ALTERNATIVE CABLE LAYING

A conceptual design for an offshore power cable lay system on non-cable lay vessels

B. GIJSBERTS

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended on Thursday August 29, 2019 at 09:30 AM.

Student number:	4140869	
Project duration:	November 19, 2018 – August 29, 2019	
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This thesis is confidential and cannot be made public until August 29, 2024.

TU Delft

Preface

This thesis marks the end of my MSc Offshore & Dredging Engineering and therefore, the end of my journey as a student at the Delft University of Technology. In cooperation with Boskalis and Delft University of Technology, I had the opportunity to put the learned theory during my studies into practice in this graduation internship. The basis for this research initially stemmed from my passion for combining technology and economics. By choosing a design-related subject, I had the chance to evaluate a high-level design on both technical and economic feasibility. I hope to continue combining these two during my future career.

I want to thank Hayo Hendrikse and Andrei Metrikine for sharing their insights on the design process with me during the several meetings we had. I also want to thank Lennart van Baalen for his remarks on the work I have done during my internship. Lastly, I want to thank Max Verhaegh for always making time to brainstorm together which way to go forward.

It has been a bumpy ride but a fascinating one. Thank you to everyone involved in any way for your unwavering support. On to the next challenge!

B. Gijsberts
Delft, August 2019

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
API	American Petroleum Institute
BR	Bend Restrictor
CAPEX	Capital Expenditure
CFS	Central Fleet Support
CLV	Cable Lay Vessel
CoG	Centre of Gravity
CPS	Cable Protection System
DC	Direct Current
DNV-GL	Dett Norske Veritas - Germanischer Lloyd
DOCM	Deputy Offshore Construction Manager
HDD	Horizontal Directional Drilling
JONSWAP	Joint North Sea Wave Project
LCoE	Levelized Cost of Energy
LF	Load Factor
LR	Lloyd's Register
MBR	Minimum Bending Radius
MCA	Multi Criteria Analysis
MCLS	Modular Cable Lay Spread
OCM	Offshore Construction Manager
OSS	Offshore Sub Station
OWF	Offshore Wind Farm
PM	Pierson Moskowitz
PPE	Personal Protective Equipment
QTF	Quadratic Transfer Function
TSHD	Trailer Suction Hopper Dredger
VMA	Vessel Motion Analysis
WF	Weight Factor
WROV	Working Remotely Operated Vehicle
WTG	Wind Turbine Generator

Abstract

In this thesis, an alternative cable lay system was designed that can be used on existing non-cable lay vessels. This design is conceptualized and analyzed for a specific market, following the steps in the engineering design process. The technical and economic analysis investigates the feasibility and competitiveness of the new cable lay system.

Nowadays, cables are installed over a chute at the aft of a vessel, which makes the operation very sensitive to motions, inducing high cable loads that result in limited workability. Also, load carrying capacity is limited for existing cable lay vessels within the Boskalis fleet, making the application of joints a necessity in offshore export power cable installation.

The design focuses on the international offshore export power cable installation market (both AC and DC), including interconnectors, from shore to substation or shore to shore. This market was selected because of the limited load-carrying capacity of current cable lay vessels, the internationally growing offshore wind market and the relatively low market share of Boskalis in this segment. New concepts were generated and evaluated using multi-criteria analysis, scoring them on technical and economic criteria determined for the selected market.

The concept that has been selected for further development focuses on export power cable laying through a moonpool. A Dockwise semi-submersible heavy transport vessel is targeted for this design because it is being converted into a fall pipe vessel already. This conversion includes the installation of a moonpool, opening up the possibility to make the selected vessel a multi-purpose ship. Making use of static stability software, the maximum load-carrying capacity of this vessel has been determined. From this analysis, it can be concluded that the maximum cable load that can be carried by the selected vessel is 9.000 tonnes of cable equivalent, which is approximately 110 km of currently installed export cable length. Conventional cable lay vessels from Boskalis have load carrying capacity up to 5.000 tonnes. Additionally, a deck-layout with the crucial parts of the cable lay system is designed, taking into account all necessary alterations regarding the conversion of the vessel.

The main technical challenge for the newly designed system is the second end cable pull-in. With limited space in the moonpool and vertical laying of the cable, the conventional pull-in method cannot be used here. Three solutions have been developed, based on a deployment quadrant or bight lay down. Two of these are already proven in the field, making the concept technically feasible.

A model has been made to evaluate both conventional cable lay, and cable lay through a moonpool. With the use of dynamic time-domain analysis, the operational limits have been determined for both methods, keeping the catenary shape of the cable constant. This analysis concludes that cable laying through a moonpool indeed increases the workability for the selected vessel. No significant increase can be seen for moonpool cable laying with a conventional cable lay vessel. This is due to its sensitivity to roll motions, for which the distance towards the center of gravity is equal in both concepts. For the selected vessel, cable laying over a chute is not possible for the chosen catenary shape and sea states because the maximum allowable curvature is exceeded. This is due to the large arm for pitch motions, from the center of gravity to the chute at the aft of the vessel. Cable laying through a moonpool, however, is possible up to 2 meters significant wave height. The limiting factor for all simulations that were done is the maximum allowable curvature.

To investigate the competitiveness of the newly designed cable lay concept, an economic analysis is done. Several recently acquired project cases are introduced to compare project costs for both concepts. This analysis concludes that the newly designed cable lay concept is in average conditions 21 to 40 % more expensive for all cases than the conventional way of cable laying. For cable installation during wintertime, the newly designed cable lay system is only 6.5 to 27% more expensive than the conventional cable lay system.

This illustrates that the newly designed cable lay system is technically feasible but not competitive with conventional methods at the moment according to this analysis. However, the costs and installation time of joints with the conventional methods are not taken into account here due to limited available data. Therefore, the new cable lay concept still has the potential to be competitive for the selected market. Further research must be done to substantiate this.

Contents

1 Introduction

1.1. Background

Increasing demand for energy combined with the tightening of climate change policies resulted in the rapid growth of the Northern European offshore renewable market over the last decade. In the North Sea area, the main focus within the offshore renewable energy sector is on wind energy, due to its relatively shallow water areas and strong winds.
As a result of the growing offshore wind market and increasing competition in the sector, the Levelized Cost of Energy (LCoE) of offshore wind energy dropped significantly over the last seven years as can be seen in Figure 1.1 [24]. This downward trend is expected to continue in the upcoming ten years, which can be seen in Figure 1.2 [8]. The fact that the first offshore wind farm without government subsidies is being built right now emphasizes this [11].

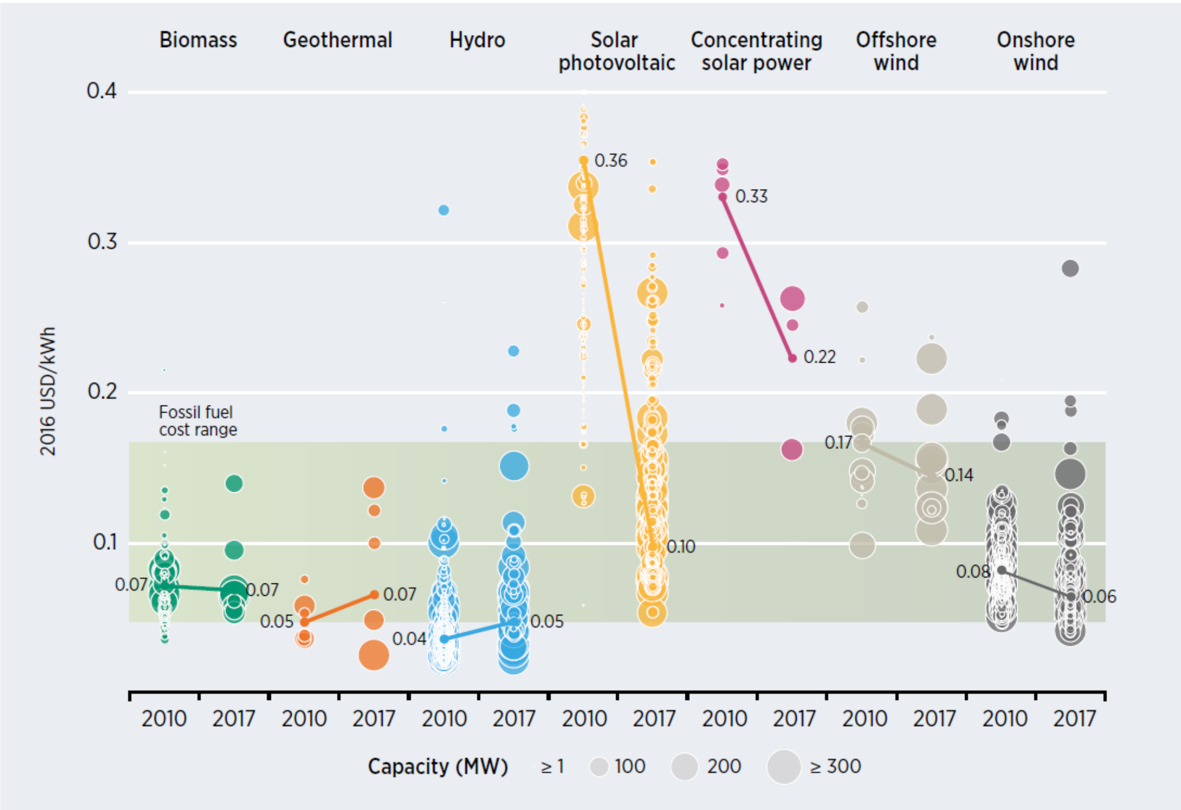


Figure 1.1: Global LCoE from utility-scale renewable power generation technologies 2010-2017 [24]

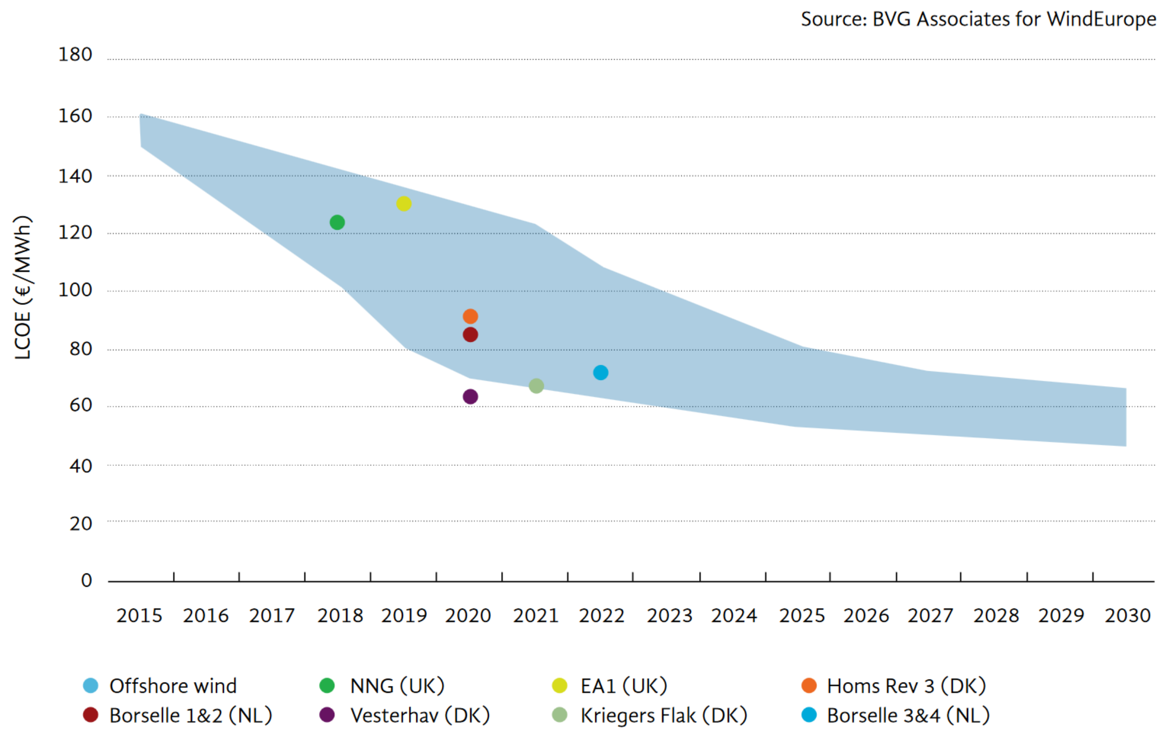


Figure 1.2: Projected evolution of the LCoE of offshore wind energy in Europe from 2015 to 2030 [8]

So the offshore wind market becomes more competitive from an economic perspective. From a technical point of view, wind farms tend to move further offshore to deeper waters and harsher environmental conditions. Also, environmental regulations on for example noise levels and carbon emission become more and more strict. This requires clever technical solutions for design, transport, installation and decommissioning and is expected to boost the offshore wind market in the upcoming years.
To cope with these technical and economic challenges, offshore contractors like Boskalis are constantly looking for ways to stay ahead of their competition by minimizing risk, improving efficiency and developing new innovative and cheaper installation methods.

1.2. Company Objective

According to Boskalis, its general business strategy is to respond to key macro-economic factors that drive worldwide demand in the energy market. For example the expansion of the global economy, the increase in energy consumption, the rapid global population growth and all the challenges that come with climate change. A part of the solution to these challenges lies in the offshore wind sector, where Boskalis is mainly active in the subsea installation of offshore power cables.
Nowadays, offshore power cable lay for offshore wind farms is mainly done by cable lay vessels or barges. Since the workability of barges is limited (low sea states and shallow waters) and the open water behavior of flat bottom cable lay vessels (like the Boskalis vessels) is insufficient for long-distance travel, bigger vessels are designed to work in harsher conditions and further offshore. These bigger vessels are being built by competing offshore contractors at the moment. But building these vessels requires a big investment. Since Boskalis already has a large fleet consisting of many different vessel types, large initial investments in newly built cable lay vessels can potentially be avoided by coming up with new cable installation methods using the existing fleet. Also, it might be possible to enter new markets by coming up with a new design for a cable lay system.

So Boskalis wants to discover if cable laying is possible with existing non-cable lay vessels and if this can open up new markets where Boskalis is not yet fully present. Besides that, implementing such a new design in the existing fleet potentially saves a lot of money and increases the time that already existing vessels are in operation.

1.3. Problem Definition

At the moment Boskalis does not know how to investigate whether it is possible to install offshore power cables with vessels from the existing fleet. Hence, a new design that can be competitive in offshore power cable installation for a selected market, has to be developed and assessed. Given is that no investments in new ships will be done, so the design has to be focused on already existing non-cable lay vessels within the Boskalis fleet. This designed system has to be competitive in a market specified in this project for offshore cable installation.

Therefore, the aim of this thesis is:

"Conceptualize a competitive cable lay system for a selected market that can be used on already existing non-cable lay Boskalis vessels and assess the systems technical and economic feasibility."

To answer this question, several sub research questions per category are formulated:

Aim

1. What is the suitable conceptual design process for a competitive cable lay system design?

Background Research

2. In which way are offshore power cables installed right now and what are the main issues within those methods?
3. What are the limiting cable properties in the current installation process that can cause the failure of an offshore power cable?
4. Which alternative concepts have already been developed for offshore power cable installation?
5. Which vessels are present in the Boskalis fleet and how can they be categorized?

Design Requirements

6. What (new) market is interesting for Boskalis to focus on when introducing a new design for a cable laying system?
7. What are the requirements concerning the selected market to ensure successful cable installation?

Concept Generation

8. How can a brainstorm session be organized (problem, aim, method, boundaries) to generate sufficient and innovative concepts?

Concept Selection

9. What are important economic and technical criteria, based on the selected market, for initial concept selection?
10. How can these criteria be prioritized and what weight factors should be assigned accordingly?
11. How to design a selection tool that can perform a Multi-Criteria Analysis for initial concept selection?

Technical Design

12. What are the main components necessary to lay cable with the selected concept?
13. What are the main technical challenges regarding the selected concept?
14. What are possible solutions for these main technical challenges?

Technical Analysis

15. Does the developed concept assure cable integrity?

Economic Evaluation

16. What economic parameters are important to assess economic feasibility?
17. Can the designed concept be more competitive in the selected market than conventional cable lay methods?

All research questions above will be answered within this thesis report. Whenever such a question is discussed, it is highlighted below the section header.

1.4. Approach

Question 1: What is the suitable conceptual design process for a competitive cable lay system design?

The steps that are taken in this project can be seen in Figure 1.3, which shows an overview of the Engineering Design Process. This Engineering Design Process is an example of a design methodology frequently used by engineers [17]. In general, a design method is developed to structure the process of designing. Following such a method stimulates creative thinking and makes sure that only one step at the time is taken. Another advantage of using a specific design method is that planning a design project becomes much easier because it is divided into clear steps. On the right side of Figure 1.3 this Engineering Design Process is specified for this particular preliminary design project.

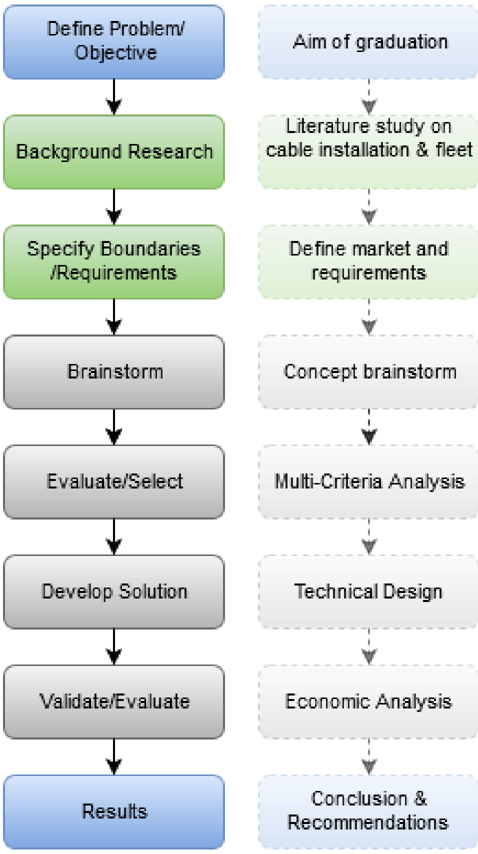


Figure 1.3: Schematic overview of the engineering design process

1.5. Report Structure

Keeping an eye on the Engineering Design Process (EDP), the report is divided into eight parts. These parts cover all steps of the EDP. The structure of the report is stated below accordingly.

1. **Scope**
   In this chapter, some background information is provided on offshore wind and the renewable energy market. A growth perspective is given, which indicates the relevance of this research for the coming decade. The company objective and corresponding problem definition are stated. Also, the approach chosen is explained by the use of a technical design framework. The report structure is adapted to this accordingly.

2. **Background Research**
   To acquire sufficient knowledge for this design project, the cable lay process has to be studied extensively. In this introductory chapter, the most important aspects of offshore power cables and cable lay are explained. Besides that, the Boskalis fleet is divided into categories.

3. **Design Requirements**
   In this chapter, the specific market that is stated in the problem definition in Chapter 1 is chosen. Also, the selection process is explained. The requirements are stated here as well, divided into two groups: technical and economic criteria. Both criteria will be input in the Multi-Criteria Analysis in Chapter 5.

4. **Concept Brainstorm**
   To generate a wide variety of concepts, several brainstorm sessions in different groups are undertaken. Here, the brainstorm methodology is explained and the output is presented.

5. **Concept Selection**
   In this chapter, the selection process to come up with one promising idea that can be further worked out is explained. As input, the requirements stated in Chapter 3 are used. Weight factors are assigned to the input to indicate the importance of every individual requirement. The selection is done by the use of a Multi-Criteria Analysis (MCA). The output of this MCA is a promising concept that will be further worked out in Chapter 6.

6. **Technical Design**
   After selecting one concept in Chapter 5, that idea is worked out more thorough here. A technical design is developed, keeping in mind the research questions stated in Section 1.3. Also, a technical feasibility study is done for proof of concept.

7. **Economic Evaluation**
   After the development of a technical design that is described in Chapter 6, an economic evaluation has to be done to evaluate the economic competitiveness of the designed system, which is discussed here.

8. **Conclusions & Recommendations**
   Finally, the research question will be answered in this chapter. First, all assumptions are stated and their corresponding implications are discussed. The conclusions of this research are stated and recommendations for further research are presented.

2

Offshore Power Cable Installation

Subsea cables are already in use for over a century and their application shifted over time. In the early days, a lot of offshore cables were primarily used for power supply to isolated facilities like lighthouses, infirmary ships, and near-shore islands. Nowadays, the application of subsea power cables shifts more towards the power supply for oil and gas production facilities and power extraction from offshore wind farms (OWF). Other applications of offshore power cables are the power supply for subsea equipment, pipeline heating, and subsea observatories. The installation is done by specialized cable lay vessels (CLV) [27]. This chapter gives insight into different kinds of subsea power cables used in the industry, their application, and their installation process.

2.1. Offshore Power Cables

Offshore power cables are a very important part of an OWF as they transport the harvested green energy from the individual wind turbine generators (WTG) to shore. A schematic overview of an OWF grid can be seen in Figure 2.1. Export cables transport the electricity generated by an OWF from the substation to onshore grids. Array/in-field cables connect the individual WTG's with each other and the substation. The fabrication and installation of offshore power cables account for approximately 15% of the CAPEX of an OWF [16].

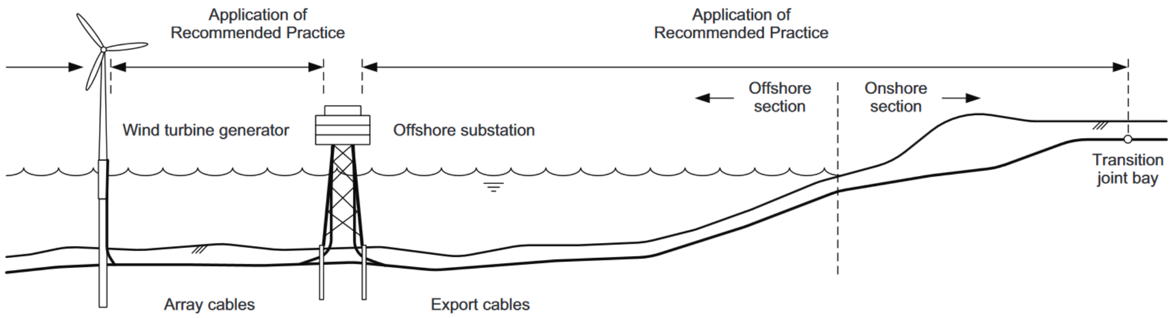


Figure 2.1: Offshore wind farm power grid to shore [5]

2.1.1. Anatomy

Over the years, many different subsea power cables have been developed. As wind turbines become larger and their capacity increases, electricity yield grows. Therefore, subsea power cables have to be changed constantly due to the higher amount of electricity that needs to be transported.

Cables can be divided into roughly two groups: cables that transport alternating current (AC) and cables that transport direct current (DC). AC cables have three conductors that transport

(a) AC Cable

(b) DC Cable

Figure 2.2: Cables for offshore power transport [19]

electricity at different phases. DC cables only have one big conductor and are usually laid in pairs or bundles of multiple separate cables. Conductors are usually made of copper, but also aluminum is used nowadays. An example of an AC - and DC cable can be seen in Figure 2.2a and 2.2b. As wind farms move further offshore, the usage of DC export cables rises. DC cables transport electricity with lower losses, but are also more expensive due to the power conversion equipment needed. The break-even point where DC cables become favorable over AC cables is around 60km of export cable length [3]. But these days AC cables are still installed for lengths up to 120km, by the use of a booster station in the middle.

2.2. Cable Installation

Question 2: In which way are offshore power cables installed right now and what are the main issues within those methods?

Offshore cable installation is done by specially designed cable lay vessels or barges. The installation starts at the loadout point of the cable. Here, the cable is loaded into a carousel on board of the vessel. After loading the export cable, the vessel transports the cable to the landfall. Cable lay vessels try to get as close to the shore as possible to limit the shore pull distance. The shore pull is performed using flotation devices to support the cable while pulling. The export cable will be laid across the sea defense through a hole made by horizontal directional drilling (HDD) of in an open-cut trench. After the pull towards shore and crossing the onshore landing, the offshore cable is jointed to an onshore power cable. From the landfall location, the cable is laid towards the substation. When the to be installed cable length exceeds maximum cable length that can be loaded onto the cable lay vessel, a joint has to be installed to connect another cable. Despite the routing of the cable will be determined by engineers, cable crossings cannot be avoided. To protect the cables at cable crossings, mattresses or rock dumping is used. When arriving at the offshore substation (OSS), the cable is cut to the right length, a cable protection system (CPS) is installed and the cable is pulled into the OSS via a J-tube using a winch. Another option is to wet-storing the cable and use another, less expensive vessel, to perform the second end pull-in.

Like with marine pipelines, cables can be laid in several ways. The two commonly used methods are J-lay and S-lay. S-lay is done over a chute or a stinger at the aft of the vessel. Boskalis only installs offshore power cables using the S-lay method with chute. The schematic process of this S-lay method can be seen in Figure 2.3.

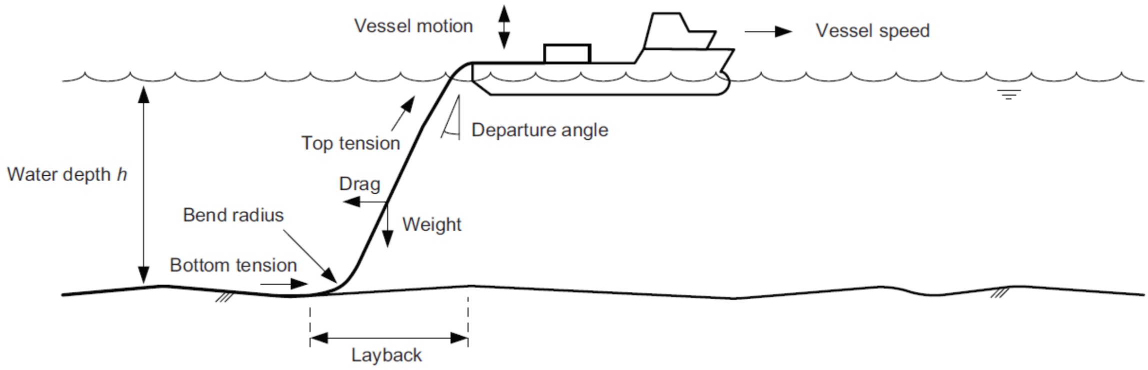


Figure 2.3: Schematic overview Offshore Power Cable Installation [5]

2.2.1. Cable Lay Vessels

Nowadays, cable lay vessels are more and more designed to act as multi-purpose vessels. For the design, the main drivers are load-carrying capacity, deck space, maneuverability, sea-keeping properties, accommodation and bollard pull. Bollard pull becomes important when using a cable plough for cable burial. The cables are stored in a carousel, static coil or drum. An overview of a cable lay vessel including all necessary onboard equipment (carousel, load arm, cable engine, tensioners, quadrant, chute, jointing house) can be seen in Figure 2.4a and 2.4b.

2.2.2. Cable Burial

Despite that cable burial is not included in the scope of this project, it is an important part of offshore power cable installation because it protects the cable from damaging and therefore assures cable integrity. Several cable protection techniques are being used nowadays. The technique is chosen depending on the project, project site and cable lay vessel characteristics. Cable protection techniques can be roughly divided into four groups: pre-lay trenching, simultaneous lay & burial, post-lay burial, and artificial coverage. In Figure 2.5 the applied techniques per group can be seen.

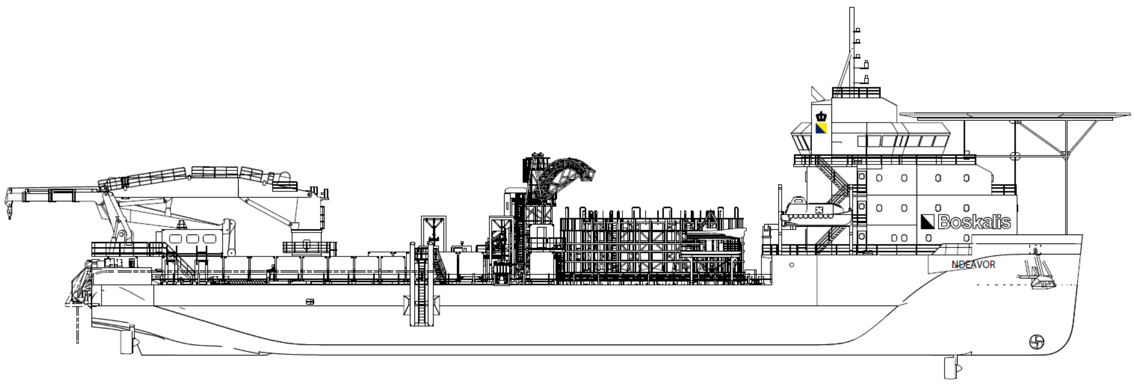
2.2.3. Issues

The main issue that Boskalis is facing during cable laying over a chute is the large motions at the aft of the ship. Because the aft of the vessel is far away from its center of gravity, especially heave motions due to pitch are significantly larger here compared to locations closer to the center of gravity. These motions limit operability, especially for the second end cable pull in. Other issues regarding conventional cable laying will be discussed in Chapter 3 because they are input for the design requirements of a new offshore power cable lay system.

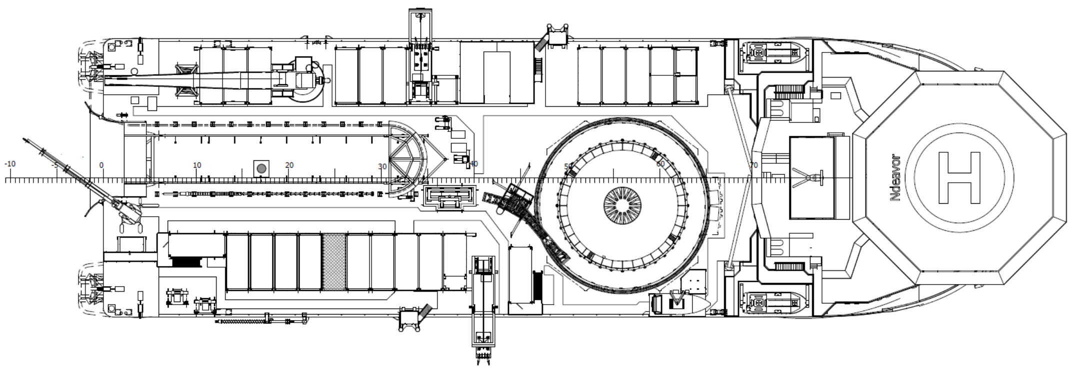
2.3. Limiting properties of Offshore Power Cables

Question 3: What are the limiting cable properties in the current installation process that can cause failure of an offshore export power cable?

Power cables are manufactured to transport electricity and data with minimum losses. During the cable installation, the power cables are externally loaded, which might impact the integrity of the cable. The most important limiting factors are compression, tension, bending, squeezing/crushing and torsion [23].



(a) Side view



(b) Top view

Figure 2.4: Overview of Boskalis cable lay vessel Ndurance [4]

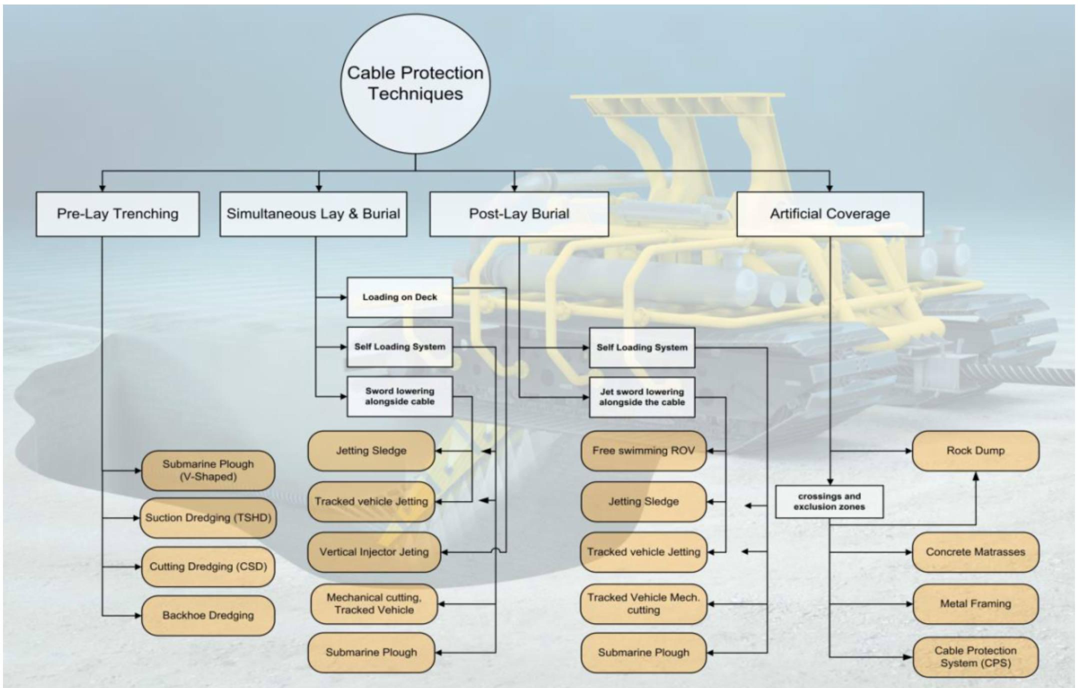


Figure 2.5: Cable Protection Techniques (courtesy of VBMS)

2.3.1. Compression

Compression in a cable is possible due to the rapid movement of the cable caused by hydrodynamic loads. Because little is known about compression in offshore power cables, no industry standard defines compression limits yet. Therefore, cable manufacturers often state that offshore power cables cannot be loaded in compression, or marginally. According to these specifications, compression is most of the time the limiting factor for offshore cable installation with current techniques.

2.3.2. Tension

Tension in the cable can be generated by the tensioner, self-weight, vessel motion, and bottom friction. When the cable is in tension, the armored wires move slightly to the inside of the cable, compressing the core. This might damage the cable harming its integrity.

2.3.3. Bending

An offshore power cable consists of nearly a dozen different components. Therefore, it is hard to quantify cable properties. Bending of the cable generates axial stresses, due to which the cable might fail. Failure may occur in the form of buckling, signal loss, water ingress, bird caging, etc.. The minimum bending radius (MBR) is an important variable because it can be a limiting factor in operability. The MBR is determined by the cable manufacturer. In the design of several cable lay components, like the chute and quadrant, the curvature of that component is dependent on the MBR of the cable. The MBR itself is dependent on the tension that is applied during the installation process. Therefore, cable manufacturers often supply contractors with a graph in which the allowable MBR versus tension is displayed.

2.3.4. Squeezing/Crushing

During cable installation cables will go through cable engines, through a tensioner, and over a chute/stinger. This generates in some cases a squeezing load or a side-wall pressure. These (a)symmetric loads might cause the cable to flatten or deform. Therefore, squeezing and crushing loads can be a limiting factor in offshore cable installation. Maximum side-wall pressure and maximum cable pressure both are defined by the cable manufacturer.

2.3.5. Torsion

Torsion can occur when a cable is being coiled. A coil is a spiral to store ropes or cables efficiently. Coiling with single protection layer cables can be done for storage inside a carousel. Due to torsion in a cable, armored wires on the outside of the cable that serves as protection might open up. This potentially damages the cable harming its integrity.

2.3.6. Combinations

Also, a combination of two or more of the above cable limitations can be important, for example, tension while bending. When bending over a chute, for example, tension can result in a high sidewall pressure on the cable. Therefore, manufacturers also define a maximum sidewall pressure for each cable.

2.4. Alternative Concepts

Question 4: Which alternative concepts have already been developed for offshore power cable installation?

The offshore wind sector is looking for new, more efficient solutions to install offshore power cables and decrease failure probability during or due to installation. Boskalis Subsea Cables & Flexibles has an R&D department that is constantly looking to innovate cable lay processes to make them more time and cost-efficient. Therefore, some of the concepts that might be interesting for this research, which are publicly known and already investigated by Boskalis or competing offshore contractors will be displayed below.

Cable pulling

During present near-shore power cable installation operations, the export cable is pulled in from the cable lay vessel towards shore by an onshore winch. Floaters are attached to the power cable to make the pull-in easier.
Another method that is already used by competitors is the pulling of prefabricated pipes where power cables and data cables are already installed inside. The limit for such a pulling operation is approximately 15 km from the shore.

Multiple vessels

Another idea is to make use of multiple vessels for offshore cable installation. The power cable installation can be divided into different parts, which do not necessarily have to be done by only one vessel. The near-shore operation can be performed by a flat hull-shaped vessel with the possibility to beach during low tide. The cable laying part can be performed by a relatively cheap cargo vessel equipped with cable lay equipment. The pull-in can be done by a more expensive DP-2 class vessel with large deck space for the quadrant. Doing this potentially can lower the hiring expenses drastically. The total mobilization costs, however, will increase with every extra asset that is used.

MCLS

In the offshore industry, ships are built to act as multipurpose vessels more and more. Hence, deck equipment and designs are becoming modular. An example of this is the in-house developed modular cable lay spread (MCLS). The MCLS makes it easier to fit cable lay equipment on a barge or non-cable lay vessel and can be removed when not necessary anymore.

SCARGO/ATLAS

Together with Technalia and SMD, Boskalis is developing a concept to lay infield cables with a vehicle on the seabed. This vehicle, which can be seen in Figure 2.6, attaches the cable end to the pull-in wire using a robotic arm. From there it drives to another OWT while laying the cable in a self-created trench.

Cable laying over the side of the vessel

Nowadays, offshore power cables are being laid over the aft of a cable lay vessel. This makes the operation vulnerable to pitch motions, because of the large distance to the center of gravity (CoG) which generates large heave motions due to the pitch angle of the vessel. A

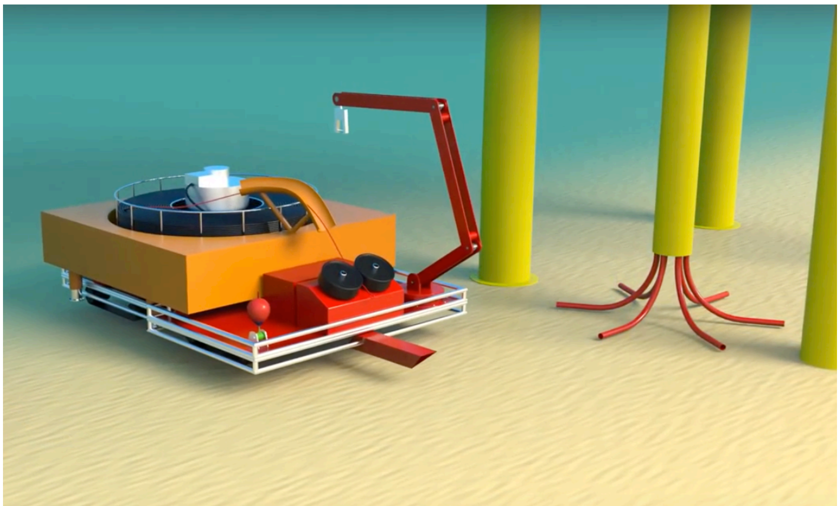


Figure 2.6: SCARGO/ATLAS concept [25]

possible solution for this is to lay cable over the side of the vessel close to the CoG. The operation will be more vulnerable to roll motions instead of pitch motions, but the distance to the CoG will be much smaller. A disadvantage of this is that the excessive length that can be created in the cable for the second end pull-in, which is needed to prevent an unfavorable heading change of the vessel during the pull-in operation, will also be reduced.

Carousel on semi-sub
Because of their high load-carrying capacity due to its high stability and their excellent open water behavior, semi-submersible Boskalis (former Dockwise) vessels could be ideal to transport large quantities of offshore power cables in carousels over large distances. An idea generated by the R&D Department of Boskalis SC&F is to put carousels on separate barges, which can be loaded onto a semi-submersible vessel. This will potentially make it possible to lay cables in high sea states and transport cable over large distances, but on the other hand, it also creates flexibility in near-shore conditions. Barges can sail in shallower water depths and thus lay cable closer to shore when deployed individually.

2.5. Boskalis Fleet

Question 5: Which vessels are present in the Boskalis fleet and how can they be categorized?

Boskalis has a fleet of approximately 900 vessels, of which only three vessels are specifically built for offshore power cable lay. These cable laying vessels are the Ndurance, Ndeavor and Stemat Spirit. A database containing all specifications of the whole Boskalis fleet is not available yet. Therefore, a new database of the 180 best-known vessels is made for further categorization. An overview of this database can be seen in Appendix A.

2.5.1. Vessel Categorization

Vessels can be categorized in several ways. For example based on function, size, shape, maneuverability, behavior, etc. Based on their function, the Boskalis fleet can be divided into two main categories: dredgers and offshore vessels. These main categories can be divided into various subcategories, which are displayed in Figure 2.7. This is mainly done to get a feeling of the wide employability of the Boskalis fleet.
For comparison, a more consistent way that is used to categorize vessels in the maritime sector is necessary. For this master thesis project, the categorization of Lloyd's Register (LR) is used. LR is a renowned maritime classification society, that made a directory with technical specifications of vessels based on size, load-carrying capacity, installed power, etc.

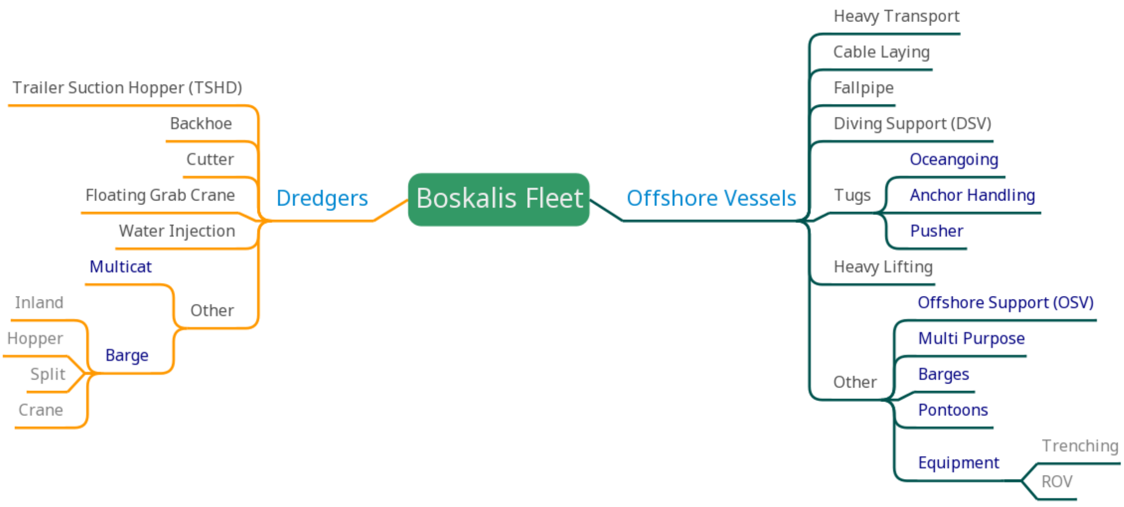


Figure 2.7: Different vessel functions withing Boskalis fleet

This directory is called Lloyd's List [15]. For offshore export power cable installation, the categories mentioned in Table 2.1 are design parameters that are currently important for CLV's. Therefore, these are used to categorize the individual vessels in the Boskalis fleet. Based on these specifications, a database is made in Excel where these specifications are filled in [14]. In Chapter 6 this categorization will be used to choose a specific vessel for the selected cable lay system.

Parameter	**Unit**
Length	m
Breadth	m
Depth	m
Draft	m
Displacement	m^3
Deck Space	m^2
Deck Strength	tonnes/m^2
Maximum Speed	kts
Main Propulsion	kW
DP Class	#
Bollard Pull	tonnes

Table 2.1: Vessel categorization [15]

3 Design Requirements

The boundary conditions of this research are set by the initial conditions explained in Chapter 1. Besides these initial conditions, a selected market is the focus-point of this conceptual design process because it is estimated to become more and more important in the next decade and Boskalis is not yet fully present in this market. In this chapter, the specific market that is stated in the problem definition in Chapter 1 is chosen. The requirements are stated here as well, divided into two groups: technical and economic requirements. These requirements will be input as criteria in the Multi-Criteria Analysis explained in Chapter 5.

3.1. Market Selection

Question 6: What (new) market is interesting for Boskalis to focus on when introducing a new design for a cable laying system?

First it is important to point out why a specific market is selected. As explained earlier, the offshore cable lay market can be divided into roughly two groups: in-field/array cable and export cable/interconnector installation. These two groups come with their own, often contradictory challenges. Therefore, a specific market must be selected. Besides that, one of the objectives of this thesis is to add value to the company Boskalis. Meaning that it is important to select a specific market in which Boskalis can increase its market share in the upcoming decade.

To get a feeling for the offshore power cable lay market at this moment, several interviews have been conducted with Boskalis employees. One of the employees who is focusing on the offshore cable lay market daily is Tim van Keulen, solutions manager at Boskalis Subsea Cables & Flexibles (BSC & F). He answered a total of fifteen questions in which he explains how the cable lay market is right now, what Boskalis' strengths and weaknesses are within this market, and how he thinks the market will develop in the upcoming decade and where there is potential to grow for Boskalis. The minutes of the conducted interview can be found in Appendix B. The most important parts of the interview with Tim van Keulen are input for the market selection in this thesis.

Since the market tends to move further offshore and is expanding from the North Sea area to other continents, with the main focus on the U.S. and Taiwan, the strategy of Boskalis is likely to change accordingly in the upcoming decade, according to Tim van Keulen. With three cable lay vessels in the fleet that are widely employable, there is sufficient capacity to send one of the vessels to Taiwan shortly leaving two vessels operative in the North Sea area. The strong suits of these vessels are their employability near shore and beaching capability. The weaknesses are the relative high day rate compared to competitors and the relatively low load-carrying capacity. Load-carrying capacity becomes important in the interconnector and export cable installation process as joints are expensive and preferably avoided by the client. Also open water behavior is insufficient to sail long distances, due to the flat hull made specifically for beaching. At this moment, Boskalis' CLV's can handle loads ranging up to 5000 tonnes. This is approximately 50 kilometers of export cable equivalent [20]. Export cable installation with a load of over 5000 tonnes, so for distances above 50 kilometers, are done with bigger vessels by cable manufacturers like NKT, Nexans, and Prysmian itself. Besides that, Boskalis is considering to invest in another cable lay vessel focusing on in-field offshore power cable installation only.

Because of the potential investment in a new in-field offshore power cable installation vessel and clever systems like a modular cable lay spread (MCLS) for the installation of in-field cables, the growing international offshore wind market with wind farms going further offshore and low market share of Boskalis in export cable installation, this concept design will focus primarily on export cable installation for far shore offshore wind projects. Besides that, it is desirable that this concept is applicable all over the world, as new markets like Taiwan, The U.S. and perhaps even floating wind in Japan are emerging, according to Tim van Keulen. Therefore, the design conceptualized in this thesis project will focus on:

"The international offshore export power cable installation market (both AC and DC), including interconnectors, from shore to substation or shore to shore."

3.2. Boundary Conditions

To scope the thesis' subject, as stated in Chapter 1, boundary conditions are divided into initial conditions, market boundaries and vessel categorization. The main concept selection will be done on the market boundaries, that have been divided into two parts: technical and economical criteria.

3.2.1. Initial Conditions

As stated in Chapter 1 there are a few initial conditions that limit the scope of this design project. These conditions are:

- No investments in new vessels
- Design must be competitive in selected market
- Design must make use of existing Boskalis fleet
- Burial will not be included in the design

3.2.2. Market Boundaries

Question 7: What are the requirements concerning the selected market to ensure successful cable installation?

From the selected market several criteria can be derived. These criteria can be divided into two groups: technical and economic criteria. The criteria defined below are input in the MCA in Chapter 5.

Technical Criteria

Important in the international export cable installation is load-carrying capacity. Ships from competitors in the cable lay industry, like Tideway's Livingstone, have a load-carrying capacity of up to 8.000 tonnes. The main advantage of this is that no (or less) joints are needed in a cable that has to be installed over a large distance and that no heading change is needed during the second end pull-in of the cable. Joints are expensive to fabricate and have a larger probability to fail over time. Therefore, clients take the number of joints into account when a project is being tendered. The more joints a company has to make, the lower the chance of successfully tendering the job.

Because the offshore wind market expands from the North Sea area towards Taiwan and The United States, it becomes more important that a cable lay system can be transported over large distances. One of the issues with the existing CLV's is that their open water behavior is very poor due to its flat bottom hull shape. Therefore, the ability to transport the system over long distances (>500km) is an important factor to take into account in concept selection. Besides that, more and more DC cables will be used, due to lower losses over long distances. Therefore, the design must be suitable for both AC - and DC cables.

According to safety regulations, a vessel can only approach an Offshore Sub Station (OSS) by less than 500 meters if it has at least DP-2 capability.
The scope of this thesis is to design an export cable lay system that can install the whole cable, from shore landing to platform. Therefore, separate criteria for the facilitation of the shore landing and the second and pull-in have been included.

Summarizing, the system has the following boundary conditions, defined from the selected market:

- Load-carrying capacity of at least 8.000 tonnes
- Near-shore installation capacity/beaching
- Possibility to be transported over large distances (>500km)
- Suitable for AC export cable installation
- Suitable for DC export cable installation
- At least DP-2 class
- Facilitates shore landing
- Facilitates 2^{nd} end pull-in
- Operable up to at least 2.5 meters significant wave height

The importance of every criterion will be further discussed in Chapter 5.

Economic Criteria
There are a lot of important economic parameters that can be taken into account to evaluate a design concept. For example day rate of assets, mobilization cost of the asset, estimated investment, risk, etc. For the initial economical analysis that is taken into account for concept selection, only three are taken as input because they are dominant compared to the others. Besides that, some are hard to quantify for a large number of concepts. For example, the risk is hard to evaluate for a large number of high-level concepts. The three criteria that are used are the day rate, mobilization cost, and estimated investment. These economic criteria will act as assessment categories in the preliminary economic analysis for the high-level comparison of concepts. A more detailed economical analysis for the selected concept is discussed in Chapter 8.

Day rates and mobilization costs are very sensitive information in the tendering process. Because of this, only estimations are given in this thesis. Per vessel category (described in Chapter 2) a bandwidth is given and the average is taken for first calculations. Mobilization costs are expressed in the number of days times the day rate of a vessel. An estimate of the day rates and mobilization costs are used in this analysis, but because day rates are competitively sensitive information, the estimates will not be mentioned in this report. Besides the variable costs described above, an estimated investment is assigned to every concept.

To distinguish between easily implementable concepts with relatively low estimated investment and concepts that are harder to implement with a relatively high estimated investment, several investment levels have been developed. These five investment levels are:

- 1: Very low investment <€500.000
- 2: Low investment €1.000.000
- 3: Medium investment €2.500.000
- 4: High investment €5.000.000
- 5: Very high investment >€10.000.000

Summarizing, the system has the following economic criteria:

- Day Rate
- Mobilization Costs
- Investment Costs

4

Concept Brainstorm

According to the Engineering Design Process, background research and setting design requirements are followed by conceptualization. Conceptualization is, in fact, the generation of ideas, taking into account the pros and cons of implementing those ideas. This concept generation can be done in several ways, for example by morphological analysis, synectics, or brainstorming. For this project, the ideation of brainstorming has been chosen. In this way input from different groups with varying educational backgrounds could be gathered. This is important because participants might be prejudiced by their previous education. This is not beneficial for conceptualization. Hence, holding on to participants with a strictly technical background might result in the generation of many similar or obvious ideas.

In Chapter 2, the most common way of offshore export power cable laying these days has been explained. In this chapter, concept brainstorm, new concepts for offshore export power cable laying are generated in several brainstorm sessions. A specific brainstorming method has been selected that supports the generation of the desired output.

4.1. Criteria

Question 8: How can a brainstorm session be organized (problem, aim, method, boundaries) to generate sufficient and innovative concepts?

To determine which setup can be used best for the brainstorm sessions, first, the brainstorm criteria have to be defined. These criteria are based on the project scope, practical requirements, and desired outcome. Therefore, the first question that should be answered is: *"Are there any restrictions or is there a framework in which should be operated?"*
In this case, the brainstorm session is very much time-restricted. This is done to make the step to participate in a brainstorm session as small as possible because a session will only take a limited amount of time. Secondly, it is important to have a broad framework in which ideas can be generated. This will generate a wide variety of ideas that can be narrowed down later on. Hence, if a brainstorm session starts with a too-narrow focus, it is not possible to widen its focus subsequently. Lastly, it is important that participants can influence each other's ideas by sharing their thoughts. This lets participants think outside of the box because they can get inspired by other participants' ideas, of which they may have never thought of themselves. This can open up more ideas, resulting in a greater number of concepts generated.

With the framework set, the constraints for the brainstorm sessions must be stated as well. The second question that should be answered is *"What should the brainstorm session focus on and what should be left out?"*
Ideally, this brainstorm session should generate a large number of concepts. With a large number of generated concepts, there is a larger probability that ideas will differ from each

other when gathering them and promising ideas are included. To keep the sessions focused on the main goal, which is generating as many ideas as possible, the elaboration, selection, and evaluation of concepts are not included. In other words, there is no room for discussions during the brainstorm sessions. From a more technical perspective, the burial of the cable is not included because this is not in the scope of this thesis. Another constraint is that the proposed solution has to be based on offshore export power cable installation only.

