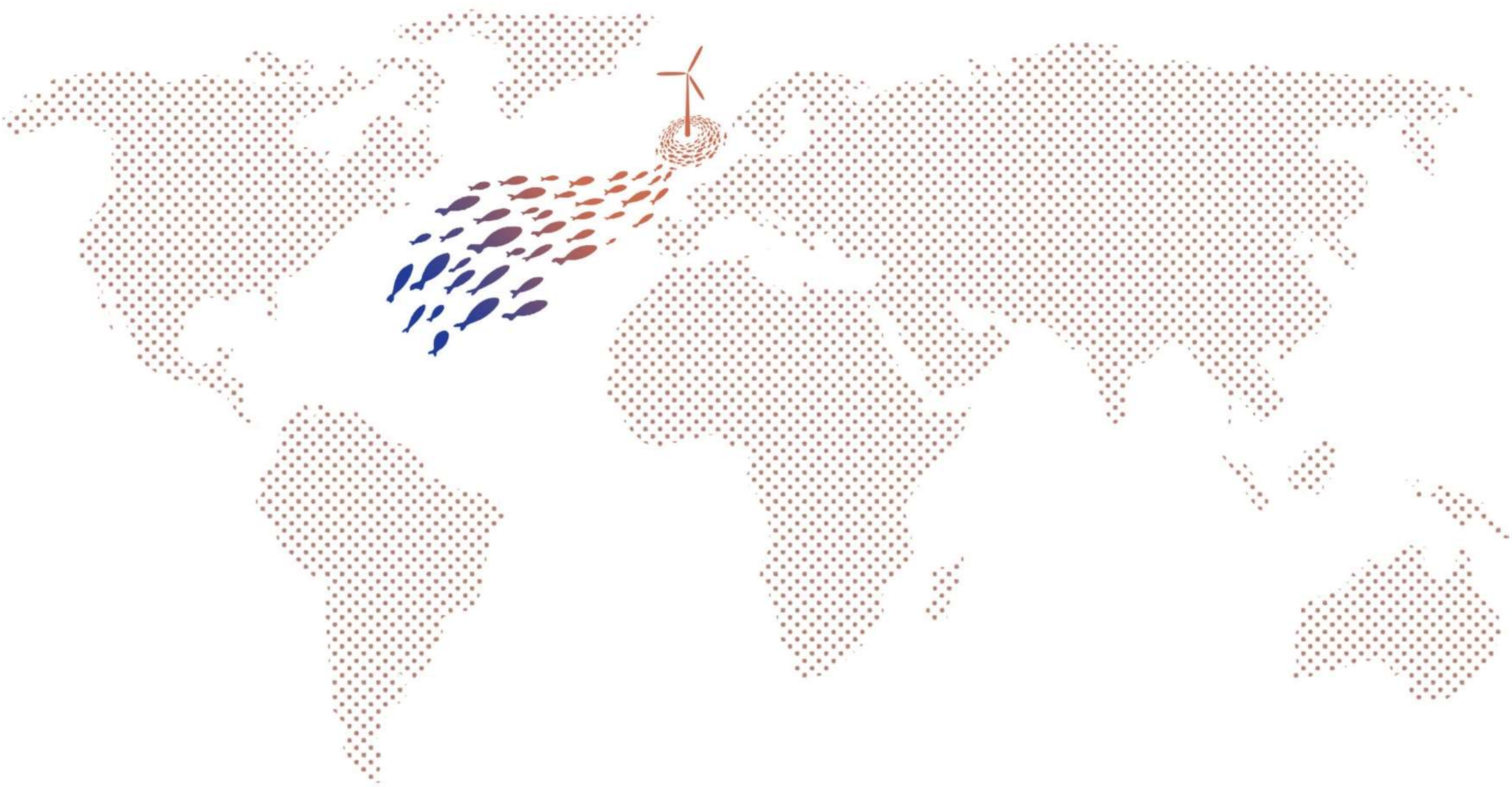
CONCEPT STUDY

FISH-AS-A-SERVICE IN THE NORTH SEA

SUSTAINABLE FISHERY IN OWF



TU Delft

WAGENINGEN UNIVERSITY & RESEARCH

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A MULTIDISCIPLINARY PROJECT

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General information

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Preface

Before reading this feasibility study, one should note that this project team consists of different disciplines. This feasibility study is concerned with a topic that is very much one of its time and exceptionally promising to the project participants. The biologists of the team, Milan Jagt and Paulien Verschuyl, both sepcialize in Aquaculture and Marine Resource Management at Wageningen University and Research. Their expertise helped us to gain a deeper understanding of the ocean environment, including its potential biomass before and after the implementation of a bio-enhanced, artificial reef within an Offshore wind farm (OWF). The design of a sustainable system that should function in a proper way, has been investigated by Chris van Hulten and Kamal Laghmouchi, both students at the TU Delft. Chris van Hulten follows the MSc-track Hydraulic Engineering and specializes in hydraulic structures. Kamal Laghmouchi specializes within the same field but follows Structural Engineering. Kije Zijlstra and Sebastiaan van Ham, also TU Delft students, are studying the MSc-track Construction Management and Engineering. Together they performed a financial feasibility study and created a process design in which the stakeholders' views and preferences are taken into account. Each team member has had a valuable contribution in the establishment of a dynamic group process.

We would like to thank Tinka Murk for her valuable knowledge on marine systems, Mark Voorendt for his costly input in maintaining the design progress, Daan Schraven for his enlightened look on the finances of such a project and Martijn Leijten on implementing a "Fish-as-a-Service"-system. Regarding stakeholder analysis, we thank Simon Bush from Wageningen University and Research for his fascinating input on the diverse opinions and conflicts surrounding multi-purpose OWFs. Additionally, we would like to give special thanks to the companies and research institutes that were involved. Boskalis N.V.'s department led by Paul Peeters gave us the opportunity to expand our practical knowledge by means of interactive sessions with their professionals at their head office in Papendrecht. We also express our gratitude to Han Lindeboom (NIOZ), Joop Coolen and Rob Witbaard. They provided us with their experience on artificially bio-enhanced OWFs at an arranged meeting inside the Royal Netherlands Institute for Sea Research (NIOZ) on Texel. To mention in particular, Han Lindeboom has been a vital link in kick starting this inter university research process and thereby making this research possible. Without the commitment and willingness of Han Lindeboom, the project would have ran less smoothly, to say at least. Furthermore, we also express sincere thanks to Marnix Poelman from Wageningen Marine Research, who provided us with information on the mulit-use OWF concept. Many thanks to Nicolas Blanc from the Portuguese NGO Sciaena, who broadened our knowledge by giving us an international perspective on the artificial reef concept. Marit Nederlof, from the Aquaculture and Fisheries chair group at Wageningen University and Research was also invaluable in providing us with much needed advice on the execution of the biological part of the project.

We also had the much appreciated opportunity to interview Arnoud Bosch and Marcel Osseweijer of Seaway Heavy Lifting concerning offshore commissioning and decommissioning projects considering both the technical as well as the financial aspects. For those others not mentioned here but involved in this process, we express our sincere gratitude as well. This study has brought out the creative, innovative and highly cooperative characteristics of each team member. It has shed light for all of us on the importance of multi-disciplinary work regarding complex topics such as the ones covered in this report.

We hope you enjoy the reading.

Yours sincerely,

Chris van Hulten
Kamal Laghmouchi
Kije Zijlstra
Milan Jagt
Paulien Verschuyl
Sebastiaan van Ham

Delft, February 9, 2020.

Glossary

Artificial reef	A reef which is originally created by men.
Arthropods	Invertebrate animal having an exoskeleton, segmented body and paired jointed appendages. Including crustaceans, arachnids, myriapods and insects.
Basalt	A volcanic rock type that is originates through the coagulation of lava on the surface of the earth.
Bathymetry	This is the study of underwater depth of lakes, rivers and oceans.
Benthic	Referring to organisms living in or near the bed of fresh or marine waters.
Biofouling	Accumulation of micro- and larger organisms on wet surfaces of objects with a mechanical function.
Bivalves	Class of molluscs with a laterally compressed body enclosed by a shell with two hinged parts. Examples are clams or mussels.
Catch per unit effort	An indirect measure of the abundance of a target species.
Cephalopods	Class of marine mollusks including squids, octopuses and nautili.
Cone Penetration Test	Test at which an iron pen is forced in to the soil, measuring the resistance of exerted by the soil at each depth.
Confidence interval	This is a interval set with a band with as such that there is a x% certainty (often a 95% confidence s used) that values lay within that interval.
Consumption-biomass ratio	The amount an individual from a species group must consume of its own body weight annually.
Clinker	Limestone and clay burned at 1500°C that is used as a bind material in cement.
Crustaceans	Subphylum of the arthropods, including crabs, lobsters, crayfish, shrimp, krill and barnacles.

Decapods	order of crustaceans including groups like crabs, lobsters, crayfish, prawns and shrimp. Literally "ten-footed".
Demersal species	Species living and feeding on or near the bottom of seas and lakes.
Detritus	Dead particulate organic material. Typically includes dead organisms and feacal material.
Diet composition	Set of information on the factors of feed items in the diet of an organism.
Ecotrohic Efficiency	The proportion of the biomass that is consumed in the system for each component of the system.
Elasmobranchs	Subclass of cartilaginous fishes including sharks, rays and skates.
Eutrophication	Process of accumulation of plants in water due to the excessive nitrogen.
Fallpipe vessel	Type of vessel that is equipped with a long pipe of a certain diameter and used for waterborne operations such as laying rocks on the seabed and dredging.
General Pareto Distribution	This is a stochastical distribution that is commonly used for modelling extreme values.
Hydrodynamics	A study that is related to the wave and current conditions at sea.
K-strategist	Organisms focusing on quality of offspring rather than quantity.
Low Astronomical Tide	This is the lowest reference tide of a water body.
Macroalgae	Abundant plant species that grows in many parts of the world.
Metocean	Something that is referred to wind, wave and oceanic climate combined.
Migration	The large-scale movement of members of a species to a different environment.
Mollusks	Invertebrate species with a week body.
Monopile foundation	Hollow tubular foundation that is commonly used for an wind turbine in a medium water depth.
Morphodynamics	A study which is concerned with the time-dependent behaviour of soil (particles) at sea.
Morphology	A study which is concerned with the soil composition and soil behaviour at/below the bed level of a water body.
Multibeam echosounder	This is a tool that is used to map the depth profile. A sound pulse is emitted from beneath the hull in the direction to the seabed. The distance travelled to the seabed and back to the ship is determined by the velocity and the migration time of the sound.

Multitrophic	Referring to a system consisting of multiple species in different levels of a food chain.
Oceanography	This is the study of a wide range of aspects at sea, from marine life to waves and currents.
Passive fisheries	Fisheries using gear based on movement of the target species towards the gear rather than using gear focusing on chase.
Peaks Over Threshold method	A way to model extreme value by excluding them and modelling the tail that exceeds a chosen threshold.
Piscivorous	Feeding primarily on fish.
Planktivorous	Feeding primarily on plankton.
Plankton	Organisms unable to swimm against the current.
Polyamide	A composition of amids with a fibrous structure that is used in plastic, nylon.
Polycheates	Bristle worms. Generally marine worms with a pair of fleshy protrusions.
Polyvinylchloride	A plastic that is created through the polymerisation (composition) of monomeres and different additives. This material is used for a wide variety of applications such as the construction field and mechanical industry.
Production-biomass ratio	The annual instantaneous mortaity (Z) where growth follows a von Bertalanffy curve.
r-strategist	Organisms focusing on quantity of offspring rather than quality.
Sand waves	Bedforms that are under action of tidal currents. Sand waves can be up to several meters high and their migration speed is low.
Sexual maturity	Age at which an organism is capable of reproduction.
Still Water Level	The water level with no deviations in the elevation of the water surface line.
Tender procedure	This is a procedure where the applicant/tenderer is aiming at achieving a certain product or service. An example is a contractor holding a tender for a building contract.
Trophic level	The position an organisms occupies in the food web. The trophic level of an organism is the number of steps it is from the start of the food chain.
Turbulence	The speed of the motion of a fluid particle at a certain moment relative to the average fluid velocity

List of abbreviations

AFWD	Ash Free Dry Weight
B	Biomass
CAPEX	Capital Expenditures
CMU	Concrete Masonry Unit
DC	Diet Composition
EE	Ecotrophic Efficiancy
EEZ	Exclusive Economic Zone
EMODnet	European Marine Observation and Data Network
EN13383	Euronorm 13383
EwE	Ecopath with Ecosim
HARMONIE	*HIRLAM ALADIN Research on Mesoscale Operational NWP in Euromed*
FINO1	*Forschungsplattform In Nord- und Ostsee (English: Research platform in the Nordsee and Ostsee)*
FW	Fresh Weight
GPD	General Pareto Distribution
IRR	Internal Rate of Return
LAT	Low Astronomical Tide
MSL	Mean Sea Level
MWL	Mean Water Level
NIOZ	*Nederlands Instituut voor Onderzoek der Zee* (English: Dutch Institute for Sea Research)

NNE	North-North-East
NNW	North-North-West
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value
NWP	Nearest Way Point
OFL	Overlegorgaan Fysieke Leefomgeving (English: Consultative body physical living area)
OPEX	Operational Expenditures
OWF	Offshore Wind Farm
P	Production
PCB	Polychlorinated Biphenyl
POT	Peaks Over Threshold
PSU	Practical Salinity Unit
PVC	Polyvinylchloride
Q	Consumption
RvO	Rijksdienst voor Ondernemend Nederland (English: Dutch Enterprise Agency)
RWL	Relative Working Length
SHL	*Seaway Heavy Lifting*
SSW	South-South-West
SWAN	Simulating WAves Nearshore
SWL	Still Water Level
WFZ	Wind Farm Zone
WW	Wet Weight
WGS84	World Geodetic System 1984

Management Summary

The use of the North Sea has transitioned into an intensely used industrial area, with the climate agreement as a driving force. The Paris agreement demands countries to change their main energy resources from oil, coal and gas to renewable resources such as wind. The Dutch government chose to use the space offshore for the development of wind farms. These developments require a durable collaboration between the various stakeholders in the North Sea. Tensions exist between the different stakeholders in the North Sea, and the projected developments are expected to pressure these relationships even further. The need for shared multi-use areas grows as the North Sea is used more and more intensely. This report presents a multidisciplinary design for an artificially enhanced fisheries system within an offshore wind farm (OWF). The goal of this design is to provide a nature inclusive solution to increasing pressure on the fishing industry by the growing offshore wind sector.

The possible implementation of a fishing industry within OWFs was analysed. This resulted in a number of applicable solution spaces. A notable solution was the Fish-as-a-Service concept, which resolves several issues that currently hinder the development of multi-purpose OWFs. In this solution, a company would fulfil the role of managing the fisheries in OWFs without the need for wind farm clients to actively partake in the fishing industry. Five target species were selected that could be harvested from an artificial reef system within an OWF. These species were European lobster, Brown crab, Atlantic cod, European seabass and Cuttlefish. The selection of these species was made based on economic interest, ecological interest, the potential for non-intrusive fishing methods and previous successes in other studies and/or projects. These species formed the basis of further ecological and financial examinations.

Based on the biological and technical criteria following from the stakeholder and biological analysis, the most suitable wind farm site where an artificially enhanced fishing area could be implemented was selected. It was concluded that the Borssele Wind Farm Zones 1 and 2 would be the most suitable sites. The bathymetry, soil conditions, seabed dynamics and metocean data were further analysed in order to create a design for the artificial reef. A range of possible reef concepts were developed, including loose rock revetment, placed block revetment, layer cakes, biohuts, block reefs, layered pipes, shipwrecks and decommissioned oil or gas platforms. These concepts were verified for their operability and whether they met the requirements for bio-enhanced fisheries. Three preliminary designs for an artificial reef system in the Borssele OWF were made based on these reef concepts and the circumstances at the site. Of these designs, the most desirable one includes block reefs, natural stones, layer cakes, decommissioned oil or gas platforms and shipwrecks in order to promote biodiversity and yield as much biomass as possible.

An Ecopath with Ecosim model was designed using available literature studies. This model was used to predict the amount of biomass produced in an OWF with and without hard substrate. An immense biomass increase in the target species European lobster (2.157.265%) and Brown crab (857.281%) was predicted with the addition of hard substrate. additionally, target species Atlantic cod and cuttlefish showed an increase of 1897% and 175% respectively. Surprisingly, European seabass was predicted to decrease with 93%. The estimated biomass was included in a study in the strengths and weaknesses of the business opportunities based on the Fish-as-a-Service concept. Costs and revenues throughout the lifetime of the sustainable fishery were taken into account, resulting in a final investment advice. The PERTH method was used to account for the uncertainty of estimating the costs of such a project. A detailed cash flow analysis was carried out in order to present a clear view on the different financial scenarios. The cash flow analysis showed a final Net Present Value (NPV) at year 25 of values between 3000 and 6000 mln EUR. This shows the profitability of the proposed design, with an Internal Rate of Return after tax of 69,90%.

Contents

Chapter 1

Introduction

As a result of the Paris Agreement 2015, many countries were obliged to focus on CO2 reduction. Participating countries started to increasingly invest in sustainable energy production. Of these the different alternative energy options, the favored type became wind energy, mostly generated at sea. It is expected that the number of offshore wind farms (OWF) will continue to increase. Most recent plans show the implementation of enormous energy hubs, far offshore. For instance, the network operator giant TenneT aims to realize 100 to 200GW of OWFs before 2050 [TenneT, 2019b]. The current conversion is around 6MW per km2, meaning approximately 33.000 km2 of new OWFs in today's standard [J. Matthijsen, 2018]. Consequently, the number of conflicts in the upcoming process surrounding the spatial planning of the North Sea will likely increase. This conflict will be particularly apparent between the current users, such as fishermen, shipping companies, oil and gas companies, nature organisations and prospective OWF owners. Next to a changing North Sea, the world-wide increase in food demand, considering population and welfare growth, demands the need for sustainable solutions. This will undoubtedly place extra pressure on the North Sea ecosystem, which already faces considerable ecological degradation.

What is more, the offshore wind sector undergoes fast advancements in technology as many governments are heavily investing in OWFs. The first investments started in Northwestern Europe but are already spreading to other countries worldwide. This makes the offshore wind industry an increasingly more economically attractive energy source. Currently, however, offshore wind operators refuse ancillary activities such as fisheries in their OWFs. The decreasing available sea surface for fisheries naturally has a significant impact on the economic viability of the fishing sector. For this reason, there is still a continuing urge for the development of a synergetic solution space between the stakeholders. Establishing a sustainable fishery in OWFs can form a suitable solution that satisfies the majority of the actors involved. In this report, the ecological, technical and financial feasibility of implementing a multi-purpose OWF will be explored.

The report is structured in four separate parts to enhance the overall readability. The first part "Initiation phase" starts with chapter 2. Here, a concrete problem analysis is done wherein the connection between the current situation and the ambitions of the ministries is explored. Hereafter comes chapter 3, an elaboration on methodology used for this project. Chapter 4, a stakeholder analysis, uncovers the interest and concerns of the stakeholders involved. The first part ends with chapter 5, a preliminary research exploring the options for the most fitting fish species in a multi-purpose OWF. The second part of the report "Design phase" begins with chapter 6. This chapter assembles the output from the stakeholder analysis and fish species selection into a definite program of requirements. Chapter 7 will discuss the potentialities for the preliminary designs, whereafter chapter 8 will verify the design possibilities in accordance with the program of requirements. The second part of the report ends with chapter 9 that evaluates two drafted variants in pursuit of an ecological and stakeholder management perspective. Continuing to the third part of the report is the part "Business case". This part begins with chapter 10, where the modelling system Ecopath is used to provide biomass estimates that are then used for the financial model in the subsequent chapter 11. Next, chapter 12 assembles all the data from the preceding chapters and composes a business case, based on a new concept: Fish-as-a-Service. Lastly, the fourth part of the report consists of the general discussion in chapter 13, followed by a conclusion and recommendation in chapter 14.

Part 1

Initiation phase

Chapter 2

Problem Analysis

2.1 Noordzeeakkoord

Over the last decades the use of the North Sea has intensified. With the climate agreement as a driving force, it has transitioned to an intensely used industrial area. In order to manage the changing stakeholders and their interests, the changes have been subdivided in the following transitions: energy transition, food transition and nature transition.

2.1.1 Energy transition

The energy transition initiated by the Paris climate agreement demands many countries worldwide to change their main energy resources from oil, coal and natural gas to renewable sources such as wind or solar. Along with climate change and seawater temperature increase, the North Sea will experience other climate induced changes such as ocean acidification, sea level rise and the change in the structure of fish assemblages. These consequences, which in many cases are already occurring, make the need for an energy transition even more urgent. The Dutch government as many other European governments did choose for using space at sea to build offshore wind farms. With current wind energy technology and current energy demand, a sizeable part of the North Sea is to be used for offshore wind only. Through this, the available space for fishermen decreased significantly impacting fish resources. Therefore, a decent consideration on how to deal with nature and the offshore marine ecosystem needs to be made. This is especially true when taking into account the future plans of energy storage offshore within islands and large energy hubs offshore.

The announcement of the Dutch government supporting the large roll-out of offshore wind on the North Sea is well received all across the board. Many environmental NGOs expect significant positive changes within the next few decades. Nonetheless, the emergence of another energy sector on the the North Sea simultaneously reminds of a former massive energy transition a few decades earlier, namely, the oil and gas industry, which has left a distinct mark on the area. Environmental protection organisation have been stressing the obligation of oil and gas companies to remove obsolete rigs, typically combined with considerable protest. The most famous protest for the North Sea was Brent-Spar, which became an issue of public concern in 1985. Largely provoked by Greenpeace, the notice that Shell wanted to dispose the storage and tanker loading buoy at sea, sparked a surge of national protest against the oil and gas giant Shell. This led to a widespread boycott of Shell service stations [K. Schwartz, 1988]. Ever since, the decommissioning process around obsolete oil and gas rigs became even more sensitive. In the upcoming decades, 600 obsolete rigs need to be decommissioned [Gerard Reijn, 2019]. What should be done with these platforms? Currently, the debate around this topic is still raging and a solution that fully satisfies both of the opposing parties is still missing.

2.1.2 Food transition

The changing users and said power of certain users in the North Sea demand the fishing industry to search for alternatives and opportunities. Therefore, the supply chain of the fishing industry must be considered. This process must begin with the availability of fish resources and the possibility for cost-effective and sustainable fisheries. The fishing fleet also needs to be restructured and redesigned as conventional fishing methods no longer suffice. In addition, because the fishermen are suffering from many policy-related decisions, the industry needs a stable future. As the name of the section suggests, the future of growing food offshore such as mariculture and growing algae could be utilized in the North Sea in the future. The technology and thereby technical and financial feasibility of growing these species is evolving. With a changing supply and demand these products could be grown on a large scale.

Restricting the damaging practice of bottom trawling is one advantageous aspect of an OWF, which can aid in the food transition of the North Sea. This would leave the fishery as well as the seafloor in the wind park's perimeter undisturbed. Since the 16th century bottom trawling has been both a fishing method in the Dutch North Sea and a subject of serious contention. Already in the late 1500s fishermen were complaining about the damage bottom trawling caused to the seafloor, as well as the depletion of their fisheries [S.J. De Groot, 1983]. In addition, it is now well known that bottom trawling affects the age and size structure of fishing stocks by reducing the size at maturity for many species, meaning fish are caught at smaller sizes and often before they are able to reproduce [G. Bianchi, 2000]. Using OWFs as a conservation tool to restrict bottom trawling or replace it with alternative, passive fishing methods should be strongly considered in the food transition's planning process.

2.1.3 Nature transition

The current state of the North Sea ecosystem is weakening. There is a decline in biodiversity and fishing practices are disturbing the benthos. In order to increase the use of the North Sea in a responsible way, the health of the ecosystem has to be recovered and maintained. A transition in the way we perceive marine ecosystems is needed to continue increasing the use of the North Sea without destabilising the ecosystem. Where the North Sea ecosystem was viewed as a static system in the past, we now have to realize that the system is in fact dynamic. Through the installation of platforms and wind farms, new off-shore habitats can be created and the natural system can potentially be enhanced. A significant challenge moving forward will be to fill the knowledge gap, especially regarding biomass surveys and species monitoring within OWFs. It is vital that consistent monitoring is put in place, so that the true impact of these new off-shore constructions is better understood. In addition, this collection of data should focus on specific areas within the North Sea, to gain a more detailed picture of the region's various conditions. Furthermore, since a healthy North Sea serves the public, optimization of the nature protecting policies is necessary. A continuous process of monitoring and acquiring knowledge will help optimize the policies in order to help the North Sea recover and remain healthy in the future.

2.1.4 Aim of the report

This report aims the present a profitable business case that enables sustainable fisheries within OWFs through enrichment of the ecosystem. It will explain the preliminary analyses of the current situation and potential solutions and the process of reaching the final design. The solution proposed in this report will fit perfectly in the current and future transitions on the North Sea. It responds to the growing offshore energy sector, while taking the needs of the fisheries industry into account. Trough this nature inclusive design of the OWFs and addition of artificial hard substrate to the seafloor, the ecosystem, fisheries and offshore wind sector will all benefit.

Chapter 3

Methodology

A cornerstone of this project is the interaction between the three biological, technical, and financial disciplines. Since the outcome of the project is one preliminary design, the method of obtaining such a design is the integrated design method. The method described by van Roozenburg and Eekels in the publication Product Design, Fundamentals and Methods [N. Roozenburg, J. Eekels, 1995] is adjusted and made suitable for this interdisciplinary project.

3.1 Part I: Preliminary study

The logical starting point is a problem analysis that is used to make a basis of design. To do that, certain boundary conditions and a program of requirements are set as verification criteria. The target species for this project were chosen based on the following criteria: 1) economic interest, 2) ecological interest, 3) potential to use alternative, non-intrusive fishing gear, and 4) demonstrated success or potential with other projects and research studies.

Another important aspect is to perform a stakeholder analysis. Obviously, it is necessary to find and resolve the current friction point between owners of offshore wind farms, contractors, and the fishery, so that ultimately all parties benefit. In order to do this in a systematic matter, a network analysis is drawn up to make an inventory of all the different stakeholders that are concerned with the outcome of current developments. Here, all the actors are identified. Next, a stakeholder analysis was formulated, which contains information about the views, interests and overall dedication of the stakeholders. If there is insufficient information found in reports online, for example from the website of the Overlegorgaan Fysieke Leefomgeving (OFL), interviews with stakeholders were done. Preparing all this information, eventually the power/interest grid, resources dependencies and critical actors were determined. By choice, this part of the stakeholder analyses was later expressed in quantitative results. The next step was preparing a SWOT/TOWS diagram, which shows the internal and external strengths and weaknesses. Finally, the stakeholder analysis was finalized with a stakeholder engagement strategy. This formed the basis for the later part of the stakeholder management plan: the process design.

The second part started with an actor scan, where the views, interests and core values, risk and opportunities, incentives and disincentives and pluriformity of the actors are established. Thereafter, the process component with process and sharing dilemmas, and the rules of the game were concluded. Substance components were divided into several rounds whereafter a suitable order was chosen. Ultimately, the agenda was fixed and the process design was tested.

3.2 Part II: The design

Based on existing models of the seabed, sea conditions, and biological aspects, innovative alternatives which are needed for the artificial reef system were designed. Several potential concepts were created and afterwards analyzed based on the program of requirements in the following stage. On the technical aspect, the North Sea offshore conditions were analyzed, which were also included in the program of requirements and boundary conditions. Finally, there were also legal requirements, which should not be overlooked. These legal aspects were counted as boundary conditions.

Subsequently, the verification was performed where the construction was calculated based on existing mechanical methods. The potential concepts were verified according to the program of requirements and the boundary conditions. The aim of this part was to explore realistic alternatives for a bio-enhanced fishery in Borssele I+II that fit all technical and ecological demands.

Eventually, an evaluation was done, and the suitable alternatives which were determined in the verification phase were at this stage further elaborated on. Further enhancement of the realistic alternatives or the combination of them was considered here. Possible considerations or improvements were taken into account at this level.

3.3 Part III: Business case

For the biomass analysis of this project the potential biomass of the system studied is predicted for a scenario with an artificial reef present. This prediction was done using the modelling software Ecopath. This modelling software can create a helpful and illustrative picture of what such a system would look like, including species interactions within the system. Therefore, based on this model, calculations were done to predict the biomass such a system could produce before and after hard substrate was added to the system.

In the following stage, a financial feasibility study was executed. As the input of the technical and ecology disciplines was constantly changing, the financial model was created via an iterative process. The costs and incomes that are generated with the bio-enhanced fishery system were determined by the chosen preliminary design and the biomass analysis that followed from the previous parts (part I and II).

The financial study considered the necessary monetary costs to construct the system and the potential returns that are expected to be generated by the system. By making use of a cash flow analysis (covering OPEX, CAPEX, DECEX) the profitability of the project can be measured and guarded throughout the project, making sure a suitable return on investment is guaranteed. A cash flow analysis allows an evaluation from the owner's point of view on whether the project is financially attractive. The costs are determined based on general offshore rates and the income is determined on fish catch models. The result of the financial study consisted of net present values and internal rates of return. Besides, in order to reveal the essential parameters within the financial feasibility study, a Monte Carlo simulation was used to execute the sensitivity analysis. Finally, together with the financial study a reliable and as cheap as possible system was researched based on rules of thumb for offshore steel constructions. At last, a Fish-as-a-Service system is designed. This chapter concludes part III and sheds light on how a future bio-enhanced offshore wind farm would be realised considering the different parties that are involved such as: knowledge institutes, fisheries, and clients. Moreover, a study on how the future regulations and demands are taken into account was presented.

3.4 Part IV: Conclusions and general discussion

In the final step, discussions, a general conclusion and recommendations are provided. The discussions outline the issues that have occurred in the approach. The general conclusion in this part highlights the most important results that came forward during the design of a bio-enhanced artificial reef fishery within an OWF. At last, the recommendations provide information on how the different models could be improved from the perspective of each discipline.

Chapter 4

Stakeholder Analysis

4.1 Introduction

This chapter analyzes the possible implementation of a fishing industry in OWFs on the North Sea, creating a multi-purpose OWF 2.0. For this case, the hypothetical assumption is made that our project team is commissioned as an external process management consultancy by the Ministry of Infrastructure and Water State. In reality, the Ministry of Infrastructure and Water State requested the Overlegorgaan Fysieke Leefomgeving (OFL) on 18 october 2018 to officially oversee the negotiation around the Verkenning Noordzee Akkoord 2030, due to the immense complexity encompassing the future division of the (Dutch) North Sea. In the words of the responsible minister Van Nieuwenhuizen at that time: "the intended result is establishing a durable collaboration between the stakeholders involved in the North Sea policy and maintainability, and the accountable ministries" [OFL, 2019]. Nevertheless, the main aim of this design is forming a process that leads towards optimisation of the goals of the ministry, and finding a solution that collectively solves issues regarding the energy, nature and food transitions. In addition, the outcome of the stakeholder analysis will at the same time form the basis for the program of requirements that will be discussed in chapter 6. Eventually, the program of requirements will translate into a concept design for the multi-purpose wind farm, discussed in chapter 8.

Essentially, the chapter stakeholder analysis provides an advise based on an actor and network scan. Subsequently, both of these methods will form the basis for the SWOT/TOWS analysis. For this analysis, the aim is forming solution spaces that later can be utilized in the designing phase. Finally, the chapter will conclude with a stakeholder engagement plan. As for this process, creating widespread support considerably increases the likelihood of successful implementation of a multi-purpose concept. Before, however, the actor scan will be presented, and a short summary of the current scenario is provided that further sketches the complexity of the process as an addition on the problem analysis. Thereafter, the diversity of the stakeholders will briefly be discussed. After these two points, the network and actor scan can finally be covered.

