamarans from Table 6-2 are indeed heavier than the monohulls, but they are in line with weight trends established by Bondarenko [103]. Note that the wider catamaran should actually be heavier because more material is required to bridge the two demihulls. The corresponding draught is T = 1.41 m. Furthermore, these catamarans exceed the davit's lifting capacity. But a new cradle would be needed to store a catamaran DC, so the lifting capacity is considered less of a constraint. Further discussion on weight (reduction) is given in section 7.2.2.

6.4.5 Hull generation

The method to model the new DCs is similar to that given in section 5.5. The models are shown in Figure 6-16 and Figure 6-17. It only shows one version of each hull type since the other version is similar. M1 is nearly identical to the parent hull but has an Axe bow, giving it less flare. M2 is simply a widened version of M1, obtained by giving the control points the desired offset. Minor corrections were made to streamline the fore section. C1 was generated using the "quick start" module to create a catamaran with the desired primary hull parameters. The demihulls were then given the desired dimensions and shape. C2 is identical to C1, but the demihulls were moved to give it a wider clearance. The fender was removed from these models to save modelling time since it does not affect the simulations.

6.4.6 Righting arms

Figure 6-18 contains the righting arms (GZ) of each new DC, which vary with the heeling angle due to a changed submerged geometry. As discussed in section 5.1.2, a positive righting arm ensures that a vessel rotates back to its initial (upright) position. Negative righting arms will (tend to) capsize the vessel. Note that the new DC models did not include a fender like the parent hull, which offers additional buoyancy reserve. As a result, their stability ranges are slightly lower. Also, the vessels were assumed to be intact and watertight.

All in all, the parent hull and catamarans have a comparable stability range, but the latter have a much stiffer response. So, those DCs will react stronger to external heeling moments. This was expected as Figure 5-4 shows that catamarans generally have steep initial slopes. Moreover, the wider catamaran (C1) is stiffer and has a slightly larger stability range than C2. The monohulls, however, have much smaller stability ranges. Especially M1 has a dangerously low initial slope which gives it a slow response. As a result, it is prone to capsize at a mere 15°-20° heel. Based on the GZ-curve alone, this vessel would be unattractive to use in rough waves. Furthermore, the same initial slope of M2 and the parent hull are the same, which means the reaction speed is the same. But the angle of vanishing stability (when the GZ curve passes through 0) occurs at a much lower heeling angle than the parent hull. So, M2 will capsize earlier. Still, both monohulls were included in the following analysis to gain insight into seakeeping performance.

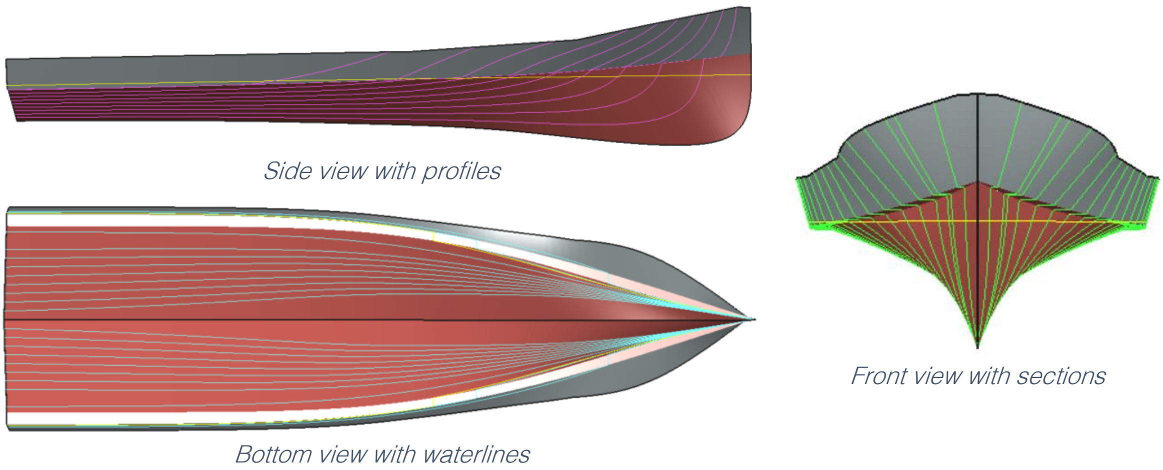


Figure 6-16: Model of "Monohull 1"

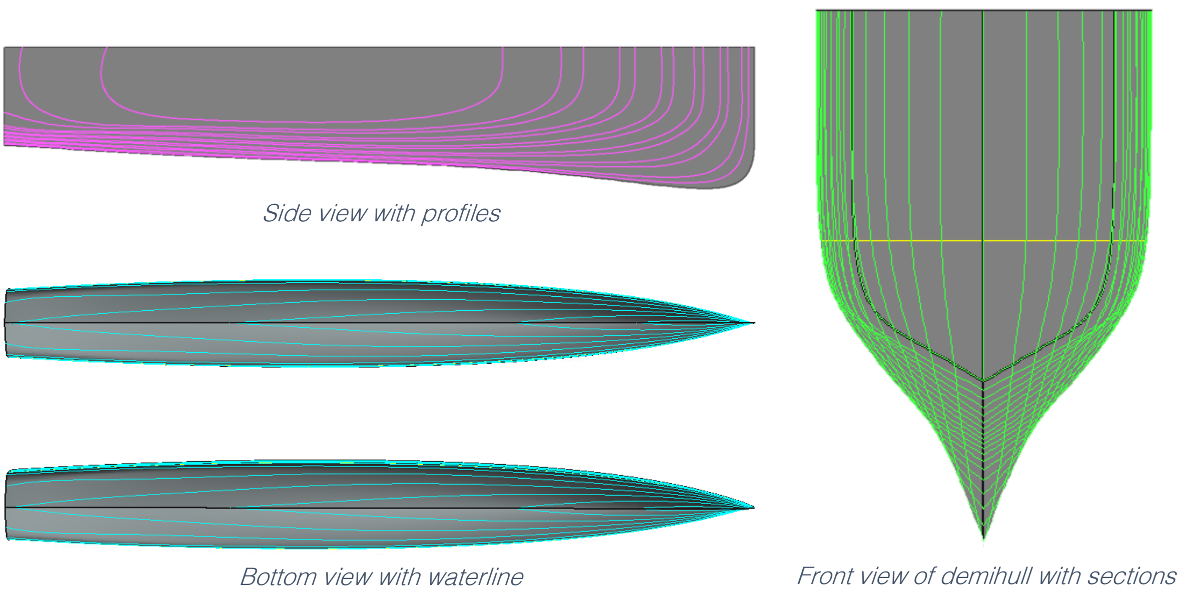


Figure 6-17: Model of "Catamaran 1" (and 2)

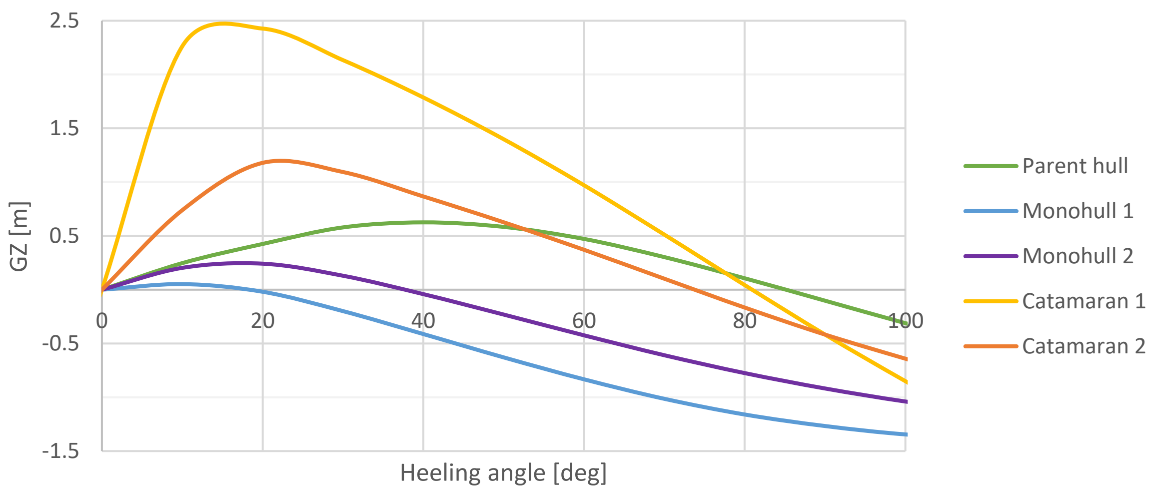


Figure 6-18: Intact stability of the parent hull and DC prototypes

7 Needs validation

This chapter is the final step in the *Needs Analysis* phase within *Concept Development*. It includes an effectiveness analysis directed at determining if a system is feasible and satisfies the operational objectives [13]. The effectiveness will be analysed in a single mission context: allowing technicians to transfer safely onto the boat landing.

The resulting performance is evaluated against measures of effectiveness (MOE). For transit, this is done using reputable seakeeping criteria. However, the transfer thresholds (given in section 6.2.2) were deemed too idealistic to be feasible, especially for far-offshore wind farms that frequently observe rough weather conditions. So, in section 7.1, the new DCs are evaluated against the parent hull, whose performance represents the MOE. Furthermore, section 7.2 introduces additional high-level solutions that can be implemented to further improve the seakeeping performance of both monohulls and catamarans.

7.1 Comparison with parent hull

This section compares the seakeeping performance of the new DC concepts to the parent hull, i.e. the medium DC. The results were obtained using the same method applied to the original three DCs. This chapters also uses the labels assigned to the DCs in Table 6-2. Like the parent hull, the wider monohull (M2) was also given a low number of mapping sections (17) because a higher amount would always cause at least one section to distort. However, it was possible to apply a higher number of section (≥ 32) to the remaining vessels, including M1. The results show very little difference between the three monohulls. Thus, it is presumed that the low number of sections do not significantly overestimate the performance.

Furthermore, all new DC models were all fitted with an Axe bow. The difference between Monohull 1 and the parent hull, for example, is not only due to the decreased GM. Still, this analysis will isolate the effects of all the modifications.

7.1.1 Response Amplitude Operators

The RAOs are compared first to understand the differences in regular waves. The graphs also include the wave occurrence distributions to see if the DCs' natural frequencies will be matched often and in which range wave heights, see section 5.6.1.1 for a more in-depth explanation. Note that encounter frequencies outside of these ranges will occur, but just not as often and for low(er) wave heights.

The effectiveness of the DCs' RAOs was analysed by comparing the normalised area under their RAOs to that of the parent hull at five separate frequency ranges. The first four ranges correspond to the four sets described in section 5.6.1.1, and the last range includes the RAOs at the higher (uncommon) frequencies. Furthermore, each effectiveness graph compares the DCs in a specific wave direction. All in all, these graphs make it easier to compare the RAOs of the DCs to the parent hull, which represents the MOE. Specifically, they give a better indication of how the RAOs change and how the different DCs perform in certain wave conditions. Also, note that both catamarans behave the same for heave and pitch motions, which is why only one set of results is visible.

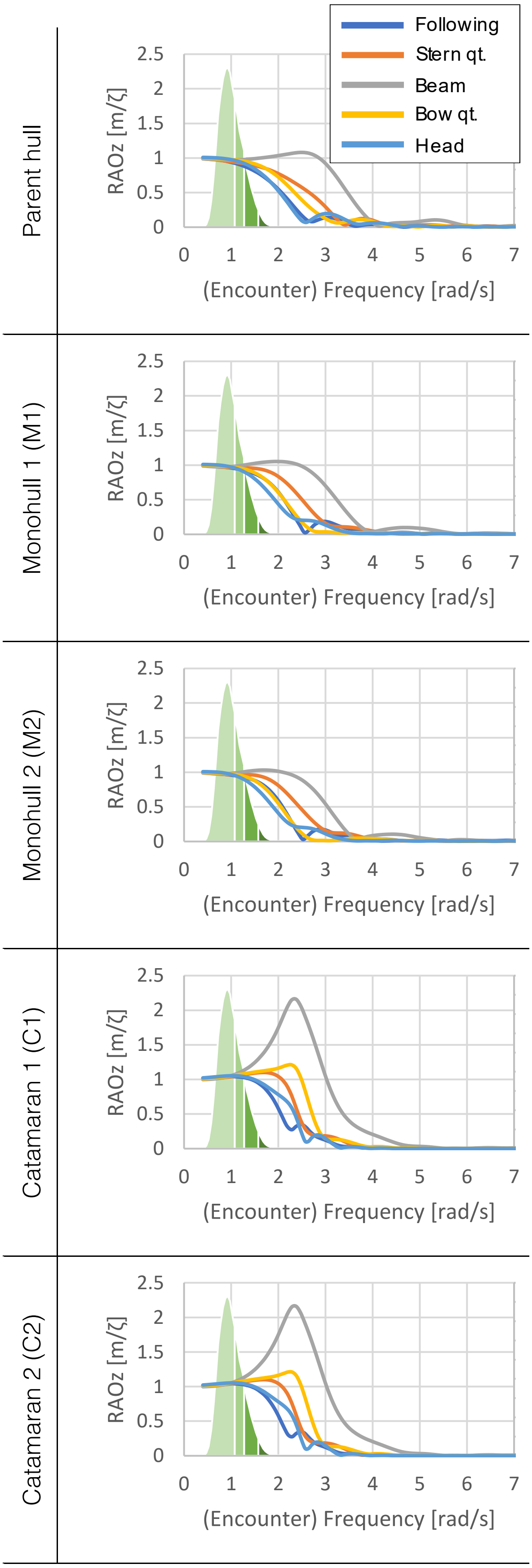


Figure 7-1: Heave RAOs at the bow

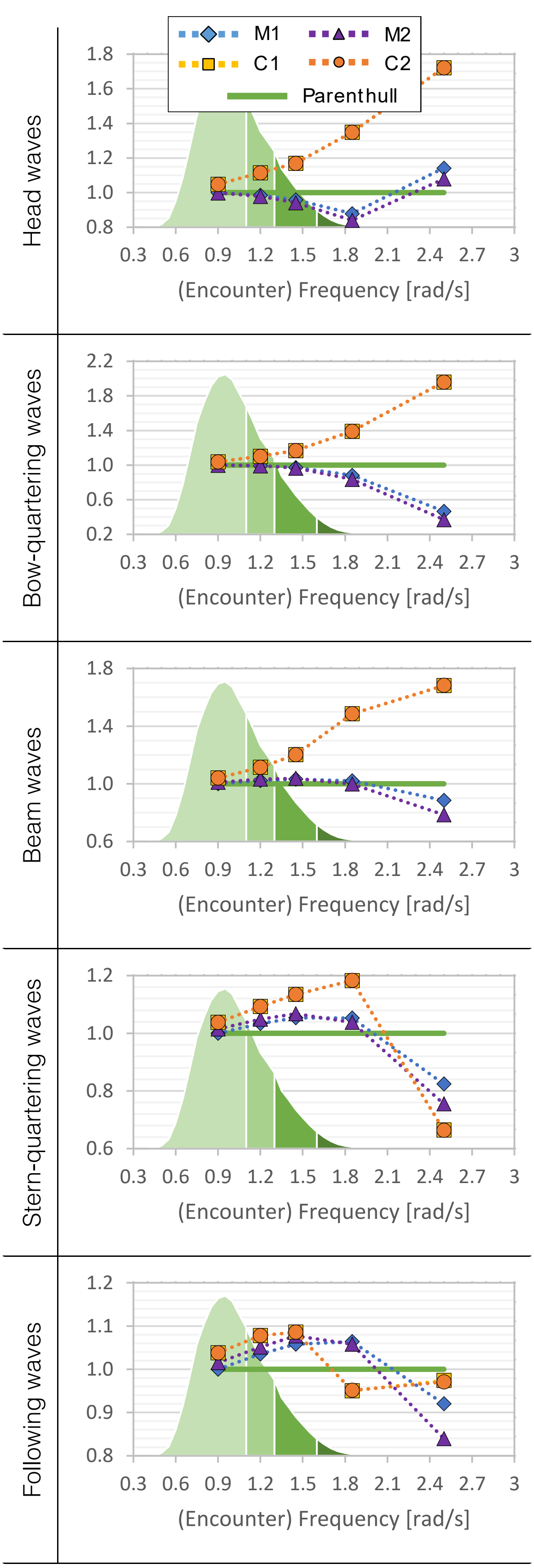


Figure 7-2: Effectiveness on heave RAOs

7.1.1.1 Heave at the bow

Figure 7-1 contains the heave RAOs at the bow transfer point. The results for the wheelhouse are located in appendix F for conciseness because the RAOs and conclusions are similar. Compared to the parent hull, the monohulls' natural frequencies (i.e. resonance peaks) in beams waves at both locations moved closer to the peak of common wave frequencies. This shift is presumably due to the Axe bow since the response from M1 and M2 are similar. So, the Axe bow seemed to have changed the secondary parameters such that natural frequency is lowered. Still, according to Figure 7-2, which shows the level of effectiveness, their (the monohull prototypes) absolute responses are generally similar to that of the parent hull; only at higher frequencies is there a notable decrease compared to the parent hull. Only in following waves do the monohulls perform poorer than the parent hull.

The catamarans show a much larger resonance peak at their natural frequency in beam waves, see Figure 7-1. Although it is positioned outside the range of expected encounter frequencies, Figure 7-2 shows how the heave response to beam ways is always higher than the parent hull and the new monohulls. The same goes for the other wave directions.

In short, the performance of each DC match at the first range of frequencies. As the frequencies rise, the catamaran shows the poorest performance while the monohulls are comparable to the parent hull.

7.1.1.2 Roll

To start, the roll damping coefficient (ν) was set at 0.15 and 0.20 for all monohulls. It did not need to be specified for the catamarans because MAXSURF Motions computes it from the heave damping properties. Based on a series of simulated free-decay tests, it was determined that the catamarans have ν = 0.20. Appendix G contains the calculations used to determine the catamaran's roll damping coefficient.

According to Figure 7-3, the monohulls have the same resonance amplitude as the parent hull. However, M1 has a lower natural frequency than the parent hull and M2. It is presumed that the natural frequency shifted due to a lower GM and not the Axe bow. Moreover, it is fairly in the range of wave frequencies expected to occur often, which is a considerable disadvantage. Figure 7-4 confirms this: M1 matches the rest of the DCs in the first frequency range but is the worst at the mid-frequencies. So, M1 would be ill-suited to use at Hornsea One and Gemini, where beam waves frequently occur (see section 4.2.4). The roll response from M2 is similar to the parent hull. Besides a slightly decreased amplitude after the resonance peak, the roll RAOs are unaffected by a wider beam.

In Figure 7-3, the resonance amplitude from both catamarans is significantly lower than the parent hull: C1 and C2 reduced the amplitude by roughly 50% and 18%, respectively. Moreover, C1's natural frequency shifted farther from the frequency spectrum's peak, while C2 shifted closer to it. So, C1 is most effective in reducing the roll motions in all (oblique) wave directions, especially in beam waves. The same conclusion is drawn from Figure 7-4, which shows it is the best in all wave frequencies.