4.2. Method

To structure the brainstorming process, the so-called hourglass model is used. This model is based on the input of Max Verhaegh, R&D Engineer within Boskalis SC&F [12]. This model defines a challenge, several constraints, and a goal. A schematic overview of this model can be seen in Figure 4.1. By stating the challenges, constraints, and goal of the brainstorm session in advance and presenting these to all participants before the start of the session, it becomes clear what problem needs to be solved, why this needs to be solved and what is not included in the scope of the brainstorm sessions. Clearly stating this in advance potentially saves a lot of questions and prevents ambiguities from arising during the session later on. This is very important since the brainstorm sessions are time-restricted.
The challenge of this brainstorm session is ***"How can offshore export power cables be installed in a new manner?"*** The corresponding constraints are that ***"burial is not included"***, there will be ***"no discussions on the concepts during the session"***, and the proposed outcome is ***"a large number of concepts generated***" within a session. The higher goal of this brainstorm session is ***"To come up with an innovative and competitive idea for offshore export power cable installation."***

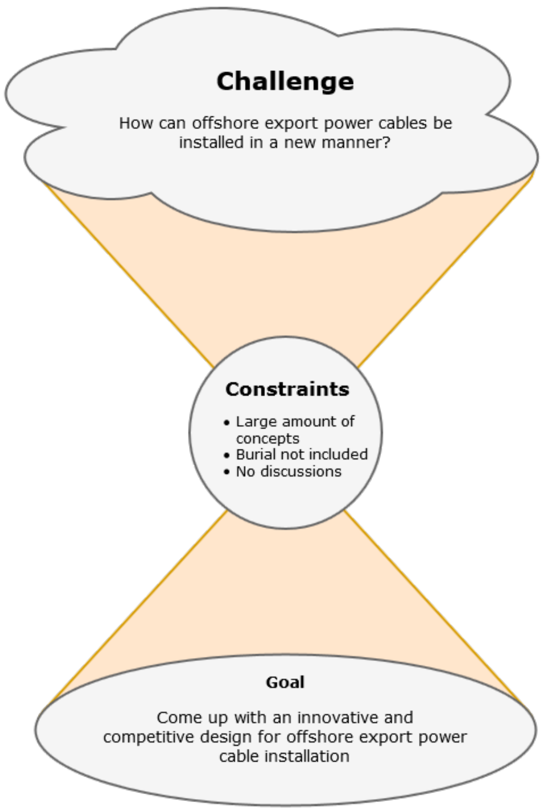


Figure 4.1: Hourglass model brainstorm

4.3. Groups

To make sure that a wide variety and large quantity of concepts is generated, different groups, consisting of three to four people, are put together. To stimulate idea generation, even more, the composed groups consist of participants with different educational backgrounds ranging from strictly technical to economical and even to marketing and art. This is important, because participants might be prejudiced by their previous education and working experience.

- Group 1: Non-technical participants
- Group 2: Offshore Engineering students
- Group 3: Mix of Technical students
- Group 4: Boskalis Graduate Students
- Group 5: Boskalis SC&F R&D Department

4.4. Brainstorm Sessions

The brainstorm sessions are divided into an introduction and three rounds. The introduction, which takes approximately 5 minutes, consists of a short presentation where the structure of the brainstorm session is explained. The problem, aim, method, and boundaries are explained to the participants to prevent any ambiguities from appearing during the session. In the first round, which takes approximately 10 minutes, small modifications to the regular cable lay method have to be developed individually. In the second round, which takes approximately 10 minutes, different cable lay methods are developed individually. Before the third session, cable lay concepts are briefly explained and presented to other group members, which takes approximately 10 minutes. In the third round, which takes approximately 15 minutes, two participants collaborate to merge their ideas from previous rounds into other new concepts. Between rounds, a small break of 3 minutes is scheduled. In total, a brainstorm session takes about 1 hour.

4.5. Generated Ideas

As mentioned before, all ideas presented in this section were generated in brainstorm sessions with groups of different educational backgrounds. All generated ideas have to satisfy the initial conditions mentioned in Chapter 1 to be suitable for testing against other ideas. The resulting generated ideas are tested against the criteria mentioned in Chapter 3. The method used for this is a multi-criteria analysis (MCA). The extensive selection process is explained in Chapter 5. All generated ideas are recorded in a database system. In Appendix C, these ideas including the database system can be seen, in which the concepts are grouped by the following categories:

- **Floating:** Concepts that primarily use floating equipment
- **Subsea:** Concepts that primarily use subsea equipment
- **Special:** Extra-ordinary concepts that are not realistically implementable
- **Modifications:** Adjustments that can be applied to the current CLV's

4.5.1. Floating Concepts

Floating concepts utilize floating equipment. This is the most promising category for this project because the scope of this thesis is to design a new cable lay system that can be used on already existing vessels, i.e. with the use of floating equipment. Therefore, several interesting floating concepts are displayed here. These concepts can be seen in Figures 4.2 to 4.5.

Cable Pulling

One of the possibilities that came out of a brainstorm session is to pull the cable from shore to substation, by a vessel with a large bollard pull capacity. In this case, an anchor handling tug can be used because it is also equipped with DP-2 capability. Pulling cables is already done from a CLV to the shore landing but only over a limited distance. In Figure 4.2, a sketch of this concept is displayed.

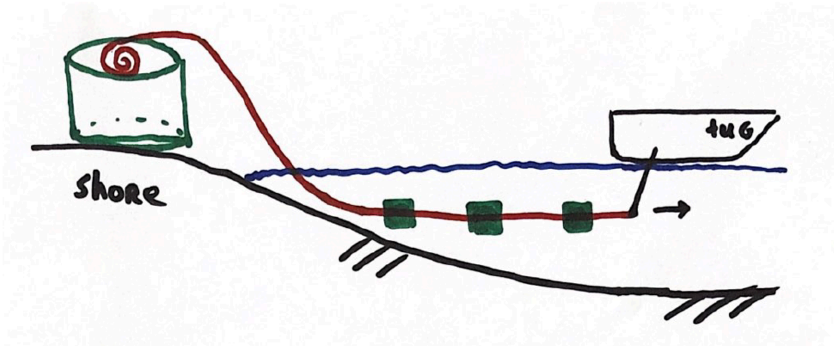


Figure 4.2: Cable pulling cable lay concept

Cable Lay with Rock Dumping or TSHD Equipment

An example of using existing vessels where the cable goes through a confined space, protecting it from hydrodynamic loads, are cable laying through rock dumping fall pipe or through a TSHD suction arm. A sketch of the TSHD concept is provided in Figure 4.3.

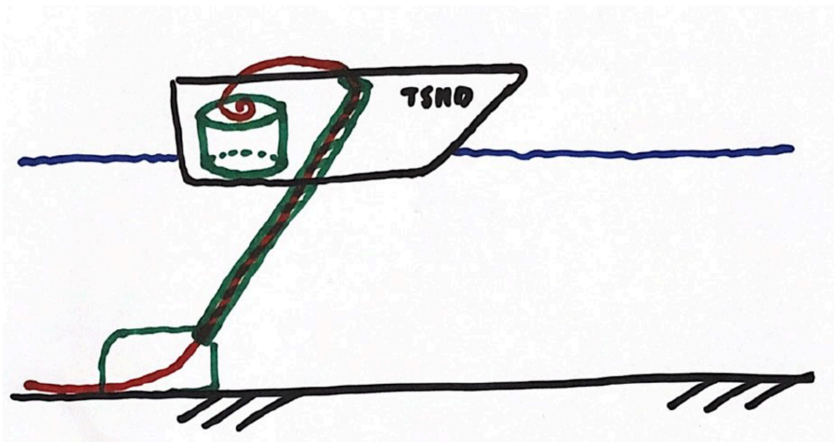


Figure 4.3: Rock dumping or TSHD cable lay concept

Barges on Semi Submersible Vessel

One of the ideas to combine nearshore and open water operations is to put barges equipped with a cable carousel on a semi-submersible heavy transport vessel. An example of this concept can be seen in Figure 4.4.

Cable Laying through a Moonpool

Another idea to reduce cable loads, which is similar to J-lay pipelay, is to install export cables through a moonpool. This can be done with for example a fall pipe vessel, which is often equipped with a moonpool for rock dumping purposes. The carousel that contains the export cable can be stored below or on deck. An overview of this concept can be seen in Figure 4.5.

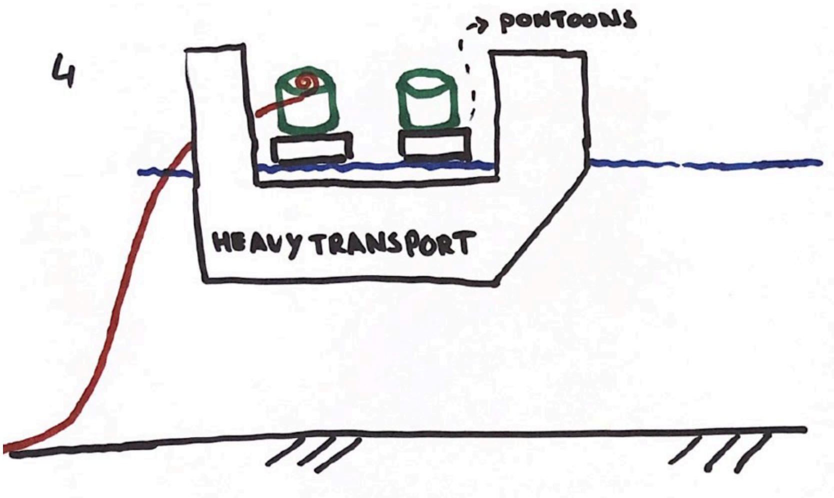


Figure 4.4: Barges on semi submersible vessel cable lay concept

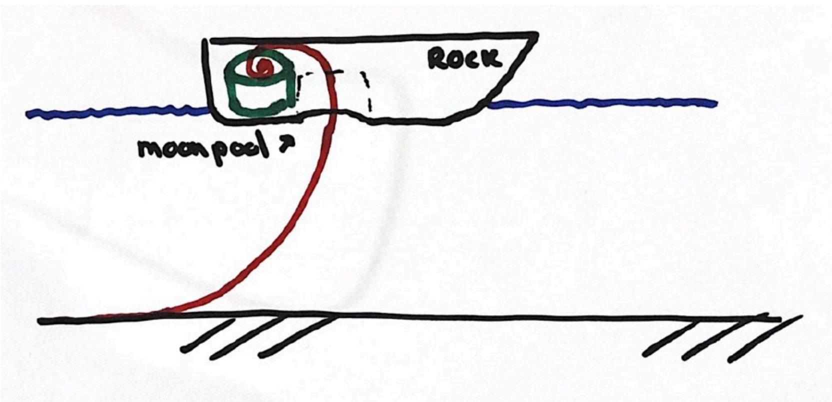


Figure 4.5: Moonpool cable lay concept

4.5.2. Subsea Concepts

Subsea concepts primarily utilize equipment deployed on the seabed. This can be an ROV, winch for cable pulling, etc. Subsea equipment can be applied in combination with existing vessels, for example, ROV monitoring, deploying equipment, etc.

Subsea ROV

Subsea concepts can make use of subsea ROV's like the SCARGO project, mentioned in Chapter 2. An example of a subsea ROV concept is given in Figure 4.6, where the cable is pulled over the seabed towards the substation.

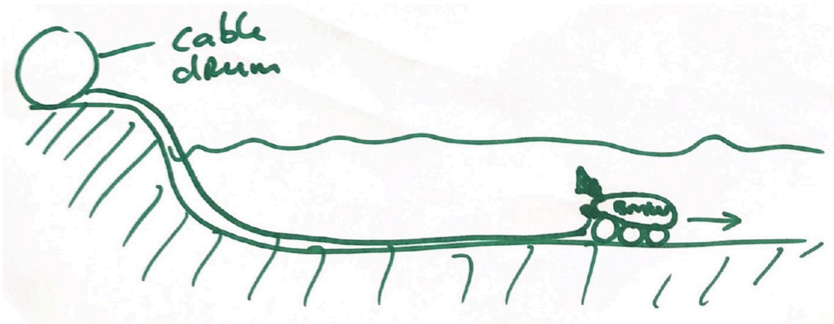


Figure 4.6: Subsea ROV cable lay concept

4.5.3. Special Concepts

This category represents extra-ordinary ideas that do not seem realistically implementable. Think of airplane of submarine usage, a floating cable factory, harpooning the cable over long distances, etc. Despite this, the concepts are generated during a brainstorm session and therefore included in the concept database. This concept database can be seen in Appendix C.

4.5.4. Modifications

Modifications are changes to the current cable lay process, resulting in cost reduction or reducing project lead time. This category is redundant because a new concept for offshore export power cable laying needs to be developed. However, these modifications might be interesting for Boskalis and are implemented more easily than a completely new method of cable installation. Therefore, these modifications are also included in the database which can be seen in Appendix C.

5
Selection

In this chapter, the selection process to nominate a final concept is explained. This final concept is further developed in Chapter 6. As input, the requirements stated in Chapter 3 are used. Weigh factors are assigned to all criteria to indicate the importance of every individual requirement. The selection is done using a Multi-Criteria Analysis. Both technical and economic aspects are assessed in the MCA.

5.1. Selection Method

A Multi-Criteria Analysis is a scientific evaluation method that provides a framework to be able to make a rational choice between discrete alternatives based on more than one criterion. These criteria could be for example economic, ecologic, technical, ethical, social, etcetera. An MCA consists of five steps:

- **Problem Analysis:** group criteria, define units, assign scores
- **Standardization:** standardize scores linearly between *0* and *1*
- **Apply Weight Factors:** assign weight factors to criteria
- **Calculate and Sort:** calculate weighted scores and sort concepts based on scores
- **Evaluate:** evaluate top scoring concepts and substantiate winning concept

5.2. Selection Criteria

Question 9: What are important economic and technical criteria, based on the selected market, for initial concept selection?

Input for the MCA are the criteria mentioned in Chapter 3. The criteria are divided into two parts. A technical part, representing the selected market requirements, and an economical part that takes into account the estimated fixed and variable costs as well as the estimated investment costs. Safety is included in the MCA by using common industry standards as guideline for technical criteria. The safety of the final concept has to be monitored during the design phase.

5.3. Weight Factors

Question 10: How can these criteria be prioritized and what weight factors should be assigned accordingly?

Weight factors are very important in an MCA. Without these, all criteria are equally important but in real life that is not the case. To distinguish between these different criteria and to determine their importance, weight factors have to be assigned. Some of the criteria are critical to the success of a concept, while others are just auxiliary improvements. The criteria and their corresponding weight factors can be seen in Figure .

Criteria	Weight Factor
Use of Vessels	1.0
Load Carrying Capacity > 8.000 tonnes	1.0
Operable Near Shore	0.4
Possible to transport > 500 km	0.4
Suitable for AC export cable	1.0
Suitable for DC export cable	1.0
At least DP-2 class	1.0
Facilitates shore landing	0.4
Facilitates 2^{nd} end pull-in	0.7
Operable in $H_s \geq 2.5$ m	0.2

Table 5.1: Market Criteria with corresponding Weigh Factors

5.3.1. Crucial Criteria

All weight factors (WF) equal to *1.0* indicate crucial criteria, or 'deal breaker'. If a concept does not score on a criterion with a weight factor equal to *1.0*, the concept is discarded.
In common industry standards, like the American Petroleum Institute (API) standard [2], it is stated that a vessel can only approach an offshore substation (within 500 meters) if it has at least DP-2 classification. Because this DP-2 criterion is critical due to safety regulations, DP-2 has a weight factor equal to *1.0*.
It is stated in the scope of this thesis that an alternative cable lay concept must be developed using existing vessels within the Boskalis fleet. Therefore, the criterion of using vessels has a WF equal to *1.0*.
Since competitors in the export cable lay industry have a load-carrying capacity of up to 8.000 tonnes and clients prefer to avoid the usage of joints as they are expensive and sensitive to failure, the criteria of the load-carrying capacity of > 8.000 tonnes is also a criterion which has a WF equal to *1.0*.
The concept has to be developed to lay both AC and DC cables on the seafloor. Therefore, it is important to take cable integrity into account. Both AC and DC cables must be able to operate for the total lifespan of the offshore wind farm. So also these criteria have a WF that is equal to *1.0*.

5.3.2. Other Criteria

Some criteria are important, but not mandatory for this project. Here, all these other criteria are discussed.

Near shore capacity

The current CLV's are operable near shore and even have the possibility to beach. This becomes useful when installing cables in shallow waters near the coast. Therefore, the criterion to be operable near the shore is important. This criterion can be mitigated by using a separate vessel, like a barge, that is more suitable for near shore cable installation.

Shore landing

The current CLV's can approach the coast enough to facilitate a short range pulling operation of the cable towards the shore landing. This leads to easy connection of the export cable to the onshore grid. This criterion can be mitigated by introducing a long distance cable pulling operation from the vessel to shore.

Transportable

Since the offshore wind market grows more and more overseas in areas like the U.S. and Taiwan, it becomes important that the vessel can be transported over a large distance to operate all around the world. This can be done by assuring sufficient open water behavior or by transporting the cable lay system and vessel with a heavy transport Dockwise vessel towards the project site.

Second end pull-in
The second end pull-in is often a more complex operation than the shore landing. The operation is close to an OSS that is very sensitive to damage and is at the open sea. Although the second end pull-in can be done by a separate vessel as well, it is more convenient to implement it in the new concept due to the large distance to shore.

Operability
The operability is preferably above a significant wave height of 2.5 meters because this is the limit for cable installation performed by competitors right now. Increasing operability, on the other hand, decreases project duration, leading to less income. So in fact operability is an economic criterion which also depends highly on the hydrodynamic conditions at the project site location.

5.3.3. Assigning Weight Factors
According to the importance of every criteria described above, an order from low (1) to high (3) is made to assign weight factors:

1. Operable at Hs > 2.5 m
2. Transportable > 500 km; Shore landing; Near shore capability
3. Second end pull-in

Thus, out of these criteria, the second end pull-in is the most important compared to the others, although it can still be mitigated. Therefore, the WF is chosen to be equal to 0.7. Operability is an economic criterion, which is not decisive for project sites with relatively mild weather conditions. Hence, a WF of 0.2 is assigned to this criterion. The other three criteria are equally important and estimated to be more important than operability and less important than the second end pull-in. Hence, the WF must be between 0.2 and 0.7. Because of the importance of the second end pull-in, its technical challenges and sensitivity to failure, the WF of these three criteria lies more towards the lower bound. Therefore, the WF is chosen to be equal to 0.4, rounding down the average of the other two weight factors.

5.4. Reference Project
For this thesis, a recently acquired project by Boskalis is chosen as reference project. The scope of this project is to connect the offshore wind parks Arcadis Ost 1 and Baltic Eagle with the German coast by installing in total 270 km of 220 kV AC copper export power cables.

5.4.1. Project Overview
The reference project connects two offshore wind parks, Arcadis Ost 1 and Baltic Eagle, situated 40 km north-east of Rügen island, with the German coast. The exact location of these two OWF's can be seen in Figure 5.1. The two wind parks combined consist of 110 OWT's that together have a capacity of 725 MW. Water depth at both wind parks exceeds 40 m. The seabed consists of a 5-10 m mud layer followed by a 20 m soft sediment layer. This reference project will be discussed more in-depth in Chapter 7 because it will be used for both technical and economic analysis. All relevant parameters regarding the project site can be seen in Table 5.2.

Parameter	Value	Unit
Turbines	110	-
Capacity	723	MW
Water Depth	> 40	m
Cable Length	270	km

Table 5.2: Project specifics reference project

Figure 5.1: Project Site Reference Project [1]

5.5. Selection Tool

Question 11: How to design a selection tool that can perform a Multi-Criteria Analysis for initial concept selection?

The input of the concept selection tool consists of several parts. First, all concepts generated in a brainstorm session have to be implemented. This is called the brainstorm database. This information will be used automatically by the macro implemented in the sheet. Secondly, a reference project has to be stated, day rates of ships and their corresponding mobilization costs have to be inserted. Lastly, concepts have to be scored in the MCA itself and the weight factors have to be adjusted. When all this is done, carefully following the instruction sheet, the selection process can start.

In the technical part the concepts are scored by replacing a 'Yes' with a value of *1.0* and a 'No' with a value of *0*. These values are multiplied by their weight factors and added up together, resulting in a final score expressed in percentage. If a weight factor is equal to *1.0*, this means that criterion is mandatory for a concept to pass selection. So if a concept scores a 'No' on certain criteria that are weighted with a factor of *1.0*, it will be discarded from further selection as mentioned earlier.

For the economical part, a total hiring cost for the used vessels is calculated based on the day rate and mobilization cost. Added to this are the estimated initial investment costs, which results in the gross total costs for every concept for a specified project.

Because day rates and mobilization costs are confidential information for Boskalis, only a lower and higher bound per vessel type is provided. Based on this range, an average day rate and mobilization cost are calculated per vessel type. With the input of a reference project, these values can be converted to total predicted cost. But these variable costs are not the only important economic parameters that need to be taken into account. Also, investment and risk are important to consider. To do so, the initial investment per concept is divided into five parts. For each concept the initial investment is estimated, ranging from under 500 thousand euros up to 10 million euros.

5.6. Final Selection

All concepts generated in the brainstorm sessions are scored on all technical and economical criteria mentioned in Section 5.2. This results in a total score in percentage, an estimated investment, and an estimated total cost per project. Based on these three factors, a shortlist is created and sorted on the total cost per project. This shortlist can be seen in Figure 5.2.

Concept Code	Category	Vessel Type	Estimated Investment [1: Low - 5: High]	Concept Name	Estimated Investment	Total Cost per Project	Total Score (%)
OS02E-2	Floating	Anchor Handling Tug Small	2	Curtains rail	€ 1,000,000	€ 213,000	97%
NT03AM-2	Floating	Anchor Handling Tug Small	2	Curtains rail	€ 1,000,000	€ 213,000	97%
RD03MBJ-3	Floating	Multiple	2	Combine big and small	€ 1,000,000	€ 1,213,000	97%
B01-1	Floating	Multiple	2	Cargo Ship + DP Ship + Barge	€ 1,000,000	€ 1,213,000	97%
B01-2	Floating	Multiple	3	TSDH + DP Ship + Barge	€ 2,500,000	€ 1,213,000	97%
RD01L-1	Floating	Fallpipe	3	Rock dumper	€ 2,500,000	€ 1,218,000	92%
RD02L-2	Floating	Fallpipe	3	Moonpool cable lay	€ 2,500,000	€ 1,218,000	92%
RD02L-1	Floating	Heavy Transport	2	Barges + Semi Sub	€ 1,000,000	€ 1,405,000	97%
OS01W-3	Floating	Heavy Transport	2	Semi sub power	€ 1,000,000	€ 1,405,000	92%

Figure 5.2: MCA Selection Short List

5.6.1. Short list

Hence, after performing an MCA, only nine concepts are left for further evaluation. Here, these concepts are analyzed step-by-step to see which concept is most suitable for further development.

Cable Pulling

The cable pulling concept represents a pulling operation over a very large distance, from shore to substation. This concept scores very high on a technical point of view, but also has a low estimated cost per project and investment. Despite its high scores, a pulling operation might not be feasible due to an operation over a large distance close to the sea surface, hindering other marine traffic. There might be a solution to pull the cable several meters under the sea surface. Despite this, during a pulling operation over a large distance cable handling limits are very likely to be exceeded. Therefore, the concept of pulling a cable from shore to substation is discarded for further technical conceptualization.

Combining Multiple Vessels

Combining multiple vessels might also be an option. For cable laying over a long distance, a relatively cheap ship like a cargo ship or Trailer Suction Hopper Dredger (TSHD) can be used. The nearshore part can be done by barges, which can operate easily in shallow water conditions. The second end pull-in can be done by a more expensive DP vessel, like an anchor handling tug. Combined, these three vessels can execute the whole export power cable installation process. This is already applied in the offshore industry and does not require an innovative, new technical design. Therefore, the concept of combining multiple vessels is discarded for further technical conceptualization.

Cable Lay with Rock Dumping Equipment

One of the main advantages of this concept is that the cable is protected from direct hydrodynamic loads because it is protected by the fall pipe of the rock dumping vessel. Also, applying cable laying on a rock dumping vessels ensures a high load-carrying capacity. The main disadvantage is that rock dumping equipment is very large and high above the deck, which makes deck space very limited and not suitable to apply other equipment. A possibility can be to change the deck lay-out from rock dumping to cable laying.

Barges on Semi Submersible Vessel
Barges are very suitable for near-shore conditions because they have a limited draught. Also, multiple barges can be combined increasing the cable length that can be transported. A solution has to be figured out to store a cable over multiple carousels without cutting the cable. Putting multiple barges on a heavy transport vessel makes cable laying over large distances possible. Boskalis already looked into this concept some years ago. This was not further developed due to high expected costs. Therefore, the concept of putting barges on a semi-submersible vessel is discarded for further technical conceptualization.

Cable Laying through a Moonpool
Cable lay through a moonpool seems to be a competitive alternative for offshore export cable installation. The deck-layout can be kept fairly similar to that of a CLV where the cable goes over a chute at the aft of the vessel. An interesting point to look at will be the second end pull-in operation. Normally, this is done by creating a large cable length on deck and then lowering a quadrant while the cable is being pulled into the OSS. A solution for the second end pull-in via a moonpool has not yet been developed.

5.6.2. Final Concept Choice

After analyzing all ideas on the shortlist, which was created after an extensive MCA, cable laying via a moonpool came out as a most promising idea with an average score of 92%, an estimated investment of €2.500.000,- and project cost for the reference project of €1.218.000,-. This concept potentially satisfies all crucial criteria. It involves already existing vessels, i.e. a Boskalis rock dumping vessel, which has a high load-carrying capacity with at least DP-2 class. The deck layout can be designed in such a way that it is suitable for both AC and DC export cable installation. The only downside is that it cannot beach and is not operable in nearshore conditions, due to its hull shape and relatively large draught. Despite this, the shore landing can still be facilitated by a floating pull-in operation. This is already applied extensively in the industry for distances smaller than two kilometers. There are risks and uncertainties to this concept but they can all be potentially mitigated. This makes moonpool cable-laying a technically feasible concept. Since offshore export power cable laying via a moonpool is not yet done in the offshore industry, it is also a very innovative concept. This can be a risk but might also be a unique selling point in the tendering process which may lead to a competitive advantage.

Besides scoring high in the MCA, cable laying via a moonpool might bring other advantages for Boskalis. The cable will go through a hole in the vessels' hull, close to the CoG. Therefore, the arm towards the point where the cable leaves the vessel is smaller than conventional cable laying over a chute at the aft of the vessel. This is expected to lead to smaller motions of the cable, which leads to fewer forces in the cable resulting in a potential increase in workability. Also, vessels are more and more employed as multi-purpose vessels. A fall pipe vessel with a moonpool can be suitable for offshore export cable laying via a moonpool as well. This requires clever deck lay-out design, taking into account, for example, the placement of the deck reinforcements for heavy equipment. Also, the equipment can be made modular to guarantee easy conversion from rock dumping vessel towards cable lay vessel and the other way around.

The main challenge regarding this concept will be the second end pull-in. There is no current solution to execute a regular pull-in through a moonpool due to limited space. Therefore, a clever solution has to be developed. Several options for this challenge will be presented and discussed in Section 6.4.

The expectations regarding the final concept are summarized here:

- **Main technical challenge**: second end pull-in (*discussed in Chapter 6*)
- **Main technical advantage**: cable leaves the vessel close to CoG, expected to result in lower cable loads (*discussed in Chapter 7*) and higher workability
- **Main competitive advantage**: a multi-purpose vessel potentially create competitive advantage due to flexible employability of fleet (*discussed in Chapter 8*)

In Chapter 6, a suitable vessel for the selected concept is introduced.

6 Technical Design

6.1. Vessel

The concept selected in Chapter 5 is based on cable laying through a moonpool, situated near the CoG of the vessel. For this concept, only ships with a moonpool can be selected. Within Boskalis several vessels have a moonpool through the deck. Most of these ships are operative as fall pipe or rock dumping vessels. Two examples of fall pipe vessels are the Rockpiper and the Seahorse. Another possibility can be the conversion of a vessel by installing a moonpool. Within Boskalis, the department Central Fleet Support (CFS) is constantly looking at how to change the purpose of the Boskalis fleet and how the vessels can be converted. In a meeting with CFS, one project that is currently being investigated is the conversion of the Fjell. The Fjell is a Dockwise semi-submersible heavy transport vessel, with large deck space and a high load-carrying capacity because of its current function. CFS is looking into the possibility to convert the Fjell into a rock dumping vessel. For this, a moonpool has to be made through the vessels' hull and the deck layout has to be adjusted for rock dumping purposes.
As mentioned in Chapter 3, both existing and newly built vessels are more and more deployed as multipurpose vessels these days. Therefore, it can be beneficial to not only investigate the possibility to convert the Fjell into a rock dumping vessel but into a multipurpose vessel instead. For this particular reason, the Fjell is chosen as a vessel on which the new cable lay system will be focused. In Figure 6.1 and 6.2 a schematic overview of the Fjell is displayed.

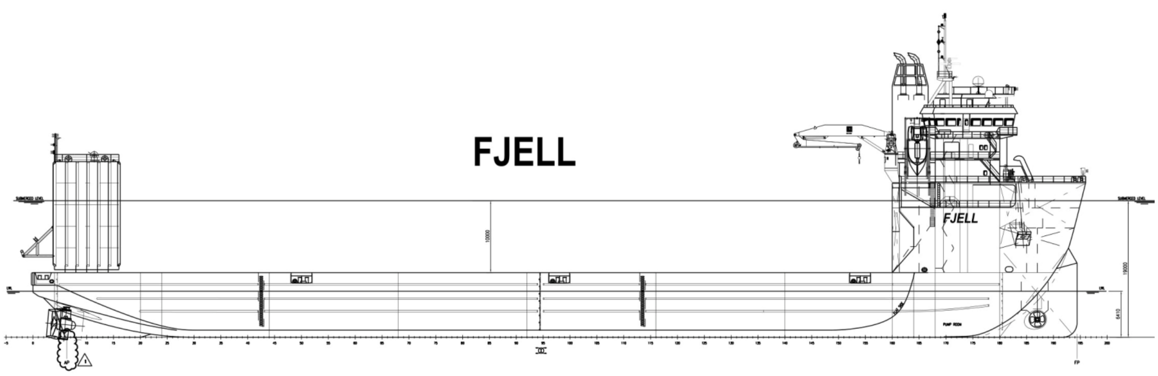


Figure 6.1: Side view heavy transport vessel Fjell

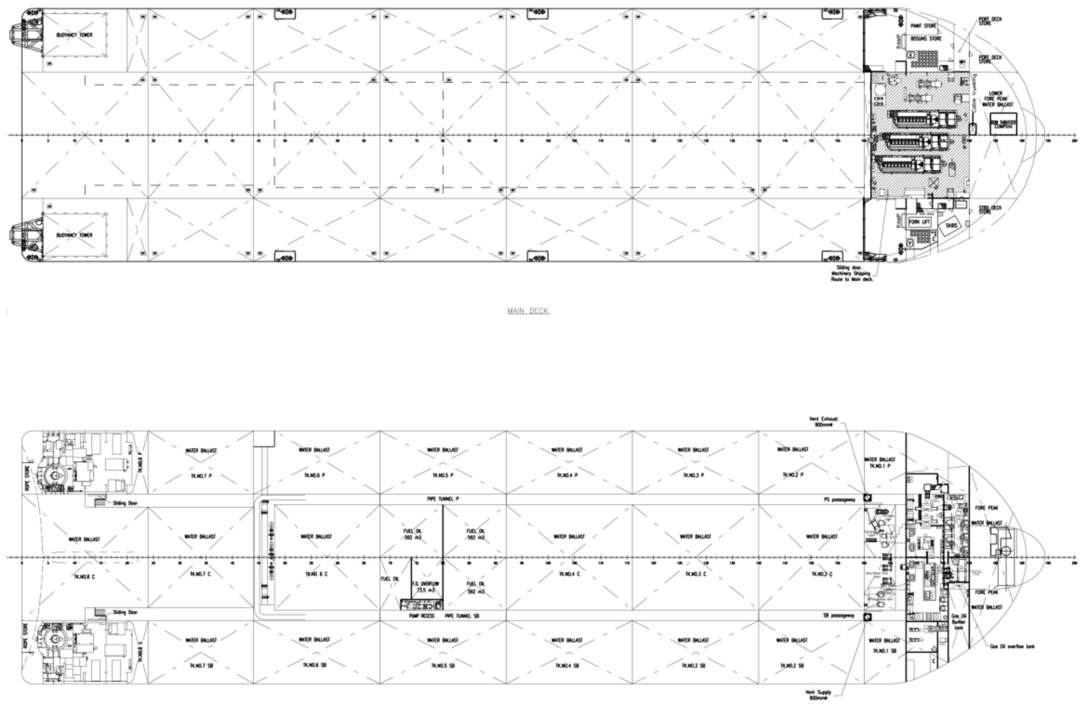


Figure 6.2: Top view heavy transport vessel Fjell

6.2. Equipment

Question 12: What are the main components necessary to lay cable with the selected concept?

For offshore export cable installation, several components are necessary on deck. For cable laying only, leaving out the shore landing and the second end pull-in, first, a storing device for the cable has to be designed. This is often a static drum or carousel. Secondly, a guiding frame for the cable is needed to guide the cable from the carousel to the tensioners. A tensioner has to hold the cable in place, slowly moving it over the ship. At the point where the cable leaves the vessel, often a chute is applied to ensure that the maximum allowed curvature is not exceeded.

6.2.1. Carousel

The Fjell has a range of draughts between which it can operate. Taking into account the stability criteria, which will be further explained in Chapter 7, the maximum load that can be balanced by ballasting the vessel is 10.000 tonnes. This 10.000 tonnes load represents the carousel and cable combined. A rule of thumb for carousel dimensions is used to estimate the weight of the carousel within Boskalis. This rule of thumb states that the carousel weighs approximately 10% of the cable load it holds. So for 10.000 tonnes combined load, the weight distribution is 9.000 tonnes of cable and a 1.000 tonnes carousel.

In Table 6.2 an overview of the dimensions of the carousel for different cable types can be seen. The cable types presented in Table 6.2 are export power cables of recently acquired projects. All cables have a specific diameter, weight in air, and stacking height specified by the cable manufacturer. With a load factor (LF) of 1.05, an admissible stacking height of 30 layers, an outer diameter of the carousel that is limited to the ships width at 32 meters, a minimum bending radius on the carousel of 2.9 meters, and a cable load of 9.000 tonnes the carousel height can be calculated using Equation 6.1. This is done for different inner diameters of the carousel, taking into account the MBR during storing of the cable. An overview of the parameters used for carousel dimensioning can be seen in Table 6.1.

Mechanical Property	Value	Unit
MBR installation	4.9	m
MBR storing	2.9	m
Admissable stacking height	30	layers
Maximum cable Load	9000	tonnes

Table 6.1: Overview of cable parameters for carousel dimensioning [20]

After the tank height has been calculated, the load on the cable can be calculated using 6.2. The pressure on the carousel floor must not exceed the deck strength of the chosen vessel, which can be checked using Equation 6.3. An overview of the carousel dimensions can be seen in Table 6.2. The bold numbers represent the limiting design factor per cable type. For the copper cables, this is the load-carrying capacity of the chosen vessel. For the aluminum cables, this is or the load-carrying capacity of the chosen vessel or the stacking height, depending on the chosen inner diameter of the carousel. In Figure 6.3, a schematic overview of a carousel including gooseneck and boom crane can be seen.

The required height of the carousel can be calculated as follows:

$$h_{\text{tank}} = \left(\frac{L_{\text{cable}} * D_{\text{cable}}}{\frac{D_{\text{o}}-D_{\text{i}}}{2} * \pi * \frac{D_{\text{o}}+D_{\text{i}}}{2}} \right) * \frac{D_{\text{cable}}}{LF} \qquad [m] \tag{6.1}$$

The load on the cable is equal to:

$$F_{\text{cable}} = \frac{h_{\text{tank}}}{D_{\text{cable}}} * M_{\text{cable}} * g \qquad [\frac{kN}{m}] \tag{6.2}$$

The pressure on the carousel floor can be calculated as follows:

$$p_{\text{deck}} = \frac{M_{\text{cable\_tot}}}{\frac{\pi}{4} * ({D_{\text{o}}}^2 - {D_{\text{i}}}^2)} \qquad [\frac{tonnes}{m^2}] \tag{6.3}$$

Cable	D_{cable}	M_{cable}	D_{o_tank}	D_{i_tank}	L_{cable}	h_{tank}	M_{cable_tot}	F_{cable}	p_{deck}
NKT	*[mm]*	*[kg/m]*	*[m]*	*[m]*	*[km]*	*[m]*	*[ton]*	*[kN/m]*	*[ton/m2]*
Cu	244.0	104.0	32.0	6.0	87.0	6.36	***9048.0***	26.58	11.66
Cu	244.0	104.0	32.0	4.0	87.0	6.23	***9048.0***	26.05	11.43
Alu	245.0	86.5	32.0	6.0	105.0	7.74	***9082.5***	26.79	11.70
Alu	245.0	86.5	32.0	10.0	105.0	***7.80***	8563.5	27.01	11.80

Table 6.2: Carousel Dimensions (Aluminium and Copper export power cables) [20]

6.2.2. Goose neck and Tensioner

To guide the cable from the carousel a gooseneck, or lay tower has to be installed. The gooseneck transports the cable from the carousel to the tensioners, which are normally installed on deck in the horizontal direction. For cable laying via a moonpool, these tensioners have to be installed vertically because the cable leaves the vessel through the moonpool in the vertical direction. Therefore, the tensioners have to be integrated into the gooseneck. An example of this can be seen in Figure 6.4, where a gooseneck is developed for vertical cable lay over the side of a vessel.

Vertical cable lay requires a larger height of the gooseneck. This has an advantage that there will be a larger buffer between the tensioner and the carousel, due to the catenary shape of

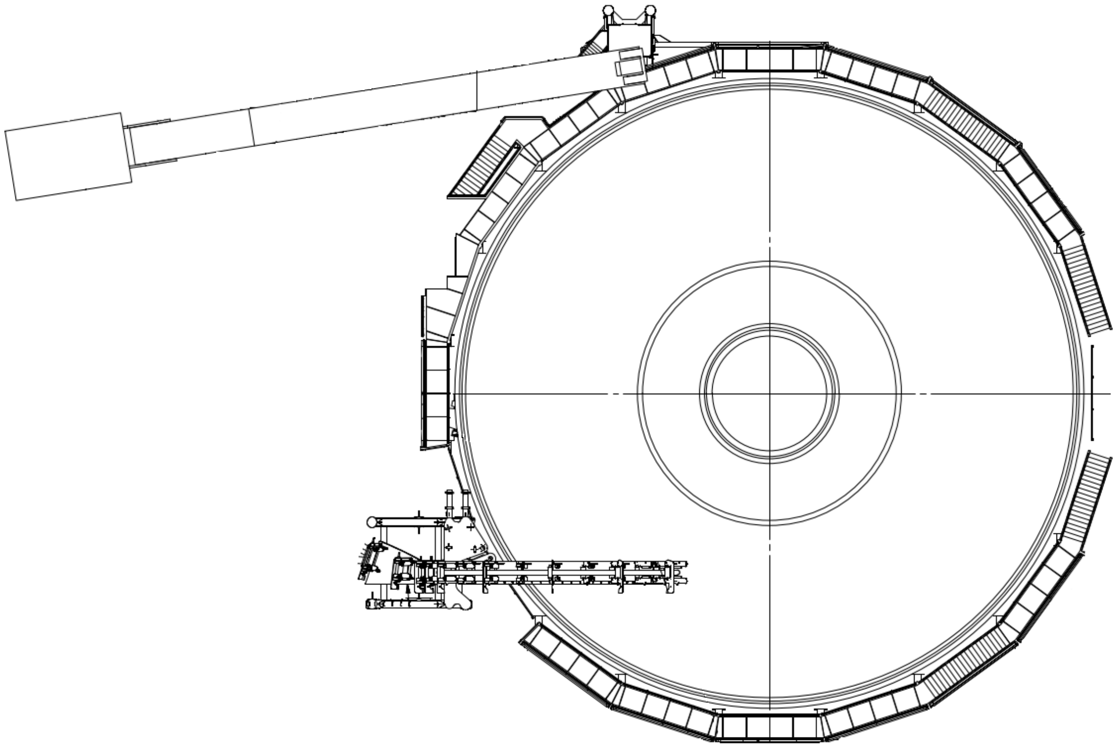


Figure 6.3: Top view of Carousel, goose neck and crane

the hanging cable. This buffer makes sure that if the carousel stops moving and the tensioners keep pulling, a certain amount of cable can be consumed first before overstretching it. Also, if the tensioner stops moving and the carousel keeps rolling off the cable, the catenary shape will change accordingly. This assures cable integrity by not immediately over-bending the cable. A second buffer is present between the vessel and the seabed. This allows the vessel to keep on moving while not rolling off the cable or vice versa. Besides acting as a buffer, a high gooseneck is needed to manually install the cable protection system for the second end pull-in. Several platforms have to be attached to the lay tower to make CPS installation possible. These modifications to the lay tower make it more vulnerable to wind loading, heavier on deck and more dangerous to workers than horizontal on deck CPS installation. Therefore, another option can be post-installing the cable protection system. With this method, the CPS installation does not happen on deck but on the seabed. Post installing a cable protection system is more time-consuming, but since the second end pull-in operation only has to happen once per export cable, this method is favorable over elongating the lay tower design.

An deck-layout including all equipment mentioned above can be seen in Figure 6.5.

6.3. Challenges

Question 13: What are the main technical challenges regarding the selected concept?

6.3.1. Cable Bending

When the fixation point is high above deck or when the cable goes through the moonpool close to its side, the cable is likely to touch the side of the moonpool when exiting the vessel, resulting in over bending. A normal CLV has the same issue during cable installation at the aft of the ship. Therefore, the cable is guided over a chute to ensure maximum curvature is not exceeded. To prevent this from happening at the moonpool, the fixation point must be close to the deck and a chute can be installed where the cable leaves the vessel. Although

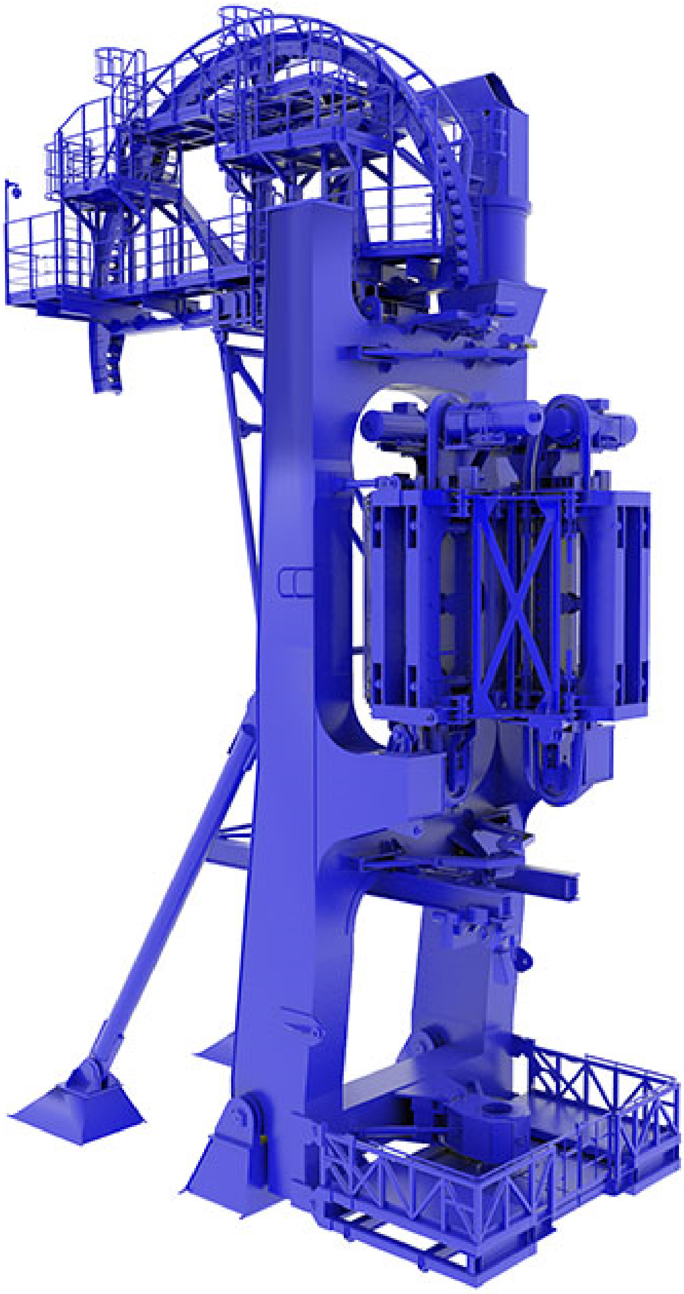


Figure 6.4: 3D overview of Goose Neck including vertical tensioners [18]

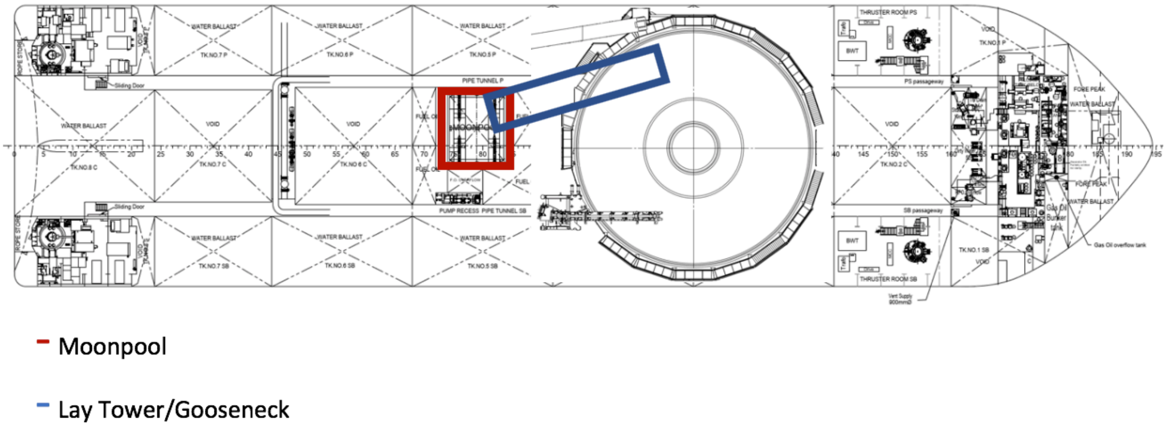


Figure 6.5: Deck-layout for moonpool cable lay system

this solves the bending restriction, it is not convenient to install a chute there because of its bad accessibility, installation before the operation, and removal after the operation.

6.3.2. Second end pull-in

The second end pull-in on a CLV is done over the aft of the ship, sliding a quadrant along the deck and over the chute. A crane is used to lower the quadrant, while the cable is being pulled into the substations J-tube. A quadrant has a c-shape with a diameter of minimum two times the MBR of the export cable. This means that the size of a quadrant for the cables mentioned in Table 6.2 has to be at least 10 meters in diameter. With the demand for offshore wind energy growing, the capacity of newly installed OWF's increases. To transport the produced electricity to land, cables have to grow with increasing OWF capacity as well. A moonpool in a ship can be designed accordingly but is often limited to a rectangle shape with a long edge of fewer than 10 meters wide. Therefore, another clever solution for the second end pull-in through a moonpool has to be developed.

6.4. Solutions

Question 14: What are possible solutions for these main technical challenges?

6.4.1. Bend Restrictors

An alternative to a moonpool chute is attaching a bend restrictor (BR) to the vessel through which the cable can be laid. Bend restrictors are used to protect cables or pipelines from over bending during installation. A BR is a chain of beads that link into each other and together cannot exceed a certain curvature. An in-house developed variant of a BR is already used by Boskalis, i.e. the sea proof Cable Protection System (CPS) design for Horns Rev 3. Applying a bend restrictor removes the necessity of a chute near the exit of the moonpool. An example of a bend restrictor that Boskalis will use for Triton Knoll OWF, can be seen in Figure 6.6.

6.4.2. Second end pull-in

For the second end pull-in, three different options are developed. Two solutions are based on the use of a deployment quadrant. The other solution is based on wet storing and the laydown principle.

Deployment Quadrant

The power cable is placed over a deployment quadrant. The quadrant is supported by a boom crane installed on the vessel. Other support options are an A-frame or winch that is installed on the deck of the vessel. The quadrant is slid over the deck and lowered into the water by a crane while the cable is being pulled in towards the OSS at the same time. This operation can be seen in Figure 6.7. When arriving at the seabed, the quadrant is laid

Figure 6.6: Example of a bend restrictor [26]

down and tilted to release the power cable on the seabed. This operation must be monitored closely, to prevent the cable from coiling on the seabed. Cable lowering speed and pull-in speed must be adjusted while keeping the vessel in place.

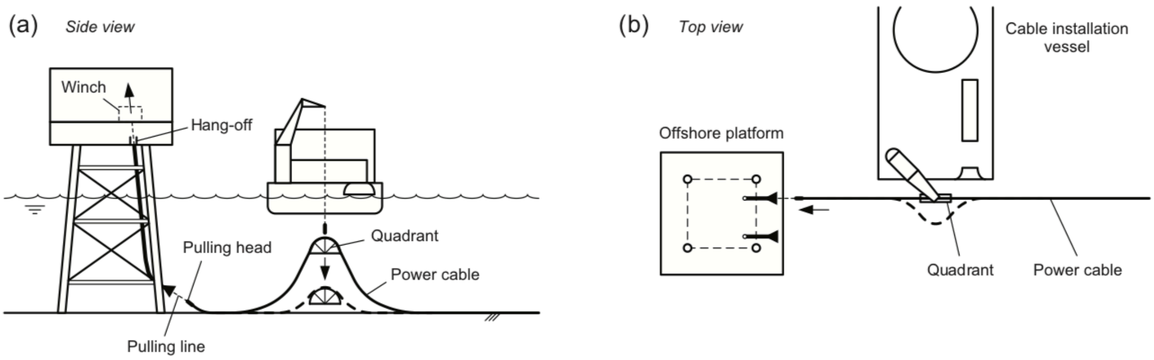


Figure 6.7: Deployment quadrant second end pull-in [7]

Vessel Side

The first option is to lower the cable to the seabed out of the moonpool. After wet storing it on the seabed it can be picked up and pulled over a quadrant hanging on a boom crane on the side of the vessel. When the CPS is installed, the pulling operation can commence by inserting the pull-in wire into the J-tube of the OSS. The operation is further proceeded as a conventional pull-in operation, explained in Figure 6.7. This solution is already sparsely used in the offshore industry because vessel motions are less compared to a pull-in over the aft of a vessel.

Moonpool

A more technically challenging option is a pull-in operation through the moonpool. For this, the cable is pulled over a deployment quadrant hanging next to the guiding frame of the lay tower. This quadrant is guided through the moonpool diagonally, using a guiding frame installed in the moonpool corners. To prevent the cable from bending, a bend restrictor is attached to the vessel through which the cable is laid. This solution has been explained in Section 6.4.1. From here, the pull-in operation is proceeded according to the method explained in Figure 6.7. Important is to keep the vessel steady during the second end pull-in operation.

Bight lay down

It is important to survey the area to map the laydown area. This area should be free of boulders, cobbles or other obstacles that may harm the cables integrity during the pull-in operation. Also, soil friction must be within the acceptable range for cable pulling over the seabed. Before cable installation, the second cable end is wet stored on the seabed in the form of an S-shaped or Ω-shaped bight. To make pulling into the OSS possible, a pulling line is attached to the cable. During the pull-in operation, cable handling limits should be monitored closely to ensure cable integrity after installation. An overview of this operation can be seen in Figure 6.8.

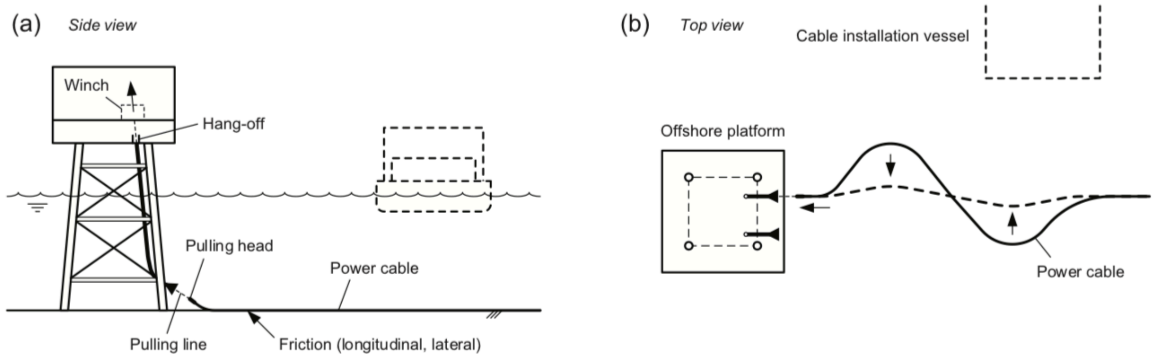


Figure 6.8: Bight lay down second end pull-in [7]

6.4.3. Technical Readiness

Regarding the technical challenges, for both the second end pull-in and cable bending already existing solutions are suggested. Bend restrictors are already used in other applications, for example in the CPS. Here, bend restrictors replace the necessity of a chute at the moonpool bottom. For the second end pull-in, using bight lay down was a frequently applied technique before it has been replaced by the use of a deployment quadrant. This was mainly done to decrease installation time for infield cable installation. Also, curvature in the cable during pull-in can be controlled more easily using a quadrant. Hence, in both categories, most proposed solutions are already field-proven so technical readiness for offshore export power cable installation via a moonpool is already feasible by only combining existing technology that is being applied for other purposes at the moment.