4.1.1 Complexity of the problem

The North Sea is one of the most intensively used seas on the globe and this use continues to grow. For surrounding countries it has tremendous economic value. Large sections of the North Sea are already used for oil, gas, sand and wind energy production. So far, the North Sea counts 28 OWFs [Carbon brief, 2019]) and 160 production locations in the Dutch part of the North Sea alone [Noordzeeloket, 2019c]. Furthermore, some of Europe's most important ports are situated next to it, resulting in bustling shipping routes that scatter the sea surface area. The total surface area used for industry and commerce in the North Sea is 3,600 km2, which consists of sea routes, approach areas and clearways [Noordzeeloket, 2019d]. In addition, the navy and air-force uses more than 7% of the Dutch part of the North Sea for military purposes [Noordzeeloket, 2019b]. Lastly, the North Sea is a precious and vulnerable ecosystem that functions as a food resource for man and nature. Over the years, an increasing amount of area becomes protected under the European legislation as Nature 2000 areas, and rightfully so according to marine biologists. To give perspective on the situation, in 2016, Europe's total seas covered 5.7 million km2, more than Europe's land area. The total coverage of MPAs in 2016 was 10,8%. Moreover, specific Marine Natura 2000 sites covered even less: 15.000 km2 or 8.9%. Luckily, the Greater North Sea is performing better, with the highest MPA coverage of 27.1% [European Environment Agency, 2018]. At the same time, the North Sea faces many threats, including: increasing sea temperatures, ocean acidification, oxygen-scarce layers resulting in dead zones, sea level rise, the upsurge of invasive species and changes in the distribution of local fish stocks. In sum, the above mentioned issues in combination with spatial planning make the discussion around the future of the North Sea a highly complex problem.

4.1.2 Diversity of stakeholders

As could be expected, serious tensions already exist between nature organisations, the energy sector, the central government and food production sector, or more specifically, the fishing industry. Furthermore, in the next years the Climate Treaty will result in a sharp increase in the area of OWFs in the North Sea, worsening these tensions. Therefore, wise and extensive planning is needed for the division of the North Sea. This planning should be done with the consensus of the majority of the parties involved.

4.2 Actor scan and network scan

In this section, an actor and network scan will be carried out. The main objective of these scans is gathering certain data about each individual actor and their relation in the network. With this information, the behaviour of a certain actor in the process can be predicted and the possible consequences of strategies can be better understood. In the actor scan and network scan, the following aspects of every actor will be determined:

- Interest
- Level of Power
- Problem perception
- Goals
- Important resources
- Replaceability
- Dependency
- Critical Actor

The outcome of these aspects are displayed in a table that can be found in the appendix A.

First, this subsection will start with the identification of the stakeholders. Which stakeholders are involved in this process? Besides the names of the stakeholders, background information on the different actors will be provided. Thereafter, the core interest of the stakeholders will be stated. Next, the relation between actors and their power level will be explained. The connection between the power and interest of the stakeholders will be also be illustrated in the form of a power-interest grid. Then, an elaboration will be made on interdependent relations within the network. The subsection concludes with the actor-issue coupling, wherein the division of the process rounds will be constructed.

4.2.1 Stakeholder identification

In the process of implementing a multi-purpose OWF, 15 stakeholders are involved that can be divided over 5 categories. All the different stakeholders are enumerated down below:

Ministries

- Ministry of Infrastructure and Water State
- Ministry of Agriculture, Nature and Food Quality

Fisheries

- VisNed
- Nederlandse Vissersbond

Transport Organisations

- Branche Organisatie Zeehavens
- Port of Rotterdam

Energy companies

- Nederlandse Windenergie Associatie
- Energie Beheer Nederland
- Tennet
- Netherlands Oil and Gas Exploration and Production Association (NOGEPA)

Environmental organisations

- Stichting Noordzee
- World Wide Foundation
- Greenpeace
- Vogelbescherming Nederland
- Stichting Natuur en Milieu

4.2.2 The actors

Due to the fact that there is such a diversity between the stakeholders, the chances are limited that the reader is acquainted with every stakeholder. Hence, there is a need to provide further background information on the actors. This information provided will later serve as the basis for further decisions regarding the determination of the power level of the actors and their main interest.

Fisheries

The first category of actors that will be discussed is the fishing industry. The two main actors involved in the negotiation from the Dutch fishery around the Noordzee Akkoord are VisNed and the Nederlandse Vissersbond. In order to get better acquainted with both actors, information of the organisation's structure and influence are provided below.

VisNed

This organisation is the largest representative for the Dutch Trawler Fisheries and operates as an overarching organisation for 5 of the 7 producer organisations (PO's) that are active in The Netherlands:

- De Coöperatieve Producentenorganisatie en Beheergroep Delta Zuid U.A.
- De Coöperatieve Producentenorganisatie en Beheergroep Texel U.A.
- De Coöperatieve Producentenorganisatie en Beheergroep West U.A.
- De Coöperatieve Producentenorganisatie en Beheergroep Wieringen U.A.
- De Coöperatieve Producentenorganisatie voor de Visserij Urk U.A.

Nederlandse Vissersbond

The Nederlandse Visserbond is active on a regional, national and international level to look after the interest of the fishing industry. The organisation is the first point of contact for politicians, policy makers, and social-cultural NGOs. Also, the union has strong relations with the policy makers in Brussels. The Nederlandse Vissersbond represents the following two PO's:

- Coöperatieve Producentenorganisatie Nederlandse Vissersbond (NVB)
- Coöperatieve Producentenorganisatie IJsselmeer

Influence of the fishing industry

For future comparison, it is vital to have an idea of what level of power these actors possess. This leads to the question: How important is the fishing industry for the Dutch economy and more importantly; how important is the bottom trawling sector? The Netherlands is in the top 10 list of fish exporters and is the 5th largest exporter in Europe [Nederlandse Vissersbond, 2019b]. The total revenue obtained from all the fish caught by the Dutch fleet was 506 million euros in 2018. In comparison, the total Dutch food export was 85 billion euros that year. In addition, the Dutch fishing industry is roughly divided into 5 different disciplines: The trawler industry, small-scale coast fishery, big sea fishery, mussel farming and the oyster sector. Economically speaking, the trawling industry is the most significant sector of all five, earning a total of 308 million euros in 2019. In second place is the big sea fishery with 128 million euros [Arie Mol, 2018]. Overall, the size of the Dutch fleet is decreasing. In 2009 the Dutch Fisheries counted a total of 666 ships. In 2018 the fleet consisted of 592 ships [Arie Mol, 2019c]. Furthermore, in 2018 the bottom trawling fleet counted 289 ships, catching a total of 76 million tonnes of demersal fish species [Arie Mol, 2019a]. Demersal fish species are fish such as shrimp, plaice, flounder, gurnard, etc. These fish are mainly caught using bottom trawling methods. In contrast, the big sea fishery, consisting of only 8 Dutch-registered ships, caught a grand total of 317 millions tonnes of pelagic fish [Arie Mol, 2019b]. These are fish such as herring, mackerel and whiting, and are caught without the use of bottom trawling. This means that 2 'Big trawlers' caught more tonnes of fish than the entire 289-counted fleet of bottom trawlers. To conclude, both actors hold significant power in terms of their impacts on fisheries. VisNed represents a sector that is economically speaking more important for The Netherlands, whereas the Nederlandse Vissersbond has a seemingly more influential relationship to the national and international political landscape.

Nature organisations

Stichting Natuur en Millieu

The organisational structure of the Stichting Natuur en Millieu is established in 1972 by four environmental protection organisations:

- Contact-Commissie voor Natuur- en Landschapsbescherming
- Nederlandse Vereniging tegen Water-, Bodem- en Luchtverontreiniging
- Stichting Centrum Milieuzorg
- Vereniging Natuurmonumenten

These four organizations give some idea what this non-profit organisation stands for. In the almost 50 years that this foundation existed, it engaged and gained the support of numerous people. For a non-profit organization, the following three criteria are of significance when determining their power: Number of online supporters, media coverage and total sum of donations made. Currently they have more than 150.000 online supporters. In 2018, the organisation was mentioned a total of 2.829 times for both online and radio news coverage. In 2018 they acquired 775.110 euros total in donations [Stichting Natuur en Millieu, 2019b]. In collaboration with the Stichting Noordzee, the organisation launched the project 'De Rijke Noordzee'. The main purpose of the project is proving that the sustainable energy transition and the nature recovery of the North Sea go hand-in-hand [Stichting Natuur en Millieu, 2019a].

Vogelbescherming Nederland

The Dutch Bird Protection Federation is an independent, national nature protection organisation. Furthermore, it is an active association, supported by some 140.000 members, companies, foundations and institutions. Moreover, the Dutch Bird Protection Federation is the Dutch partner of the much larger BirdLife International, an organization that protects birds and their habitat all over the globe. Over the past years, the Dutch Bird Protection Federation managed restoring the population of several Dutch bird species by making use of protection programs, intensive collaboration, political lobbying, juridical action, providing education and implementing effective campaigns. Their vision statement is a world with a rich variety of birds in their natural habitat, for people to relish and further protect their existence [Vogelbescherming, 2019].

Greenpeace

Worldwide Greenpeace is active in over 55 countries, one of which is The Netherlands. Yearly, Greenpeace The Netherlands receives a total of € 22,1 million from contributions and inheritances. Of noteworthy mention is the fact that Greenpeace works independently, meaning that it does not accept money from governments and companies. At the end of 2018, Greenpeace The Netherlands was actively supported by 361.275 contributors. In addition, they are active via digital communication and social media. At present, 62.000 supporters have a subscription on their newsletter. 696.000 people are reached via other mail services. Their Facebook page has 130.000 likes [Greenpeace, 2019].

World Wide Foundation

Presently the World Wide Foundation for Nature (WWF) operates from over 100 countries, spread over 6 continents. In addition, 606.000 contributors provide financial support to the organisation. Surprisingly, 112.000 of those are young people. Combined those people provided a total of €20.967.000 in 2018. WWF NL also acquires money from lotteries, subsidies from government organisations, merchandise, and investment, resulting in a total income of €57.022.000. As for social media, WWF-NL has 380.000 followers and/or friends on social media. [WWF, 2019].

Stichting Noordzee

Since march 1980 this nature organisation aims to protect the North Sea through the co-hosting of activities, for instance, beach and ocean cleaning days. In 2018 the total income was €2.121.324, consisting mainly of donations and contributions from organisations such as the Postcode Loterij. The Stichting Noordzee is less active and thereby less influential compared to other nature organisations on social media. However, the Ministry of Economic Affairs approached the foundation in 2017 with the request to research the feasibility of the North Sea Agreement [Stichting Noordzee, 2019], making them a powerful player in this process. Their short term goals from 2018 to 2020 were defined as:

- Committed in the current process of creating 20-25 percent of marine protected areas in the Dutch North Sea by 2030
- Closely involved in the new research regarding bottom protection and furthermore the ecological effects of sand exploitation and supplementation
- Continually advocating for sustainable fisheries
- Avoiding risks and exploring opportunities concerning the new aquaculture industry in the North Sea

The North Sea foundation sees it as their mission to strive for a flourishing, viable North Sea for humans and nature. Part of this mission is to form a sea with an optimal functional ecosystem that is resilient and can readily endure impacts by man. This is paramount if future generations also wish to enjoy the North Sea and her nature.

Energy companies

TenneT

TenneT is a leading network operator for the European Energy Network. Its main activities are based in The Netherlands and Germany. It is one of the largest investors in national and international electricity nets, on land and sea. There are more than 22.000 km of high voltage connections that deliver electricity to over 41 million end users. With 3.000 consumers they realise 4,176 billion euros in revenue. This has over the years resulted in a total asset value of over 21,783 billion euros [TenneT, 2019a]. In 2016, TenneT was appointed by the Dutch government to act as the operator on the Dutch North Sea. TenneT decided then on a three-step approach. On the short term, this means that 3,5GW is in development until 2023, relatively close to the shore. In the next phase, from 2023 to 2030, the total capacity will be increased with another 7 to 10GW. Lastly, in the third and final stage, a grand total of 100 to 200GW will be added until 2050, by creating so called energy islands made of massive areas of wind farms. For comparison, Borssele I, II, III, IV, and V combined are 1,4 GW [Rijksoverheid, 2019]. Regarding the long term vision, a consortium consisting of TenneT The Netherlands, TenneT Germany, Energinet, the Dutch Gas Union, and the port of Rotterdam is currently exploring the option to create a North Sea Power Hub [TenneT, 2019b]. Tennet sees it as essential switching to an internationally coordinated roll-out with power hubs/islands for the electricity network on sea, instead of the current individual national connections. A main driver behind this aspiration is the need for efficiency, which in turn can be translated to a decrease in operational costs.

Nederlandse WindEnergie Associatie

Currently, the Nederlandse WindEnergie Associatie (NWEA) has over 300 members that cover a diverse spectrum within the offshore wind sector. This sector includes wind farm exploitants, producers, consultancies, financial and legal companies, contractors and others. Premium members are companies such as Eneco, Shell, Vattenfall, Vestas and Orsted [NWEA, 2019b]. In the past years, the Dutch Wind Energy Association has taken the position as a conversation partner with the ministries and other organisations, where it speaks on behalf of their substantial member base. In the policy report 2018-2010, the NWEA stated five action points that according to them need improvement in the near future. In particular, point two concerns the improvement of communication with stakeholders in a more targeted effective way [NWEA, 2019a]. This point was raised as an area of concern since in some cases after the announcement that a wind farm will be constructed, the affected local population will protest against development of the wind farm.

Energie Beheer Nederland

Energie Beheer Nederland (EBN) is fully owned by the Dutch Government. In 2016, EBN shared its energy policy with the Ministry of Economic Affairs and Climate [Energie Beheer Nederland, 2019b]. Until 2016, the organisation was mainly engaging in activities such as tracking down, extracting and storing oil and gas. Today, the Dutch energy transition is becoming a larger focus point for them. For example, EBN is researching the possibilities to acquire energy with the use of geothermal exchangers. This system utilizes geothermal energy that was directly obtained from the heat exchange between water that is pumped past past hot rocks deep in the earth's crust. EBN is also investing much of their human capital in exploring the options for carbon capture, both onshore and offshore. The company has an adequate reason to do so, as EBN is still very much in favor of exploitation of oil and gas fields in the North Sea. This can be particularly seen in their mission statement: Obtaining value from geological energy sources in a safe, sustainable and economically responsible way [Energie Beheer Nederland, 2019a]. In addition, EBN works closely with oil and gas companies as a non-operating partner. Together, they advise their participants, and, if possible, invest further in the exploration and extraction of Dutch gas.

NOGEPA

The Nederlandse Olie & Gas Exploratie en Productie Associatie is an organisation that has protected the interest of companies possessing a licence to track down and extract oil and gas fields on Dutch soil, on land and in the sea since 1978 [Noordzeeloket, 2019c]. Currently, 13 companies are in the possession of such a licence [NOGEPA, 2019]. The company has the indirect function to maintain a stable relationship between society and the oil and gas sector. Furthermore, NOGEPA stimulates innovation for safer, more efficient extracting methods for fossil fuels. As the organisation sees it, it is an undeniable fact that gas extracted from Dutch ground is a key facilitator in the energy transition. Over the last few years, they have been pressuring this opinion to the greater public. NOGEPA also explores alternative uses for depleted oil and gas fields and their infrastructure [OffshoreWerken, 2019]. Even though little to no hard figures can be found about the organisation that are essential in determining their power level, a fairly reasonable prediction can be made when looking at the members they represent. Some of these members are: the Nederlandse Aardgas Maatschappij (NAM), Total, and Dana Petroleum. These companies had revenues of accordingly 3,4 billion euros, 135 billion euros and 1,2 billion euros in 2019. Furthermore, NAM is for 50% owned by Shell and the other 50% owned by ExxonMobil, two massive players in the oil and gas industry.

Transport Organisations

Port of Rotterdam

This company is director, operator, and developer of the harbour and industrial area of the port of Rotterdam, the biggest port of Europe. It is approximately 70% owned by the City of Rotterdam. The rest of the port is owned by the State. In 2018, the Port of Rotterdam had a revenue of about 1.2 billion euros that it mainly collected from the 469 million tonnes of transshipment they processed [Port of Rotterdam, 2019].

Branche Organisatie Zeehavens

The Branche Organisatie Zeehavens is the point of contact for sea ports in The Netherlands for consultation and coordination with the State concerning policy development. There is consultation between the managing board of the seaports and the direction over the advocacy of the sector. The biggest ports involved are the Port of Rotterdam, Haven Amsterdam, Havenbedrijf Moerwijk, Zealand Ports and Groningen Seaports [Branche Organsatie Zeehavens, 2019].

Ministries

The last category of stakeholders in this process are the ministries. Even though there are seven ministries involved in the process around the Noordzee Strategie 2030, the two main players are the Ministry of Infrastructure and Water State and the Ministry of Agriculture, Nature, and Food Quality. They have the political responsibility to lead the development of the Strategische Agenda Noordzee and that of the Uitvoeringsprogramma Noordzee 2030 [Leefomgeving, 2018]. Both Ministries have to hold up to the SER Energy Agreement. This agreement states that in 2023 at least 16 percent of the Dutch energy consumption should come from sustainable sources.

Minister of Infrastructure and Water State

The Minister of Infrastructure and Water State wrote a letter to the House of Representatives wherein the current interest and views of the Ministry were communicated. The first interest was reaching an ecologically healthy and resilient North Sea in combination with sustainable and responsible use. The second concerned finding a balance between the energy transition, nature recovery and food supply in conjunction with the development of other sectors and coast regions. The third interest was promoting and developing a competitive Blue Economy [van Nieuwenhuizen Wijbenga, 2018]. This new way of thinking encourages better stewardship of our ocean or 'blue' resources and encompasses all economic activities related to oceans, seas and coasts. The Blue economy covers a wide range of interlinked established and emerging sectors, such as aquaculture, marine transport, ocean energy, desalination, and many more [Maritime Affairs and Fisheries, 2019].

Ministry of Agriculture, Nature, and Food Quality

The Ministry of Agriculture, Nature, and Food Quality has one principal goal in this process. This goal is to find a solution for the ever shrinking Dutch fishing fleet. The challenge for this institution is that it is both politically responsible for the fishing industry, but also for the compliance with EU law regarding the Nature 2000 areas. At present, destructive bottom trawling fishing methods are doing more harm than good. Unfortunately, these past years the ministry has experienced tension with the fishing industry. The introduction of the fish landing obligation (Dutch: aanlandplicht) resulted in major resistance from the fishing industry. In addition, the recent ban on pulse fishing method was not received well either. Therefore, the ministry's pursuit to strive for a sustainable and circular fishing industry is not receiving much support from the fishing sector.

4.2.3 Interest

The previous section provides sufficient background information on the stakeholders involved. Nonetheless, the core interests of the actors can be defined more concretely. Enumerated down below are the main interests of the stakeholders involved:

- **VisNed:** Securing job availability for the Dutch bottom trawler fishermen, striving for fair fishing legislation, protecting the bottom trawler fishermen against a dynamic political landscape.
- **Nederlandse Vissersbond:** Continuing the unification of the Dutch fishery by educating and certifying fishermen in sustainable fishing methods that are still deemed profitable for them.
- **Vogelbescherming Nederland:** Ensuring future the well-being of local North Sea bird populations by designating protected areas in the region.
- **Greenpeace:** Fighting for cleaner seas where over-fishing is banned completely and large areas are designated as marine protected areas.
- **WWF:** Protecting the local flora and fauna in and around the North Sea and safeguarding the top predators in the food pyramid by restricting current destructive fishing techniques.
- **Stichting Noordzee:** Strive for a flourishing, viable North Sea for humans and nature and ensuring an optimally functioning ecosystem that is resilient and can readily endure impacts from people.
- **TenneT:** Significantly expanding the current number of OWFs on the North Sea and ultimately transforming the North Sea into a internationally coordinated power hub.
- **Nederlandse WindEnergie Associatie:** Protecting the interest of their members by promoting policies and legislation in favor of offshore wind that among other things will lead to an improved revenue model.
- **Energie Beheer Nederland:** Protecting the current position of the Dutch Oil and Gas sector by promoting innovation and circularity in the sector.
- **NOGEPA:** Advocating the use of fossil fuels for the energy transition, while also stimulating innovation in the sector.
- **Port of Rotterdam:** Strengthening the competitive position of the Port of Rotterdam as a logistical cross section and an industrial complex on an international level.
- **Branche Organisatie Zeehavens:** Protecting the interest of the branch and safeguarding the negotiation position of seaports in The Netherlands.
- **Ministry of Infrastructure and Water State:** Reaching an ecologically healthy and resilient North Sea in combination with sustainable and responsible use, finding a balance between the energy transition, nature recovery and food supply, and promoting and developing a competitive Blue Economy.

- **Ministry of Agriculture, Nature, and Food Quality:** Finding a sustainable solution for the Dutch fishing industry.

4.2.4 Actors and their power level

The main interests of the actors are now evident, and the next phase in this analysis is to determine the power level of the stakeholders. For such a complex subject as the future division of a large section of the North Sea, it is important that the resources of the actors are apparent. Resources are vital because they define how much influence the actors have on a process to achieve their interests. Examples of resources are knowledge, reputation, funds, and authority. Nonetheless, the network of actors might also be of particular importance, as prominent actors have a higher possibility to gain support from other actors. In short, gaining support of actors with large networks might prove essential for a positive outcome in the negotiating process. Likewise, the power level is determined by the fact if a relation between actors are of a repetitive character. In other words, is it likely that future encounters between the actors will occur. Damaging a relationship with such an actor might proof detrimental for future conventions. However, if such future encounters are unlikely, more possibilities for open conflict do exist. The summation of all these characteristics are presented as three different power positions in the book: Management in Networks on Multi-actor decision making by De Bruijn and Ten Huevelhof. These power positions are named as follows:

- **Production power:** Determines if that actor can make a positive contribution towards the realization of the proposal.

- **Blocking power:** Illustrates whether an actor has the power to prevent or halt a particular action.

- **Diffuse power:** With a diffuse power position, it is unclear to an initiator what the power position of a particular actor will be, meaning the fact if the other actor will change his/her power position is unclear.

In this analysis, there are a number of organisations that posses production power. First, the NWEA has production power because the organisation represents an extensive network of different stakeholders that can be used to gain support for the concept of a multi-purpose wind farm. By the same token, the organisation possesses practical knowledge on the construction of OWFs that can be used to further develop a multi-purpose concept. Moreover, the NOGEPA and Energie Beheer Nederland enjoy production power, mainly due to their extensive knowledge on oil and gas rigs. Also, TenneT (the energy net operator) has production power, due to their knowledge on operating wind farms. This expert knowledge includes the safety requirements that are enforced in such a wind farm and the reason behind them.

There are also several parties that can use their blocking power. The transport organisations Branche Organisatie Zeehavens and the Port of Rotterdam, both have a significant power level. Comparing the two, the Port of Rotterdam most likely has the higher power level in this process. After all, the Port of Rotterdam is vital for the Dutch Economy. For comparison, the direct and indirect added value of the Port of Rottterdam to the Dutch economy is 45,6 billion euros. This translates to 6.2% of the Dutch GDP [Haven van Rotterdam, 2019]. With this fact, the Port of Rotterdam can put significant pressure in the form of blocking power on governmental bodies such as the two ministries involved. The environmental organisations also have considerable blocking power, including WWF, GreenPeace, Vogelbescherming Nederland, and Stichting Natuur en Millieu. All of these organisations might execute their blocking power in the form of protest, contacting news organisations or filing an official objection against the plan at the ministries. This can result in delays or even a total abandonment of a plan. With Stichting Noordzee however, this is more complicated. This foundation has multiple members from relevant knowledge institutes, for instance, the Royal Netherlands Institute for Sea Research (NIOZ) and Wageningen University and Research. Naturally, these knowledge institutes possess extensive ecological knowledge about the North Sea. In a later stage, this knowledge might become crucial in the further development of the multi-purpose concept. Still, when opposing the plan, their power position can just as well switch to the blocking type. Hence, the power position of the Stichting Noordzee could best be labelled as diffuse power. In a way, the same dilemma arises for the fishermen: VisNed and the Nederlandse Vissersbond. For one thing, both organisations are in the possession of considerable practical knowledge regarding fisheries in the North Sea. The likelihood that this information is needed later in the process is significant. Besides that, the fishermen both organisations represent could play a compelling executive role once the plan is launched. On the contrary, if the plan is not well received, both organisations can launch serious counter campaigns, perhaps similar to those of the Dutch farmers in mid 2019. Thus, both VisNed and the Nederlandse Vissersbond can best be categorized as actors with diffuse power. Finally considered are the ministries, both of them holding a significant power position in this analysis. As became clear in the numerous interviews with several offshore contractors, the contractors operate in a reactive fashion. This means that if the Dutch Government does not set new environmental and/or safety legislation, the chances that an offshore contractor pro-actively improves a certain working method in either of those fields are limited. For that reason, the ministries perform a vital role in this development, as they are the designated party to force environmental innovation on the sector, such as creating multi-purpose wind farms. Moreover, they control permits and are especially in the position to stimulate innovation via funding. Nevertheless, both ministries can equally obstruct the progress of an innovative concept, due to their close connection with the law or by making use of their extensive network. The summary of the different power positions and the power level of the different actors are summed up in table 4.1.

Table 4.1: Power position and level of the stakeholders

Stakeholders	Power Position	Level of Power
Ministry of Infrastructure and Water State	Diffuse power	High
Ministry of Agriculture, Nature and Food Quality	Diffuse power	High
VisNed	Diffuse power, but most likely blocking Power	Low
Nederlandse Vissersbond	Diffuse power, can use blocking Power	Medium
Branche Organisatie Zeehavens	Blocking Power	Low
Port of Rotterdam	Blocking Power	High
NWEA	Production Power	High
Energie Beheer Nederland	Production Power	High
Tennet	Production Power	High
NOGEPA	Production Power	Medium
Stichting Noordzee	Blocking Power	Medium
WWF	Blocking Power	Low
Greenpeace	Blocking Power	Low
Vogelbescherming Nederland	Blocking Power	Medium
Stichting Natuur en Milieu	Blocking Power	Low

4.2.5 Power vs Interest

For numerous reasons, involving all the actors in such a process is rarely desirable. It can cause excessive complexity and exaggerated interaction costs might be disproportionate with the additional benefits. Next, parties start to behave strategically when they realise the initiator expresses his intention for reaching consensus. Lastly, per definition inviting all parties to the table is not an objective criterion, as some parties might not even have direct benefits by the proposed decision and should not automatically be included in the process. Hence, selecting parties intelligently is more of a strategic decision.

A well-known tool that can be used prior to the selection of the stakeholders is the power-interest grid. Here, the level of power is set against the actual interest of the actors. The level of interest forms an important consideration in making the selection. Also, interests that play a role in a decision making process should at least be somewhat represented in the process [**?**]. The reason behind this is to largely avoid the 'catch-as-catch-can' risk. This risk means that less powerful parties today can evolve into the big player of tomorrow. By inviting at least one actor to the table with the same interest, other parties have less a right to complain about exclusion. Essentially, the interests of the smaller parties are represented and they are given access to the process. Looking at the power interest grid, actors are distributed over four different sections. The left-bottom corner is categorized as the 'crowd' and should be monitored, investing minimum effort in the stakeholders. Next, the right-bottom corner is named the 'corner setters', a group with high interest but low power level. Keeping this group informed on developments and showing some form of consideration is sufficient in a process. Next come the parties with a high power level. The top-left titled 'subjects', sometimes also referred to as 'sleeping giants', should generally be satisfied throughout the process by meeting their needs. Lastly, the top-right corners are the key players [Bryson, 2004]. Above all, these should be managed closely and should be involved in the process.

The power level has already been determined in the previous subsection. Here, the level of interest is described. First, all environmental organisations have high interest in this matter. The well-being of the North Sea has been an important point on their agenda for some time. The strategy for managing them, besides the Stichting Noordzee, is keeping them informed. In contrast are the energy companies with a relatively low interest in the subject. Their main interest lies in the oil and gas industry with little to no interest in the offshore wind industry. Therefore, creating a multi-purpose wind farm is not a direct concern to them. Nonetheless, both organisations should at least be kept satisfied. Next are the transport organisations, the Branche Organisatie Zeehavens and the Port of Rotterdam. Although the Port of Rotterdam has considerable power, their interests are nominal. In fact, their only concern in this process is guaranteeing the continuation of certain shipping routes. One of the stakeholders with the greatest interest is the NWEA. The majority of their members are closely connected to the offshore wind industry. Having a societal debate on the future function of OWFs, also with the safety regulations in mind, affect many of them directly. The same holds true for TenneT. Their long-term target is attaining one large energy hub on the North Sea. Any opportunities regarding the realisation of that vision, is of great interest to them. Lastly, both the ministries are engrossed by innovative developments around the North Sea, although for slightly different reasons. The Ministry of Infrastructure and Water State bears the responsibility to achieve an agreement with the stakeholders on the Nationaal Programma Noordzee 2022-2025 and in a later stage an agreement on the Noordzeeakkoord 2030. For the Ministry of Agriculture, Nature and Food quality however, the interest is related more to the future of the Dutch fishing industry. However, both causes are valid and translate to a high interest level for both parties. All of the above mentioned aspects have been translated to a the power-interest grid in figure 4.1.

Figure 4.1: Power-interest Grid

4.2.6 Interdependent relations

Here, the topic of interdependent relations is discussed. Introducing the fishing area within an OWF results in a high degree of interdependence between different actors. In networks the actors normally have a multi-value dependence. In this case, actors are dependent on each other for different values, such as money, goodwill, land etc. Moreover, the complexity of the process is also based on the fact that there are multilateral agreements. For example, key players are dependent on other key players, but also on context setters. This complicates the process of coming to mutual agreements. For the multi-purpose wind farm the agreements are mostly multilateral agreements. For example, the Ministry of Infrastructure and Water State is dependent on the knowledge of NWEA, but in turn also dependent on the goodwill of TenneT. Another type of interdependency is synchronous vs asynchronous, or, do the actors need each other at the same time or at different times? The latter complicates the situation further. For instance, the stakeholders of the fishing sector will be involved much later in the process, compared to actors like TenneT and NWEA. Another question that can be asked in the process is: Are dependencies coupled simultaneously to each other or are they more sequential? Dependencies of a sequential fashion are commonplace in networks. An actor can only perform a certain action if another actor performed a preceding action. In addition, there is the issue of whether dependencies are dynamic or static. In a network it is more likely that during the process dependencies change, bonds are broken and new technologies are developed [de Bruijn, 2010].

Apart from the different types of dependency, the replaceability of a certain actor is crucial to determine. The replacebbility in turn is based on whether the actor has important resources. Examples of important resources are funding, authority, but also the ability to mobilise protest. Another example of an important resource is unique knowledge. Unique knowledge is knowledge that cannot be obtained elsewhere. For instance, the ecological knowledge of the Stichting Noordzee is knowledge that no other stakeholder has in the process and falls into this category. Therefore, unique knowledge translates into low replaceability for an actor. Of noteworthy mention: the relevance of the knowledge also plays a decisive role in the determination of the replaceability. Hence, if the knowledge is not relevant to the decision making process then the replaceability will be high.

How is it decided whether an actor is critical or non-critical? The label critical actor is used when an actor has a low replaceability power and the success of the decision making process highly depends on this fact. For example, in the case of the ministries, the success of the process highly depends on the authority and the availability of funds, giving them a low replaceability score. Similarly, the ministries are involved in almost all of the multi-value issues, while also being involved in many of the multilateral relations. Hence, both governmental bodies score high on dependency, making them critical actors in this process. The final result encompassing the whole actor and network scan is summarized in one table found in appendix A.