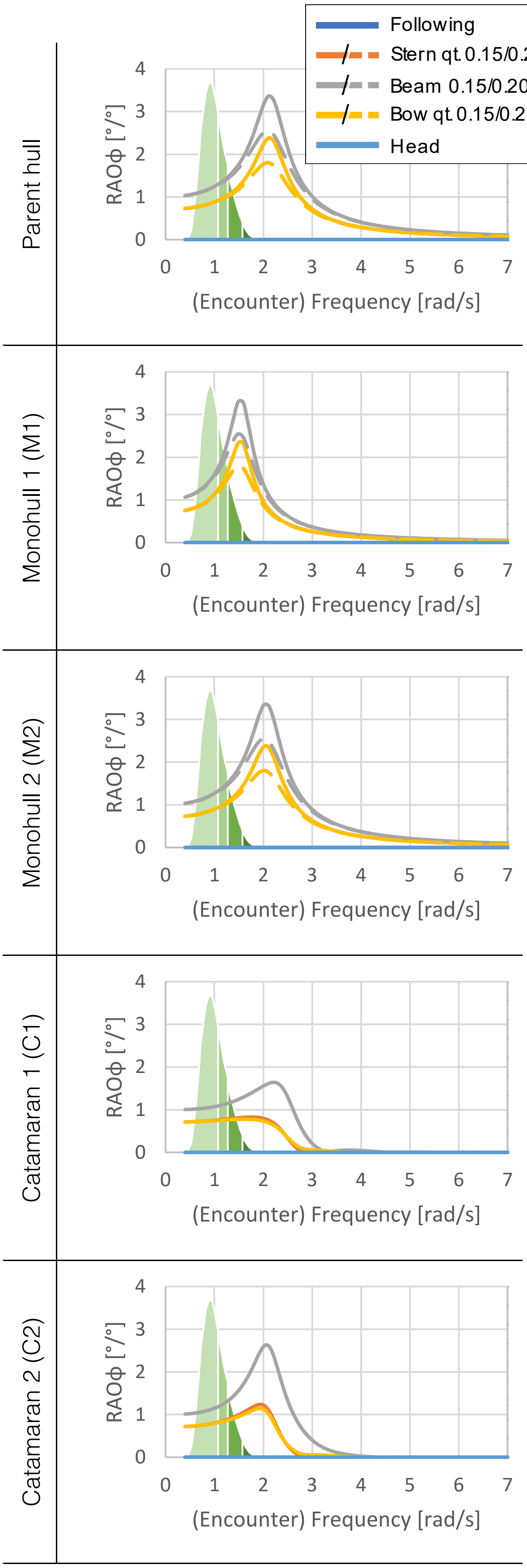


Figure 7-3: Roll RAOs at the bow and wheelhouse

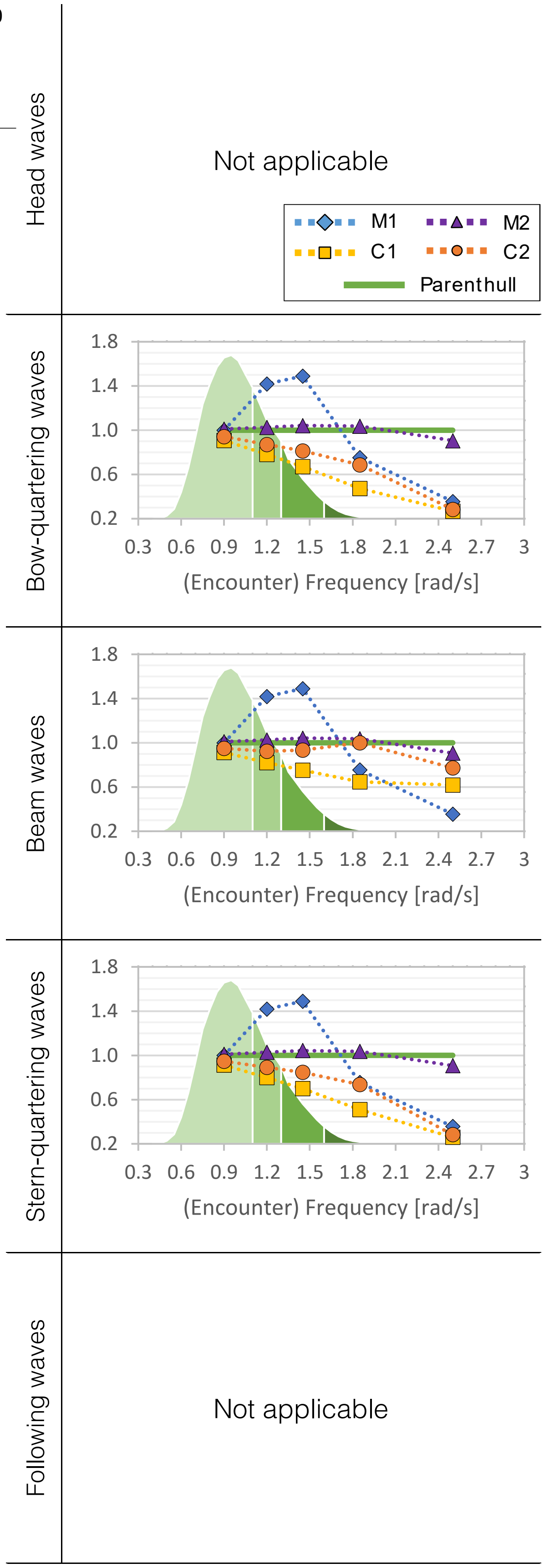


Figure 7-4: Effectiveness on roll RAOs for $\nu = 0.20$

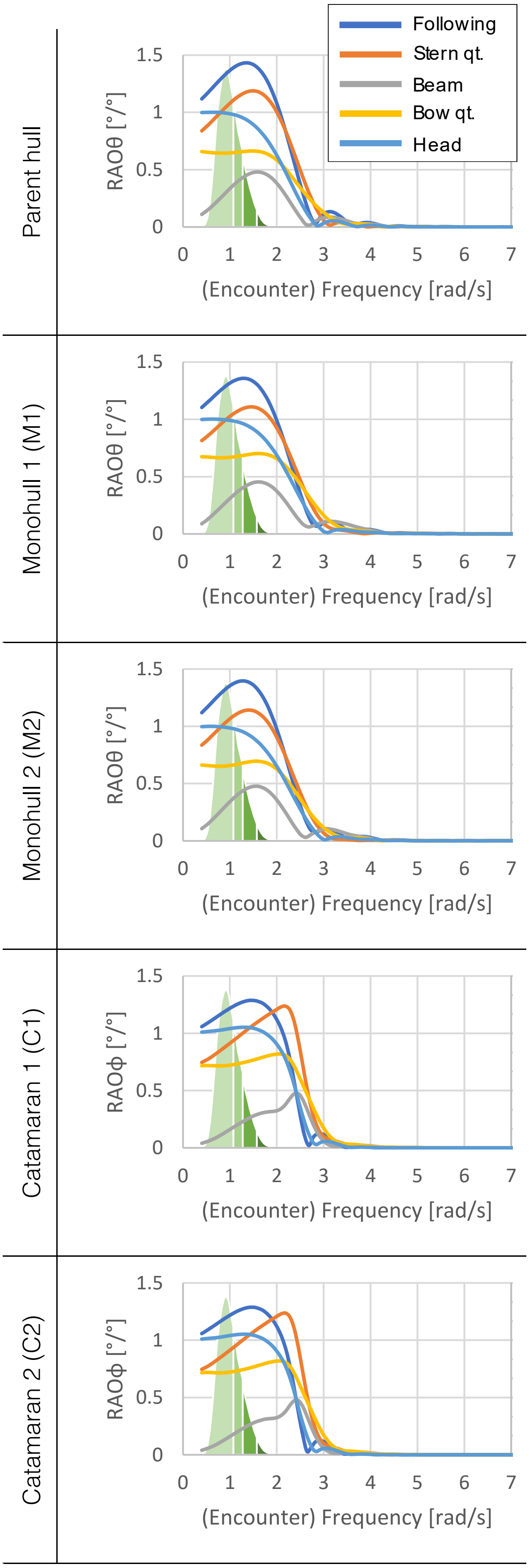


Figure 7-5: Pitch RAOs at the bow and wheelhouse

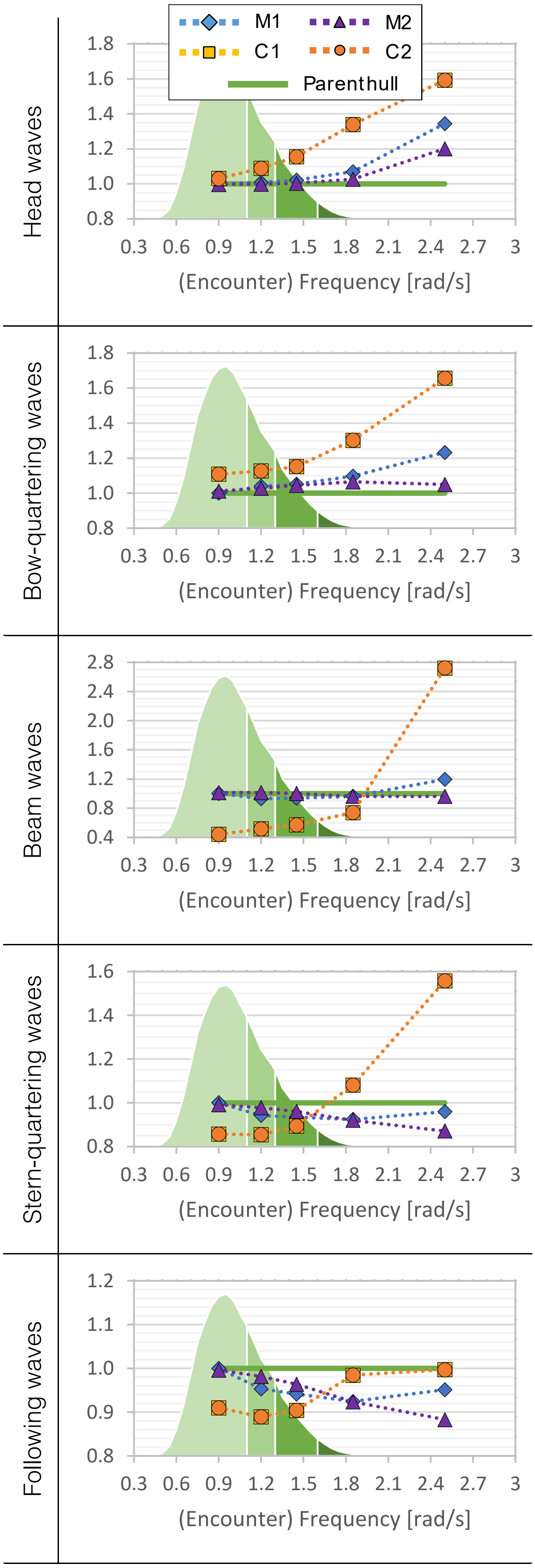


Figure 7-6: Effectiveness on pitch RAOs

7.1.1.3 Pitch

Figure 7-5 contains the pitch RAOs of the DCs. The response from both monohulls is nearly identical to that of the parent hull. Figure 7-6 confirms this for the common frequencies and most wave directions. This was anticipated since the modifications (Axe bow and shift of LCB) were known to have little effect on pitch. The LCB of M1 even moved backwards instead of forwards, but the (negative) effect is not large. Also, it seems that the positive LCB shift of M2 was not large enough for there to be a notable reduction.

The natural frequencies of the catamarans did shift farther from the frequency spectrum's peak; see Figure 7-5. According to Gutsch et al. [97], this is what lowers vessel motions. So, although the absolute pitch response in stern-quartering waves is higher than the monohulls, the natural frequency shifted to a more favourable position. Furthermore, the resonance amplitude in following waves was reduced as well. It seems that the catamarans' LCB was moved forward enough for it to (positively) affect pitch. Figure 7-6 shows that catamarans performed best in following stern-quartering and beam waves, except in the high (uncommon) frequencies. Only in waves from the front did they perform slightly worse than the monohulls for all frequencies. Considering that head waves occur the most due to the boat landing's orientation, catamarans would not immediately be the vessel of choice. However, it could be useful for farms, such as East Anglia Three, where waves from the aft occur most frequently as well.

7.1.1.4 Corkscrew effect

According to Yun et al. [32], when the natural frequency for pitch and roll are close to one another, the crew will experience a corkscrew-like motion in oblique (quartering) seas. This is common for vessels with a relatively small L/B, such as catamarans. The effect can cause motion sickness to the crew that operates the DC if they have to endure multiple transfers per trip. Based on the RAOs in Figure 7-5, C1 could experience this effect is in beam waves while C2 could experience it in quartering waves.

7.1.2 Long-term response to (wind) waves

For conciseness, this section will only discuss the performance at the bow and propulsor ventilation because there is relatively less risk for technicians waiting or moving in the wheelhouse, and bow diving does not occur. The graphs can still be found in Appendix H.

7.1.2.1 Absolute vertical motions and accelerations

Figure 7-7 shows the vertical motions and accelerations at the bow transfer point. The monohulls have nearly identical responses to the various wave spectra. Just like the parent hull, the highest response is induced by head and following waves.

The catamarans show larger motions for all wave directions. This alone does not indicate that the catamarans are less safe, but the accelerations are higher as well. However, their accelerations in longitudinal waves are very similar to the monohulls. The difference found here corresponds to the results found by the RAOs; the catamarans also had a higher response to quartering and beam waves compared to the monohulls.

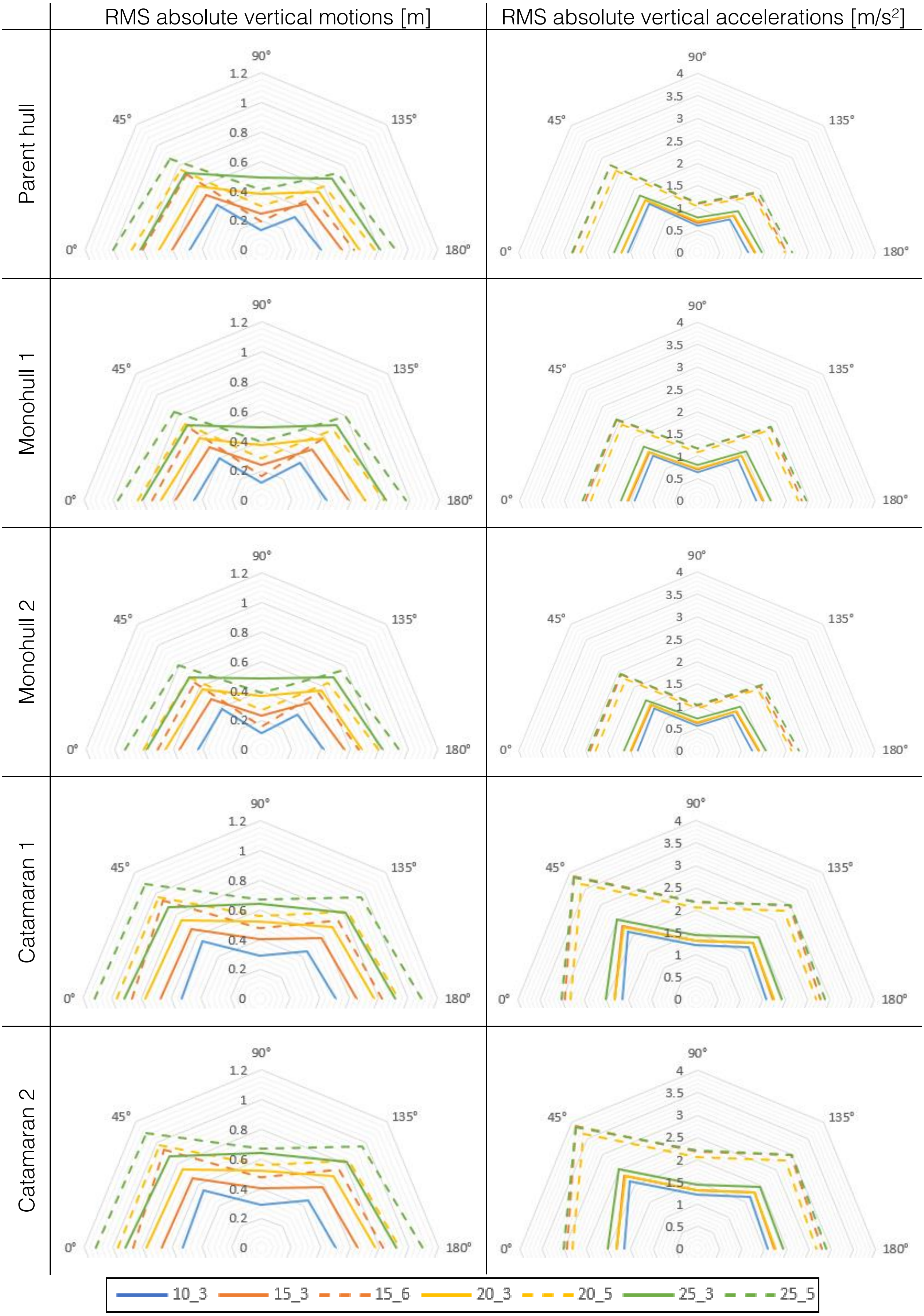


Figure 7-7: Comparison of vertical motions and accelerations at the bow transfer point

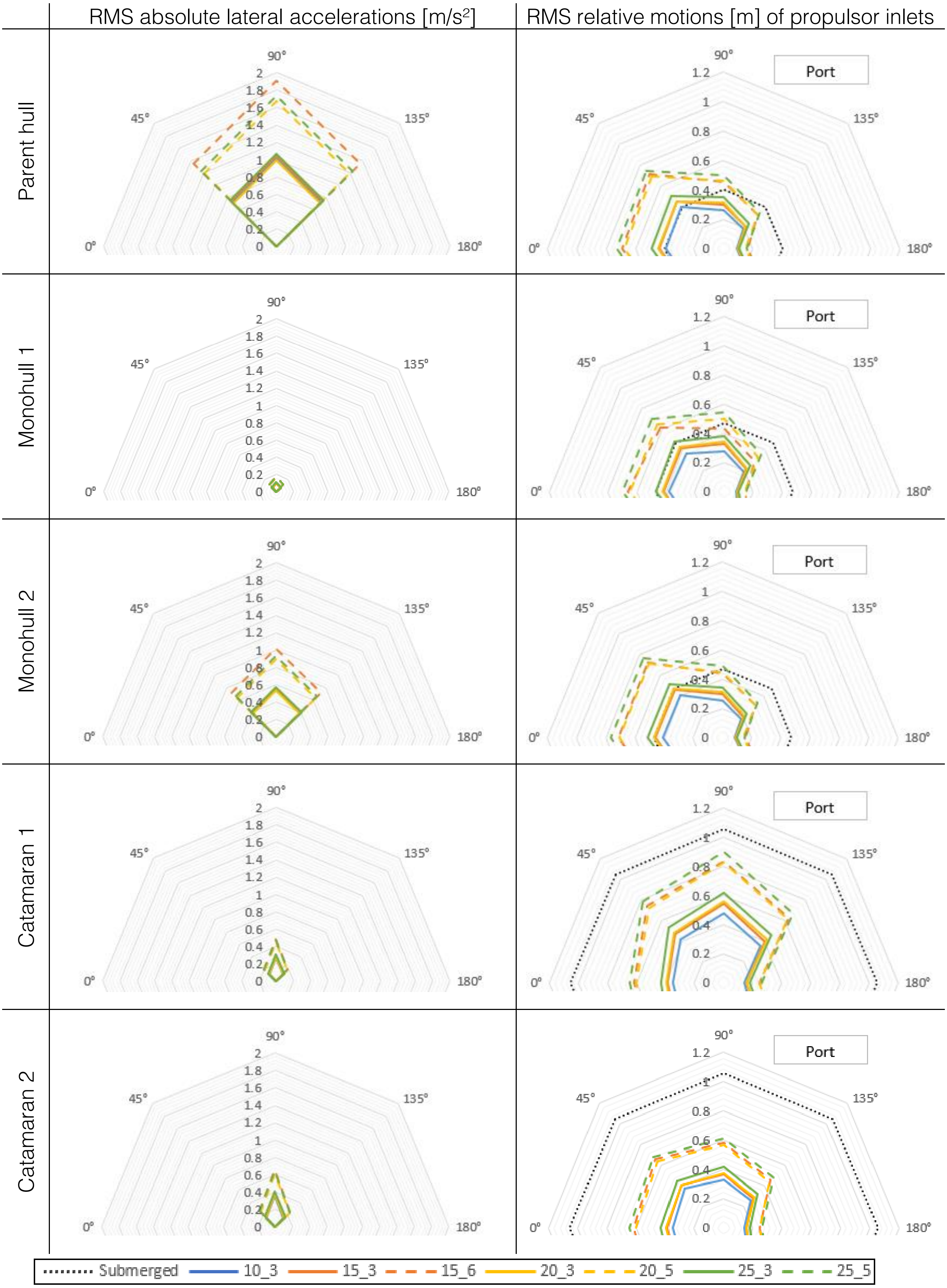


Figure 7-8: Comparison of lateral accelerations at the bow and relative motions of propulsor inlets

7.1.2.2 Lateral accelerations of the bow

Figure 7-8 shows the lateral accelerations at the bow transfer point. It is unclear how much influence the Axe bow has on these motions. Furthermore, the following conclusions also apply to the wheelhouse. In this case, the parent hull has the largest accelerations. The lowered GM significantly reduces the lateral accelerations to near-zero levels, and at first glance, this is the ideal response. This reduction was expected because, as explained in section 5.1.2, a smaller GM leads to a smaller righting arm, which slows down the roll period. However, M1 is more prone to capsizing in rough waves, see Figure 6-18. So, this particular DC is deemed unpractical and will not be promoted for far-offshore use. M2 has the same GM as the parent hull and a wider beam. As a result, the accelerations were cut in half, but a wider beam was not as “effective” as a lowered GM. This corresponds with the conclusions by Gutsch et al. [97].

Both catamarans also have significantly reduced accelerations. Those of the quartering waves are even reduced with a greater scale. C1 has the lowest accelerations among the two, so the larger clearance is more effective in lowering the lateral accelerations; the same conclusion was drawn for the RAOS. Also, their lateral accelerations at the wheelhouse matched the thresholds proposed by Phillips et al. [61] (section 6.2.2) in quartering waves.

7.1.2.3 Relative motions of propulsor inlets

Here, only the motions of the port-side propulsor are shown. Although the propulsor at the starboard-side has a slightly different response, it is still similar enough for only one half of the plot to be shown. The entire plots can be found in appendix H. The propulsors of the monohulls were placed at roughly the same locations. Consequently, propulsor depths are similar since the stern did not change much. Like the parent hull, both M1 and M2 still ventilate in (steep) following, stern-quartering and beam waves. Only the M1, with the lowered GM, managed to reduce the risk slightly, but not enough for it to be useful.

The catamarans show more favourable behaviour. Not because the motions are lower, but because the propulsors have more leeway than those of the monohulls. So, although the absolute motions are larger, the propulsors remain submerged and will not ventilate, especially in common wave spectra. Furthermore, both C1 and C2 have the same draught, but C2’s smaller clearance removes the risk of ventilation in the steepest waves.

7.1.3 The best performing DCs for conditions at far-offshore wind farms

This section summarises the results from the previous sections by presenting which model performed the best for various seakeeping parameters. Specifically, three points were considered to determine which DC (type) is most useful at the reference farms: the most prominent wave directions (section 4.2.4), the notion that the response should be as low as possible (to meet the ideal seakeeping criteria for transfers given in section 6.2.2) and the estimation of their intact stability (section 6.4.6).

An overview is given in Table 7-1 and is mostly based on performance at the bow. It also shows which wave directions the reference farms observe the most. If there was no observable difference between a particular hull type's performance, the overview names the hull type. However, a specific version is named if it had distinct results. If no DC stood out positively or negatively, then there is “no winner”.