7 Technical Analysis

7.1. Reference Project

To say something about real-life cable properties, cable handling limits, project duration, water depth, and hydrodynamic conditions, a reference project has to be chosen. This reference project is already introduced for the initial concept selection in Chapter 5. Here, more details on this reference project are presented, which will be used in the technical and economic analysis.

7.1.1. Mechanical Cable Properties

For Orcaflex simulations and for dimensioning the carousel and quadrant, cable properties like the outer diameter and weight (in air/in water) must be known. In Table 7.1, the mechanical properties of the reference export cables are displayed.

Mechanical Property	Value	Unit
Outer Diameter	244	mm
Cable Weight in Air	104	kg/m
Cable Weight in Sea Water	71	kg/m
Total Cable Length	270	km
Bending Stiffness	13	kN*m^2
Axial Stiffness	474	MN
Torsional Stiffness	1146	kN*m^2

Table 7.1: Mechanical Properties Reference Offshore Export Power Cables [20]

7.1.2. Electrical Properties

For this project, alternating current is chosen to be transported by three copper conductors. The regarded grid frequency is 50 Hz and the nominal voltage between phases U_N is 220 kV. In Table 7.2, these electrical properties are displayed.

Electrical Property	Value	Unit
Conductor Type	Copper	-
Current Type	AC	-
Grid frequency	50	Hz
Nominal voltage	220	kV

Table 7.2: Electrical Properties Reference Project

7.1.3. Cable Handling Limits

To quantify cable limitations, cable handling limits based on the export power cables which will be used in the reference project are displayed in Table 7.3. These cable limitations and their importance have already been explained in Section 2.3.

Cable Handling Limit	Value	Unit
Maximum allowable axial compression	33.8	kN
Maximum allowable tension	215.0	kN
Minimum Bending Radius during installation	4.9	m
Minimum Bending Radius during storing	2.9	m
Maximum allowable crush load	33.8	kN
Admissible Sidewall-Pressure	50.0	kN/m

Table 7.3: Cable Handling Limits Reference Offshore Export Power Cables [20]

7.1.4. Hydrodynamic Parameters

Hydrodynamic parameters can be divided into wind, waves, and current. Wave loading is most important here because significant wave height is the limiting factor for workability.

Wave

At this moment, project-specific wave parameters like significant wave heights, peak periods and wave directions and spreading are obtained from hind-cast metocean data. For the North Sea area, a Joint North Sea Wave Project (JONSWAP) spectrum is often used. However, because this project is focusing on worldwide offshore export power cable installation with a reference project in the Baltic Sea, a more generic Pierson Moskowitz (PM) spectrum is used. The PM spectrum is an empirical relationship that describes the distribution of energy within a fully developed sea. It is equal to a JONSWAP spectrum with a peak enhancement factor (γ) equal to 1. It assumes constant wind for a long time over a large area, resulting in an equilibrium between waves and wind. The PM spectrum is normally defined by wind speed U [m/s]. The spectrum can also be defined by zero-crossing wave period T_z [s] and the significant wave height H_s [m] as can be seen in Equation 7.1. The spectrum is dependent on the wave frequency ω [2π/s].

$$S_{PM}(\omega) = 4\pi^3 \frac{H_s^2}{T_z^4} \cdot \frac{1}{\omega^5} exp\left[-\frac{16\pi^3}{T_z^4} \cdot \frac{1}{\omega^4}\right] \quad (7.1)$$

$$T_p = \left(\frac{5\pi}{4} {T_z}^4\right)^{\frac{1}{4}} \quad (7.2)$$

In Equation 7.3 and 7.4 the dimension linear scaling factor of wave energy alpha is calculated using zero-crossing wave period and peak wave period respectively.

$$\alpha = \frac{4\pi^3}{g^2} \frac{H_s^2}{T_z^4} \quad (7.3)$$

$$\alpha = \frac{5\pi^4}{g^2} \frac{H_s^2}{T_p^4} \quad (7.4)$$

Regarding the vessel, zero forward speed is used. This is mainly done for faster calculation purposes.

Wind and Current

Because the reference project is situated in the Baltic Sea, hydrodynamic current is not of large influence because it is relatively small at the project site (< 0.1 m/s). Besides that, the current is often not taken into account in the dynamic analysis because it is assumed that current dampens the vessel motions and cables oscillations in most cases. However, when current and waves act in the same direction this is not the case. Hence, not taking into account the current in most cases acts as a safety factor, making the model more conservative with respect to cable loads. Wind, on the other hand, becomes dominant on tall structures on deck, with a large exposed area. Even though these structures on deck are included in the stability criteria to calculate RAO's, they are not modeled in Orcaflex. Therefore, an added wind force will only act on the side of the vessel, which area is small compared to the area of a carousel, bridge, tower, or crane that can be loaded by a wind force. Hence, wind force is not taken into account in this analysis.

7.2. Vessel Motions Analysis (VMA)

To quantify the motions of the as-is cable installation without running large simulations which take a large amount of time, first, a vessel motion analysis (VMA) is performed. The VMA is done for the NDurance to see what the motions are in conventional cable laying over the chute of this vessel. This VMA uses ANSYS Aqwa models to calculate vessel motions. ANSYS Aqwa can calculate the effects of hydrodynamic loads like wind, wave, and currents on different offshore structures like FPSO's, TLP's, Ships, OWT's, etc. This VMA uses an in-house developed software program that uses 3D linear radiation and diffraction analysis in combination with an ANSYS Aqwa model to calculate the most probable maximum displacements, velocities and accelerations in all six degrees of freedom: surge (X), sway (Y), heave (Z), roll (Rx), pitch (Ry), yaw (Rz). Performing this VMA will also show if water depth has a large influence on vessel motions and at which peak frequencies the vessel is most sensitive to excitation. This gives insight in which parameters should be used later on in the Orcaflex quantification, which potentially saves a lot of time running less of these time-consuming Orcaflex simulations.

7.2.1. Input Parameters

For this VMA, a varying water depth between 10 and 50 meters is used. This is a frequent water depth at export cable lay projects, where the close to shore part is approximately 10 meters and most OWF's are installed up to 50 meters water depth. The water depth is varied to see if there is an effect on the vessel motions. A spreading exponent (n) of 10 is used, which means that waves in a certain direction will also result in out of plane movements because of wave spreading. This factor is used in all vessel motions analysis done at Boskalis, to represent the real-life situation more accurate because waves never come from one precise direction. Peak wave periods (Tp) are varied between 4 and 20 seconds. This is done because every vessel reacts differently on every peak wave period, and thus has a different critical peak wave period. For peak wave periods higher than 20 seconds the vessel motions will be different because the wavelength becomes very large compared to the ship. This should be taken into account in swell conditions like in the Gulf of Guinea but is less necessary for the North Sea area, Taiwan and the U.S. The analysis is designed to estimate vessel motions in mild to moderate sea states at zero forward vessel speed because linear theory is used. Linear theory means that second-order wave forces are not taken into account in this analysis. These higher-order wave forces become more dominant at higher significant wave heights. A significant wave height (Hs) equal to 1.0 is used because this linearly relates to the vessel motions, which means that the results can be scaled accordingly. The draft (T) of the vessel can be chosen at normal loading or heavy loading condition (4.2 m and 4.7 m). Because export cable laying is considered here, which implies a large load on deck, the draft is chosen at heavy loading conditions. Therefore, the draft of the vessel in this analysis is 4.7 m.

Input Parameters	Symbol	Value	Steps	Unit
Water depth	d	10 - 50	10	m
Peak enhancement factor	γ	1.0	-	-
Spreading exponent	n	10	-	-
Peak wave period	Tp	4 - 20	0.5	s
Significant wave height	Hs	1.0	-	m
Forward speed	V	0	-	m/s
Draft	T	4.7	-	m

Table 7.4: Input parameters for Vessel Motion Analysis

7.2.2. Results

The VMA for the NDurance is performed at three locations, as can be seen in Figure 7.1. These locations represent the chute at the aft of the vessel, the center of gravity and the side of the vessel. The CoG location is added to compare the movements of the other locations to the CoG of the vessel. Important to mention is that a moonpool is often positioned (in X - and Y direction) near the CoG of a vessel. By choosing an analysis location at the CoG, this location can be used as both a reference point and a fictional moonpool location. The location on the side of the vessel near the CoG is added to see if cable laying over the side of the vessel is a feasible alternative. The exact coordinates of the VMA locations are presented in Table 7.5.

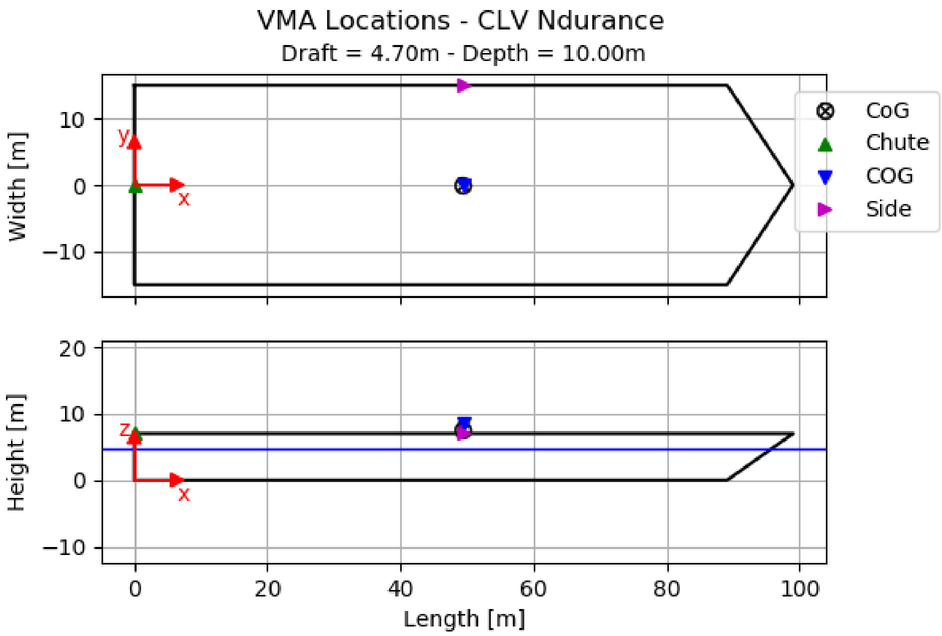


Figure 7.1: VMA Locations NDurance

Location	X	Y	Z	Unit
Chute	0	0	7.0	m
CoG	49.3	0	8.5	m
Side	49.3	-15.0	7.0	m

Table 7.5: Input parameters for Vessel Motion Analysis

Heave, roll and pitch motions are subjected to gravitational restoring forces which makes them sensitive to oscillation at a natural frequency. Surge, sway, and yaw, on the other hand, are not subjected to restoring forces and moments, which means they cannot be ex-

MPM - Heave (Z) - Displacement [m]

Tp [s] \ Directions [deg]	0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.10	0.10	0.09	0.09	0.09	0.10	0.10	0.10	0.08	0.06	0.04	0.04	0.04
4.5	0.16	0.16	0.15	0.16	0.17	0.18	0.18	0.17	0.15	0.11	0.08	0.07	0.06
5	0.23	0.22	0.23	0.25	0.28	0.29	0.28	0.26	0.24	0.18	0.13	0.10	0.10
5.5	0.30	0.30	0.32	0.36	0.40	0.40	0.38	0.37	0.34	0.28	0.20	0.14	0.13
6	0.37	0.38	0.41	0.48	0.53	0.52	0.49	0.48	0.46	0.38	0.28	0.20	0.17
6.5	0.44	0.46	0.52	0.60	0.65	0.63	0.59	0.59	0.58	0.49	0.36	0.26	0.22
7	0.52	0.54	0.62	0.71	0.75	0.72	0.68	0.69	0.68	0.59	0.45	0.33	0.28
7.5	0.59	0.62	0.71	0.81	0.85	0.81	0.76	0.77	0.78	0.69	0.54	0.40	0.35
8	0.67	0.71	0.80	0.89	0.92	0.87	0.82	0.84	0.86	0.78	0.62	0.48	0.43
8.5	0.75	0.79	0.88	0.97	0.99	0.92	0.87	0.90	0.93	0.85	0.70	0.56	0.51
9	0.83	0.86	0.95	1.03	1.04	0.97	0.91	0.95	0.98	0.92	0.78	0.64	0.59
9.5	0.90	0.93	1.01	1.08	1.08	1.00	0.95	0.99	1.03	0.97	0.85	0.72	0.67
10	0.96	1.00	1.07	1.13	1.11	1.02	0.97	1.02	1.07	1.02	0.91	0.79	0.74
11	1.07	1.10	1.15	1.19	1.15	1.06	1.01	1.06	1.12	1.10	1.01	0.92	0.88
12	1.15	1.17	1.21	1.23	1.17	1.07	1.03	1.08	1.15	1.15	1.09	1.02	0.98
15	1.25	1.26	1.26	1.24	1.16	1.07	1.03	1.08	1.17	1.21	1.20	1.17	1.16
20	1.24	1.24	1.22	1.17	1.09	1.01	0.99	1.03	1.11	1.18	1.21	1.22	1.23

MPM - Roll (Rx) - Displacement [degree]

Tp [s] \ Directions [deg]	0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.06	0.07	0.10	0.12	0.15	0.20	0.21	0.18	0.12	0.08	0.06	0.04	0.04
4.5	0.09	0.11	0.15	0.21	0.30	0.39	0.43	0.37	0.25	0.15	0.10	0.07	0.06
5	0.14	0.17	0.24	0.36	0.55	0.75	0.82	0.72	0.49	0.28	0.17	0.12	0.10
5.5	0.21	0.26	0.38	0.61	0.98	1.34	1.48	1.30	0.91	0.52	0.29	0.19	0.16
6	0.30	0.37	0.56	0.96	1.58	2.15	2.37	2.09	1.48	0.86	0.45	0.28	0.23
6.5	0.39	0.48	0.76	1.37	2.25	3.05	3.36	2.98	2.14	1.24	0.64	0.38	0.30
7	0.46	0.58	0.95	1.76	2.89	3.90	4.29	3.82	2.76	1.62	0.82	0.46	0.37
7.5	0.52	0.65	1.12	2.09	3.43	4.62	5.07	4.53	3.29	1.94	0.98	0.53	0.41
8	0.55	0.70	1.25	2.35	3.85	5.16	5.65	5.06	3.69	2.20	1.11	0.58	0.44
8.5	0.56	0.73	1.34	2.53	4.11	5.49	6.01	5.39	3.96	2.37	1.20	0.61	0.46
9	0.56	0.75	1.39	2.63	4.24	5.64	6.16	5.54	4.09	2.47	1.26	0.64	0.46
9.5	0.55	0.75	1.42	2.66	4.27	5.65	6.17	5.56	4.12	2.51	1.30	0.65	0.46
10	0.54	0.75	1.43	2.66	4.24	5.59	6.09	5.49	4.09	2.52	1.31	0.66	0.46
11	0.52	0.74	1.41	2.59	4.07	5.33	5.80	5.24	3.94	2.47	1.32	0.66	0.45
12	0.51	0.73	1.38	2.48	3.84	4.99	5.42	4.92	3.73	2.37	1.30	0.67	0.45
15	0.47	0.68	1.23	2.08	3.11	3.96	4.28	3.91	3.03	2.01	1.17	0.64	0.44
20	0.42	0.59	1.00	1.57	2.23	2.76	2.96	2.73	2.19	1.53	0.97	0.57	0.41

MPM - Pitch (Ry) - Displacement

Tp [s] \ Directions [deg]	0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.10	0.10	0.09	0.09	0.10	0.11	0.11	0.11	0.10	0.08	0.06	0.06	0.05
4.5	0.16	0.15	0.15	0.16	0.19	0.19	0.19	0.19	0.17	0.14	0.11	0.10	0.09
5	0.22	0.22	0.23	0.27	0.30	0.31	0.29	0.28	0.28	0.23	0.18	0.15	0.14
5.5	0.29	0.30	0.33	0.39	0.44	0.43	0.39	0.39	0.39	0.34	0.27	0.21	0.20
6	0.36	0.38	0.44	0.53	0.59	0.56	0.50	0.50	0.52	0.47	0.37	0.29	0.26
6.5	0.44	0.47	0.55	0.67	0.73	0.68	0.60	0.61	0.64	0.59	0.47	0.37	0.33
7	0.52	0.56	0.67	0.81	0.86	0.79	0.68	0.69	0.75	0.71	0.59	0.47	0.42
7.5	0.61	0.66	0.78	0.93	0.97	0.87	0.75	0.77	0.84	0.82	0.70	0.57	0.51
8	0.70	0.76	0.89	1.03	1.06	0.94	0.79	0.82	0.92	0.92	0.80	0.67	0.62
8.5	0.80	0.86	0.99	1.12	1.13	0.99	0.83	0.86	0.99	1.00	0.89	0.77	0.72
9	0.90	0.95	1.08	1.20	1.19	1.02	0.85	0.89	1.04	1.07	0.98	0.87	0.82
9.5	0.99	1.04	1.16	1.26	1.23	1.05	0.86	0.92	1.08	1.13	1.06	0.96	0.91
10	1.08	1.13	1.23	1.31	1.26	1.06	0.87	0.93	1.11	1.18	1.13	1.04	1.00
11	1.23	1.26	1.34	1.38	1.29	1.06	0.87	0.94	1.14	1.25	1.24	1.18	1.15
12	1.33	1.36	1.41	1.42	1.29	1.05	0.85	0.93	1.16	1.29	1.31	1.28	1.26
15	1.47	1.47	1.46	1.39	1.21	0.95	0.76	0.86	1.11	1.30	1.38	1.40	1.40
20	1.41	1.40	1.34	1.22	1.02	0.76	0.61	0.72	0.96	1.16	1.29	1.35	1.37

(a) 10 m water depth

MPM - Heave (Z) - Displacement [m]

Tp [s] \ Directions [deg]	0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.14	0.14	0.13	0.12	0.13	0.13	0.13	0.12	0.10	0.08	0.06	0.05	0.05
4.5	0.23	0.23	0.23	0.23	0.25	0.25	0.24	0.23	0.21	0.16	0.12	0.10	0.09
5	0.34	0.34	0.35	0.38	0.40	0.39	0.37	0.36	0.34	0.28	0.21	0.16	0.15
5.5	0.46	0.46	0.49	0.54	0.56	0.54	0.51	0.51	0.49	0.42	0.32	0.24	0.22
6	0.58	0.59	0.63	0.68	0.71	0.67	0.63	0.64	0.63	0.56	0.44	0.35	0.31
6.5	0.69	0.71	0.76	0.81	0.83	0.78	0.73	0.75	0.76	0.68	0.56	0.46	0.42
7	0.80	0.82	0.87	0.92	0.92	0.86	0.81	0.83	0.85	0.79	0.67	0.57	0.53
7.5	0.89	0.91	0.96	1.00	0.98	0.91	0.87	0.90	0.92	0.88	0.77	0.67	0.64
8	0.97	0.99	1.03	1.05	1.03	0.95	0.91	0.94	0.98	0.94	0.85	0.77	0.74
8.5	1.03	1.05	1.08	1.10	1.06	0.98	0.94	0.97	1.01	0.99	0.92	0.85	0.82
9	1.08	1.10	1.12	1.12	1.08	1.00	0.95	0.99	1.04	1.03	0.98	0.92	0.89
9.5	1.12	1.13	1.15	1.14	1.09	1.01	0.97	1.00	1.06	1.06	1.02	0.97	0.95
10	1.15	1.16	1.16	1.15	1.10	1.02	0.98	1.01	1.07	1.08	1.05	1.02	1.00
11	1.18	1.19	1.18	1.16	1.10	1.02	0.98	1.02	1.08	1.10	1.10	1.08	1.07
12	1.20	1.19	1.18	1.15	1.09	1.02	0.98	1.02	1.08	1.11	1.12	1.11	1.11
15	1.16	1.16	1.14	1.10	1.04	0.98	0.96	0.98	1.04	1.08	1.11	1.12	1.12
20	1.08	1.07	1.05	1.02	0.97	0.94	0.92	0.94	0.97	1.01	1.04	1.06	1.06

MPM - Roll (Rx) - Displacement [degree]

Tp [s] \ Directions [deg]	0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.06	0.08	0.10	0.12	0.14	0.15	0.16	0.13	0.10	0.08	0.06	0.05	0.04
4.5	0.09	0.12	0.16	0.21	0.27	0.33	0.35	0.31	0.22	0.15	0.11	0.08	0.07
5	0.14	0.18	0.26	0.38	0.56	0.72	0.78	0.69	0.50	0.32	0.20	0.13	0.11
5.5	0.20	0.27	0.43	0.71	1.07	1.38	1.50	1.35	1.00	0.63	0.36	0.21	0.16
6	0.27	0.38	0.66	1.13	1.71	2.21	2.40	2.17	1.63	1.03	0.57	0.31	0.22
6.5	0.34	0.49	0.90	1.56	2.35	3.02	3.27	2.97	2.26	1.45	0.80	0.42	0.28
7	0.40	0.59	1.11	1.93	2.90	3.70	4.00	3.64	2.79	1.81	1.00	0.51	0.34
7.5	0.45	0.68	1.28	2.21	3.31	4.21	4.54	4.14	3.19	2.08	1.17	0.59	0.38
8	0.48	0.74	1.39	2.39	3.55	4.50	4.85	4.43	3.44	2.26	1.28	0.65	0.42
8.5	0.51	0.77	1.45	2.47	3.64	4.59	4.94	4.52	3.53	2.34	1.34	0.69	0.45
9	0.52	0.79	1.46	2.47	3.62	4.55	4.89	4.48	3.51	2.35	1.37	0.72	0.46
9.5	0.52	0.79	1.46	2.43	3.54	4.44	4.76	4.38	3.44	2.32	1.36	0.72	0.47
10	0.52	0.78	1.43	2.37	3.43	4.29	4.61	4.24	3.34	2.27	1.35	0.72	0.48
11	0.51	0.76	1.36	2.22	3.18	3.96	4.24	3.91	3.10	2.13	1.29	0.71	0.48
12	0.49	0.72	1.27	2.05	2.91	3.60	3.85	3.56	2.84	1.98	1.21	0.68	0.46
15	0.42	0.60	1.02	1.58	2.19	2.68	2.86	2.65	2.15	1.54	0.98	0.58	0.41
20	0.32	0.44	0.72	1.07	1.45	1.74	1.84	1.72	1.42	1.05	0.70	0.43	0.31

MPM - Pitch (Ry) - Displace

Tp [s] \ Directions [deg]	0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.14	0.13	0.13	0.12	0.13	0.14	0.13	0.13	0.12	0.10	0.09	0.08	0.08
4.5	0.23	0.23	0.23	0.25	0.27	0.27	0.25	0.24	0.24	0.21	0.17	0.15	0.14
5	0.34	0.34	0.36	0.41	0.45	0.42	0.38	0.38	0.39	0.35	0.29	0.24	0.23
5.5	0.46	0.47	0.52	0.59	0.63	0.58	0.51	0.52	0.55	0.52	0.44	0.36	0.34
6	0.58	0.61	0.68	0.77	0.80	0.72	0.62	0.64	0.70	0.68	0.59	0.50	0.47
6.5	0.72	0.75	0.83	0.92	0.93	0.83	0.70	0.73	0.82	0.82	0.74	0.65	0.61
7	0.84	0.88	0.96	1.04	1.03	0.89	0.75	0.79	0.91	0.94	0.87	0.79	0.75
7.5	0.96	0.99	1.07	1.13	1.09	0.93	0.78	0.83	0.97	1.03	0.98	0.91	0.88
8	1.06	1.09	1.15	1.19	1.12	0.94	0.78	0.85	1.01	1.09	1.07	1.02	0.99
8.5	1.14	1.16	1.21	1.22	1.14	0.94	0.78	0.85	1.03	1.13	1.14	1.10	1.08
9	1.20	1.22	1.25	1.24	1.14	0.93	0.77	0.84	1.04	1.16	1.18	1.16	1.14
9.5	1.25	1.26	1.27	1.25	1.13	0.91	0.75	0.83	1.04	1.17	1.21	1.20	1.19
10	1.27	1.28	1.28	1.24	1.11	0.89	0.73	0.82	1.03	1.17	1.23	1.23	1.23
11	1.30	1.30	1.28	1.21	1.06	0.83	0.68	0.77	0.99	1.15	1.23	1.26	1.26
12	1.29	1.28	1.25	1.16	1.00	0.78	0.63	0.73	0.95	1.12	1.21	1.25	1.26
15	1.18	1.16	1.10	1.00	0.83	0.63	0.50	0.60	0.80	0.97	1.08	1.14	1.16
20	0.95	0.93	0.87	0.76	0.62	0.45	0.36	0.44	0.60	0.75	0.86	0.92	0.94

(b) 50 m water depth

Figure 7.2: NDurance Most Probable Maximum Displacement at Chute

cited at a natural frequency. Because of this, only heave, roll, and pitch will be considered here. The analysis is done from 0 to 360 degrees, where 180 degrees represent head waves (coming from the front of the ship). Because there was a very small difference between the port side and the starboard side, the output is assumed to be symmetric in the xz-plane.

To see what effect water depth has on the vessel motions, different cases are compared to each other. When looking at the different water depths (10 to 50 meters) for heave, roll, and pitch, all critical most probable maximum displacements decrease with increasing water depth. As an example, the 10 m and 50 m cases for heave, roll, and pitch displacement are compared in Figures 7.2a and 7.2b. The red cells indicate the highest values, which are slightly larger for a water depth of 10 meters compared to the 50 m case.

The motions are highly dependent on the hull shape. For the Boskalis flat bottom hull shape CLV's like the NDurance it is known that their resistance against roll is very poor. From Figure 7.2a and 7.2b can be seen that the MPM displacements due to roll and pitch peak at a peak frequency between 8 and 10 seconds, for a 90 or 270 degrees heading. For heave and pitch, the MPM displacements are at 0 and 180 degrees wave directions at a peak frequency higher than 12 seconds. So in general roll motions are dominant in waves from the side, where vessel motions due to heave and pitch are dominant in head waves. For significant wave heights lower than 6 meters, these conditions are assumed to be swell conditions. Also, vessel size has an impact on the vessel motions. Larger vessels (vessel length ≫ wavelength) have smaller motions because they are less influenced by short waves.

When looking at the most probable maximum accelerations for heave, roll, and pitch, these differences are less evident. For this heave and pitch, the 50 m VMA results in slightly higher accelerations. For roll, the 10 m VMA results in slightly higher accelerations. These accelerations can be compared to the Nordforsk criteria for human exposure to motions to see if humans are still able to work in these conditions. An overview of the allowable accelerations can be seen in 7.6. In this analysis, only technical limits will be assessed. Stating the technical limits of a cable lay system expresses its capabilities and makes it comparable to other cable lay systems.

MPM - Heave (Z) - Acceleration [m/s^2]

Tp [s]	Directions [deg] 0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.18	0.18	0.16	0.14	0.15	0.17	0.17	0.16	0.13	0.10	0.07	0.06	0.06
4.5	0.24	0.24	0.22	0.21	0.23	0.25	0.25	0.24	0.20	0.15	0.11	0.09	0.09
5	0.30	0.29	0.28	0.29	0.32	0.34	0.33	0.31	0.27	0.21	0.15	0.12	0.12
5.5	0.34	0.34	0.34	0.37	0.41	0.42	0.41	0.39	0.35	0.27	0.19	0.15	0.14
6	0.38	0.38	0.39	0.44	0.48	0.49	0.47	0.45	0.41	0.33	0.24	0.18	0.16
6.5	0.40	0.40	0.43	0.49	0.54	0.54	0.51	0.50	0.47	0.38	0.28	0.20	0.18
7	0.42	0.43	0.47	0.53	0.58	0.57	0.54	0.53	0.51	0.43	0.31	0.22	0.20
7.5	0.43	0.44	0.49	0.56	0.60	0.59	0.56	0.55	0.54	0.46	0.34	0.25	0.21
8	0.44	0.45	0.50	0.57	0.61	0.59	0.56	0.56	0.55	0.48	0.36	0.27	0.23
8.5	0.44	0.46	0.51	0.58	0.61	0.59	0.56	0.56	0.56	0.49	0.38	0.28	0.25
9	0.44	0.46	0.52	0.58	0.61	0.58	0.55	0.56	0.55	0.49	0.39	0.30	0.27
9.5	0.44	0.46	0.51	0.57	0.59	0.56	0.53	0.54	0.55	0.49	0.39	0.31	0.28
10	0.44	0.46	0.51	0.56	0.58	0.55	0.52	0.53	0.53	0.48	0.40	0.32	0.29
11	0.43	0.45	0.49	0.53	0.54	0.51	0.48	0.49	0.50	0.46	0.39	0.33	0.30
12	0.41	0.43	0.46	0.49	0.50	0.47	0.44	0.46	0.47	0.44	0.38	0.32	0.30
15	0.35	0.35	0.37	0.39	0.38	0.36	0.34	0.35	0.37	0.36	0.32	0.29	0.28
20	0.24	0.25	0.26	0.26	0.25	0.24	0.23	0.23	0.25	0.24	0.23	0.22	0.21

MPM - Roll (Rx) - Acceleration [degree/s^2]

Tp [s]	Directions [deg] 0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.11	0.14	0.18	0.22	0.26	0.31	0.33	0.28	0.19	0.13	0.10	0.08	0.07
4.5	0.14	0.18	0.23	0.30	0.39	0.50	0.54	0.46	0.32	0.20	0.14	0.10	0.09
5	0.17	0.22	0.30	0.40	0.57	0.76	0.83	0.72	0.49	0.29	0.19	0.14	0.11
5.5	0.21	0.26	0.37	0.54	0.83	1.13	1.24	1.08	0.75	0.43	0.26	0.18	0.15
6	0.26	0.32	0.46	0.73	1.16	1.58	1.74	1.53	1.07	0.62	0.34	0.23	0.19
6.5	0.30	0.37	0.56	0.93	1.51	2.05	2.26	2.00	1.41	0.82	0.44	0.28	0.23
7	0.34	0.41	0.64	1.12	1.82	2.48	2.72	2.42	1.72	1.00	0.52	0.32	0.26
7.5	0.36	0.44	0.71	1.27	2.07	2.81	3.08	2.74	1.97	1.15	0.59	0.34	0.28
8	0.37	0.46	0.75	1.37	2.24	3.02	3.32	2.96	2.13	1.25	0.64	0.36	0.29
8.5	0.36	0.46	0.77	1.42	2.32	3.12	3.43	3.06	2.22	1.31	0.67	0.37	0.29
9	0.35	0.45	0.77	1.43	2.33	3.13	3.43	3.06	2.23	1.32	0.67	0.36	0.28
9.5	0.34	0.43	0.76	1.41	2.29	3.06	3.36	3.00	2.19	1.31	0.67	0.35	0.27
10	0.32	0.42	0.74	1.37	2.22	2.97	3.25	2.91	2.13	1.27	0.65	0.34	0.26
11	0.29	0.38	0.69	1.27	2.04	2.73	2.98	2.67	1.97	1.19	0.61	0.32	0.24
12	0.26	0.35	0.63	1.16	1.86	2.47	2.70	2.42	1.79	1.08	0.56	0.29	0.22
15	0.19	0.26	0.47	0.85	1.35	1.78	1.94	1.75	1.30	0.80	0.43	0.22	0.16
20	0.12	0.16	0.29	0.52	0.82	1.08	1.17	1.06	0.79	0.50	0.27	0.14	0.10

MPM - Pitch (Ry) - Acceleration [degree/s^2]

Tp [s]	Directions [deg] 0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.18	0.17	0.15	0.14	0.15	0.17	0.18	0.18	0.16	0.13	0.10	0.09	0.09
4.5	0.24	0.23	0.22	0.22	0.24	0.26	0.26	0.26	0.24	0.19	0.15	0.14	0.13
5	0.29	0.29	0.28	0.30	0.34	0.36	0.35	0.34	0.32	0.27	0.21	0.18	0.17
5.5	0.34	0.33	0.34	0.39	0.44	0.45	0.42	0.42	0.40	0.34	0.26	0.22	0.21
6	0.37	0.37	0.40	0.47	0.53	0.52	0.48	0.48	0.48	0.41	0.32	0.26	0.24
6.5	0.39	0.40	0.45	0.54	0.60	0.58	0.53	0.53	0.53	0.47	0.37	0.30	0.27
7	0.41	0.43	0.49	0.59	0.65	0.62	0.55	0.56	0.57	0.52	0.41	0.33	0.30
7.5	0.43	0.45	0.52	0.63	0.68	0.64	0.56	0.57	0.60	0.55	0.45	0.36	0.32
8	0.44	0.47	0.55	0.65	0.70	0.64	0.56	0.57	0.61	0.57	0.47	0.38	0.35
8.5	0.45	0.48	0.56	0.66	0.70	0.64	0.55	0.56	0.61	0.58	0.49	0.40	0.37
9	0.46	0.49	0.57	0.66	0.69	0.62	0.54	0.55	0.60	0.58	0.50	0.42	0.38
9.5	0.47	0.49	0.57	0.65	0.68	0.61	0.52	0.53	0.59	0.58	0.51	0.43	0.40
10	0.47	0.50	0.57	0.64	0.66	0.58	0.50	0.52	0.57	0.57	0.50	0.44	0.41
11	0.47	0.49	0.55	0.61	0.61	0.54	0.45	0.47	0.54	0.54	0.49	0.44	0.41
12	0.45	0.47	0.52	0.57	0.56	0.49	0.41	0.43	0.50	0.51	0.47	0.43	0.41
15	0.39	0.40	0.43	0.45	0.43	0.36	0.30	0.32	0.38	0.40	0.39	0.37	0.36
20	0.28	0.28	0.29	0.29	0.27	0.23	0.19	0.20	0.25	0.27	0.27	0.26	0.26

(a) 10 m water depth

MPM - Heave (Z) - Acceleration [m/s^2]

Tp [s]	Directions [deg] 0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.25	0.24	0.21	0.19	0.19	0.20	0.20	0.19	0.16	0.12	0.10	0.08	0.08
4.5	0.35	0.33	0.31	0.31	0.32	0.33	0.32	0.30	0.26	0.21	0.15	0.13	0.12
5	0.44	0.43	0.42	0.43	0.46	0.46	0.44	0.42	0.38	0.31	0.23	0.18	0.17
5.5	0.51	0.51	0.52	0.55	0.58	0.57	0.54	0.53	0.49	0.41	0.31	0.24	0.22
6	0.57	0.57	0.60	0.64	0.67	0.65	0.62	0.61	0.59	0.50	0.38	0.29	0.26
6.5	0.61	0.62	0.66	0.71	0.73	0.70	0.67	0.67	0.65	0.57	0.44	0.34	0.31
7	0.64	0.65	0.69	0.74	0.76	0.73	0.69	0.69	0.69	0.61	0.49	0.39	0.36
7.5	0.66	0.67	0.71	0.76	0.77	0.73	0.69	0.70	0.70	0.63	0.52	0.43	0.39
8	0.66	0.68	0.71	0.75	0.76	0.72	0.68	0.69	0.70	0.64	0.54	0.45	0.42
8.5	0.66	0.67	0.70	0.74	0.74	0.70	0.66	0.67	0.68	0.63	0.55	0.47	0.44
9	0.65	0.66	0.69	0.72	0.71	0.67	0.64	0.65	0.66	0.62	0.54	0.48	0.45
9.5	0.63	0.64	0.67	0.69	0.69	0.64	0.61	0.63	0.64	0.61	0.54	0.48	0.46
10	0.61	0.62	0.64	0.66	0.66	0.61	0.58	0.60	0.61	0.59	0.53	0.47	0.46
11	0.57	0.58	0.59	0.61	0.59	0.55	0.53	0.54	0.56	0.54	0.50	0.46	0.44
12	0.52	0.53	0.54	0.55	0.54	0.50	0.48	0.49	0.51	0.50	0.46	0.43	0.42
15	0.40	0.40	0.41	0.41	0.40	0.37	0.35	0.36	0.38	0.38	0.36	0.34	0.34
20	0.26	0.26	0.26	0.26	0.25	0.24	0.23	0.23	0.24	0.24	0.24	0.23	0.23

MPM - Roll (Rx) - Acceleration [degree/s^2]

Tp [s]	Directions [deg] 0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.12	0.14	0.19	0.22	0.24	0.25	0.24	0.21	0.16	0.13	0.11	0.09	0.07
4.5	0.15	0.18	0.24	0.30	0.35	0.40	0.42	0.36	0.27	0.20	0.15	0.12	0.10
5	0.18	0.22	0.31	0.41	0.54	0.67	0.72	0.63	0.46	0.30	0.21	0.15	0.13
5.5	0.22	0.27	0.40	0.59	0.85	1.10	1.18	1.05	0.77	0.49	0.30	0.20	0.16
6	0.25	0.33	0.52	0.83	1.24	1.60	1.73	1.55	1.16	0.73	0.42	0.25	0.20
6.5	0.28	0.38	0.64	1.07	1.61	2.08	2.25	2.03	1.53	0.97	0.55	0.31	0.23
7	0.31	0.42	0.75	1.27	1.92	2.46	2.66	2.41	1.83	1.17	0.65	0.35	0.25
7.5	0.32	0.46	0.82	1.41	2.13	2.73	2.94	2.67	2.04	1.31	0.73	0.38	0.26
8	0.33	0.47	0.87	1.49	2.23	2.85	3.08	2.80	2.14	1.39	0.78	0.40	0.27
8.5	0.32	0.47	0.88	1.50	2.24	2.85	3.08	2.80	2.16	1.41	0.79	0.41	0.27
9	0.32	0.47	0.86	1.47	2.19	2.78	3.00	2.74	2.11	1.38	0.78	0.41	0.27
9.5	0.31	0.45	0.84	1.42	2.11	2.68	2.88	2.63	2.04	1.34	0.76	0.40	0.26
10	0.30	0.44	0.80	1.36	2.02	2.56	2.75	2.52	1.95	1.29	0.74	0.39	0.25
11	0.27	0.40	0.73	1.24	1.82	2.30	2.48	2.27	1.76	1.17	0.67	0.36	0.24
12	0.24	0.36	0.66	1.11	1.62	2.05	2.20	2.02	1.57	1.05	0.61	0.32	0.21
15	0.18	0.26	0.47	0.78	1.14	1.43	1.54	1.41	1.11	0.75	0.44	0.24	0.16
20	0.11	0.16	0.28	0.47	0.68	0.85	0.91	0.84	0.66	0.45	0.27	0.15	0.10

MPM - Pitch (Ry) - Acceleration [degree/s^2]

Tp [s]	Directions [deg] 0	15	30	45	60	75	90	105	120	135	150	165	180
4	0.24	0.23	0.21	0.19	0.20	0.21	0.21	0.21	0.20	0.16	0.14	0.13	0.12
4.5	0.33	0.33	0.31	0.32	0.34	0.34	0.33	0.33	0.31	0.27	0.22	0.19	0.19
5	0.42	0.42	0.42	0.46	0.50	0.49	0.45	0.45	0.44	0.39	0.32	0.27	0.26
5.5	0.50	0.51	0.53	0.59	0.64	0.61	0.55	0.55	0.56	0.51	0.42	0.36	0.34
6	0.57	0.58	0.63	0.71	0.75	0.70	0.62	0.63	0.66	0.61	0.52	0.43	0.41
6.5	0.62	0.64	0.70	0.79	0.82	0.76	0.66	0.67	0.72	0.69	0.59	0.51	0.47
7	0.66	0.68	0.75	0.83	0.86	0.78	0.67	0.69	0.75	0.74	0.65	0.56	0.53
7.5	0.68	0.71	0.77	0.85	0.86	0.77	0.66	0.68	0.76	0.76	0.68	0.60	0.57
8	0.70	0.72	0.78	0.85	0.85	0.75	0.64	0.66	0.75	0.76	0.70	0.63	0.60
8.5	0.70	0.72	0.78	0.83	0.82	0.72	0.61	0.64	0.73	0.75	0.70	0.64	0.62
9	0.69	0.71	0.76	0.80	0.79	0.68	0.58	0.61	0.70	0.73	0.69	0.64	0.62
9.5	0.68	0.70	0.74	0.77	0.75	0.65	0.55	0.58	0.67	0.71	0.68	0.63	0.62
10	0.66	0.68	0.71	0.74	0.71	0.61	0.51	0.55	0.64	0.68	0.66	0.62	0.60
11	0.62	0.63	0.65	0.67	0.64	0.54	0.45	0.48	0.57	0.62	0.61	0.58	0.57
12	0.57	0.57	0.59	0.60	0.56	0.48	0.40	0.43	0.51	0.56	0.55	0.54	0.53
15	0.43	0.43	0.44	0.43	0.40	0.33	0.27	0.30	0.36	0.40	0.41	0.41	0.40
20	0.27	0.27	0.27	0.26	0.24	0.20	0.16	0.18	0.22	0.25	0.26	0.26	0.26

(b) 50 m water depth

Figure 7.3: NDurance Most Probable Maximum Accelerations at Chute

Vertical Acceleration [$^{m}/_{s^2}$]	Lateral Acceleration [$^{m}/_{s^2}$]	Roll [degrees]	Description
1.96	0.98	6.0	Light manual work
1.47	0.69	4.0	Heavy manual work
0.98	0.49	3.0	Intellectual work
0.49	0.39	2.5	Transit passenger
0.20	0.29	2.0	Cruise liner

Table 7.6: Nordforsk Criteria for human exposure to motions [21]

7.3. Orcaflex quantification

To quantify cable loads and prove that the new cable lay concept is technically feasible, an Orcaflex quantification of the cable loads is performed. First, all input parameters are discussed and how they are obtained. After that, the two different Orcaflex models, one for conventional cable laying and one for cable laying through a moonpool are discussed. Finally, the simulated cable loads are displayed.

7.3.1. Input Parameters

The input parameters are divided into four parts: Sea state, simulation, displacement RAO's, and Roll damping. All four will be discussed here.

Sea State

For the Orcaflex quantification, sea state input is fairly similar to that of the VMA. To save calculation time, only one water depth is chosen, because the VMA showed that with linear theory the differences over 10 to 50 meters water depth were negligible. Peak periods (T_p) are limited to five values, ranging from 4 to 12 seconds with steps of 2 seconds. The peak periods that can occur are dependent on the significant wave height. DNV-GL describes a relation between peak period (Tp) and significant wave height (Hs) for a PM spectrum [6]. This relation can be seen in Equation 7.5.

$$3.6 < \frac{T_p}{\sqrt{H_s}} < 5.0 \tag{7.5}$$

Filling in Equation 7.5 results in Figure 7.4. Combinations of significant wave height and peak period below the lower boundary are referred to as swell. Combinations above the upper boundary represent breaking waves.

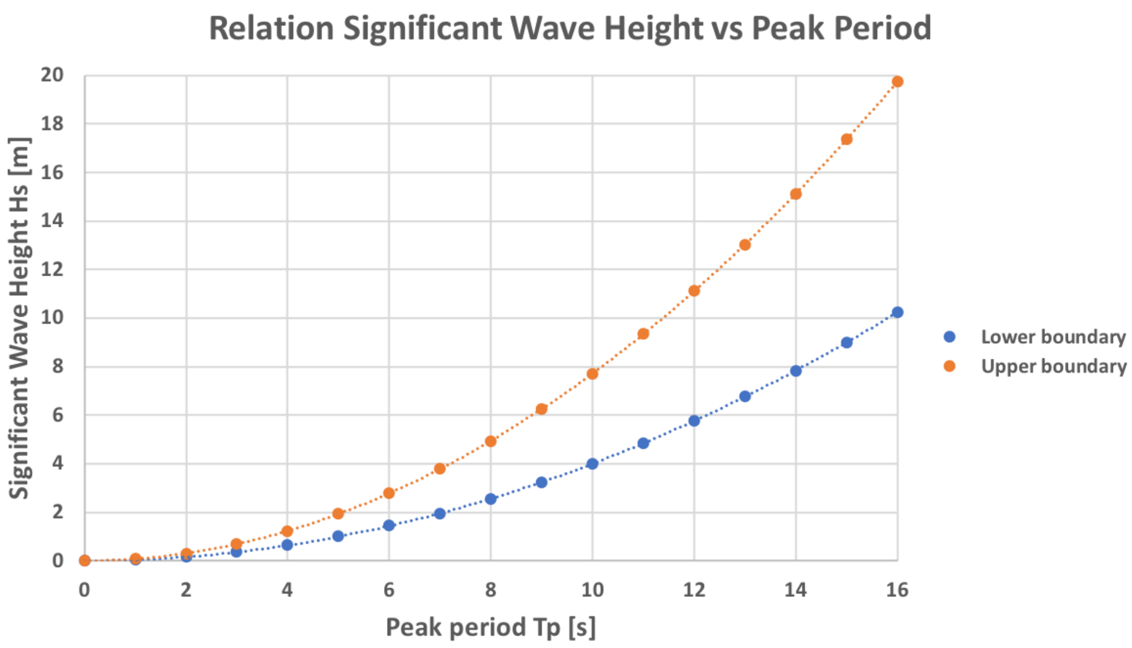


Figure 7.4: Significant wave height boundaries for different peak periods

Simulation

For this Orcaflex quantification, the simulation parameters in Table 7.8 are used as input for all simulations. Common industry standards on analysis methods, like Dett Norske Veritas

Input Parameters	Symbol	Value	Steps	Unit
Water depth	d	30	-	m
Peak enhancement factor	γ	1	-	-
Spreading exponent	n	10	-	-
Peak wave period	Tp	4 - 12	2	s
Significant wave height	Hs	[1.5, 2, 3]	-	m
Heading	Dir	180 - 360	15	degrees
Forward speed	V	0	-	m/s
Current speed	V_c	0	-	m/s
Wind speed	V_w	0	-	m/s
Draft NDurance	T	4.70	-	m
Draft Fjell	T	6.55	-	m

Table 7.7: Input parameters for Orcaflex Quantification

(DNV-GL) RP-H103, recommend that hydrodynamic forces should be predicted based on a 3-hour sea state [22]. A total number of 5 seeds is used in this simulation, from which the seed with the most critical sea state is used for the generation of results. To repeat the calculations with the developed model, only the seed on which the results are based is mentioned here.

Simulation Parameters	Symbol	Value	Unit
Time step	Δt	0.1	s
Maximum Iterations	I_{max}	100	-
Tolerance	$\varnothing$	25E-6	-
Built-up	t_0	60	s
Duration	D	3	hours
Seed	S	12345	-

Table 7.8: Simulation parameters Orcaflex

Displacement RAO's

The most important part for ship motions, together with the defined sea state, are displacement RAO's from the used vessel. Normally, vessel motions are obtained by importing displacement RAO's from an ANSYS Aqwa diffraction model and combining these with a certain sea state. In this case, for the Fjell, there was no ANSYS Aqwa model to obtain the displacement RAO's and also no lines plan available to get the Fjell in ANSYS Aqwa. Therefore, another option had to be figured out.

First, static stability calculations were performed using GHS software. Included in these static stability calculations were loads of the deck equipment mentioned in Chapter 6. GHS software addresses factors like flotation, strength, trim, and stability, by calculated all involved forces using a mathematical model of the Fjell. Here, the maximum loading capacity was calculated. The ballast tanks were used to compensate for the heavy load on deck to keep the ship within sailing limits, i.e. maximum sailing draft and position of the center of flotation. Ballast tanks placed where the moonpool will be added where disabled. The carousel load had to be scaled back to a maximum of 10.000 tonnes including cable, based on this stability analysis. Therefore, maximum cable load for this ship is limited to 9.000 tonnes.

Secondly, SHIPMO, which is an in-house developed software program by Marin that computes ship motions using a 2D diffraction method, is used to calculate displacement RAO's. Also, added resistance is calculated using *Gerritsma and Beukelman's (1972)* method [10]. Roll damping in SHIPMO is predicted using Ikeda's method [9], which is explained in Section 7.3.1. Load Quadratic Transfer Functions (QTF's) are not used for this analysis, which means that no non-linear effects like higher-order wave forces are taken into account. The RAO's for the NDurance and the Fjell for head waves and side waves are displayed in Appendix D.

Roll Damping

By multiplying the obtained displacement RAO's with a certain sea state, roll motions are obtained. Based on these roll motions, a roll damping component is calculated and corrected back in the displacement RAO's. SHIPMO uses *Ikeda's (1978)* method to predict roll damping at zero forward ship speed. Roll damping at zero forward ship velocity, according to *Ikeda's (1978)* method, consists of a friction component (B_F), a wave component (B_w), an eddy component (B_E), and a bilge keel component (B_{BK}). The roll damping coefficient is calculated in Equation 7.6.

$$B_{44} = B_{\mathrm{F}} + B_{\mathrm{W}} + B_{\mathrm{E}} + B_{\mathrm{BK}} \tag{7.6}$$

The bilge keel component B_{BK} is the largest roll damping component and accounts for approximately 50% of the roll damping. It is dependent on the distance between the water surface and the CoG compared to the draft of the vessel. The second-largest term is the wave component which can be calculated using potential theory. This term accounts for approximately 30% of the roll damping. Eddy roll damping has a relatively small contribution to the total roll damping, according to *Ikeda (1978)*. Furthermore, the friction component is predicted by *Kato's (1958)* formula but is not used in this analysis because this term can often be neglected for a full-scale ship [13].

7.3.2. Models

For this analysis, two different models are developed. The first model represents conventional cable laying over a chute. The second model represents cable laying through a moonpool. The origin is at the aft of the vessel, at the keel in the midship, creating symmetry in the XZ-plane. Positive X-direction points towards the forecastle of the ship, where positive Z-direction points upwards and positive Y-direction points towards portside. A wave heading of 180 degrees represents head waves, traveling in negative X-direction (coming from the front of the ship).

Chute

The chute is modeled as a shape with very high stiffness and a 5-meter bending radius, which can be seen in Section 7.5. The bending radius of the chute has to be equal or higher than the MBR of the cable. The chute is rigidly attached to the aft of the vessel. End A of the cable is attached to the top of the chute where it can rotate freely, leaving the aft of the vessel in negative X-direction. Translation at End A with respect to the vessel is not allowed.

Moonpool

The moonpool is modeled as a trapped water shape through the midship, which can be seen in Figure 7.6. The moonpool is rigidly attached to the vessel. End A of the cable is attached to the vessel at deck level, where it can rotate freely, representing the place where it leaves the tensioners into the moonpool. Translation at End A with respect to the vessel is not allowed.