4.2.7 Actor-issue relations

The last step in the actor and network scan is deciding the different actor-issue relations. The negotiation around implementing a fishing industry in OWFs basically revolves around 8 issues. Considering the interdependence of the actors and the issues, these issues are subdivided into 2 process rounds. The first process round is labelled *sustainability*. Here, issues covering the existing and future involvement of the oil and gas industry in the North Sea will be discussed. Similarly, the future of the Dutch Fishing fleet will be examined. The second process round *Spatial Planning* focuses on the issues that are related to the future division of the North Sea. Also, the issue regarding safety will be covered. Not every actor is involved in every round. For instance, in the first round, the oil and gas companies are mainly involved, whereas they have no significant role in the second round. The overview of the issue-actor relations are displayed in figure 4.2 and figure4.3. Both figures display the frequency of encounters different actors have and the complexity surrounding the issue. Important to note, the construction of an in-depth process design, wherein the two process rounds are fully excogitated, fall outside of the scope of this report. The main purpose of the actor-issue diagram is illustrating the overall involvement of the actors in the process around the implementation of a multi-purpose OWF.

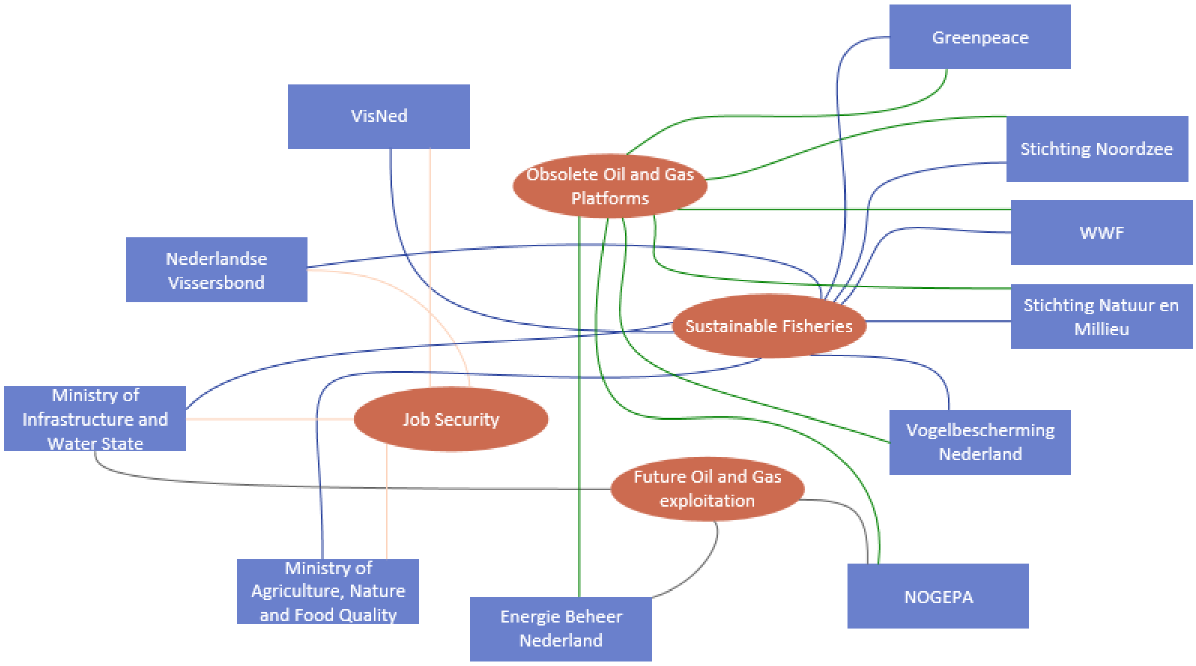


Figure 4.2: Process round - Sustainability

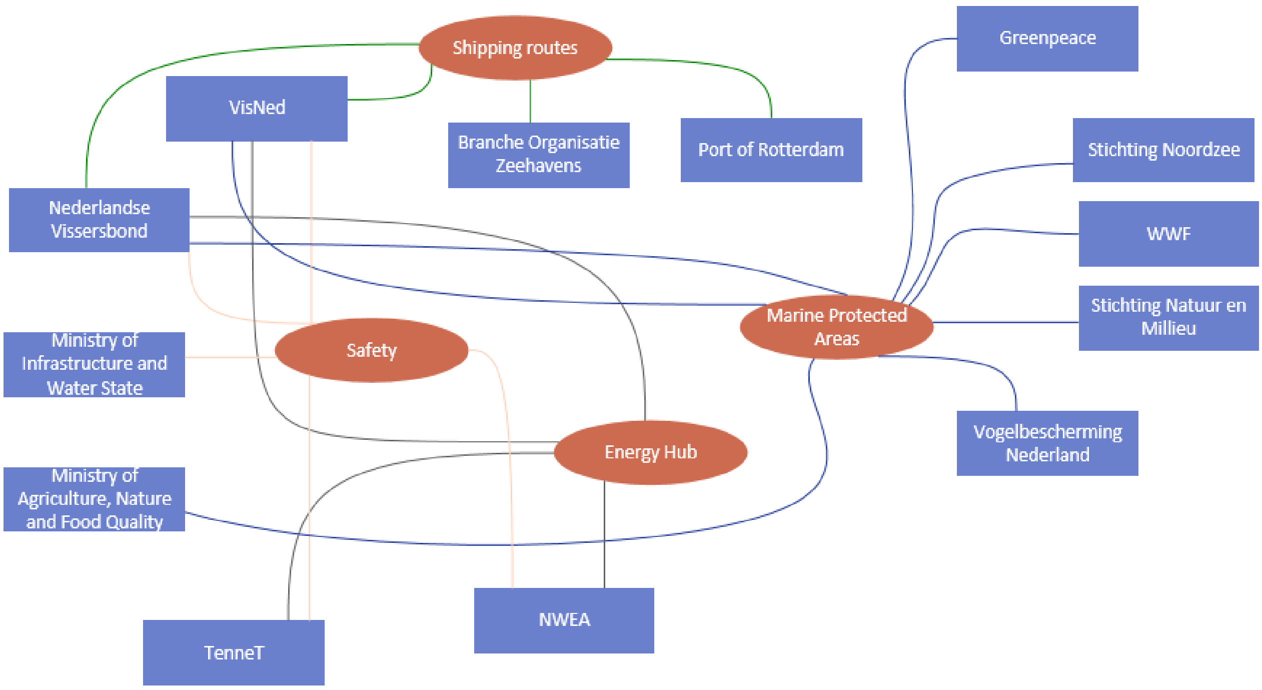


Figure 4.3: Process round - Spacial planning

4.3 SWOT/TOWS Analysis

A key preceding step in realising the final stakeholder engagement strategy is drawing up a SWOT/TOWS analysis. The creative process behind the construction of the analysis forms the basis for future negotiation strategies. The upcoming paragraph describes the reasoning behind the SWOT analysis in greater detail. The second paragraph continues on this reasoning and adds four strategies that later form the foundation for the stakeholder engagement strategy.

4.3.1 SWOT

The main purpose behind the SWOT analysis is designing a framework for the decision-strategy based on the relevant information that is obtained in previous sections. The analysis identifies the strengths and weaknesses of an organisation and the opportunities and threats in the direct environment. Both strengths and weaknesses are identified by an internal appraisal of the organisation, whereas the opportunities and threats are identified by an external appraisal [Dyson, 2002]. The internal appraisal examines all aspects of the organisation. For example, personnel, facilities, and location are examined. The external appraisal scans the political, economic, social, technological and competitive environment with a view to identify opportunities and threats [Dyson, 2002]. In the end, strategies might develop that build on strengths, eliminate weaknesses, exploit opportunities or counter threats. This process will be further explored in the next paragraph.

4.3.2 TOWS

In this section, the internal and external factors will be connected. The foregoing analysis of connecting environmental opportunities and threats with the company's strengths and weaknesses, encourages a creative process for the development alternatives [Weihrich, 1982]. The method consists of four different strategies. First the strengths - opportunities(SO) will be covered. Every company aims to be in a position where it can both maximize strengths and opportunities. Normally, a company tends to land in situation where they can work from strengths in order to take advantage of opportunities. Second, the strength - threat(ST) strategy that an organisation can use minimizes the threats by maximizing the organisation's strength. The third strategy is the weakness-opportunity (WO) strategy. This is where overcoming the situation where certain opportunities have been identified, but internal weakness initially prevents a company from taking advantage of them. Lastly, the situation that every organisation should seek to avoid, the weakness-threat position(WT). Here, the aim is minimising both weaknesses and threats. An organisation encountering this situation may indeed be in a precarious situation [Weihrich, 1982].

- Strength - Opportunity (Maxi-Maxi)
- Strength - Threat (Maxi-Mini)
- Weakness - Opportunity (Mini-Maxi)
- Weakness- Thread (Mini-Mini)

For the case of the multi-purpose OWF, the SWOT are combined using the four TOWS-strategies mentioned above. The result gives more insight in potential negotiation strategies, while also forming a solution space that will later be used for the developments of concepts. The outcome of the procedure has been summarized in the appendix B.

4.3.3 Fish-as-a-Service

During the development of the SWOT/TOWS matrix, different threats and weaknesses were drawn up that proved difficult to tackle in the current situation. To start, none of the actors involved were able or willing to carry the extra risk involved with implementing a fishing industry in the OWFs. The additional risk of accidents in a free-for-all situation would simply be too high. For instance, strict safety regulations are required to control the ancillary activities in the multi-purpose OWF. Also, the valuable investment costs that are required to enhance the current poor state of the North Sea are not something that a specific stakeholder is willing to bear. Without an apparent business case containing a solid revenue model, the construction of a bio-enhanced artificial reef fishery is not likely to occur. Over all, the establishment of a overarching concept is required. For this process, the Fish-as-a-Service concept has high potential. This concept will be briefly explained in the following paragraph. However, a comprehensive explanation will also be provided in chapter 12.

The Fish-as-a-Service concept is largely based on the farming-as-a-service (FaaS) theory. This theory is, among other things, used for financially-less fortunate farmers in India. The farm management solutions that come with the FaaS concept allow stakeholders to make data-driven decisions to boost productivity and efficiency. FaaS converts fixed upfront costs into variable ongoing costs for farmers, thus making the techniques more affordable for a majority of small farmers [Shruti Kedia, 2019]. The same system can be used for the multi-purpose OWFs. The financial capacity of the fishery sector is not likely adequate enough to finance those large investment costs. Hence, an external organisation steps in and takes full responsibility for the implementation and funding for the ancillary activities in the area. This starts with the cost for the realisation of the bio-enhanced area. In a later stage of the project, the company periodically transfers part of the revenue from the ancillary activities to the OWF owners as an allowance for the usage of the wind farm. Besides the financial difficulty, safety is a massive concern of some of the critical actors involved. Thus, the external organisation arranges all the safety regulations around the wind farm, so that it is of no more concern to the OWF owners. Here, the organisation can demand that fishing ships and bypassing cargo vessels are equipped with special GPS systems that constantly monitor the location of these ships. If those ships get too close to one of the wind turbines, a warning signal goes off, alarming the steersman. Similarly, the external organisation might require that fishermen follow a safety training, before they are allowed to fish in the wind farms. The solution mentioned above are just some examples of the possible benefit a Fish-as-a-Service system brings for the multi-purpose OWF. Again, more information on the Fish-as-a-Service concept is presented in chapter 12, but this paragraph should contain enough information for the reader to grasp the concept and understand the solution spaces mentioned in the upcoming paragraphs.

SO

I: Multi-purpose use in combination with sustainable fishing might give a positive effect on the image of offshore wind companies [S9, O1, O19, O19]

Over the past years, the OWFs are getting more and more bad publicity. The former impeccable image held by the public has slowly been replaced with a more critical attitude. Recently, the NOS published an article stating that OWFs are costing the Dutch government 5 billion euros in expenses [NOS, 2019]. More importantly, the CO2 emissions that are directly and indirectly emitted during the construction of such a wind farm are much higher then previously expected. This new perspective on OWF might be treacherous for the future development of new OWFs. None surprisingly that in the policy plan 2020-2022 of the NWEA, specifically in their action point *Surrounding*, NWEA mentions their aim to launch a new online platform to communicate more actively and directly with the public [NWEA, 2019a]. With this new platform, the company strives to improve the overall image of (offshore) wind energy, mainly to create a better understanding of the general public. Moreover, what kind of positive publicity can the implementation of an artificial reef fishery in an OWF provide? For starters, the sustainable fishery sector strives for the restoration of the North Sea to her former glory. Hence, by allowing the development of sustainable fishery within the OWF, the biodiversity will be drastically improved. Consequently, the public becomes more aware of the positive effects that a bio-enhanced wind farm has on the local environment and a positive image of a multi-purpose OWF. With this revised image of an OWF, the protest surrounding the construction of it might decrease and the offshore wind industry can continue to see a large increase in the realization of new OWFs.

II: Reduce decommissioning costs by reusing out of service oil and gas platforms as hard substrate [S4, S6, O4, O8, O9, O16, O17]

Oil and gas companies have an agreement with environmental and governmental organisations that the old oil and gas infrastructures should be removed. This means that in some cases sinking (parts of) the rigs could be less expensive then the regular decommissioning, when the platforms are taken apart on land. Lastly, as mentioned before, in the upcoming decades 600 obsolete rigs need to be decommissioned [Gerard Reijn, 2019]. This inevitable decommissioning increases the need for a sustainable solution, while simultaneously also providing plenty of choice for potential platforms.

III: Creating a Fish-as-a-Service system enables room for less economical strong parties such as fishermen and research institutes [S2, S3, S9, O6, O7]

Currently, research institutes such as NIOZ are struggling to perform basic field research in Dutch OWFs, as the strict safety regulations, introduced for offshore maintenance activities, apply to them as well. This results in the fact that researchers are forced to use extremely oversized ships for their expeditions, costing tens of thousands of euros for a single day of research. Hence, Dutch researchers are unfortunately forced to perform field research in Belgian OWFs, where the safety regulations are less. Therefore, if a fish-as-service concept is implemented with different safety regulations for research institutes, more research can be executed in a Dutch OWF. Also, due to the fact that it is the government's core value to serve the people, it can be argued that they should give the people/organisation the opportunity to make use of mother nature. This increases the pressure to establish a Fish-as-a-Service system.

IV: Together with the Dutch favourable investment conditions for sustainable initiatives and the innovative Dutch fishing industry new technologies might be developed for alternative and productive fishing methods and/or aquaculture [S3, S6, O3, O5, O6, O7, O10, O11, O12]

The Dutch fishing fleet belongs to the most modern fleets in the world [Nederlandse Vissersbond, 2019a]. Additionally, the progressive attitude of the fleet has translated to a multitude of innovations in the fishing sector. A recent example is of course the pulse fishing method. Thus, when the option is likely that OWFs become open for fishing, development of new specific fishing will likely simultaneously evolve.

V: Reducing decommissioning and installation costs by making use of the not booked period of offshore vessels [S10, O1, O7, O8]

Normally, agreements are made with contractors to decommission oil and gas platforms in a flexible period of around 2 years. Therefore, a larger time period can be used to still use the particular oil and gas rigs for the multi-purpose OWFs. Potentially, this will further lower decommissioning costs.

VI: Using the new system, fishermen obtain job security for the next 25 years [S2, S6, O6]

At the moment, many fishermen experience large uncertainty in the future existence of their jobs. Implementing a new fishing industry in an OWF enables the fishermen to obtain job security for at least the expected lifetime for the wind farms, which is 25 years.

VII: Knowledge could be transferred to foreign countries, resulting in a strong export product [S3, S11, O2, O5, O11, O13]

Other countries surrounding the North Sea are experiencing similar spatial problems affecting the fishing industry. Scotland, for example, is partially economically dependent on their fishing industry and is experiencing problems with the construction of new OWFs and the recent creation of marine protected areas [European MSP Platform, 2019]. Successful implementation of a multi-purpose OWF could become an attractive export product.

VIII: Ministries can indirectly draw up new laws requiring the reduction of the environmental impact in the construction of OWF [S1, S3, S9, O1, O14, O15]

Possibly, the legal power of the ministries can impose a change in approach that further reduces the environmental impact regarding the construction of an OWF. Moreover, tax cuts for more sustainable wind farms can positively encourage owners to implement, for example seaweed or crustacean farms in their OWFs. The carbon removal of seaweed farms is substantial and can possibly result in OWFs that are built in a more CO2 neutral fashion [Lindsay Green-Gavrielidis, 2019].

IX: Parts of the OWF can be used for commercial fishing, while others might be used for diving and recreational fishing activities [S2, S9, O11, O15]

Instead of mainly focusing on the fishing industry, the possibilities can be extended to other industries, such as the tourism industry. Recreational fishing can be a lucrative business. For instance, the Atlantic States Marine Fisheries Commission and the Mid-Atlantic Fishery Management Council initiated on August 2002, Amendment 13 to the Summer Flounder, Scup and Black Seabass Fishery Management Plan. As a result, the population of black seabass tripled over the past 15 years, drastically boosting the local recreational fishery [Caitlin Starks, 2019]. Similarly, the possibility to use the artificial reefs that are created to bio-enhance the area as a commercial diving spot, where divers have to buy a permit before they can enter the OWF.

WO

I: Aquaculture system in the North Sea might prove difficult due to the rough sea conditions, however possibilities for sustainable fishing methods with long lines might still prove profitable [W5, W10, O6, O12, O20]

Whereas an aquaculture system using traditional fish cages is difficult to maintain in the rough North Sea conditions, long lines and/or lobster cages can still be implemented. This system requires little maintenance and above all are not as susceptible for rougher sea conditions. Also, the likelihood that those type of fishing methods harm the wind turbines are marginal.

II: By boosting the biodiversity in OWFs, for example by biotope enhancement, the nature organisations will change their view on those wind farms and become a less oppositional party [W6, W7, W11, O1, O13, O14, O18, O19]

The environmental protection organisations are able to put significant pressure on the construction of new OWFs by demanding to see the effects such a wind farm has on the surrounding ecosystem. Normally, this is done using an environmental impact analysis. However, when the initiator shows that his OWF actually actively stimulates the biodiversity of the local flora and fauna, nature organisations will likely change their viewpoint to a more sympathetic position. What effect does this have? Less conflict might lead to a reduced application time for permits. Therefore, the construction of the wind farm would start sooner and result in a greater profit margin for investors/wind farm operators.

III: Research on the ecological development in the area, that is currently close to non-existent, can give researchers a better idea on area enhancing projects in the future [W1, W4, O2, O6, O13, O18]

Although exact data on the possible future fish stocks in the North Sea do not exist, an confidential exploratory research project of Wageningen University and Research shows the dramatic increase on biomass possible certain areas are restored in their original state. More definite research can convince governmental bodies and/or investment companies to show the potential of a multi-purpose OWF. In a later stage, this can result in expanding the concept on a larger scale.

IV: Part of the revenue from the extraction of new gas fields can be transferred into a transition fund. [W4, W6, W9, O16]

The oil and gas industry on the North Sea is still a highly profitable industry. As a consequence, the chance that companies working in that business are willing to give up their profits is slim. Nonetheless, this industry faces an ever growing concern from environmental organisations, as well as the general public. The process around the exploration, extraction and storing of oil and gas is already highly optimized and under strict safety regulations. However, the industry is still highly polluting. Hence, there might be a synergenic solution where oil and gas companies are allowed to extract the less environmentally detrimental fossil fuels, for example gas, in exchange to donate part of the revenue to a transition fund. Then, the transition fund would partially contribute to the increase in insurance fees or the construction costs needed to bio-enhance the OWFs.

V: Successfully implementation a Fish-as-a-Service concept in the North Sea with her rough sea conditions, will likely result in successful implementation in other regions [W5, W8, W10, O11, O13, O18, O19]

Whereas this project focuses fully on the North Sea, a proven concept could with minimal adjustment work well in other regions of the world. Taiwan, for example, is at present heavily invested in their offshore wind sector, and the south part of the island has relatively calm sea conditions compared to the North Sea. Accordingly, one can argue that knowledge obtained from a proven multi-purpose OWF can be moderately applied to a Taiwanese OWF, making it an attractive export product.

VI: - Creating a Fish-as-a-Service concept takes the large lump sum investment costs away from the fishermen [W4, W9, O3, O5, O7, O10, O15]

As already discussed in the beginning of this chapter, the Fish-as-a-Service concept brings the possibility to spread out the considerable investment costs, while giving them the option to periodically pay a part of the investment costs back.

VII: Fish stocks of top predators in the North Sea are still relatively low compared to the high times [W3, W7, W9, W11, O2, O7, O15, O20]

Currently, stocks of top predatory fish are across the board a fraction from what they were in the past. The Atlantic cod population was 2,5 times larger in 1970 then it currently is in 2020 [Compendium voor de Leefomgeving, 2019]. Also, arthropods such as lobster suffered greatly under the degradation of the North Sea seafloor. From a more positive perspective, these types of older data show what is possible when the sea bottom is restored to its original state. This means that there is much to gain. More information on the different types of fish and arthropods can be found in chapter 5 in the biological analysis.

VIII: In the earlier phase of the process, the fishing industry can focus on fish and arthropods that grow and multiply faster[W3, W7, W9, O2, O7, O12]

Sadly, it will take some time before stocks of top predatory fish, such as the Atlantic cod are returned to a healthy level. In the mean time, the fishing sector should focus on different target species. Nevertheless, the workability of the fishing industry cannot be deduced, as they depend on their job for a living. Fortunately, there are other species, in particular cuttlefish and brown crabs that reproduce quickly, where after they reach a harvestable size relatively quickly. Thus, these are the fish species on which the fishing industry could focus in the beginning phase of the process.

IX: Using regular stones as hard substrate can significantly lower the investment costs [W4, W5, W6, W9, W10, O2, O4, O18, O20]

The first lesson one learns in any financial course is that large investment in an early stage of a project should be avoided as much as possible. The same lesson applies for the construction costs of the bio-enhanced area. Hence, using expensive fully-researched and trademarked artificial reefs for the whole area is financially not attractive. Luckily, many of the target species are not too picky and require general forms of hard substrate, preferably in somewhat varying sizes. For this reason, the same stones that are normally used for scour protection around the turbines could be applied for the creation of hard substrate. The benefit of using these are the low acquisition cost and a uncomplicated installation process.

X: Even though a portion of the fish species is not constantly present in the wind farms, still a significant part of the territorial fish can be harvested throughout the year [W1, W11, O20]

Although there is some uncertainty in the precise biomass in the wind farm due to the absence of cages and the fact that fish are free to swim where ever, the fishery can still depend on the territorial fish and arthropods. Research in the chapter 10 gives an estimation of the quantity of biomass that will be more or less be present in the wind farm both before hard substrate has been added and after.

XI: Start with a pilot focusing on target species which can later be expanded to a larger scale [W1, W3, W4, W9, O2, O3, O5]

An OWF in the Dutch part of the North Sea easily covers tens of square kilometers, a significant area. Nonetheless, bio-enhancing the OWF does not directly apply to the entirety of that area. As the realisation of a multi-purpose OWF comes with considerable costs, uncertainties and risks should preferably be dealt with before a project is launched on full-scale. Currently, this is not the case. In this situation, launching a pilot in a small section of the wind farm might remove the concern about the feasibility of the concept at relatively low costs.

ST

I: The government has the possibility to use their legal power to force offshore wind operators to share the nutrient-rich area [S1, S2, S4, T1]

The wind farm operators cannot endlessly hide behind their safety concerns. At some point, the ministries can put significant legal and authoritative power on the operators, if during the process the operators are reluctant to participate in the negotiation. In the end, the ministries, indirectly, decide on on the fact if permits are granted for new OWFs [Loket, 2015].

II: Sinking an old decommissioned offshore construction might be less impactful on the environment, compared to removing it completely and thereafter it will be on land [S1, S2, S3, S7, S10, T5]

The government can impose the execution of a full environmental impact analysis on the owners of an obsolete oil and gas platform, which in turn can point out that sinking (part of) a platform might be less harmful for the environment. If after the research by an independent institute shows that this indeed is the case, then environmental protection organisations should come with counter proof, or ultimately acknowledge the result. Organisations such as Greenpeace are steadfast on the issue.

III: Creating a Fish-as-a-Service system means a high level of control over fishing regulations for the area [S9, T9, T11]

The Fish-as-a-Service construction allows for stronger possibilities to implement and safeguard the use of designated fishing methods due to strict regulations regarding the issuing of licenses. This includes preventing the use of bottom-disruptive fishing methods. In the next paragraph, a solution space *IV* becomes apparent with the possible control measure for this. Lastly, the risk of overfishing will be mitigated.

IV: Using a Fish-as-a-Service system enables the option that fishing ships and bypassing cargo vessels, using the wind farm, should be in the possession of a GPS coupled to security software [S11, T1, T2, T4, T6, T7]

The data-driven approach of Fish-as-a-Service utilizes many technologically related opportunities. Too name but a few, GPS devices monitor the movement on the ships in the wind farm, as previously mentioned in this chapter. What other opportunities, besides the warning system preventing collision with turbines, does this bring into being? One option might be to tackle illegal fishing. For example, by tracking fishing ships in the wind farm and determine if there not illegally fishing with bottom trawling techniques by checking their sailing speed and course.

V: Building a OWF closer to shore in shallower water is, in general, more beneficial for biomass production [S8, T10]

Where normally there might be difficulty in finding an overlapping location for an offshore wind farm, that simultaneously has the biological necessities to create an abundance on biomass, the current ministries aim to build closer to shore, covering both demand [The Blue Deal, 2019]. On average, the North Sea is shallower closer to shore. Resulting in more sunlight reaching the sea bottom that in turn, in dependence of other factors, thrives the growth of flora and fauna.

WT

I: Creating a multi-purpose wind farm whereby the interests of all government bodies are included, might result in wide support for the Fish-as-a-Service concept [W2, W3, W11, T9]

Even though the Ministry of Infrastructure and Water State and the Ministry of Agriculture, Nature and Food Quality have slightly different interests, the multi-purpose OWF basically solves the two main concerns of them both. Especially, the issue surrounding the future of the Dutch Fishing industry is covered. Due to the misstep of the Dutch government to lose the vote in the European Commission concerning the future of pulse fishing, the fishing industry is hesitant on the good intentions of the ministries. By creating a Fish-as-a-Service concept managed by an external organisation, the fisheries do not have to directly rely on the dynamic opinion of the ministries and are perhaps drawn again to develop another sustainable fishing method.

II: The slow development time of a sustainable fishery creates an opening for a gradual learning curve. Meaning as the fishing activity in the area slowly increases, the external company can use more time to steadily fine-tune the the safety measures [W3, W8, T7]

Admittingly, safety legislation should be impeccable from the start. Experience shows, however, that creating a waterproof concept straight from the start is not realistic. Most of the time, minor adjustments are still needed in the early phase of a project, so-called "teething" problems. Luckily, the fishing intensity is marginal in the beginning phase of the project, as the fish stocks have not fully developed yet. As a result, the responsible organisation still has some steering capacity in fine-tuning the safety regulations.

III: The jacket construction, in contrast to the top sides of the oil and gas platforms, contain almost no toxic materials [W10, T5, T12]

The strongest argument of the environmental organisation against sinking old oil and gas platforms as a whole is the remaining toxic materials that are left behind in the construction. Materials such as asbestos were often used in the 1960 till 1980 on topsides for various reason [YOUNG FIRM, 2019]. Other examples of chemicals are heavy metals in batteries(cadmium and lead), mercury in Fluorescent Tubes, diesel, Polychlorinated biphenyls (PCB) in the transformers, etc. To give an example of the quantities of hazardous materials in a platform, the Delta platform of Shell can be used. The 300m high Delta platform contain among other thing: 10 tonnes of asbestos, 31 tonnes of batteries and 900 ton of paint [Bert van Dijk, 2019]. Nonetheless, the toxic materials mentioned are often only located in the topsides of the rigs. In contrast, the jacket construction underneath can still be used. The concept of solely sinking jacket construction is already known in the Gulf of Mexico as Rigs-2-Reef. As of April 15, 2018, 532 platforms previously installed on the U.S. Outer Continental Shelf have been reefed in the Gulf of Mexico [Bureau of Safety and Environmental Enforcement, 2019]. Also, by picking such a jacket construction that is close to a OWF, perhaps transport costs can be saved for the oil and gas companies. Lastly, the wind farm operators can still hold on the 500m exclusion zone around the turbines that established for safety concerns [Anne-Marie Taris, 2019]. In this case, jacket construction can still be sank in the cross section between 4 turbines with a spacing of 1km of each other. A final benefit that jacket constructions bring, is that the construction are high enough to avoid sand waves from covering them. Possibly resulting in the additional attraction of fish species in the top of the water column, further enhancing biodiversity.

IV: - Due to the likely substantial increase in fish stocks, the fishermen are less likely to refuse the terms regarding safety legislation [W11, T6, T9]

The eagerness of the fishing industry to make profit in combination with the current job uncertainty makes it unlikely that the fishermen will refuse to adjust to the strict offshore safety regulation. Even though, the regulation might be too intense for their taste. Otherwise, the fishermen would fear that there might be a significant risk for them that they will be banned from the area completely.

V: The high safety standard that comes with the Fish-as-a-Service concept in combination with the already strict offshore safety regulations largely prevents serious accidents in the wind farm [W8, T4, T6]

The positive aspect of the rigorous safety enforcement is that (fatal) accidents in general are much likely to occur. As a result, the chance that the new concept will attract negative publicity due accidents labeled as careless behaviour is minimal.

VI: Additional data obtained from research that was enabled due to the Fish-as-a-Service, provides hard proof on the impact of, for instance, OWFs on the sea life [W1, T13]

Recently the fishing industry is blaming the OWF operators and indirectly the scientific community that data on the impact of OWF is largely missing [VisNed, 2019]. With this argument, the fishing industry tries refuting the argument of the scientific community that exploratory research shows that OWF actually have a positive effect on the local biodiversity and biomass production [J.W.P. Coolen, 2019]. Overall, this development might turn-out harmful for the process around the spatial planning of the North Sea. By allowing more researchers in the OWF under the new Fish-as-a-Service concept, maritime biologist are provided the opportunity to justify their initial claims with more future obtained data.

VII: Early studies show that seabirds tend to avoid OWFs on the whole [W12,T14]

Research executed by the British Trust for Ornithology and the University of the Highlands and Islands in Scotland pointed out the large sea birds, such as ganet, avoid OWFs completely. Smaller birds, for example sea gals, fly into the farms to hunt but stay far away from the rotating blades. In fact, exploratory research pointed out that 99% of the sea birds change there course completely to avoid OWFs as a whole [A. Cook, 2014]. Nonetheless, the small portion of flights that fly through the wind farm, while also resulting in collision with the blades cannot be ignored completely. Hence, the continuation of careful spatial planning surrounding the construction of new OWFs is still necessary. Yet, the head of Planning and Development for the Royal Society for the Protection of Birds (RSPB) finds the report a major step forward in helping to ensure decisions are based on the best available evidence [A. Cook, 2014].