Table 7-1: DCs best suited for combinations of seakeeping and wave direction

	Head	Beam	Stern-qtr.	Following
Hornsea One	✓	✓		✓
Gemini	✓	✓		
East Anglia Three	✓		✓	✓
Heave RAO	Monohulls	Monohulls	Parent hull	Parent hull
Roll RAO	Not applicable	C1	Catamarans	Not applicable
Pitch RAO	Parent hull and monohulls	Catamarans	Catamarans	Catamarans
Vertical bow response	Parent hull	Monohulls	Monohulls	Monohulls
Lateral bow response	Not applicable	Catamarans	Catamarans (matched threshold in common steepness)	Not applicable
Propulsor ventilation	No winner	C2	C2	Catamarans

In short, monohulls are suitable if only head waves are considered. Once other wave angles are included in the analysis, catamarans start to outperform the monohulls in roll related behaviour and propulsor ventilation. C2 was only best for propulsors ventilation because it had the lowest relative motions, but C1 did not show the tendency to ventilate either. The new monohulls also had poorer transverse stability than the parent hull. M1 will even tend to capsize at low heeling angles, which is why it was not considered the winner for lateral bow responses. Still, there are occasions when the catamarans are slightly inferior, i.e. heave and vertical responses. But these DCs were simulated to be floating freely. The heave results could perhaps improve when the interaction with the boat landing is included in the analysis.

7.2 High-level solutions to achieve lower motions

The disadvantages of both hull types can be overcome by equipping the DCs with additional seakeeping devices and redeveloping their secondary design parameters. Furthermore, it is presumed that responses could be reduced even further by looking into solutions that include the boat landing, but this is elaborated in section 8.4 as a topic for further research.

7.2.1 Motion stabilisation devices

A significant disadvantage of monohulls is their roll performance in oblique waves and must rely on additional devices to reduce the roll motions. This is the most feasible solution for existing DCs to become more useful for far-offshore locations since most can be installed in a refit. These solutions can also be applied to catamarans.

Active ride control systems can be equipped to regulate thrust or reduce resistance and vertical motions in waves to increase a vessel's operability for transit. These are seen by van Deyzen et al. [104] as valuable solutions for vessels whose length cannot be increased. But during transfers, there is no need for thrust control because there is zero-speed. Moreover, controllable transom flaps (or interceptors) are only useful at higher speeds [105]. At zero-speed, DCs will require motion stabilisation devices. Gyro stabilisers, active fin stabilizers, anti-rolling tanks and an active ballast system are proven and popular devices for large CTVs, but Yang et al. [42] state that these are not applicable to vessels ranging from 14-20 metres due to the small hull and limited deck spaces.

7.2.1.1 Popular devices for DCs

The two most popular techniques applicable to small vessels, like the DC, are rubber bumper systems (or fenders, see Figure 5-7) and hydraulic gripper systems (Figure 7-9) [42]. The latter is a device that grips the turbine ladder and, in a way, imitates a push-on transfer. The advantage is that the thrusters do not need to run to keep the DC in place. However, the high waves could flood the DC's deck due to the fixed contact point [42].

Figure 7-9: Hydraulic gripper system [42]

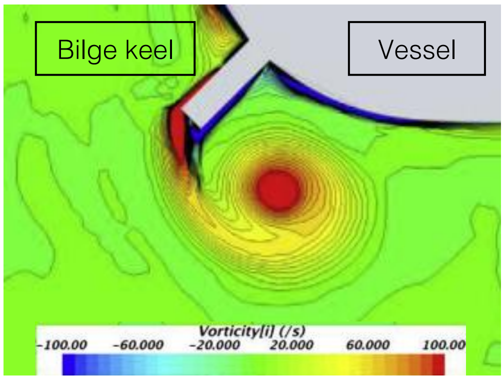


Figure 7-10: Bilge keel creating a vortice [99]

7.2.1.2 Bilge keels

A relatively cheap, simple and widely used solution to reduce roll motions is bilge keels, which are essentially passive fin stabilisers. Viscous flow field predictions show that bilge keels cause large flow separation and dissipate the ship's kinetic energy [106]. An example of how vortices are generated is shown in Figure 7-10. Various studies investigate the effects of bilge keels and configurations, and all agree that the reduction of the roll angle (φ) is faster for larger initial heel angles.

Irkal et al. [99] simulated, among others, the free roll decay of a ship's midsection and compared the results of a vessel with and without a bilge keel. In Figure 7-11, BK00 is the model without a bilge keel and BK10 with a bilge keel, and it shows how the bilge keel dampens the roll motion at a faster rate; the bilge keel increased the roll damping by 140%. Their results also show that whether the bilge keel has a sharp or blunt end (i.e. a narrowing or constant thickness) has no impact on the roll damping. Lastly, they concluded that bilge keel length increases the roll damping and added inertia and natural period. The latter is useful to ensure the DC's natural roll period is located outside of the range of regularly observed frequencies, given in section 5.6.1.1.

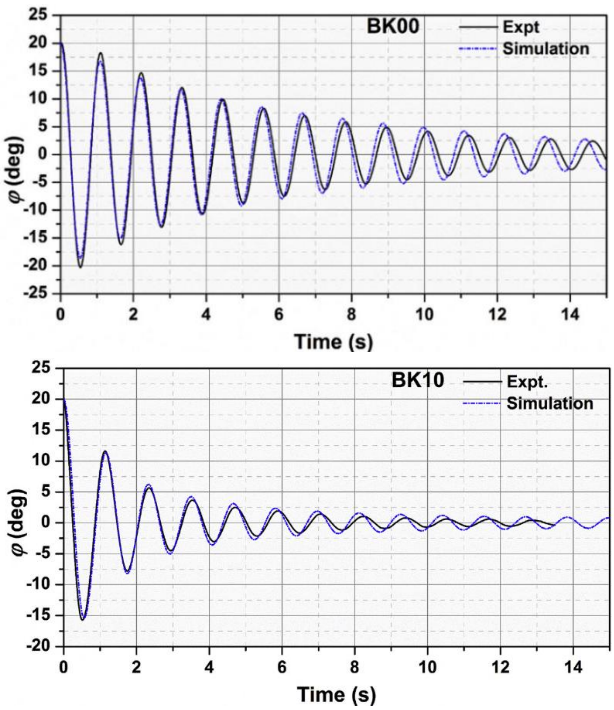


Figure 7-11: Comparison of measured and simulated free roll decay for $\varphi_0 = 20°$ [99]

Jiang et al. [106] studied the influence of various bilge keel configurations. Their conclusion about the bilge keel length agrees with Irkal et al. [99] and add that there is a point when the length will decrease the growth rate of roll damping. In their case, shown in Figure 7-12, bilge keel lengths greater than 40 mm would no longer increase roll damping.

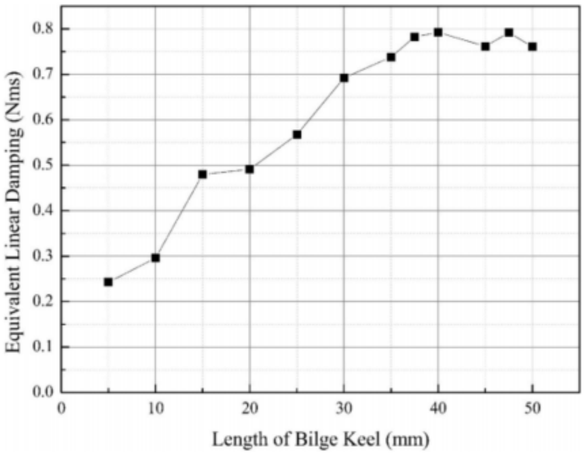


Figure 7-12: Equivalent roll damping for different bilge keel lengths [106]

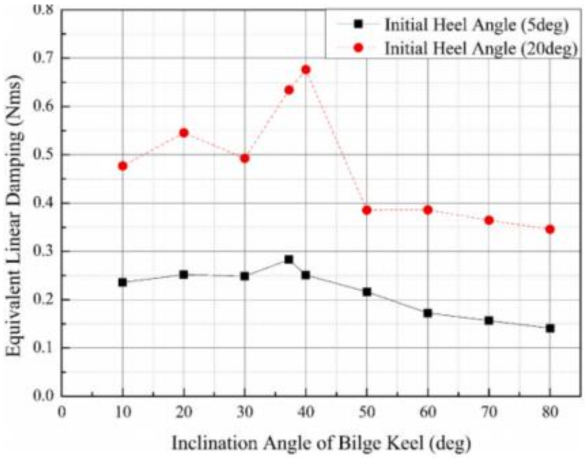


Figure 7-13: Equivalent roll damping for bilge keels of different installation orientations [106]

The installation angle also influences the roll damping, but the magnitude depends on the initial heel angle. Figure 7-13 shows the results for bilge keels installed at different angles and two initial heel angles by Jiang et al. [106]. Horizontal (0°) and vertical (90°) bilge keels were also tested but in a separate set of experiments. Generally, horizontal bilge keels are better than the bare hull and vertical bilge keels. But “diagonal” bilge keels work better since the distance from the tip to the vessel’s roll centre is larger.

All in all, there is an optimal angle that can deliver the highest roll damping (for most heel angles). In general terms, the contribution of bilge keels to the total roll damping coefficient will be largest when the extrapolating lines of the bilge keels intersect at the roll centre of the model [107]. For the model used by Jiang et al. [106], this is the angle set at 37.2°.

7.2.1.3 Magnus rotating roll stabilisers

Another device that can increase roll damping is a set of Magnus rotating roll stabilisers. These are swinging and rapidly rotating cylinders, see Figure 7-14, that provide roll stabilisation by generating an up or downward pressure through the Magnus effect. A more in-depth explanation of the working mechanism is given by Liang et al. [108]. Liang et al. [109] consider Magnus rotating roll stabilisers to be the most efficient devices to provide roll damping at low speed since they do not depend on water flow like (active) fin stabilizers.

Liang et al. [108] investigated the hydrodynamic characteristics of Magnus rotating roll stabilisers, though only its anti-rolling effect at low ship speed will be discussed here. They simulated the performance of a (large) vessel with various low forward speeds when H_s = 3.3 m and recorded the roll angles with and without the stabilisers. Only one set of results is shown in Figure 7-15 since the others were similar. The abbreviation RRC stands for roll reduction control. The results clearly show how effective the Magnus rotating roll stabilisers are in reducing roll. All in all, with speeds ranging from 2-6 knots, the roll was reduced by 60.7-77.4% [108].

Figure 7-14: RotorSwing Magnus stabiliser [110]

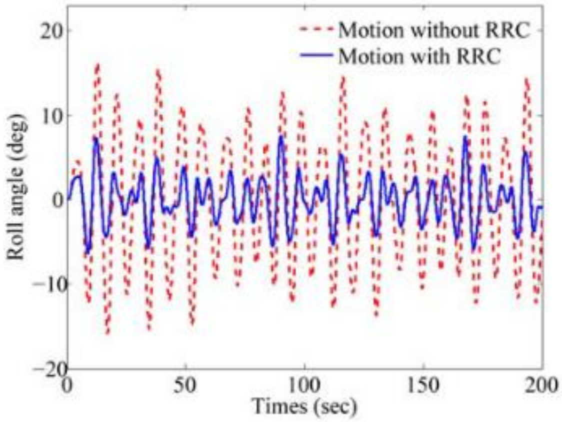


Figure 7-15: Simulation results at 3 knots [108]

Although their lowest test speed was 2 knots, RotorSwing recently developed a ZeroSpeed version optimised for vessels at anchor or afloat [110]. Furthermore, Liang et al. [108] also considered these stabilisers less suited for higher ship speeds because the drag generated is almost proportional to the square of the sailing speed, which causes speed loss and drives up fuel consumption. But RotorSwing also developed an adaptive RAKE system, which swings the Rotors adaptively towards the aft to minimize drag [110].

7.2.1.4 Heave plates

Yang et al. [42] studied a heave motion stabilisation device for DCs through numerical and experimental research, which was inspired by the contribution of heave plates which suppress the heave motions of floating structures. They tested the influence of size and depth of the heave plates on their vessel's motions in beam waves and compared the results to a vessel without heave plates. For conciseness, only the figures from the experiments will be shown since the numerical results give similar conclusions but are less apparent. This is because viscous effects were neglected, which otherwise amplify the results [42].

The results from experiments (and the numerical tests) show that the heave plates successfully reduce the motions for especially heave and roll, even more so when the size and depth from the water surface are increased, see Figure 7-16 and Figure 7-17. There is a small error in Figure 7-17c: The colours for depth is 50 mm, and 150 mm should be switched. Although the pitch motion is relatively small in beam waves, larger and deeper heave plates also reduce that magnitude of motion. Regarding the depth, Yang et al. [42] explain that this is because sea waves have less influence on the heave plates when they are located deeper underwater while the hydrodynamic damping increases. What was also more evident than from the numerical results is that the application of heave plates decreases the response at the vessel's natural frequency. This is because the larger heave plates increase the vessel's physical and added mass [42].

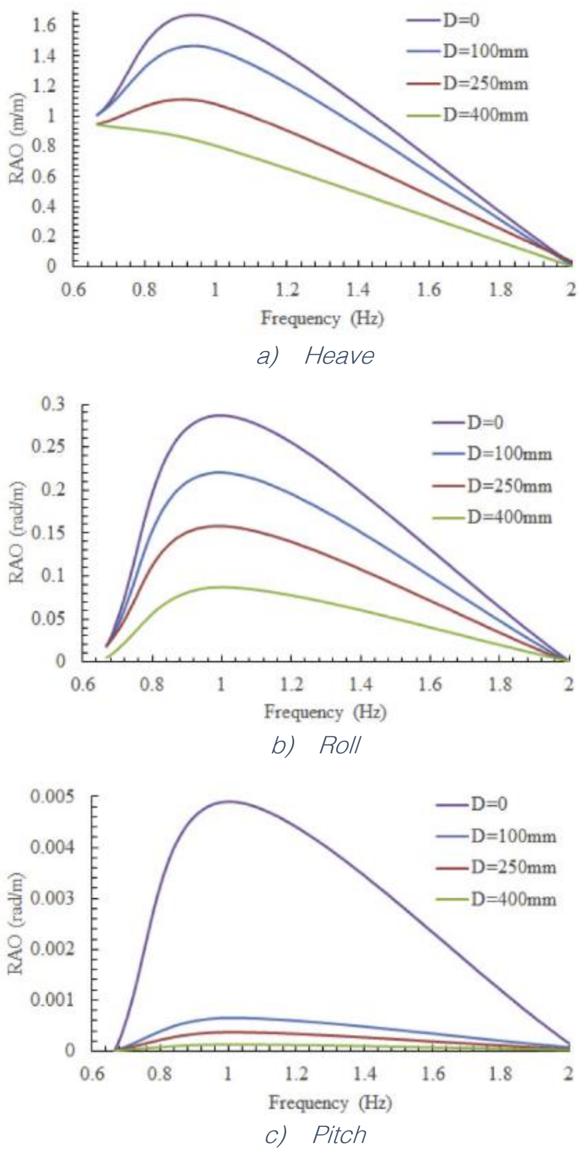


Figure 7-16: *Influences of the size of heave plates at underwater distance 0.05 metres* [42]

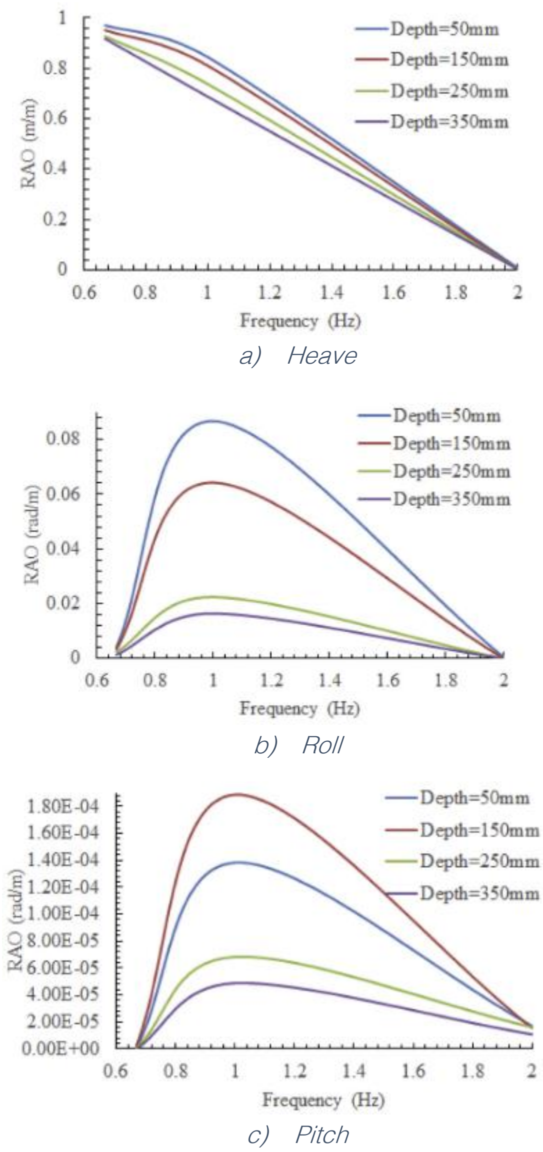


Figure 7-17: *Influences of the underwater distance of heave plates* [42]

7.2.2 Catamaran weight reduction is not necessary

As stated in section 6.4.4.4, the catamarans from Table 6-2 exceed the current davit's lifting capacity (and do not fit in the cradle). If the davit crane is a hard constraint, theoretically, the catamaran weight can be reduced by building (part of) its structures using sandwich composites. The ship will then have a reduced volume displacement. However, according to trends by Nazarov [100], see Figure 7-18, a 13-metre catamaran's weight would only reduce by roughly 1 tonne if it is made of composites instead of aluminium. More sizable weight reductions seem more practicable for larger vessels.

Furthermore, a heavier DC is more resistant to high frequencies. In other words, a DC with more inertia would move less during transfers. So, the weight is not a parameter that should be lowered.

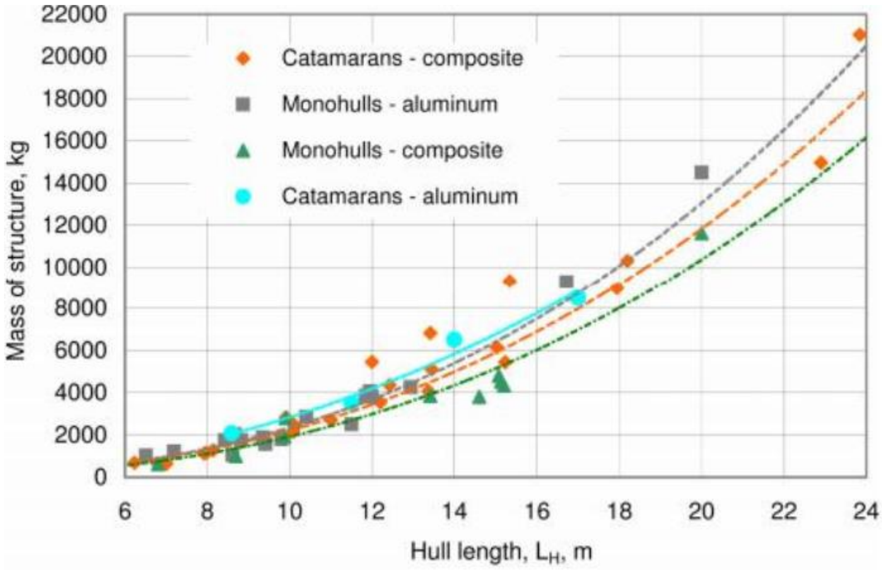


Figure 7-18: Data on structure mass for catamarans and monohulls built with composite and aluminium [100]

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8 Conclusions and recommendations

This chapter finalises the thesis by discussing the results (section 8.1), identifying the limitations (section 8.2), providing a general conclusion by answering the main research question (section 8.3), and proposing topics for further research (section 8.4).

8.1 Discussion

This thesis aimed to give an answer to what the shortcomings of current DCs are and how these access vessels can be modified to operate year-round at far-offshore wind farms. Before a final conclusion is given to the main question, the sub-questions are resolved, and the results are discussed here first, along with limitations. This section ends by discussing the contribution of this thesis.

1. *Why is there a need for offshore wind farms to move farther from shore, and who are the key stakeholders?*

Wind farms in Europe are moving farther from shore due to depleting locations near shore, but also to harness the power of the stronger winds. These far-offshore locations can be economically attractive if the relevant technology is sufficiently developed. So, it depends on the advancement of O&M technology to establish whether and when these locations are practical enough. The stakeholders who have a high interest in and high power to influence the far-offshore activities are the wind farm owners/investors, the turbine supplier, the vessel supplier, and the O&M operator's technicians. Either of the two former stakeholders can also take on the additional role of O&M operator, whose primary interests are preserving turbine availability, minimising costs and ensuring turbine accessibility. The TU Delft is an external stakeholder who has high interest since they wish to encourage and contribute to the energy transition but has low influence because they are not involved in how the business is run.

2. *How are (other) state-of-the-art access vessels used in O&M of offshore wind farms?*

Modern access vessels are diverse and purpose-built designs. SOVs are best suited for calendar-based maintenance due to their large weather window. Their ability to remain offshore for extended periods make them more efficient as well due to the reduced transit time. Some SOVs are fitted with DCs or can be if it is requested by the O&M operator. These are ship-based vessels used to send technicians to wind turbines for corrective/preventive maintenance or to prepare the wind turbine before the SOV arrives. But these vessels are only operable in the summer due to their smaller weather window. CTVs are similar to DCs but are much larger and port-based vessels. These are used to cover the entire range of maintenance strategies. However, they are more suitable for offshore wind farms located not far from the shore to limit transit times and avoid motion sickness. An SATV combines the capabilities of CTVs and SOVs. They can also remain offshore for (less) extended periods, which reduces transit times, and can cover the entire range of maintenance strategies because they are (or at least should be) assigned to smaller wind farms. Lastly, helicopters are the only non-seaborne access vessel at an O&M operator's disposal. They are not limited by metocean phenomena but are mainly used for urgent corrective maintenance.