Constraints

To guarantee a similar catenary shape in both models, top and bottom tension, water depth, layback distance, cable length, and cable departure angle have to be equal in both cases. The layback distance is the horizontal distance between End A and anchor point End B. Top and bottom tension are chosen based on experience. In this case, bottom tension is chosen to be equal to 5 kN, with a departure angle at the chute and in the moonpool of approximately 14 degrees. Hence, all constraints combined guarantee a similar cable catenary shape in both models, which makes it possible to compare both concepts. The departure angle of the cable is limited to the moonpool dimensions. During cable laying, this catenary shape is optimized. Therefore, cable laying over a chute has another ideal catenary shape than moonpool cable

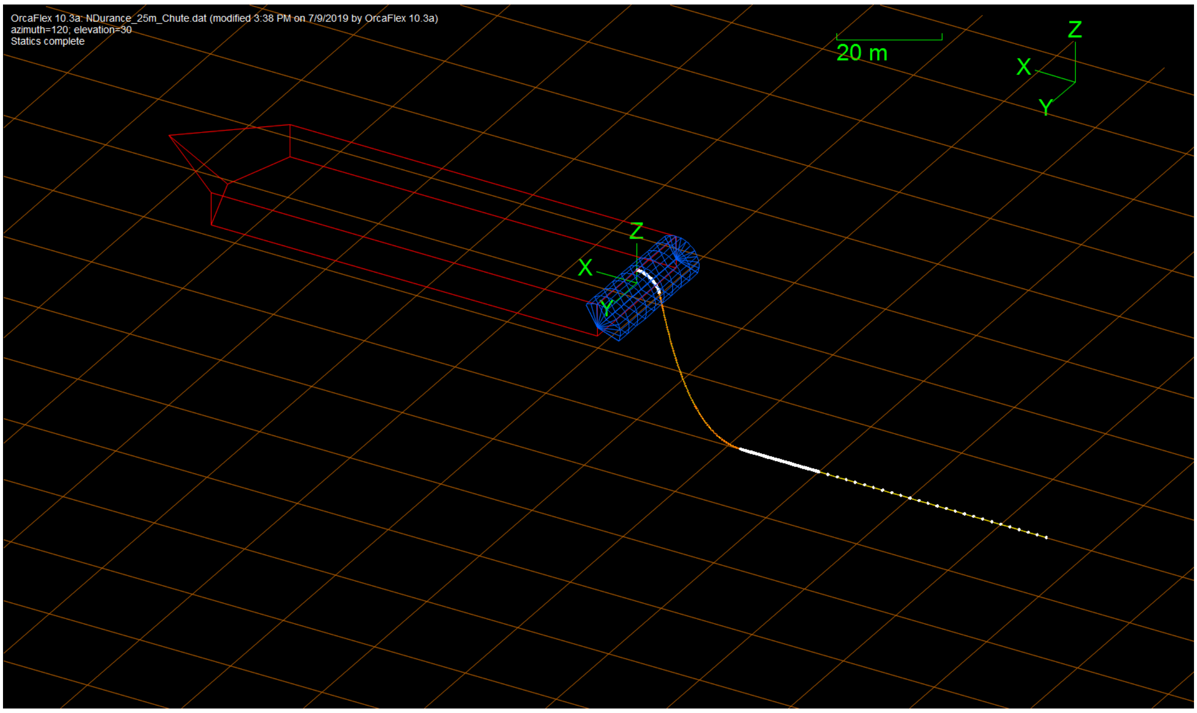


Figure 7.5: Cable laying over a chute modelled in Orcaflex

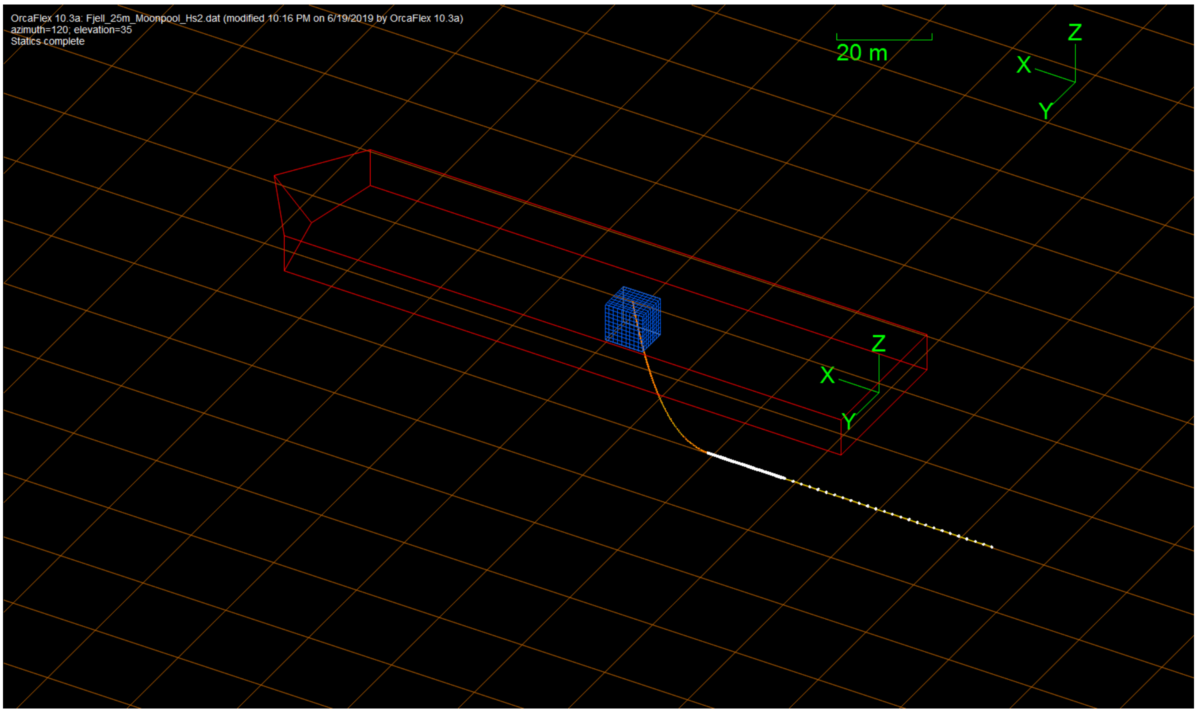


Figure 7.6: Cable laying through a moonpool modelled in Orcaflex

laying. In this analysis, only one catenary shape is analyzed to give an initial insight in the cable loads. An overview of all catenary parameters can be seen in Table 7.9. The catenary shape can be described by the hyperbolic cosine in Equation 7.7, where a is the catenary shape parameter.

Catenary Parameters	Symbol	Value	Unit
Top Tension	T	30	kN
Bottom Tension	T_0	5	kN
Departure Angle	ϕ	14	degrees
Layback Distance	X_l	35	m
Anchoring Distance	X_a	85	m
Water Depth	D	30	m
Cable Length	L	115	m

Table 7.9: Catenary Parameters

$$y = a \cdot cosh\left(\frac{x}{a}\right) = \frac{a\left(e^{\frac{x}{a}} + e^{\frac{-x}{a}}\right)}{2} \tag{7.7}$$

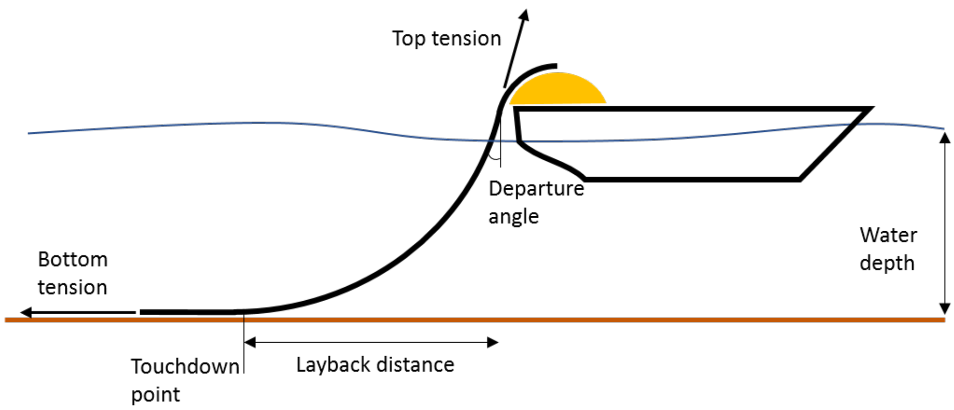


Figure 7.7: Catenary Parameters

Simulations
For both cases, 2 vessels, 3 wave heights, 13 wave headings, and 4 peak periods are used. This already results in:

$$N_{sim} = n_v \cdot n_{Hs} \cdot n_w \cdot n_{Tp} = 2 \cdot 3 \cdot 12 \cdot 4 = 312 \text{ simulations per case} \tag{7.8}$$

With two cases, the chute and the moonpool model, 624 simulations must be done in total. Each 3-hours simulation has a real-time duration of approximately 1.5 hours. A normal computer can run 4 simulations at the same time, resulting in nearly 10 days of simulation duration.

7.3.3. Results

Question 15: Does the developed concept assure cable integrity?
As explained in Chapter 2, there are several important limitations during cable laying. These limitations are design requirements that have to be fulfilled at all times to ensure cable integrity after installation. The main limitations for offshore power cables and the points where they will be evaluated are:

- Maximum Compression (End A, Touchdown, End B)
- Maximum Tension (End A, Touchdown, End B)
- Curvature (Whole Cable)
- Maximum Squeezing/Crushing Load (Chute)
- No Torsion (for DC cables) (Whole Cable)

Tension/Compression
The minimum, mean, and maximum tension are measured in Orcaflex over the full length of the cable. Here, minimum, mean and maximum tension are evaluated in end A, the touchdown point, and end B of the export cable. When the tension becomes negative, the cable is in compression at that point during the measuring. Hence, a negative tension value will be referred to as compression. The maximum allowable tension during the installation of the reference cable is 215 kN. The maximum allowable axial compression is 30 kN. The cable is laid with a bottom tension of 5 kN, as can be seen clearly in 7.8.

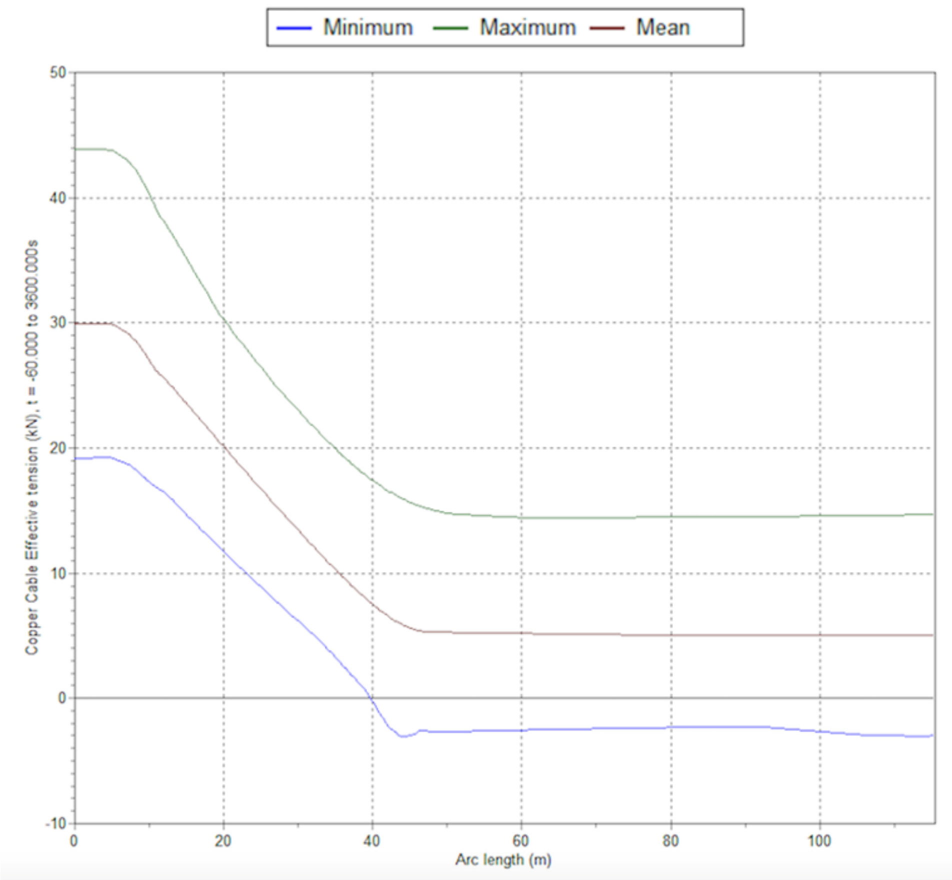


Figure 7.8: Tension Cable NDurance Moonpool for Hs = 3 m

In Figure 7.9 the maximum effective tension can be seen for all wave directions, for different peak periods and a significant wave height of 3 meters. In Figure 7.10, the minimum effective tension can be seen for all wave directions. Neither tension nor compression cable limits are exceeded in all simulations. Therefore, other cases can be seen in Appendix E.

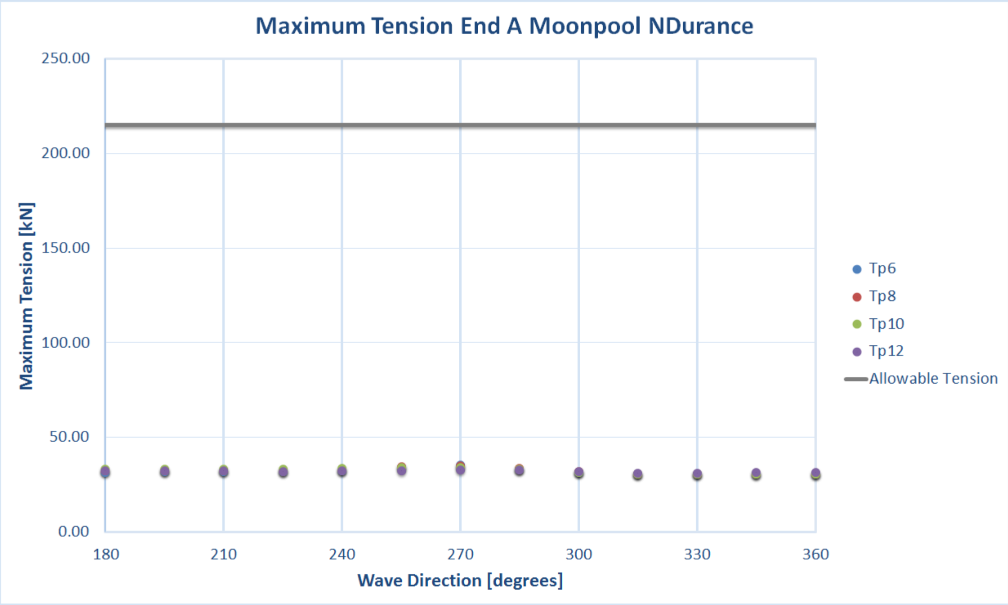


Figure 7.9: Maximum Tension End A NDurance Moonpool for Hs = 3 m

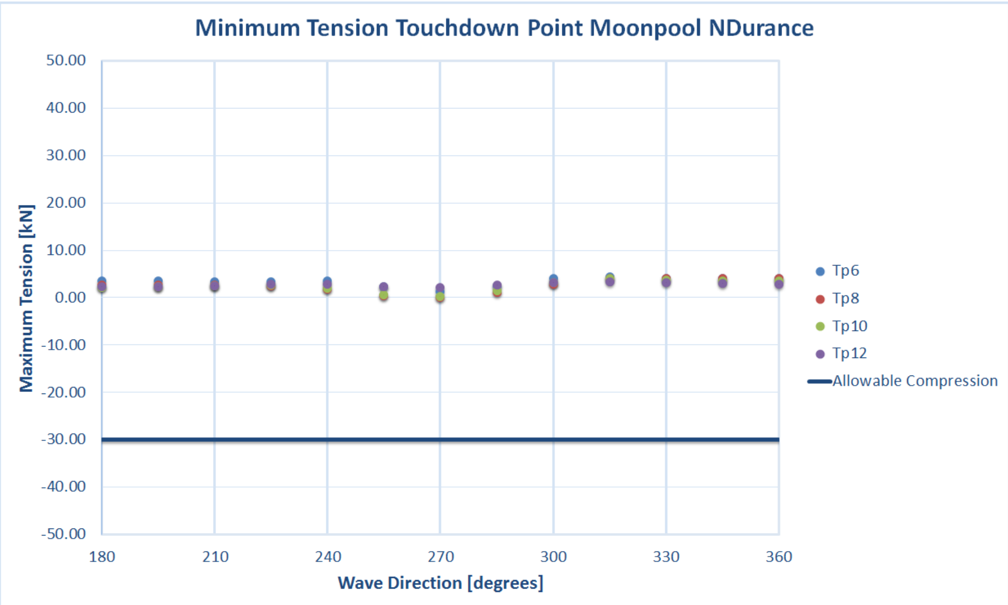


Figure 7.10: Minimum Tension Touchdown Point NDurance Moonpool for Hs = 3 m

Curvature

Curvature is determined as one divided by the bending radius. Every cable has a maximum allowable curvature, or minimum bending radius, which is determined by the manufacturer. If this curvature is not exceeded, the cable manufacturer ensures cable integrity. For the reference cable with an MBR equal to 4.9 m, the maximum allowable curvature is 0.204 m^{-1}. In this analysis, the cable is tested for exceedence of the maximum allowable curvature.

More detailed information on the place in the cable where maximum curvature occurs and in which plane this occurs can be found in Appendix G.

NDurance Chute

First, the conventional method of offshore power cable installation is being investigated. In Figure 7.11, the curvature is plotted against the incoming wave directions for peak periods between 4 and 12 s, and a significant wave height of 1.5 meters and 2 meters. This figure shows that the maximum allowable curvature is not exceeded for a significant wave height up to 1.5 meters, for all wave directions and peak periods. This means the vessel can proceed cable installation in these conditions. However, for a significant wave height of 2 meters and a peak period between 8 and 10 seconds, the maximum allowable curvature is exceeded for several wave directions. This means cable integrity cannot be guaranteed any more. Figure 7.4 showed that a peak period higher than 7 seconds represent swell conditions for a significant wave height of 2 meters. In these swell conditions, the maximum curvature is exceeded. Since swell from the north is likely to occur in the North Sea area, the operational limit is set at 1.5 meters significant wave height for these project sites. Hence, cable installation cannot be executed in higher sea states.

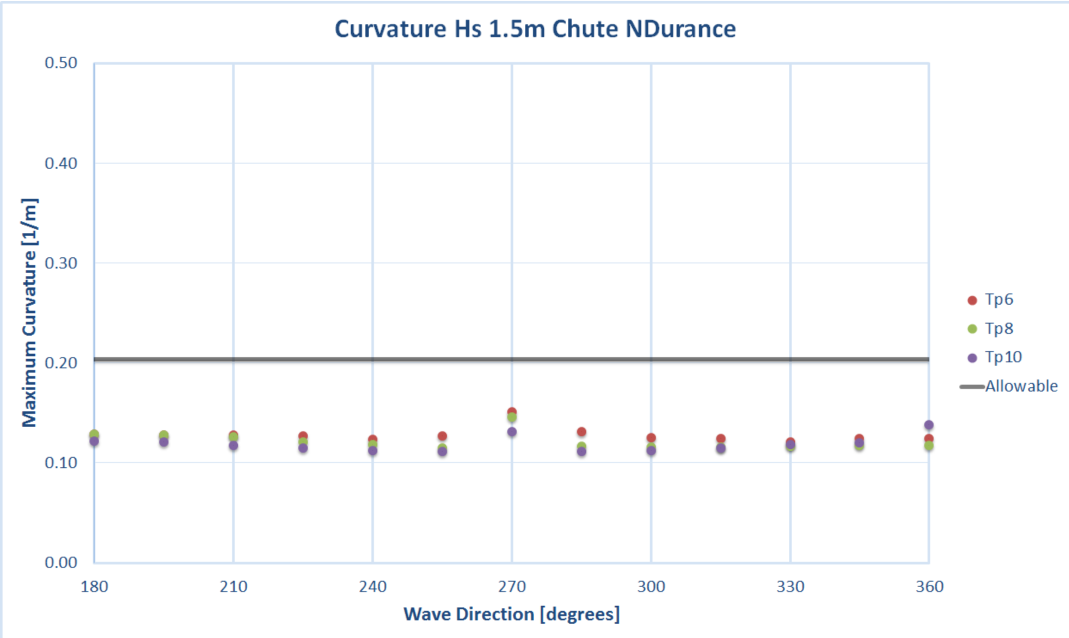
NDurance Moonpool

So the operational limit for conventional cable installation with the NDurance is 1.5 meters significant wave height, independent of the location, based on this catenary shape. The second case that is being investigated is cable laying via a moonpool with the NDurance. This case assumes that the NDurance would have a moonpool, situated in the same place as on the Fjell. This means the lateral and transversal arm towards the CoG is assumed to be equal to that of the Fjell. In Figure 7.12, it can be seen that the limiting significant wave height is lower than 2 meters for this case. Especially side waves with a peak period of 8 to 10 seconds, coming in from 255 - 270 degrees, will lead to exceedance of the maximum allowable curvature in the cable. In Section 7.2.2, it is already explained that the cable motions for these wave directions are dominated by roll motions of the vessel. This is illustrated in Figure 7.2a and 7.2b. Hence, the operational limit for cable laying via a moonpool with the NDurance is a significant wave height of 1.5 meters as well for all wave directions and tested peak periods.

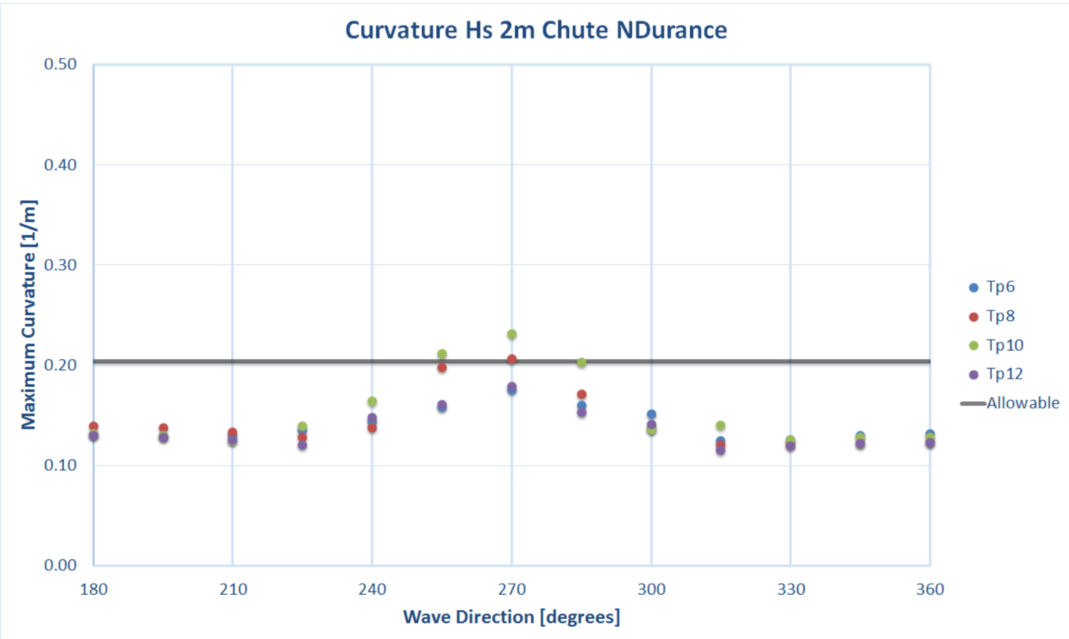
Despite the same operational limit as for conventional cable lay, the critical wave directions are only waves from the side for high peak periods. According to Figure 7.4, peak periods of 7 seconds or higher only occur in swell conditions for a significant wave height equal to 2 meters. Despite this, the operational limit is set at 1.5 meters significant wave height for this concept because swell is likely to occur in many areas, like the North Sea area.

Fjell Chute

Conventional cable laying over a chute with the Fjell has a very low operability limit, according to Figure 7.13. This is caused by the large arm for pitch motions, because the cable leaves the vessel at the aft over the chute. With a ship length of close to 150 meters, the large distance from chute to the CoG results in large heave motions due to pitch, which results in a whip crack effect in the cable. This is a sudden bend in the cable that moves along the cable, due to rapid vertical motion of the chute. The cable is slammed on the seabed, resulting in a very large exceedance of the maximum allowable curvature. In side wave conditions, motions due to pitch are not present. Therefore, the maximum curvature is much lower for this wave direction. Based on this analysis, no operability limit can be determined for conventional cable laying with the Fjell for this particular catenary shape. In fact, the operability limit is expected to be far below 2 meters significant wave height. However, the catenary shape can be adjusted to prevent the whip crack effect from happening, which will increase the operational limit.

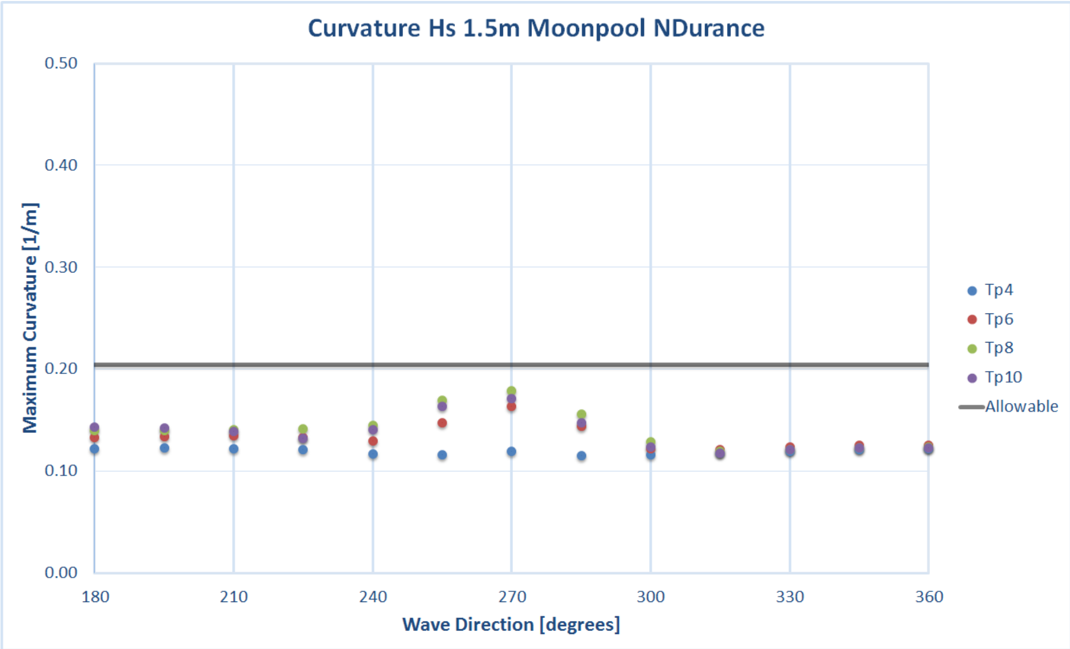


(a) Hs = 1.5 m

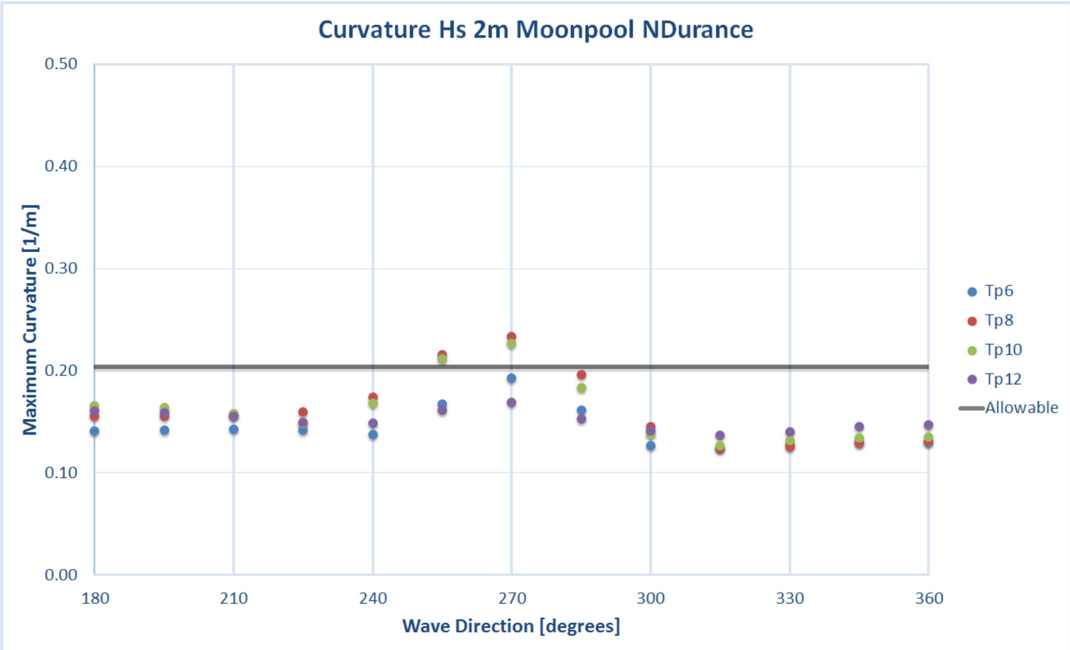


(b) Hs = 2.0 m

Figure 7.11: Curvature per wave heading conventional cable laying NDurance

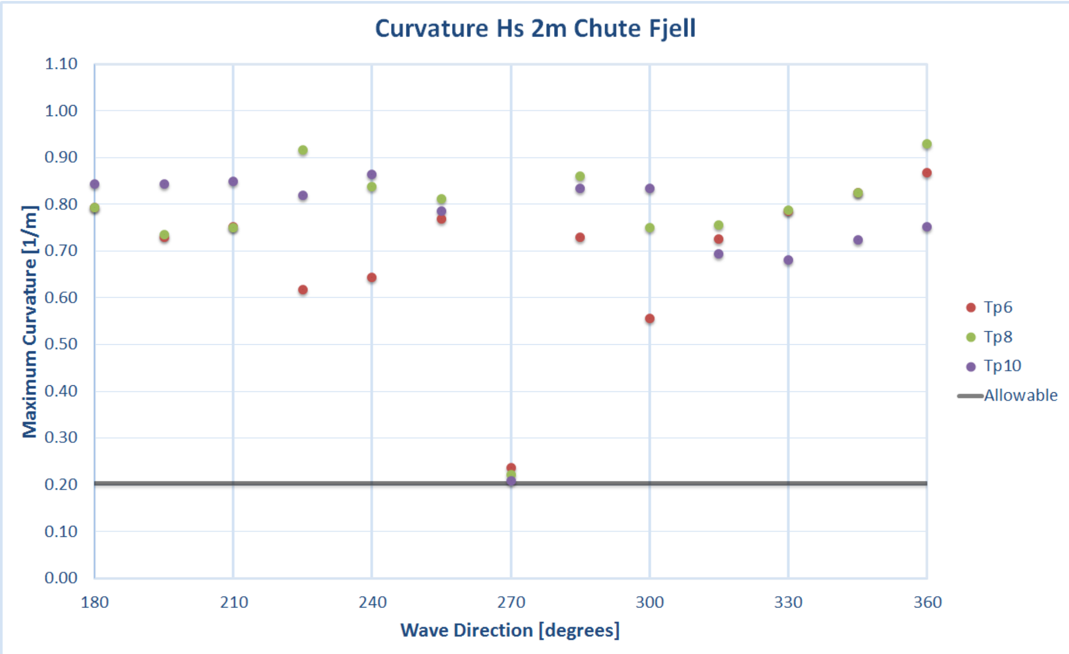


(a) Hs = 1.5 m

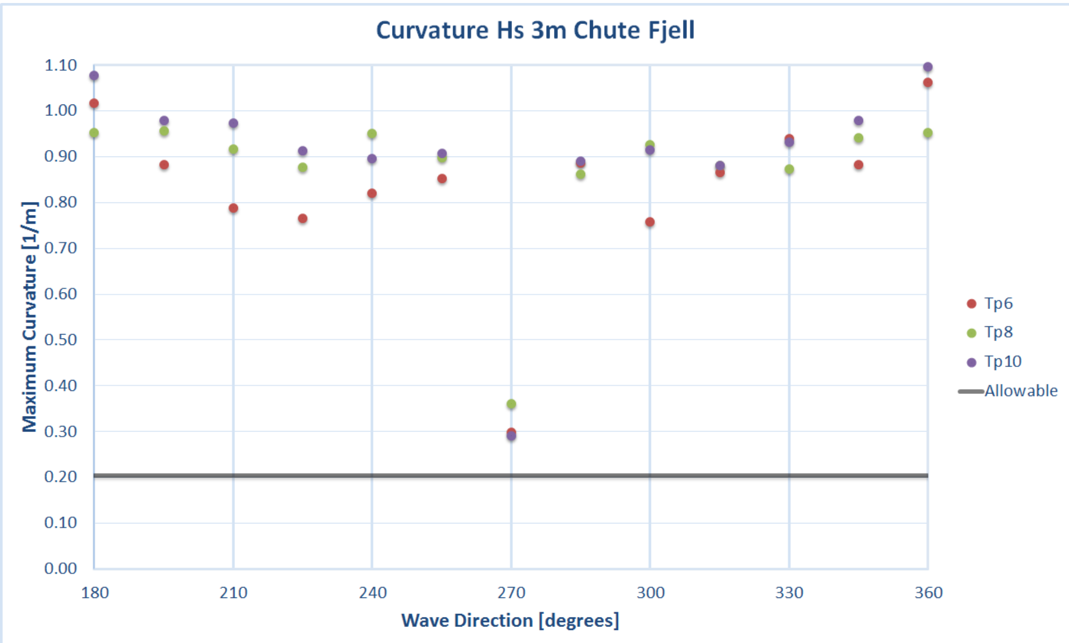


(b) Hs = 2.0 m

Figure 7.12: Curvature per wave heading moonpool cable laying NDurance



(a) Hs = 2.0 m



(b) Hs = 3.0 m

Figure 7.13: Curvature per wave heading conventional cable laying Fjell

Fjell Moonpool

For the newly designed concept, described in Chapter 6, the operational limit is expected to be higher than for conventional cable laying. In Figure 7.14, it can be seen that this concept has a workability up to 2 meters significant wave height. Since the maximum allowable curvature is not exceeded with a maximum curvature at 270 degrees wave direction of approximately 0.17, the operational limit might be even higher. Hence, the operational limit lies between 2 and 3 meters significant wave height, but cable integrity can be assured up to 2 meters significant wave height. Therefore, the operational limit is set at 2 meters significant wave height for all wave directions and tested peak periods. For 3 meters significant wave height, there is a relatively large spreading of maximum curvature in the cable. This spreading also differs per peak period. For peak periods equal to 4 seconds, three peaks at 180, 270 and 360 degrees can be seen. When increasing the peak period, vessel motions become more severe. This is reflected in cable curvature for especially high peak frequencies, exceeding the maximum allowable curvature in most wave directions. When looking at the simulations, it can be seen that these large curvatures are caused by two reasons:

1. Oscillation at the natural frequency of the system
2. Ringing/whip cracking of the cable due to fairly steep departure angle of the cable

Torsion

DC cables cannot be twisted because they have a single conductor which cannot withstand torsional loads. Therefore, it is important to evaluate if the cable is twisted during the simulation. All simulations are checked for torsion, but this was not present in any of them. An example can be seen in Figure 7.15, which displays the minimum, main, and maximum twist over the cable length. All three are equal to zero in all simulations. Although minimum, main, and maximum twist over the cable length are equal to zero in all simulations, this is not the case in real life. Bending of the cable cannot occur without torsion. Hence, in reality a cable is always twisted during cable installation.

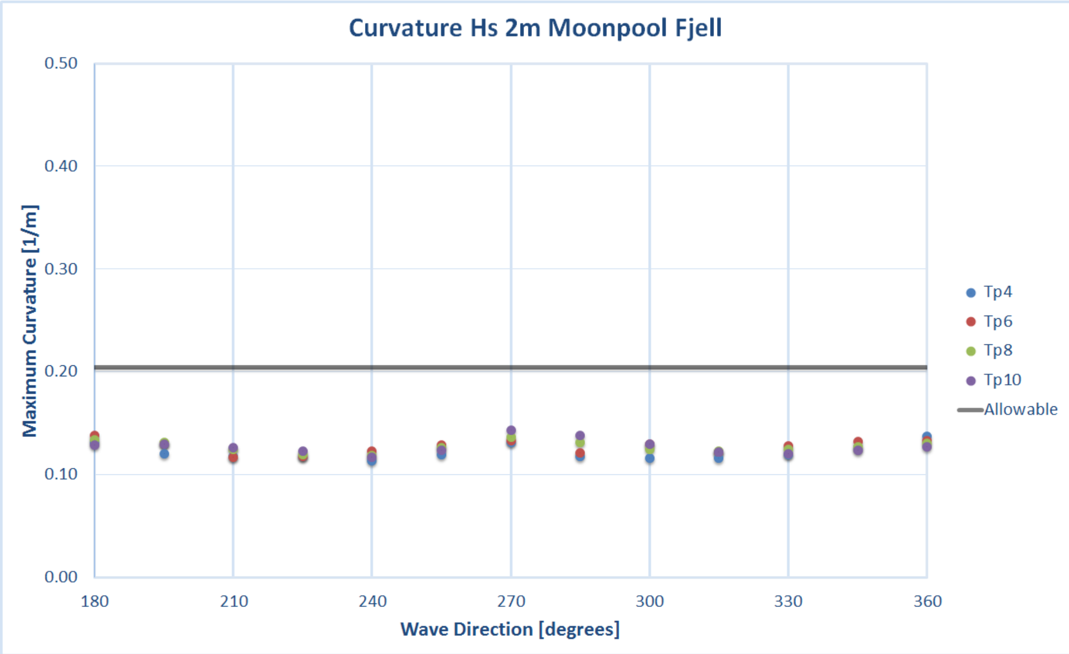
7.4. Comparison

After all simulations have been done, the cable loads are extracted and compared to the cable handling limits mentioned in Section 7.1.3. Section 7.3.3, explained that curvature was the limiting factor for all analysis done.

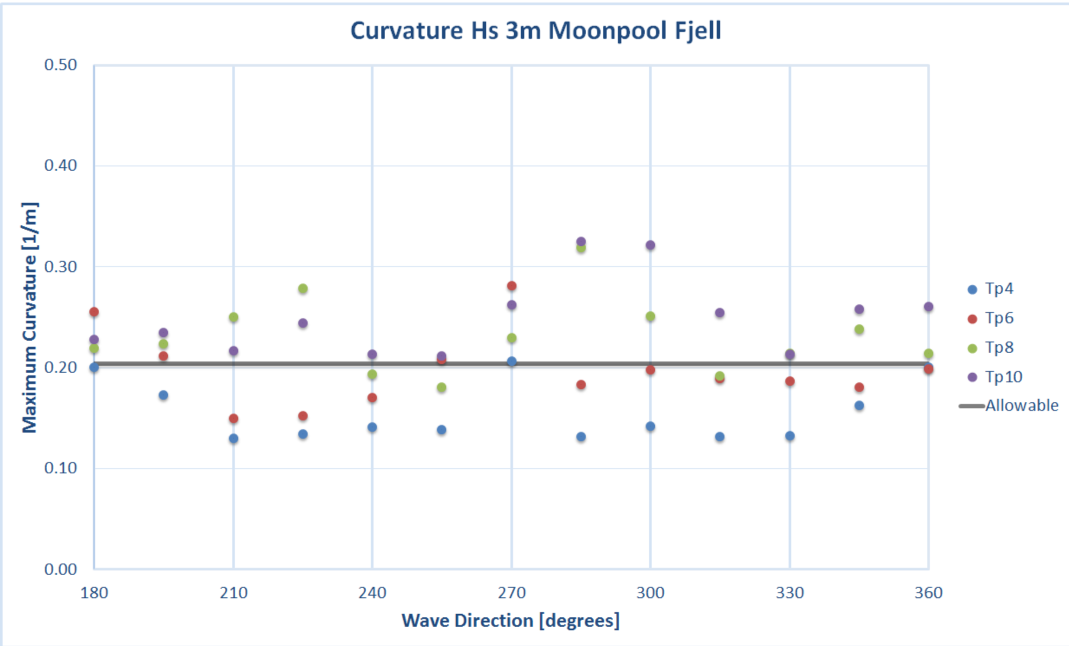
For all four cases an operational limiting significant wave height has been determined at one particular catenary shape. These operational limits are:

- Conventional Cable Lay NDurance: **Hs = 1.5 m**
- Moonpool Cable Lay NDurance: Hs = 1.5 m
- Conventional Cable Lay Fjell: Hs = 0 m
- Moonpool Cable Lay Fjell: **Hs = 2 m** - 3 m (estimated at 2.5 m)

From this list can be seen that the new cable lay concept, cable installation via a moonpool, has higher workability for the Fjell. This is due to the shorter arm towards the CoG, which lowers the impact of roll and pitch motions. Hence, with the newly designed concept, cable loads will be less than with conventional cable laying and cable handling limits are exceeded at higher sea states. For the NDurance, the workability of cable installation via a moonpool is similar to that of conventional cable lay. In Figure 7.16 and 7.17, workability percentages for a significant wave height of 1.5 and 2 meters can be seen for the North Sea area. Colors indicate a visual difference between high and low workability, where red indicates very low workability and green very high workability. These workability percentages are calculated using metocean hindcast data. Boskalis has an in-house developed interface, called Boskalis World, where this hydrodynamic data is being converted into graphical overviews.



(a) Hs = 2.0 m



(b) Hs = 3.0 m

Figure 7.14: Curvature per wave heading moonpool cable laying Fjell

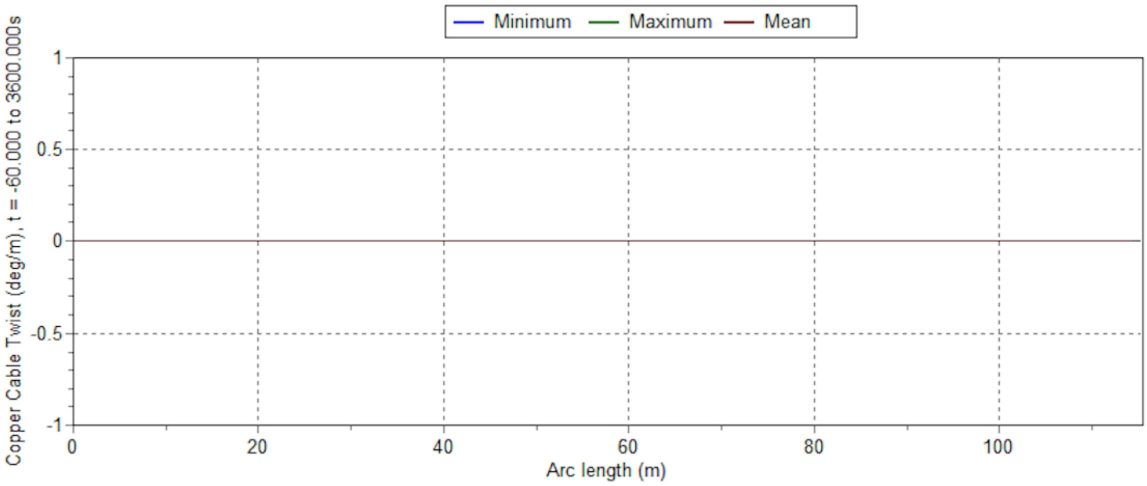


Figure 7.15: Twist in cable NDurance Moonpool Hs = 3 m

This interface is used to calculate the average workability percentages at different project sites for both cable lay concepts. These average workability percentages act as input for the economic analysis in Chapter 8. For conventional cable lay with the NDurance, a significant wave height of 1.5 meters is used. For moonpool cable lay with the Fjell, a significant wave height of 2.0 meters is used. Although the estimated operational limit for the Fjell is higher, the limit up to where cable integrity can be assured is used for further analysis.

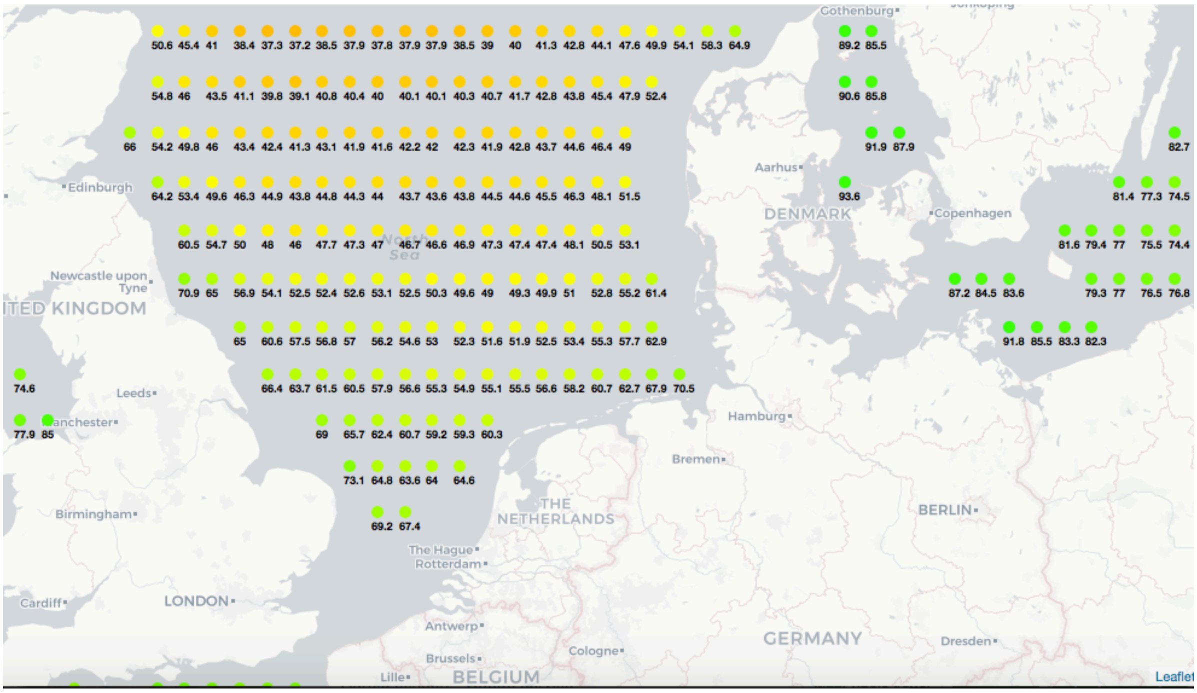


Figure 7.16: Workability percentages North Sea area for Hs = 1.5 m

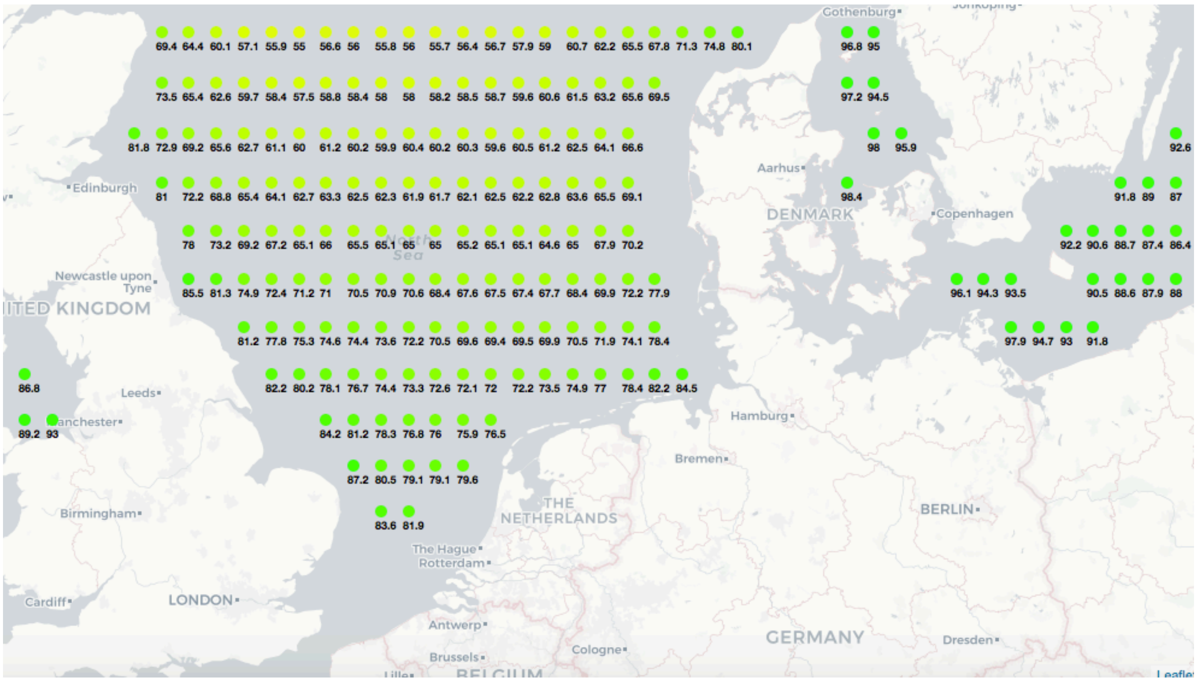


Figure 7.17: Workability percentages North Sea area for Hs = 2 m

8
Economic Evaluation

Question 16: What economical parameters are important to assess economic feasibility?
To compare the new cable lay installation method via a moonpool to the conventional method of export power cable installation over a chute, an economic evaluation has been performed. This economic evaluation is divided into three parts, which only focus on cable laying itself. Risks like the second end pull-in, shore landing, installation of joints, failures, and delays are taken into account in a risk margin, which means they are not evaluated in depth. These three parts represent the cost price related to the used vessel, the required equipment, and the investment necessary to realize the new concept. To compare the conventional cable lay method to the new method, three different cases are introduced. These cases represent project sites in different areas of the world. In Section 8.4 for these three cases, the minimal necessary profit margin for the new cable installation method is described. This profit margin is needed to break even with the conventional cable lay method.

The actual numbers used in this economic evaluation are sensitive information for Boskalis and its competitive position in the tendering process of offshore projects. Therefore, price estimates are used for the costs in the categories depreciation, crew costs, and other expenses.

8.1. Vessel Costs
In this part, all costs related to the used vessel are described. The costs are divided into two parts: day rate and mobilization costs. The differences between the Fjell and the NDurance are also explained.

Day rate
The day rate of the vessel is dependent on a lot of factors. The factors include depreciation of the ship's initial investment, maintenance, crew costs, fuel costs, and other expenses. Also lost interest and margins are included in this rate to cover for potential losses during the project and ensure profitability.

8.1.1. Depreciation
When an investment in a new vessel is done, the investment is being depreciated over a certain amount of time. To calculate the day rate of a vessel, first, the initial investment has to be divided by the number of years over which the owner wants to depreciate it. For this calculation, both vessels will be depreciated over 15 years with estimated accounting operability of 200 days per year. For the NDurance, an estimated investment of €60.000.000 is used and for the Fjell an investment of €80.000.000.

8.1.2. Maintenance

The maintenance of the vessel has to be done annually. The maintenance costs are estimated as a percentage of the initial investment in the vessel. In this case, the annual maintenance costs for both vessels are estimated to be 2% of its initial investment, resulting in €1.200.000 for the NDurance and €1.600.000 for the Fjell.

8.1.3. Crew Costs

The vessel crew can be divided into two groups: the marine crew and project crew. The marine crew is always on board and ensures that the vessel can operate and will be on board permanently, independent of the project. The project crew will only be on board during a specific project. The project crew for both the Fjell and the NDurance is estimated to consist of 2 Foremans, 8 Riggers, 4 ROV specialists, 6 Burial specialists, 1 Offshore Construction Manager (OCM), 1 Deputy Offshore Construction Manager (DOCM), 3 Survey Engineers, 1 Field Engineer, 1 QHSE agent, 4 Equipment operators and 2 Crane operators per shift of 24 hours. This project crew works in two shifts of 12 hours each. Every worker has a day rate which can be multiplied by the number of days on-site, ranging from approximately €200,- to €2000,- per worker per day depending on its discipline. For the NDurance, the marine crew exists of 25 people, with a worker's day rate average of approximately €500,-. For the bigger Fjell, the marine crew is estimated to consist of 30 people. Multiplying and adding up these amounts generates a cost estimate for both the marine crew and the project crew.

8.1.4. Fuel Costs

The NDurance has an average fuel consumption during the cable installation of approximately 15 m^3 per day. Because the displacement of the Fjell is approximately 1.5 times larger, the average fuel consumption for this vessel is estimated to be 22.5 m^3, which is 1.5 times larger as well. The fuel price for marine fuel is approximately €400,-/m^3. Lubricants are also included in this category.

8.1.5. Other Expenses

Here, other expenses like Work Remotely Operated Vehicles (WROVs), Onboard survey Equipment, Personal Protective Equipment (PPE) & Modification, Board & Lodging and Travel Costs are calculated.

8.1.6. Interest Rate

When no initial investment in new ships would have been done, interest would have been paid over the amount of money that was still in the bank. This potentially lost interest by investing rather than saving, has to be taken into account. The interest rate taken in this evaluation is equal to 3%, which will be applied as a multiplication factor over the day rate.

8.1.7. Risk Margin

To account for potential losses or delays during the project a risk margin is added. This margin can be seen as a safety factor and normally ranges between 0% and 20% depending on the market, the current order book, and the amount of risk the company is willing to take. In this calculation, a risk margin equal to 5% is used for both the Fjell and NDurance case.

Mobilization

Mobilization includes both mobilization and demobilization costs. Mobilization cost represents all costs related to the transportation of personnel, supplies, and equipment to the project site. Demobilization represents all costs by removing these from the project site.

8.1.8. (De)Mobilization Costs

Mobilization and demobilization are often expressed in the number of days and are multiplied by the day rate of the used vessel. For the NDurance, the mobilization costs are estimated at 4 times the day rate and demobilization at 2 times the day rate per project of the vessel. For the Fjell, mobilization and demobilization costs are estimated to be twice as high, so 8 times the day rate and 4 times the day rate per project respectively.

8.2. Equipment Costs

In this part, all costs related to the used equipment are described. Think of burial tools, ROV's, quadrants, goosenecks, tensioners, carousels, etc. The costs are again divided into two parts: day rate and mobilization costs.

Day rate

The day rate of equipment is calculated in the same manner as the day rate of an operating vessel. Hence, the equipment used is most of the time developed in-house. Therefore, depreciation, maintenance, and interest rate have to be taken into account here as well.

8.2.1. Depreciation

The equipment is being depreciated over a lifetime of 10 years. When calculating a day rate, an operability of 100 days per year is assumed for the equipment used in the new cable lay concept. The cable lay equipment will not be used throughout the year, because the Fjell will act as a multi-purpose vessel. For now, the plan is to also deploy it as a rock dumping vessel but in the future other applications can be added as well. For the NDurance, a regular CLV, an operability of 200 days per year is assumed for the use of all equipment. Cable lay equipment will be always on board because the NDurance is only deployable as a CLV. Therefore, the operability of equipment is the same as for the vessel itself.