4.4 Stakeholder Engagement

In the closing paragraph of the stakeholder analysis, all of the previous sections are largely drawn up to provide a solid basis for an engagement plan. With the use of the solution spaces created in the SWOT/TOWS analysis, a strategy can now be established to engage or disengage certain actors. In other words, their interest in the process could be changed. Over all, it proves helpful drawing players with a useful production power to the table, that initially were not interested in participating in the process. These types of actors can be referred to as so called *saviors*. Engaging saviors can be done by offering them something for the SWOT/TOWS or even by defining the problem with a broad perspective. A practical example of saviors in this process are the NOGEPA and Energie Beheer Nederland. Both actors possess considerable production power that is highly relevant for the creation of a multi-purpose OWF. By offering them something that is in-line with their core values and/or objectives, the actors can be motivated to participate. For instance the engagement strategy for Energie Beheer Nederland, the creation of transition fund sets up the possibility for a perfect pretext for the environmental-friendly course the oil and gas industry is taking. Consequently, the extraction of fossil fuels in the North Sea can continue in exchange for a minor percentage of the profit margin. Similarly, a strategy can be formulated that attempts to disengage certain actors from the process. Actors with extreme high interest and significant blocking power might be detrimental for the momentum of the process. Normally, two tactics are optional for a disengaging strategy for these distinct actors. First, the solution spaces created in the SWOT/TOWS analysis can take away their concern. Again, a practical example used in the engagement strategy, this time for the WWF. Their current problem perception is that current fishing techniques are destroying the North Sea and that the sea does not get the possibility to recover. Hence, a possible disengagement strategy for them is stipulating that a sustainable fishery is the core value in a Fish-as-a-Service concept and that bottom-disruptive techniques are not allowed in the OWF. Additionally, the data-driven approach in a Fish-as-a-Service strategy enables closely monitored control over the fish stocks, largely eliminating the changes of overfishing. Another approach might be to make them irrelevant, although this technique was not suitable for this case. On the whole, both engagement and disengagement strategies should be executed with discretion, as there are risks that certain strategies will backfire, sometimes referred to as *time bombs* or *trip wire*.

Lastly, the level of involvement and the contact frequency for each actor need to be determined. How much energy should the process manager invest in a certain actor in order to reach a satisfying result? Here, actors that are vital for the process but also should be engaged, should generally be empowered in order to trigger their interest. In contrast, less important stakeholder where the process managers opt for disengagement, should be kept on a lower level of involvement. Thus, by purely informing or consulting them infrequently. The entire stakeholder engagement strategy can be found in appendix C.

4.5 Conclusion

Ultimately, the stakeholder analysis resulted in many applicable solution spaces, carrying a wide-spread support and likely triggering the engagement of the actors in the process. In turn, these solution spaces will form the foundation of the program of requirements, described in chapter 6. The most interesting solution space that was conceived is the concept of Fish-as-a-Service, resolving several issues that currently had a pernicious effect on the advancement of the process around implementing multi-purpose OWFs. These issues can be addressed by taking away concerns of the actors, such as the safety concerns, the sustainable fishing matter, the uneasiness around the considerable upfront costs investment costs and worrying about job security. The concept will be further elaborated in chapter 12, while directly linking the Fish-as-a-Service concept with the economics of sustainable fisheries, forming a solid business case.

Chapter 5

Target Species Selection

5.1 Introduction

In this chapter, the target species that may be potentially harvested by fisheries from an artificial reef system within an OWF are described. Artificial reef structures include the scour protection around monopiles, shipwrecks, or other hard substrate on the seabed. An overview outlining the biology, the organism's current status in the North Sea, and specific motivation for harvesting in the context of a wind park is given. The motivation for selecting these species are based on the following criteria: 1) economic interest, 2) ecological suitability 3) potential to use alternative fishing gear and 4) demonstrated success or potential with other projects and research studies. The selected species are known to be attracted to or associated with reef structures or scour protection. These species will form the basis of biological criteria for the design of the area and the economic analysis.

5.1.1 European Lobster (*Hommarus gammarus*)

Figure 5.1: European lobster

Biology

The European Lobster (*Hommarus gammarus*) is the largest decapod crustacean in the southeastern North Sea, and can reach up to 60 cm long and weigh on average 5-6 kg [M.J.C. Rozemeijer, K.E. van de Wolfshaar, 2019]. They have a hard exoskeleton, which they grow and must replace through the moulting process. Their prey consists of blue mussels, hermit crabs, benthic invertebrates, and polychaete worms among others. The tolerated temperature range for the European Lobster is from 1-25 °C. They exhibit a slow growing k-strategy life style, not reaching sexual maturity until at least four years. Reproduction occurs during the summertime coinciding with moulting of the female. Eggs are large, but clutch sizes are small in comparison with other decapods. After eggs hatch, the larvae enter a pelagic phase where they spend 10-18 days in open water until they undergo metamorphosis and settle to the hard substrate bottom [M.J.C. Rozemeijer, K.E. van de Wolfshaar, 2019]. They have a considerable life span reaching up to 60 years with some female specimens reaching 72 years [R. Krone, A. Schroder, 2011].

Current status

Adult European Lobster are solitary, living on the edges or within rocky crevices, meaning that the success of their population size and distribution is largely dependent on hard substrate availability, except for during earlier life stages when they depend on muddy seafloor for burrowing [M.J.C. Rozemeijer, K.E. van de Wolfshaar, 2019]. In the southeastern North Sea where the ocean floor is dominated by sandy-muddy substrate this remains a challenge. However, the presence of large wrecks such as airplanes, ships, and crates can also provide important habitat [R. Krone, A. Schroder, 2011].In the German Bight region of the North Sea, a small sub population of European Lobster is found on the rocky island of Helgoland. After the lobster fishery crashed in the mid 1950s in the region, catches have remained low, but attempts to rebuild the fishery through artificial reefs remain a popular solution [B.H. Buck, G. Krause, B. Pogoda, B. Grote, L. Wever, N. Goseberg, M.F. Schupp, A. Mochtak, D. Czybulka, 2017].

Target motivation

This project chooses to focus on European Lobster as a potential target species for several reasons. First, as a highly sought after seafood product, it is perhaps one of the most economically viable species. Catches can fetch 16,30 euros per kg in the Dutch landings market. Since many European Lobster fisheries in the North Sea have been overexploited [A. Sundelhof, V. Grimm, M. Ulmestrand, O. Fiksen, 2014], there is great ecological interest in restoring these fisheries either through management strategies, stock enhancement, and/or habitat enhancement [R.C.A. Bannister, J.T. Addison, 1998]. In addition, European Lobster can be relatively easily harvested under such conditions using non-intrusive methods such as cages or pots [Sustainable Fisheries Partnership, 2020]. Several studies have already shown the potential to revitalize European Lobster stocks through the introduction of artificial hard substrate [M.J.C. Rozemeijer, K.E. van de Wolfshaar, 2019], [R. Krone, A. Schroder, 2011], [A. Jensen, K. Collins, P. Smith, 2000]. Rozemeijer *et al.* (2019) discussed the potential of using Reef Balls, a structure with many holes of various sizes constructed from pouring concrete into a fiberglass mould. The need to accommodate different life stages with different crevice sizes was emphasized. The Poole Bay Artificial Reef Project, executed in the UK in 1989, was an artificial reef constructed from blocks made of cement stabilized pulverized fuel ash. Pot catches from monitoring the site were dominated by lobster and tagging experiments showed individuals were highly attracted to the structure [A. Jensen, K. Collins, P. Smith, 2000].

5.1.2 Brown crab (*Cancer pagurus*)

Figure 5.2: Brown crab

Biology

The Brown crab or edible crab can reach an adult size of up to 300 mm [J. Steenbergen, M. Rasenberg, T. van der Hammen, S. Biermans, 2012] and weigh up to 4 kg. Brown crab feed on other crabs, snails, bivalves, and detritus. They tolerate temperatures consistently below 15 °C [L. Tonk, M.J.C. Rozemeijer, 2019]. Like the European Lobster, Brown crab have hard exoskeletons they must shed by moulting in order to grow. They are also slow growing and reach sexual maturity at around four years. The life span of the Brown crab is typically 25-30 years [J. Steenbergen, M. Rasenberg, T. van der Hammen, S. Biermans, 2012]. Brown crab reproduce from July to September and eggs, once attached to the female, take 7-8 months to develop. A single female carries around 0.25 to 3 million eggs depending on her size. Once eggs hatch they enter a pelagic phase where they inhabit the water column and then finally settle to the sea bottom where they grow into adults. In the adult stage Brown crab tend to occupy muddy sand and/or hard substrate [L. Tonk, M.J.C. Rozemeijer, 2019].

Current status

Brown crab fisheries only have a strong presence in England, Ireland, and France, and there is currently no management for the Brown crab fishery in the Dutch North Sea [J. Steenbergen, M. Rasenberg, T. van der Hammen, S. Biermans, 2012]. Stocks in the central North Sea are reported as low, but in some offshore areas around the UK they have doubled. More monitoring is needed on their population status to better gauge numbers in Dutch North Sea waters [J. Steenbergen, M. Rasenberg, T. van der Hammen, S. Biermans, 2012].

Target motivation

Occupying the same niche as the European Lobster, the Brown crab also has the potential to become an important, viable economic fishery. Catches in the Dutch landings market fetch 1,47 euro per kg. Passively fishing crab using pots within an offshore wind park could relieve pressure on lobster stocks at certain times and vice versa. The low status of the fishery also motivates its enhancement in a wind park setting. Van den Bogaart *et al.* 2019 carried out a feasibility study showing the qualitative habitat suitability for Brown crab fisheries in the North Sea based on individuals found on hard substrate and environmental factors. As an example, the Borrsele offshore area was rated as "very good" regarding habitat quality. In a study in the German Bight by Krone *et al.* 2017, 5000 brown crabs per anti scouring surface per monopile were reported, twice as many than with structures without scouring present.

5.1.3 Atlantic cod (*Gadus morhua*)

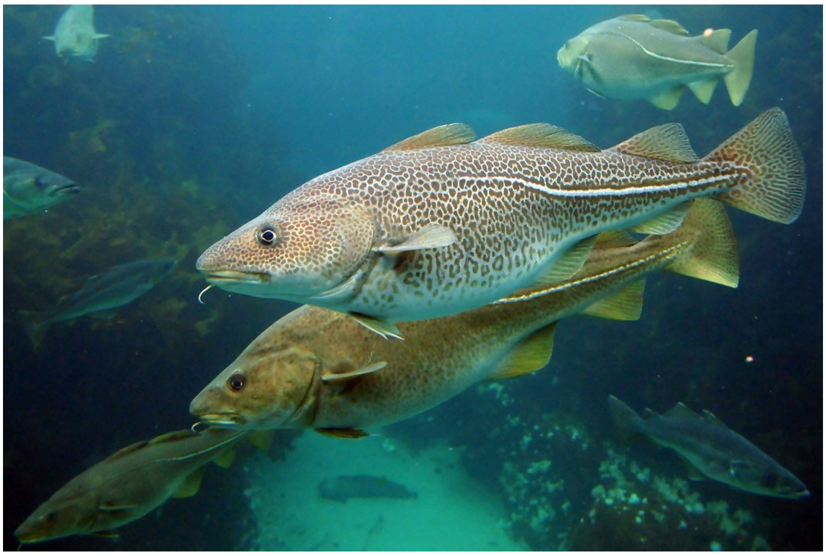


Figure 5.3: Atlantic cod

Biology

Atlantic cod (*Gadus morhua*) is a demersal species of fish from the family *Gadidae*, living primarily in the benthos and swimming in groups called shoals. They live a largely stationary life style within the same territory. Adults range in size from 61 cm-1.2 m in length and can weigh up to 40 kg. Cod are considered top predators eating a variety of live food at different sizes. Their optimal temperature range is 8- 12 °C, but they can tolerate -1-23 °C in some cases. They reach sexual maturity at 2-4 years of age and migrate inshore for spawning once a year from late winter to spring. After hatching, cod grow as larvae in the water column for 3 weeks until settling to the sea bottom [N.W.P Breve, 2010].

Current status

While there are many different sub populations of Atlantic cod in the North Sea with some mixing [N.W.P Breve, 2010], overall stocks are declining at different rates. Since 2015 the standing stock biomass (SSB) is in decline and recruitment remains low (ICES 2019b). While the lack of hard, complex substrate in some areas of the North Sea limits recruitment, juvenile cod have been observed occupying shipwrecks in the Dutch North Sea [W. Lengkeek, J. Coolen, A. Gittenberger, N. Schrieken, 2013]. The IUCN Red List of Threatened Species reports Atlantic cod as "vulnerable".

Target motivation

Due to the poor state of the North Sea cod stocks, there is great interest to improve the fishery either through habitat enhancement or even aquaculture [B.H. Buck, G. Krause, B. Pogoda, B. Grote, L. Wever, N. Goseberg, M.F. Schupp, A. Mochtak, D. Czybulka, 2017]. There has long been a demand for this fish species economically, with a reported landings market price of 3,21 euros per kg. There is great potential to use passive fishing methods for this species. Gill nets that do not touch the seafloor or bottom long lines with a baited hook can be implemented in place of more intrusive methods like trawling [Sustainable Fisheries Partnership, 2020]. Studies have reported cod aggregating around monopiles in wind parks, meaning that this may provide important habitat for the fishery [J.T. Reubens, U. Braeckman, J. Vanaverbeke, C. van Colen, S. Degraer, M. Vincx, 2013] [J.T. Reubens, S. Degraer, M. Vincx, 2014]. In an acoustic telemetry study, cod were tagged and observed over a period of time. Over summer and autumn, the individuals studied had a high residency and strong site fidelity to hard artificial substrate in the Belgian North Sea within wind park designated areas [J.T. Reubens, F. Pasotti, S. Degraer, M. Vincx, 2013]. These studies point to the promising outlook for targeting cod within or in the surrounding area of wind parks.

5.1.4 European seabass (*Dicentrarchus labrax*)

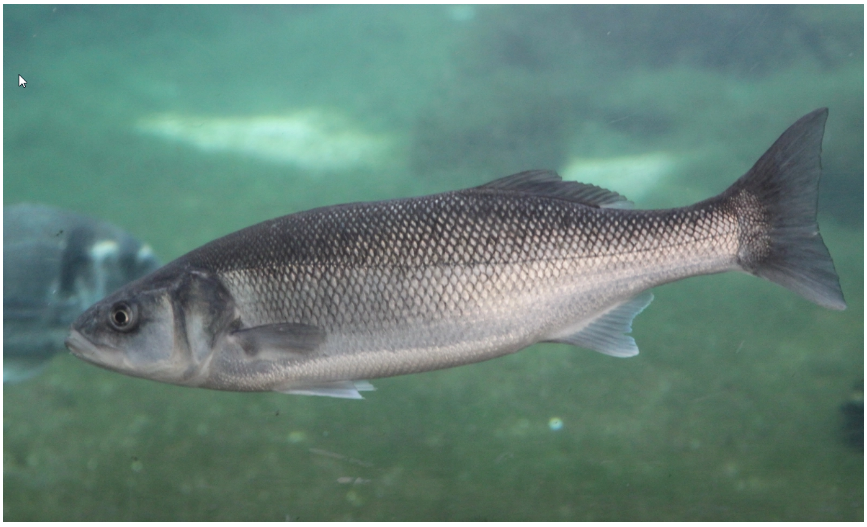


Figure 5.4: European seabass

Biology

The European seabass (*Dicentrarchus labrax*) is a demersal species of fish with an adult length from 23 to 46 cm and can weigh up to 12 kg. As juveniles, they strictly feed on marine invertebrates and as adults shrimps, mollusks, smaller fish, and crustaceans. They swim to depths of 100 m and spawn annually in groups during the winter. Spawning involves a small migration closer to shore or even into river mouths [F. Quirijns, T. van der Hammen, H. van Overzee, 2013].

Current status

European seabass is best known for its cultivation in aquaculture, mostly in the Mediterranean. In the North Sea, the majority of landings are taken at the English and French coasts, while the Dutch fishery is still rather small. Stocks are stable, but as the fishery becomes more and more important for this region, intelligent management should be developed over time [F. Quirijns, T. van der Hammen, H. van Overzee, 2013].

Target motivation

European seabass is a very popular fish for both recreational fishing and commercial fisheries. In the Netherlands, they fetch a price of 12,78 euros per kg. Since seabass are so popular for recreational fishing, they are often caught using hand operated pole and lines, which can be applied in a wind park setting [Sustainable Fisheries Partnership, 2020]. Another reason motivating the interest for this species is the warming of the North Sea. This means some typically more southern dwelling fish species like seabass are migrating to higher latitudes [I. Montero-Serra, M. Edwards, M. Genner, 2015]. As a target species, this makes seabass a reliable candidate for production in a North sea wind park, since it is likely that their stocks will increase in the future [F. Quirijns, T. van der Hammen, H. van Overzee, 2013].

5.1.5 Cuttlefish (*Sepia officianalis*)

Figure 5.5: Cuttlefish

Biology

The Cuttlefish (*Sepia officianalis*) is a cephalopod reaching 49 cm in mantle length and weighs up to 4 kg. Cuttelfish eat crabs, shrimp, clams, small fish and snails [J. Wang, U. Piatkowski, I. Bruno, L. Hastie, G. Pierce, J. Robin, A. Moreno, 2009]. They are relatively short lived from 1-2 years and reach sexual maturity between 14-18 months. Females lay 100-1000 eggs, which are attached to seaweed, shells, and other substrate during development. In contrast to most of the target species discussed here, Cuttlefish prefer sandy substrate, but have also been observed in sea grass beds. Cuttlefish only migrate for spawning inshore during the spring and summer [M. Gras, B.A. Roel, F. Coppin, E. Foucher, J.P. Robin, 2014].

Current status

Cuttlefsh are considered non-threatened by the IUCN Red List of Threatened Species. Globally they occupy a wide range: from the eastern Atlantic to the North Sea to South Africa and the Mediterranean. In the North Sea, they are found on either side of the English channel during the early spawning period as well as the French Atlantic coast [M. Gras, B.A. Roel, F. Coppin, E. Foucher, J.P. Robin, 2014]. Currently, catches dominate in the English Channel and Bay of Biscay, but catches are also reported in the Southern North Sea. ICES reports that Cuttlefish landings have fluctuated greatly since 1995, but with no clear trend present [G. Pierce, I. Young, J. Wang, 2002].

Target motivation

Because the Cuttlefish is so short lived but has many offspring (ie an r-strategist), it seems an interesting candidate to target in an artificial reef-wind park scenario. This is especially true since the other target species in this project of great economic as well as ecological interest are generally slow growing, which means that a longer time period is needed for significant profit to be reached. In addition, Cuttlefish remains an unexplored fishery in the Dutch North Sea, which could lead to new fishing opportunities via artificial reefs. Cuttlefish also do not require a large amount of complex, hard substrate, which means no extra effort is needed to attract them. It is also possible to harvest them using traps, a passive, responsible fish practice leaving the benthos undisturbed [Sustainable Fisheries Partnership, 2020].

5.1.6 Conclusion

The high potential for the aforementioned species to be harvested responsibly, their economic viability, their natural suitability to the region of interest (ie Dutch North Sea) and numerous studies suggesting their successful adaptation in an OWF make them promising candidates for such a scenario. It is suggested that these species continue to be the subject of research for this specific purpose, and will thus be the focus in the ecosystem modelling approach and biomass estimations described in chapter 10.

Part 2

Design phase

Chapter 6

Basis of Design

This chapter addresses a site comparison of several potential wind farms in the North Sea. Different significant biological and technical criteria are analysed for each location. Based on these criteria, a decision will be made about a practical wind farm location.Consequently, the chosen location is addressed in more detail in section 6.2. For design purposes a summary of requirements and boundary conditions is provided in this chapter as well. Considering the method that is used, a basis of design acts as a fundamental for the design process. A short explanation is given on the requirements and boundary conditions to be used. Eventually, the requirements and boundary conditions for this project is included.

6.1 Site selection

Different aspects are taken into account in the analysis of the few North Sea wind farm sites. It will be clear that for design purposes, most desirable aspects lay more within the hydrodynamic and morphodynamic conditions than the wind conditions. Site data is available in sources such as project reports and map viewers. Map viewers that are commonly used in oceanography such as the following sources are used:

- NOAA Wavewatch III for worldwide wave climate [Environmental Modelling Center USA Government, 2018]
- Noordzeeloket by Rijkswaterstaat for general data [Noordzeeloket, 2019a]
- EMODnet for data about soil conditions [European Marine Observation and Data Network, 2017]
- RvO Netherlands Enterprise Agency, wind energy on sea, for general data [Netherlands Enterprise Agency, 2019]

The importance of some parameters in the left-column of table 6.1 below are negligible when comparing it with other parameters. For example, the 100 year average wind speed (10 m above sea level) is less normative than the presence of shipwrecks, nutrient levels, significant wave height H_{m0} and sand wave characteristics, since the latter parameters influence the living environment below water surface level. For specific reasons regarding construction, logistical input is also taken into consideration. Borssele appears to be highly preferable when looking at its nutrient level, soil conditions and available hard substrate. In conclusion, one can argue the Borssele wind farm area to be the most suitable site for further exploration. On top of that, a smaller area consisting of only Borssele Wind Farm Zones 1 and 2 will be considered for this project.

Table 6.1: Site comparison of North Sea wind farms

Location	*Gemini*	*Luchterduinen*	*Borssele*
Environment			
Nutrient levels			
a) Nitrogen	5-10 umol/l	25 - 30 umol/l	30-35 umol/l
b) Phosphorus	0.25-0.50 umol/l	0.75-1.00 umol/l	1.00-1.25 umol/l
c) Chlorophyll a	2.1 mg/l in growing season	5,6 mg/l in growing season	7,3 mg/l in growing season
Water temperature	2-20 C	2-20 C	2-20 C
Soil conditions	Sand	Sand	Mostly sand, small parts mud or coarse substrate
Artifical reef	Nothing in proximity	2 wrecks in proximity	3 wrecks in proximity
Salinity level	31,5-33,5	31,5-33,5	33-34.5
Technical			
H_{m0} 50 yrs	9.1 m	7.3 m	9 m
T_{m0} 50 yrs	13.8 s.	12.2 s.	10.74 s
Sand waves (height, migration speed)	H = 1.4 m	H = 3.0 m, Um = 15.2 m/year	H = 1.6 - 7.0 m, Um = 1.6-1.8 m/year
Current speed depth-averaged 50 yr.	0.9 m/s	1.1 m/s	1.25 m/s
Water depth	32 m (EMODnet)	21 m (RvO Luchterduinen)	14-36 m (EMODnet)
Wind speed 100 m above MSL (U_{100})	Mean: 10.1, Max: 35.9	Mean: 9.8, Max: 35.2	9.6 m/s
Logistics			
Distance to shore	85 km	23 km	23 km
Distance to closest suitable port	88 km	31 km	57 km
Area availability	68 km^2	25 km^2	344 km^2

6.2 Input criteria

The Ørsted owned wind farm site has been investigated for the tender procedure. The independent research institute Deltares had considered the metocean parameters by the use of existing historical data sets and HARMONIE, SWAN and Delft3D-(FLOW) packages. A subsoil surveying consultancy company named Fugro conducted the research of the subsoil at the Borssele Wind Farm. Its data is summarized and significant numbers are provided for this project. This chapter summarizes the significant environmental parameters. For simplicity, the parameters can be subdivided into the following categories:

- Waves
- Currents
- Bathymetry
- Soil conditions
- Seabed dynamics

The soil conditions are the different soil layers of the subsoil and the dynamics of the seabed regarding sand waves. The wind speed and the governing directions are especially important for the wind turbines and will not be encountered at all.

Important facts are the effective workable areas of Borssele 1 and 2. The effective area is determined by subtracting the area of cables, pipelines and their safety zones from the total area. The total net area is:

$$49.1\ km^2\ (\text{WFZ1}^1) + 63.5\ km^2\ (\text{WFZ2}) = 112.6\ km^2.$$

[1] WFZ stands for 'wind farm zone'. The Borssele Wind Farm is categorized in zones from 1 to 5.

6.2.1 Bathymetry

Bathymetry is the first item that is discussed. It considers the water depth throughout the wind farm area 1 and 2. Surveying is done with a multibeam echosounder. With this tool hydrographical surveying vessels are able to sail throughout the area and measure the distances to the seabed with single echo beams. The distance is measured with the travel time of the echo sound.

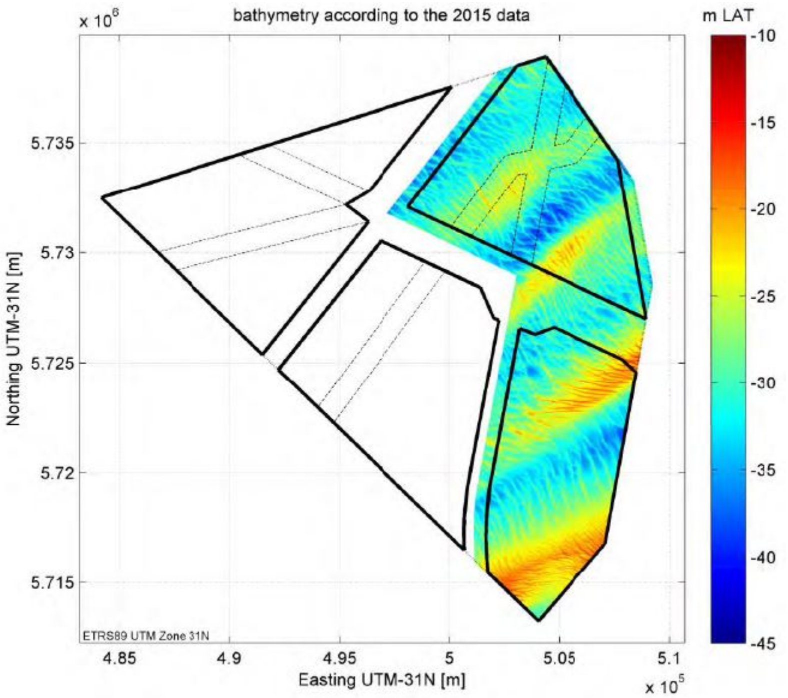


Figure 6.1: Bathymetry map of the wind farm area found by a multibeam echosounder [R. Hasselaar, 2015, p.7]

As appears in figure 6.1, the bathymetry at the Borssele area is characterized by sand waves. The bathymetry relative to Low Astronomical Tide (LAT) is:

- Borssele I: water depth of LAT - 17.8 m to LAT - 39.7 m
- Borssele II: water depth of LAT - 14.0 m to LAT - 38.5 m

Sand waves and their effect on bathymetry are considered in more detail in section 6.2.3.

6.2.2 Soil conditions

A geotechnical survey was conducted by Fugro in 2015. Several surveying methods used are:

- Borehole drilling
- Downhole sampling
- Downhole in situ testing
- Seafloor in situ testing

Figure 6.2 presents the test locations in Borssele I and II. Appendix F presents the cone penetration diagram and the borehole that were created with the soil surveys. The yellow-marked location yields the cone penetration test figure as presented in Appendix F. The cone penetration test measures the cone resistance in MPa (N/mm^2) of the subsoil at a penetrated depth x.

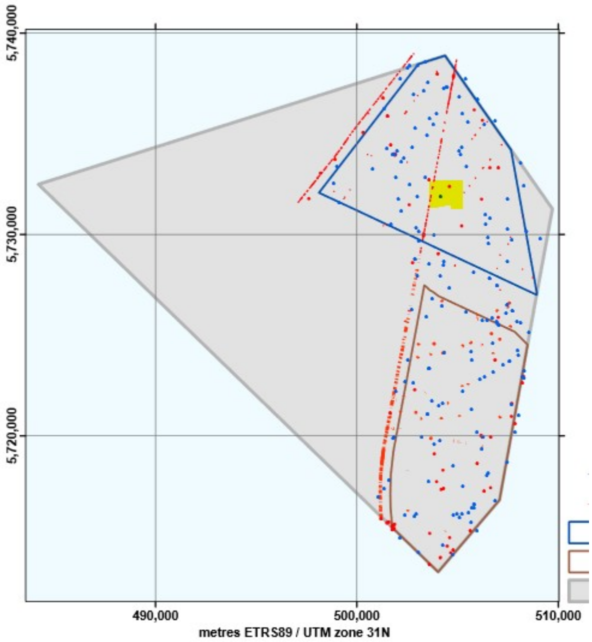


Figure 6.2: Test locations in Borssele I+II

The coarser sediment particles are found on the crests of the sand banks. The finer particles are in the deeper parts of the seabed. Mainly two soil types are found in this area: muddy sands and medium sands. Muddy sands are sands with larger quantities of silt and clay particles (finer grains). Muddy sands are characterized by small sand grains with clay and silt particles (in the range between 0.02 - 0.2 mm). Medium sands have medium-sized grain particles, often in the range of 0.20 - 6.3 mm [European CEN, 2002]. Small amounts of coarse sand and gravel are also found on the seabed, the according nominal $d_{50} = 0.25$ mm.

6.2.3 Sand waves

The North Sea bottom is continuously changing in the form of migrating sand waves. Because of their mobility, the presence of sand waves is a major obstacle for designing an artificial reef system. These waves can be in the order of several meters or more, with wavelengths of hundreds of meters [J. M. Damen, T. A. G. P. van Dijk, S. J. M. H. Hulscher, 2017]. Extensive studies have been done about the seabed morphology in the Borssele wind farm area. Therefore, some numbers will be cited from the report "Morphodynamics of the Borssele Wind farm Zone" [R. Hasselaar, 2015]. Sand waves will completely cover any low object placed on the seabed if it is not strategically placed. This risk must be mitigated as best as possible. In order to reduce the risk of sand covering the artificial reef, the sand wave characteristics of the area must be analysed. A data set has been obtained describing most sand wave characteristics of the Dutch North Sea. To obtain this data set, the researchers "use high-resolution multibeam echo soundings, hydrodynamic models, and databases and sedimentary data for the analysis of, respectively, sand wave shape characteristics and the comparison to hydrodynamic and sedimentary characteristics for the Netherlands Continental Shelf" [J. M. Damen, T. A. G. P. van Dijk, S. J. M. H. Hulscher, 2017]. The data set was produced in 2017 and contains point locations which describe:

- The location of the crests of the sand waves. The location is expressed as x (m) and y (m) coordinates in the Universal Transverse Mercator coordinate system (grid zone 31N), modelled by the World Geodetic System WGS84.
- The height of the sand wave in meters.
- The length of the sand wave in meters.

- The asymmetry of the sand wave. The definition is given by [J. M. Damen, T. A. G. P. van Dijk, S. J. M. H. Hulscher, 2017]. For the scope of this project it is relevant to know that full symmetry is given by the value 0, and full asymmetry by the value 1.
- The lee slope of the sand wave in degrees relative to the horizontal.
- The bathymetry of the North Sea, which is expressed as the depth (m) relative to low astronomical tide (LAT).

For illustrative purposes, the bathymetry of the Dutch North Sea is shown in figure 6.3 with the location of Borssele 1 and 2 marked in red.

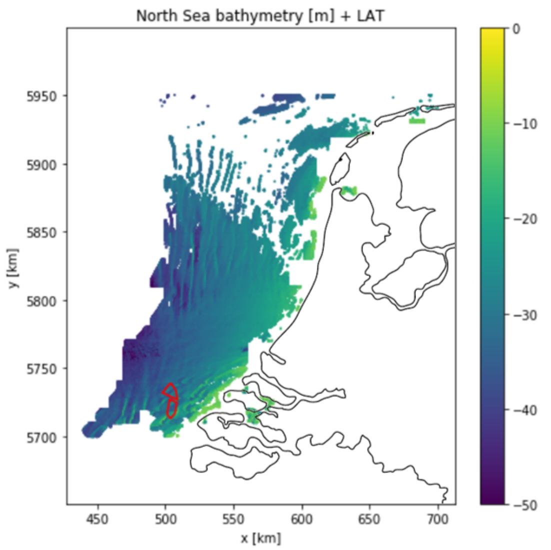
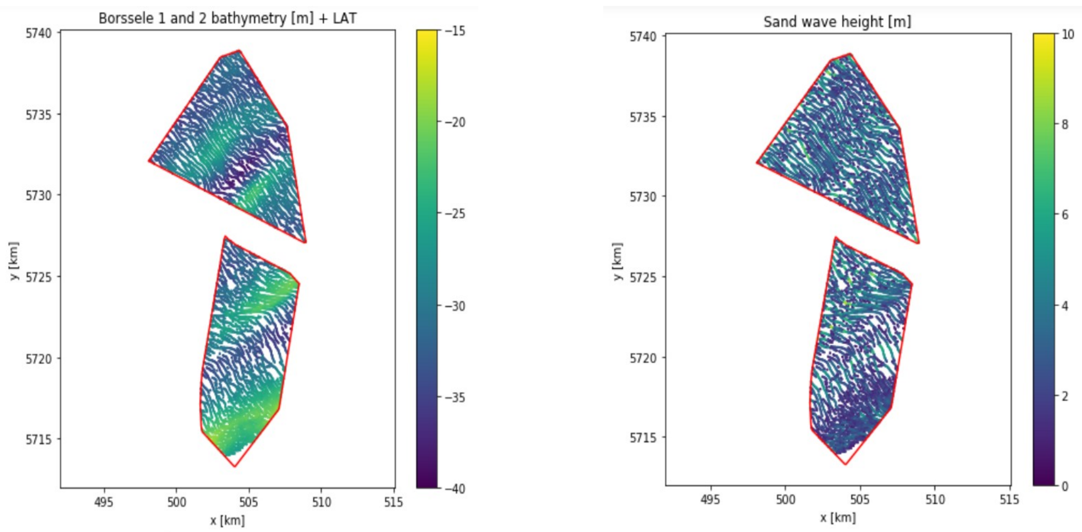


Figure 6.3: The bathymetry of the North Sea at the Netherlands, Borssele I+II marked in red.