3. *What are the daughter craft's operational objectives when they are required to operate in areas farther from shore?*

Since DCs are SOV-based vessels, their overarching objective is to increase the multitasking capability of the SOV assigned to far-offshore wind farms. These far-offshore locations are characterised by wave conditions that are, based on the DC's original requirements, expected to induce extreme responses from existing DCs. So, the DC's operational objectives are deficiency driven. The primary operational objectives are connected to explicit tasks, safety/comfort, capabilities, and storage and represent categories of objectives.

The operational objective of concern to this thesis is "Allow access in $2.0 \leq H_s \leq 2.5$ m" and falls under the category of capabilities. It addresses the main deficiency by describing the (potentially) desired seakeeping performance that should provide the DC with year-round accessibility. Specifically, it is expected to give the DC an average accessibility level similar to the SOV and thus make the DC practical in the winter as well, rather than in the summer alone. This means that seakeeping performance must be improved. This applies to both the transit and transfer phase, but it is mainly an enhanced objective with respect to the original transfer requirement since existing DCs are already required to transit in $H_s \leq 2.5$ m.

Additionally, different phenomena are present during high-speed transits and zero-speed transfers. This makes it hard to optimise a system towards both access phases. However, it was determined that 25 knots should no longer be required as a design speed but become the desired top speed. This is because the SOV-based DCs are always closer to their destination than port-based access vessels. Furthermore, in rougher wave conditions, it is deemed more important that the DC reaches its destination safely rather than quickly. So, a lower (but still unknown) design speed would depolarise both access phases in terms of seakeeping performance. As a result, it becomes easier to consider both access phases in the design process.

4. *Which system functions are relevant to the desired objectives, and how do they perform in current and new environments?*

The hull is the system function-of-interest because seakeeping can be improved by altering the hull type and modifying its main dimensions and proportions. This was also determined based on an observation made on CTVs: there exists a variety of hull forms that have different limits for significant wave height. After three existing DC mock-ups (that vary in length) were modelled and studied, it was determined that both wave height and wave steepness affect vertical motions, while mainly wave steepness affects the accelerations. This means that wave periods have more influence on acceleration levels and safety than wave heights. So, vessel suppliers should also inform O&M operators of the performance of their vessels in steep waves rather than high waves alone. Moreover, O&M operators should also consider wave period along with wave height to decide whether it is safe to deploy their DCs.

Furthermore, it is clear that having the boat landing oriented such that head waves are encountered is beneficial for transfers. Then, the vertical accelerations are relatively low, and, in the ideal case, there are virtually no lateral accelerations. In the other wave directions, the DCs experience larger accelerations or a combination of vertical and lateral accelerations. As a result, steep and oblique waves are riskier conditions for DCs to carry out transfers in. And these conditions are not significantly less likely to occur than head waves. So, accessibility is increased if DCs have lower responses in these conditions too.

5. *How should these functions be modified or implemented in a new system considering system constraints?*

System interfaces impose constraints on size, weight, and seakeeping performance. In the end, four prototypes were generated. Regarding the primary hull parameters, it is only possible to increase the hull beam and not the overall length due to space constraints of the reference SOV. Thus, a monohull was made wider, and the DC also took on the form of a catamaran. The beam of the monohull was established by referring to promising results obtained for larger vessels. The approach here was to convert the large step sizes to percentages so that they can be applied to the smaller DC.

Furthermore, secondary design parameters can still be altered. So, the waterline length of all four prototypes was maximised to emulate an increased ship length. The forebodies ultimately resembled an Axe Bow, and it was expected to reduce heave and pitch responses. One monohull had a smaller metacentric height aimed at reducing roll motions, which was also based on the results of a larger vessel. The two catamarans had different clearances to gain insight into the effect on the roll motion. Lastly, only the catamarans exceed the weight constraint, but the davit was considered less of a constraint in this case due to the hull shape.

6. *How effective is a new system in improving access to far-offshore wind turbines?*

Depending on the wave direction, either the parent hull or the monohull prototypes were best for heave and vertical (bow) responses. Neither M1 nor M2 stood out positively or negatively, but that is because they both have roughly the same (bow) shape.

The main difference between the two monohulls was their roll performance. Although M1 (with the smaller GM) had the lowest lateral accelerations, it was deemed impractical because its natural frequency was also closer to the range of common wave frequencies, and it would tend to capsize at a low 15°-20° heel. The fact that the angle of vanishing stability decreased was expected since small GMs are known to decrease the GZ-curve slope. But it was surprising how low it turned out to be. Furthermore, M2's wider beam also successfully lowered the lateral accelerations. But its angle of vanishing stability was less than half that of the parent hull. So, it is clear that converting the step sizes used for larger vessels into percentages for smaller vessels did not lead to the same (positive) results. In other words, the design parameters of small DCs cannot fully rely on the results observed for larger vessels.

On the other hand, the catamaran DCs did have better performance for roll, especially C1 with the wider clearance if the RAOs are considered. In fact, they outperformed all of the monohulls for a majority of the remaining responses and conditions, even in terms of the pitch motion in non-head waves. This means for any non-head wave direction, which is not significantly less likely to occur, catamarans have an overall better performance. Furthermore, note that these simulations were done for free-floating vessels. So, although catamarans' performance for heave and vertical responses are currently inferior to the monohulls, it is presumed that the catamarans could have better responses if their interaction with the boat landing is included in the analysis.

8.2 Limitations

This section identifies and discusses three limitations that potentially impact the quality of this thesis' findings. First, **no thresholds were adopted as transfer criteria**. This thesis compared the DCs to each other, and there was only a winner if a (type of) DC had a significantly lower response than the rest. If the analysis were to adhere to transfer criteria, the results would be presented as operability plots. The conclusion could then have differed in two ways: (i) no prototype met the criteria, and so feasibility could not be established, or (ii) multiple prototypes met the criteria, which then pose as a basis for the "optimal" design.

Second, **some hull modifications were applied based on research concerning larger vessels with a (low) forward speed**. This thesis could not apply the same step sizes because it would make the DCs severely disproportional. So, it was opted to work with those increments as percentages instead, but one DC turned out to have impractical static stability.

Third, **it is uncertain how accurate the simulated responses are**. For one, this thesis used mock-ups, whose resemblance to the original DCs were inspected visually rather than optimised DC designs. Also, Strip Theory was expected to overestimate the responses since non-linear effects were excluded. In the early design stage, these results still provide useful insight into seakeeping performance. But further development would require more accurate and valid results. Moreover, the DCs were studied as they were floating in various wave spectra. Due to the interaction with the boat landing, the results generated here do not entirely represent the responses experienced during transfers. How these limitations can be overcome is given in section 8.4, along with additional recommendations for further research.

8.3 General conclusion

The general conclusion was formulated by answering the main research question: *What are the deficiencies of current DCs, and how can these access vessels be modified to operate year-round at far-offshore wind farms?*

The first notable deficiency of current DCs stems from their operational requirements: transfer in $H_s \leq 1.5$ m. As a result, DCs will have a low accessibility rate in areas frequented by higher significant wave heights, which undermine their value for far-offshore applications. The second deficiency is that they are required to achieve a high speed of 25 knots in transit when the emphasis should be laid on safe transfer conditions. This is due to their closer proximity to the wind farm than port-based O&M access vessels. Furthermore, sailing speed and course heading can (almost) always be altered to maintain safe transit conditions, but safe transfers depend on the vessel's stationary seakeeping performance.

For existing DCs already under a charter-contract, it is recommended to refit them with motions stabilisation devices to improve their seakeeping performance at zero-speed. For future DCs meant to operate far-offshore, this thesis recommends requiring them to be able to access wind turbines in $2.0 \leq H_s \leq 2.5$ m to realise year-round access. Various combinations of solutions were analysed to establish the feasibility of the access requirement while focusing on the transfer phase. There was no prototype that had improved responses in all conditions. But overall, the prototypes outperformed the parent hull for a majority of conditions. Moreover, the catamaran DCs have a high potential to realise year-round accessibility to far-offshore wind farms due to their performance in oblique waves. Lastly, it is believed that accessibility can be improved further if the wind turbine facilitates the daughter craft during transfers. But this solution is more suited for wind farms still in the development phase.

All in all, DCs are already useful assets during the summer because (i) the DCs can be deployed due to the calmer conditions, (ii) they can take over the corrective maintenance tasks from SOVs and (iii) their transit times are not as long as port-based CTVs. If O&M operators wish to obtain year-round access (to a far-offshore wind turbine), their DCs will need to become deployable in the winter as well. This thesis recommends refitting existing DCs and setting the access requirement to $2.0 \leq H_s \leq 2.5$ m for future DCs. Based on the results from this thesis, it is considered feasible and necessary for O&M operators require this from vessel suppliers. But year-round access would be facilitated further by inquiring about wind turbine related solutions for future wind farms.

8.4 Recommendations for further research

Explore wind turbine related solutions to reduce responses further

When the DC pushes onto the boat landing, the responses could be reduced even further if both interacting systems are modified towards near-zero motions. In other words, safer transfers will be more feasible if the boat landing facilitates the DCs. Various examples of wind turbine related solutions are as follows. First, the boat landing is already oriented such that head waves are encountered most. But waves from other directions are not significantly less likely to occur. One solution would be to apply multiple boat landings. Another more expensive solution is to design a dynamic boat landing that can rotate around the monopile. Furthermore, all ladder rungs are currently the same colour. Perhaps multiple/alternating colour indications could ease the identification of the transfer rung given by the deckhand to the transferee. Lastly, the boat landing could act as an additional and external damper to the DCs. Note that this would impose higher forces onto the DC's structure.

Establish the O&M costs and gains

Whether these modifications are worth the investment, depends on if it provides a financial profit or loss. In other words, although higher accessibility increases uptime and revenue, the equipment costs must not outweigh the revenue gains. So, the regained revenue must be evaluated against the costs made to obtain that level of accessibility. As presented throughout this report, many factors can contribute to higher accessibility. First, the existing daughter craft can be refitted with stabilisation devices. The associated costs could be minimised if this is done during the winter when these vessels are mostly idle. Second, future DCs could be catamarans. But the charter rate could increase since these vessels are generally more expensive than monohulls. Third, the wind turbine could help dampen the responses of the DCs during transfers. But costs could be increased due to extra design/engineering, material and possibly maintenance.

Test the vessels in transit conditions

The seakeeping performance of existing DCs and prototypes was determined at zero-speed. Furthermore, the prototypes were made following design guidelines for (near) zero-speed. However, both transfer and transit must be possible to access a wind turbine. Therefore, these (or improved) DCs should also be tested during transit conditions. This would serve to identify which trade-offs emerge when designing for both access phases.

Then, motion sickness should also be considered, even while at the turbine. When multiple teams are dispatched in one trip, some technicians will have longer transit times than others. So, there must be an analysis to determine if technicians will experience motions sickness during transit, which includes sailing and waiting time.

Establish feasible transfer thresholds for far-offshore operations

This recommendation concerns the first limitation discussed in section 8.2. The research could either establish the feasibility of the transfer criteria proposed in section 6.2.2 or define them from scratch. It may also be worthwhile to determine if the thresholds must only be formulated in terms of accelerations or motions as well. That is because transfers will be less risky if the relative motions between the bow transfer point and designated ladder rung are not too great. Once proper transfer thresholds have been established, it will be possible to make operability plots. This can later be used to define the most suitable design characteristics for DCs.

Establish more suitable DC characteristics

Four DC prototypes were tested in this thesis. The monohulls were adapted from the parent hull, and the catamarans had rudimentary hull shapes. Their performance could be improved by applying more appropriate secondary hull parameters—especially the catamarans, which were only tested with two clearances while the optimal c/L is still unknown. Furthermore, the vertical clearance was not included, while the seakeeping of catamarans strongly depends on it due to wet deck slamming.

Furthermore, this thesis determined the new monohull parameters by making use of a study aimed at lowering the roll response of larger vessels. The approach here was to convert the large step sizes to percentages so that they can be applied to the smaller DC. These prototypes ended up being impractical with regards to their roll performance. So, the monohull DCs would benefit from a more designated set of design guidelines for small vessels at zero-speed. These designs would also be more eligible for 3D calculations since there is a more precise impression of what would work best.

Conduct the simulations in the time domain

This thesis analysed the seakeeping performance using a linear and frequency domain approach. However, this method did not capture non-linear effects caused by large motions and the wedge-like hull shape. Furthermore, the analysis was only able to show if propulsor ventilation would occur, but not when and how often. So, time-domain simulations are proposed to simulate the operations more accurately. But this approach is only recommended for more established DC designs to prevent lost computation time.

Investigate the applicability to other operational areas

This thesis only considered wind farms in the North Sea. Since wind farms are also going to be placed in other locations, the problem may arise that different locations require different vessels for efficient accessibility. A trade-off could then be to design a vessel that is deployable in a wide range of geographically different locations but will not be as valuable everywhere or design (one-off) vessels that were optimised for a particular region. This would require an analysis of costs as well.

Conduct a multibody analysis for interaction between the DC and the boat landing

During transfers, DCs interact with the wind turbine through the boat loading. However, this thesis studied the responses while the DCs were floating freely, which means that the boat landing's contribution was excluded. Furthermore, the wake generated by the wind turbine's structure could also influence the performance of the DC. This needs to be studied to gain a more complete picture of the operating conditions.

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Appendix A: Weather conditions

A.1 Gemini weather data

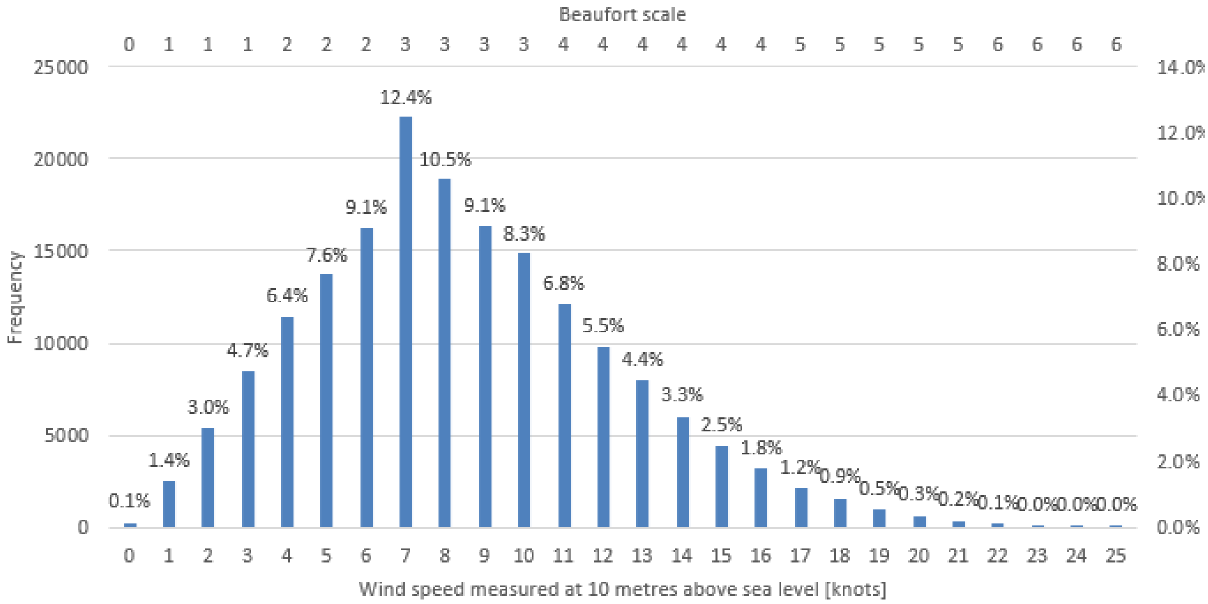


Figure A-1: Histogram of occurring wind speeds at Gemini

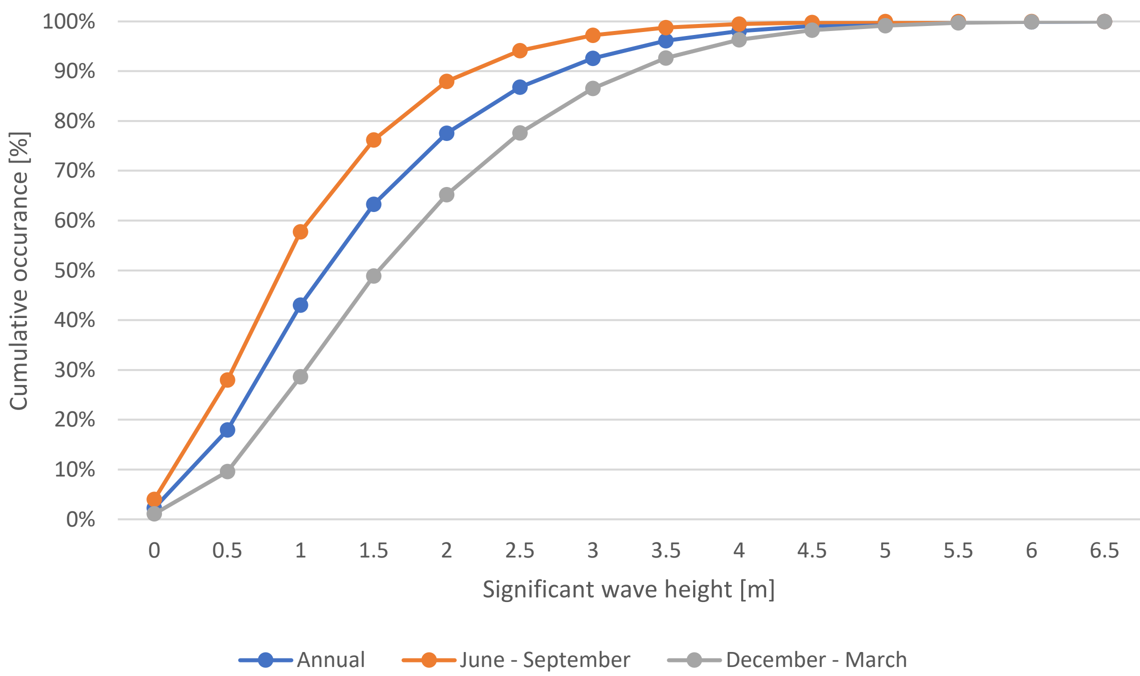


Figure A-2: Measured wave data at Gemini (adapted from [51]*)*

Gemini	Significant wave height (Hs)														
Peak period (Tp)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	Sum
0.0	35	24													59
0.5	9	26													35
1.0	19	23													42
1.5	11	18													29
2.0	11	58													69
2.5	13	68	1												82
3.0	45	691	20												756
3.5	820	2941	223												3984
4.0	822	4331	3522	18											8693
4.5	465	3061	6000	838											10364
5.0	251	3456	6756	3053	154										13670
5.5	206	3665	5775	5477	866	33									16022
6.0	168	2405	5057	5822	2979	274	4								16709
6.5	97	1650	4262	5305	5120	1224	67								17725
7.0	97	1115	3299	4403	4637	2784	284	8							16627
7.5	76	791	2318	2760	3671	3742	1433	138	1						14930
8.0	155	946	1964	2640	2817	3902	3778	1066	115	2					17385
8.5	105	836	1504	2127	2126	1875	2160	2173	407	24	2				13339
9.0	92	525	786	1009	1044	916	1014	1281	1183	268	17	2			8137
9.5	130	654	1159	1024	1020	930	807	877	834	607	161	15		1	8219
10.0	54	231	597	436	340	279	307	382	425	319	179	64	7		3620
10.5	110	285	832	576	289	256	231	226	249	309	258	196	67	4	3888
11.0	38	112	264	209	140	94	120	78	100	102	116	56	16	8	1453
11.5	98	140	263	376	153	143	83	74	74	94	124	97	43	15	1777
12.0	42	49	85	84	46	49	38	12	20	12	19	13	9	6	484
12.5	36	59	115	125	72	38	40	38	43	26	12	14	12	9	639
13.0	20	18	62	45	51	17	15	25	9	10	11	5	4	7	299
13.5	7	17	34	21	36	16	5	10	13	14	4	8	4	4	193
14.0	11	25	48	24	55	52	2	5	2	6	5	6	7	5	253
14.5	3	9	20	3	4	6		1	5		2				53
15.0	5	6	12	5	9	13	5	5	9	6	2	1	3		81
Sum	4051	28235	44978	36380	25629	16643	10393	6399	3489	1799	912	477	172	59	179616

No data here because waves break due to steepness

Figure A 3: Scatter diagram of sea states at Gemini (adapted from [20])