8.2.2. Maintenance

Some of the equipment is more sensitive to wear than others. For example, burial tools are exposed to high friction forces in the seabed, which makes them wear more easily. Therefore, significant maintenance is required more often. Maintenance costs are represented by a percentage of the day rate of all equipment. When leveling out these differences in maintenance periods, costs are estimated to be 5% of the equipment's initial investment annually.

8.2.3. Interest Rate

The interest rate is added for the same reason as before when analyzing the economics of the vessels. When no initial investment in new equipment would have been done, interest would have been paid by the bank over the amount of money that was still in Boskalis' bank account. The interest rate for the used equipment is equal to 3%, which will be applied as a multiplication factor over the day rate.

Mobilization

Mobilization is also important for equipment used in a project. Despite being such an important part in cable installation, mobilization and demobilization will take less time than mobilizing a vessel. Equipment is often already in place, or easily movable. Therefore, the mobilization time will be shorter.

8.2.4. (De)Mobilization Costs

Because equipment can be deployed easily on board of a vessel, both mobilization and demobilization will only take approximately 1 day when a conventional CLV is used or when the Fjell is already equipped with its cable lay setup. When the whole deck lay-out has to be transformed from rock dumping to cable lay setup, demobilization of the rock dumping equipment and mobilization of the cable lay equipment will take approximately 7 days each, so 14 days altogether.

8.3. Investment Costs

For the new cable lay concept via a moonpool an investment has to be done for Engineering, Procurement, Contracting, and Installation (EPCI). To simplify, but give a reasonable estimation, a gross material price is used for this analysis.

8.3.1. Material

The material represents the cost of raw material, i.e. the amount of steel that has to be added to realize the concept. Also included in the price are engineering costs, electronics, operating systems, and other materials/services. This gives a gross estimate of the investment needed to fabricate a working deck layout. In this case, the material is divided into 5 categories. These categories differ from low class, cheap steel, and other materials to high-class expensive steel and other components. Every category has its price, which can be multiplied by the weight of every component needed in this concept. The 5 categories range from €5.000,- to €15.000,- per metric ton steel and go up by steps of €2.500,- per category. Most of the deck-layout, like the carousel and the gooseneck, are made of category 5 steel, which represents high-class machined steel including bearings and other hardware, with an average price of €15.000,- per metric ton. In Appendix F, an overview of the most important deck equipment, the corresponding weight, and steel category is displayed. Adding up all material costs, results in an investment for the new cable lay concept of approximately 22.5M Euro.

8.4. Concept Comparison

Question 17: Can the designed concept be more competitive in the selected market than conventional cable lay methods?

To assess whether the newly designed cable lay concept can be more competitive in the selected market than conventional cable lay methods, first, the overall day rate has to be calculated. This is also called the cost price. When adding a profit margin to the cost price, the commercial price that is used in the tendering process is obtained.

The day rate can be calculated as follows:

$$DR = \left(\frac{D}{O * LT} + \frac{M}{O} + C + F + OC \right) * IR * MR \tag{8.1}$$

with:

- Day Rate (DR) in [€]
- Depreciation (D) in [€]
- Operability (O) in [days/year]
- Lifetime (LT) in [years]
- Maintenance (M) in [€]
- Crew costs (C) in [€]
- Fuel costs (F) in [€]
- Other costs (OC) in [€]
- Interest Rate (IR) in [-]
- Margin Rate (MR) in [-]

The day rate is being multiplied by the number of days it takes to execute the project. To see what the difference is, three different project cases are tested against each other. In these three cases, three recently acquired projects are analyzed. Both concepts are tested for conventional cable laying with the NDurance and cable installation through a moonpool with the Fjell. Taking into account the operability limits determined in Chapter 7 for every specific cable lay concept and vessel, the workability percentages can be calculated. This is done using metocean data, taking a significant wave height of 1.5 meters for conventional cable laying with the NDurance and a significant wave height of 2.0 meters for cable laying via a moonpool with the Fjell. The workability percentages for every case can be seen in Table 8.1 and 8.3. These percentages are averaged over a year. A profit margin that generates an equal amount of profit for cable laying through a moonpool with the Fjell is calculated with a given 3 percent profit margin for conventional cable laying with the NDurance for every case.

	Case 1	**Case 2**	**Case 3**
Sea	Baltic Sea	North Sea	Atlantic Ocean
Location	North-East Germany	East England	East U.S.
Capacity	723 MW	1386 MW	1000 MW
Workability	83.6 %	69.0 %	66.3 %
Project Duration	23 days	40 days	22 days
Cable Length	270 km	380 km	200 km
Daily Cost	€109.700,-	€100.500,-	€110.600,-
Project Cost	€2.522.000,-	€4.019.000 ,-	€2.434.000 ,-
Annual Cost Price	€12.610.000,-	€20.093.000,-	€12.170.000,-
Profit Margin	3.0 %	3.0 %	3.0 %

Table 8.1: Project cases for NDurance

	Case 1	**Case 2**	**Case 3**
Sea	Baltic Sea	North Sea	Atlantic Ocean
Location	North-East Germany	East England	East U.S.
Capacity	723 MW	1386 MW	1000 MW
Workability	93.5 %	84.2 %	81.4 %
Project Duration	21 days	33 days	18 days
Cable Length	270 km	380 km	200 km
Daily Cost	€168.100,-	€147.600,-	€177.500,-
Project Cost	€3.530.000 ,-	€4.870.000 ,-	€3.195.000 ,-
Annual Cost Price	€17.649.000,-	€24.348.000,-	€15.974.000,-
Minimum Profit Margin	**2.1 %**	**2.5 %**	**2.3 %**

Table 8.2: Project cases for Fjell

In Table 8.3 the minimum profit margin that needs to be added to the annual cost price in all three cases is displayed. The day rates of the Fjell are higher in all cases, but with a higher workability project duration is less. Despite this, project costs are higher with the new cable lay concept.

The new cable lay concept has several advantages that can still make it a more competitive solution for export cable installation. The duration and costs of joints are not taken into account here, due to the lack of sufficient data. Also, the concept is likely to work more days per year because it can be deployed during harsher conditions. Hence, it is possible to work for a longer time, without having to terminate cable installation at the end of autumn and the beginning of winter.

To check this last case, workability percentages for the three project cases during summer and winter are compared in Table 8.4. For the scenarios during wintertime, the project costs for conventional cable laying and moonpool cable laying do not differ a lot. Therefore, further research has to be done. An example for further research is the implementation of joints, which is a major disadvantage of conventional cable lay vessels.

	Case 1	**Case 2**	**Case 3**
Workability Summer NDurance	93.7 %	91.1 %	90.4 %
Workability Summer Fjell	98.9 %	96.6 %	98.1 %
Workability Winter NDurance	72.7 %	53.4 %	50.9 %
Workability Winter Fjell	88.1 %	74.2 %	68.6 %
Project Cost Summer NDurance	€2.346.000,-	€3.138.000,-	€1.906.000,-
Project Cost Summer Fjell	€3.418.000,-	€4.311.000,-	€2.860.000,-
Project Cost Winter NDurance	€2.874.000,-	€4.987.000,-	€2.962.000,-
Project Cost Winter Fjell	€3.641.000,-	€5.316.000,-	€3.530.000,-

Table 8.3: Project cases per season

9

Conclusions & Recommendations

9.1. Conclusions

In this thesis, a cable lay system has been designed that can be used on existing non-cable lay vessels. This design is conceptualized and analyzed for a specific market, following the steps in the engineering design process. The technical and economic analysis investigates the feasibility and competitiveness of the new cable lay system.

The selected market is the international offshore export power cable installation market (both AC and DC), including interconnectors, from shore to substation or shore to shore. For this selected market, both technical and economic requirements have been determined. In brainstorm sessions, participants with varying educational backgrounds came up with new ideas for export power cable lay systems. The generated concepts were evaluated using multi-criteria analysis, scoring them on technical and economic criteria determined for the selected market. The final concept that has been selected for further development focuses on export cable laying through a moonpool. The Fjell, a Dockwise semi-submersible heavy transport vessel is targeted for this design because it is being converted into a fall pipe vessel already. This conversion includes the installation of a moonpool, opening up the possibility to make the Fjell a multi-purpose ship. With its reasonably good open water behavior, specially designed for long-distance transport with heavy loads, it can be employed all around the world.

The main technical challenge for the newly designed system is the second end cable pull-in. With limited space in the moonpool and vertical laying of the cable, the conventional pull-in method over the deck cannot be used here. Three solutions have been developed, based on a deployment quadrant or bight laydown. Two of these methods are already proven in the field, making them technically feasible. With the application of already proven techniques like bend restrictors and guiding frames, the third option where a quadrant is lowered through the moonpool is also technically feasible for quadrant sizes limited to the diagonal dimension of the moonpool.

Using static stability software, the maximum load-carrying capacity of this vessel has been determined. From the stability analysis, it can be concluded that the maximum cable load that can be carried by the Fjell is 9.000 tonnes of cable equivalent. This nearly doubles the capacity of conventional cable lay vessels within the Boskalis fleet, which have a load-carrying capacity of up to 5.000 tonnes. This capacity relates to approximately 110 km of currently installed export cable length, which means that the newly designed concept can install the vast majority of export cable lay projects without the use of joints, creating a competitive advantage.

An Orcaflex model has been made to evaluate both cable lay methods. Cable handling limits have been determined and are tested in different hydrodynamic conditions. The limits that are tested are axial compression, effective tension, sidewall pressure, torsion, and curvature. Using dynamic time-domain analysis, the operational limits have been determined for both conventional cable lay, and cable lay through a moonpool. This analysis concludes that cable laying through a moonpool indeed increases the workability for the Fjell with this particular catenary shape, which is limited by the dimensions of the moonpool. No significant increase can be seen for moonpool cable laying with the NDurance because only steps of 0.5 m significant wave height are analyzed. For the Fjell, conventional cable laying over a chute is not possible because the maximum allowable curvature is exceeded. This is due to the large arm for pitch motions, from the center of gravity to the chute at the aft of the vessel. Cable laying through a moonpool is possible up to at least 2 meters significant wave height. Furthermore, the limiting factor in all simulations is the maximum allowable curvature of the cable in the xz-plane. Maximum curvature always occurs in the segbend, moving closer to the touchdown point when the angle of departure of the cable is decreased.

To investigate the competitiveness of the newly designed cable lay concept, an economic analysis has been done. Several recently acquired project cases are introduced to compare project costs for both concepts. These project cases are situated around the world to investigate several project sites where offshore wind projects are commenced. Workability limits from the technical analysis are input for the calculation of project duration. These limits are generated using the operational limits and compare them to hydrodynamic data at different project sites. This analysis concludes that the newly designed cable lay concept is in average conditions 21 % to 40 % more expensive for all project cases than the conventional way of cable laying. An investment of approximately 22.5M Euro has to be done to realize this new concept. This illustrates that the newly designed cable lay system is not competitive with the conventional methods at the moment according to this economic evaluation.

However, the costs and installation time of joints with the conventional methods are not taken into account here. Also, similar cable lay speed is assumed for both concepts. Moonpool cable lay has a larger buffer between the gooseneck and carousel due to its high lay tower so that lay speed can be increased. Besides that, workability limits change per season. For cable installation during wintertime, the newly designed cable lay system is only 6.5 % to 27% more expensive than the conventional cable lay system depending on the project site. It is expected that when all these remarks are taken into account, for some cases cable laying through a moonpool can be favorable. Therefore, the new cable lay concept still has the potential to be competitive for the selected market. More research must be done to substantiate this. Recommendations for further research are done in Section 9.2.

9.2. Recommendations

In this section, recommendations for further analysis and development are provided. These recommendations are sorted by the different stages from the engineering design process.

9.2.1. Design

Burial

Burial of the cable is not included in the scope of this research but does account for a large amount of time within a project. Also, burying the cable bring a lot of technical difficulties. Both could result in a significant increase in costs. Therefore, it should be investigated which methods are available for export cable burial and how these can be incorporated in the design.

Lay Speed

The cable lay speed for the Fjell should be estimated Because of a larger buffer on deck due to the catenary shape between the high gooseneck and the carousel, the cable lay speed for the Fjell might be higher than for the NDurance. In the economic analysis in this report, both lay speeds are similar. Increased lay speed could result in shorter project duration.

9.2.2. Technical Analysis

ANSYS Aqwa Model Fjell

To rule out any differences, the displacement RAO's for the Fjell should also be generated in ANSYS Aqwa. For the Fjell, the sea states had to be determined beforehand to estimate the roll damping. Making a lines plan to incorporate the Fjell in ANSYS Aqwa, the sea states can be determined in Orcaflex. Therefore, the analysis in Orcaflex is not bounded to predetermined peak periods and significant wave heights. Thereafter, a full analysis has to be done for peak periods ranging from 4 - 12 seconds and significant wave heights ranging from 1 to 4 meters, with steps of 0.25 m.

Incorporate pull-in in Model

In this report, an operational limit for cable laying has been determined for both conventional cable laying and cable laying through a moonpool. The operational limits for the second end pull-in, for the nearshore operation and shore landing are not yet determined. This should be incorporated into the moonpool and chute model to estimate the workability for a project more accurate.

Optimize Catenary Shape

The catenary shape can be optimized for both concepts. This will prevent whip cracks from happening in the cable, resulting in a more realistic representation of cable laying. Bottom tension, departure angle, layback, cable length, and top tension can be altered with to optimize the catenary shape. Also, the catenary shape parameter can be changed. The ideal catenary shape for S-lay can be different from that of J-lay because the departure angle of the cable through a moonpool is limited to the moonpool dimensions.

QSHE

Safety is not yet assessed for this preliminary design. A QSHE analysis should be done to prove that the concept is safe for workers and the environment. Procedures should be developed, evaluated, and incorporated into industry standards.

Human motions limit

Another important issue is to look at operational limits for workers, in accordance with the Nordforsk criteria. An insight has already been given in this report, but accelerations should be checked to assess if technical limits do not exceed human operational limits.

9.2.3. Economic Analysis

Joints

Despite being a major advantage for the new cable lay concept to lay an export cable without joints, joints are not incorporated in the economic analysis due to a lack of data. Therefore, further research on costs and installation time has to be done. This data should be incorporated into the model to estimate project costs more accurately.

2nd end pull-in & shore landing

The costs for the second end pull-in and shore landing are not included in the model because this represents only a limited amount of time compared to the whole export cable installation. To estimate the total project costs more accurately, the second end pull-in, nearshore installation and shore landing should be included in the economic analysis.

Risk

Risk is taken into account in a margin, representing possible delay or failure during installation. A risk assessment matrix has to be made, quantifying all economic, technical, commercial, organizational, and political risks and how they can be mitigated to an acceptable level.

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A Ship Database

To get insight in the different vessels that Boskalis possesses, an overview including technical specifications has been made. These specifications are used to categorize these assets.

Name	Fleet Class	Function	Length [m]	Breadth [m]	Depth [m]	Draft [m]	DP
Argonaut	Dredging	TSHD	58.9	14.0	6.3	4.2	None
Attila	Dredging	Backhoe	37.5	15.0	3.0	2.2	None
DB2	Offshore	Inshore/Coastal Dive	12.5	4.4		0.7	None
DB1	Offshore	Inshore/Coastal Dive	12.5	4.4		0.7	None
Baldur	Dredging	Backhoe	73.1	19.0	5.5	3.4	None
Barent Zanen	Dredging	TSHD	133.6	23.1	10.0	6.8	None
Beachway	Dredging	TSHD	118.5	21.0	7.7	5.1	None
E1601	Offshore	Pontoon CC/RoRo	60.0	13.0	3.0	1.6	None
E1506	Offshore	Pontoon CC/SA/TA	65.0	16.0	3.4	1.6	None
Beaver St. Lawrence	Dredging	Cutter Suction	46.3	9.1	2.0	1.5	None
BKM102	Dredging	Multicat	26.5	11.8	3.9	2.6	None
BKM103	Dredging	Multicat	26.5	11.8	3.9	2.6	None
BKM104	Dredging	Multicat	31.5	13.3	4.4	2.6	None
Capricorn	Dredging	Cutter Suction	107.0	19.0	7.6	4.9	None
Causeway	Dredging	TSHD	92.1	19.0	7.3	6.4	None
Ceres	Dredging	Cutter Suction	66.8	9.8		1.6	None
Coastway	Dredging	TSHD	97.7	23.0	7.0	5.4	None
Suzanne	Offshore	Multipurpose	26.0	9.5		2.0	None
Rebecca 5	Offshore	Multipurpose	26.0	9.5		2.0	None
E3505	Offshore	Pontoon CC/TA	66.0	23.0	4.0	2.0	None
Colbart	Dredging	Backhoe	50.0	15.0	3.5	2.5	None
Kim	Offshore	Multipurpose	21.6	9.0		2.0	None
Cornelius	Dredging	Backhoe	42.0	15.0	3.0	1.8	None
Smitbarge 12	Offshore	Pontoon CC	75.0	23.5	4.5	2.1	None
Smitbarge 14	Offshore	Pontoon CC	75.0	23.5	4.5	2.1	None
Smitbarge 11	Offshore	Pontoon CC	75.0	23.5	4.5	2.1	None
Smitbarge 10	Offshore	Pontoon CC	75.0	23.5	4.5	2.1	None
Crestway	Dredging	TSHD	97.5	21.6	7.6	5.6	None
Cyrus II	Dredging	Cutter Suction	107.0	19.0	7.6	4.9	None
Nova K	Offshore	Multipurpose	32.0	11.1		2.3	None
Deo Gloria	Dredging	TSHD	71.4	14.0	3.8		
Dina M	Dredging	Crane Barge	60.0	22.4		1.9	None
E1703	Dredging	Pontoon CC/SA	50.0	18.0	3.5	1.6	None
E1704	Dredging	Pontoon CC/SA	50.0	18.0	3.5	1.9	None
Tessa	Offshore	Multipurpose	23.6	9.9		2.4	None
Sidi C	Offshore	Multipurpose	32.0	11.1		2.4	None
E3004	Offshore	Pontoon CC/RoRo	67.0	18.0	4.5	2.5	None
Lydia D	Offshore	Multipurpose	31.1	10.0		2.5	None
E3504	Dredging	Pontoon CC	60.0	21.5	4.0	2.1	None
E801	Dredging	Inland Barge	36.1	16.1	2.1	1.0	None
Edax	Dredging	Cutter Suction	89.2	18.3	5.0	3.5	None
Elisa	Dredging	Floating Grab Crane	50.0	14.0	3.0	1.9	None
Fairway	Dredging	TSHD	230.7	32.0	16.9	13.5	None
Bokabarge 7	Offshore	Pontoon	84.0	23.5	5.5	2.8	None
Bokabarge 8	Offshore	Pontoon CC/Sub	84.0	23.5	5.5	2.8	None
Bokabarge 6	Offshore	Pontoon CC/Sub	84.0	23.5	5.5	2.8	None
Smitbarge 9	Offshore	Pontoon CC/Sub	84.0	23.5	5.5	2.8	None
Yvonne	Offshore	Multipurpose		11.0		2.8	None
Cork Sand	Offshore	Split Hopper	65.0	11.8	4.3	2.8	None
Long Sand	Offshore	Split Hopper	65.0	11.8	4.3	2.8	None
Freeway	Dredging	TSHD	92.1	19.0	7.3	6.4	None
Frigg	Dredging	Hopper	60.0	11.4	4.5	3.0	None
Gateway	Dredging	TSHD	143.5	28.0	13.5	9.0	None
Goodwin Sand	Dredging	Backhoe	35.9	9.8	2.5	1.4	None
Goomai	Dredging	Grab dredger	54.6	19.8	3.4	2.0	None
Helios	Dredging	Cutter Suction	152.0	28.0	8.9	5.4	None
HH 203	Dredging	TSHD	69.9	9.54		2.5	None
Bokalift 1	Offshore	Crane	216.0	43.0	13.0	8.5	2
Huislift 2	Dredging	Pontoon TA	10.4	5.3	3.0	0.6	None
Huislift 3	Dredging	Pontoon TA	10.4	5.3	3.0	0.6	None
Jan van Gent	Dredging						
Smitbarge 2	Offshore	Pontoon CC	91.7	30.8	7.6	3.6	None
Taklift 7	Offshore	Floating Sheerleg	72.6	30.5	5.5	3.7	None
Giant 6	Offshore	Semi-Sub	137.0	36.0	8.5	4.2	None
Giant 5	Offshore	Semi-Sub	137.0	36.0	8.5	4.2	None
Koura	Dredging	Backhoe	33.5	14.0	3.0	2.3	None
Kuokka-Pekka 2	Dredging	Backhoe					None
Magnor	Dredging	Backhoe	72.0	20.4	5.5	3.4	None
Taklift 4	Offshore	Floating Sheerleg	83.2	36.9	7.0	4.5	None
Diamond	Offshore	Anchor Handling Tug	35.8	11.0	5.6	4.8	None
Rockpiper	Offshore	Fallpipe	158.6	36.0	13.5	9.4	2
SMIT Kamara	Offshore	Anchor Handling Tug + OSV + ROV	70.9	16.0	7.0	4.8	None
Seahorse	Offshore	Fallpipe	162.0	38.0	9.0	6.3	2
Atlantis	Offshore	DSV	115.4	22.2	9.0	7.0	2
Sapphire	Offshore	Anchor Handling Tug	35.8	11.0	5.6	4.8	None
Manu-Pekka	Dredging	Backhoe	47.9	15.0	3.0	2.0	None
Martina	Dredging	Cutter Suction	52.3	8.6	2.75	1.7	None
Da Vinci	Offshore	DSV	115.4	22.2	9.0	7.0	2
FSP 102	Offshore	Barge	60.0	40.0	6.0	5.0	None
FSP 101	Offshore	Barge	60.0	40.0	6.0	5.0	None
Medway	Dredging	TSHD	121.3	21.0	7.7	3.3	
Meri-Pekka	Dredging	Floating Grab Crane	47.5	18.5	2.7	1.9	None
MP 27	Dredging	Backhoe	49.3	18.1	3.0	2.4	None
MP 40	Dredging	Backhoe	60.0	18.0	3.5	2.7	None
BOKA Sherpa	Offshore	Oceangoing Tug	75.1	18.0	8.0	5.4	None

Fairmount Glacier	Offshore	Oceangoing Tug	75.1	18.0	8.0	5.4	None
Fairmount Alpine	Offshore	Oceangoing Tug	75.1	18.0	8.0	5.4	None
Fairmount Summit	Offshore	Oceangoing Tug	75.1	18.0	8.0	5.4	None
Fairmount Expedition	Offshore	Oceangoing Tug	75.1	18.0	8.0	5.4	None
Nordic Giant	Dredging	Backhoe	55.0	17.0	4.0	3.0	None
Oranje	Dredging	TSHD	156.0	28.0	15.0	9.7	None
Wrestler	Offshore	Anchor Handling Tug	40.7	12.7		5.5	None
Union Warrior	Offshore	Anchor Handling Tug	40.7	12.7	6.9	5.5	None
Packman	Dredging	Floating Grab Crane	43.9	15.2	3.4	2.3	None
Phoenix I	Dredging	Cutter Suction	132.3	19.2	8.2	5.6	None
Prins der Nederlanden	Dredging	TSHD	156.0	28.0	15.0	9.7	None
Queen of the Netherlands	Dredging	TSHD	230.7	32.0	16.4	12.0	None
Rhone	Dredging	Cutter Suction	64.9	12.44		2.1	None
Smit Nicobar	Offshore	Anchor Handling Tug	70.9	16.0		5.7	
Union Boxer	Offshore	Anchor Handling Tug	40.7	12.7	6.9	5.9	None
Fighter	Offshore	Anchor Handling Tug	40.7	12.7	6.9	5.9	None
Union Manta	Offshore	Anchor Handling Tug	75.5	18.0	8.0	6.0	None
Fjord	Offshore	Heavy Transport	159.2	45.5	9.0	6.1	None
Seraya	Offshore	Anchor Handling Tug	51.8	15.0	6.5	6.2	None
Sovereign	Offshore	Anchor Handling Tug	67.4	15.5	7.5	6.2	None
Sentosa	Offshore	Anchor Handling Tug	51.8	15.0	6.5	6.2	None
Union Princess	Offshore	Anchor Handling Tug	67.4	15.5	7.5	6.2	None
Ndurance	Offshore	CLV	99.0	30.0	7.0	4.8	2
Rind	Dredging	Hopper	60.0	11.4	4.5	3.0	None
Rocky I	Dredging	Backhoe	50.8	16.0	3.1	2.3	None
Seaway	Dredging	TSHD	171.9	22.0	12.5	8.1	None
SMIT Angola	Offshore	OSV	49.5	15.0	6.8	6.4	None
Fjell	Offshore	Heavy Transport	147.2	36.0	9.0	6.4	None
Giant 7	Offshore	Multipurpose	137.0	36.0	8.5	6.5	None
Seine	Dredging	Cutter Suction	64.0	11.4	2.9	1.9	None
Shoalway	Dredging	TSHD	90.0	19.0	7.3	6.8	None
Ndeavor	Offshore	CLV	99.0	30.0	7.0	4.8	2
Union Bear	Offshore	Anchor Handling Tug	73.5	16.4	8.0	6.9	None
EDT Protea	Offshore	DSV	91.2	14.8		6.8	3
Stemat Spirit	Offshore	CLV	90.0	28.0	6.5	3.3	2
Shoreway	Dredging	TSHD	97.5	21.6	7.6	5.6	None
Constructor	Offshore	DSV	76.0	18.0	6.1	5.0	2
Mighty Servant 1	Offshore	Heavy Transport	190.0	50.0	12.0	8.8	None
Transshelf	Offshore	Heavy Transport	173.0	40.0	12.0	8.8	None
Sinaloa	Dredging	Cutter Suction					None
Saspan Dau	Dredging	TSHD	72.8	14.3	3.8	2.6	None
Smit Komodo	Offshore	DSV + OSV + ROV	70.9	16.0	7.0	4.8	2
Mighty Servant 3	Offshore	Heavy Transport	181.2	40.0	12.0	9.5	None
Strandway	Dredging	TSHD	92.1	19.0	7.3	6.4	None
Taurus II	Dredging	Cutter Suction	112.6	24.0	7.5	4.9	None
Swift	Offshore	Heavy Transport	181.0	32.3	13.3	9.7	None
Swan	Offshore	Heavy Transport	181.0	32.3	13.3	9.7	None
Forte	Offshore	Heavy Transport	216.8	43.0	13.0	9.9	None
Teal	Offshore	Heavy Transport	180.9	32.3	13.3	10.0	None
White Marlin	Offshore	Heavy Transport	216.7	63.0	13.0	10.0	None
Black Marlin	Offshore	Heavy Transport	217.8	42.0	13.3	10.1	None
Blue Marlin	Offshore	Heavy Transport	224.8	63.0	13.3	10.2	None
Triumph	Offshore	Heavy Transport	216.8	44.5	14.0	10.4	None
Trustee	Offshore	Heavy Transport	216.8	44.5	14.0	10.4	None
Talisman	Offshore	Heavy Transport	216.8	44.5	14.0	10.4	None
Treasure	Offshore	Heavy Transport	216.8	44.5	14.0	10.4	None
Transporter	Offshore	Heavy Transport	216.8	44.5	14.0	10.4	None
Target	Offshore	Heavy Transport	216.8	44.5	14.0	10.4	None
Terra Plana	Dredging	Water Injection	39.8	12.0	4.1	3.0	1
Terraferre 301	Dredging	Hopper	71.9	14.6	5.8	5.2	None
BOKA Vanguard	Offshore	Heavy Transport	275.0	70.0	15.5	31.5	None
HD3	Offshore	Plough	N/A	N/A	N/A	N/A	N/A
BSS-II	Offshore	Burial Tool	N/A	N/A	N/A	N/A	N/A
ROV trencher 107-1100	Offshore	ROV	N/A	N/A	N/A	N/A	N/A
Trenchformer	Offshore	Subsea Cable Trencher	N/A	N/A	N/A	N/A	N/A
Seaeye Cougar XT	Offshore	ROV	N/A	N/A	N/A	N/A	N/A
Smit HD W-ROV	Offshore	ROV	N/A	N/A	N/A	N/A	N/A
Seaeye Falcon	Offshore	ROV	N/A	N/A	N/A	N/A	N/A
Seaeye Tiger	Offshore	ROV	N/A	N/A	N/A	N/A	N/A
Seaeye Panther	Offshore	ROV	N/A	N/A	N/A	N/A	N/A
Smit Borneo	Offshore	Crane + Accomodation	110.0	30.0	7.6		None
Asian Hercules III	Offshore	Floating Sheerleg	106.4	52.0	10.0		None
Asian Hercules II	Offshore	Floating Sheerleg	91.4	43.4	5.6		None
Terraferre 302	Dredging	Hopper	71.9	14.6	5.8	5.2	None
Terraferre 501	Dredging	Hopper	94.3	16.6	7.2	5.5	None
Terraferre 502	Dredging	Hopper	94.3	16.6	7.2	5.5	None
Terramare I	Dredging	Multipurpose	30.1	9.1		3.2	None
Union Onyx	Dredging	Pusher Tug	33.0	11.0		4.4	None
Union Topaz	Dredging	Pusher Tug	33.0	11.0		4.4	None
Wadden 1-4	Dredging	Split Barge	60.0	11.3		3.1	None
Waterway	Dredging	TSHD	97.7	23.0	7.0	5.4	None
Willem van Oranje	Dredging	TSHD	143.5	28.0	13.5	9.0	None
Pontra Maris	Offshore	CLV	70	23.8	5.7	2.2	None
Smit Ranger	Offshore	DSV	12.9	4.4	1.8	1.1	None
Parrot 2	Offshore	DSV					
Wodan	Dredging	Backhoe	56.4	17.4	3.7	1.7	None

Figure A.1: Ship Categorization Database Extract

B

Summary Interview Market Selection Tim van Keulen

To define the market on which this thesis project focuses, an interview with Boskalis SC&F Solutions Manager Tim van Keulen has been conducted on January 16, 2019. Below a summary of this interview.

1. **What is the main business and focus of Boskalis in offshore cable lay right now (export vs. in-field, short distance vs. long distance, etc.)?**
   Boskalis tenders as much in all sectors as possible, so the diversity of projects is very large. In practice there are less export cable lay projects than in-field.

2. **What are Boskalis' strong suits in offshore cable lay right now (beaching, small draft, etc.)?**
   - *Having three cable lay ships*
   - *Having a lot of trenching tools*
   - *Widely employable as company (multiple activities in one tender)*
   - *Having the longest track record in offshore cable lay*
   - *Having excellent near shore capacity*
   - *Having long-lasting relationships with: NKT, Nexans, Prismian (only NKT for DC cables)*
   - *Prioritizes local content*
   - *Having flexible + modular equipment*

3. **What are Boskalis' weaknesses in offshore cable lay right now (capacity, open water behaviour, etc.)?**
   - *Less export cable projects because of maximum load capacity of 5000 tonnes*
   - *Price*
   - *Joints needed to install cables over longer distances*

4. **What sort of cables will Boskalis primarily focus on in the next 10 years (in-field, export, interconnectors, etc.)? Where can it grow in market share?**
   - *Focuses more on export (and interconnectors)*

- *Projects will be further offshore*
- *Projects will open up in Taiwan and The U.S.*

5. **What kind of current will Boskalis primarily focus on in the upcoming 10 years (DC or AC)?** *No particular type of current, but AC is still used most frequent.*

6. **What will be the capacity that has to be transported accordingly (cable + carousel tonnage)?**
The load carrying capacity needs to be about 10.000 tonnes, which matches approximately 100km of offshore power cable. AC solutions now also become feasible for long distances with the use of booster stations.

7. **What has to be the lifetime of a new cable lay concept or already existing cable lay vessel?**
The lifetime for most cable lay equipment is 20 years, depending on size, usage, etc.. The lifetime of cable lay vessels are up to 50 years. Sometimes, also old vessels can be overhauled to a CLV.

8. **What is the most important thing in the decision making process in concept selection in offshore cable lay?**
Cost and risk are the most important factors in the decision making process.

9. **Are there new markets that are opening up and interesting for Boskalis (interconnectors, floating wind, offshore islands, energy hubs, etc.)?**
The projects where Boskalis is not yet fully present focus on export cables and interconnectors for international wind farms. Also floating offshore wind might be opening up in the upcoming decade, but that market will be small compared to bottom founded offshore wind.

10. **Where are the projects situated that Boskalis will focus on in the next 10 years (Taiwan, The U.S., etc.)?**
Probably one ship will go to Taiwan in the future, so then there are two ships left in The Netherlands. Therefore, a conceptual design that can be placed on already existing Boskalis vessels will come in handy. Also, management is looking to buy another vessel for in-field cable installation.

11. **Are there any other requirements (multi-purpose, modular, etc.) that you would like to see in a cable lay concept?**
There is very much a shift towards multi-purpose vessels. This is the case in most offshore sectors, not only in the cable installation sector.

12. **Are there any other trends we see in the market that are becoming more and more important?**
Environmental rules due to government regulation/demands will be more strict, subsidies will disappear.

13. What implementations have to be done to the concept regarding sustainability?
Sustainability will be taken into account by the customer in the tender process, besides price, duration and quality.

14. What opportunities do you see to create synergy between cable lay and other sectors (oysters, artificial reefs, etc.)?
So far only oysters on cable crossings where rock dumping took place, maybe its possible to think out a few other ideas.

15. What is, besides economical and technical feasibility, the main deal breaker when evaluating a concept for Boskalis?
None.

C

Brainstorm Database and Ideas

Here, an overview of the ideas generated during the brainstorm sessions can be seen, presented in sketches.

Concept Name	Category	Vessel Type	Concept Basis	Investment [1: Low - 5: High]
Less and Faster	Modifications		Less fuel, crew and faster winch, carousel	1
Maximize cable capacity	Modifications	Heavy Transport	Install more cable capacity on export vessel	1
1er failure rate	Modifications		Double redundant cable installation	1
Semi Sub Carousel	Floating	Anchor Handling Tug Big	Semi sub unrolls cable, driven by motor on tug	2
Floating Cable Factory	Floating	Multiple	Fabricating cable while shipping	5
Lighten Cable	Modifications		Make cable lighter so a CLV can bring more cable length	1
CLV's Combined	Modifications	CLV	One nearshore, one offshore CLV	1
Underwater Quick Connector	Modifications		Quick connector for 2nd end pull in	1
Pulling to OSS	Subsea		Pulling cable to sub station by winch	3
Pulled Drum	Floating	Anchor Handling Tug Small	Floating drum pulled by vessel	4
Cable Cart	Subsea	DSV	Cable pulled by underwater car/tank	4
Rock dumper	Floating	Fallpipe	Lay cable through rock dumping buckets	3
Beach filling	Modifications	Barge	Lay cable on beach and pick up with near shore barge	1
Improve joints	Modifications		Improve joints (speed + workability)	1
Barges + Semi Sub	Floating	Heavy Transport	Load multiple carousels on barges on semi sub transport vessel	2
Moonpool cable lay	Floating	Fallpipe	Lay cable through moonpool of ship	3
Catamaran vessel	Floating	Multiple	Two vessels with drum floating inbetween	4
Hoovercraft	Modifications		Make carousel float by hoovercraft system	5
Booster	Modifications		Use AC booster station to lay shorter lengths	4
Vessel + ROV	Floating	Multiple	Underwater rov installing cable	2
Tug + Barge	Floating	Anchor Handling Tug Small	Tug towing barge with carousel	1
Floating Basket	Floating	Anchor Handling Tug Small	Basket flowing in water and pulled by tug boat	4
Semi sub Barge	Floating	Anchor Handling Tug Small	Floating basket without DP, being pulled by Anchor handling tug	4
Combine big and small	Floating	Multiple	Large cheap vessel + dp2 small vessel for cable laying	2
Squeezed cable drum	Floating	Multiple	Drum inbetween two ships	4
ROV pulled drum	Floating	DSV	Floating cable drum pulled by ROV on seabed	4
Wide spools	Modifications		Multiple spools connected for more capacity	1
Connect & Go	Modifications	Anchor Handling Tug Small	Connectible carousel can be attached to ship	5
Semi sub power	Floating	Heavy Transport	Semi sub including multiple carousels	2
Boat cable storage	Modifications	CLV	Coil cable around whole ship	3
Middle exit	Modifications		Cable exit over middle bow of ship	2
Vertical buffer	Modifications	CLV	Make vertical buffer instead of horizontal	3
Re-use of Pipelines	Subsea		Lay cable throug already existing pipeline	4
Walking factory	Special		Make a walking factory, by moving the jack up legs	5
Shore2Shore pull	Floating	Anchor Handling Tug Small	Pull cable with rope and winch to substation/other shore	3
Hoover boat	Floating		Hoover boat for near shore capacity	5
Tug reel	Floating	Anchor Handling Tug Small	Floating storage in carousel, pulled by tug boat	4
Subsea moonlander	Subsea	DSV	Moonlander ROV that pulls cable over seafloor	5
Multi use tunnel	Subsea		Make a tunnel for crew/maintenance and cable lay to platform	5
Curtains rail	Floating	Anchor Handling Tug Small	Pull cable in and attach floaters, like a curtains rail	2
Swimming ROV	Floating	Multiple	Use cable drum on vessel and pull with swimming ROV	4
Hydrogen Transport	Special		Store and transport energy by converting to hydrogen	5
Dual tug life	Floating	Multiple	Catamaran vessel with carousel inbetween	4
Cable 4way	Subsea		Lay pipe segments where optics, DC, hydrogen and hyperloop are combined	5
Vertical Axis Floating Spool	Floating	Anchor Handling Tug Small	Pulled carousel by tug, cable installed using floaters	4
Airplane laying	Special		Put carousel in airplane and 1er cable like this	5
Curtains rail	Floating	Anchor Handling Tug Small	Pull cable toward plaftform which is supported by floaters	2
Subsea tunnel	Subsea		Drilling tunnel and lay cable throug it	5
ROV subsea	Subsea	DSV	Let ROV drive with cable behind it	4
Cargo Ship + DP Ship + Barge	Floating	Multiple	Cargo ship with large carroussels and cable lay equipment and AHT to get near platform	2
TSDH + DP Ship + Barge	Floating	Multiple	Cable throug TSHD pipe with AHT to get near platform	3

Figure C.1: Brainstorm Database for Concept Generation

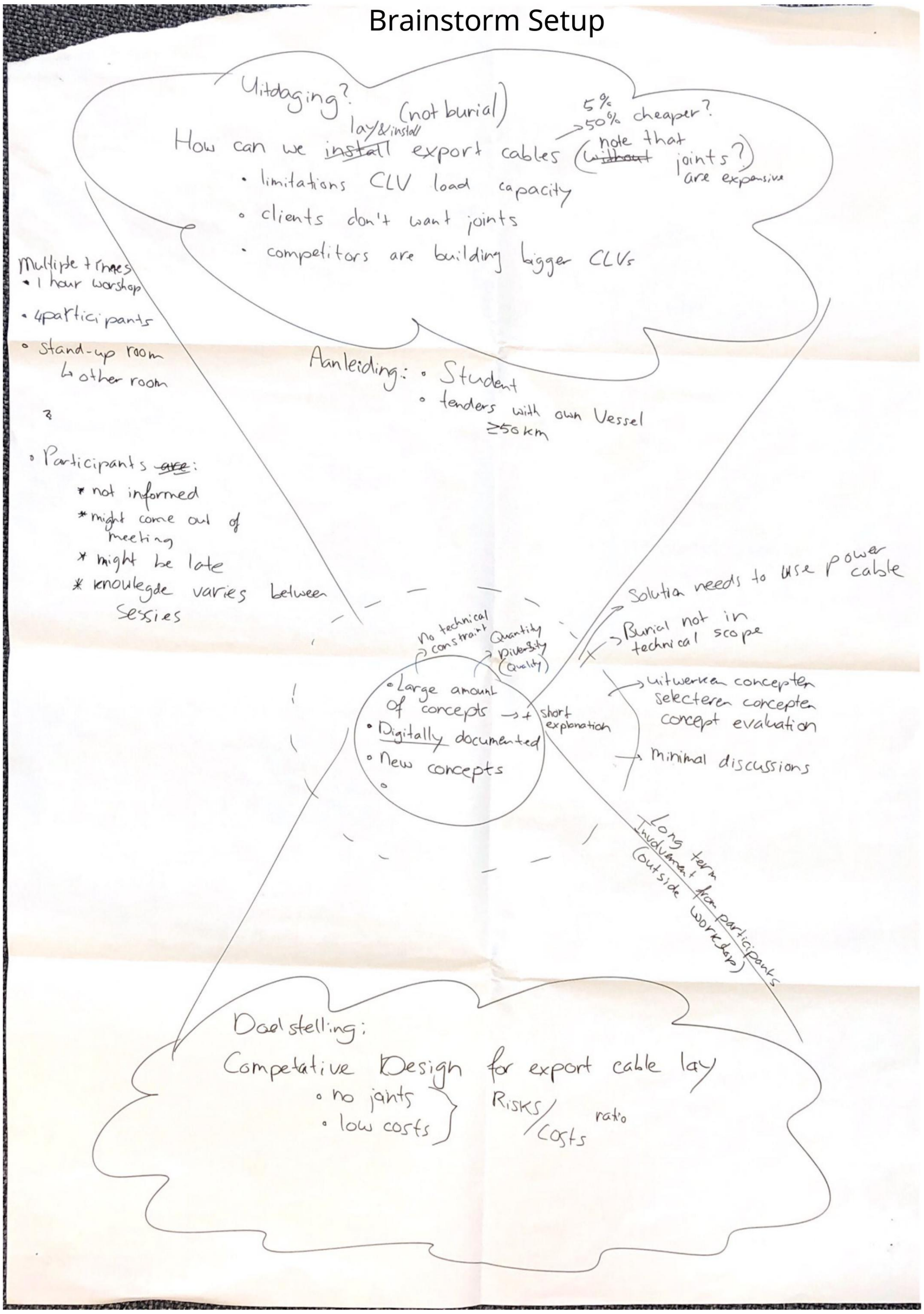


Figure C.2: Brainstorm Setup Hourglass Model

Technical Students

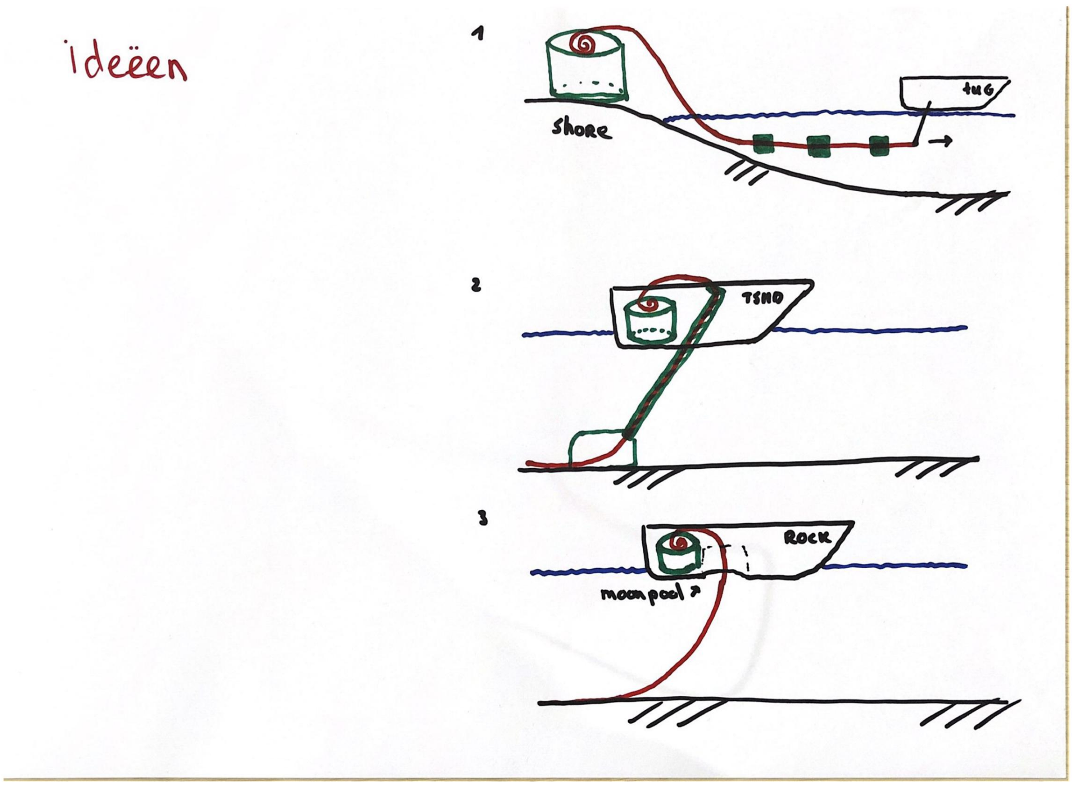


Figure C.3: Cable pulling, Cable through TSHD suction pipe, Cable through moonpool of fall pipe vessel

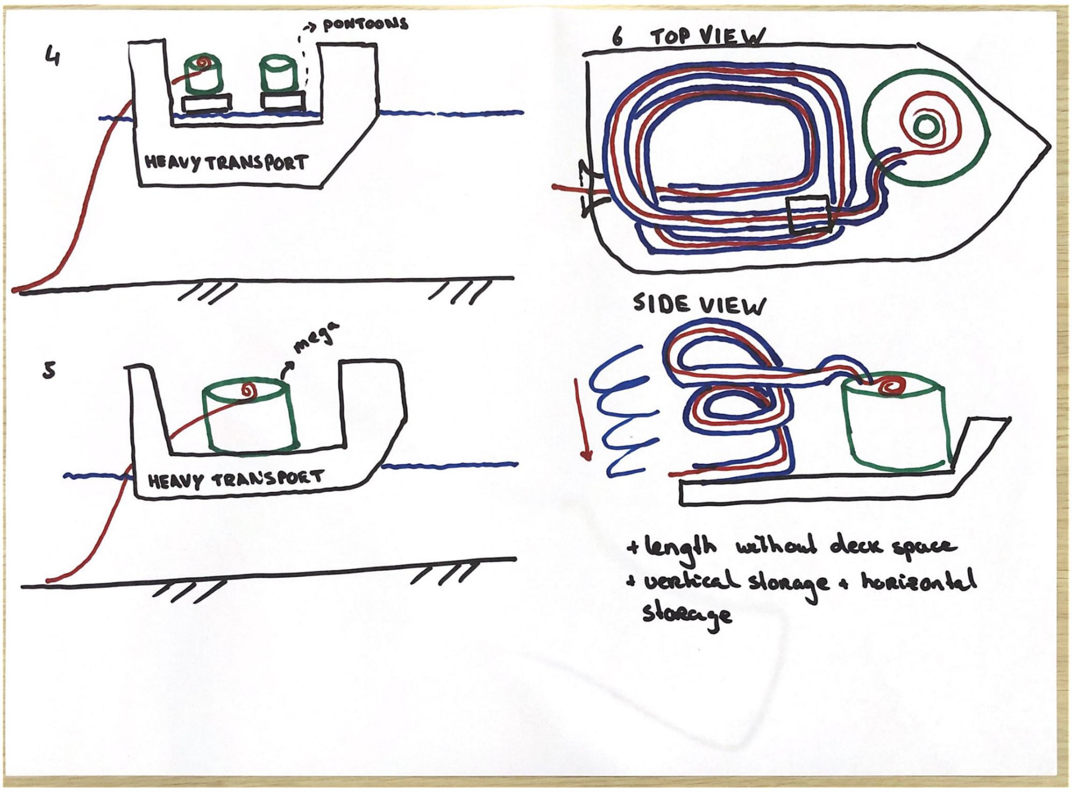


Figure C.4: Pontoons on heavy transport vessel, Large carousel on heavy transport vessel, stacked cable highway on deck