Only the values within the perimeter of Borssele 1 and 2 are relevant. The results are plotted in the figures below.



(a) Bathymetry map of Borssele I+II (enlarged)

(b) Height of the sand waves at Borssele I+II

Figure 6.4: Sand wave data

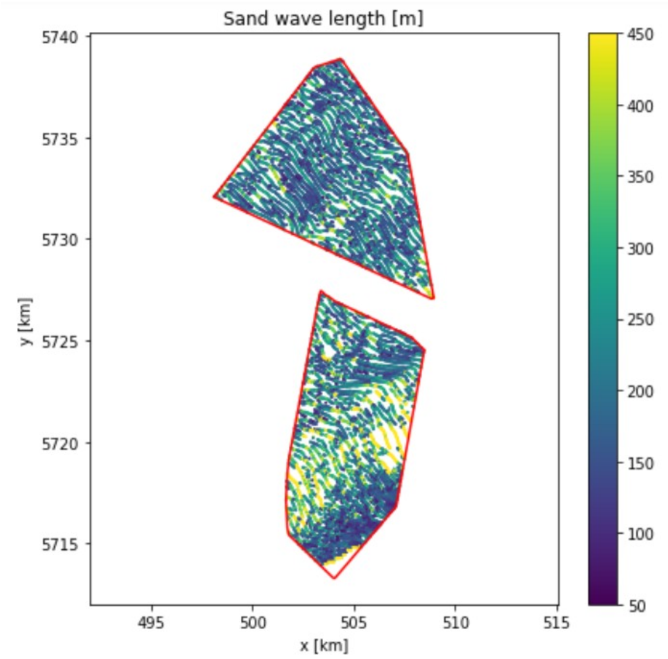


Figure 6.5: Sand wave lengths in Borssele I+II

The most important parameters are summarized in table 6.2. All this data has been analysed using Python scripts, which is provided upon request in a separate booklet.

Table 6.2: Summary of sand wave data

	Height [m]	Length [m]	Assymetry [-]	Lee slope [°]	Depth [m]
Mean	3.04	225.14	-0.045	2.35	29.18
Minimum	0.82	47.92	-2.94	0.45	18.12
10_{th} percentile	1.52	126.22	-0.98	1.41	22.67
50_{th} percentile	2.88	201.14	0.00	2.28	29.80
90_{th} percentile	4.75	336.75	0.92	3.34	34.07
Maximum	9.66	1701.15	3.37	8.6	38.8

6.2.4 Shipwrecks

While researching the bathymetry of the site, some histroical artiacts were found on the seabed. Three shipwrecks have been identified in the Borssele Wind Farm area. One of them is located in Borssele I+II.

6.2.5 Metocean data

Metocean data is including data about the physical characteristics of wind, waves and currents. Data research was conducted by Deltares back in 2014. This data on wind, wave and current conditions are based on the report that was initially created for Borssele Wind Farm Zone I, but holds for the whole potential area (I, II, III, IV V) as well. The effect of wind is already captured in models of waves and currents.

Waves

Figure 6.6 presents the wave magnitude H_s under a 'severe sea state' (as defined in [H.J. Riezebos, 2015]) as a function of the return period in years. The plotted solid line is the Generalised Pareto Distribution or GPD fit. Peaks over threshold values are in this plot marked with asterisks. The Peak Over Threshold or POT method is a way to model extreme values. The GPD is a stochastical distribution that is used to model the tails of uncertainty in an extreme value distribution. The dashed lines show the boundaries of the 95% confidence interval. H_s can be expressed in the maximum wave height H_{max}, which is defined as the largest wave height in 1000 waves ($H_{0.1\%}$), see equation 6.1. Equation 6.1 is according to the Rayleigh-distribution.

$$H_{0.1\%} = 1.86H_s \tag{6.1}$$

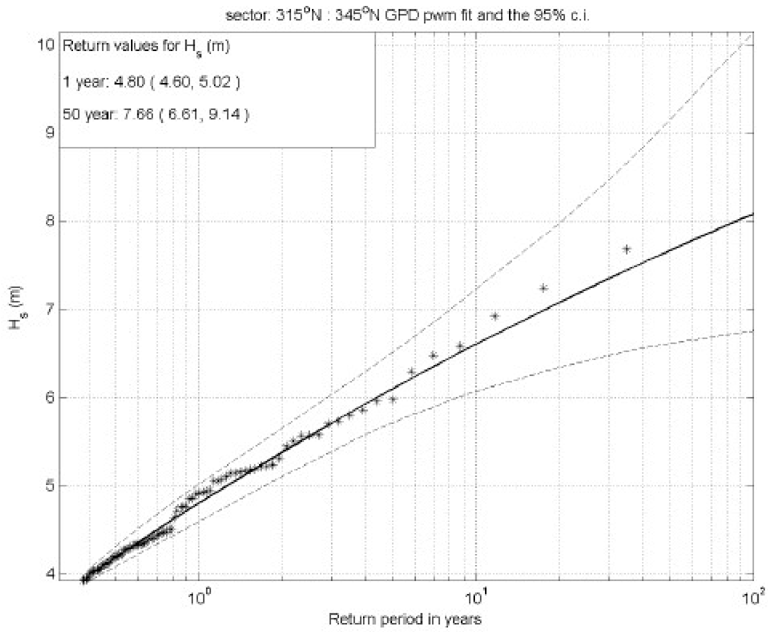


Figure 6.6: The significant wave height and its corresponding return period [H.J. Riezebos, 2015, p. 63]

A return period of 10 years yields significant values for the wave heights. As is plotted in figure 6.6 the significant wave height in the sector NNW (315°; 345°) is $H_s = 6.6$ m. The extreme value of this GPD fit is $H_{s,1,SWL} = 7.1$ m (at minimum still water level) and $H_{s,1,MWL} = 7.5$ m (at maximum still water level) [G. van Velzen, H.J. Riezebos, N. Bruinsma, 2016].

The North-North-West sector (315°; 345°) indicates the 'coming from'-direction of the wind and the waves.

Currents

The data on currents is based on simulations with Delft3D-FLOW in the period from 1992 to 2011. Based on observations of the current behaviour and estimates of depth averaged flow velocities, the following graph was made:

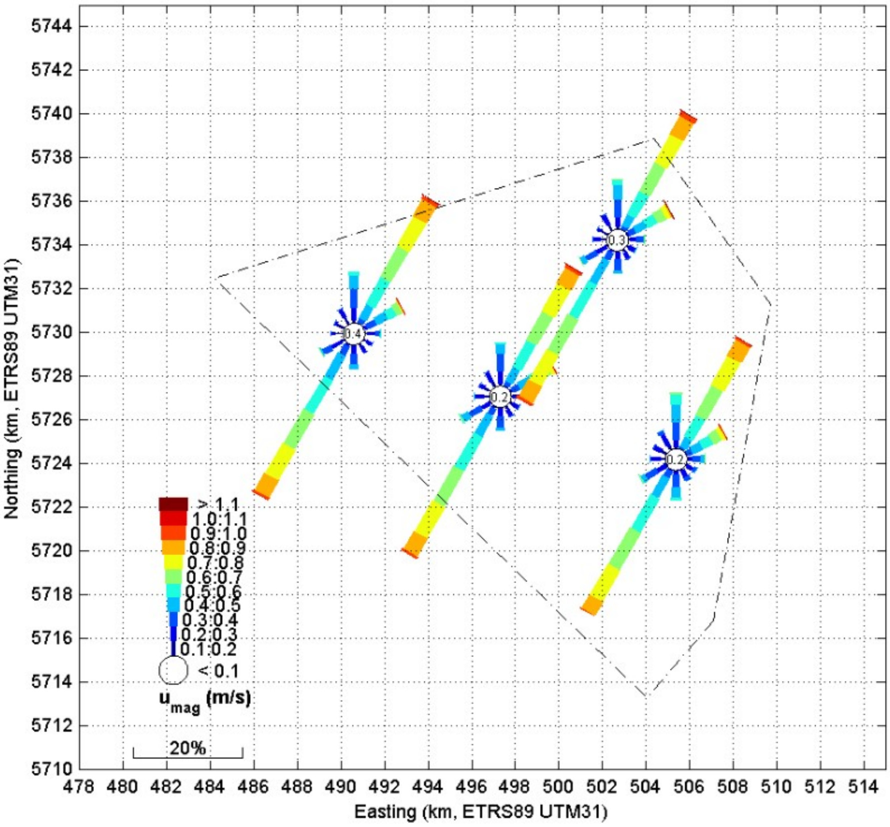


Figure 6.7: Representation of the sea current's governing directions [H.J. Riezebos, 2015, p.80]

From figure 6.7 one can conclude that the currents are predominantly directed in the two main directions of the tide. Therefore, it appears that sectors North-North-East (NNE) and South-South-West (SSW) are the governing directions.

The extreme depth-averaged current magnitudes, given a return period of 10 years, are presented by a best fit (POT-GPD). The fit has a 95% confidence interval, the boundary values $u_{c,1}$ and $u_{c,2}$ are given as well.

For the NNE-sector (towards the North Eastern direction):

- The return value $u_{current} = 1.1$ m/s,
  - $u_{c,1} = 1.20$ m/s
  - $u_{c,2} = 1.00$ m/s

For the SSW-sector (202.5 $^\circ$):

- The return value $u_{current} = 1.00$ m/s,
  - $u_{c,1} = 1.02$ m/s
  - $u_{c,2} = 0.98$ m/s

Based on the information above, one can set boundary conditions regarding the location to be considered: Borssele I+II. Physical or nautical conditions at sea set the ranges in which the wind farm area can be used. The requirements are set by potential clients and/or users of the new system. The combination of the two are also mentioned as verification criteria. Some of these criteria are listed below:

- P.1.: The effective workable wind farm area, including the wind turbines, amounts 112.6 km^2.
- P.3.: The water depth at Low Astronomical Tide (LAT) ranging between 14 – 40 m and the design maintenance vessel draught are the governing parameters that determine the design height of the biostructures.
- L.1.: Offshore construction elements may not contain or emit toxic or contaminating chemicals, such as mercury, lead paint and asbestos which will lead to a burden for the marine environment.
- P.9.: The design flow velocity of the current(s) at Borssele I+II is 1.1 m/s.
- P.11.: In the Borssele wind farm area, the significant wave height Hs is 6.6, 7.2, 7.66 m for return periods of 10, 25 and 50 years respectively.

6.2.6 Structural requirements for target species

Based on the key species of interest for this report, specific structural conditions are necessary if these organisms are to thrive within a bio-enhanced OWF. A list of structural requirements needed per species in the design are included below:

- Atlantic cod and European seabass: Hard, complex substrate is preferred of various height and rugosity for sand wave and juvenile protection (see requirement S.11.).
- European Lobster and Brown crab: Rocks and boulders of varying sizes are preferred, with the absolute requirement of varying crevice size to account for all life stages as juveniles in particular tend to rely on them for shelter (see requirement S.10.).
- Cuttlefish: Sandy and muddy substrate is a necessity for this species in contrast to other target species. Thus, it is important to leave some areas without hard substrate in the OWF. This requirement (O.21.) is mentioned in appendix D.

6.2.7 Stakeholder input

In order to achieve consensus between the actors in the network, some specification need to be included into the final design. Notably, most requirements are mainly based on future policy management and operating regulations which become important for tailoring the Fish-as-a-Service concept to the OWF. Nonetheless, there are still some functional requirements that should be implemented into the design. For starters, the recycling of jacket construction of oil and gas rigs into artificial reefs is recommended (req. F.3. in app. D). With this design requirement, a long standing issue of the oil and gas companies might be finally settled. Involving them in the process serves a main purpose: creating the possibility for the establishment of a transition fund that subsequently can be incorporated into the business case. Here it should be stressed that the topsides of those rigs cannot be used, due to usage of hazardous materials. Actors such as Greenpeace and Stichting Noordzee would under no circumstances agree with the usage of entire rigs. Furthermore, the safety concerns of the wind farm operators ought to be respected. Sinking entire jacket construction near wind turbines is detrimental for the safety regulations, and therefore for the outcome of the entire process. To eliminate the safety concern, the guideline for the exclusion zone in regular OWF can be adopted. This means that obsolete offshore construction should not be sunk within a distance of 500 m from any monopile [Anne-Marie Taris, 2019]. For instance, this should be accomplished by placing obsolete construction in the cross section between 4 turbines with a spacing of 1 km of each other. Another consideration for the final location of the rigs-2-reef constructions are the shipping routes. Branche Organisatie Zeehavens and the Port of Rotterdam want a guarantee that sea transport will not be harmed by multi-purpose OWFs. Therefore, access regulations of the OWFs will be relaxed in the near future and larger cargo vessels will be granted permission to sail through the OWFs. The ships should not be hindered as a result of the bio-enhanced area (see boundary condition L.5. in app. D). For instance, a sunken jacket construction should not obstruct ships from passing through. Accordingly, specific lanes between the raster of the OWF could be kept free from sunken offshore constructions to prevent any physical obstacles. For Borssele, this would result in lanes that would in all likelihood lead from north to south and vice versa. What is more, in general, the investment costs required for the bio-enhancement of the area should be minimized. A rough financial estimation of the required costs seems substantial, considering the OWF Borssele I and II covers an area of 115 km^2. By making use of inexpensive materials with a swift installation process such as stones, the investment costs will decrease significantly. Naturally, the lower the investment costs, the greater the chance that a Fish-as-a-Service concept can be adopted. Lastly, indirectly lowering the CO_2 emissions emitted during the construction of an OWF by integrating hang cultures with seaweed in an OWF would be attractive for OWF clients. Currently, building more CO_2 neutral infrastructure is of great interest in the construction sector. Thus, seaweed culture might be an appropriate solution under such circumstances.

6.3 Conclusion

Hence, the basis of design ends with the definition of the verification criteria. Verification criteria exist as stated requirements and accordingly, the boundary conditions on which the design specifications in chapter 8 are validated. Boundary conditions set up a framework in which the design is fitted. Before that, one may distinguish the boundary conditions and the requirements as follows [Twynstra Gudde, 2019]:

- Requirements:
  - Functional requirements describe what the end result should be able to achieve. These requirements are often derived from project objectives or stated problems that need to be solved. It is useful to track these requirements down from clients and stakeholders.
  - Operational requirements have the purpose to satisfy the users and/or the customers of the end product. These requirements emphasize on how the system has to be designed in order to work efficiently or in other words: to be 'user friendly'.
  - Structural requirements are the design limitations that follow from the assessment of the environmental conditions at Borssele Wind Farm. Basically, structural requirements specify the rules for the final tangible object.
- Boundary conditions:
  - Physical boundary conditions are limitations initiated by the physical environment. In this case, physical boundary conditions are characteristics of the North Sea in the Borssele Wind Farm Area, nautical boundary conditions e.g..
  - Legal boundary conditions are institutional conditions used to deterministically verify whether a design fits in a legal framework of an administrative body.

Appendix D presents the boundary conditions and the requirements for the artificial reef system in Borssele Wind Farm I+II. This program of requirements is based on the vision of the different involved parties and the existing official documents such as the lot decision [H.G.J. Kamp, 2016]. Here distinctions are made between the several before-mentioned categories. Table 6.3 gives an example of legal boundary conditions applied on offshore wind farms regarding sound emissions and porpoises.

Table 6.3: Standard setting of the acceptable noise levels expressed in dB for Borssele I - IV [C. van Duin, 2015]

Borssele I - IV	Maximum noise load (dB re μ Pa^{2}s on 750 m)		
380 MW per lot	Period during the year		
Number of turbines	Jan - May	Jun - Aug	Sep - Dec
77 - 95	159	165	166
64 - 76	160	166	167
55 - 63	162	167	169
49 - 54	163	169	170
43 - 48	163	169	171
39 - 42	164	170	172
35 - 38	165	171	172

Chapter 7

Development of Concepts

7.1 Concepts

Chapter 7 discusses and explores the different ideas of the basic design, some of which of them are applied worldwide. These ideas are already used in habitat enhancement or for tourism purposes. Some of the ideas are visualised in sketches and figures throughout this chapter.

7.1.1 Loose rock revetment

The seabed at Borssele wind farm zones 1 and 2 is subject to several loads caused by environmental conditions. Main contributors to the loads on the bed material are summarized below:

- Turbulence is caused by fluctuations in the flow velocity u' over time t. These fluctuations are relative to the mean flow velocity $\bar{u}$ in the dominant current direction. Figure 6.7 in chapter 6) presents the dominant direction(s) of the current in the North Sea (NNE – SSW). The magnitude of the flow velocity follows a logarithmic shape over the height of the water column and the depth is ranging between 14 and 40 m. High turbulence eddies indicate that there is a large flow velocity gradient, which are found near the seabed. Drag and lift forces are initiated by this turbulence.
- On the other hand, waves can have an amplifying effect on the flow velocity. Waves cause an orbital motion of a fluid particle in a water column. This fluid particle has a back-and-forth movement at the seabed and has a maximum flow velocity equal to the amplitude $\hat{u}_b$ ¬of this sinusoidal movement.

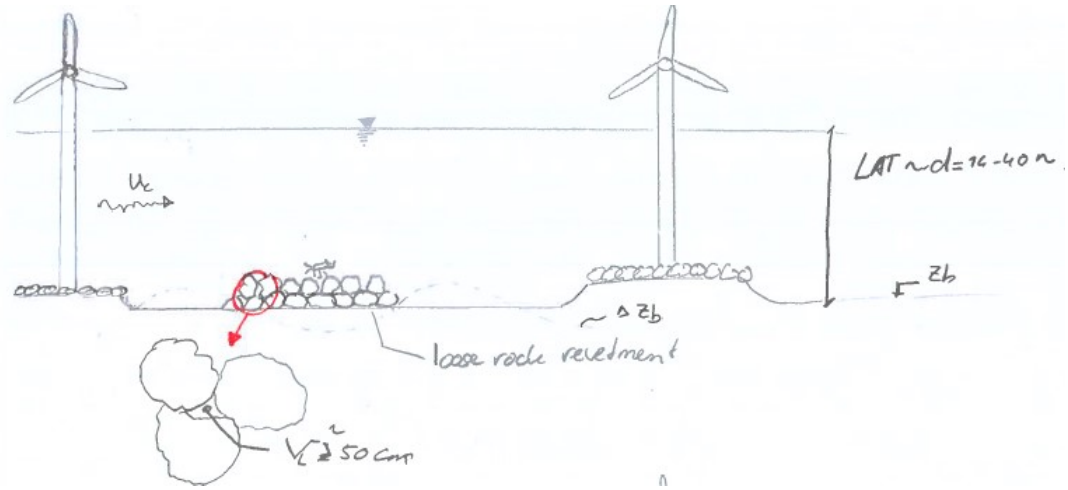


Figure 7.1: Schematisation of the placement of loose rocks.

Based on the previous information, it is clear that protection should be provided for the sea bed. Important parameters for the calculation of the bed protection are: the median grain size parameter, submerged density of the soil (D_{n50}, Δresp.) and the critical flow velocity u_c. The latter parameter depends on the influence of the wave action. $\hat{u}_b$ can have an increasing effect if the wave component is adjacent to the main current component $u_{current}$.

However, the foundations of the wind turbines and the cables are already protected by rock material, so further rock dumping may be not necessary at all.
Dumping rocks increases the roughness k_r and the variability Δz_b of the seabed, thereby improving the habitat for sessile species such as lobsters and crabs. Rocks or stones can be placed in several layers, see figure 7.1, creating openings and voids which are essential for many benthic organisms to use for shelter.

7.1.2 Placed block revetment

A comparable solution is the use of placed block revetment. Placed block revetment are composed of fabricated units (often of concrete or basalt) and can be constructed in a pattern. This solution is often used for protection along banks and shores around the still water level (SWL).

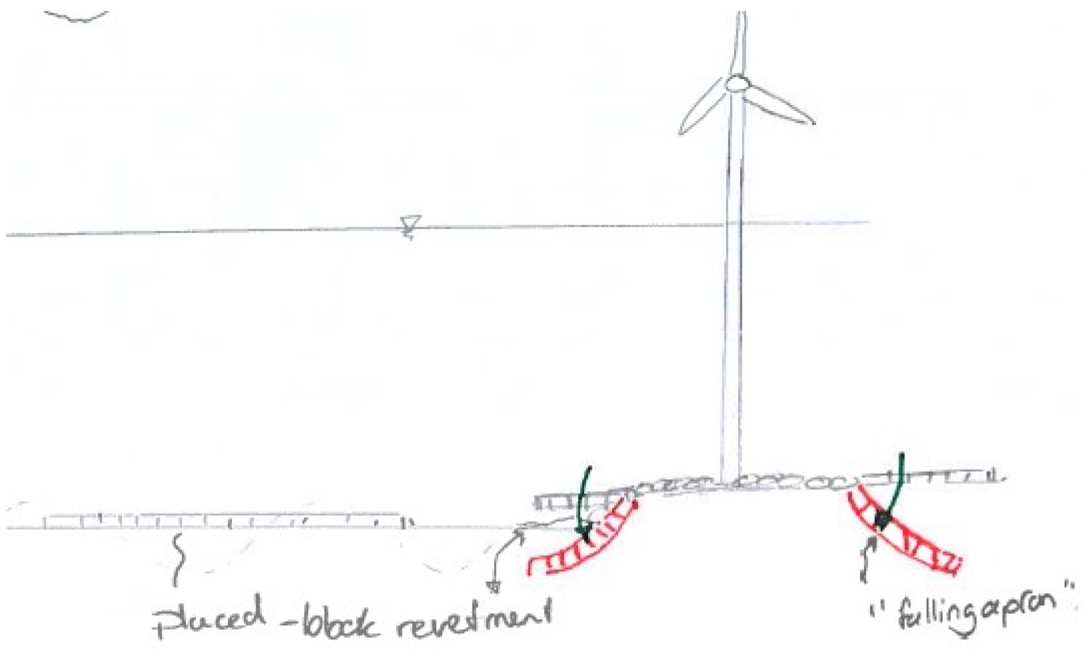


Figure 7.2: Schematisation of the placed block revetment.

The concrete or basalt elements attract microorganisms to their surface, increasing the biofouling and hence the ecological diversity. The placed blocks are interconnected and mostly have equal dimensions. Consequently, the roughness of these structures is less. Additionally, there is almost no space between the units. Hard substrate is added to the environment, but larger organisms like lobsters and crabs can not shelter between the blocks.

7.1.3 Layer cake

Another possible bio-enhancing structure is the layer cake. The layer cake is a concrete structure built up of several flat elements. The elements decrease in width as the height increases (the largest element is at the bottom). A layer cake may typically function as a shelter area for lobster and crab species. Typical dimensions and characteristics of a layer cake are:

- Width: 1.83 m
- Height: 1.16 m
- Weight: 1364 - 1909 kg
- Concrete volume: 0.57 m^3
- Surface area: 12.1 m^2

The structure's large weight makes it extremely resilient to high forces from (tidal) currents. In addition, the used concrete largely consists of limestone, which makes the concrete more compatible with a marine environment. Changes in the height of the layer cake can stimulate the surrounding biodiversity.

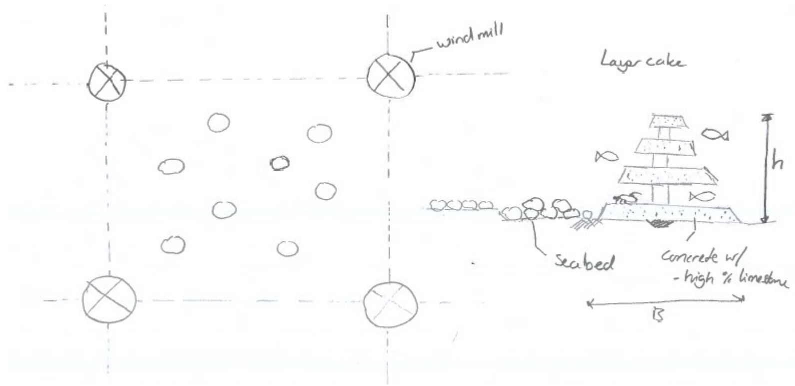


Figure 7.3: Sketch of one layer cake and the possible layout within the wind farm zone.

Figure 7.4: Sketch of one layer cake and the possible layout within the wind farm zone.

7.1.4 Biohut

The Biohut is a rectangular steel structure and consists of an interior fence and an exterior fence. The mesh sizes are 5 x 5 cm and 2.5 x 2.5 cm for the interior and the exterior fence respectively. The inside cage is filled with disinfected and empty oysters including crustaceans and algae.

The Biohut is designed as such that it only allows for small prey fishes or juveniles to enter the volume between the outside and the inside cage. Larger predator fishes cannot get through the outside fence. This increases biological recruitment for the surrounding environment.

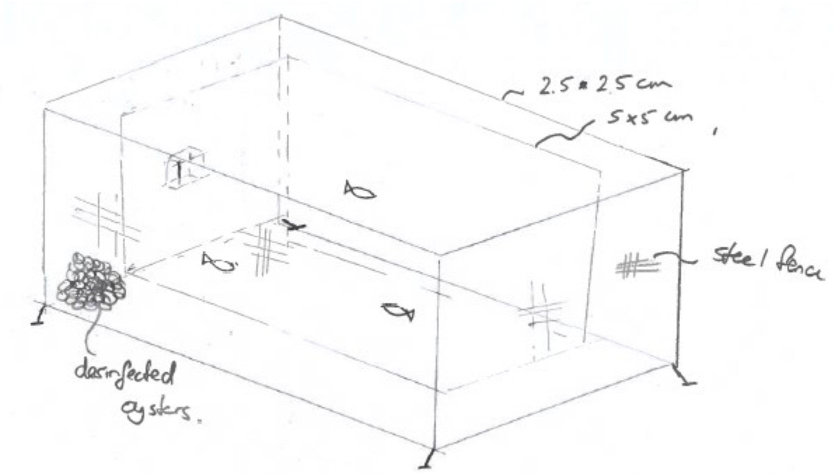


Figure 7.5: Sketch of a Biohut

Stability and rigidity of the structure can be ensured by stacking multiple Biohut units on top of each other or by arranging them next to each other. Anchoring the units might improve the stability as well.

7.1.5 Block reefs

Block reefs are artificial reefs that are built up from modular elements. These modular elements may be:

- Cinder blocks (concrete masonry blocks)
- Larger hollow cubical concrete units (often fabricated in standard dimensions)

Figure 7.6: Hollow cinder blocks applied in a marine environment.

Advantageously different structural shapes and dimensions can be created with these relatively cheap concrete elements. Moreover, a relatively large fouling surface area can be achieved. This makes the block reef unit a suitable and accessible bio-enhancing structure. Predators can also use this shelter area for ambushing prey. For this concept it can be more sustainable to use concrete with limestone as a principal ingredient, as it is applied in a marine environment.

7.1.6 Layered pipes

Pipes are also practically applicable bio-enhancing structures and are suitable for stacking or bundling. Pipes can possibly be fabricated in polyvinylchloride (PVC) and concrete. The option made of PVC is preferably bundled together, since it has a relatively small specific weight and thus an ability to easily float in the water.

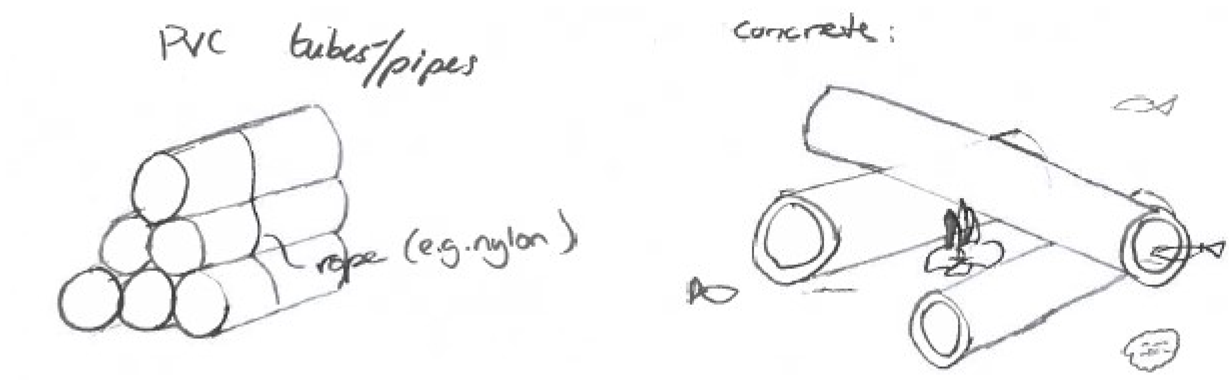


Figure 7.7: Pipes stacked on the seabed

The pipe material is relatively cheap and is easily obtained. Eggs can be protected against sunlight since the pipes can provide sufficient sheltering areas. These pipes may additionally function as potential spawning sites.

7.1.7 Shipwrecks

Three shipwrecks have previously been identified within the Borssele Wind Farm area, one of which is located in Borssele 1 or 2 according to [RVO, 2016, p.24]. These recorded shipwrecks are mentioned as obstructions in earlier reports. However, there are possibilities of reusing shipwrecks as hard substrate. Hard substrate attracts microorganisms that consequently stimulate the development of artificial habitat.

Several sources have been found regarding shipwreck data:

- The Belgian North Sea for instance (an area which is close to Borssele 1+2) contains an average amount of four shipwrecks with distances of 54, 31.5, 14.8 and 7.4 km from the coastline. An outstrip biomass of 628 g AFDW[1]/m^2 on hard substrate relative to 7.4 g/m^2 on soft sediment is found at all shipwreck locations [V. Zintzen, 2006b].

- One other source is the research conducted at the FINO1 research platform. This platform is located in the German Bight (German part of the North Sea). An area of 1280 m^2 hard substrate of shipwreck material is submerged to a water depth of 28 m. As a result, 3479 g/m^2 of biomass developed over 3 years between 2005 and 2007 [R. Krone, 2013].

[1] Ash Free Dry Weight, this is approximately 10% of the Fresh Weight (FW), also Wet Weight (WW).