Wave frequency (rad/s)	Steepness (S)	Significant wave height (Hs)												
	Peak period (Tp)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
12.6	0.5	1.28												
6.3	1.0	0.32												
4.2	1.5	0.14												
3.1	2.0	0.08												
2.5	2.5	0.05	0.10											
2.1	3.0	0.04	0.07											
1.8	3.5	0.03	0.05											
1.6	4.0	0.02	0.04	0.06										
1.4	4.5	0.02	0.03	0.05										
1.3	5.0	0.01	0.03	0.04	0.05									
1.1	5.5	0.01	0.02	0.03	0.04	0.05								
1.0	6.0	0.01	0.02	0.03	0.04	0.04	0.05							
1.0	6.5	0.01	0.02	0.02	0.03	0.04	0.05							
0.9	7.0	0.01	0.01	0.02	0.03	0.03	0.04	0.05						
0.8	7.5	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05					
0.8	8.0	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05				
0.7	8.5	0.00	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.04			
0.7	9.0	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.04		
0.7	9.5	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04		0.05
0.6	10.0	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04	
0.6	10.5	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.04
0.6	11.0	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
0.5	11.5	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.03
0.5	12.0	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.03
0.5	12.5	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03
0.5	13.0	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
0.5	13.5	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02
0.4	14.0	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
0.4	14.5	0.00	0.00	0.00	0.01	0.01		0.01	0.01		0.02			
0.4	15.0	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	

$$S = \frac{2\pi H_s}{gT^2}$$

Shows at what steepness waves will break

Figure A 4: Wave steepness at Gemini

A.2 East Anglia Three weather data

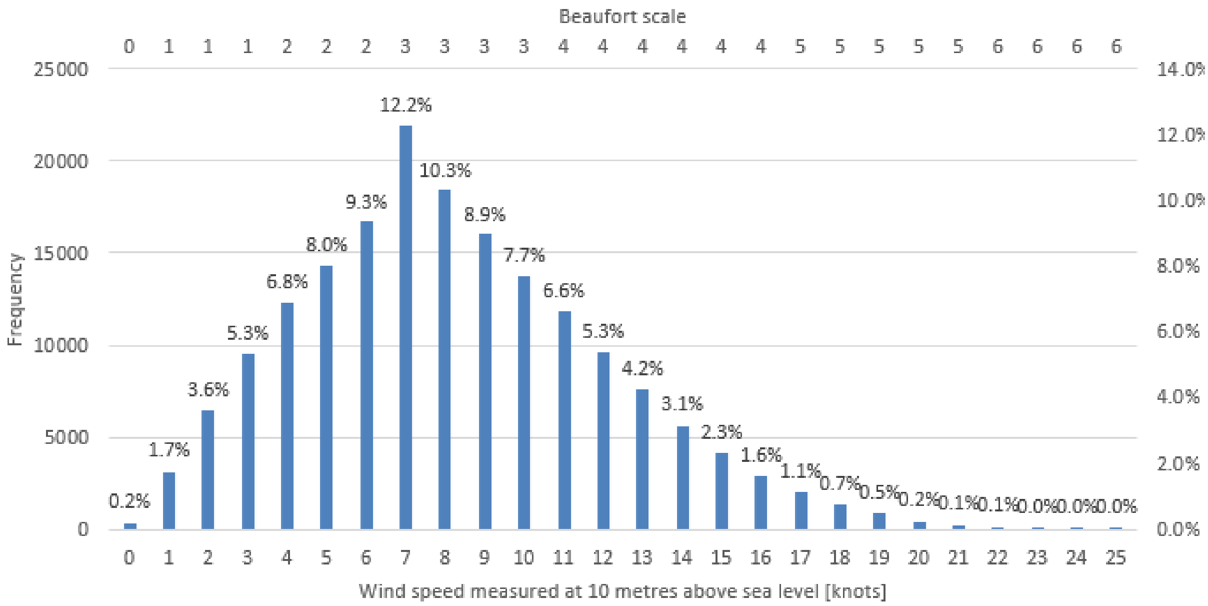


Figure A 5: Histogram of occurring wind speeds at East Anglia Three

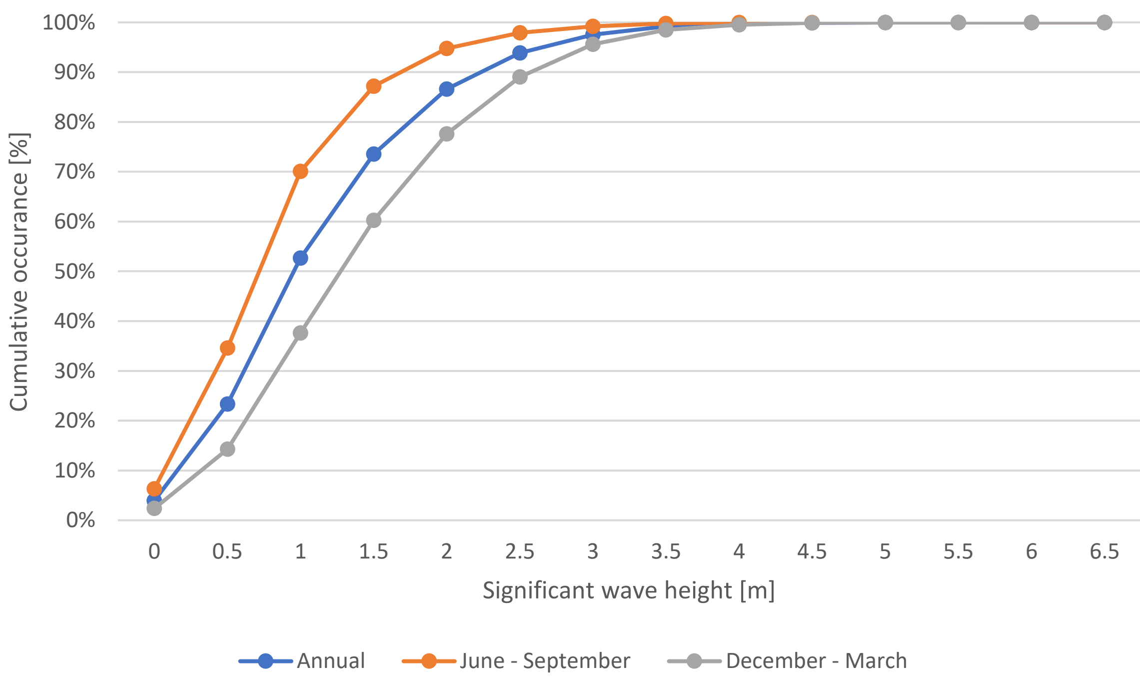


Figure A 6: Measured wave data at East Anglia Three (adapted from [51]*)*

East Anglia 3	Significant wave height (Hs)														
Peak period (Tp)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	Sum
0.0	215	53													268
0.5	60	36													96
1.0	21	69													90
1.5	28	59													87
2.0	31	31													62
2.5	55	118	1												174
3.0	135	1000	25												1160
3.5	1080	4161	235												5476
4.0	1243	6514	4176	15											11948
4.5	709	4194	9370	631	1										14905
5.0	534	3805	10930	3848	80										19197
5.5	399	2746	7179	9653	1023	6									21006
6.0	373	2458	4234	8336	4780	274									20455
6.5	367	2694	3422	4771	8396	2079	86								21815
7.0	251	2107	3687	2747	3872	4261	653	18							17596
7.5	150	1242	3505	2858	1778	2909	2053	306	11						14812
8.0	271	999	2848	2792	2080	2039	1925	1071	157	12					14194
8.5	259	700	1390	1269	1088	1067	1168	559	226	56	1	1			7784
9.0	151	351	472	265	227	282	511	505	136	86	22	3			3011
9.5	277	505	403	176	32	85	190	437	190	51	24	11	1		2382
10.0	99	272	161	74	16		5	82	190	66	13	1			979
10.5	99	357	255	43	8		3	13	74	78	25	2			957
11.0	45	97	71	12	2				7	8	10	1			253
11.5	83	106	201	37	2				2	5	3				439
12.0	35	38	28	14											115
12.5	44	75	73	26	7										225
13.0	19	33	21	9	1										83
13.5	19	12	12	5											48
14.0	31	9	12												52
14.5	5	3	1												9
15.0	2	2			2										6
Sum	7090	34846	52712	37581	23395	13002	6594	2991	993	362	98	19	1	0	179684

No data here because waves break due to steepness

Figure A-7: Scatter diagram of sea states at East Anglia Three (adapted from [20])

Wave frequency (rad/s)	Steepness (S)	Significant wave height (Hs)												
	Peak period (Tp)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
12.6	0.5	1.28												
6.3	1.0	0.32												
4.2	1.5	0.14												
3.1	2.0	0.08												
2.5	2.5	0.05	0.10											
2.1	3.0	0.04	0.07											
1.8	3.5	0.03	0.05											
1.6	4.0	0.02	0.04	0.06										
1.4	4.5	0.02	0.03	0.05	0.06									
1.3	5.0	0.01	0.03	0.04	0.05									
1.1	5.5	0.01	0.02	0.03	0.04	0.05								
1.0	6.0	0.01	0.02	0.03	0.04	0.04								
1.0	6.5	0.01	0.02	0.02	0.03	0.04	0.05							
0.9	7.0	0.01	0.01	0.02	0.03	0.03	0.04	0.05						
0.8	7.5	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05					
0.8	8.0	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05				
0.7	8.5	0.00	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.04	0.05		
0.7	9.0	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.04		
0.7	9.5	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.04	
0.6	10.0	0.00	0.01	0.01	0.01		0.02	0.02	0.03	0.03	0.03	0.04		
0.6	10.5	0.00	0.01	0.01	0.01		0.02	0.02	0.02	0.03	0.03	0.03		
0.6	11.0	0.00	0.01	0.01	0.01				0.02	0.02	0.03	0.03		
0.5	11.5	0.00	0.00	0.01	0.01				0.02	0.02	0.02			
0.5	12.0	0.00	0.00	0.01										
0.5	12.5	0.00	0.00	0.01	0.01									
0.5	13.0	0.00	0.00	0.01	0.01									
0.5	13.5	0.00	0.00	0.01										
0.4	14.0	0.00	0.00											
0.4	14.5	0.00	0.00											
0.4	15.0	0.00			0.01									

$$S = \frac{2\pi H_s}{gT^2}$$

Shows at what steepness waves will break

Figure A-8: Wave steepness at East Anglia Three

A.3 Dominant wave directions

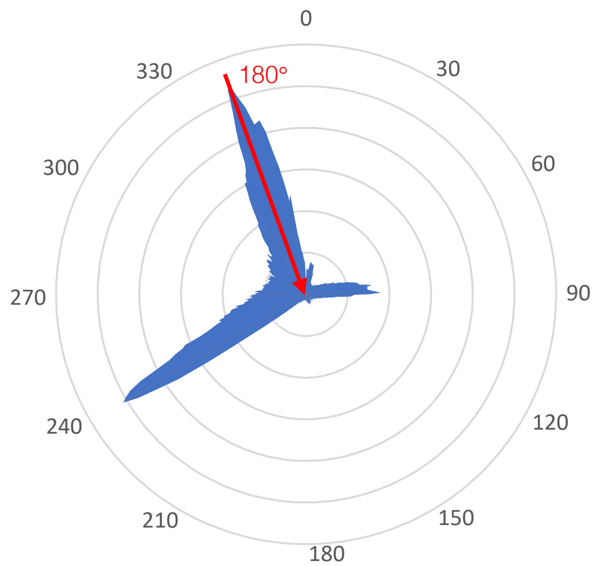


Figure A 9: Dominant wave directions at Gemini

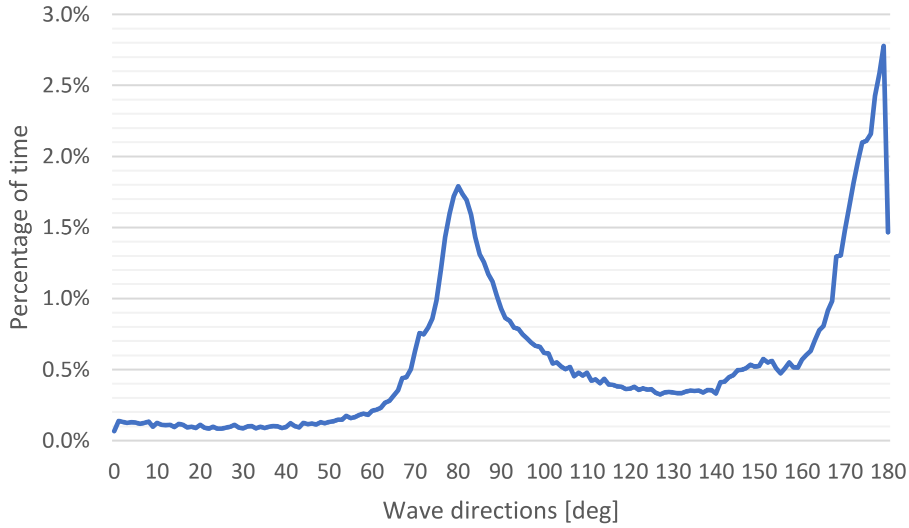


Figure A 10: Division of incoming wave angles at Gemini

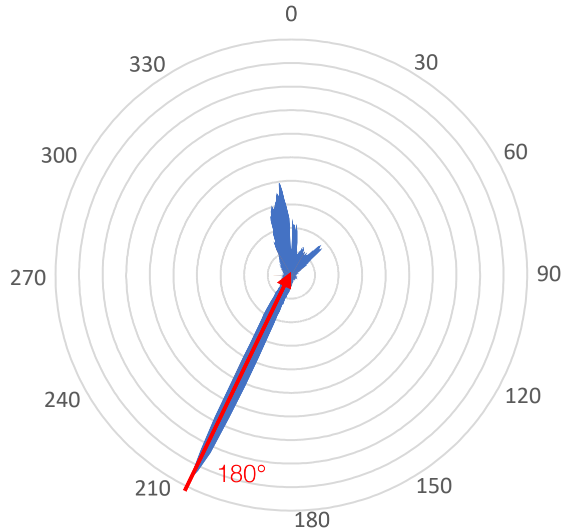


Figure A 11: Dominant wave directions at East Anglia Three

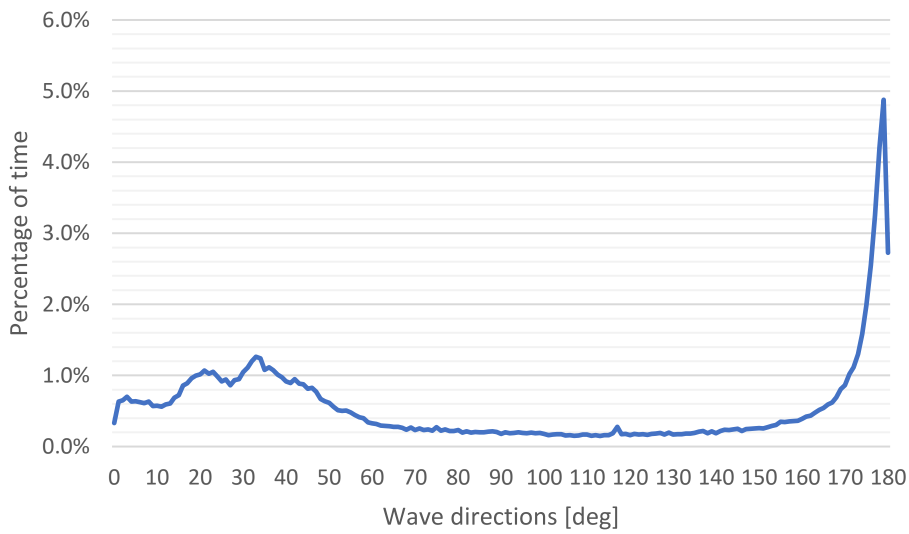


Figure A 12: Division of incoming wave angles at East Anglia Three

A.4 The importance of portrayal

Data based on monthly averages will give a different accessibility level than data based on hourly measurements. When the limit is set at H_s < 1.2 m, the result based on monthly averages are optimistic during the summer but less so for the winter. For limits set at H_s < 2.0 m and 2.5 m, the operability looks more realistic. In fact, 100% operability is never the case. So, databases that exclude the extremes give a misleading view on accessibility. Furthermore, the average operability is not shown for graphs based on monthly data because it already is an average value.

See next page for figures.