ODE Students

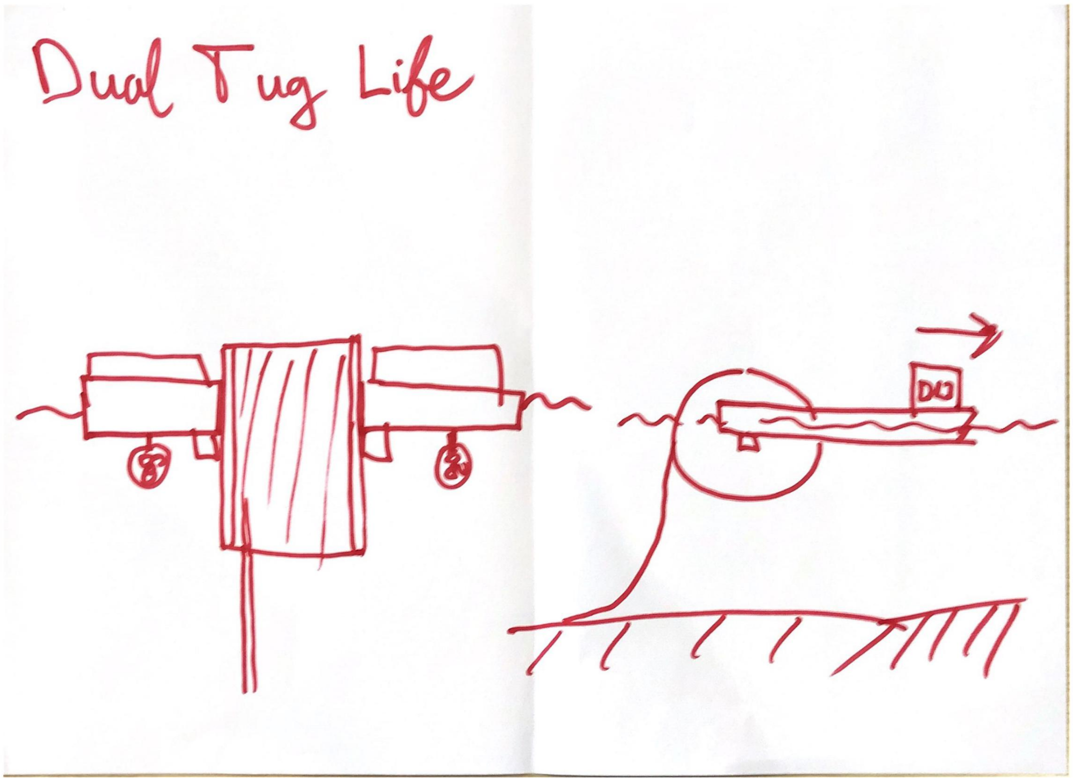


Figure C.5: Unrolling carousel with two tug boats

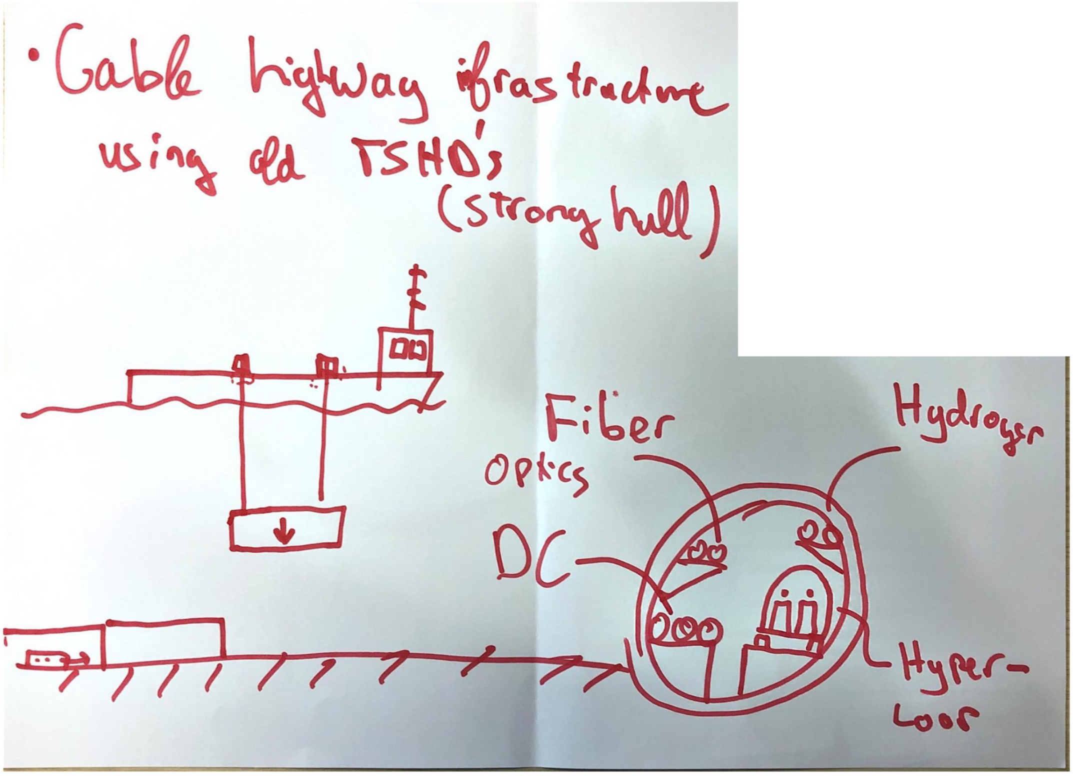


Figure C.6: Cable highway pipeline segment infrastructure

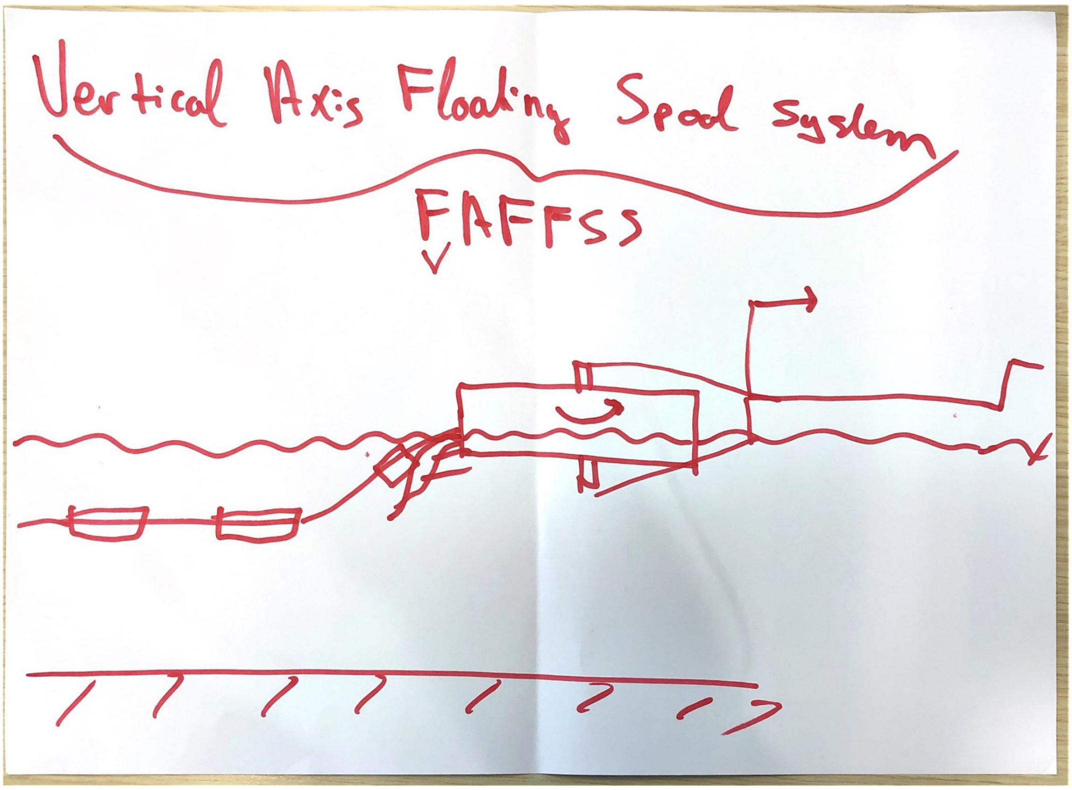


Figure C.7: Floating carousel unrolling cable

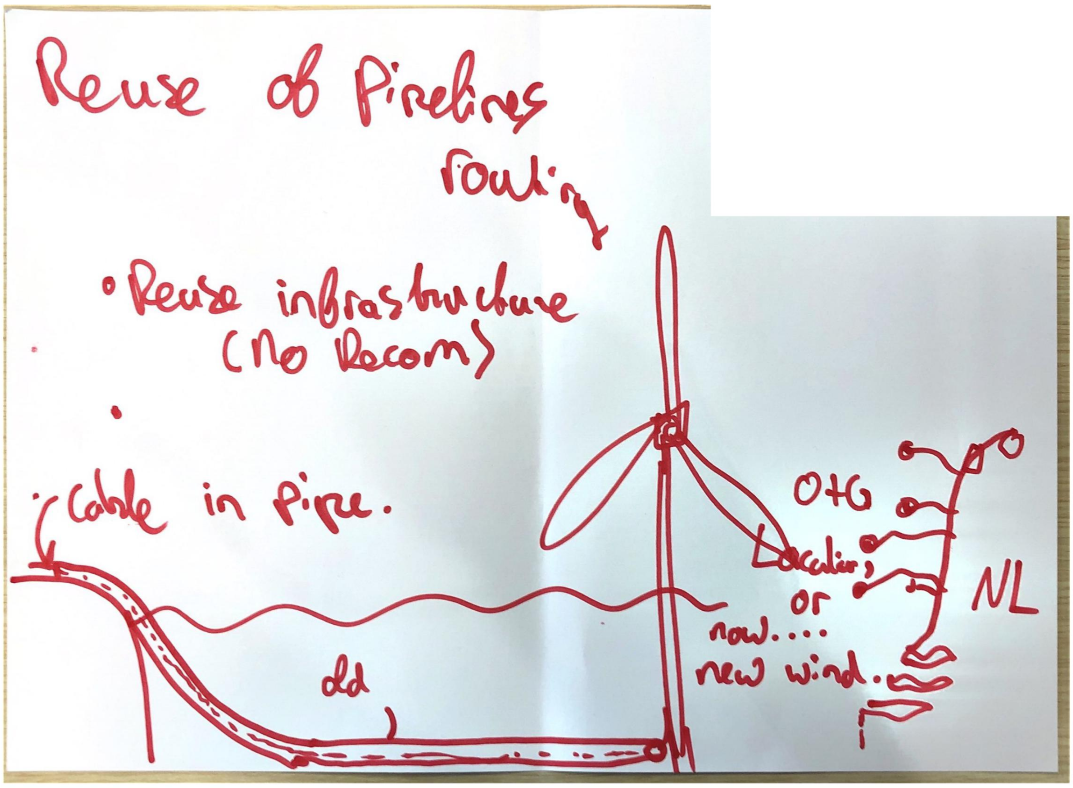


Figure C.8: Cable through existing old pipelines

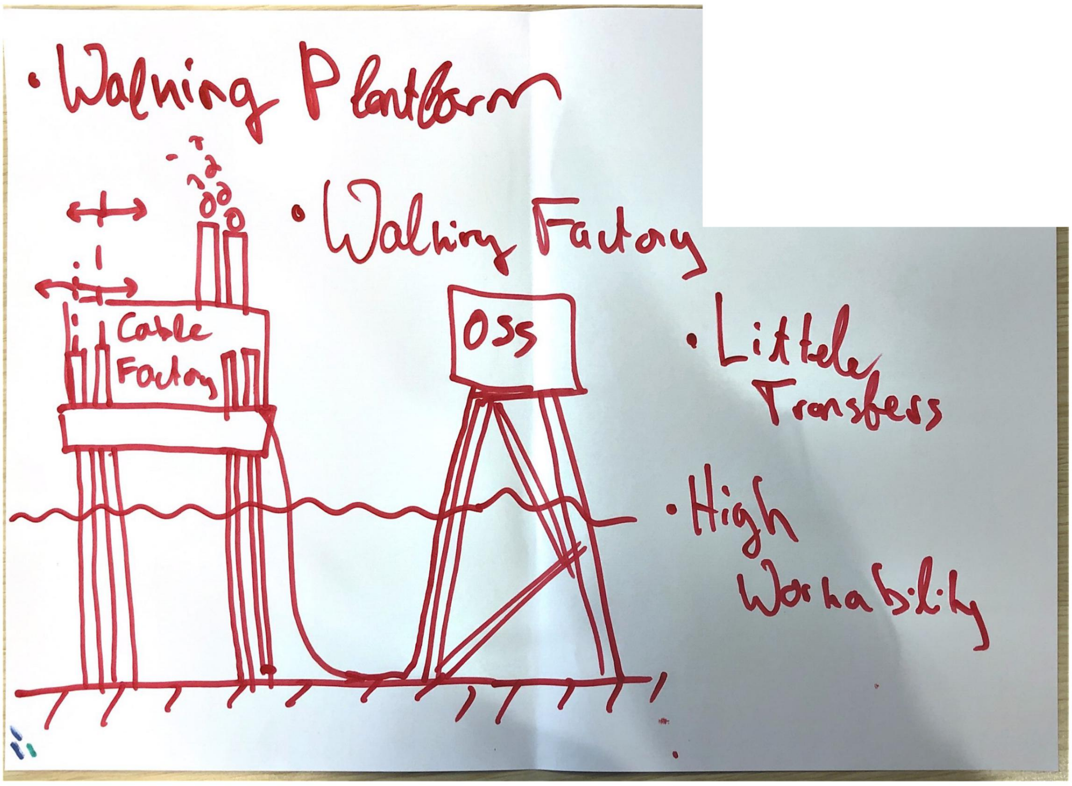


Figure C.9: Walking cable factory

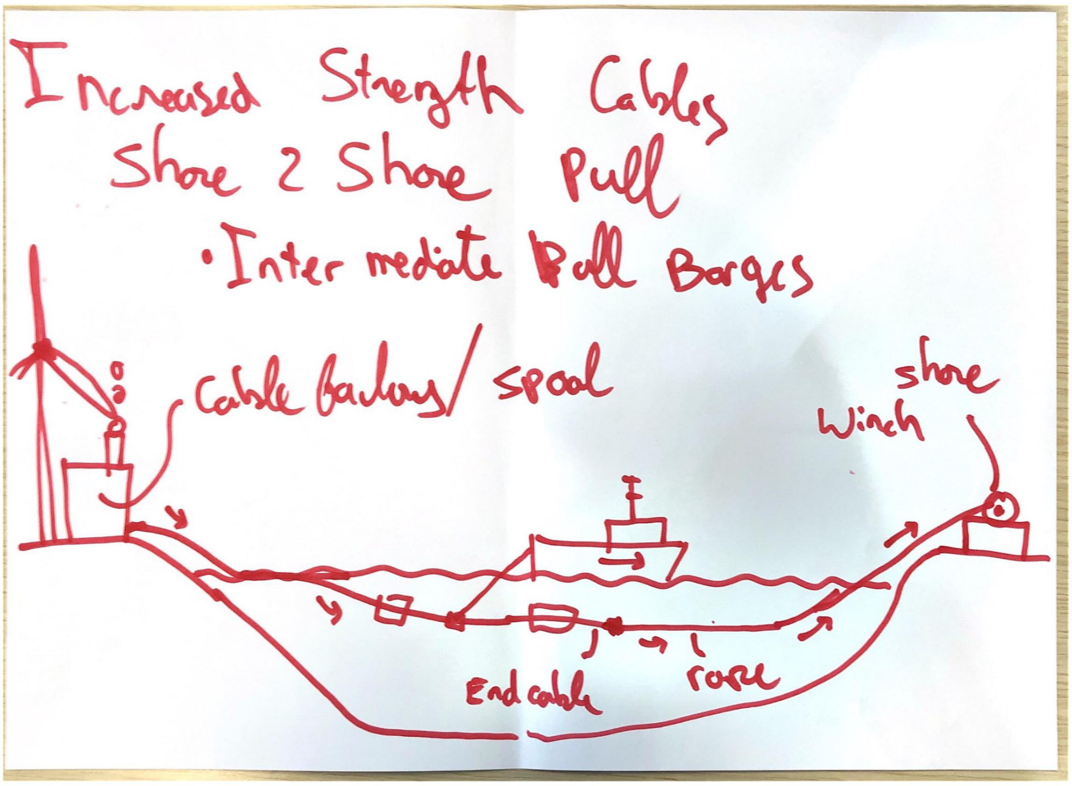


Figure C.10: Cable pulling by tug boat and winch

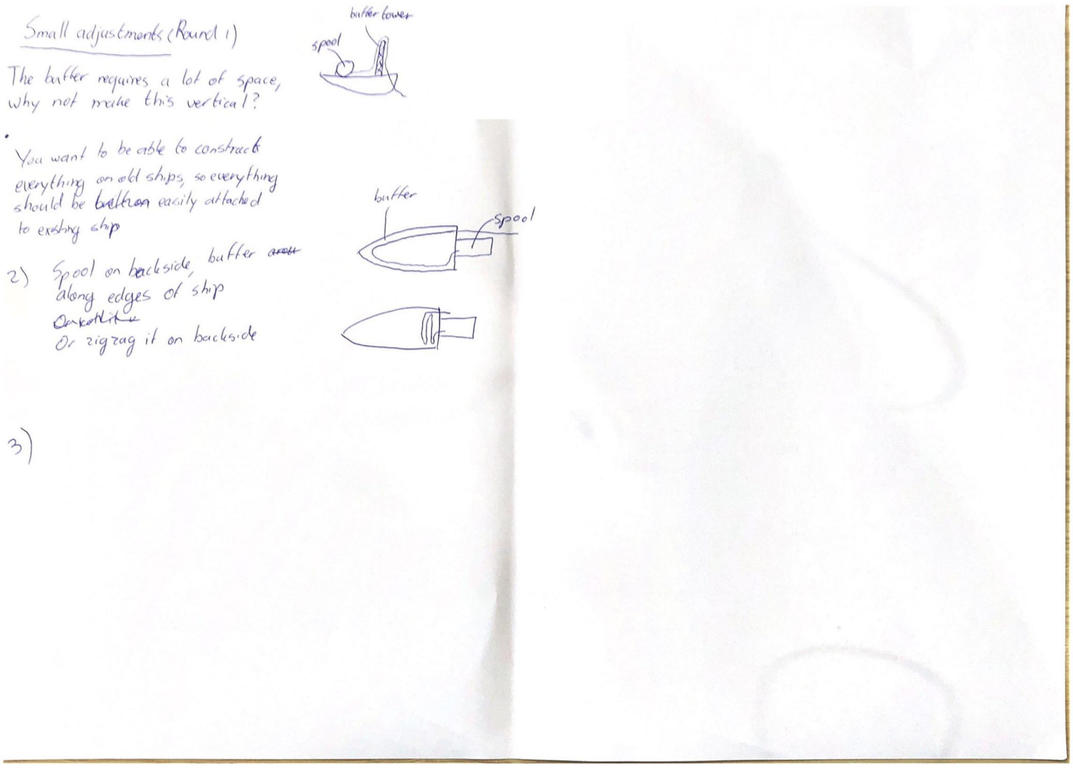


Figure C.11: Minor modifications to existing CLV's

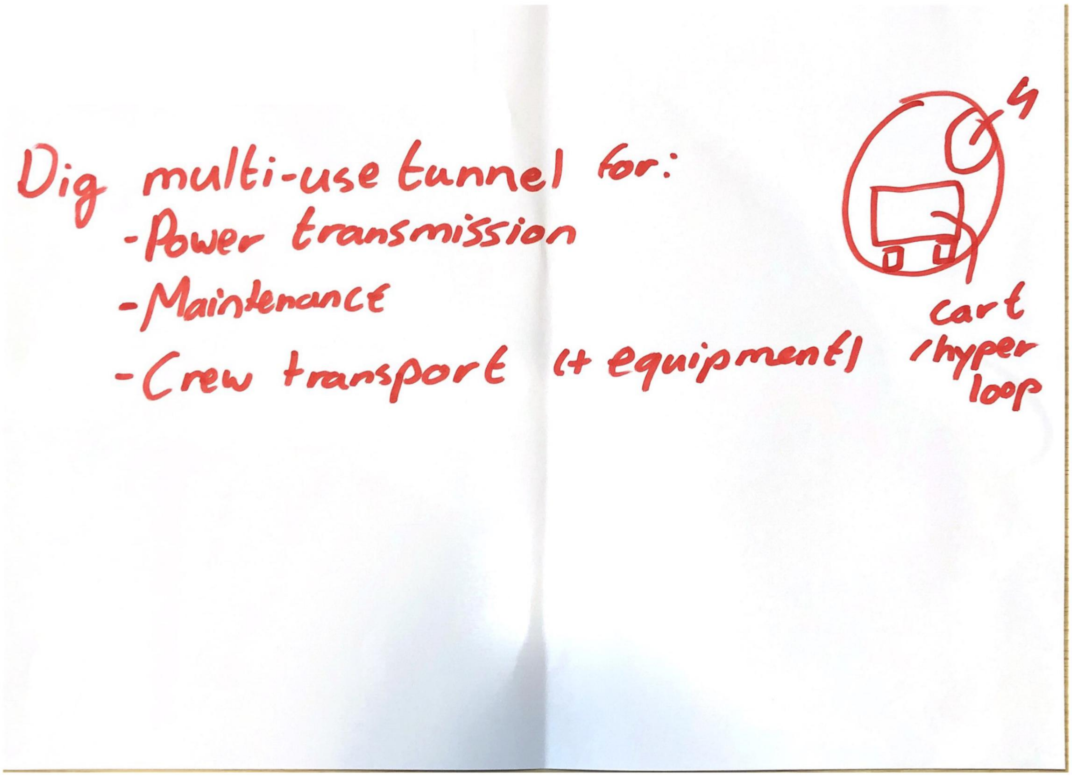


Figure C.12: Multi-use tunnel underground

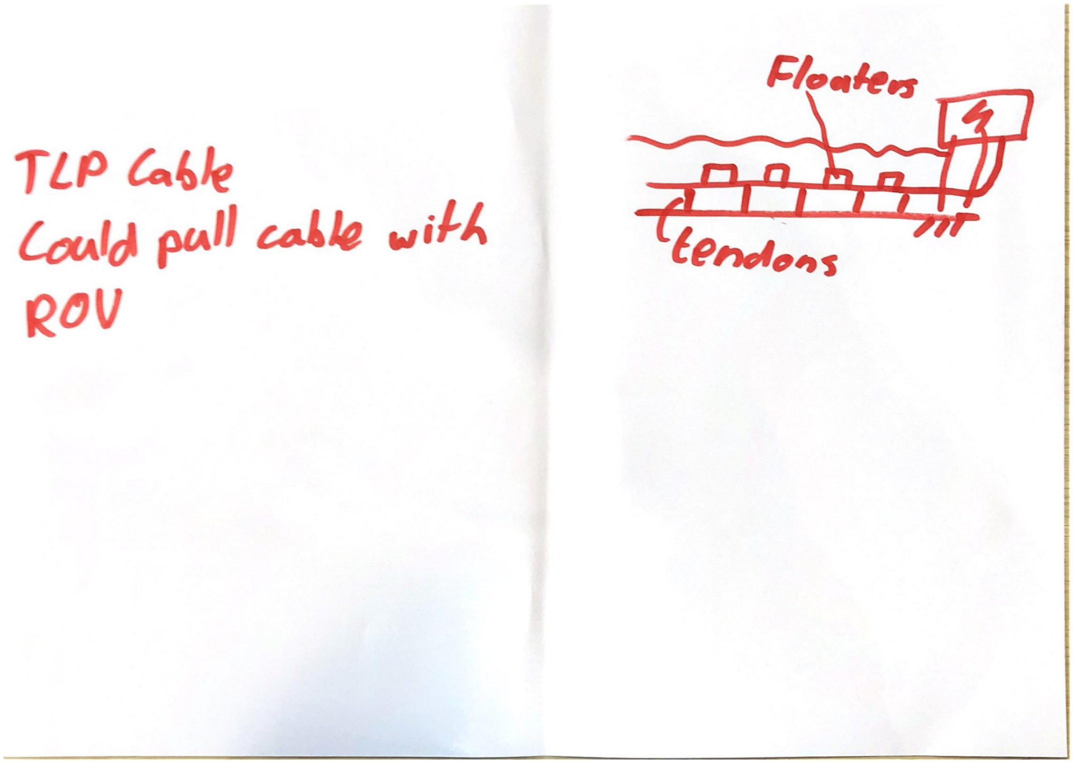


Figure C.13: ROV cable pulling on seabed

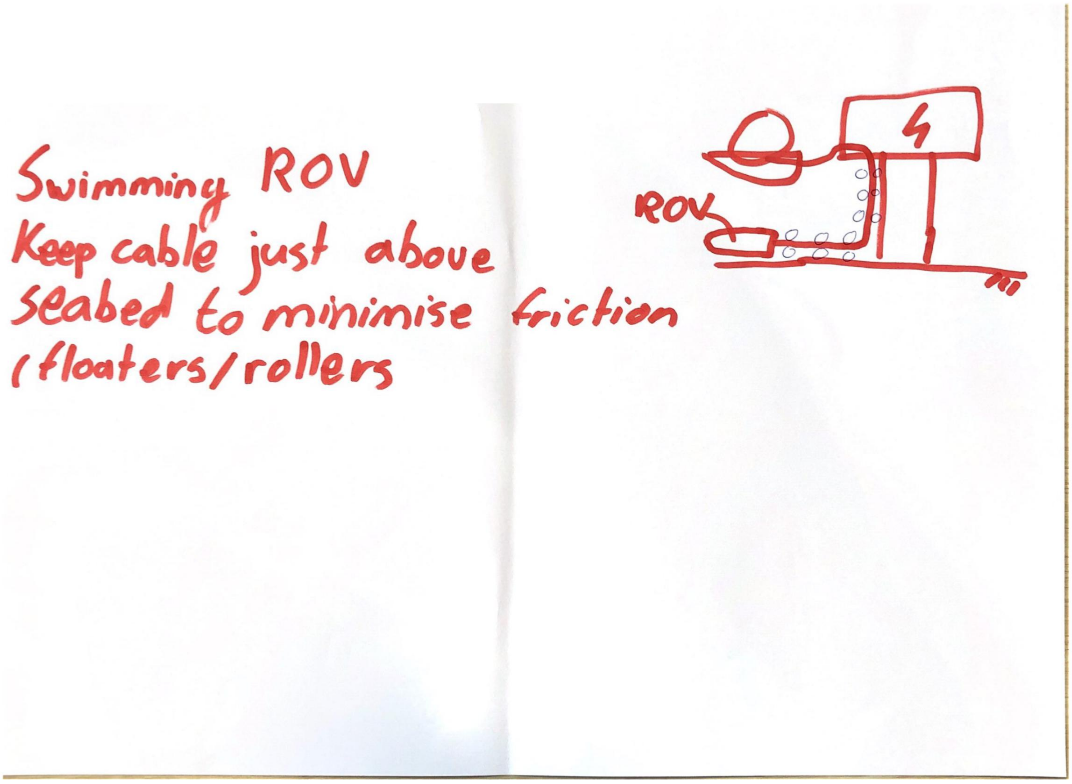


Figure C.14: ROV cable pulling

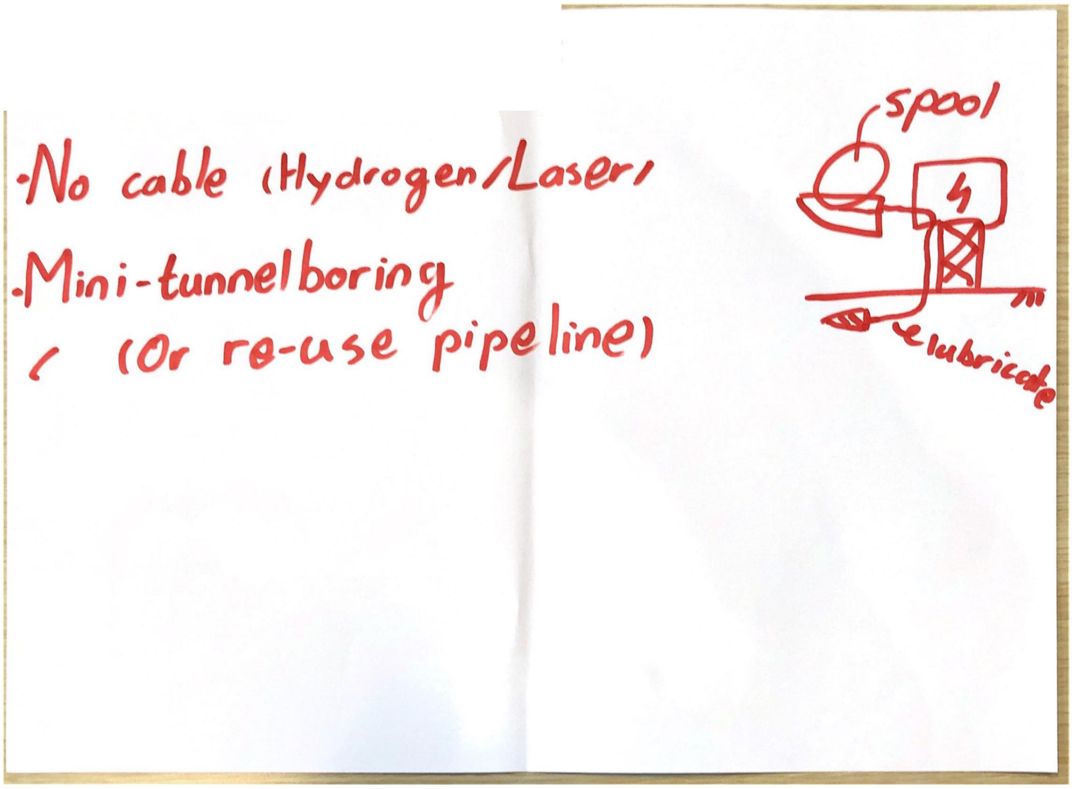


Figure C.15: Other ways of transporting energy

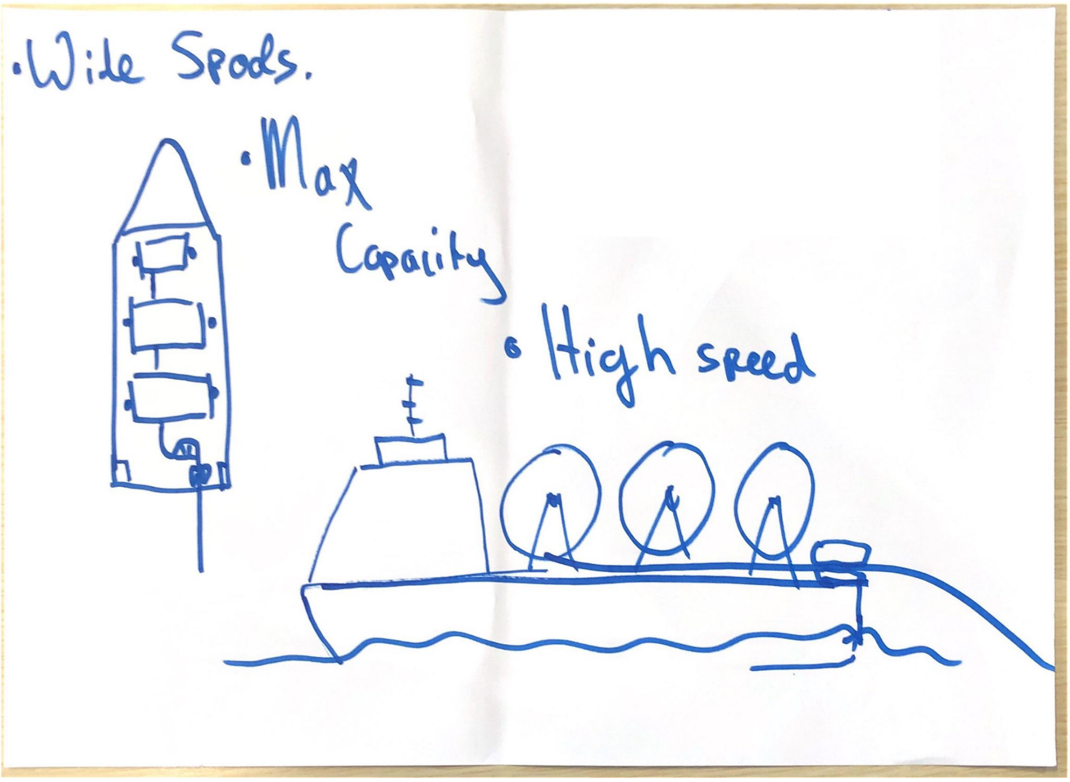


Figure C.16: Multiple carousels on deck

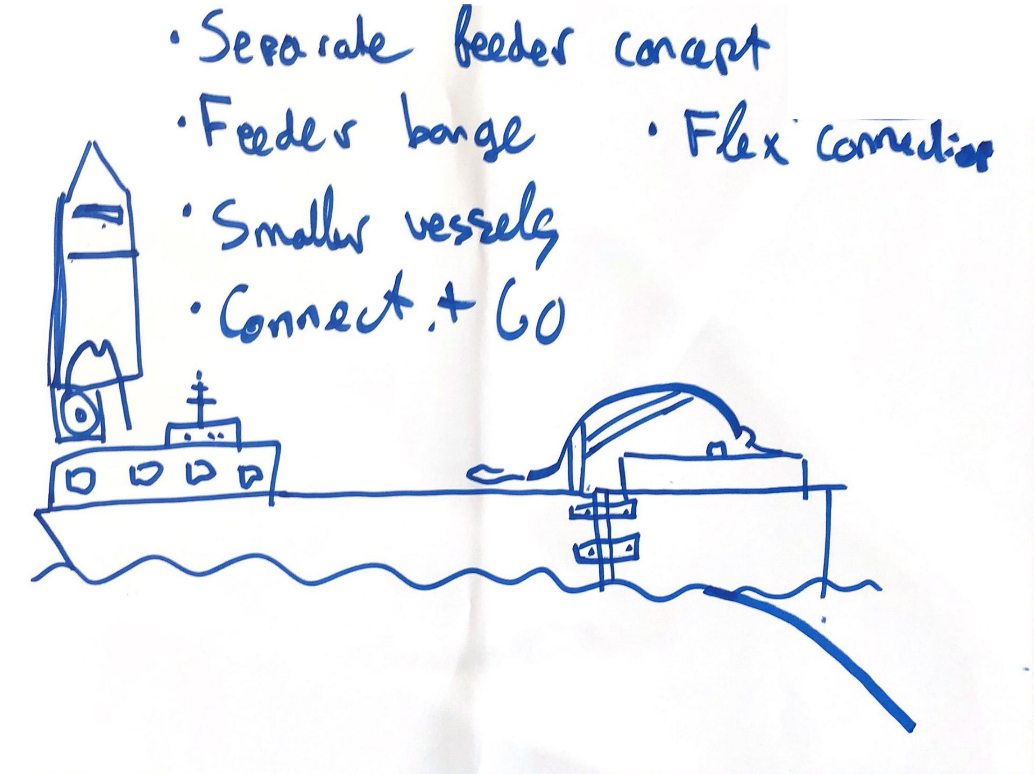


Figure C.17: Carousel trailer

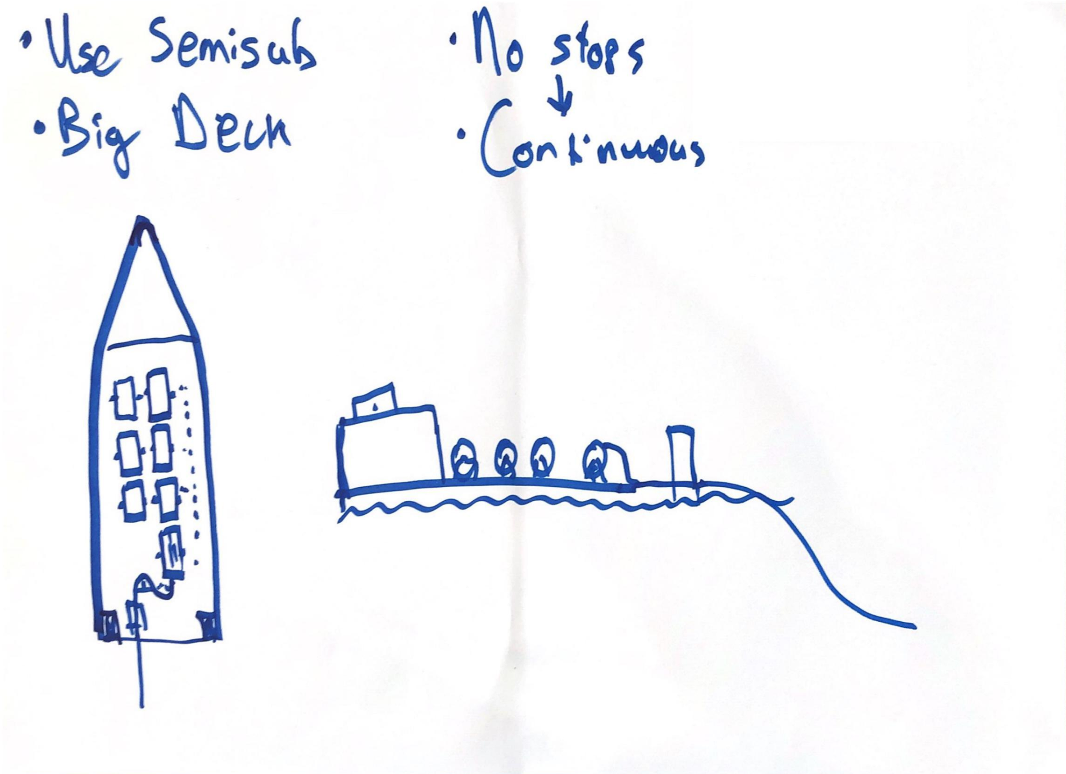


Figure C.18: Multiple carousels on deck

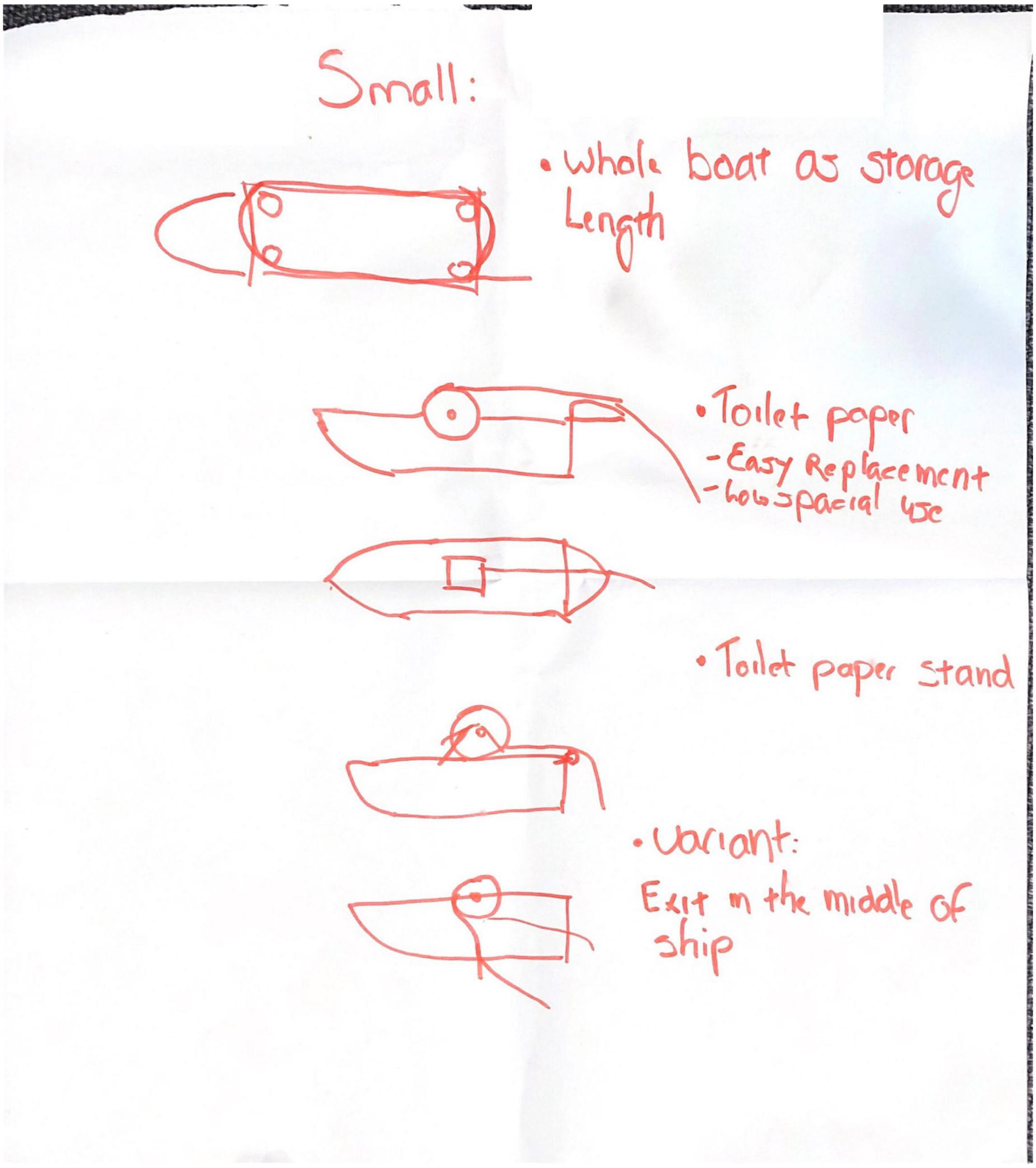


Figure C.19: Several modifications to store the cable

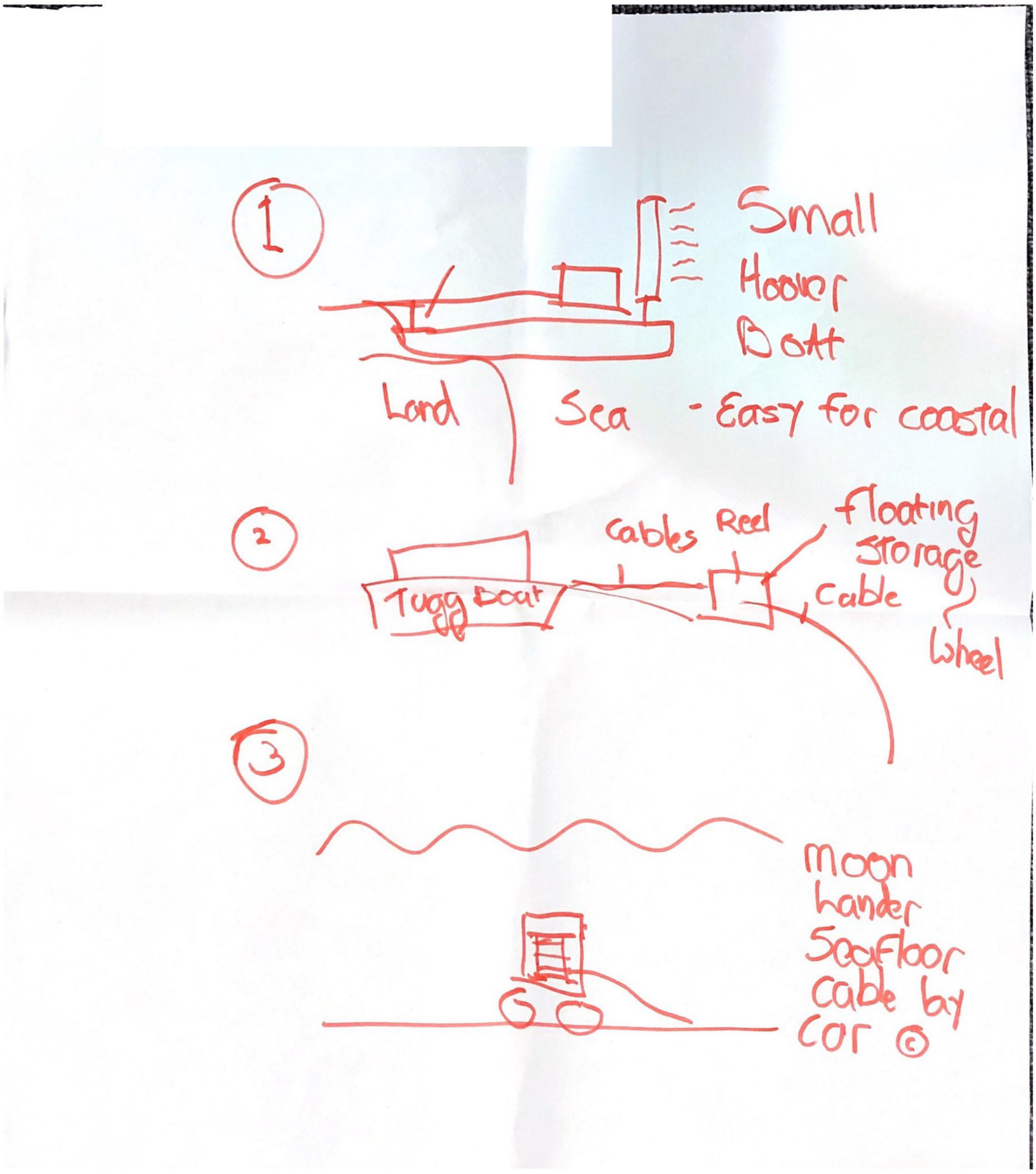


Figure C.20: Coastal hoovering, floating carousel, subsea rov pulling

Non-Technical Students

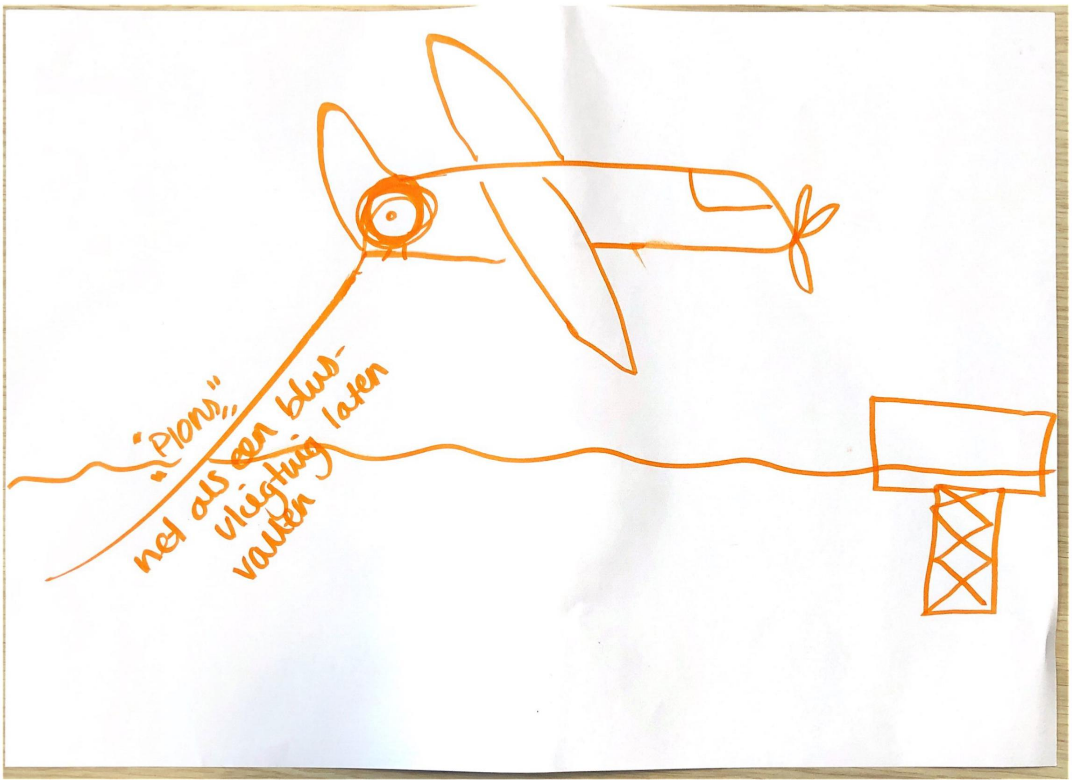


Figure C.21: Airplane including cable drum

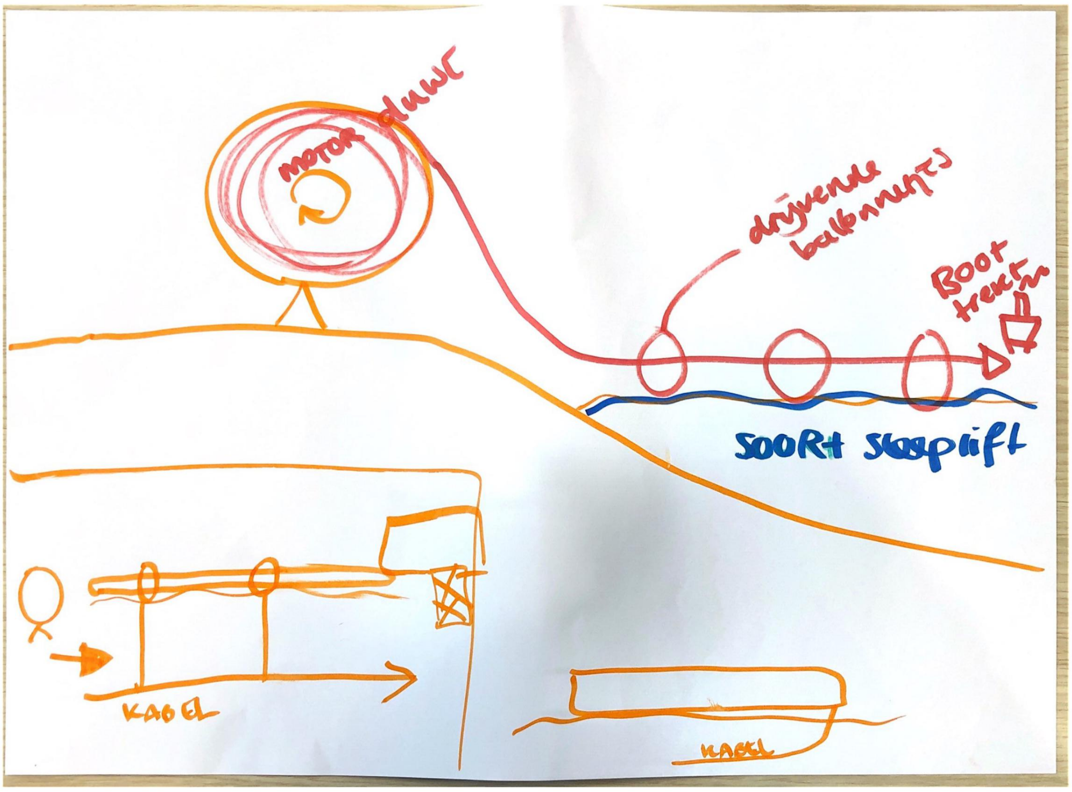


Figure C.22: Pulling operation from shore

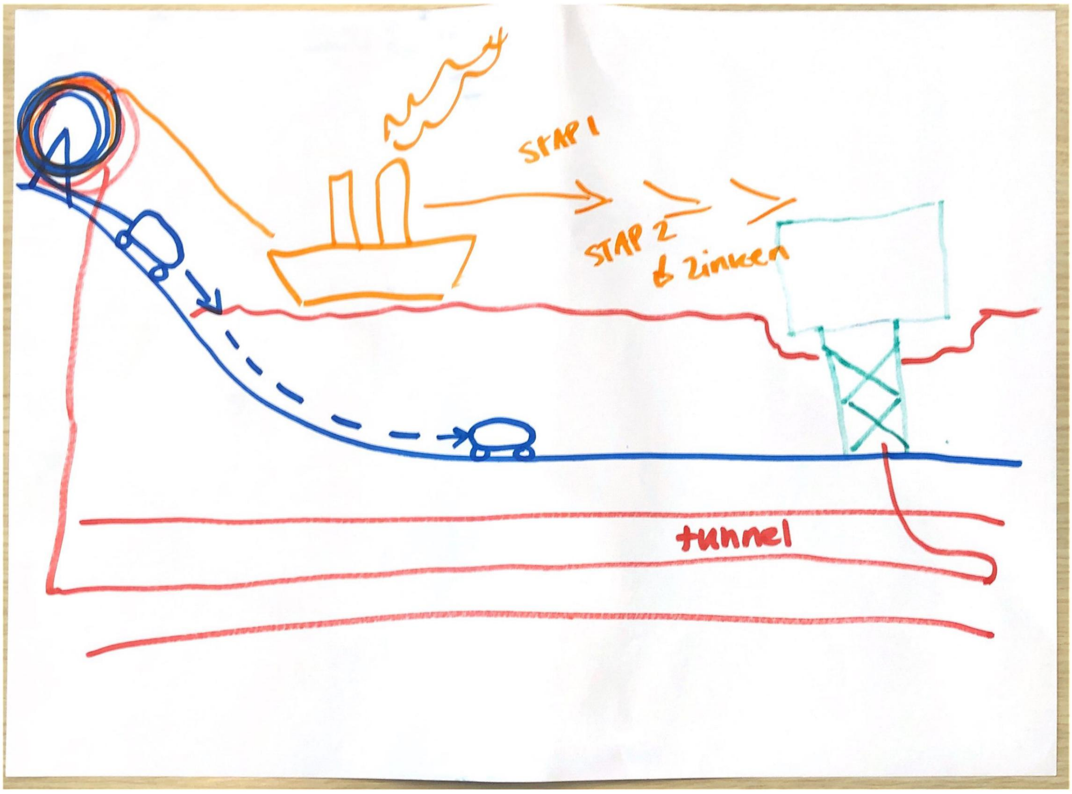


Figure C.23: Subsea rov pulling, HDD cable pulling

R&D Department

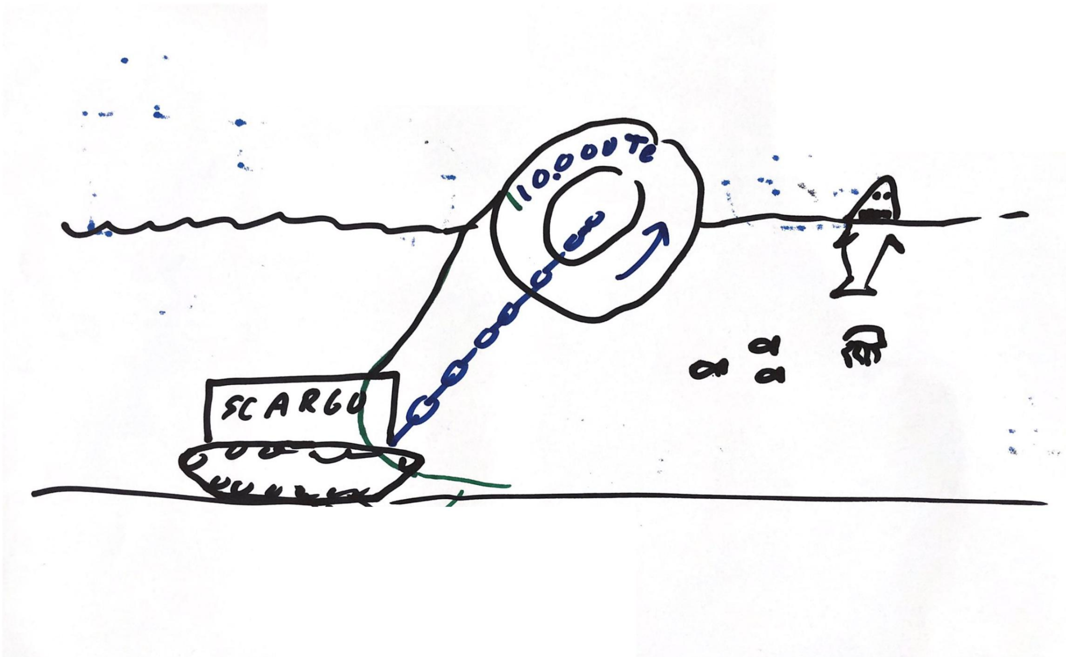


Figure C.24: Subsea ROV with floating carousel

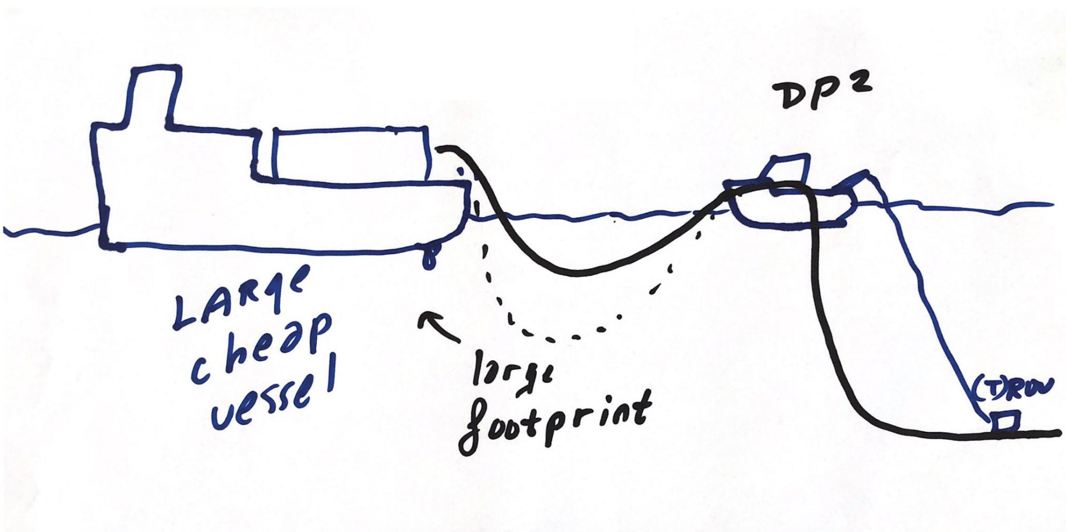


Figure C.25: Combining large vessel with DP2 vessel

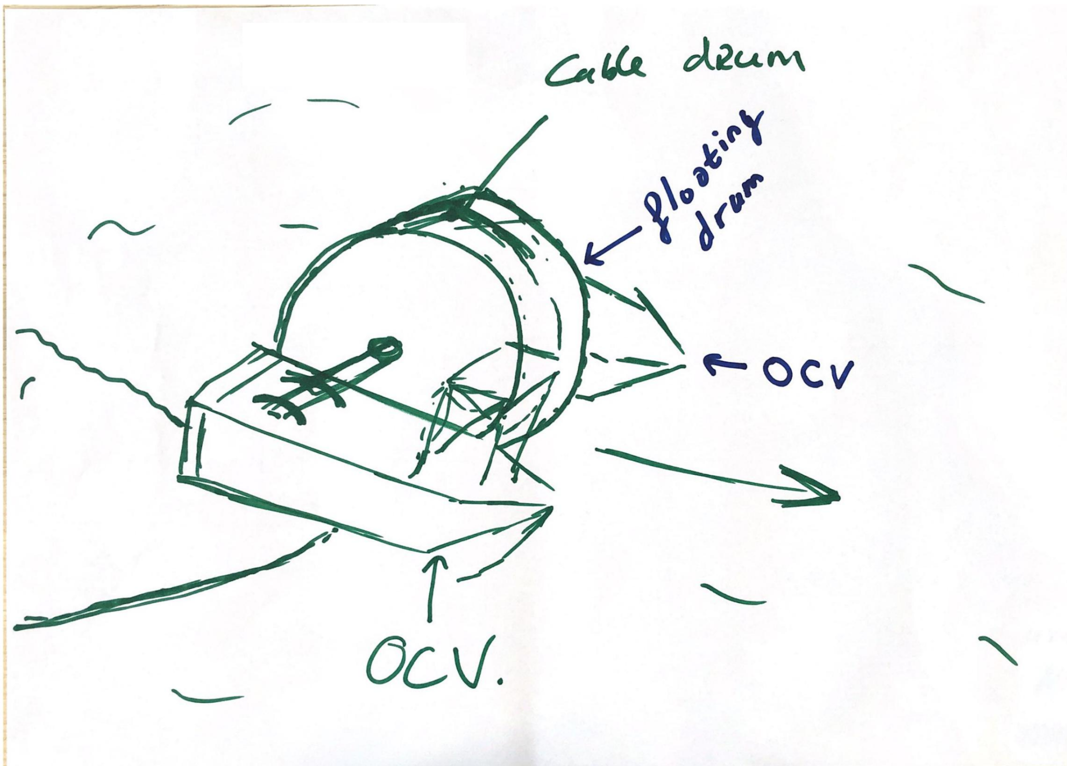