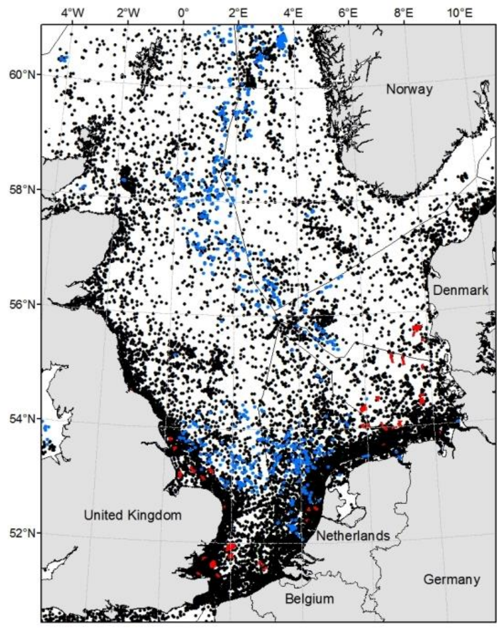


Figure 7.8: Overview of the North Sea indicating shipwrecks with black dots, oil or gas platforms with blue dots and wind farms with red dots [J. Coolen, 2018].

There are plenty of sources available that support the idea that shipwrecks improve marine habitats. Figure 7.8 presents the identified shipwrecks in the North Sea. An option is to deploy existing wrecks from other EEZ-locations to Borssele 1+2. A feasibility research has to be conducted to determine whether it is possible to transport shipwrecks to the project site.

7.1.8 Decommissioned oil or gas platforms

Fossil fuel types are running out and many countries are beginning to turn to renewable energy resources. Therefore, thousands of offshore oil and gas platforms will be decomissioned in the coming decades. Research demonstrates that offshore infrastructure, in particular offshore platforms, are capable of providing reef habitat and thereby the recruitment of overfished or threatened species [A.M. Fowler, 2018].

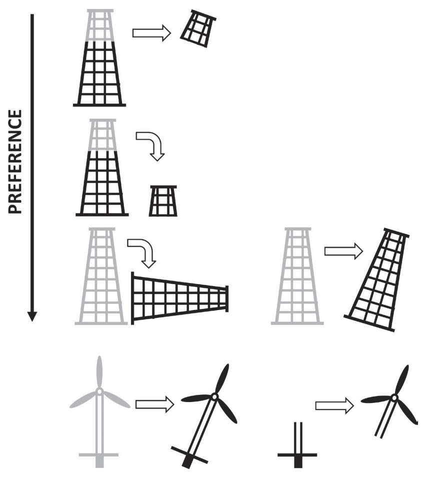


Figure 7.9: Decommissioning options for offshore infrastructure in order of decreasing preference according to surveys of several researchers [A.M. Fowler, 2018, p.5].

The deployment of decommissioned offshore infrastructure or artificial reef construction in the sea will benefit the marine environment. However, it is important that these structures are safe in terms of their chemical composition. Modules of the recycled structures need to be free from toxic or harmful compounds. Figure 7.9 shows that, due to the preferred vertical relief, most researchers would rather choose for partial removal and partial relocation to the shore [A.M. Fowler, 2018, p.5]. Initially, the morphological impact and the required fastening needs to be assessed. The surface of hard substrate that can be provided is large. On the other hand, the size and weight of offshore platforms require some complex engineering processes and heavy lifting operations. One disadvantage is the draught limitation for inspection and maintenance vessels within the wind farm.

7.1.9 Hang cultures

Different conceptual solutions are available for the ranching of seaweed, mussels and oysters. One well-known solution is the application or the fastening (in combination with other solutions) of hang cultures, such as long lines. The lines or nets can be fastened to a floating buoy, but anchoring to the seabed or an existing ocean structure is possible as well [R. Stone, 1991a]. The application of such hang cultures has positive environmental impacts such as [J.H. Reith, 2005]:

- The uptake of redundant macroalgae and nutrients (reducing eutrophication).
- Offering substrate for attachment of shelter and food for fish and benthic organisms.

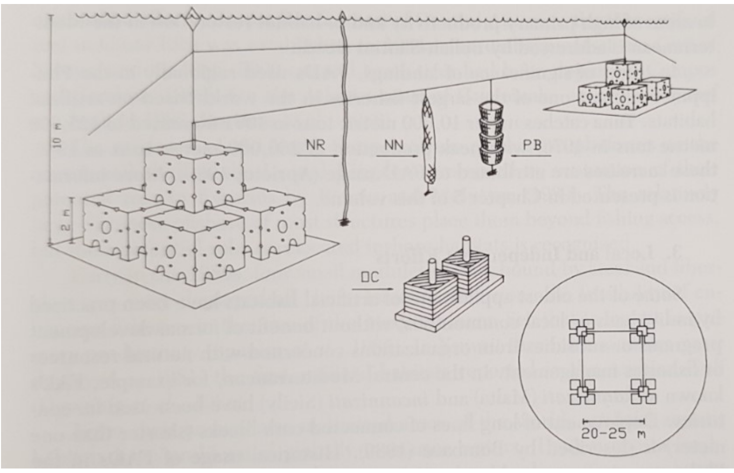


Figure 7.10: Longline solutions with nylon ropes/nets detached or attached to submerged bodies [R. Stone, 1991a]

The following loads have to be considered here:

- Loads induced by vessel-induced currents
- Loads induced by wave motion
- Tidal oscillation (change from LAT to HAT and back around)
- Loads induced by (tidal) horizontal currents

The average water depth at Borssele 1+2 is approximately 29 meters and likely has an effect on the type of species present. While this is relatively speaking a more shallow depth than perhaps other sites, greater depths also increase exposure to drag loads induced by currents. An equilibrium has to be sought for between the cable diameter, cable length and the load component induced by the currents.

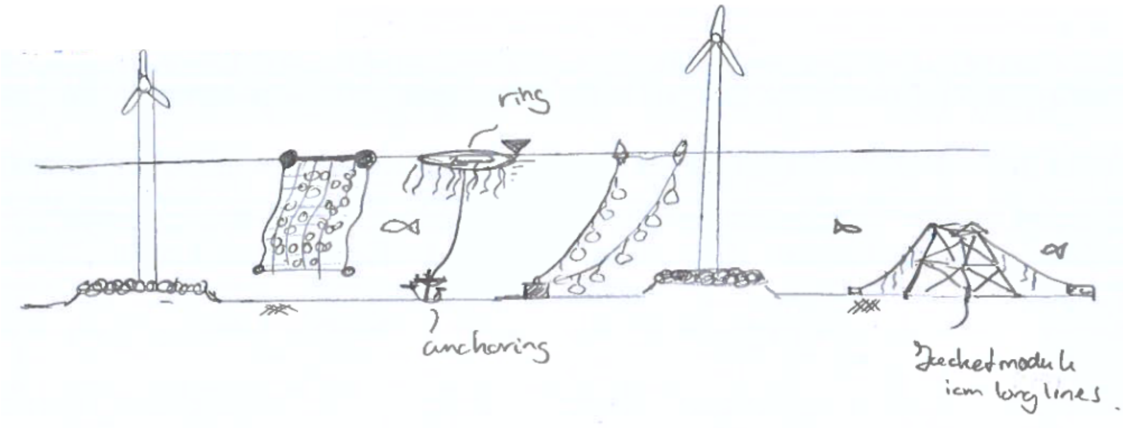


Figure 7.11: Different configurations of hang cultures with the use of cables e.g.

7.2 Conclusion

In short, different design concepts can be conceived for a bio-enhanced artificial reef system in an OWF. It is important to realize that different design concepts will attract different species according to the bio-enhancing structures chosen.
However, some of the design concepts are only applied in freshwater and have not been attempted in a marine habitat [R. Stone, 1991b]. Therefore, some of the concepts might be less attractive in a marine environment, which is subjected to severe nautical conditions, for instance, wave heights up to H = 7.5 m. The next chapter examines the possibility of applying these concepts in more detail.

Chapter 8

Verification of Concepts

Concepts that are developed should be verified on whether they are operable and meet the requirements for sustainable bio-enhanced fisheries. These requirements are assisted by the physical (P) and legal (L)[1] boundary conditions. Following chapter 7, less concepts are considered in more detail. Placed block revetments for instance are considered to be more expensive, difficultly feasible and less attractive for sheltering species when it is compared with loose rock revetment and is therefore disregarded. Further consideration of the different possible solutions is given in this chapter. Eventually, realistic (combination of) solutions are provided in the last section of this chapter.

8.1 Realistic alternatives

8.1.1 Loose rock revetment

One potential solution is the construction of loose rock revetment on the seabed of Borssele I+II. This alternative can be seen as an attractive solution since it is providing hard substrate. It has clearly been mentioned in chapter 5 that a/any kind of hard substrate increases the biological diversity. Loose rock revetment is used for bed, bank and shore protections, especially in the surrounding of structures [Gerrit J. Schiereck, 2016c, p.275].

A seagoing rock dumping vessel is able to construct the loose rock revetment. Appendix D gives an operational requirement which underlies the living environment of the European Lobster. Recall that juvenile and adult lobsters require crevice sizes of 0.11 m.
Given almost perfectly round-shaped rocks, [Gerrit J. Schiereck, 2016c, p.131] describes that a rock of diameter 0.15D just fits the space between the packed rocks with diameter D (see figure 7.1). Given this all, one can determine the required stone size of the loose rock revetment.

However, stones are not perfectly spherical and densely packed and the calculated stone size can hardly be executed with the contemporary fall pipe vessel. In addition, stones cannot be ordered by a specific diameter, but they are classified in standard ranges as defined in [Gerrit J. Schiereck, 2016c, p.360]. Furthermore, the stones have to be tested on their mobility and with that it is preferred that the stones do not move. Their mobility depends on the driving force and the stabilizing force of a particle. The Shields or Izbash types of formulae are well-known and are therefore used. Particle mobility is highly influenced by the following phenomena:

1. The bed shear velocity which depends on the bed roughness c_f and the cross-section averaged flow velocity.

[1]Letters are used to distinguish between the types of requirements and boundary conditions as presented in appendix D.

2. The velocity amplitude $\hat{u}_b$ on the seabed which is initiated by the orbital motion induced by the (significant) wave action at the water surface level.

The calculation of hard substrate is done in chapter 8.

8.1.2 Biohut

This solution provides juveniles and other sea creatures the possibility to shelter from predator species and feed themselves. The Biohut has an approximate volume of 0.1 m^3. The cage dimensions is derived from this given:

$$V = 0.1m^3 = 0.5 \cdot 0.5 \cdot 0.4m$$

The exterior mesh size of this substrate is 2.5 x 2.5 cm while the interior mesh size is 5 x 5 cm. Additionally, disinfected oyster- and mussle shells are added to the interior cage.

Hence the Biohut may be susceptible to the following cases:

- overturning
- horizontal sliding
  - soil - structure interaction
  - structure - structure interaction
- scour
- its submerged stacked weight
  - deviation in its deflection

To overcome salty marine conditions one assumed the steel to be galvanized. Hence, one can base the stability calculations on steel properties. The following properties hold for the Biohut structure:

Table 8.1: The (material) properties of the Biohut considering one cage unit

Characteristics	Unit	Value
Specific weight steel	kN/m_3	78
Specific weight disinfected shells	kN/m_3	8
Steel surface exposed to current	m_2	0.32
Steel surface bottom/roof	m_2	0.1
Steel bar diameter	m	0.005
Steel - steel dry friction	-	0.4
Steel - soil dry friction	-	0.4

One assumes the exterior steel fence to make up of 40% of the total exterior surface area. The total bottom and roof surface area of one unit is 0.5 x 0.5 m and the total side surface area is 4 $\cdot$ (0.4 x 0.5 m). Given the assumption of the steel bar diameter to be a half centimeter, one is able to derive the submerged weight and the loads. The significant depth averaged flow velocity is used for determining the drag forces on one object.

The stability of the Biohut is verified in Appendix G through calculations. As appeared in the calculations, several Biohut units are needed to provide stability against overturning and horizontal sliding. This latter makes the option of the Biohut a less effective and a less practical solution in a deep sea environment.

8.1.3 Pipes on the seabed

Many pipes, especially those that are due or in excess, are turned into rubble. However, these pipes can have a large biological value when they are used for artificial reef fisheries. Pipes can provide shelter for fishes and can protect their eggs against sunlight because of their stretched shape. It has to be checked whether the stability of the pipes and the safety of the existing infrastructure is guaranteed in the Borssele wind farm environment. This section addresses the pipes that are made of concrete or PVC.

Table 8.2 provides some estimations and assumptions that are made about the mass and dimensions of the pipes.

Table 8.2: Assumptions for material properties

Materials	Unit	Concrete	PVC
Material density	kg/m^3	2400	1450
Outside diameter	m	0.546	0.400
Inside diameter	m	0.400	0.3842
Mass[2]	260	182.1	kg/m

Based on the material properties of pipes, one can conclude the following:

- Both types are submersible due to their sufficiently large mass per unit
- Both types are heavy as such that they withstand the loads that are induced by currents of flow and wave action
- Accretion of soil and scour development at pipes is expected and not considered in detail.

Differentiation in the deflection of the pipe on the subsoil might cause stresses in the pipe material. Bending stresses due to discontinuous deflection cause tensile forces at the upper side of the pipe.

An applicable composition of concrete in this salty marine environment consists of a high amount of limestone. Traditionally Portland cement, with a higher grade of clinker, is used for concrete elements. Clinker is limestone and clay burned at 1500°C and is composed of the following minerals:

- tricalcium silicate as Ca_3SiO_5 (3CaO + SiO_2)
- dicalcium silicate as Ca_2SiO_4 (2CaO + SiO_2)
- tricalcium aluminate $Ca_3Al_2O_6$ (3CaO + Al_2O_3)
- tetracalcium aluminoferrite $Ca_4Al_2Fe_2O_{10}$ (4CaO + Al_2O_3 + Fe_2O_3)

Newly fabricated PVC pipes are less environmental-friendly material, since these are produced with fossil fuels. The same holds for pipes that are made from traditionally concrete mixed material. Concrete pipes on the other hand, are less attractive than block reefs. Block reefs can hit more target species than cylinder pipes because of their complexity in terms of squares and holes..

8.1.4 Hang cultures

Hang cultures are, as earlier mentioned, systems where flexible rope-kind materials are used to create biodiversity. Hang cultures are fastened at statically rigid objects. Examples of hang cultures are:

1. Long lines attached to monopile foundations
2. O-rings (hoop-kind of configurations) attached to a floating- or detached body

3. Lines that are attached to floating objects such as buoys
4. Lines anchored to the seabed and attached to a detached object.

These systems are vulnerable to severe, dynamic North Sea conditions. Large waves and high deviations in bed level (sand waves) are expected inside the area. Because of the possibly larger oscillations and motions of the line, only smaller organisms tend to attach themselves to the hang culture. However, ranching of seaweed and molluscs is possible by considering part of the solutions to be applicable.

Wind farm owners are often less enthousiastic about objects such as long lines to be attached to the monopiles. Item 2 is considered as space consuming and can therefore be obstructive for fishing ships during their fishing tours. Item 4 is possible when it is applied in combination with a reinstalled decommissioning offshore platform or a shipwreck, but this is difficult to execute. Hence, only the third item will be considered in more detail.

Fabricated polyamide such as nylon, has a high marine durability and strength and is commonly used in the maritime industry for mooring lines. Suppose that nylon is applied for the hang cultures, then the following characteristics apply:

Table 8.3: Cable characteristics

	Symbol	Unit	Value
Diameter	d	m	0.05
Length	l	m	14 - 40
Specific density	ρ_n	kg/m^3	1150

A schematisation is made to elaborate on the technical feasibility of the most appropriate configuration:

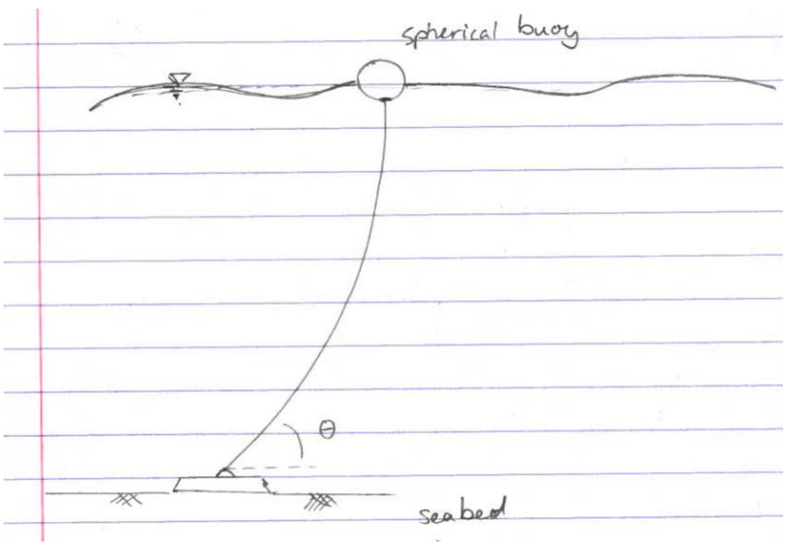


Figure 8.1: Schematisation of a Nylon 6 cable, anchored with a concrete block on the seabed and attached on a moored subsurface buoy.

The calculation of this cable configuration is added in Appendix H.

As appears the tensile stress does not exceed the tensile strength of Nylon 6 $\sigma_n = 75N/mm^2$ [WSV Kunststoffen, 2019].Hence, the application of nylon in these types of hang cultures should be resilient to static loads.

Cables do not take bending, the hang culture will therefore not be checked on bending moment capacity. Wave action causes cyclic motion in the water body and the latter causes drowsiness. This cyclic loading causes fatigue of the cable, especially at its attachment points. To account for this fatigue, one can use the following measures during the structure's lifetime [Gerrit J. Schiereck, 2016c, ch.10]:

- Failure-based maintenance: Where no action is taken until a structure, or part of it, fails. This can be an efficient maintenance since the complete lifespan is used.

- Time-based maintenance: an elaborate study on fatigue responses of the offshore hang cultures is necessary to determine the required time intervals for performing maintenance. Deterioration of these elements is hard to predict.

- One can change the natural frequency (frequency value at which the cable starts heavily vibrating) in a positive way by reducing stiffness (k) at the attachment points or by increasing the mass (m) of the cable element. One is able to recall that the natural frequency ω_0 is expressed by:

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{8.1}$$

- Acceptance of (partly) damage or failure induce by loads and/or use on/of the hang cultures.

On the other side, supervision and maintenance of these hang cultures is a profession in it self. This solution becomes therefore questionable when its efficiency is compared with the other alternatives in this chapter.

8.1.5 Reusing structures

Decommissioned offshore platforms

Most oil or gas platforms have a design life of typically 10 to 25 years [R.E. Randall, 1997, p.51]. Several offshore platforms are currently decommissioning or become due in the next decade (2020 - 2030), figure 8.2 shows the potential offshore structures for reuse. Distinctions are made here, see the legend in table 8.4:

Table 8.4: Legend decommissioning oil/gas platforms in the North Sea, this figure is provided by the interviewee (see K)

Type of work	Marker color
Ongoing decommissioning	Orange
Planned decommissioning	Green
Future decommissioning	Blue
Late life platform	Red
Late life platform partly decommissioning	Yellow
Decommissioned	Black

Figure 8.2: Decommissioning platforms in the Southern North Sea

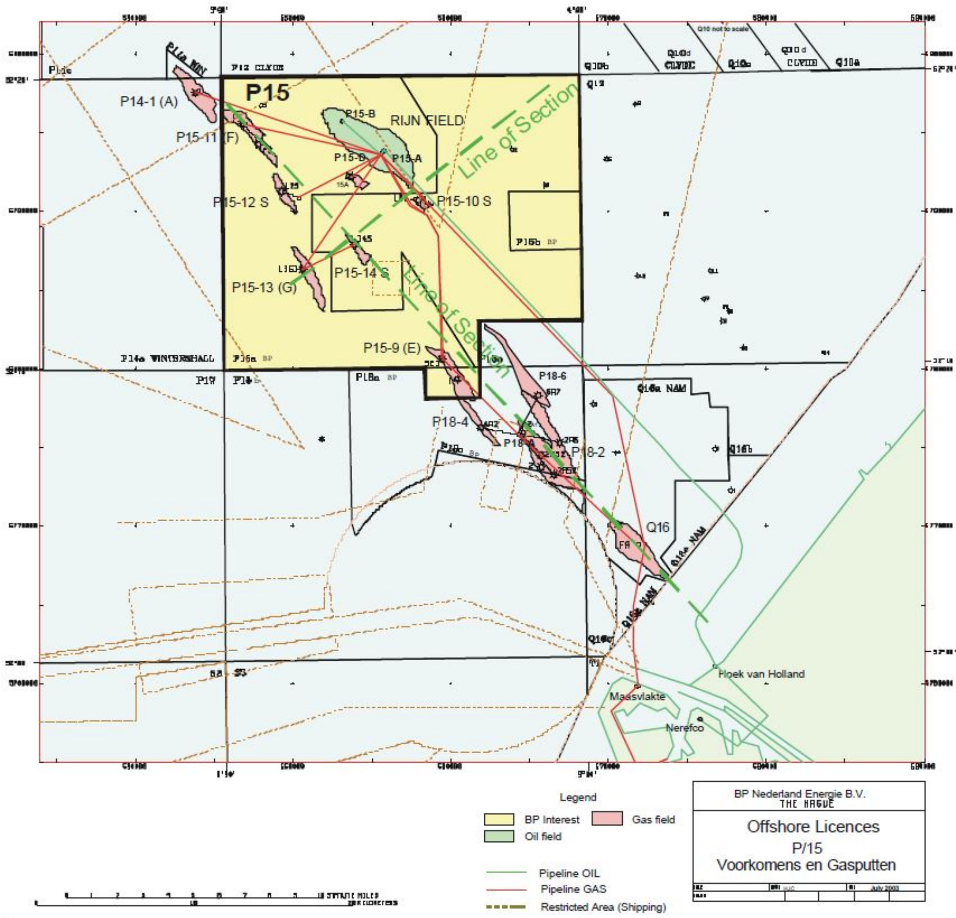


Figure 8.3: Map of current oil and gas fields at 40 km from the Dutch coast [BP Nederland Energie B.V., 2007]

The green markers highlight the offshore platforms with an identified planning for decommissioning or supporting preparation activity with a clear decommissioning trajectory, possibly including: required pre-activities, plans/notices, surveys, environmental impact assessments and so on. The red markers identify the offshore platforms at the end of their design life and unlikely to be substantially (re-)developed, the yellow markers highlight the late life offshore platforms under partly decommissioning, that is to say that a part of the oil or gas platform will still be active for supply as is stated in the interview in appendix K.

Moving marine life from the Northern part to the Southern part of the North Sea is conflicting with the environment (see appendix K) and is therefore prohibited by law. Figures 8.2 and 8.3 present the offshore structures that can potentially be used for the deployment on the seabed for improving the marine life.

A decommissioning procedure of platform P15-9(E) fits best for this project in terms of logistics, since it stands the closest-by (approximately 70 km). The foundation of the offshore gas platform is fixed as a jacketed structure and the top side is relatively clean compared to an oil rig. As can be seen in figure 8.3, P15-9(E) is has been put on the planning for decommissioning.

Another important aspect is the top side of the offshore platform. A top side consists of [R.E. Randall, 1997, p.51]:

- Drilling equipment
- Production equipment
- Crew quarters and eating facilities
- Gas flare stacks
- Revolving cranes
- Survival craft
- Helicopter pad

Platforms and especially older ones have a polluted top side. Cleaning the top side is not very complicated, the lead in the lead paint, mercury in the steel, asbestos and radioactive materials in the top side elements can contaminate the environment and its fauna, the concentrations and the environmental impact are difficult to quantify as is stated in appendix K. Top side elements are therefore not being made to be placed below the water line.

For the lowest environmental impact, the deployment of the steel frame is preferred over the top side element (see boundary condition L.1. in appendix D). Offshore structures from after 1989 contain less traces of asbestos (see appendix K).

Method

Installation, removal or transport of offshore structures requires heavy equipment. However, this method description is partly based on assumption and the experience from professionals being interviewed. These professionals are employed by a big offshore contractor named Seaway Heavy Lifting. Estimates and assumptions are based on experience from previous offshore removal projects in the North Sea such as "ST1". The procedure of the deployment of decommissioning offshore platforms for artificial

reefs can be achieved by the following steps:

1. Dredging around the platform foundation
2. Cutting the jacketed structure

3. Uplifting
4. Putting away

Step 1 has to be executed with an airlift tool or suction dredge because of the soft sandy/muddy soil on the seabed within the Borssele Wind Farm. When dredging the sand around the jacket foundation, geotechnical stability is one big issue, as sand particles tend to roll back in the hole. The jacketed structure consists of hollow tubular steel members with X- and K-joints and X and K braced members [Technical Committee CEN/TC250, 2018, p.2]. Forces are present at each end of the members, there is no perpendicular force acting vertically on the horizontal member.

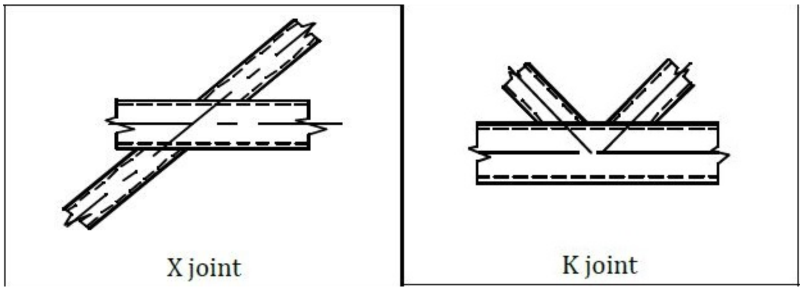


Figure 8.4: Typical configurations of tubular joints and braced members in jacketed structures [Technical Committee CEN/TC250, 2018].

Diamond wire and burners are often-used tools for cutting the jacket structure (2). Construction technically, jacket foundations are cut at 3 to 4 meter below the seabed, remaining clay can be removed with a cutter dredge and redundant sand is removable with an airlift tool. Skirt piles and main piles are sometimes filled with grout, these piles need to be cut through from the outside. Uplifting is executed with crane vessels. Depending on the structure's geometry, one is able to choose a crane vessel with sufficient capacity. For example, given the following crane vessels [Seaway Heavy Lifting, 2019]:

- Seaway Yudin with a maximum revolving capacity of 2500 tonnes.
- Seaway Strashnov with a maximum revolving capacity of 5000 tonnes at 32 m height.

A Strashnov vessel is able to lift 200-400t a day, this working rate is based on the removal project of the "ST1"-platform done by Seaway Heavy Lifing. A steel jacket frame of 4000t can be uplifted and removed within 14 days. A Strashnov vessel is larger then a Yudin vessel (A Yudin crane vessel can store <5000t on its deck) and should be able to store the platform modules. The jacket elements can be transported on the crane vessel or on a separate barge. On the other hand, crane vessels of Seaway Heavy Lifting are able to reach a sailing velocity of 14 knots (29 m/s) while loaded. The advantage of a separate barge is the additional working area on the deck of the crane vessel for cutting the jacketed frame into smaller elements. The day rate of a vessel requires however a lot of expenditures, so the latter option should be weighed against cutting the structural element onshore. Important issues have to be taken into account before and during the offshore operations:

- Before:
  - Surveying the impact of corroding materials on the environment and the stability during the operation.
  - Deteriorated welds due to fatigue or hydrogen cracking[3].
  - The mass and the centre of gravity of the structure are often not exactly known and should be encountered before the start of the operations.

[3]A weld's loss of load bearing capacity and loss of ductility due to crack generation. These cracks are due to the absorption of hydrogen atoms or molecules in the metal.

- During:
  - Workability is more efficient below a significant wave height $H_s = 2.5$ m. But this does also depend on the wave frequency which is determined by the deep sea wave period T_{op}.
  - Vessels are more efficient during the warmer months between April and September with a workability of 70%, than during the colder months between October and March (workability is approximately 30%).

While deploying the jacket structures, one should consider the maximum draught of sailing vessels inside the wind farm area. Only fishing vessels (D $\approx$ 1.5 m) and service boats with a service draught of 2.8 m may sail within the wind mill grid [World Marine Offshore, 2019]. So the jackets should be placed at least 2.8 + 1.5 = 4.3 m (taking into account trim and squat) below the water surface level at low astronomical tide (18 m water depth). The latter does automatically meet the boundary conditions L.4 and L.5. as stated in appendix D.

Shipwrecks

Multibeam- and echosounder surveys have revealed three shipwrecks to be present inside the Borssele Wind Farm area from which one is within Borssele I+II. Alternatively, deprecated vessels can be sunk to increase the amount of hard substrate on the seabed. The vertical relief of a shipwreck produces an interruption of the bottom currents and creates vortex currents, which may attract certain species (see requirements O.7 - O.13, O.18 in appendix D). Besides, these eddy generators cause low frequency vibrations, which may act as a stimuli for fish lateral line systems, a fish's sense that is used for its movement. Discarded vessels or smaller scrap material can be transported and handled in the same way by the crane vessels as previously mentioned (see interview in appendix K).

Figure 8.5: A heavy lifting vessel [Scaldis Salvage Marine contractors NV, 2019]

However, shipwrecks are commonly contaminated structures, they contain traces of: asbestos, lead, fuel and oil products, PCB's. On the other hand, the procedure of submersing vessel parts disturbs the environment due to the sound emissions. Environmental groups such as Greenpeace are therefore resilient against the solution of sinking shipwrecks to the seabed (see appendix K). This solution is therefore not attractive for an elaborated design (see requirement O.2. in app. D).

8.2 Composition of alternatives

Based on all the information, it is possible to make some preliminary designs. Three designs will be considered in this report. It is difficult to make exact designs of how the area will look like over the entire Borssele I and II area. However, it is possible to determine which kinds of structures should be where. For the designs, four different types of structures are considered: stones, block reefs (concrete hollow blocks), layer cakes and ships/jackets. Based on the properties of each type it is possible to

classify them based on the most important environmental and financial conditions, such as: depth, availability, cost and biological benefit. Stones are available in a large range of sizes, while block reef sizes are limited in commercial availability. Ships and jackets are huge structures which might hinder commercial sailing. Layer cakes are relatively massive compared to stones, however costly to produce. Based on this information it is possible to make a classification, shown in table 8.5. Based on this table, three design concepts have been derived.

Table 8.5: Assessment of the alternatives per item

	Stones	Block reefs	Layer cakes	Ships/jackets
Shallower water	+	-	++	−
Deeper water	+	+	++	+
Availability	++	++	+/-	-
Cost	++	++	−	−
Biological benefit	+	++	++	++

Design concept 1

The first design is the most simple one, that is to dump stones at every necessary location. This space is shared with empty sandy areas, which are also required for biological purposes. Also, one ship or jacket and a patch of 10 layer cakes will be placed in every necessary 1 km^2.

Design concept 2

The second design is similar to the first one. In this preliminary design, block reefs will be dumped everywhere. The block reefs are essentially just dumped Concrete Masonry Units (CMU) or in other words, hollow concrete blocks (see figure 8.6). Also here, the space is shared with empty sandy areas, which are required for biological purposes. One ship or jacket and a patch of 10 layer cakes will be placed in every necessary 1 km^2 similar to preliminary design 1. CMU's are preferred over stones because the hollow parts in the concrete grants more shelter for marine life. In other words, it's a friendlier structure to marine life than stones.

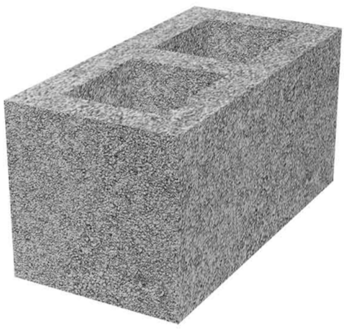


Figure 8.6: Concrete masonry unit (CMU) or block reef element

Design concept 3

The third design will generate the most diversity on a biological level. Stones will cover the shallower parts of the area, while block reefs cover the deeper parts, with sand areas in between. Also, a ship/jacket and a patch of 10 layer cakes will be placed in every necessary 1 km^2.