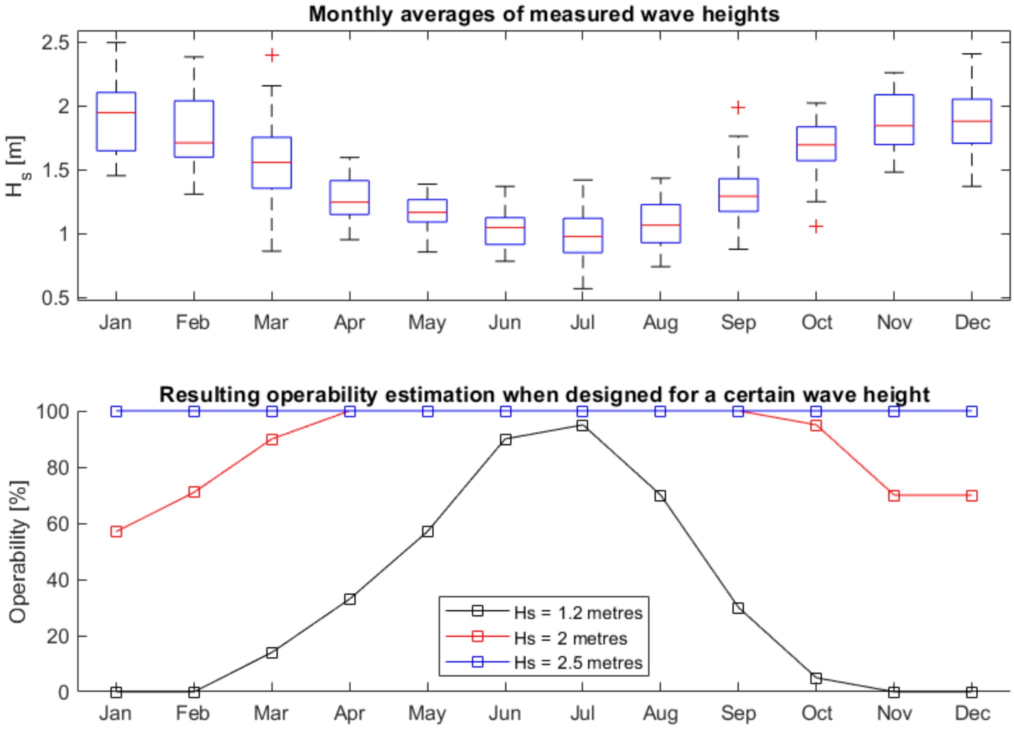


Figure A 13: Operability at Hornsea One using monthly averages

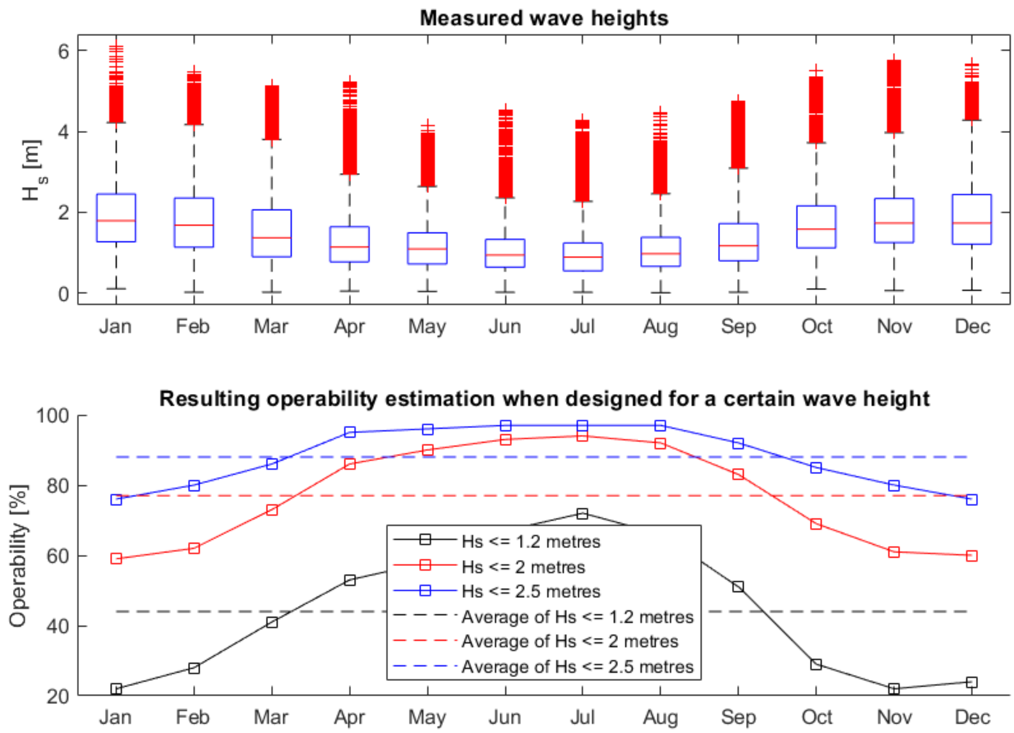


Figure A 14: Operability at Hornsea One using all data

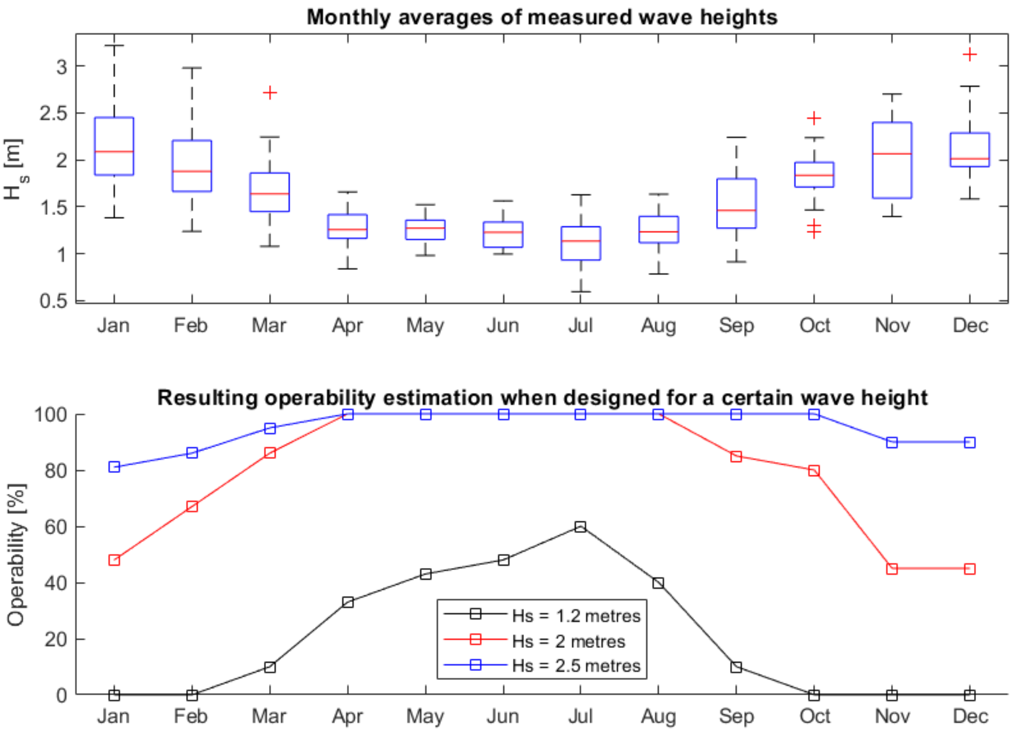


Figure A 15: Operability at Gemini using monthly averages

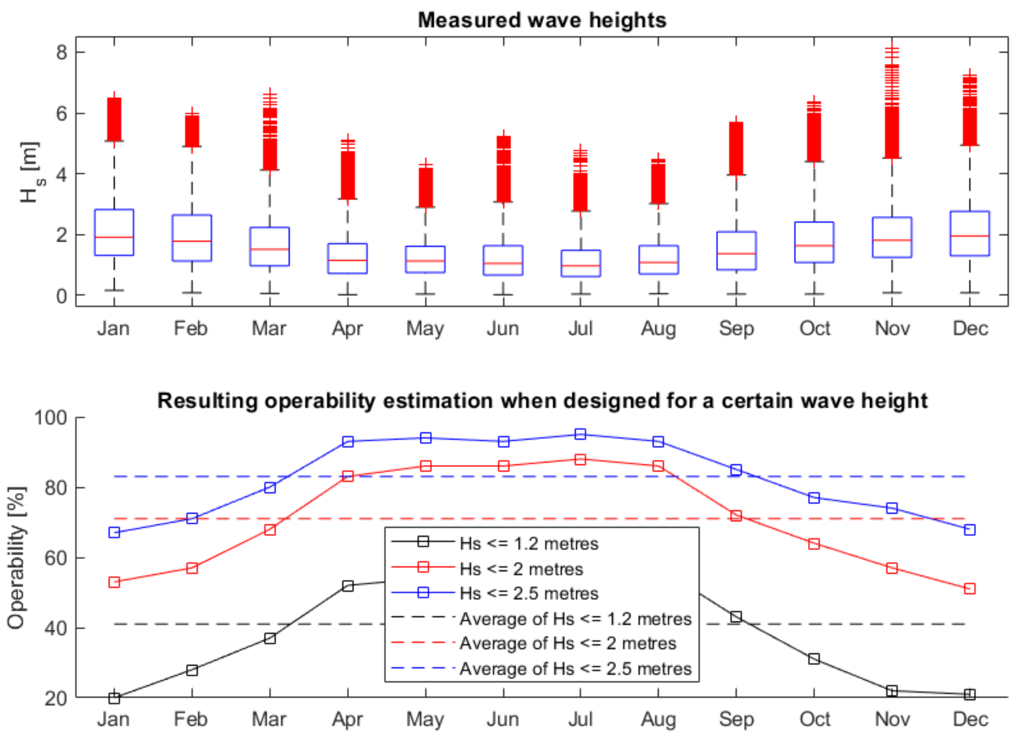


Figure A 16: Operability at Gemini using all data

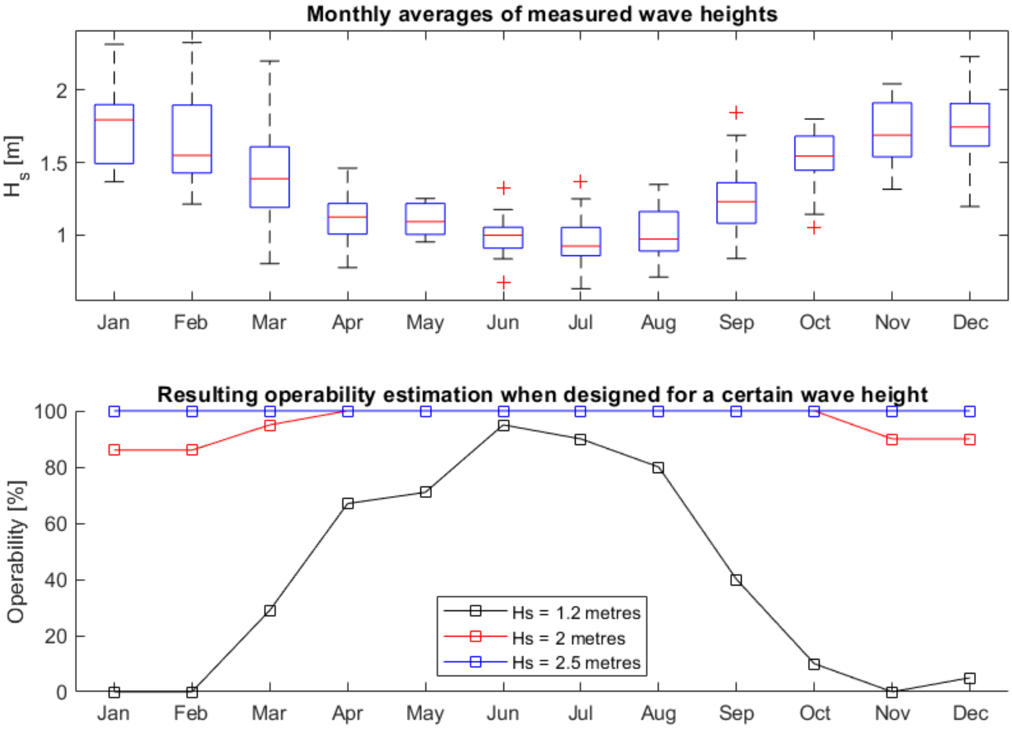


Figure A 17: Operability at East Anglia Three using monthly averages

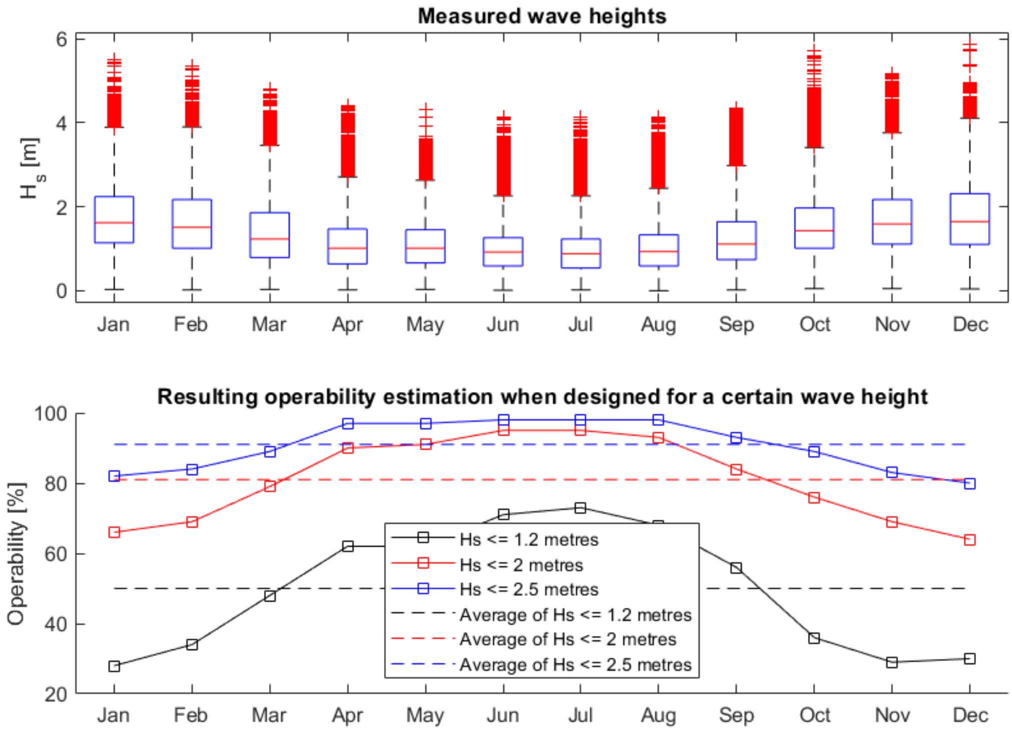


Figure A 18: Operability at East Anglia Three using all data

Appendix B: Vessel specifications and line plans

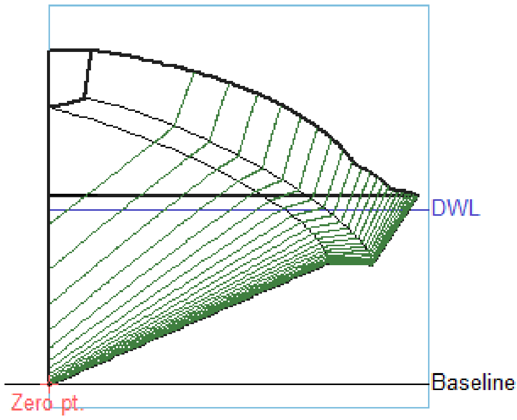
B.1 Small DC: Mare DC 12 WM

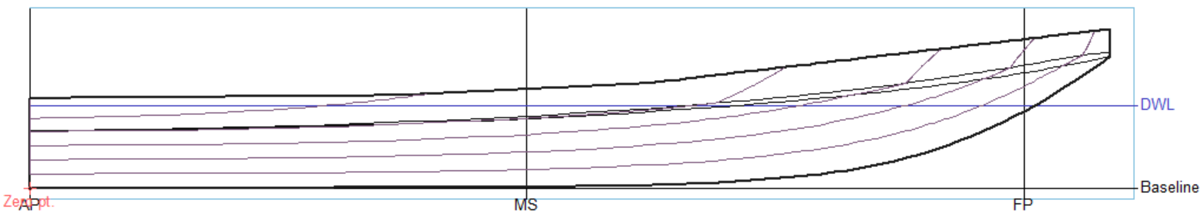
Source: Mare [35]

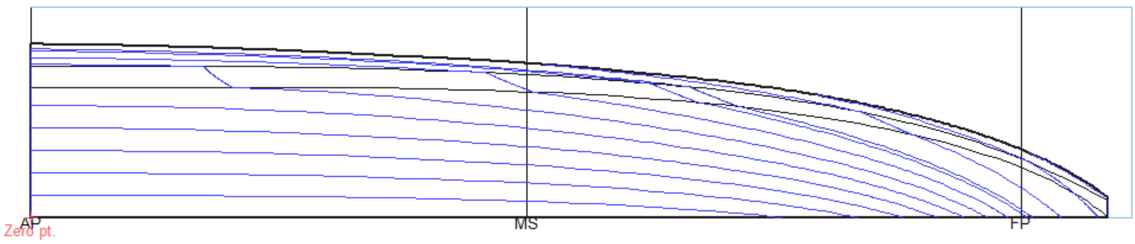
Size	Actual *[35]*	Model	
L	11.0	10.6[9]	m
B	3.8[10]	3.4	m
T	-	0.81	m
Δ	-	10.4[11]	t

Simulation input parameters & Line plans of hull model

Input parameter	Value
Number of maps	41
Max. number of mapping	6
Roll gyradius	1.51 m
Pitch gyradius	2.75 m
Yaw gyradius	2.75 m







[9] Length without fender.
[10] Including fender, which was assumed to be max 0.20 m thick.
[11] Weight difference is assumed to be due to propulsors which were not modelled.

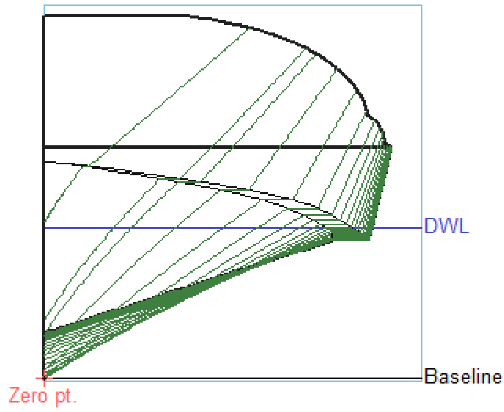
B.2 Medium DC: Esvagt STB 12

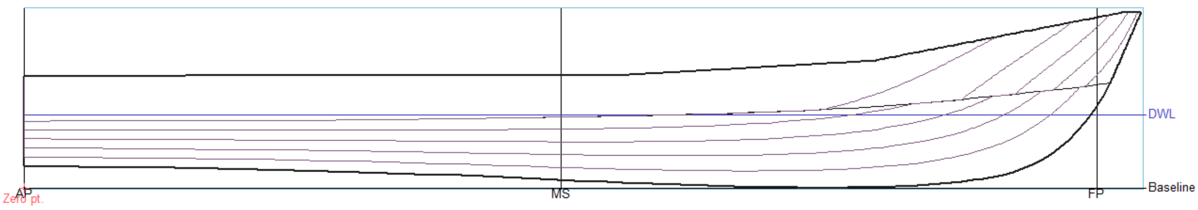
Source: *ESVAGT* [111]

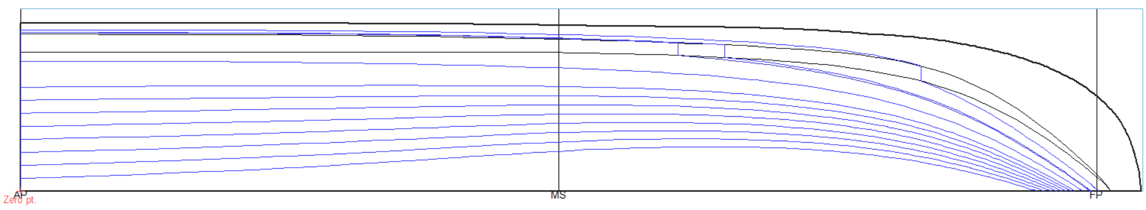
Size	Actual	Model	
L	-	13	m
B	-	3.9	m
T	-	0.85(12)	m
Δ	-	13.49	t

Simulation input parameters & Line plans of hull model

Input parameter	Value
Number of maps	17
Max. number of mapping	11
Roll gyradius	1.74 m
Pitch gyradius	3.32 m
Yaw gyradius	3.32 m







12 This DC has a slightly larger draught than the original, otherwise proper mapping could not be achieved. As a result, the mock-up is heavier than the original vessel, which may affect the RAOs and long-term performance.

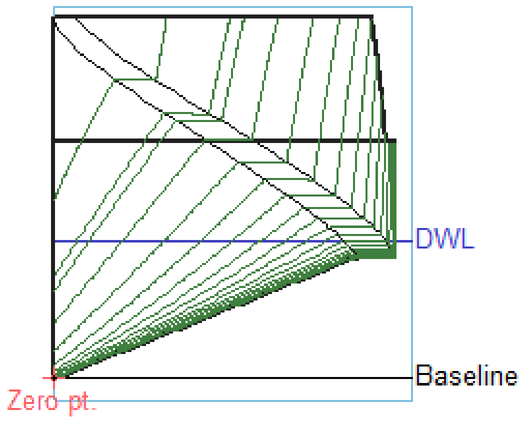
B.3 Large DC: ProZero DCW 15 m Transfer Vessel

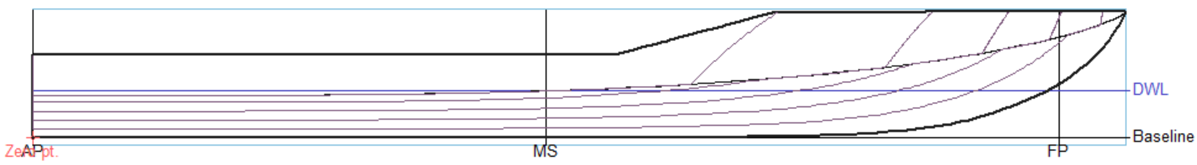
Source: TUCO Marine Group [72]

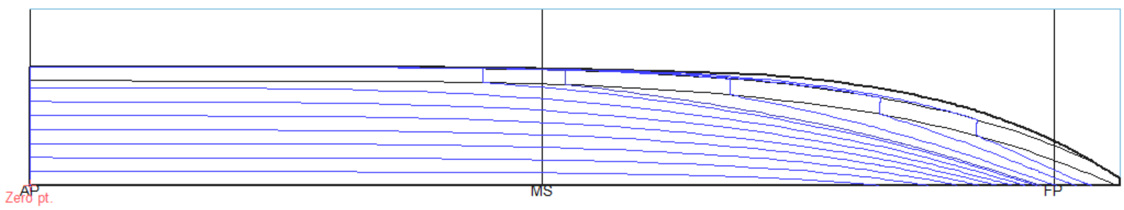
Size	Actual [72]	Model	
L	15.0	16.1[13]	m
B	3.85[14]	3.5	m
T	-	0.7	m
Δ	-	14.08	t

Simulation input parameters & Line plans of hull model

Input parameter	Value
Number of maps	29
Max. number of mapping	11
Roll gyradius	1.56 m
Pitch gyradius	4.00 m
Yaw gyradius	4.00 m







[13] Model length is based on confidential source.
[14] Including fender, which was assumed to be max 0.20 m thick.

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Appendix C: MATLAB script to convert heave RAOs

This script serves as an example that was used for the small DC to convert the RAOs at the CoG to the bow transfer point and wheelhouse.

```
%% Convert COG heave RAOs to bow and wheelhouse
clear all;close all;clc;

%% Import RAOs and Phases
run Import_106        % Imports heave RAOs from excel sheet

%% Coordinates
% Centre of Gravity (COG)
COG = [3.484 0 1.4];
disp('COG (x,y,z)=');disp(COG);

% From here coordinates w.r.t. zero-point at the corner of
aft-baseline
P_bow = [10.5 0 2.7];
P_wh = [4.7 0 2.7];

P_bow_x=P_bow(1)-COG(1);
P_bow_y=0;
P_bow_z=P_bow(3)-COG(3);

P_wh_x=P_wh(1)-COG(1);
P_wh_y=0;
P_wh_z=P_wh(3)-COG(3);

P = [P_bow_x P_bow_y P_bow_z; P_wh_x P_wh_y P_wh_z;];
loc = 1; %Fill in 1 for bow and 2 for wheelhouse

P_x=P(loc,1);
P_y=P(loc,2);
P_z=P(loc,3);

disp('P w.r.t. COG =');disp(P);

%% RAO
% Convert rotational motions and phases to radians
RAO_roll=RAO_roll*pi()/180;
RAO_pitch=RAO_pitch*pi()/180;
PHA_heave=PHA_heave*pi()/180;
PHA_roll=PHA_roll*pi()/180;
PHA_pitch=PHA_pitch*pi()/180;

% Local motions
P_cos_z=ones(40,1);
P_sin_z=ones(40,1);
omega=ones(40,1);
```

```
for d = 1:5
    for w=1:91
        omega(w)=omegas(w);

        P_cos_z(w,d) = RAO_heave(w,d)*cos(PHA_heave(w,d))-
RAO_pitch(w,d)*P_x*cos(PHA_pitch(w,d))+RAO_roll(w,d)*P_y*cos(P
HA_roll(w,d));
        P_sin_z(w,d) = RAO_heave(w,d)*sin(PHA_heave(w,d))-
RAO_pitch(w,d)*P_x*sin(PHA_pitch(w,d))+RAO_roll(w,d)*P_y*sin(P
HA_roll(w,d));

    end
end

% Motions of P
RAO_z = sqrt(P_cos_z.^2+P_sin_z.^2);
acc_z = RAO_z.*omega.^2;
pha_z = atan2(P_sin_z,P_cos_z)+pi();

figure('units','normalized','outerposition',[0 0 1 1])

subplot(1,2,1);plot(omega,RAO_z,'-','LineWidth',2);
title('RAO_z');
xlabel('Frequency [rad/s]');ylabel('RAO [m/m]');
grid on

legend('Following','Stern qt.','Beam','Bow qt.','Head')

subplot(1,2,2);plot(omega,acc_z,'-','LineWidth',2);
title('Acceleration');
xlabel('Frequency [rad/s]');ylabel('Acceleration [m/s^2]');
grid on

legend('Following','Stern qt.','Beam','Bow qt.','Head')
```

Appendix D: Righting arms of reference DCs

Spectrum label	10-3	15-6	15-3	20-5	20-3	25-5	25-3
Significant wave height [m]	1.0	1.5	1.5	2.0	2.0	2.5	2.5
Peak wave period [s]	4.5	4	5.5	5	6.5	5.5	7
Steepness [m]	0.03	0.06	0.03	0.05	0.03	0.05	0.03