Figure C.26: Using two vessels to carry large cable drum in between

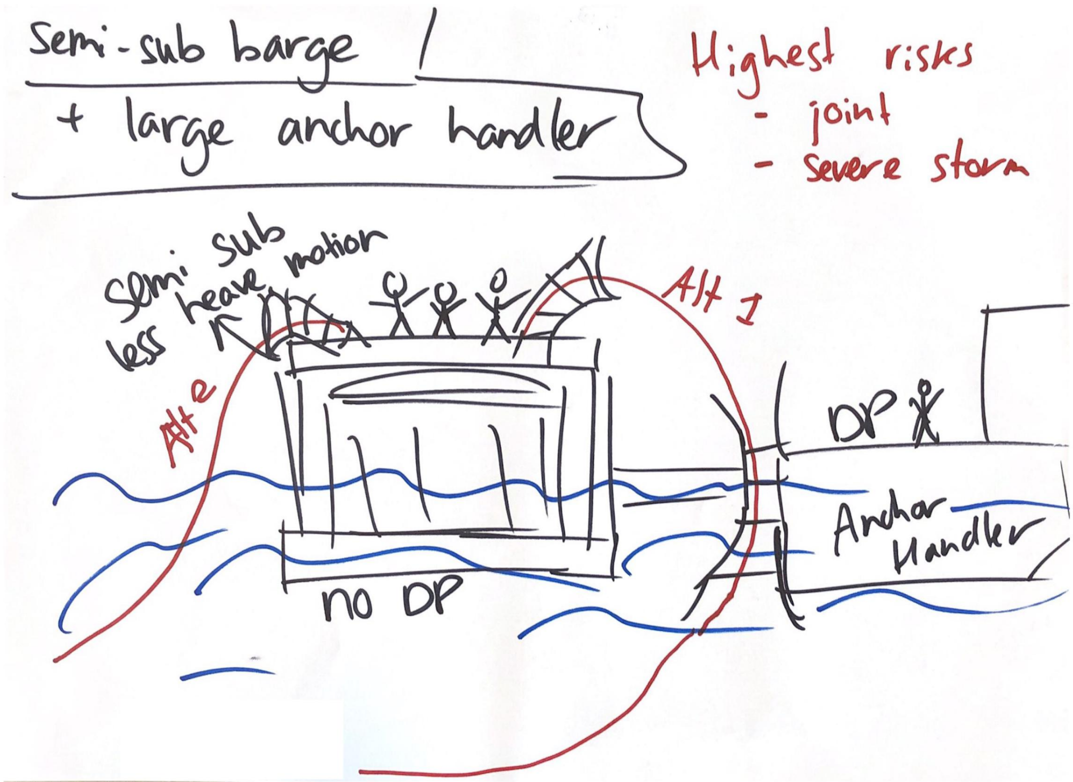


Figure C.27: Semi submersible barge combined with tug

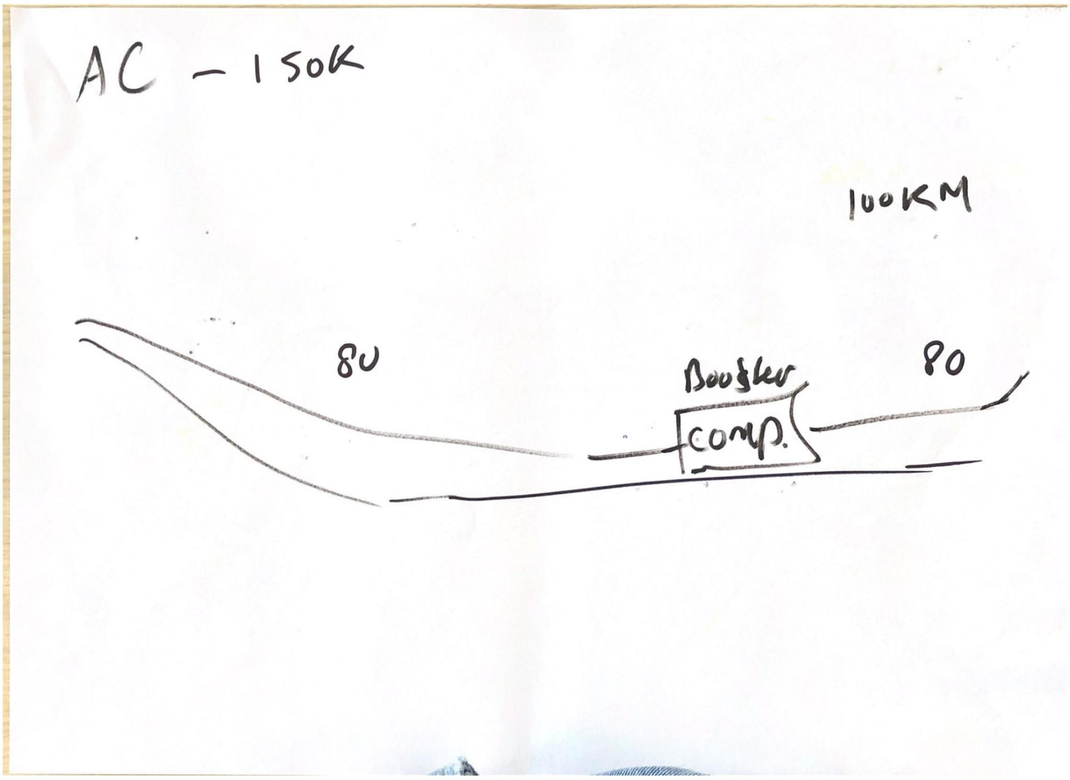


Figure C.28: Making use of booster stations to shorten cable length

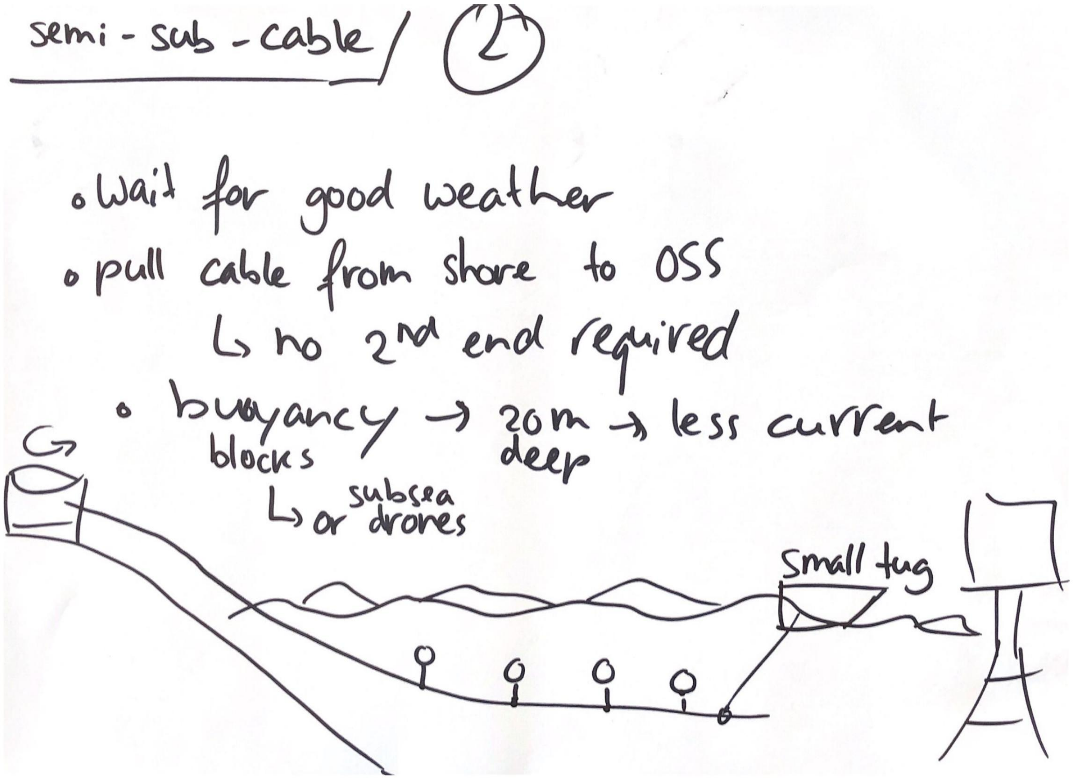
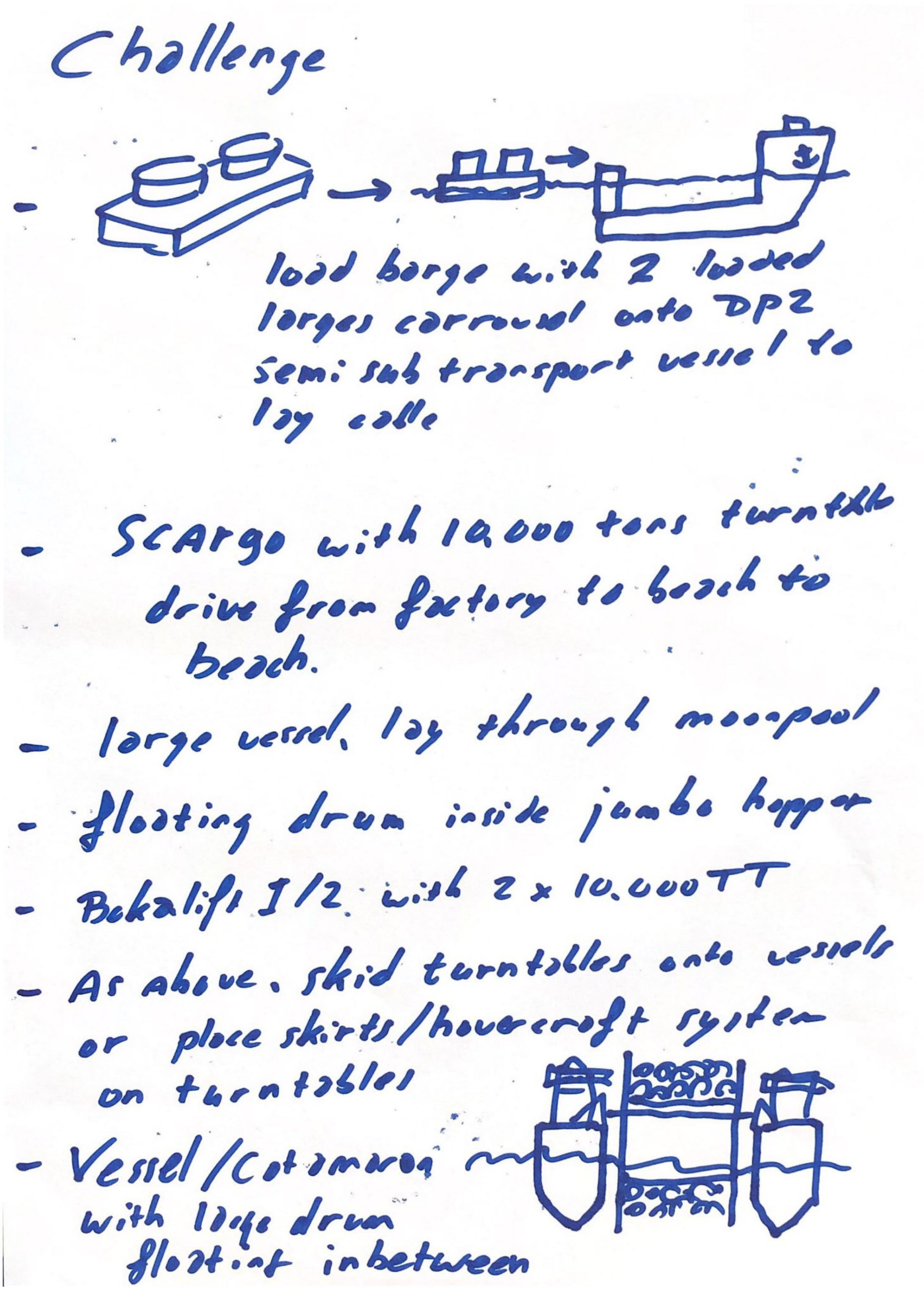


Figure C.29: Underwater cable pulling at 20 meters waterdepth



Challenge

- load barge with 2 loaded larges carrousel onto DP2 semi sub transport vessel to lay cable
- SCArgo with 10.000 tons turntable drive from factory to beach to beach.
- large vessel, lay through moonpool
- floating drum inside jumbo hopper
- Bokalift 1/2 with 2 x 10.000TT
- As above, skid turntables onto vessels or place skirts/hovercraft system on turntables
- Vessel/Catamaran with large drum floating inbetween

Figure C.30: Several concepts that combine multiple vessels

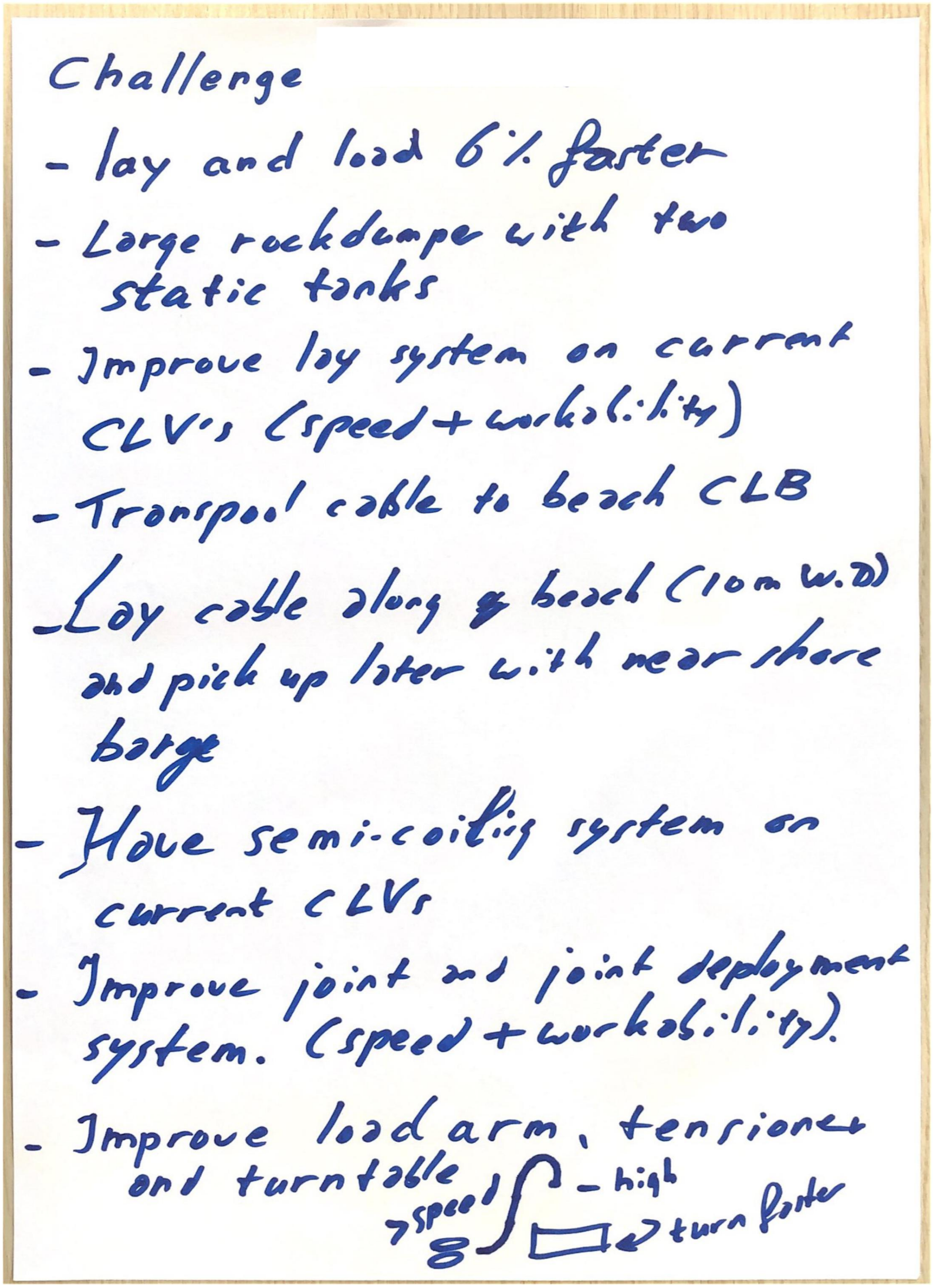


Figure C.31: Improvements on regular CLV's

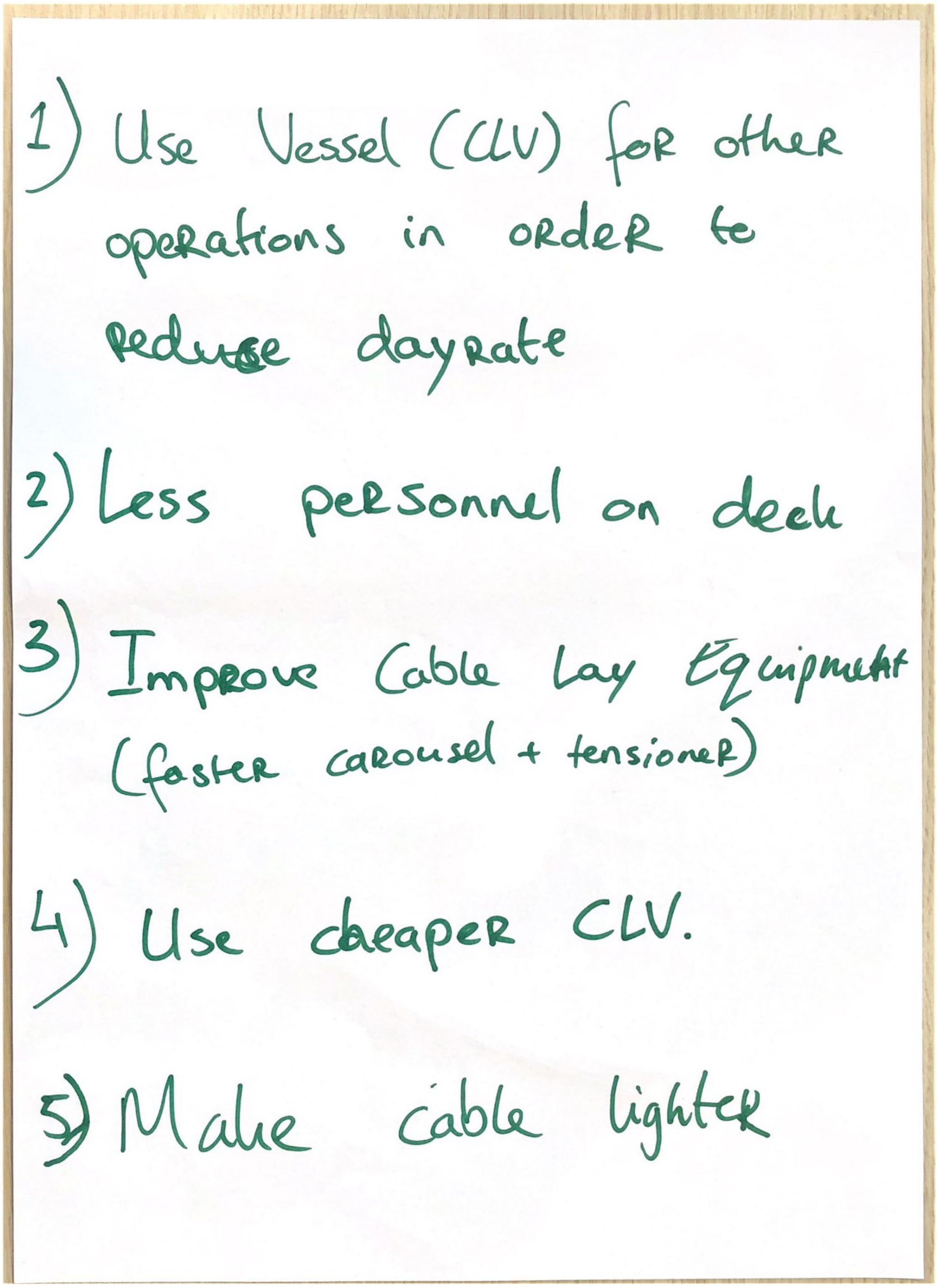


Figure C.32: Improvements on regular CLV's

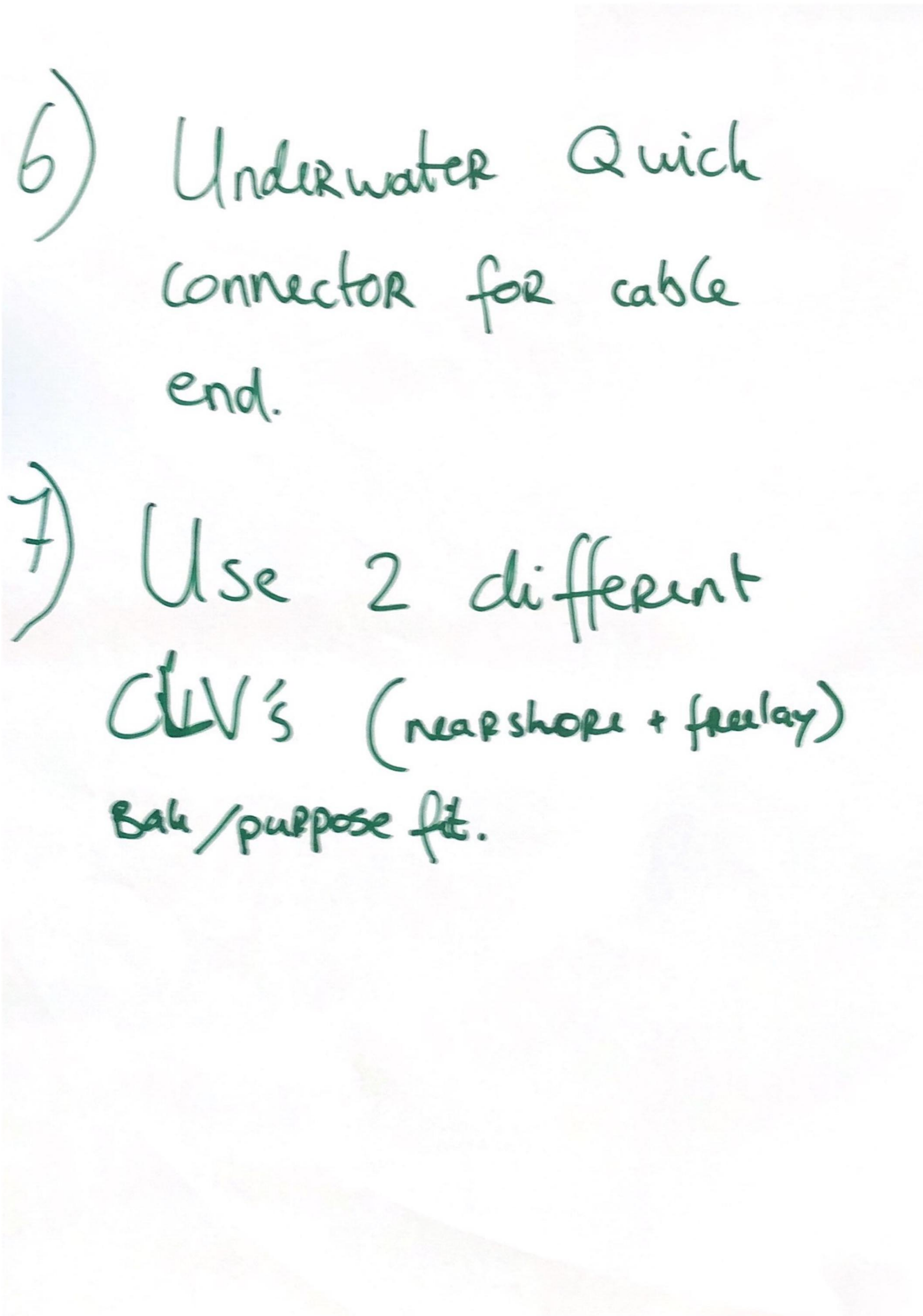


Figure C.33: Improvements on regular CLV’s

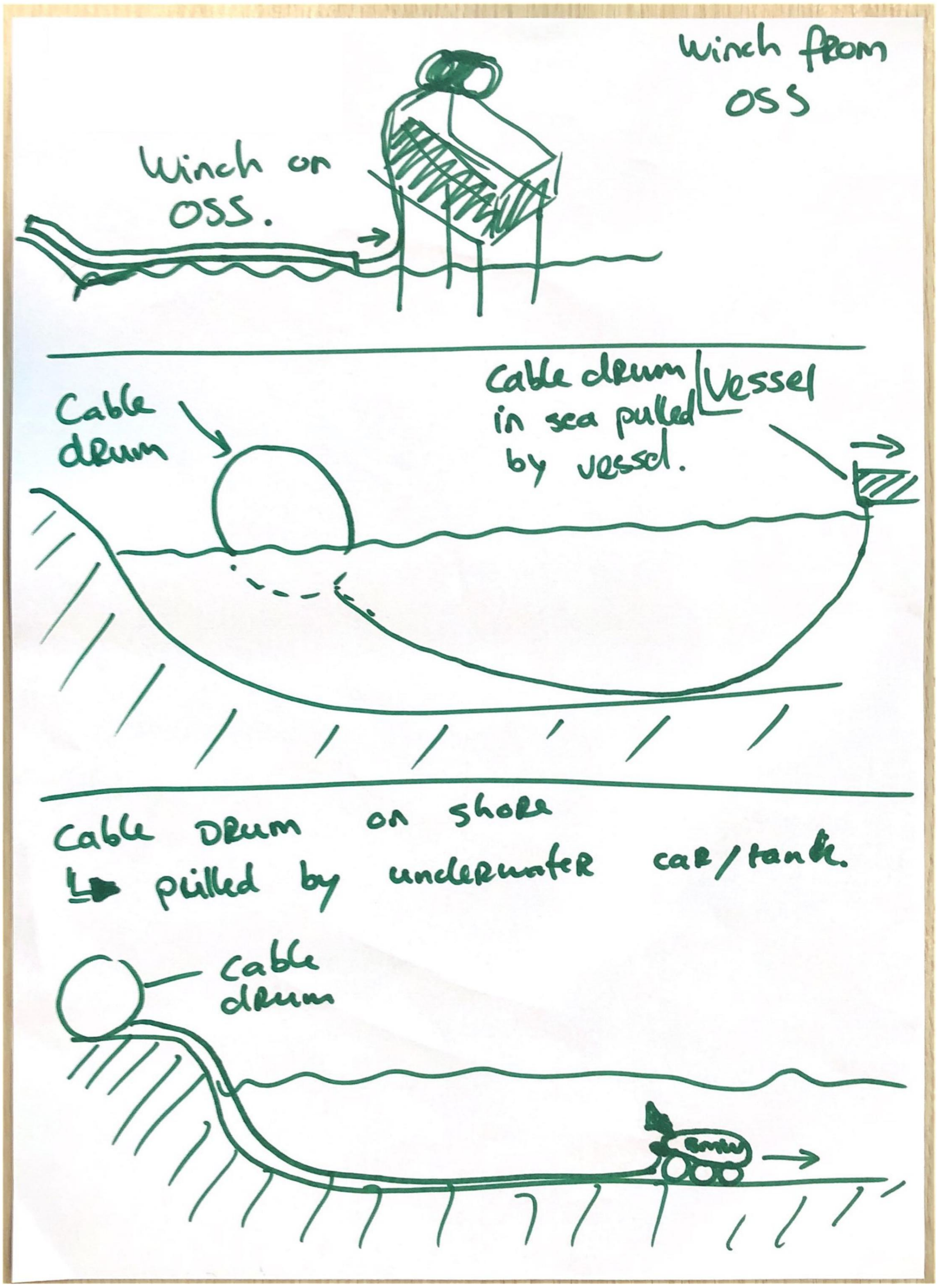


Figure C.34: Several cable pulling concepts

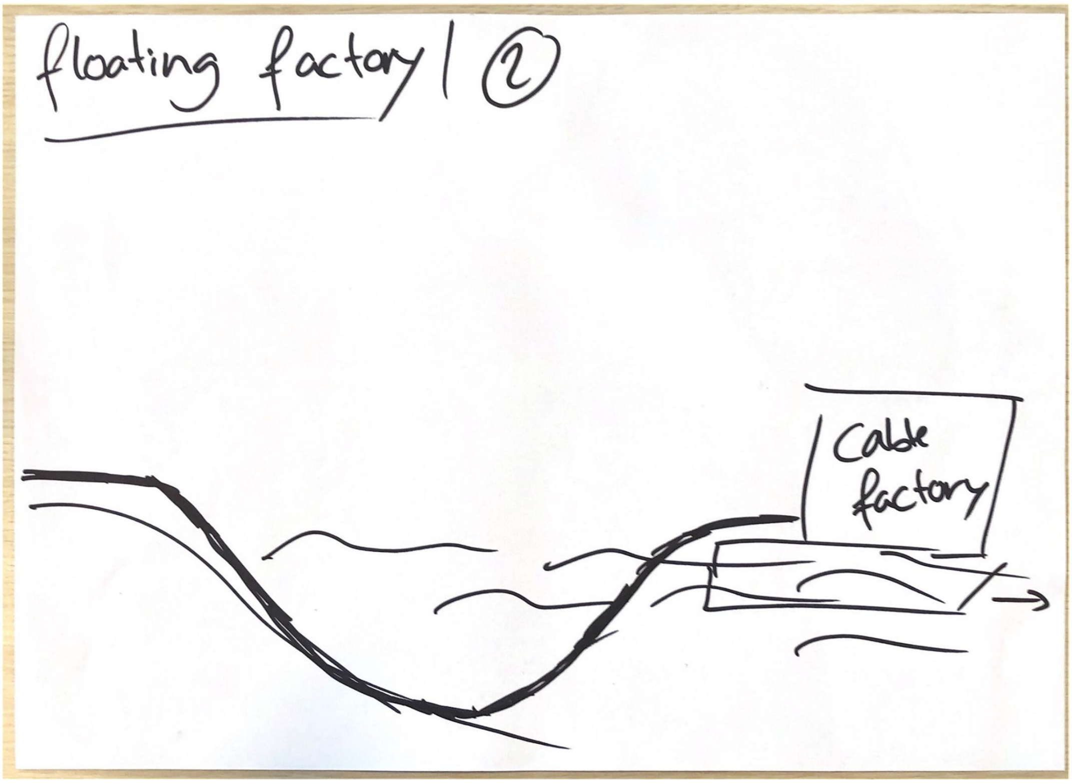


Figure C.35: Floating cable factory

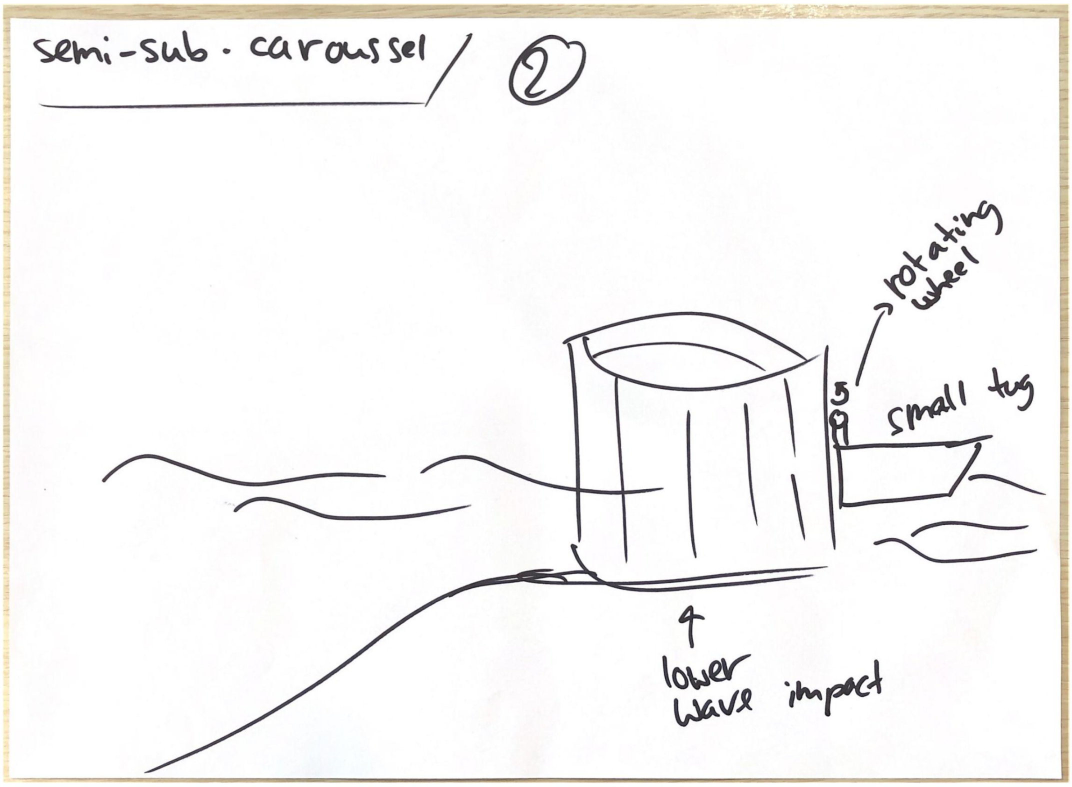


Figure C.36: Floating drum attached to tug

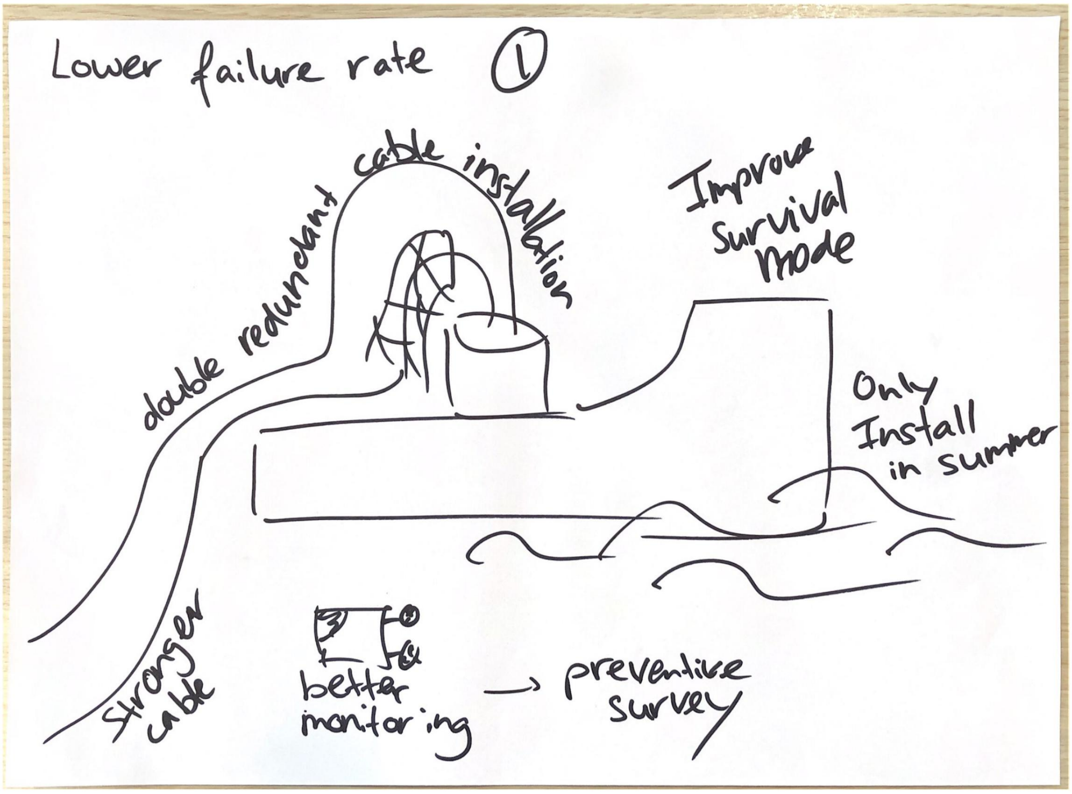


Figure C.37: Modifications to existing CLV's

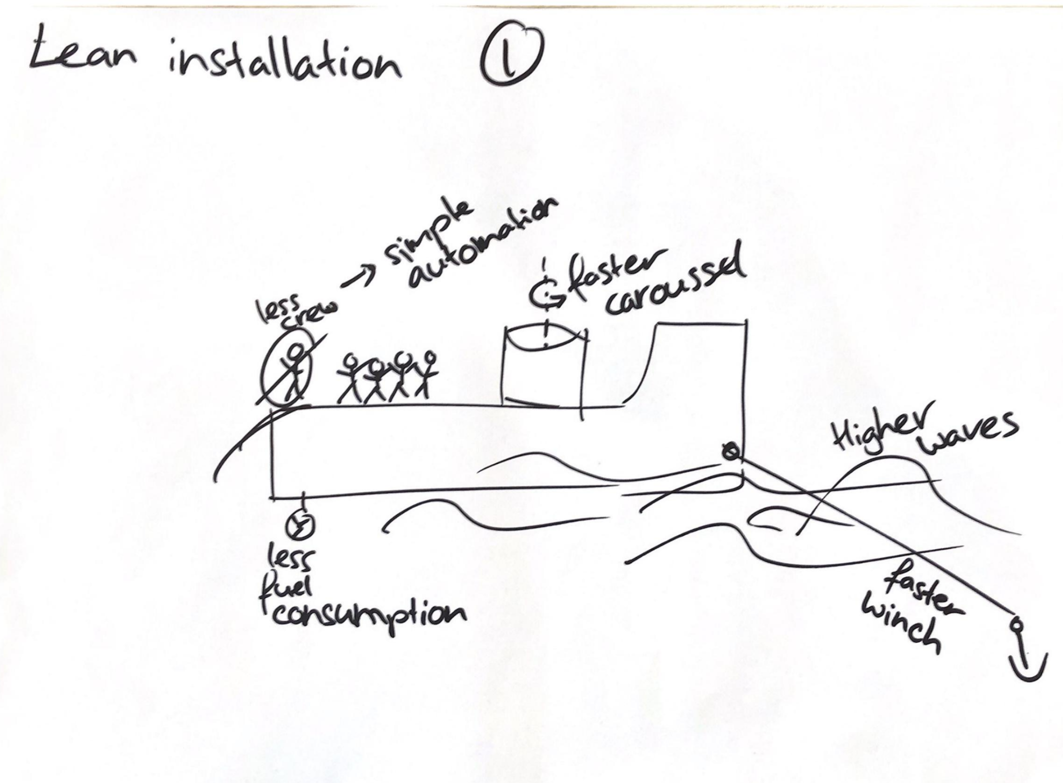


Figure C.38: LEAN

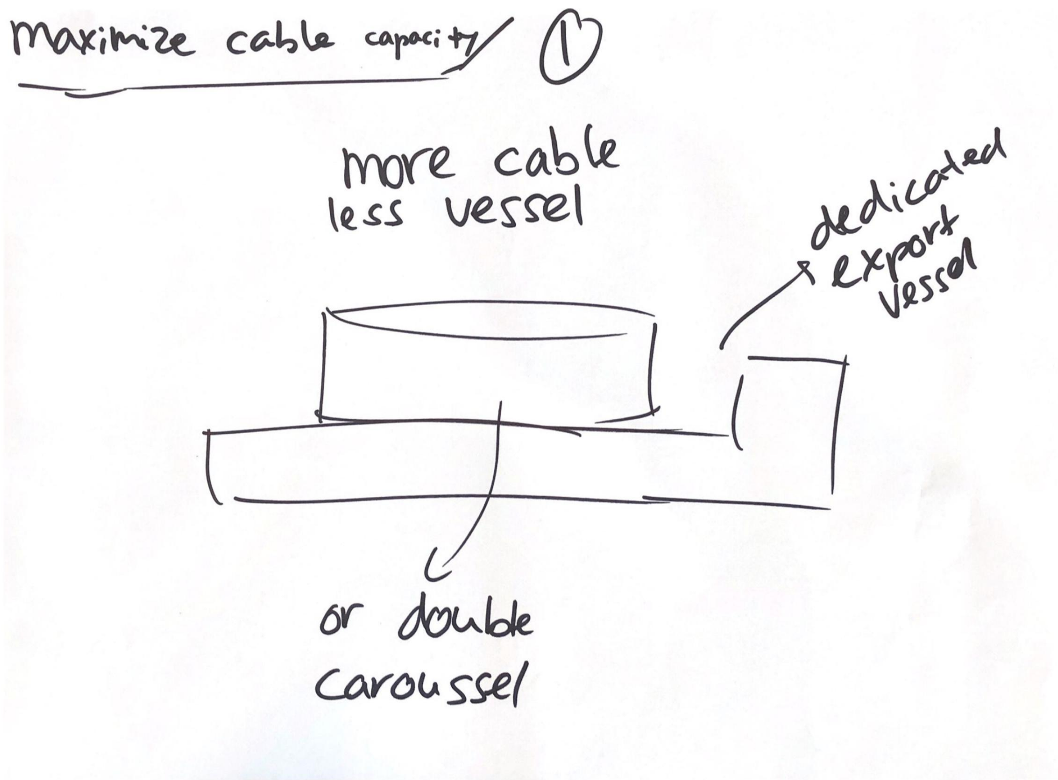


Figure C.39: Maximizing cable capacity

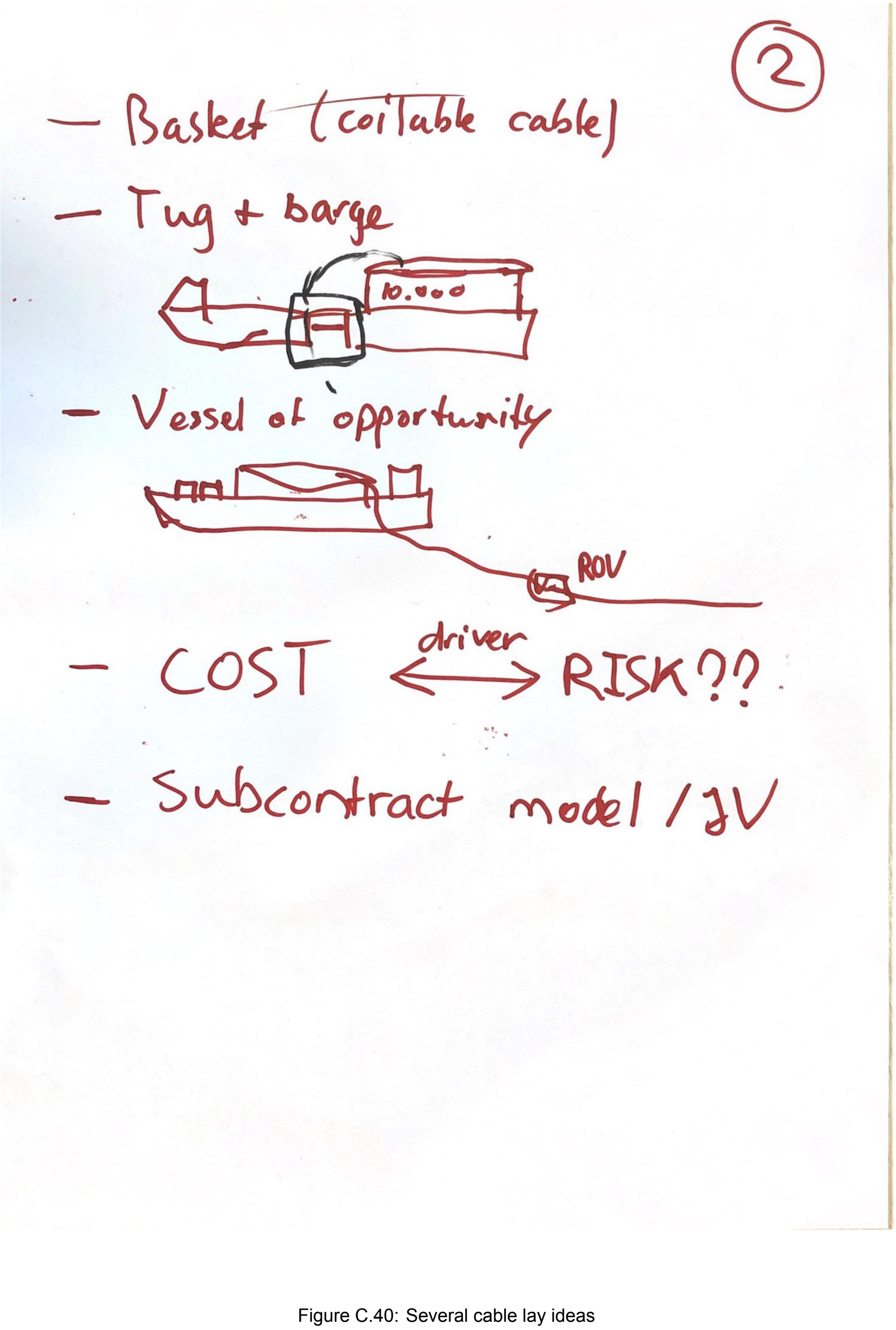


Figure C.40: Several cable lay ideas

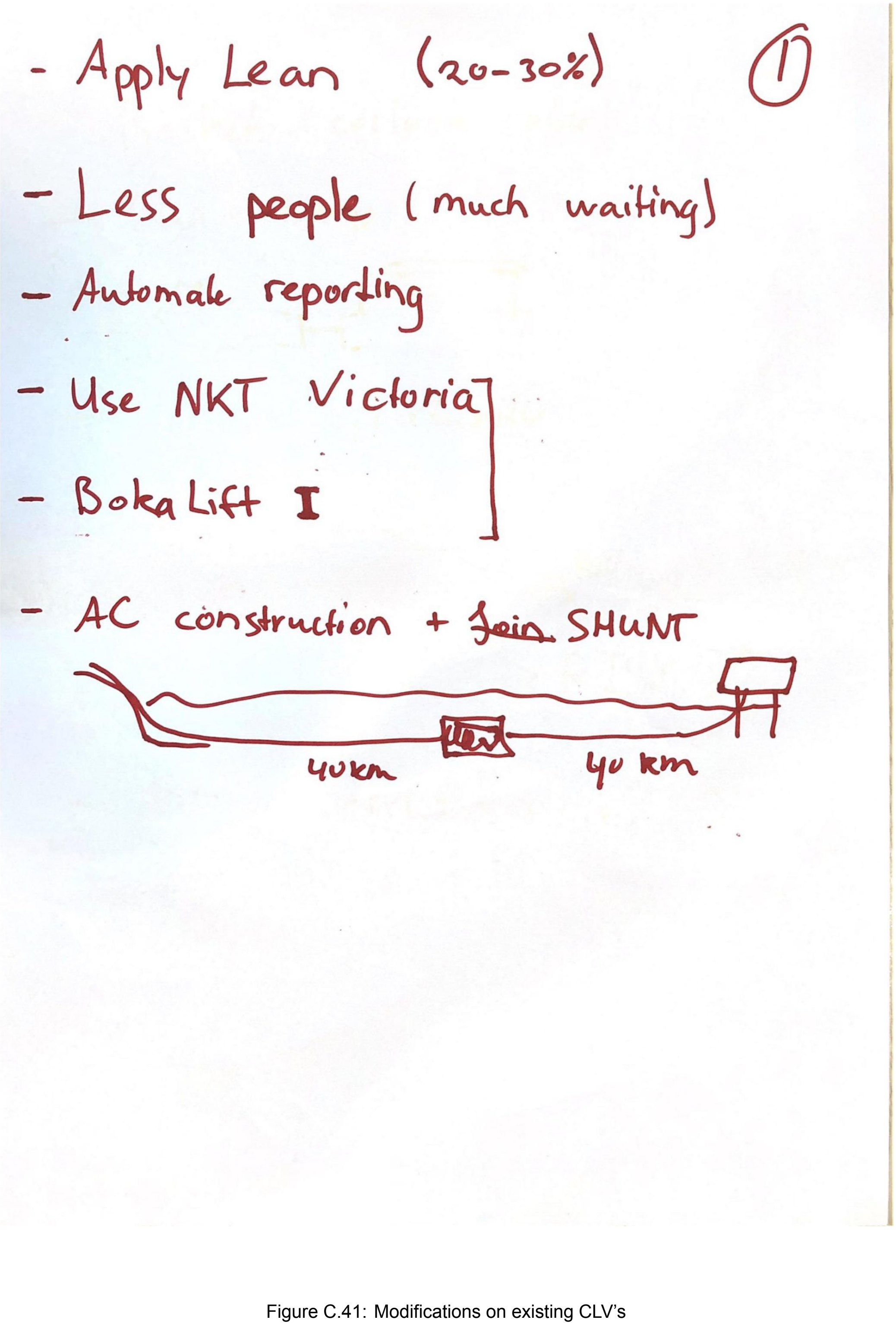
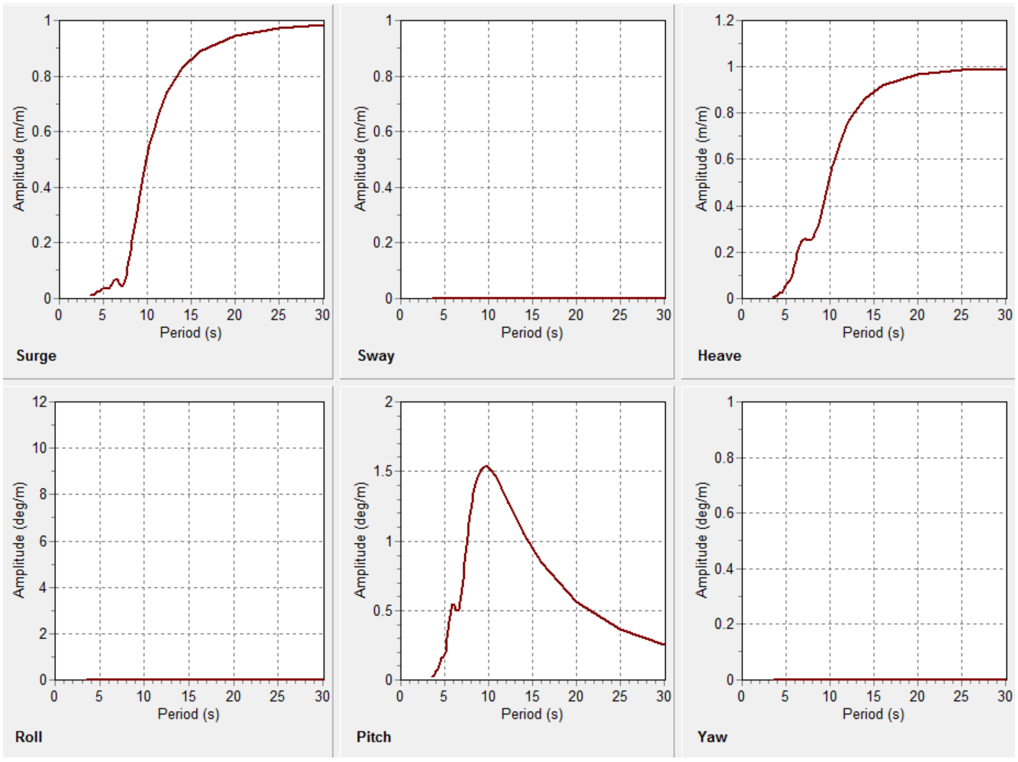


Figure C.41: Modifications on existing CLV's

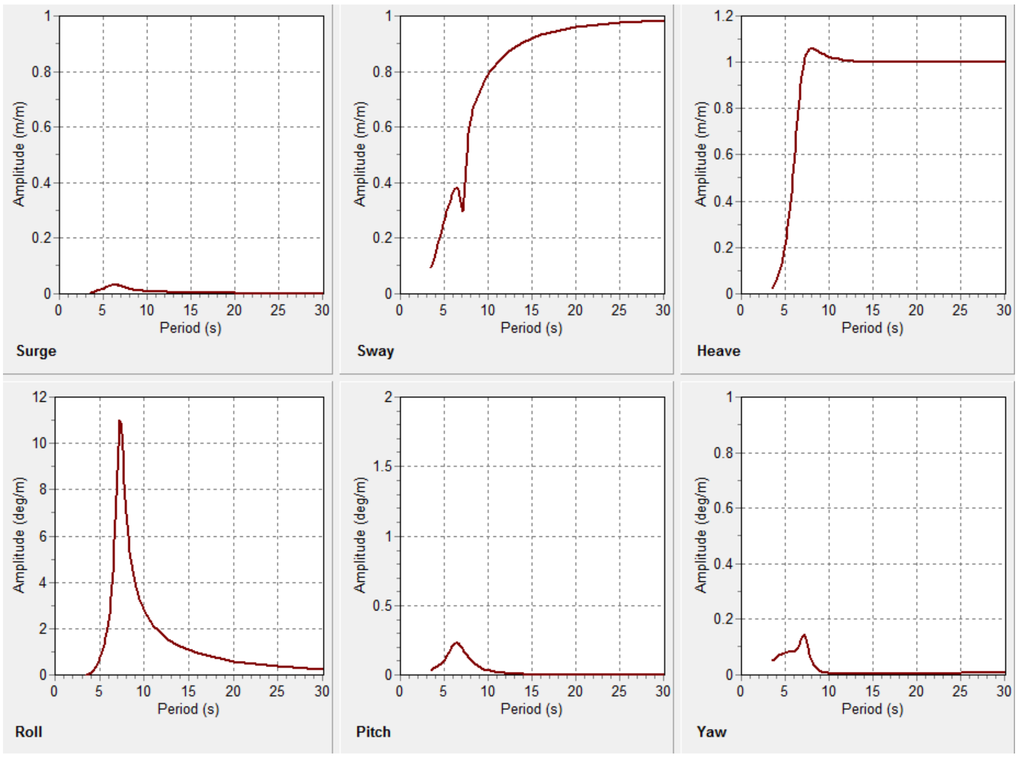
D

RAO's

The RAO's for both the NDurance and the Fjell at 180 and 270 degrees wave heading are displayed.