The seabed is dynamic, therefore it is necessary to define which parts of the seabed is usable and which parts are not. Areas that will be covered in sand in the future are considered unusable. Practically, the artificial reef must survive its entire planned lifetime, which is in the order of 25 years. This means that the total area which will be covered in sand within the next 25 years is unusable (considering requirement F.2.). The migration speed of sand waves differs in each wave. However, one significant value is used in order to simplify the calculation process. In the Borssele wind farm area, the migration speed of a sand wave with a 90 % non-exceedance rate is equal to 1.9 m/year, meaning that only 10 % of sand waves will migrate faster than this rate [R. Hasselaar, 2015]. The distance such a wave would cover in its lifetime would be 47.5 meters, this value will be considered as a design value in this project. It is therefore assumed in the calculations that each sand wave will travel this distance in its lifetime.

When analysing the wave asymmetry from the obtained dataset, one finds that the mean asymmetry of all waves combined is -0.045, which is close to zero. In fact, the negative sign shows that the lee side of the wave covers overall more area than the stoss side. According to the dataset, almost no waves are truly symmetric. Since we are interested in total usable area, the mean value will be used to cover the total Borssele 1 and 2 area.

Since the average wave is close to symmetrical, it is assumed that the wave is a triangle. This is a big oversimplification. The reason it is assumed as a triangle is because it makes performing calculations a lot easier when it comes to defining usable areas. Given all this information, the migration of a sand wave is modelled according to figure 8.7. The usable part of the sand wave is also clearly shown in the same figure.

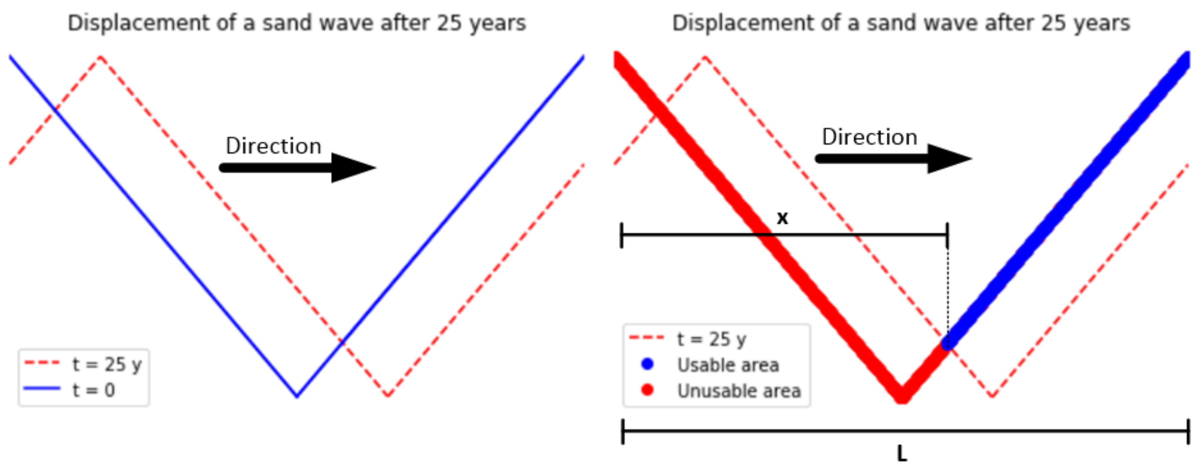


Figure 8.7: Migration of a sand wave (left) and usable area (right)

According to figure 8.7, the usable area is defined as *L-x*. However, a space of 10 m between the shallowest strip and the sand wave crest is reserved as a safety measure, to prevent hard substrate falling into the lee side. Relative to the sand wave length, this value becomes then becomes:

$$RWL = \frac{L - x - 10}{L} \tag{8.2}$$

In which RWL stands for the Relative Working Length, which is a percentage of the sand wave on which it is possible to place constructions without being submerged by the sand wave in its lifetime. The mean of this value over all data points is taken as a universal percentage over the whole area. Which means that the mean RWL is equal to the percentage of the Borssele I and II area which is accessible for construction. This value turns out to be approximately 32.2 %. The total area of Borssele I and II combined is 112.6 km^2, the total usable area is therefore 36.2 km^2. Hard substrate should cover around 5 % of the total area (D), which is around 5.6 km^2, or about 15.5 % of the usable area. This number is the fundamental basis of design, because it determines how much hard substrate should be placed. Placing strips of 8 m wide every 52 m is approximately 15.5 %, therefore it should suffice. The concept designs should have the following lay-out as illustrated in figure 8.8. A random patch of 2 by 2 km is selected in Borssele II, but the layout applies everywhere. The positions of the mono-piles are not exact positions, it merely represents an example of how the project should look like.

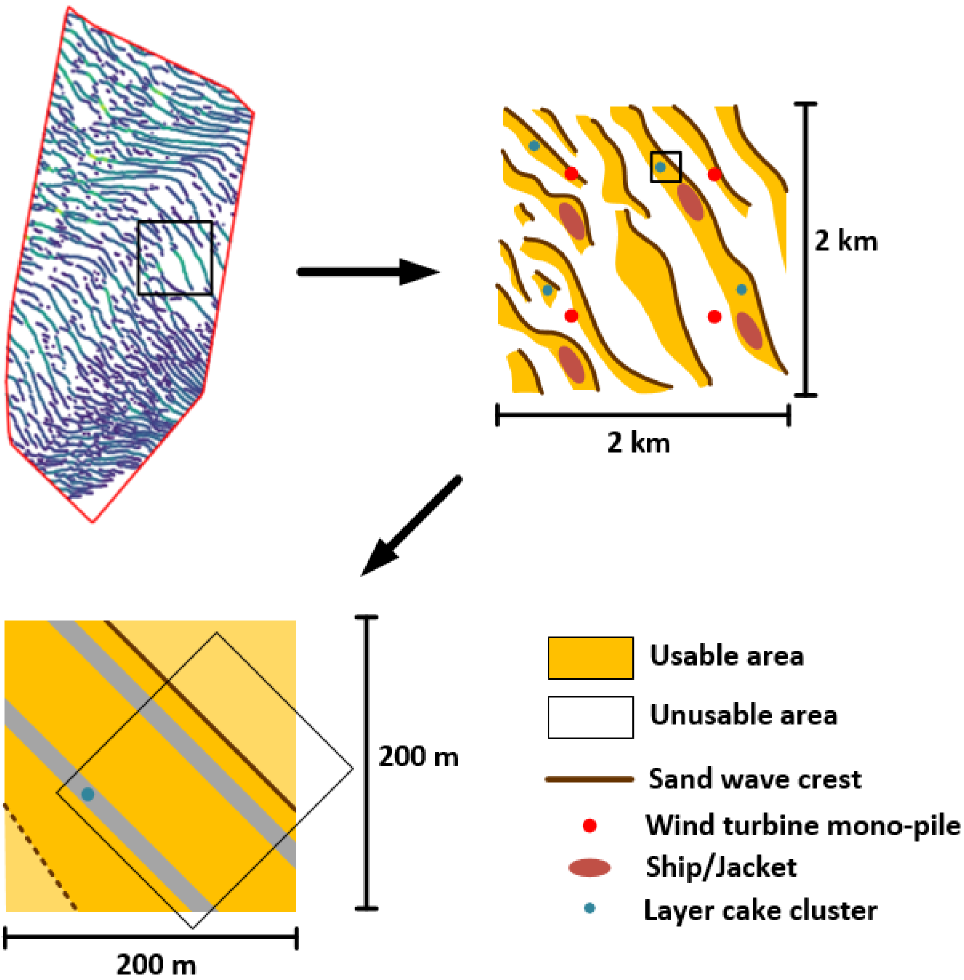


Figure 8.8: A crude design of the lay-out

The next figures show the dimensions in further detail. Strips of 8 m wide are applied every 52 m, so there is a distance of 44 m between each strip of hard substrate.

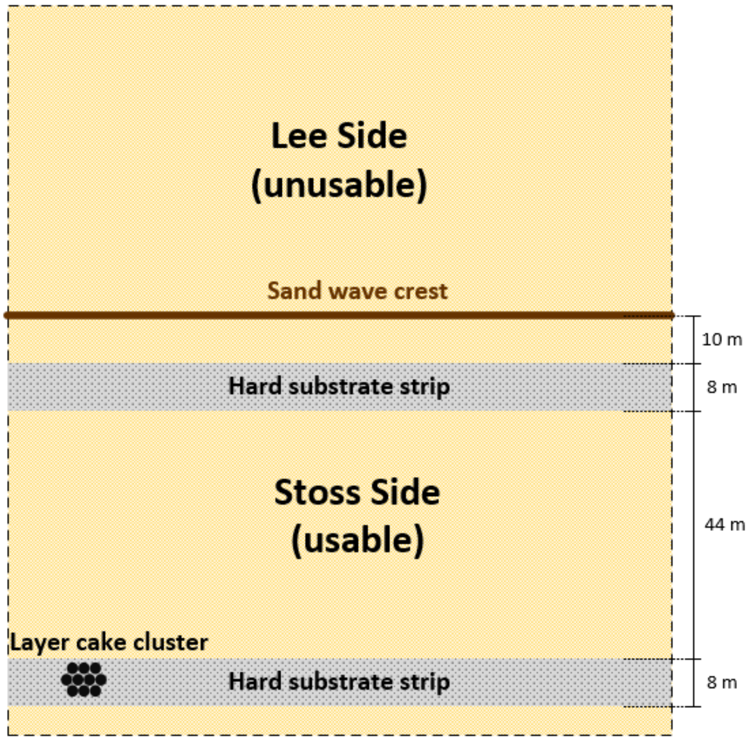


Figure 8.9: Top view

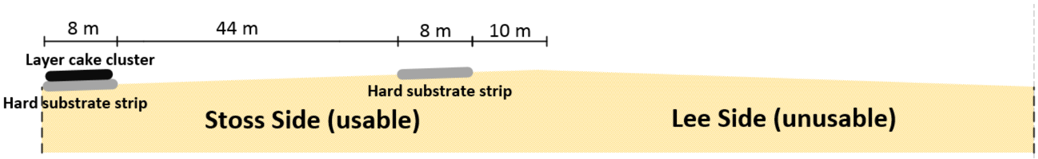


Figure 8.10: Side view

Side views of strip elements are shown in figures 8.11 until 8.13. A filter layer is applied when dumping stones, block reefs or layer cakes, in order to prevent sand to escape which causes the elements to sink into the sand.

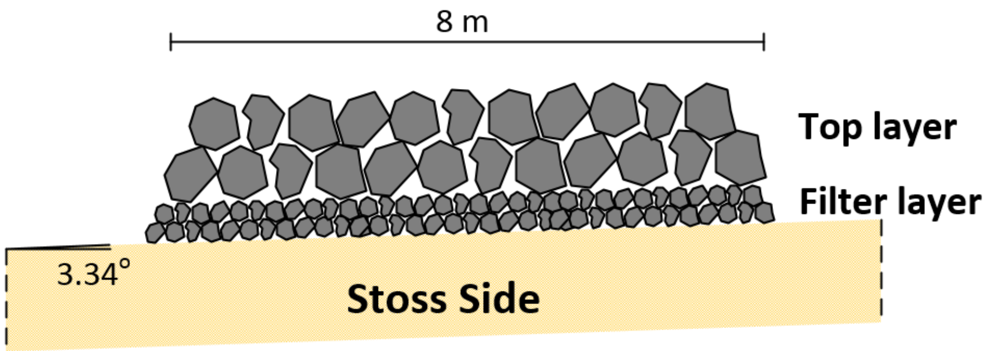


Figure 8.11: Side view of a stone strip

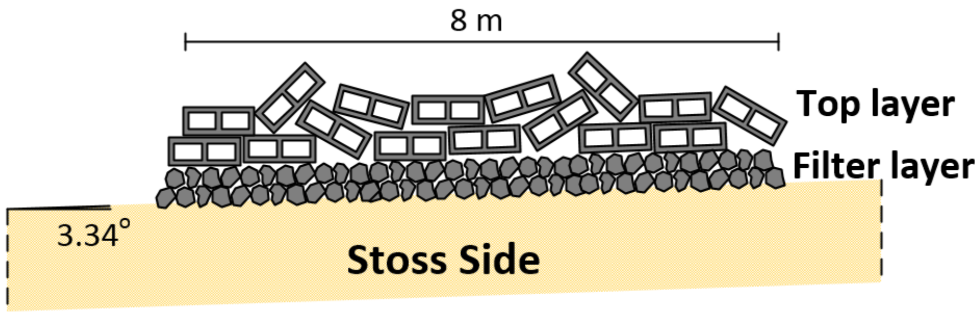


Figure 8.12: Side view of a block reef/CMU strip

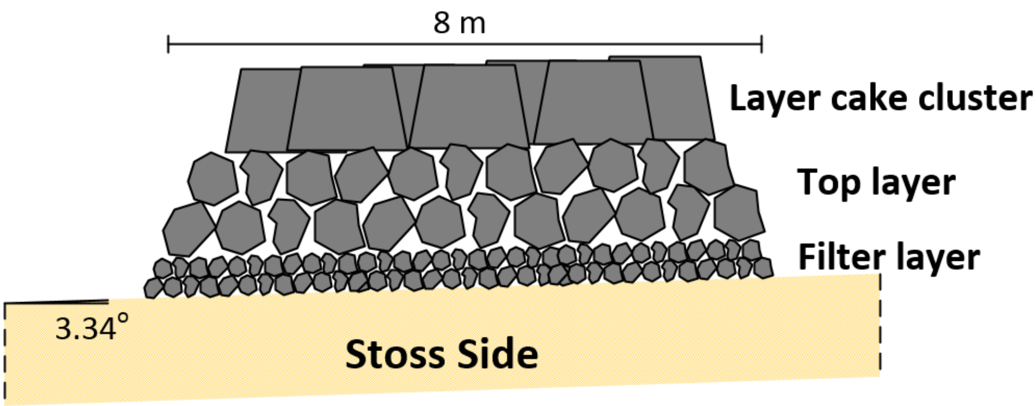


Figure 8.13: Side view of a layer cake on a stone strip

A global summary of each preliminary design is provided in table 8.6.

Table 8.6: Summary of preliminary designs

Type	Design 1	Design 2	Design 3
Stone strip	Yes	No	Yes
Block reef strip	No	Yes	Yes
Layer cake patch	Yes	Yes	Yes
Ship/Jacket	Yes	Yes	Yes

8.3 Composition of alternatives

This chapter verifies each preliminary design on its technical feasibility. It focuses on the calculation process behind determining the required stone sizes which will act as a hard substrate. Essentially, it is similar to placing a bed protection. Therefore, the construction will be treated as such. Since the location is offshore with relatively shallow depths, both the influence of waves and currents will be present on the erosion of the seabed. The calculation process is explained in detail in Appendix I, considers requirements S.4. and S.9. (see Appendix D) and is based on the theory from the book "Introduction to Bed, Bank and Shore Protection" [Gerrit J. Schiereck,]. The calculations have been made using Python scripts, which can provided upon request in a separate booklet.

8.4 Design 1

In this preliminary design, the default hard substrate are stones, or simply a bed protection. Based on table I.1, corresponding stone classes are listed per meter of depth based on the Eurocode EN13383 [NEN13383, 2015]. The stone diameter is expressed as the nominal diameter. The corresponding stone class according to EN13383 with the nominal diameter and minimum dumping amount is shown in table 8.7.

Table 8.7: Required stone class per m depth

Depth [m]	Stone class	d_{n50} [cm]	Layer thickness [cm]	Min. dumping [kg/m^2]
20	HM_A300-1000	59	88	1325
21	HM_A300-1000	59	88	1325
22	HM_A300-1000	59	57	950
23	HM_A300-1000	59	52	850
24	LM_A15-300	31	46	700
25	LM_A15-300	31	46	700
26	LM_A15-300	31	46	700
27	LM_A15-300	31	46	700
28	LM_A10-60	21	32	550
29	LM_A10-60	21	32	550
30	LM_A10-60	21	25	500
31	LM_A10-60	21	25	500
32	LM_A10-60	21	25	500
33	CP90/250	12.8	20	300
34	CP90/250	12.8	20	300
35	CP90/250	12.8	20	300

8.4.1 Filter layer

A geometrically closed granular filter layer under the stones is necessary in order to prevent erosion under the hard substrate (see requirement S.4. in appendix D). This is to prevent the risk of the stones sinking into the soft sand . The soft seabed consists of medium sand with $d_{50} = 0.25$ mm, this is an assumed value based on the cone resistance data in Appendix F. The filter layer of each stone class is presented in tables 8.8 until 8.11.

Table 8.8: Overview of top and filter layers ($d_{n50} = 59$ cm).

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	HM_A300-1000	702	88
Filter layer 1	CP90/250	152	20
Filter layer 2	Coarse gravel	30	10
Filter layer 3	Fine gravel	6.1	5
Filter layer 4	Very coarse sand	1.2	5
Base layer	Medium sand	0.25	-

Table 8.9: Overview of top and filter layers (d_{n50} = 31 cm).

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	LM_A15-300	369	46
Filter layer 1	CP45/125	76	20
Filter layer 2	Medium gravel	15	5
Filter layer 3	Very fine gravel	3.0	5
Filter layer 4	Coarse sand	0.6	5
Base layer	Medium sand	0.25	-

Table 8.10: Overview of top and filter layers (d_{n50} = 21 cm).

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	LM_A10-60	250	32
Filter layer 1	Very coarse gravel	50	10
Filter layer 2	Medium gravel	10	5
Filter layer 3	Very fine gravel	2.0	5
Filter layer 4	Medium sand	0.4	5
Base layer	Medium sand	0.25	-

Table 8.11: Overview of top and filter layers (d_{n50} = 12.8 cm).

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	CP90/250	152	20
Filter layer 1	Coarse gravel	31	10
Filter layer 2	Fine gravel	6.1	5
Filter layer 3	Very coarse sand	1.2	5
Base layer	Medium sand	0.25	-

An example of a side view of a strip of hard substrate is provided in figures 8.14. The rest is provided in Appendix I.

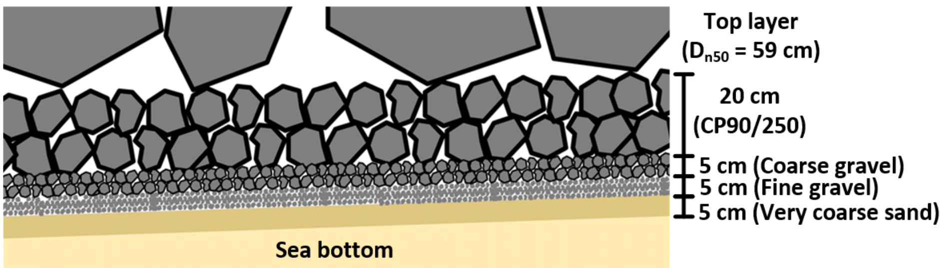


Figure 8.14: Side view of a stone strip with top layer: $d_{n50} = 59$ cm

The total stone mass required to meet this demand can be calculated based on the given dumping quantity, expressed in kg/m^2. The required amount of a particular stone class is determined based on percentages of the total area of hard substrate (which is about 5.6 km^2, see requirement S.9. appendix D). For example, stone class HM$_A$300-1000 is applied at water depths which are shallower than 24 m (LAT). The percentage of strips with this stone class are equated with the percentage of the total area which elevates higher than 24 m (LAT). This is also the same percentage of hard substrate which lies at these elevations. The area of hard substrate is then multiplied with the required dumping quantity which is provided in the last column of table 8.7. The results are shown in table 8.12.

Table 8.12: Required top layer tonnage

Top layer class	Area [%]	Area [km^2]	Stone quantity [tons]
HM$_A$300-1000	15.75	0.89	1,174,895
LM$_A$15-300	19.83	1.12	781,262
LM$_A$10-60	43.76	2.46	1,354,616
CP90/250	20.66	1.16	348,888
Total	100	5.63	**3,659,660**

For the filter layer, the same calculation process takes place. The minimum dumping quantity of small sediment particles are not mentioned in EN13383. For smaller stone classes, a dumping quantity of 300 kg/m^2 is required for a layer of 20 cm. Based on this norm, it is assumed that the dumping quantity for smaller sediments is 75 kg/m^2 per 5 cm thickness. The results are shown in table 8.13.

Table 8.13: Required filter layer tonnage

Top layer class	Area [km^2]	Filter thickness [cm]	Stone quantity [tons]
HM$_A$300-1000	0.89	40	532,028
LM$_A$15-300	1.12	35	585,946
LM$_A$10-60	2.46	25	923,602
CP90/250	1.16	20	348,888
Total	5.63	-	**2,390,464**

Total stone quantity: 3,659,660 + 2,390,464 = **6,050,124 tons**

Layer cake:
A cluster of 10 layer cakes is applied in every km^2. The total area is 112.6 km^2, therefore 1120 layer cakes are needed. Each layer cake has a minimum weight of 1364 kg, it is for this reason safe to assume that a layer cake is able to withstand any rough sea condition.

8.5 Design 2

In this preliminary design, the default hard substrate are block reefs, which will be considered as monolithic hollow stones. To determine the required Concrete Masonry Unit (CMU) size, the required mass of a stone from table I.1 is equated to the required mass of the CMU. Products from the company EMCON have been referenced as available CMU sizes. The results are shown in table 8.14.

Table 8.14: Required block reef class per m depth.

Depth [m]	Size [mm]	Weight [kg]	Min. dumping [kg/m^2]
20	N/A	N/A	N/A
21	N/A	N/A	N/A
22	N/A	N/A	N/A
23	N/A	N/A	N/A
24	N/A	N/A	N/A
25	N/A	N/A	N/A
26	N/A	N/A	N/A
27	400x300x200	30	500
28	390x190x190	21	567
29	390x140x190	16	432
30	390x90x190	13	351
31	390x90x190	13	351
32	390x90x190	13	351
33	390x90x190	13	351
34	390x90x190	13	351
35	390x90x190	13	351

Based on the information in table 8.14, it can be concluded that no block reef class exists which can withstand the sea conditions at elevations shallower than 27 m depth (LAT). When block reefs are applied at shallower depths, the risk of stones moving too much increases, which presents a danger to the hard substrate on a larger scale (scour). Since shallower depths also require hard substrate for biological reasons, this design is therefore technically unfavourable.

8.6 Design 3

The final preliminary design assesses block reefs as a hard substrate on deeper levels, while stones as applied as a hard substrate on shallower levels. In design 2, it has been concluded that block reefs are technically unfavourable at depths shallower than 27 m (LAT). For this design, block reefs as a hard substrate will be applied at water depths deeper than 27 m, while stones will be applied at depths shallower than 27 m. By combining table 8.7 and 8.14, a new preliminary design can be made.

Table 8.15: Required stone/CMU class per m depth

Depth [m]	Stone/CMU class	Min. dumping [kg/m^2]
20	HM_A300-1000	1325
21	HM_A300-1000	1325
22	HM_A300-1000	950
23	HM_A300-1000	850
24	LM_A15-300	700
25	LM_A15-300	700
26	LM_A15-300	700
27	400x300x200	500
28	390x190x190	567
29	390x140x190	432
30	390x90x190	351
31	390x90x190	351
32	390x90x190	351
33	390x90x190	351
34	390x90x190	351
35	390x90x190	351

Based on this table, it can be concluded that two different stone classes are necessary as top layers while there are four different classes of CMU covering the deeper parts of the sea.

8.6.1 Filter layer

A geometrically closed granular filter layer under the stones and block reefs are necessary in order to prevent erosion under the hard substrate, just like in preliminary design 1. The soft seabed is made of sand with $d_{50} = 0.25$ mm. The results of each stone class are presented in tables 8.8 and 8.9, but also 8.16 until 8.19 which are presented below.

Table 8.16: Overview of top and filter layers (400x300x200)

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	400x300x200	-	Min. 2 blocks
Filter layer 1	LM_A5-40	202	25
Filter layer 2	Very coarse gravel	40	10
Filter layer 3	Medium gravel	8.1	5
Filter layer 4	Very coarse sand	1.6	5
Filter layer 5	Medium sand	0.32	5
Base layer	Medium sand	0.25	-

Table 8.17: Overview of top and filter layers (390x190x190)

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	390x190x190	-	Min. 2 blocks
Filter layer 1	CP90/250	152	20
Filter layer 2	Coarse gravel	30	10
Filter layer 3	Fine gravel	6.1	5
Filter layer 4	Very coarse sand	1.2	5
Base layer	Medium sand	0.25	-

Table 8.18: Overview of top and filter layers (390x140x190)

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	390x140x190	-	Min. 2 blocks
Filter layer 1	CP63/180	107	20
Filter layer 2	Coarse gravel	21	10
Filter layer 3	Fine gravel	4.3	5
Filter layer 4	Coarse sand	0.86	5
Base layer	Medium sand	0.25	-

Table 8.19: Overview of top and filter layers (390x90x190)

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	390x90x190	-	Min. 2 blocks
Filter layer 1	CP45/125	76	20
Filter layer 2	Medium gravel	15	10
Filter layer 3	Very fine gravel	3.0	5
Filter layer 4	Coarse sand	0.61	5
Base layer	Medium sand	0.25	-

An example of a side view of a strip of hard substrate is provided in figure 8.15. The rest is provided in Appendix I.

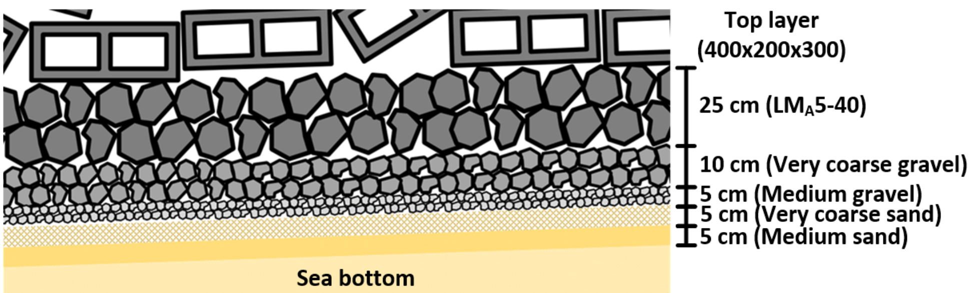


Figure 8.15: Side view of a block reef strip with top layer: 400x200x300 mm

In the same way as in design 1, the total material mass required can be calculated. The results are shown in table 8.20.

Table 8.20: Required top layer tonnage

Top layer class	Area [%]	Area [km^2]	Stone quantity [tons]
HM_A300-1000	15.75	0.89	1,174,895
LM_A15-300	14.02	0.79	552,552
400x300x200	5.80	0.33	163,364
390x190x190	7.67	0.43	244,700
390x140x190	8.64	0.49	210,042
390x90x190	48.11	2.71	950,551
Total CMU	70.23	3.95	1,568,656
Total	100	5.63	**3,296,103**

Similar to design 1, it is assumed that the dumping quantity for smaller sediments is 75 kg/m^2 per 5 cm thickness. The results are shown in table 8.21.

Table 8.21: Required filter layer tonnage

Top layer class	Area [km^2]	Filter thickness [cm]	Stone quantity [tons]
HM_A300-1000	0.89	40	532,028
LM_A15-300	0.79	35	414,414
400x300x200	0.33	50	285,887
390x190x190	0.43	40	258,941
390x140x190	0.49	40	291,724
390x90x190	2.71	40	1,624,873
Total	5.63	-	**3,407,868**

Total stone quantity: 3,296,103 + 3,407,868 = **6,703,971 tons**

Layer cake:
A cluster of 10 layer cakes is applied in every km^2. The total area is 112.6 km^2, therefore 1120 layer cakes are needed. Each layer cake has a minimum weight of 1364 kg, it is for this reason safe to assume that a layer cake is able to withstand any tough sea condition.

A summary of the results for each preliminary design is presented in table 8.22.

Table 8.22: Summary of preliminary designs

Preliminary design concepts	1	2	3
No. of element types	3	3	4
Stone quantity (excl. filter) [tons]	3,659,660	N/A	1,727,447
Filter quantity [tons]	2,390,464	Unknown	3,407,868
Stone quantity (incl. filter) [tons]	6,050,124	Unknown	5,135,315
Block reef quantity [tons]	N/A	Unknown	1,568,656
Total quantity (excl. layer cake) [tons]	6,050,124	Unknown	6,703,971
Layer cake quantity	1120	1120	1120
Ship/Jacket quantity	112	112	112
Technical feasibility	Yes	No	Yes

8.7 Conclusion

As it is proved, preliminary design 1 and 3 appear to be more effective solutions for the wind farm area Borssele I+II. Both combinations of alternatives do agree with the boundary conditions and requirements and are able to resist driving forces. Preliminary design 1 and 3 provide a larger area of hard substrate for different target species, but both designs appear to be technically feasible at each water depth within the wind farm area.

Chapter 9

Evaluation of Alternatives

In chapter 8 two preliminary designs appeared to be technically feasible and satisfied the program of requirements and boundary conditions. This chapter evaluates which design is preferred and lives up to the requirements in a better way. Water depths shallower than 27 m - LAT appeared to be less practical water areas where block reef units can be used, since CMUs are less resilient against the local destabilizing hydraulic gradients than massive loose rocks. Preliminary design 2 is therefore a limited solution when compared with preliminary design 1 and 3.

9.1 Comparison of best designs

Design 1 and design 3 will be addressed in this chapter. Eventually one design is chosen for Borssele I+II and the design will be improved where possible.

Table 9.1: Summary of preliminary designs

Preliminary design	1	3
No. of element types	3	4
Stone quantity (excl. filter) [tons]	3,659,660	1,727,447
Filter quantity [tons]	2,390,464	3,407,868
Stone quantity (incl. filter) [tons]	6,050,124	5,135,315
Block reef quantity [tons]	N/A	1,568,656
Total quantity (excl. layer cake) [tons]	6,050,124	6,703,971
Layer cake quantity	1120	1120
Ship/Jacket quantity	112	112
Technical feasibility	Yes	Yes
CAPEX [mln]	238,6	291,4
OPEX [mln]	5,47	6,53

Given the requirements as is stated in Appendix D, one should opt for a design with a high vertical relief. European Seabass and Atlantic Cod both live in a large vertical range (10-100 or 200 m water depth). Since both designs use decommissioned offshore jacket structures and layer cakes, both solutions will fit. An application of a wide range of structures enhances the dynamism and attracts more species. This is comparable with grass on levees or even better: road side verges. Road side verges with a larger ecological gradient improve the habitat quality of different species [H. Jonkers, 2019a].

According to the program of requirements, North Sea Crab and European Lobster do not tolerate current velocities of 1.5 m/s and 0.6 m/s respectively (requirements O.15. and O.5., see D). However, they have the ability to find shelter within the hard substrate. One could argue that block reefs are more favourable compared to stones, because of the higher capability of sheltering due to the hollow areas within the block. Furthermore, adult marine life require a space opening of 11 cm for shelter as is stated in requirement O.1. in appendix D. It can be intuitively concluded that block reefs are more likely to have more of these openings compared to stones. Therefore, this option is more favourable.

For the final design itself it is highly important to include the stakeholders. The project will presumably require widespread support in order to have a chance of implementation. For this, the input from chapter 4 forms the basis for the evaluation of the two best combination of alternatives. To start, both designs adopted the use of obsolete jacket systems in their design, creating an attractive opportunity for the oil and gas companies, fully in line with the contemporary circular economy concept.

Furthermore, none of the two alternatives are using the solution space Strength-Opportunity VIII: the use of a seaweed farm to counter the CO2 emissions emitted during the construction of the OWF.

In terms of biomass, nature organisations are interested in increasing biodiversity, while the fishing industry prefers the highest possible biomass for their target fish species. The ministries would like to create the highest possible biomass in order to boost the fishing industry and the economy.