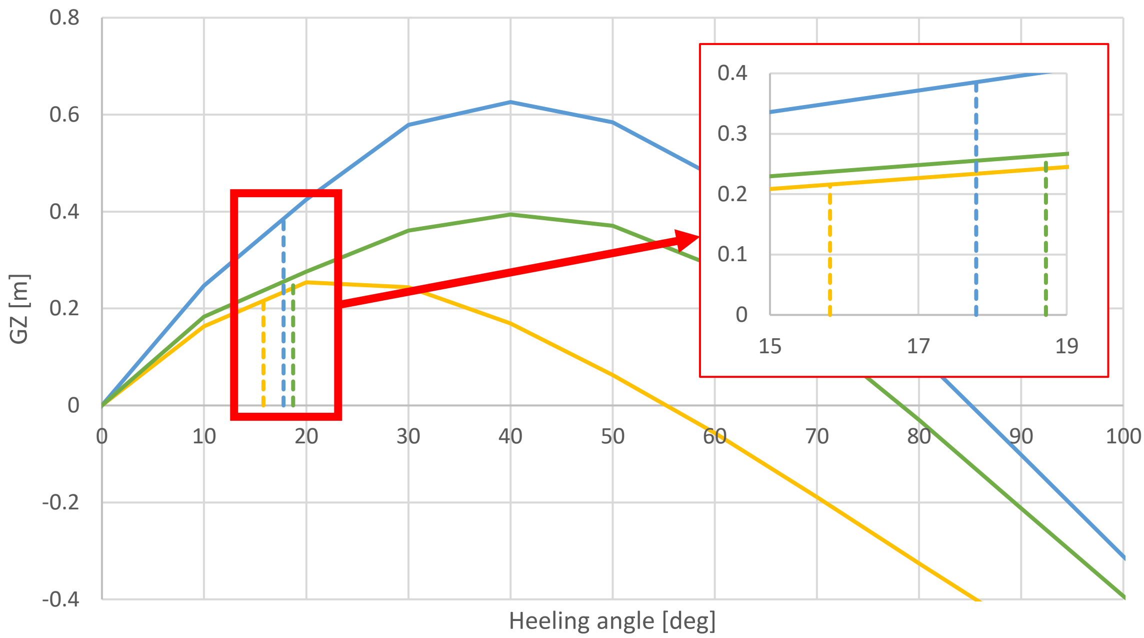

Figure D 1: Heeling angle and GZ during wave spectrum 15-6 and μ = 90°

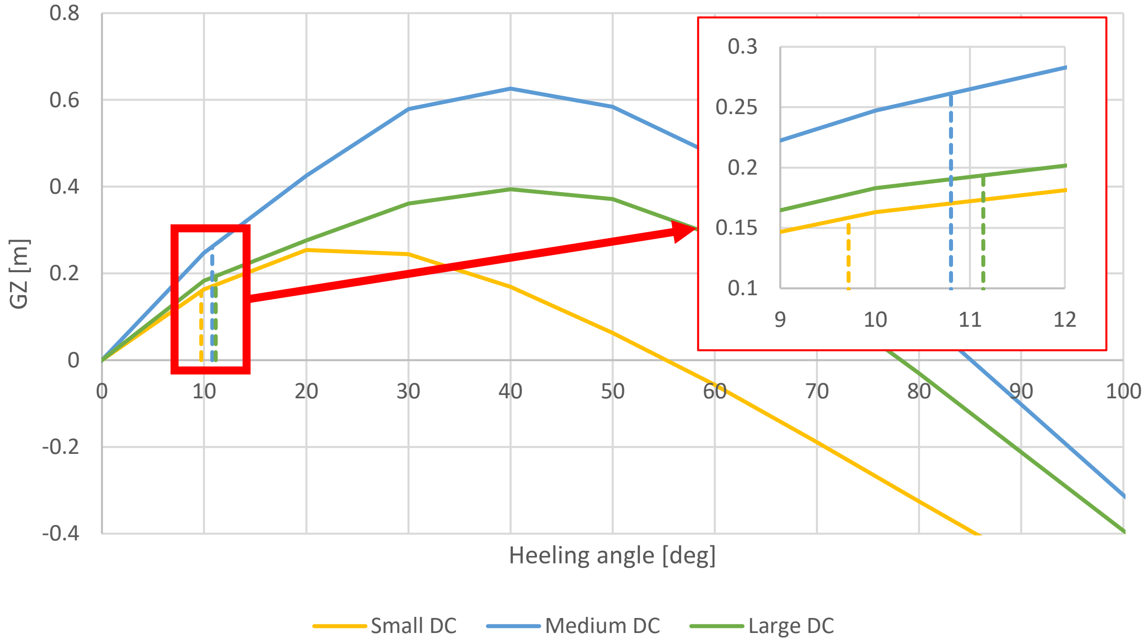

Figure D 2: Heeling angle and GZ during wave spectrum 15-3 and μ = 90°

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Appendix E: Additional results that support the use of the Axe Bow Concept for transit

This chapter briefly discusses results by de Jong [66] that justify the use of the ABC for transit.

E.1 Resistance curves of various bow forms

A study by de Jong [66] also made a comparison between the ESC and the ABC. Figure E-1 compares the resistance curves for the parent hull versus and ABC for various speeds. The wave-piercing concept (WPC) is also shown in this graph but is not regarded as a viable solution; it does show good performance in terms of ship motions and acceleration levels, but it suffers heavily from green water shipping [66], which could be hazardous to technicians and equipment during transit and transfer.

At zero-speed, there is no difference in resistance. The ABC would be favourable for transit until Fn = 0.77 (a ship speed of 35 knots) since the total resistance is then lower than the ESC. At higher speeds, the ESC would be more beneficial. However, the ship's operational profile generally plays a role when selecting hull type based on ship speed. For example, if a vessel spends most of its time sailing at 25 knots and occasionally needs to sail at 40 knots, an ABC could still be preferred because it would sail with less resistance for a majority of the time. The additional resistance at higher speeds is then accepted as a trade-off.

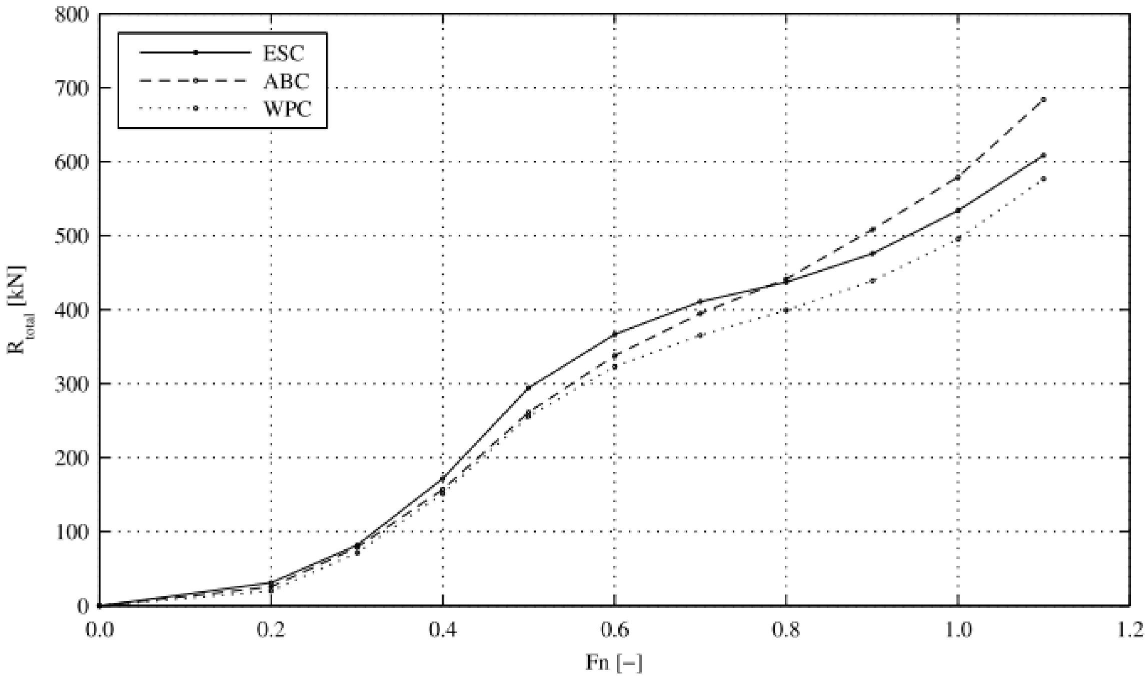
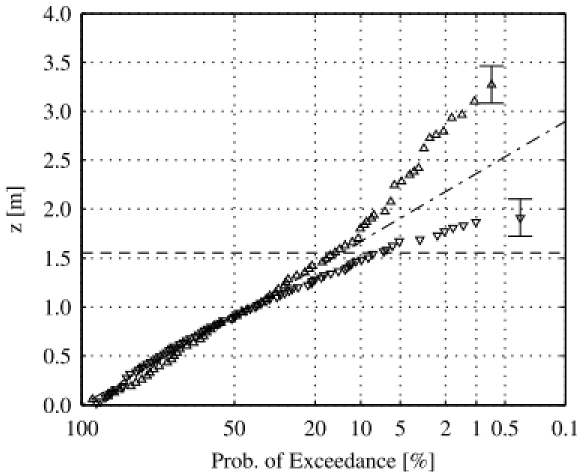


Figure E 1: Calm water total resistance of the parent hull (ESC) and the ABC [66]

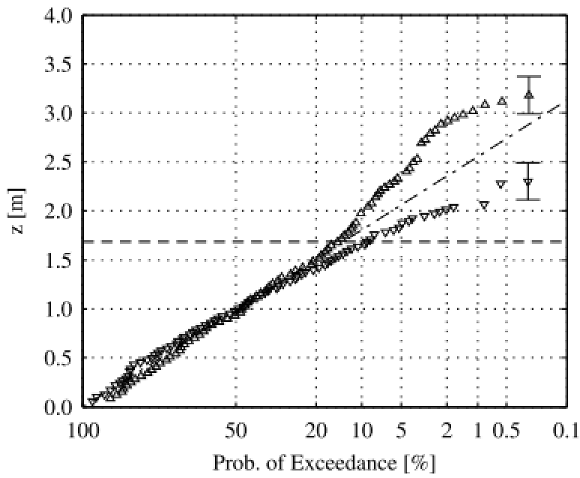
E.2 Operability assessment in irregular waves

De Jong [66] also performed experiments in irregular waves using a JONSWAP spectrum to describe the worst conditions found in the North Sea. In his case, the wave heights ranged from 2.0 m < H_s < 4.0 m, with a peak period of 7.8 seconds.

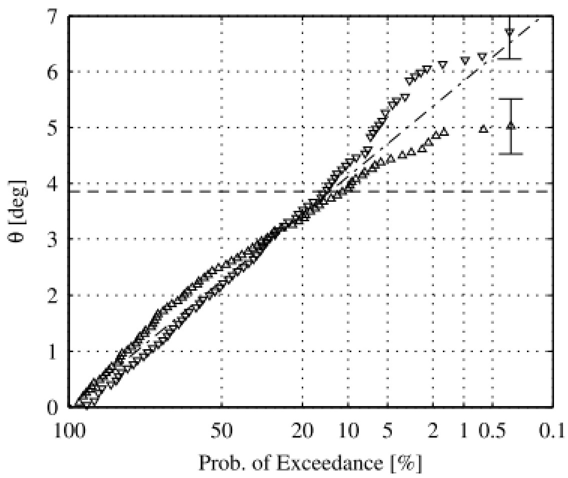
Figure E-2 presents the resulting motions using Rayleigh plots, which show the probability of exceedance of the trough and crest values. The difference in heave motions between the ESC and ABC are quite minimal. But the pitch motions of the ABC are almost linear in contrast to the ESC. Again, the reason for the different responses is presumably due to the ESC's flare. These results coincide with the results found in the previous section, but these Rayleigh plots are believed to give a more inclusive description of the motion response. In short, because RAOs show if various levels of vertical accelerations will occur, while these graphs show how often they are likely to be encountered.



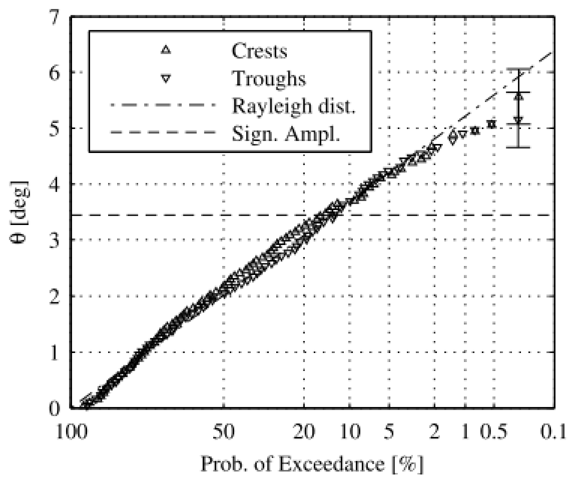
(a) Heave motion of the ESC



(b) Heave motion of the ABC



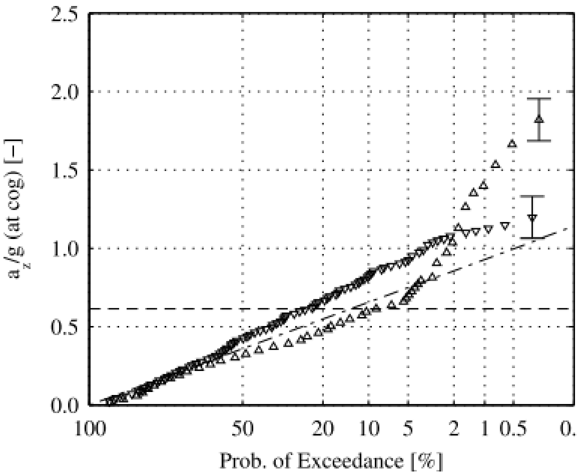
(c) Pitch motion of the ESC



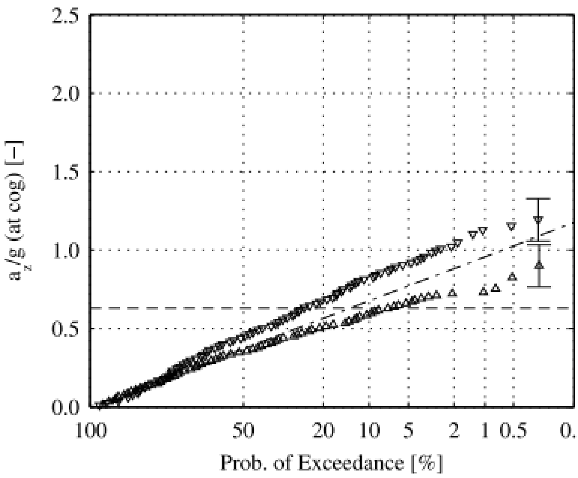
(d) Pitch motion of the ABC

Figure E 2: Rayleigh plots of ship motions, H_s = 3.5 m, V = 35 knots [66]

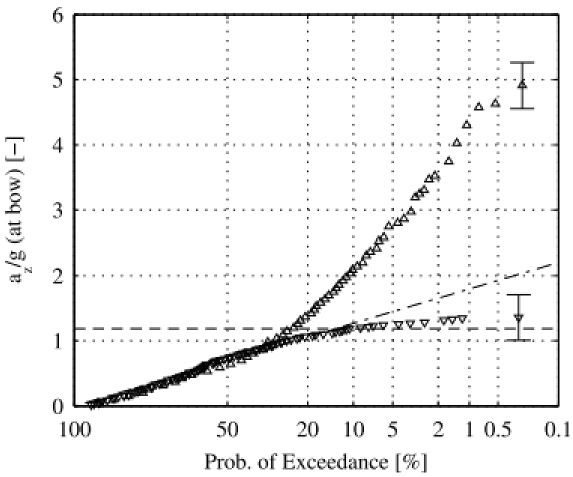
This is especially so when it comes to vertical accelerations. Figure E-3 shows the significant difference in accelerations between the ESC and ABC in irregular waves. Although the negative peaks are similar for both designs, the positive vertical accelerations at both the CoG and the ESC's bow are much larger than the ABC. Keuning and Walree [68] specify that the ABC had a reduction of more than 65%. Also, de Jong [66] supposes that the large upward peaks measured at the ESC's bow are somewhat translated to its CoG. Furthermore, the levels measured at the CoG are much lower than those measured at the bow. This is in line with the previously stated conclusion; that the accelerations (during transit) are lower at the aft than at the bow.



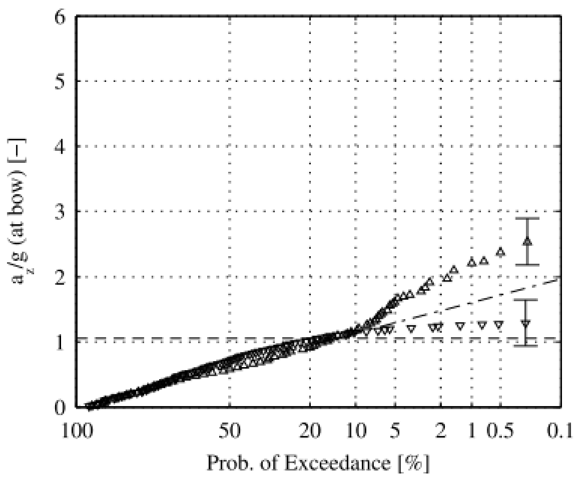
(a) At the CoG of ESC



(b) At the CoG of ABC



(c) At the bow of ESC



(d) At the bow of ABC

Figure E-3: Rayleigh plots of vertical accelerations, H_s = 3.5 m, V = 35 knots [66]

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Appendix F: RAOs for heave at the wheelhouse

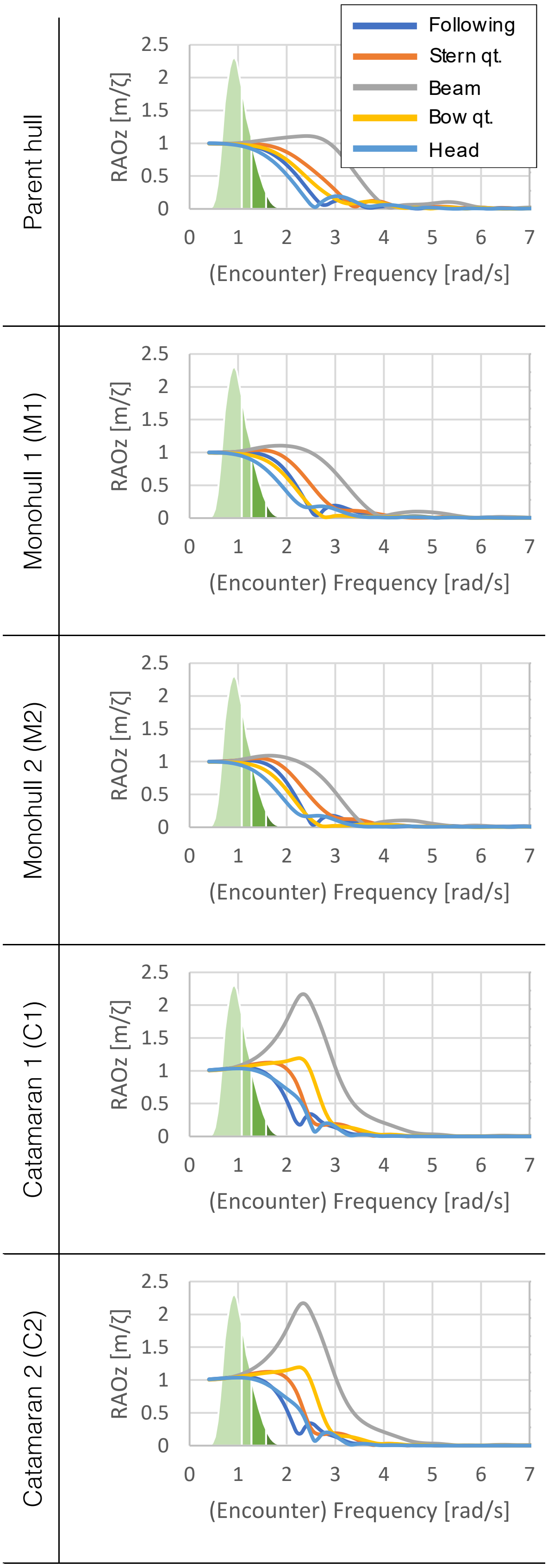

Figure F 1: Heave RAOs at the bow

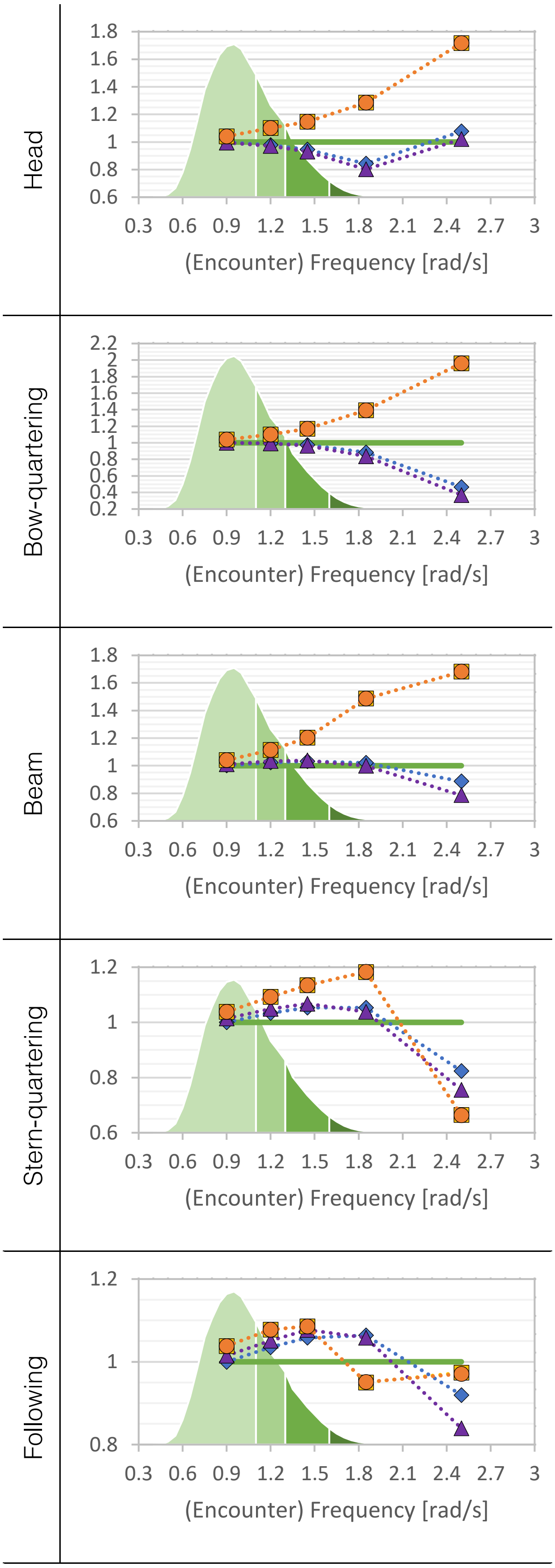

Figure F 2: Effectiveness on heave RAOs

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Appendix G:Roll damping coefficient of catamarans

The method was adopted from the MAXSURF Motions manual [86].