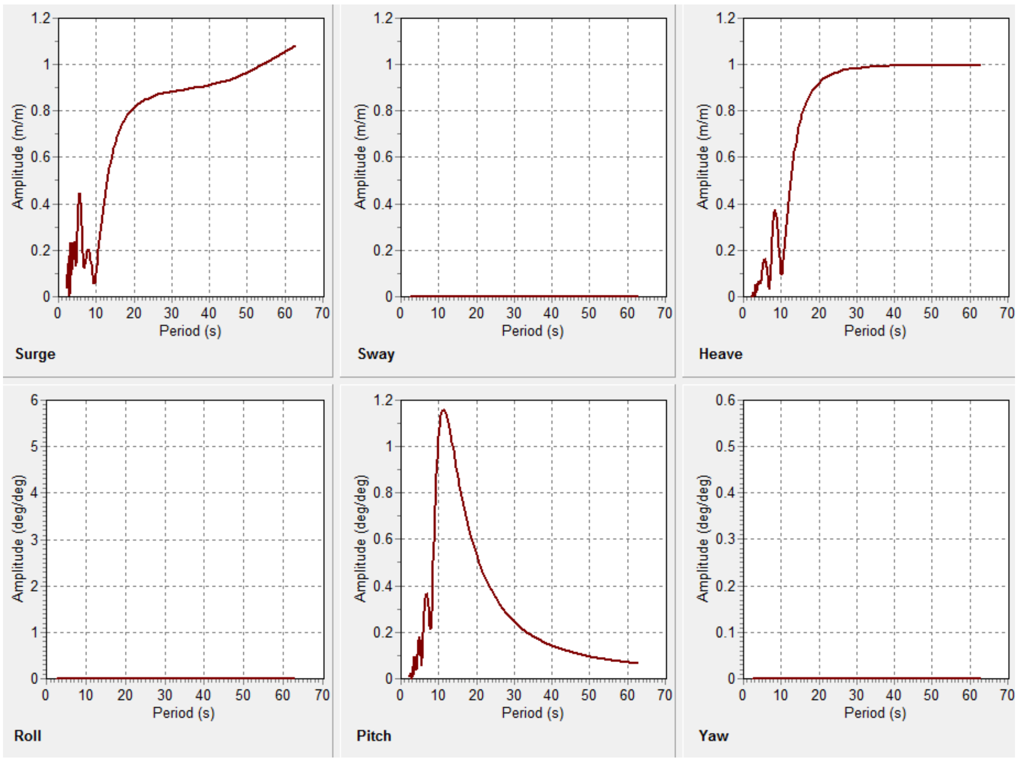


(a) 180 degrees wave direction

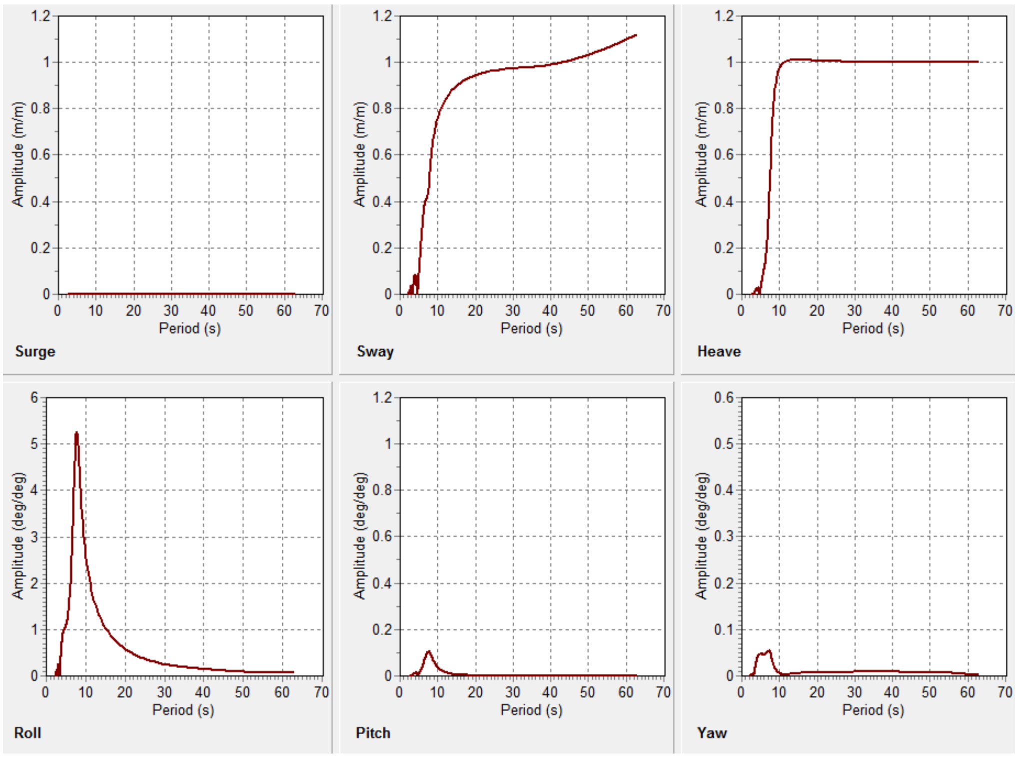


(b) 270 degrees wave direction

Figure D.1: RAO's NDurance



(a) 180 degrees wave direction



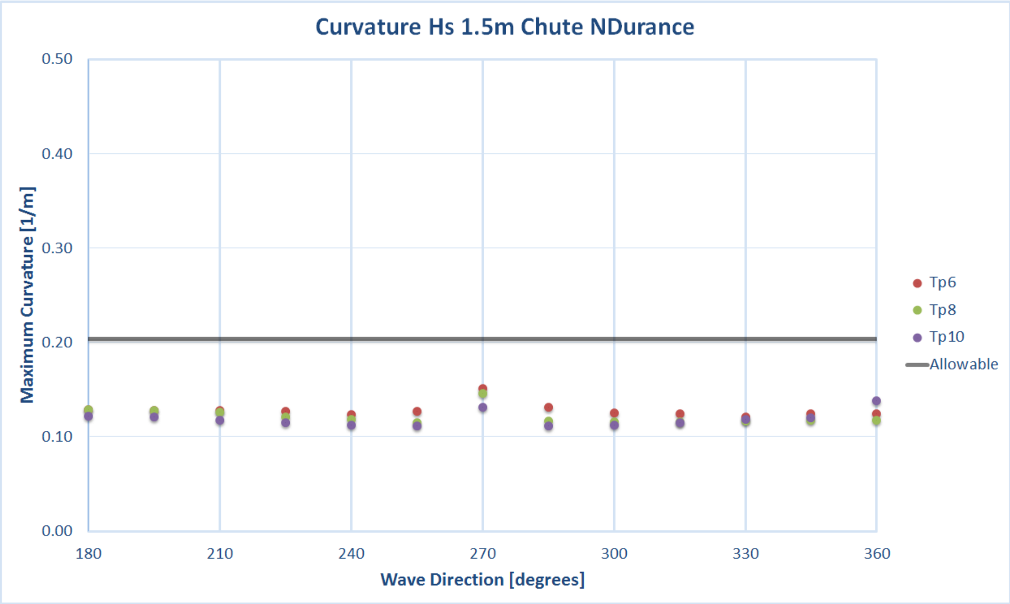
(b) 270 degrees wave direction

Figure D.2: RAO's Fjell

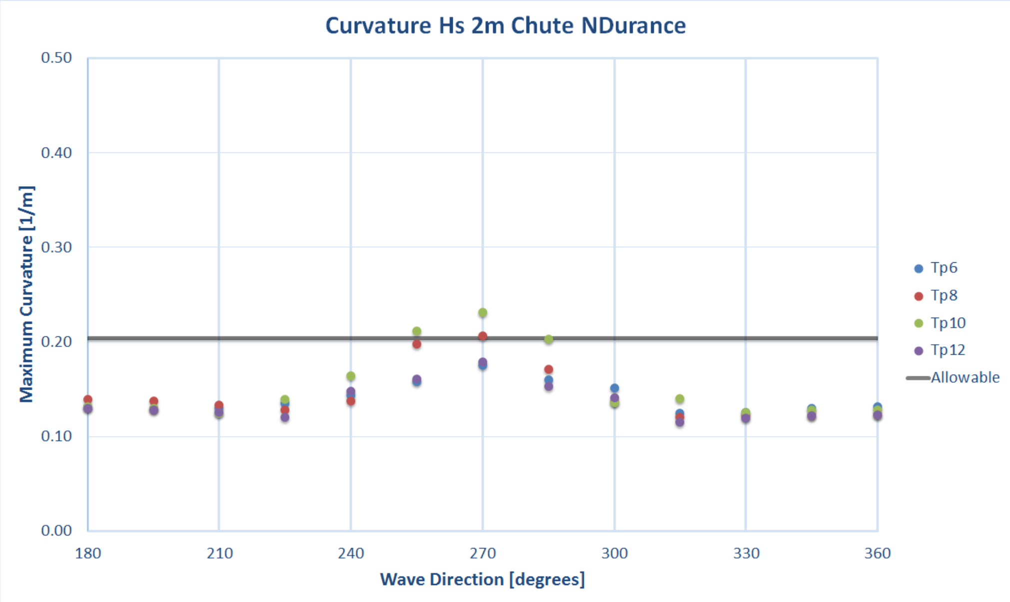
E

Orcaflex Results

All curvature results for the different situation explained in Chapter 7 are grouped here for easy comparison.

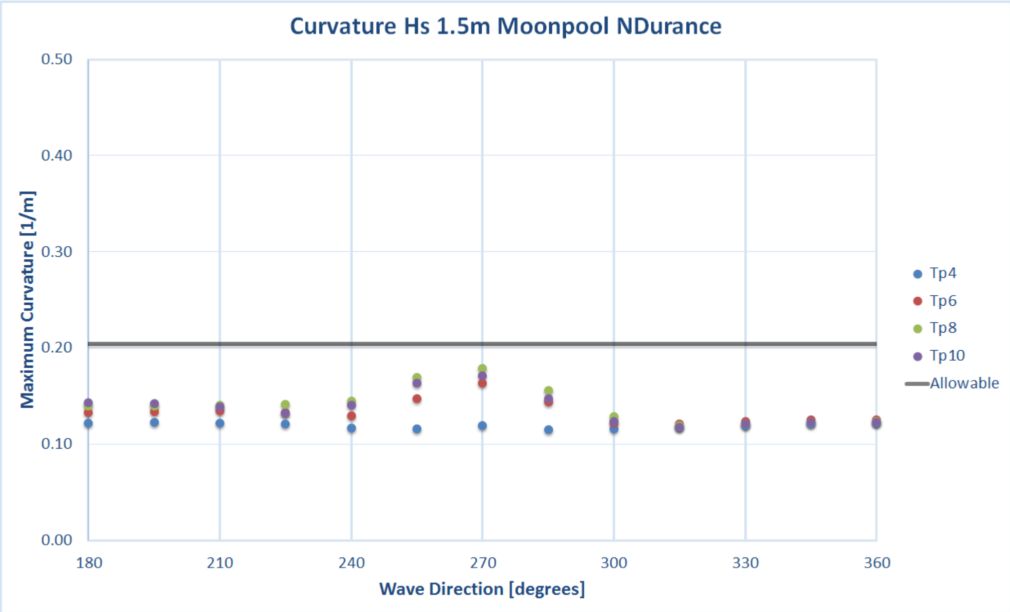


(a) Hs = 1.5 m

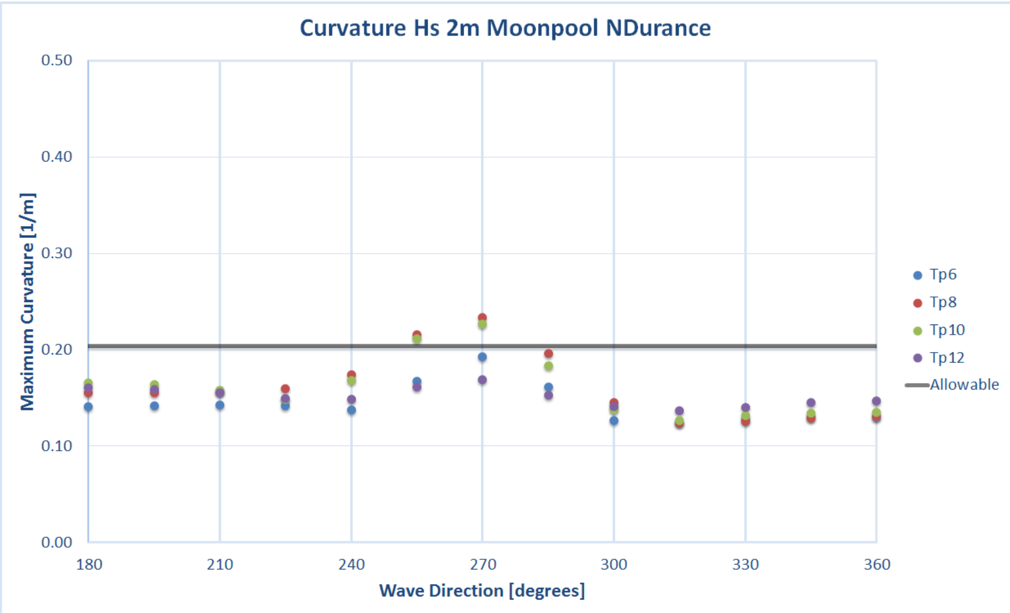


(b) Hs = 2.0 m

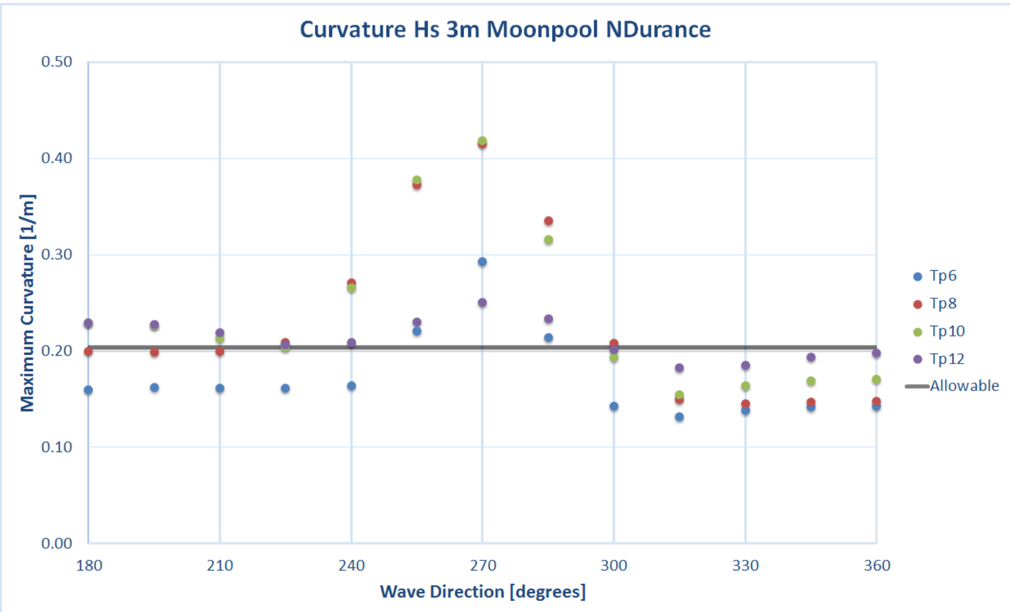
Figure E.1: Curvature per wave heading conventional cable laying NDurance



(a) Hs = 1.5 m

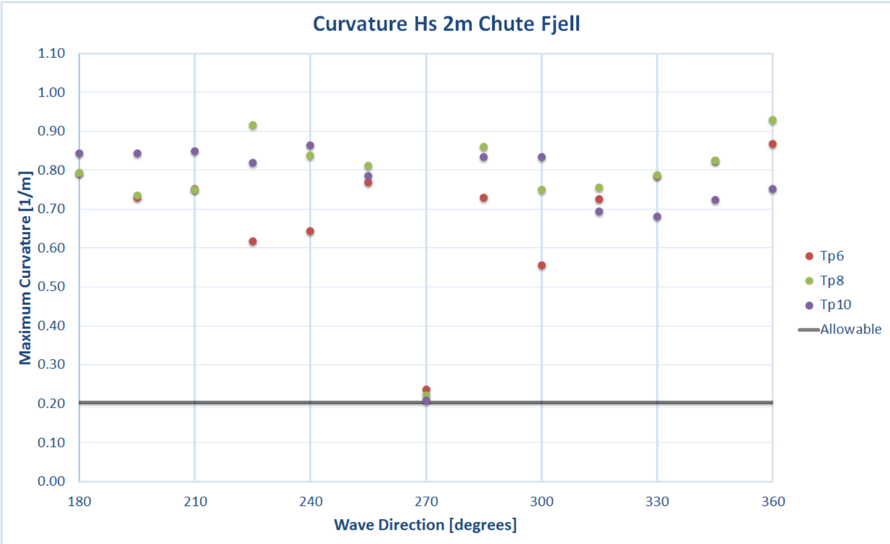


(b) Hs = 2.0 m

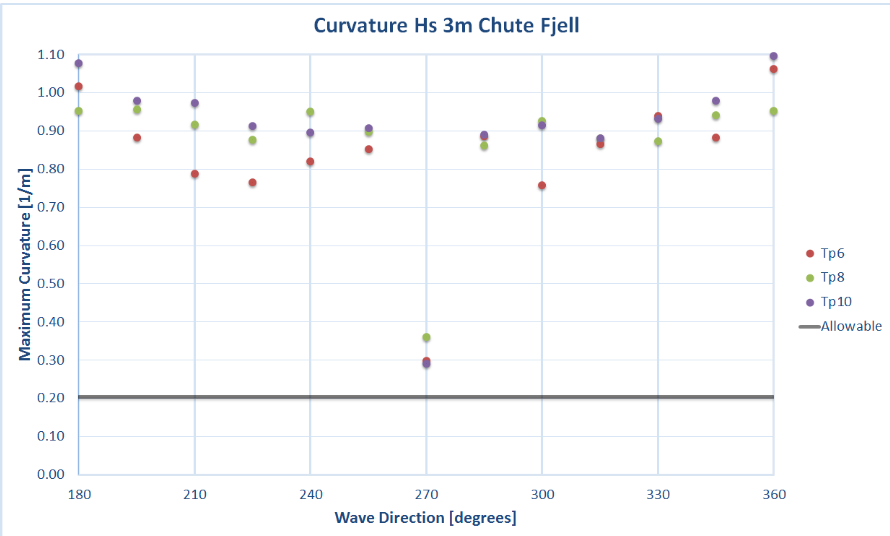


(c) Hs = 3.0 m

Figure E.2: Curvature per wave heading moonpool cable laying NDurance

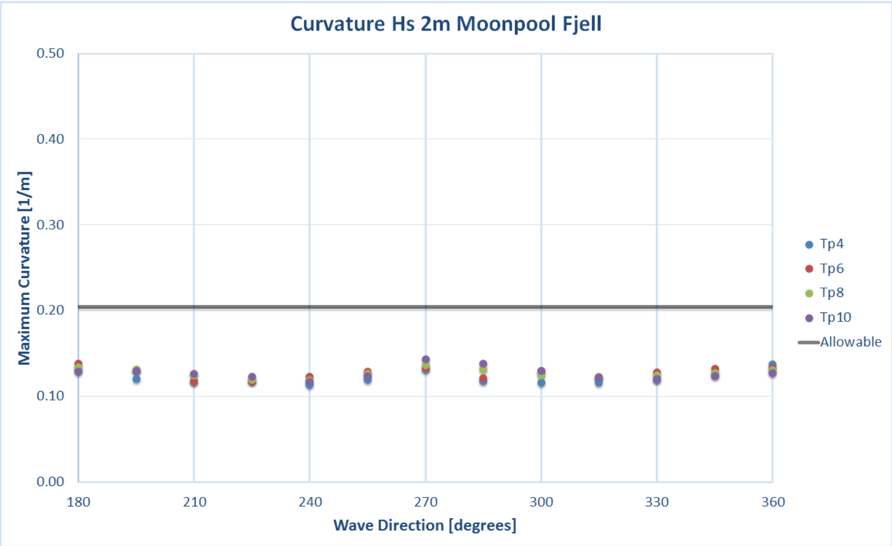


(a) Hs = 2.0 m

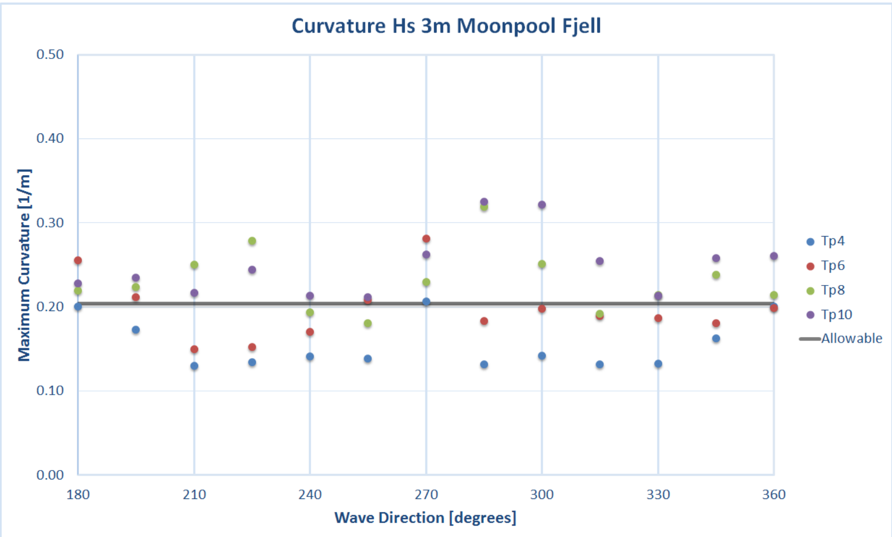


(b) Hs = 3.0 m

Figure E.3: Curvature per wave heading conventional cable laying Fjell



(a) Hs = 2.0 m



(b) Hs = 3.0 m

Figure E.4: Curvature per wave heading moonpool cable laying Fjell

F

Weight Estimate

Here, a weight estimate is presented including an estimate of the vessel's CoG. All equipment needed to convert the Fjell into a cable lay vessel is included.

	Lightship Weight Estimate					
			Weight [ton]	**Vertical Centre of Gravity [m]**	**Longitudinal Centre of Gravity [m]**	**Transverse Centre of Gravity [m]**
1	Original Vessel					
		Light ship weight	11483.0	7.7	84.2	0.0
2	Hull and preservation	*Steel mod for moonpool integration*	110.0	4.5	58.5	-3.8
		Buoyancy boxes aft + aftdeck	160.0	11.0	28.0	0.0
		Buoyancy boxes fwd	110.0	11.0	87.0	0.0
		Accomodation / Bridge extension	300.0	25.0	113.5	0.0
		Stern extension	25.0	5.6	1.5	0.0
		Removal hull plating frame 148-195	-210.0	6.0	125.0	0.0
		New hull plating frame 148-195	210.0	6.0	125.0	0.0
		Steel modifications for thruster room integration	40.0	4.5	115.0	0.0
		Steel hull fenders removal	-50.0	5.5	71.0	0.0
		Wooden fendering removal	-20.0	5.0	60.0	0.0
		Small foundations	30.0	5.0	60.0	0.0
		Miscellaneous hull and preservation	15.0	5.0	60.0	0.0
3	Outfitting tanks and cargo	*Bottom doors moonpool + actuators*	80.0	1.2	60.0	-3.8
		Deck crane midship	35.0	20.0	55.0	-3.8
		Cable lay system				
	Steel Category 5	*Carousel*	1000.0	11.0	75.0	0.0
	Steel Category 4	*Goose Neck*	250.0	15.0	58.0	0.0
	Steel Category 5	*Tensioners*	50.0	12.0	55.0	0.0
	Steel Category 3	*Quadrant*	100.0	15.0	58.0	0.0
	Steel Category 4	*Other*	200.0	11.0	75.0	0.0
4	Ship's equipment	*Life saving equipment*	5.0	11.0	113.5	0.0
		Life boats with craddle	-25.0	25.0	124.0	0.0
		Life boats with davits	30.0	15.0	116.0	0.0
		Ventilation / Heating / Airconditioning	25.0	15.0	113.5	0.0
		Hipap	10.0	5.0	60.0	0.0
		Miscellaneous equipment	10.0	12.0	113.5	0.0
5	Accommodation and service spaces	*Pannelling, partition bulkheids, ceilings, doors, etc.*	140.0	25.0	113.5	0.0
		Inventory accommodation	50.0	20.0	113.5	0.0
		Inventory bridge / TS extension	40.0	30.0	120.0	0.0
		Inventory service spaces	30.0	20.0	113.5	0.0
6	Electrical and nautical installation	*Switchboards + trafo's + drives (Bakker)*	32.0	11.0	109.8	4.8
		Remaining electrical installation	15.0	11.0	112.5	0.0
7	Main and auxiliary propulsion equipment	*Electric motors forward*	20.0	4.9	112.5	0.0
		Thrusters (2x) forward	50.0	2.5	117.0	0.0
		Miscellaneous propulsion	15.0	10.0	115.0	0.0
8	Auxiliaries and piping inside engine room	*Cooling water system*	30.0	10.0	120.0	-3.8
9	Auxiliaries and piping outside engine room	*Ballast / Bilge / FiFi system*	25.0	5.0	100.0	0.0
		Sanitary and sewage water system	20.0	10.0	113.5	0.0
	Margin on fixed weight items	5%	722.25	7.27	73.14	-0.04
	Margin on VCG	0.5				
	System filling		5.0	10.0	113.5	0.0

Figure F.1: Lightship Weight Estimate and CoG of Fjell including equipment

Light Ship Weight		**15167.25**	**8.75**	**82.81**	**-0.04**
Water in recesses					
	Water in Moonpool				
	Water in Bowthruster tunnel	30.0	2.5	140.0	0.0
	Water in Retractable thruster casings	32.0	1.5	117.0	0.0
Light Ship Weight (used in PIAS)		**15229.25**	**8.72**	**83.00**	**-0.04**
Displacement @ summer draught (B-100)	6.76 m	**31083.0**			
New Light Ship Weight		**15167.25**	**8.75**	**82.81**	**-0.04**
Crew, stores and spares		25.0	19.5	120.0	0.0
Tank filling					
	Fuel oil	750.0			
	Fresh water	99.0			
	Misc tanks	150.0			
	Water ballast	0.0			
Water in recesses					
	Water in Moonpool				
	Water in Bowthruster tunnel	30.0	2.5	140.0	0.0
	Water in Retractable thruster casings	32.0	1.5	117.0	0.0
Available Cargo Payload @ summer draught		**14829.75**	**8.74**	**83.06**	**-0.04**

Figure F.2: Available Cargo Payload Calculation

G

Curvature in different planes

Here, the curvature is presented in the xz-plane (y-curvature) and in the yz-plane (x-curvature). The curvature is displayed for 180 and 270 degrees wave heading. Also, vertical seabed clearance is displayed to give insight in which part of the cable maximum curvature occurs. In all simulations, the curvature in yz-plane was negligible for 180 degrees wave heading. For 270 degrees wave directions, the curvature in the xz-plane was the dominating curvature in the cable. Maximum curvature occurs in the segbend or at the chute. When the departure angle of the cable is decreased, the point of maximum curvature moves towards the touchdown point. When the departure angle is increased, the maximum curvature moves along the cable towards the ship.

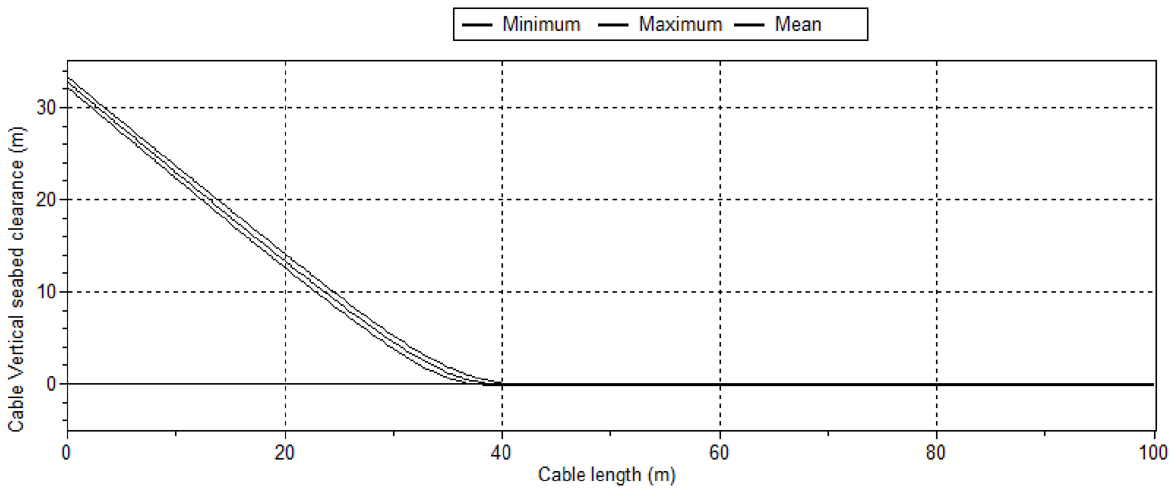


Figure G.1: Seabed clearance at 180 degrees wave direction and Hs = 2.0 m Moonpool NDurance

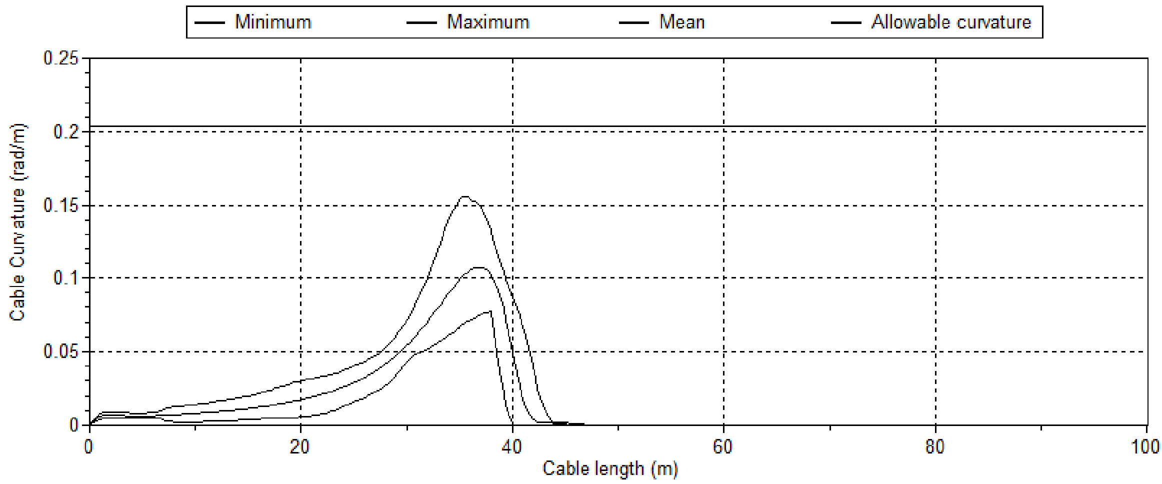


Figure G.2: Curvature at 180 degrees wave direction and Hs = 2.0 m Moonpool NDurance

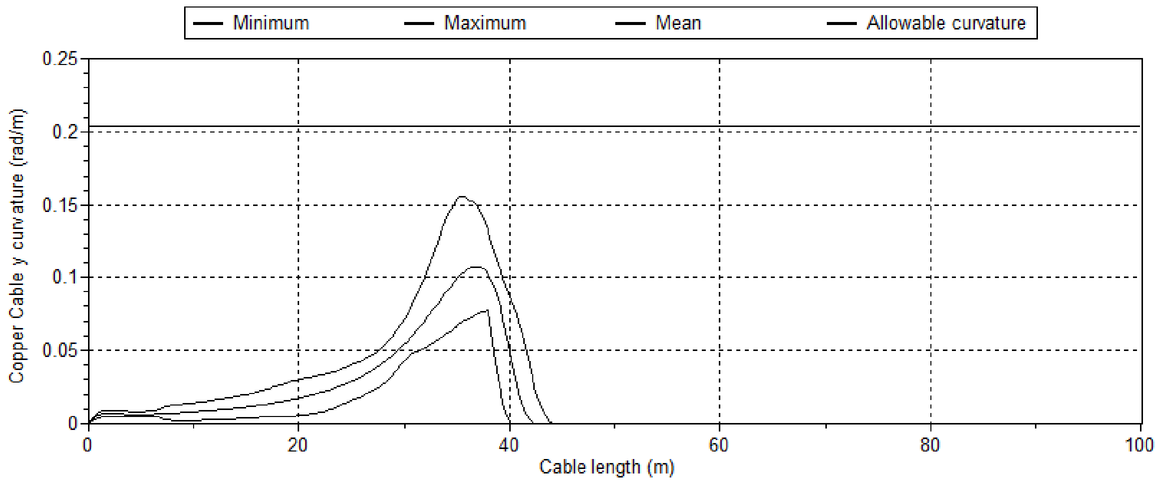


Figure G.3: Y-curvature at 180 degrees wave direction and Hs = 2.0 m Moonpool NDurance

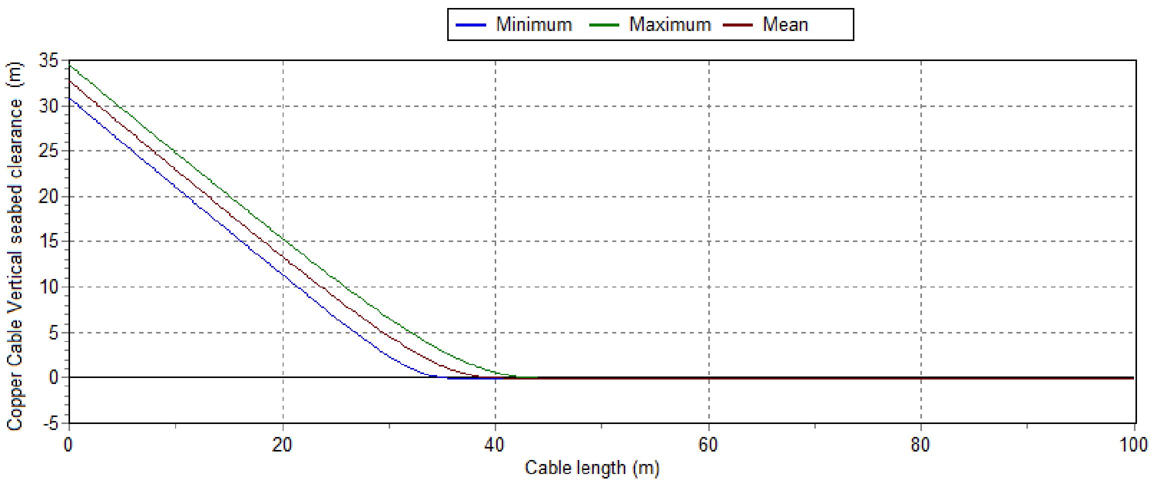


Figure G.4: Seabed clearance at 270 degrees wave direction and Hs = 2.0 m Moonpool NDurance

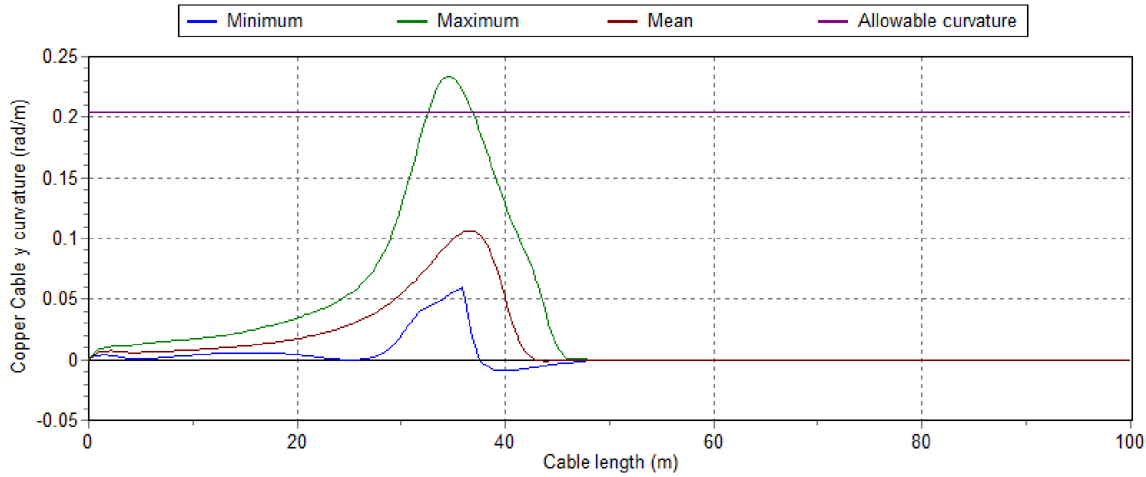


Figure G.5: Curvature at 270 degrees wave direction and Hs = 2.0 m Moonpool NDurance

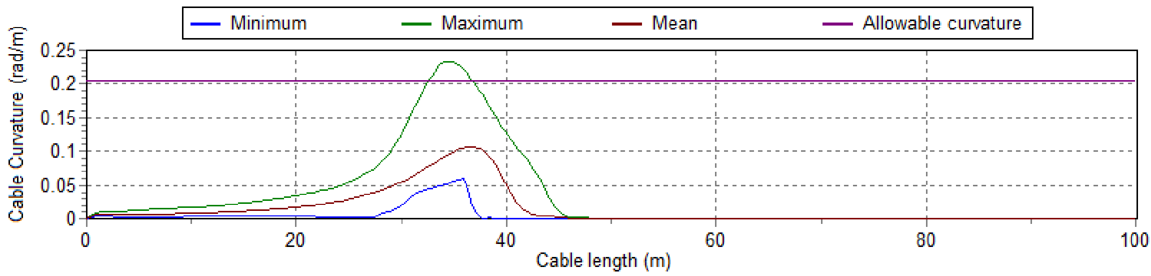


Figure G.6: Y-curvature at 270 degrees wave direction and Hs = 2.0 m Moonpool NDurance

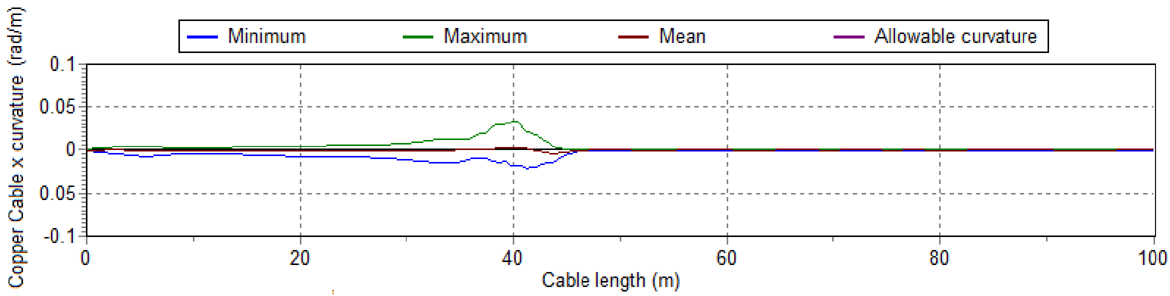


Figure G.7: X-curvature at 270 degrees wave direction and Hs = 2.0 m Moonpool NDurance

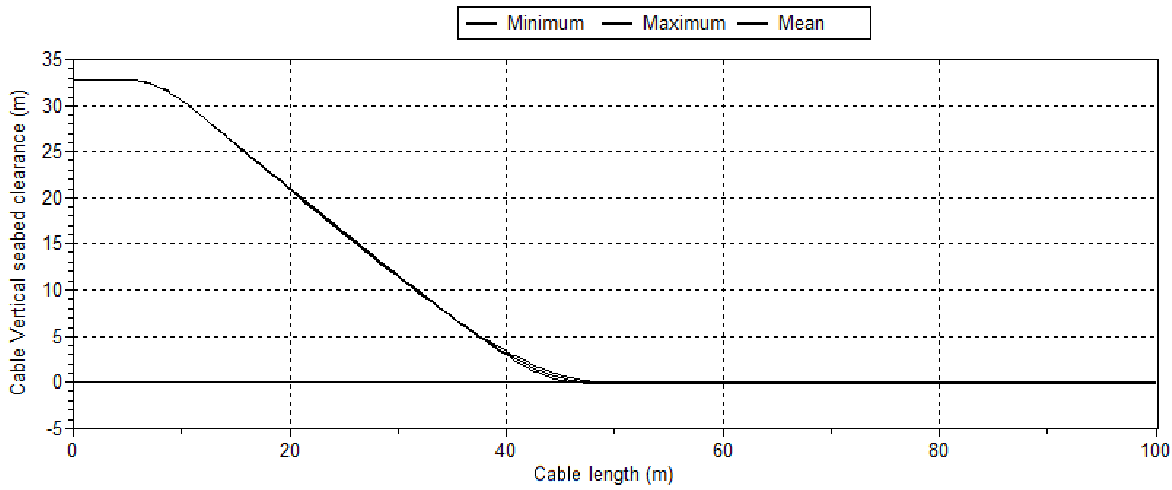


Figure G.8: Seabed clearance at 180 degrees wave direction and Hs = 1 m Chute NDurance

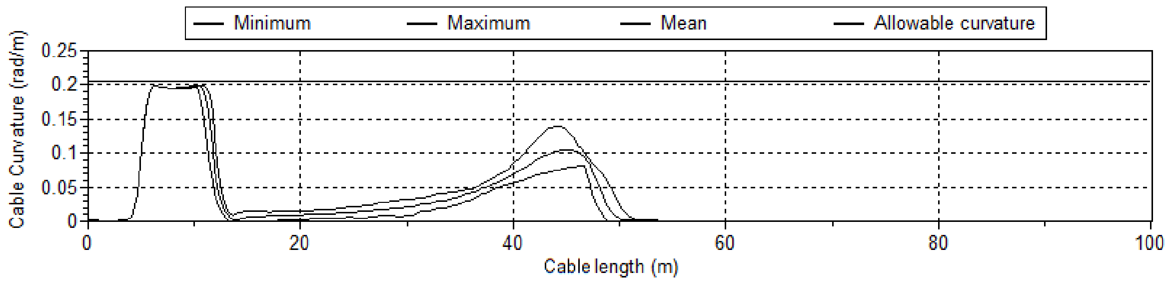


Figure G.9: Curvature at 180 degrees wave direction and Hs = 1.0 m Chute NDurance

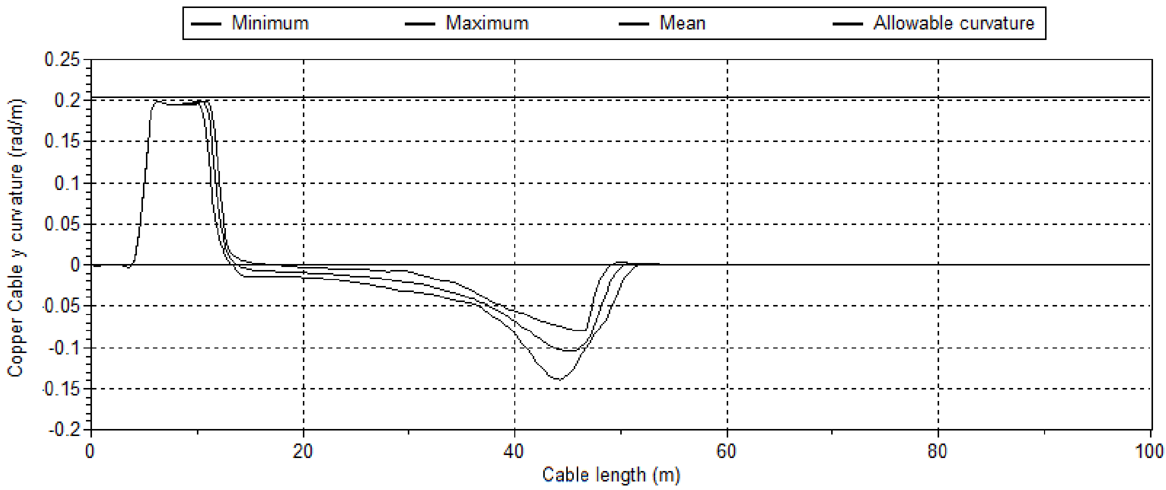


Figure G.10: Y-curvature at 180 degrees wave direction and Hs = 1.0 m Chute NDurance

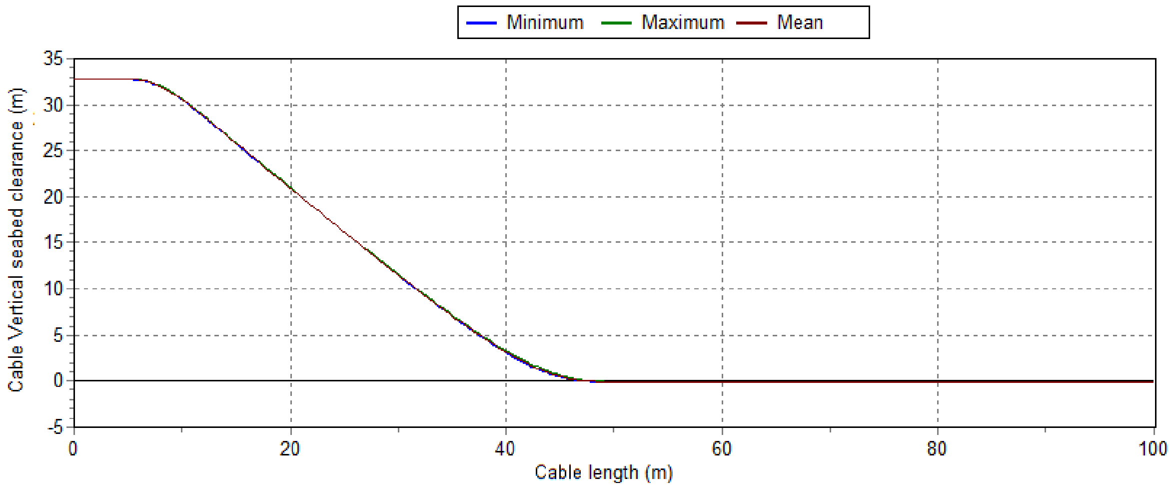


Figure G.11: Seabed clearance at 270 degrees wave direction and Hs = 1.0 m Chute NDurance

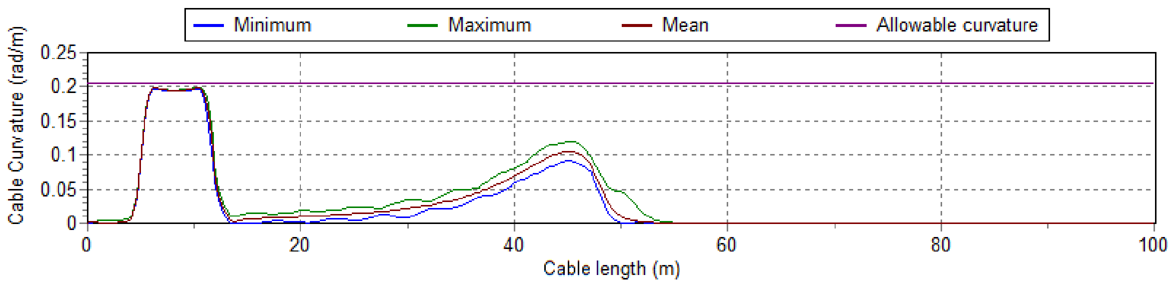


Figure G.12: Curvature at 270 degrees wave direction and Hs = 1.0 m Chute NDurance

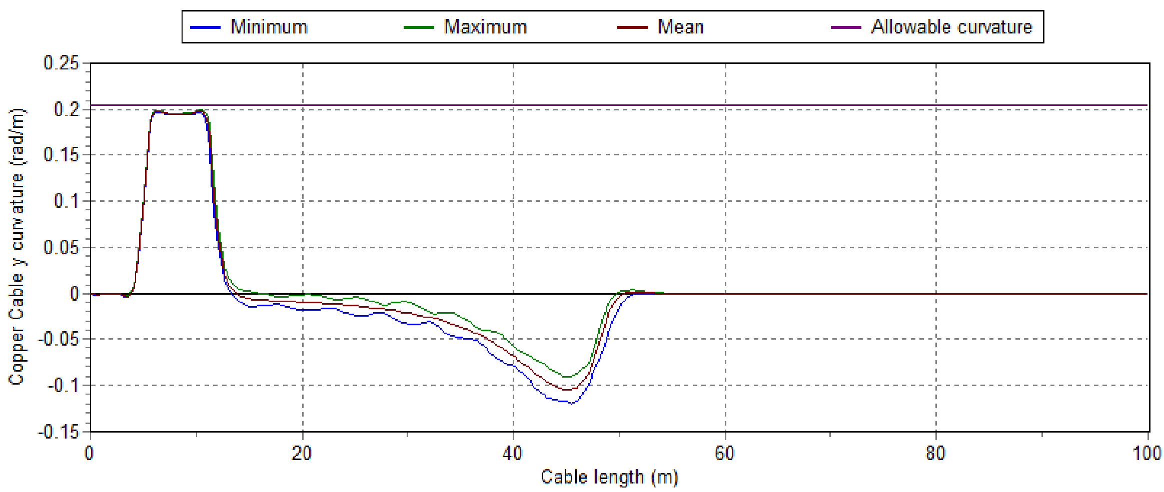


Figure G.13: Y-curvature at 270 degrees wave direction and Hs = 1.0 m Chute NDurance

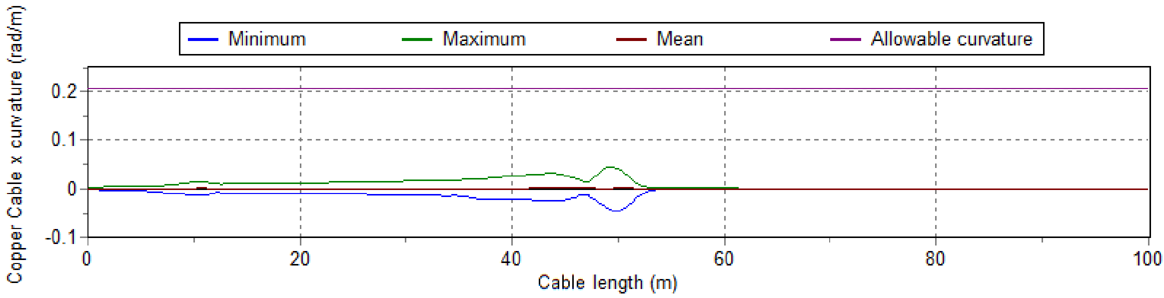


Figure G.14: X-curvature at 270 degrees wave direction and Hs = 1.0 m Chute NDurance