G.1 Catamaran 1

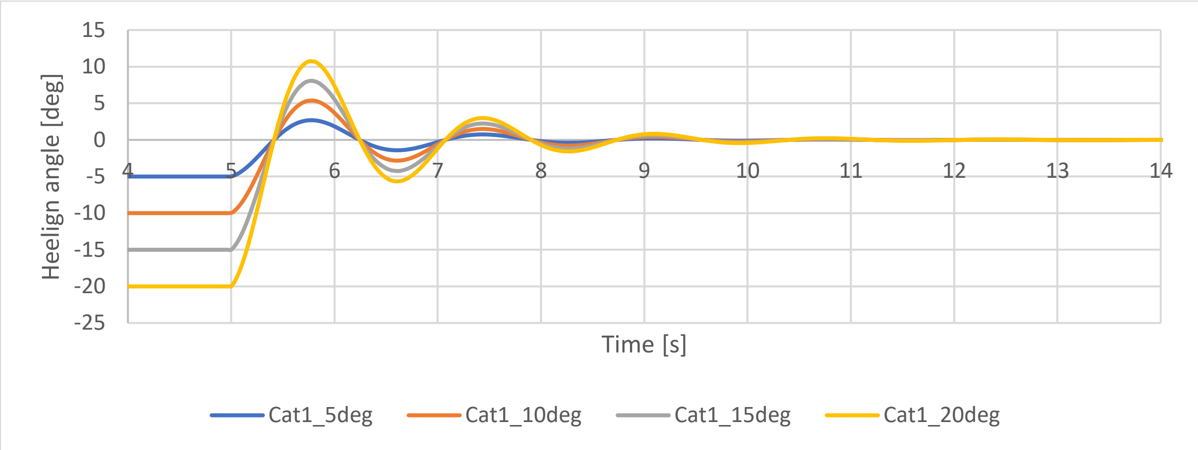

Figure G 1: Roll-decay of Catamaran 1 for multiple heeling angles

Table G1: Absolute peaks and troughs with an initial heeling angle of 20 deg

	Number	i	i+1
Trough	1	20.000	5.660
Peak	1	10.731	2.982
Trough	2	5.660	1.570
Peak	2	2.982	0.825
Trough	3	1.570	0.435
Peak	3	0.825	0.229
Trough	4	0.435	0.121
Peak	4	0.229	0.064
Trough	5	0.121	-
Peak	5	0.064	-

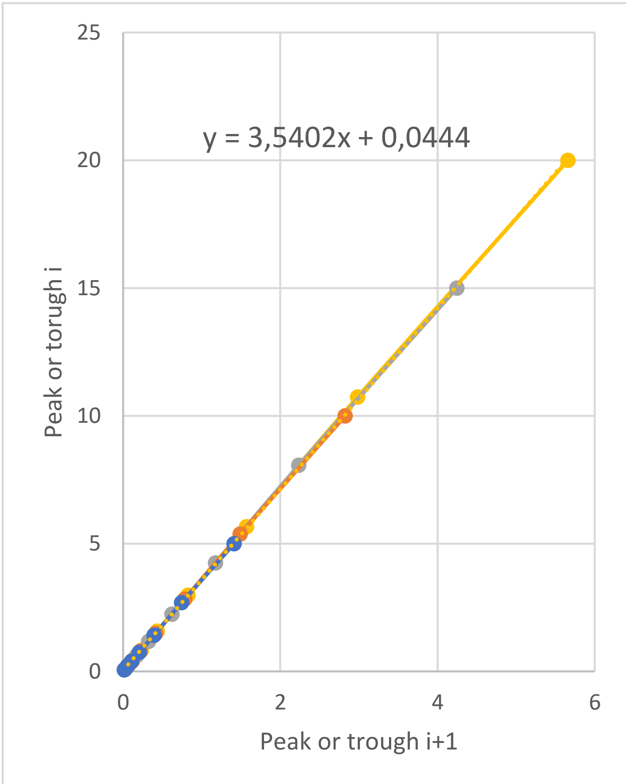

Figure G 2: Plot of peak amplitude (i) against peak amplitude of next peak (i+1)

Roll damping coefficient for Catamaran 1:

$$\upsilon_{C1} = \frac{\ln(slope)}{2\pi} = \frac{\ln\,(3.5449)}{2\pi} = 0.2012$$

G.2 Catamaran 2

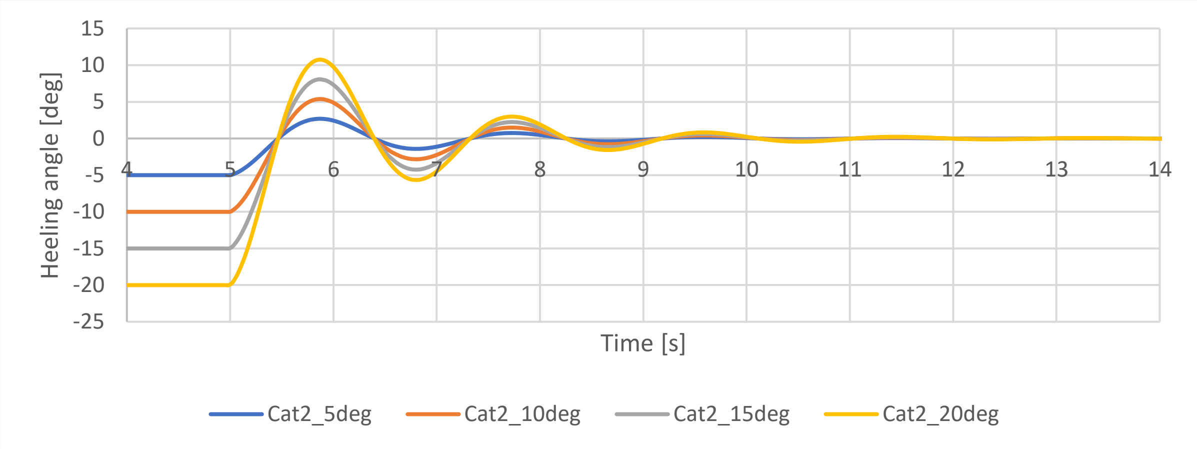

Figure G 3: Roll-decay of Catamaran 2 for multiple heeling angles

Table G2: Absolute peaks and troughs with an initial heeling angle of 20 deg

	Number	i	i+1
Trough	1	20.000	5.651
Peak	1	10.740	2.981
Trough	2	5.651	1.565
Peak	2	2.981	0.827
Trough	3	1.565	0.434
Peak	3	0.827	0.229
Trough	4	0.434	0.121
Peak	4	0.229	0.064
Trough	5	0.121	-
Peak	5	0.064	-

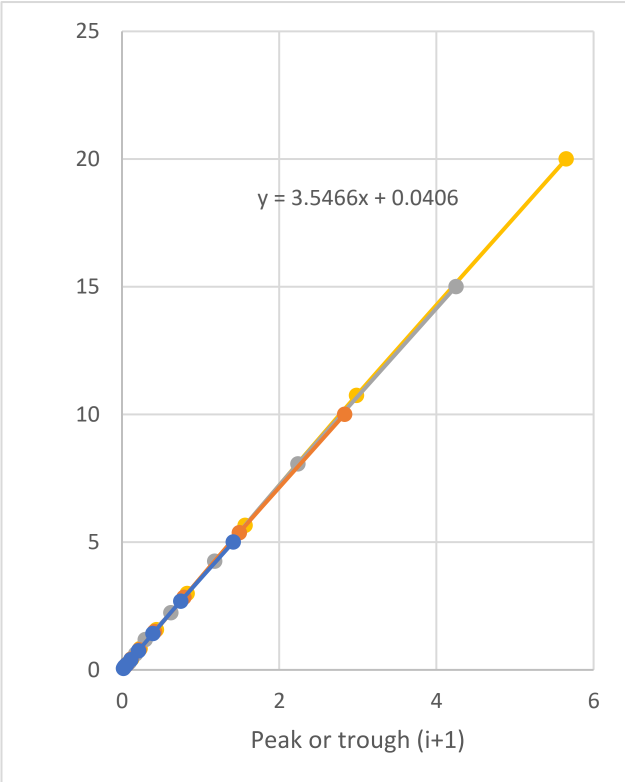

Figure 8-1: Plot of peak amplitude (i) against peak amplitude of next peak (i+1)

Roll damping coefficient for Catamaran 2:

$$\upsilon_{C2} = \frac{\ln(slope)}{2\pi} = \frac{\ln\,(3.5446)}{2\pi} = 0.2014$$

Appendix H: Long-term response of new DCs

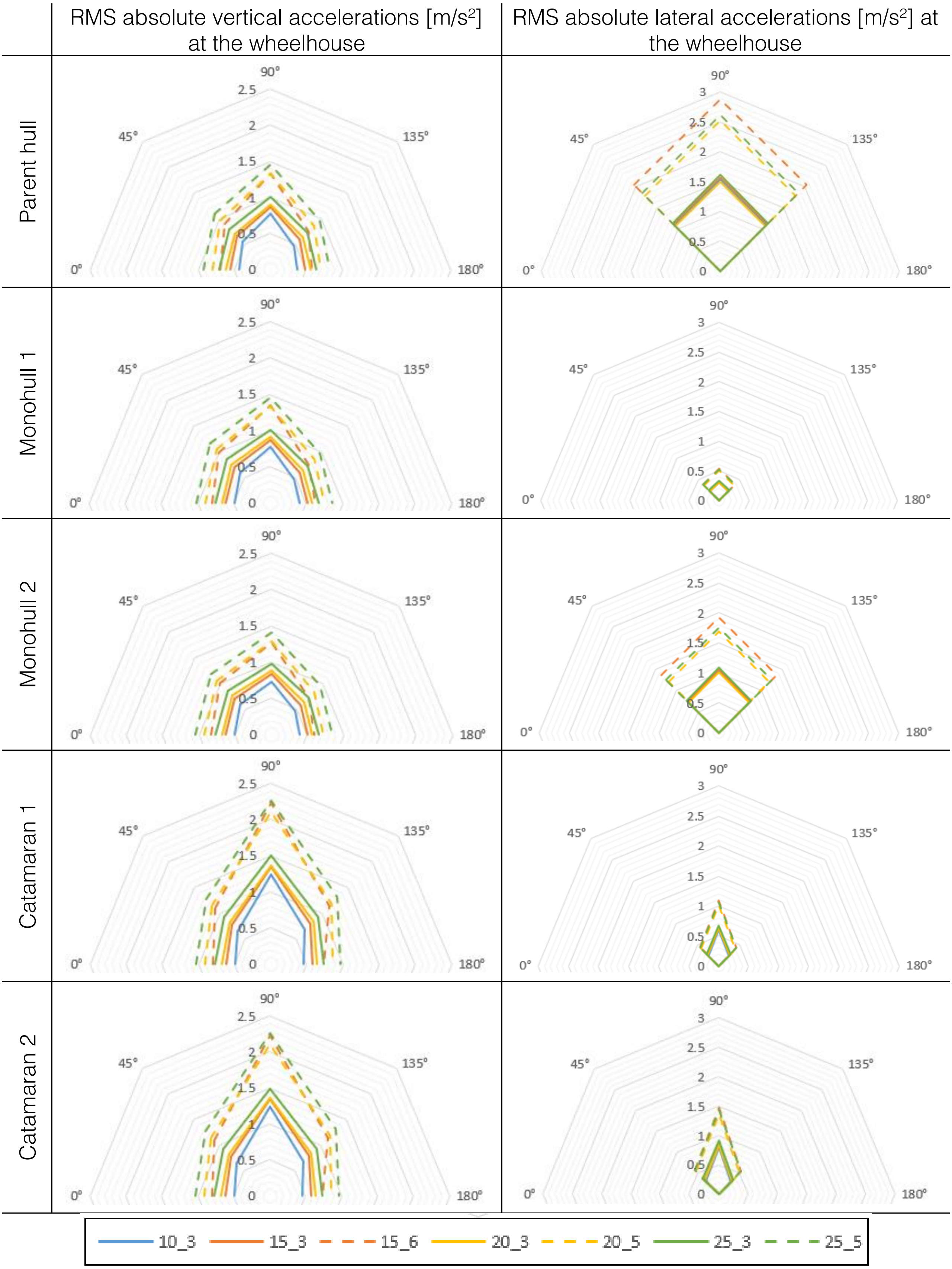

Figure H 1: Accelerations at the wheelhouse

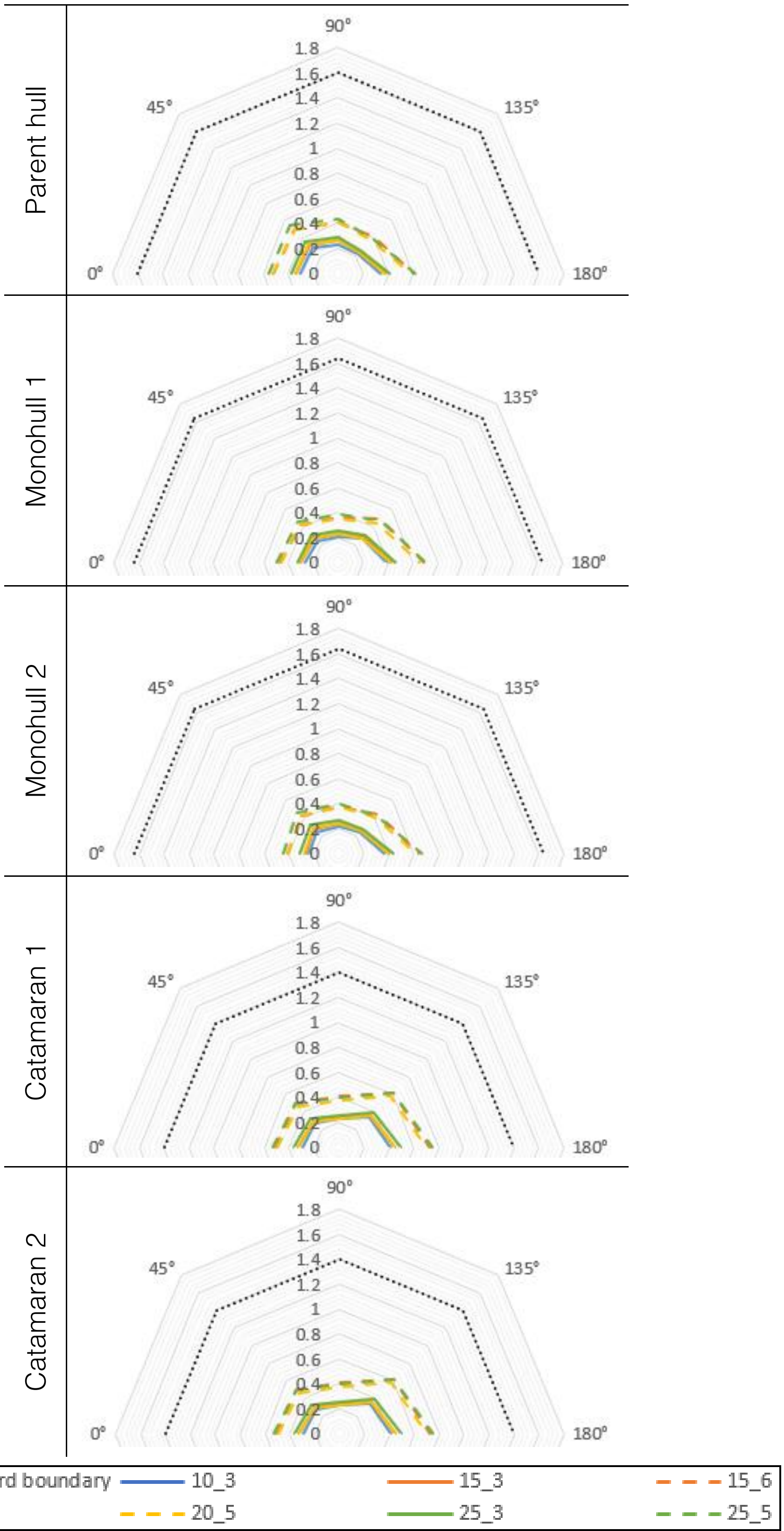

Figure H 2: RMS relative motions [m] of the bow transfer point

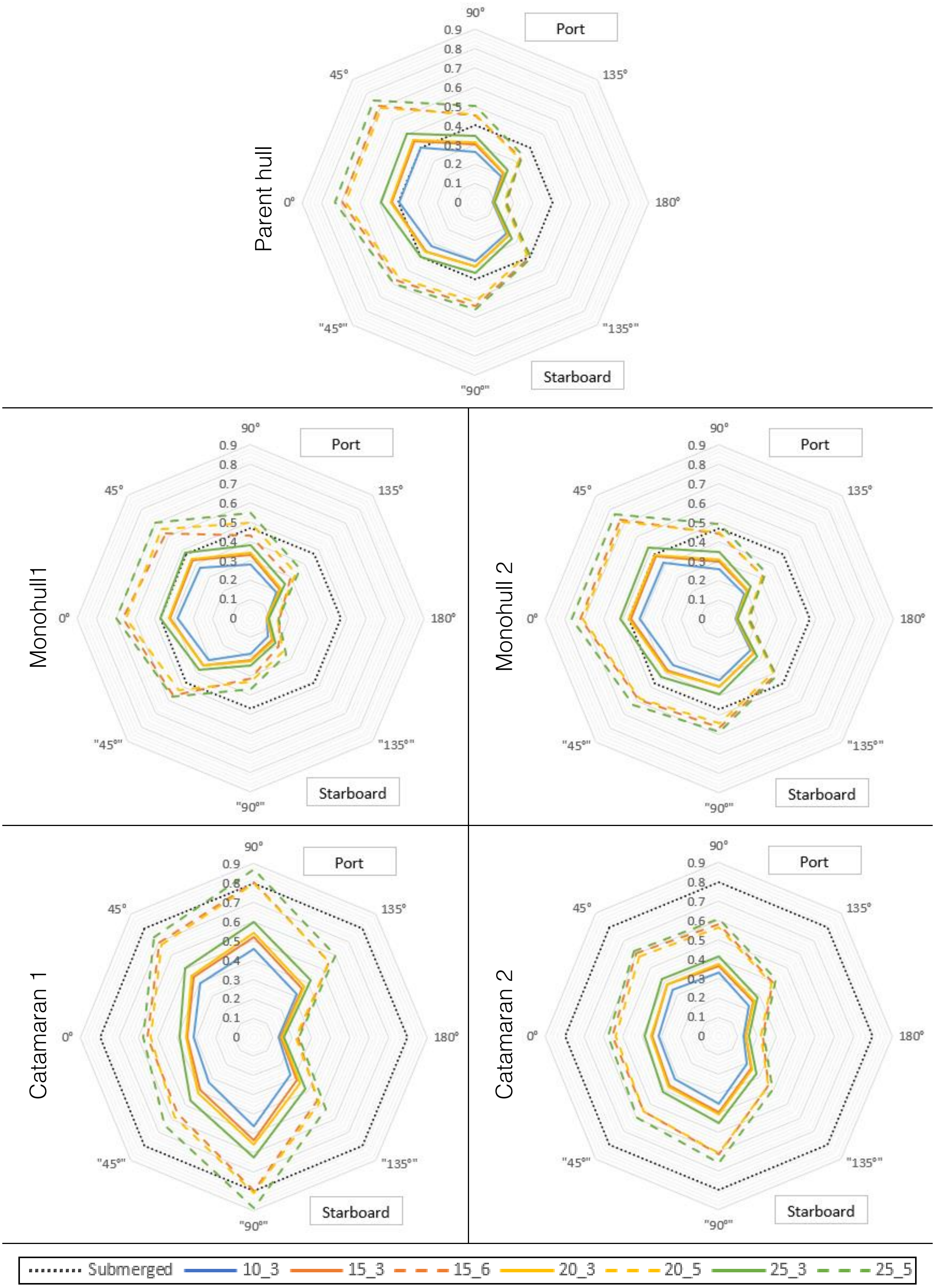

Figure H 3: RMS relative motions [m] of propulsor inlets