When considering the basis of design, different stakeholders and their influence are predominantly involved. The oil and gas industry prefers old decommissioned jackets to be reused. On the other hand, nature organisations are neutral concerning the reuse of old decommissioned jackets. However, nature organisations are opposed to the idea of using the topsides of offshore platforms, since the topsides of offshore constructions are often toxic. Topsides are part of the platform structure where among other things the crew quarters, helicopter pad, drilling equipment are located.

As one can see, stakeholders' preferences are considered in both preliminary design 1 and 3. The choice between both lays in what it yields. Preliminary design 3 uses the largest quantity of material: 6,703,971 tons. Its potential due to the higher variety of elements arguably outweighs preliminary design 1 and therefore will likely improve the biodiversity and recruitment of species.

Traditional concrete material mainly consists of Portland clinker, which is a substance that is processed in cement. The harvest and transport of clay and limestone (the basis of materials for clinker) and the modification for the production of clinker cause high CO_2-emissions. Cement production is estimated to be 350 kg/person/year and accordingly, 315 kg of CO_2 /person/year is emitted. Accordingly, a given fact is that 7% of the anthropogenic CO_2-emission is caused by cement production. One might do the following to reduce the environmental impacts [H. Jonkers, 2019b]:

- (Partly) replacing the bind material (cement) by something that is more environmentally friendly, such as volcanic ash or rice husk ash.
  - Note that strength, durability and frost resilience decrease due to the use of more sustainable material [H. Jonkers, 2019b, sl. 28].
- One could also mix industrial by- or waste products such as blast furnace slag or silica fume with cement. These materials increase the concrete strength.

On the other hand, a burial depth of 5 meters is often taken as a maximum for cables because of the danger of burning due to overheating. Heat cannot be transferred to the water body when the cables are buried too deep. The hard substrate including the top layer of rocks (max. 590 mm), block reef elements (at most 400x300x200 mm) and smaller filter layer elements can be constructed with a Boskalis dynamic positioned fallpipe vessel named Rockpiper [Boskalis NV, 2016]. This vessel has:

- A length over all (LOA) of 158.60 m
- Draught of 9.40 m
- Breadth of 13.50 m

- Cargo carrying capacity 24,000 tons
- And more importantly a pipe diameter of 700 mm

Dynamic positioned fallpipe vessels are able to create sharp turns in order to make strips. Interruptions are made in the strips to maintain the maximum burial depth for the cables. The final design is shown in figure 9.1, 9.2 and in Appendix J. The image shows a wind turbine, a jacket construction and a sunken ship. More detailed images are provided in Appendix J. Note that this layout is valid for the entire Borssele I and II area.

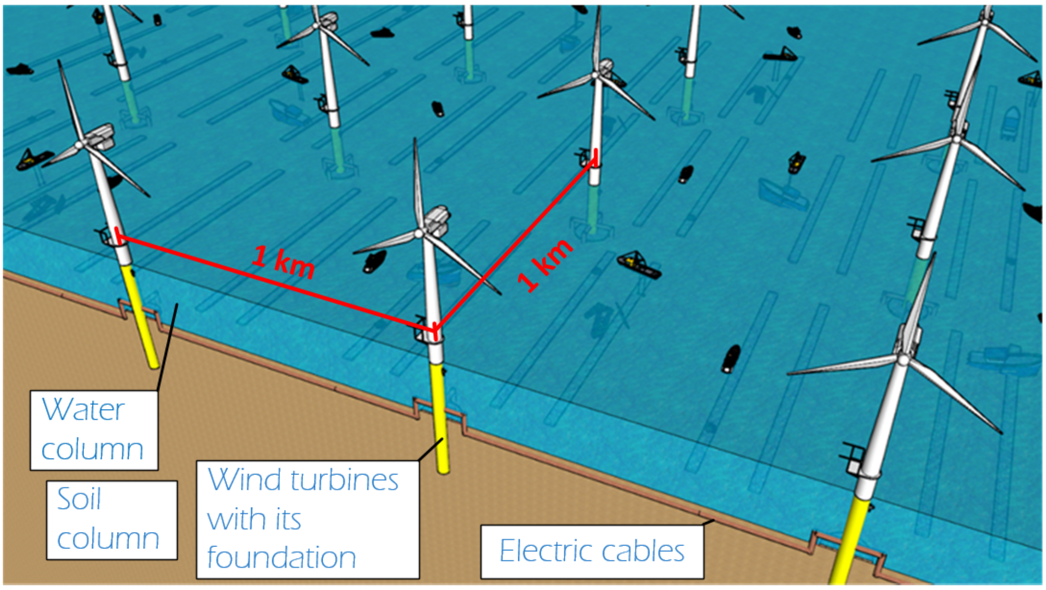


Figure 9.1: 3D view of the final design (not to scale)

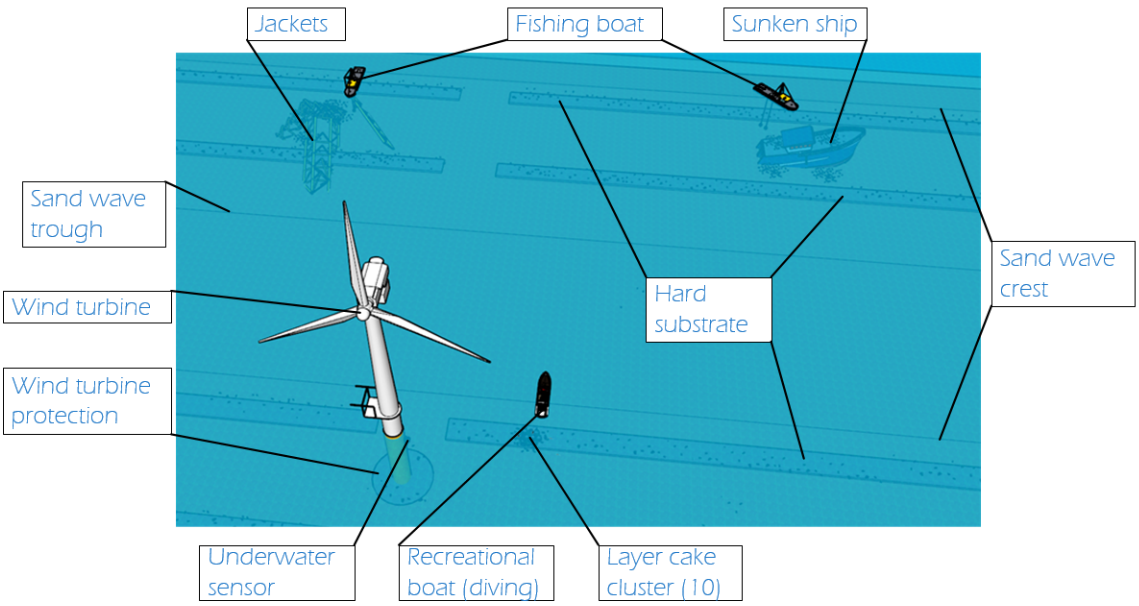


Figure 9.2: 3D view of the final design (to scale)

9.2 Conclusion

In conclusion, preliminary design 3 is most likely to provide the most optimal habitat and bring about a greater range of biodiversity, thereby enhancing the surrounding marine environment. Although this design is more expensive (see table I.17), the added value of different species is highly attractive for a self-sustaining ecosystem. The design is aligned with stakeholders' views, the demands of a wide variety of species and at the same time yields a cost-efficient solution. Part III sheds more light on how a business case of the preliminary design can be established.

Part 3

Business case

Chapter 10

Biomass Analysis

10.1 Introduction

In this chapter the ecosystem in the OWF is described. Based on the design presented in the previous chapters, the trophic stucture and potential biomass of the system is estimated. For this project we use the mass balance modelling complex Ecopath with Ecosim (EwE), to predict the amount of biomass present in an OWF while taking into account species interaction. The Ecopath model was first devised in 1984 by Jeff Polovina, when he used it to model the French Frigate Shoals ecosystem in Hawaii. It has since been used extensively for the purpose of ecological modelling for aquatic ecosystems. Since then, Ecopath has been continuously improved and developed to include Ecological Network Analysis for ecosystem comparison, Ecospace for spatial changes to the model and Ecosim for dynamic changes [J.J. Heymans, M. Coll, J.S. Link, S. Mackinson, J. Steenbeek, C. Walters, V. Christensen, 2016]. Ecopath is able to provide information necessary for marine policy planners and ecologists interested in particular ecosystems, making it useful in a management context. While very few Ecopath models have been actually used for management, Mackinson and Daskalov's model of the North Sea is used to evaluate EU commission proposals for fisheries management. It is this particular model by Mackinson and Daskalov (2017) in which our Ecopath model is based. A second study by Raoux (2007) based in the Bay of Seine located off the north-western French coast is used to simulate a before and after scenario, where the amount of biomass is estimated before the addition of hard substrate and after. This chapter outlines the parameterization of the model, its input, results and finally, a description on its limitations. Furthermore, a detailed biomass estimation over time of the five target species described in chapter 5 is given. Based on these predictions, the sustainable catch of biomass is estimated. This forms the basis for the revenues gained by fisheries described in chapter 11.

10.2 Parameterization of model

10.2.1 Parameter definitions

The main concept behind the calculations made by EwE is that biomass in the system is always balanced. Its main input parameters are biomass (B, t/km^2), production over biomass ratio (P/B, year^{-1}), consumption over biomass ratio (Q/B, year^{-1}) and the diet composition of all included functional groups. The Ecopath model estimates its parameters by balancing the following equation for each of its compartments:

$$B(\frac{P}{B})_i = \sum_j B_j(\frac{Q}{B})_j DC_{ij} + Y_i + E_i + BA_i + B_i(\frac{P}{B})_i(1 - EE_i) \tag{10.1}$$

In which in addition to the parameters described above, (j) are the predators of the compartment (i), DC is the diet composition, Y is the fishing mortality (t/km^2), E is the net migration (year^{-1}), BA is the biomass accumulation (year^{-1}) and natural mortality is represented by (1 - EE_i) in which EE is the Ecotrophic Efficiency, or the proportion of the biomass that is consumed in the system for each compartment in the system.

10.2.2 Functional groups

25 functional groups were included in the model. Group 1 “other predators” describes marine mammals, birds and elasmobranchs. Group 2 and 3 describe cephalopods, where group 3 describes the target species Cuttlefish specifically. Group 4 to 11 describe single fish species that are either target species for our economic calculations or otherwise of economic importance. The remaining fish species were pooled in groups 12 to 15, based on their role in the ecosystem. These groups describe piscivorous fish, planktivorous fish, benthic feeding fish or flatfish that are not described in groups 4 to 11. The crustacean target species European Lobster and Brown Crab are described by group 16 and 17 respectively. Smaller benthic crustaceans are included in group 18, Benthos, together with all other benthic species such as molluscs and echinoderms. Species associated with the sea floor but not living upon it (e.g. shrimp) are described by group 19, Suprabenthos. Group 20 describes the meiofauna, which consists of tiny, benthic invertebrates. Groups 21-23 describe zooplankton, bacteria and phytoplankton. Groups 24 and 25 are the detritus group and discards group.

10.2.3 Basic input Ecopath

For all groups except group 2 (Other Cephalopods), group 3 (Cuttlefish) and group 5 (European Seabass), the values for abundance, production, consumption and Ecotrophic Efficiency required by Ecopath were directly obtained from Mackinson and Daskalov (2007). The data for group 2, group 3 and group 5 were obtained from Raoux *et al.* (2017). The data from the functional groups of Mackinson and Daksolov (2007) were translated to the 25 desired groups of our model. First the total biomass of the groups that would be combined in a new functional group in our model was calculated. Than the average value for P/B, Q/B and EE was calculated by summing values proportional to the share of the group in the total biomass of the groups that would be combined. The values for groups 2, 3 and 5 could be taken directly from Raoux *et al.* (2017) without further modification. Since the Borssele OWF is a relatively small area in a highly dynamic sea, there was assumed to be a high flow through of planktonic organisms. Migration was therefore allowed for the planktonic functional groups to maintain a constant biomass level.

10.2.4 Dietary data

In order to obtain the dietary matrix, the dietary data from Mackinson and Daskalov (2007) and Raoux *et al.* (2017) was combined for the required functional groups. Where groups from the literature had to be combined to form a new functional group the same method used for translating the values for P/B, Q/B and EE was applied. Next, the trophic level of the functional groups was realised with the newly obtained dietary matrix and confirmed with available literature data where possible. When the realised trophic level was considered too high, the fraction of the diet of the lower prey items was increased (vice versa when the trophic level was too low). The “Sum diets to one” function of Ecopath was used to restore the diets when out of balance. This method was repeated until the desired trophic level was reached (table 10.1). The final dietary matrix is shown in tables 10.2, 10.3 and 10.4.

Table 10.1: Trophic level realised though combining data from [S. Mackinson, G. Daskalov, 2007] and [A. Raoux, S. Tecchio, J. Pezy, G. Lassalle, S. Degrear, D. Wilhelmsson, M. Cachera, B. Ernande, C. Le Guen, M. Haraldsson, K. Grangere, F. Le Loch, J. Dauvin, N. Niquil, 2017] (Starting trophic level), found in literature ([J. Yang, 1982] and [V. Christensen, 1992]) and the trophic level of the functional groups after adjusting the dietary matrix based on this literature (Final trophic level)

Prey/predator	Starting trophic level	Yang, 1982	Christensen, 1992	Final trophic level
Other predators	4,8	-	-	4,6
Benthopelagic cephalopods	4,7	-	-	4,2
Cuttlefish	4,4	-	-	4,1
Mackerel	4,0	3,5	4,5	4,0
European seabass	4,3	-	-	4,0
Atlantic cod	5,1	4,4	4	4,2
Whiting	4,9	4,3	4,5	4,5
Atlantic horse mackerel	4,3	-	-	4,1
Gurnard	5,0	3,9	-	4,1
Pouting	4,8	3,4	-	3,5
European sprat	3,2	3,3	3,6	3,4
Piscivorous fish	3,4	3,5	4,5	4,0
Planktivorous fish	3,5	3,3-3,7	3,1-3,5	3,5
Benthic feeding fish	3,9	3,9-4,2	3,0-5,0	4,0
Flatfish	4,3	3,7-4,6	3,1	3,8
European lobster	4,0	-	-	3,5
Brown crab	4,4	-	-	3,8
Benthos	3,3	2,1-3,3	2,0-2,3	2,7
Suprabenthos	3,4	-	-	3,4
Meiofauna	3,2	2,1-3,3	-	3,0
Zooplankton	2,3	2,1 - 3,0	2,8	2,6
Bacteria	2,3	-	-	2,3
Phytoplankton	1,0	-	1	1,0
Detritus	1,0	-	1	1,0
Discards	1,0	-	-	1,0

Table 10.2: Dietary matrix showing fractional components of the diet of the functional groups used in the EwE scenarios.

Group nr.	Prey/predator	1	2	3	4	5	6	7
1	Other predators	0,0006	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
2	Benthopelagic cephalopods	0,0043	0,0376	0,0000	0,0085	0,0000	0,0005	0,0035
3	Cuttlefish	0,0043	0,0226	0,0435	0,0085	0,0000	0,0005	0,0035
4	Mackerel	0,0135	0,0339	0,0000	0,0000	0,0000	0,0031	0,0000
5	European seabass	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
6	Atlantic cod	0,0075	0,0000	0,0000	0,0000	0,0000	0,0055	0,0015
7	Whiting	0,0246	0,0075	0,0109	0,0000	0,0000	0,0126	0,0184
8	Atlantic horse mackerel	0,0010	0,0226	0,0218	0,0060	0,0000	0,0009	0,0037
9	Gurnard	0,0003	0,0000	0,0000	0,0000	0,0000	0,0018	0,0000
10	Pouting	0,0363	0,0000	0,0544	0,0090	0,0000	0,1029	0,3629
11	European sprat	0,0067	0,0000	0,0000	0,0600	0,0000	0,1372	0,2721
12	Piscivorous fish	0,0251	0,0603	0,0109	0,0110	0,0000	0,0316	0,0179
13	Planktivorous fish	0,0028	0,0301	0,0000	0,0000	0,0000	0,0000	0,0012
14	Benthic feeding fish	0,4293	0,0376	0,0218	0,2750	0,0300	0,0544	0,2022
15	Flatfish	0,0191	0,0527	0,0000	0,0000	0,0000	0,1686	0,0042
16	European lobster	0,0005	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
17	Brown crab	0,0977	0,0000	0,0000	0,0000	0,0000	0,0462	0,0000
18	Benthos	0,2553	0,4910	0,5041	0,1590	0,5700	0,3419	0,0000
19	Suprabenthos	0,0446	0,1045	0,2240	0,0000	0,4000	0,0000	0,0000
20	Meiofauna	0,0018	0,0996	0,1088	0,0000	0,0000	0,0000	0,0000
21	Zooplankton	0,0223	0,0000	0,0000	0,2830	0,0000	0,0922	0,1089
22	Bacteria	0,0000	0,0000	0,0000	0,1800	0,0000	0,0000	0,0000
23	Phytoplankton	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
24	Detritus	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
25	Discards	0,0010	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
26	Import	0,0016	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
27	Sum	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000

Table 10.3: Dietary matrix showing fractional components of the diet of the functional groups used in the EwE scenarios (continued).

Group nr.	Prey/predator	8	9	10	11	12	13	14
1	Other predators	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0001
2	Benthopelagic cephalopods	0,0000	0,0038	0,0000	0,0000	0,0000	0,0022	0,0035
3	Cuttlefish	0,0000	0,0038	0,0000	0,0000	0,0000	0,0022	0,0035
4	Mackerel	0,0000	0,0005	0,0000	0,0000	0,0293	0,0000	0,0019
5	European seabass	0,0000	0,0000	0,0000	0,0000	0,0293	0,0000	0,0000
6	Atlantic cod	0,0060	0,0131	0,0000	0,0000	0,0102	0,0000	0,0006
7	Whiting	0,0350	0,0437	0,0000	0,0000	0,0293	0,0000	0,0063
8	Atlantic horse mackerel	0,0000	0,0005	0,0000	0,0000	0,0293	0,0000	0,0009
9	Gurnard	0,0050	0,0000	0,0000	0,0000	0,0293	0,0000	0,0012
10	Pouting	0,2290	0,0327	0,0000	0,0000	0,0293	0,0000	0,0584
11	European sprat	0,0060	0,0070	0,0000	0,0000	0,0293	0,0000	0,0169
12	Piscivorous fish	0,0490	0,0005	0,0000	0,0000	0,0293	0,0000	0,0280
13	Planktivorous fish	0,0000	0,0000	0,0000	0,0000	0,0293	0,0389	0,0023
14	Benthic feeding fish	0,1260	0,1879	0,0107	0,0000	0,0293	0,0000	0,0987
15	Flatfish	0,0000	0,0121	0,0000	0,0000	0,0293	0,0000	0,0085
16	European lobster	0,0340	0,0005	0,0000	0,0000	0,0000	0,0000	0,0072
17	Brown crab	0,0000	0,0312	0,0213	0,0000	0,0000	0,0000	0,0226
18	Benthos	0,0140	0,5220	0,6911	0,0000	0,0969	0,0103	0,3319
19	Suprabenthos	0,0000	0,0136	0,0767	0,0000	0,0000	0,0103	0,0175
20	Meiofauna	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,1571
21	Zooplankton	0,4470	0,1273	0,0177	0,8020	0,5701	0,8428	0,2261
22	Bacteria	0,0490	0,0000	0,0000	0,0990	0,0000	0,0000	0,0057
23	Phytoplankton	0,0000	0,0000	0,0000	0,0990	0,0000	0,0933	0,0011
24	Detritus	0,0000	0,0000	0,1825	0,0000	0,0000	0,0000	0,0000
25	Discards	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
26	Import	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
27	Sum	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000

Table 10.4: Dietary matrix showing fractional components of the diet of the functional groups used in the EwE scenarios (continued).

Group nr.	Prey/predator	15	16	17	18	19	20	21	22
1	Other predators	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
2	Benthopelagic cephalopods	0,0004	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
3	Cuttlefish	0,0004	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
4	Mackerel	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
5	European seabass	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
6	Atlantic cod	0,0009	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
7	Whiting	0,0061	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
8	Atlantic horse mackerel	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
9	Gurnard	0,0001	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
10	Pouting	0,0101	0,0795	0,1266	0,0000	0,0000	0,0000	0,0006	0,0000
11	European sprat	0,0072	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
12	Piscivorous fish	0,0010	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
13	Planktivorous fish	0,0003	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
14	Benthic feeding fish	0,0302	0,0119	0,1197	0,0000	0,0315	0,0000	0,0002	0,0000
15	Flatfish	0,0190	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
16	European lobster	0,0120	0,0000	0,0105	0,0000	0,0000	0,0000	0,0000	0,0000
17	Brown crab	0,0240	0,0000	0,0005	0,0000	0,0000	0,0000	0,0000	0,0000
18	Benthos	0,8075	0,6009	0,5802	0,1371	0,1818	0,0000	0,0296	0,0000
19	Suprabenthos	0,0110	0,0000	0,0005	0,0000	0,0121	0,0000	0,0004	0,0000
20	Meiofauna	0,0454	0,0000	0,0000	0,0635	0,1212	0,0449	0,0000	0,0000
21	Zooplankton	0,0244	0,0000	0,0000	0,0000	0,1818	0,0000	0,2465	0,0000
22	Bacteria	0,0000	0,1986	0,0945	0,2390	0,3272	0,6730	0,0973	0,2498
23	Phytoplankton	0,0000	0,0894	0,0000	0,3918	0,0000	0,0000	0,6103	0,0000
24	Detritus	0,0000	0,0198	0,0000	0,1686	0,1444	0,2822	0,0153	0,7502
25	Discards	0,0000	0,0000	0,0675	0,0000	0,0000	0,0000	0,0000	0,0000
26	Import	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
27	Sum	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000

10.2.5 Fisheries data

Data on fisheries landings and discards was obtained from Mackinson and Daskalov (2007). The data was reorganised to make it fit to our 25 functional groups using the same approach applied when compiling the data for P/B, Q/B, EE and diet. This data was used as the starting point for the model (table 10.5).

Table 10.5: Fisheries landings and discards of the functional groups as used to estimate population size and dynamics in EwE.

Group nr.	Landings [t/km^2/year]	Prey/predator	Discards [t/km^2]
1	Other predators	0,001226	0
2	Benthopelagic cephalopods	7E-05	0
3	Cuttlefish	7E-05	0
4	Mackerel	0,589801	0,3528
5	European seabass	0	0
6	Atlantic cod	0,018885	0,005
7	Whiting	0,051437	0,0172
8	Atlantic horse mackerel	0,098908	0
9	Gurnard	6,2E-05	0,0006
10	Pouting	0,37791	0
11	European sprat	0,100244	0,0042
12	Piscivorous fish	1,668283	0,1008
13	Planktivorous fish	0,000297	0
14	Benthic feeding fish	4,679779	0,0343
15	Flatfish	0,12263	0,315
16	European lobster	0,019683	0,0011
17	Brown crab	0,015384	0
18	Benthos	34,7164	0,0013
19	Suprabenthos	0,021511	0,0247
20	Meiofauna	0	0
21	Zooplankton	0	0
22	Bacteria	0	0
23	Phytoplankton	0	0
24	Detritus	0	0

10.2.6 Ecosim data

Group info data for Ecosim was entered following the rational from the North Sea model from Mackinson and Daskalov (2007). Top trophic level groups were given a feeding time adjustment rate of 0,1. Groups with an intermediate trophic level were set at 0,5. The lowest trophic levels were set at 1. Benthic, planktonic and the bacteria groups were set at 0. The fraction of other mortality sensitivity to changes in feeding time was set at 1 for groups 1 to 17 and at 0 for groups 18 to 22. The predator effect on feeding time was set at 0,5 for all groups except the top predators: European seabass, Atlantic cod and Whiting. These groups were set at 0 as it was reasoned that these groups were not affected by predation in their feeding behaviour.

10.2.7 Reef effect

Raoux *et al.* (2017) describes the effect of the presence of an OWF in the Bay of Seine, north-western France. We calculated the changes in values for B, P/B, Q/B and EE before and after construction on the OWF found in this article. This data was recompiled to make it fit with our 25 functional groups. The changes in these parameters were then extrapolated in accordance with the percentage of hard substrate coverage. No crab and lobster species were described by Raoux *et al.* (2017). Jensen *et al.* (2000) was used to calculate the increase of lobster biomass with addition of hard substrate. Krone *et al.* (2017) was used to calculate the increase in North Sea crab abundance and productivity. As no data on increase in lobster productivity could be found in the literature, this was assumed to be similar to the increase in Brown crab productivity as the two species have a similar biology. No data on the change in Q/B and EE could be found in the literature for either of the two species. These parameters were estimated to be equal to the average change of the other animal groups.

10.3 Current North Sea versus enhanced situation

Two EwE models were written based on the data obtained from the available literature [A. Raoux, S. Tecchio, J. Pezy, G. Lassalle, S. Degrear, D. Wilhelmsson, M. Cachera, B. Ernande, C. Le Guen, M. Haraldsson, K. Grangere, F. Le Loch, J. Dauvin, N. Niquil, 2017, S. Mackinson, G. Daskalov, 2007]. The first model described a North Sea system without any addition of hard substrate and is named the "Before" scenario. In the second model, called the "After" scenario, the basic input was extrapolated to fit a system with increased hard substrate. No changes were made in dietary compositions or fisheries effort. The resulting food webs with relative biomass per group can be seen in figure 10.1 and figure 10.2. The change in the composition of the biomass is shown in figure 10.3.

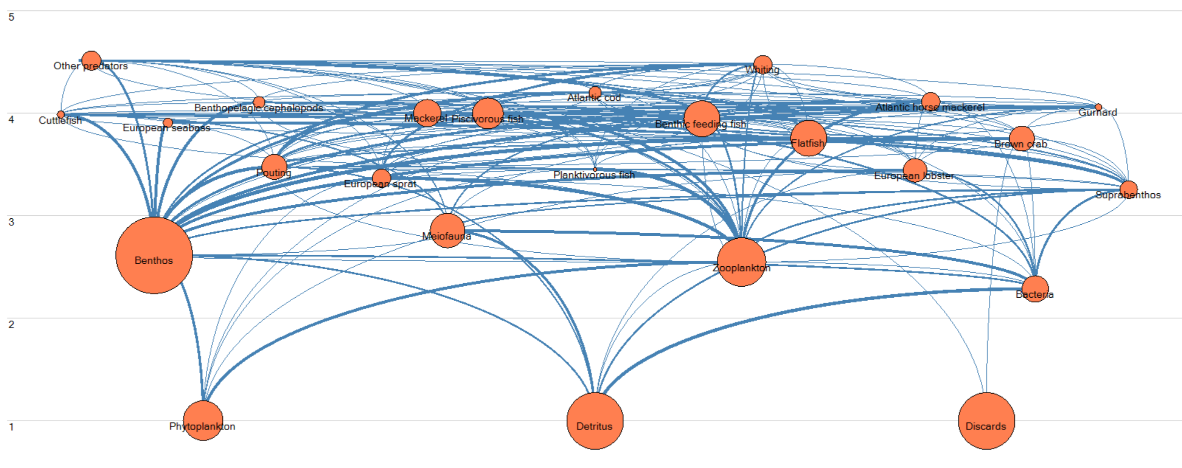


Figure 10.1: Food web with biomass flows between the functional groups before the addition of hard substrate. Groups are ranked on trophic level, with the lowest level at the bottom. Circle size shows relative biomass.

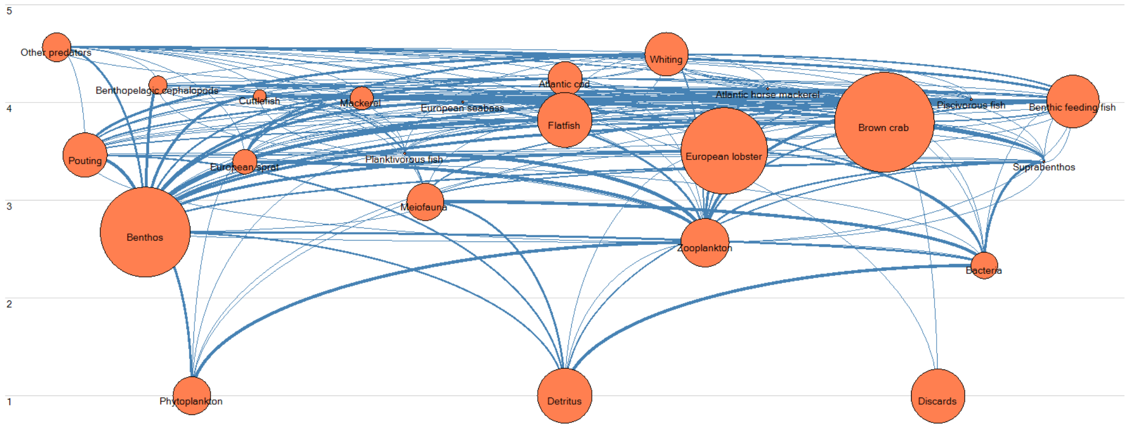


Figure 10.2: Food web with biomass flows between the functional groups after the addition of hard substrate. Groups are ranked on trophic level, with the lowest level at the bottom. Circle size shows relative biomass.

With the addition of hard substrate, the most impressive change is seen in the populations of Brown Crab and European Lobster. As a result of the increased production rate due to the substrate addition, these populations become the main components in the system, in addition to the benthos which dominated the before scenario. The tremendous increase of the population size of these two components can be seen as unrealistic. Since the Ecopath model sees the system as closed, the biomass accumulates in the area. Additionally, competition for non-food resources are not included. In reality, competition and migration would likely prevent the populations to reach these sizes. The added substrate does however provide the potential to produce this biomass. Additionally, the placement of hard substrate caused the total biomass in the system to increase. In the before scenario there was a total biomass of 653 tonnes, compared to 17.887 tonnes in the after scenario. It can be observed that several groups are not suited to survive in the after scenario. The groups Piscivorous fish, Planktivorous fish, Suprabenthos, Atlantic horse mackerel and European seabass appear to reduce to a minimum in this scenario. It should be noted here that the groups Piscivorous fish, Planktivorous fish and Suprabenthos are composed of several species combined in one functional group. This reduces the resilience of the group, as sensitivity of one species in the group to the alteration will negatively effect the entire functional group. It was however not expected that our target species European seabass would only be marginally present in a situation with increased hard substrate, as it is a species that is known to be attracted to these habitats [F. Quirijns, T. van der Hammen, H. van Overzee, 2013]. Besides these five groups, the functional group Mackerel is also reduced in absolute biomass, albeit less severe. The other functional groups all increased or remained equal in terms of absolute biomass. The changes in biomass and input parameters are shown in further detail in tables 10.6 and 10.7. Using Ecosim, the progression of biomass of the population over time can be estimated. We estimated this development for our five target species in a situation without fisheries (figures 10.4, 10.5, 10.6 and 10.7). The biomass of the two fish species and Cuttlefish decreases over time in both scenarios. For Cuttlefish and Atlantic cod the biomass after 30 years is however higher in the after scenario than in the before scenario. European seabass biomass remains at the same level of biomass after the addition of substrate. The proportion of seabass in the total biomass does however decrease over time in the after scenario, where it would slightly increase in the before scenario. Comparing the development of the two decapod species, the enormous growth of the Brown Crab biomass is immediately noticeable in the after scenario. Interestingly, where the Brown Crab population continuously grows, the European Lobster biomass decreases over time in the after scenario. In the before scenario both populations decrease slightly over time. The lobster biomass is only slightly lower in the before scenario and remains relatively proportionate over time. In the after scenario the Brown Crab biomass is however much higher compared to the lobster biomass, and continues to grow larger over time.

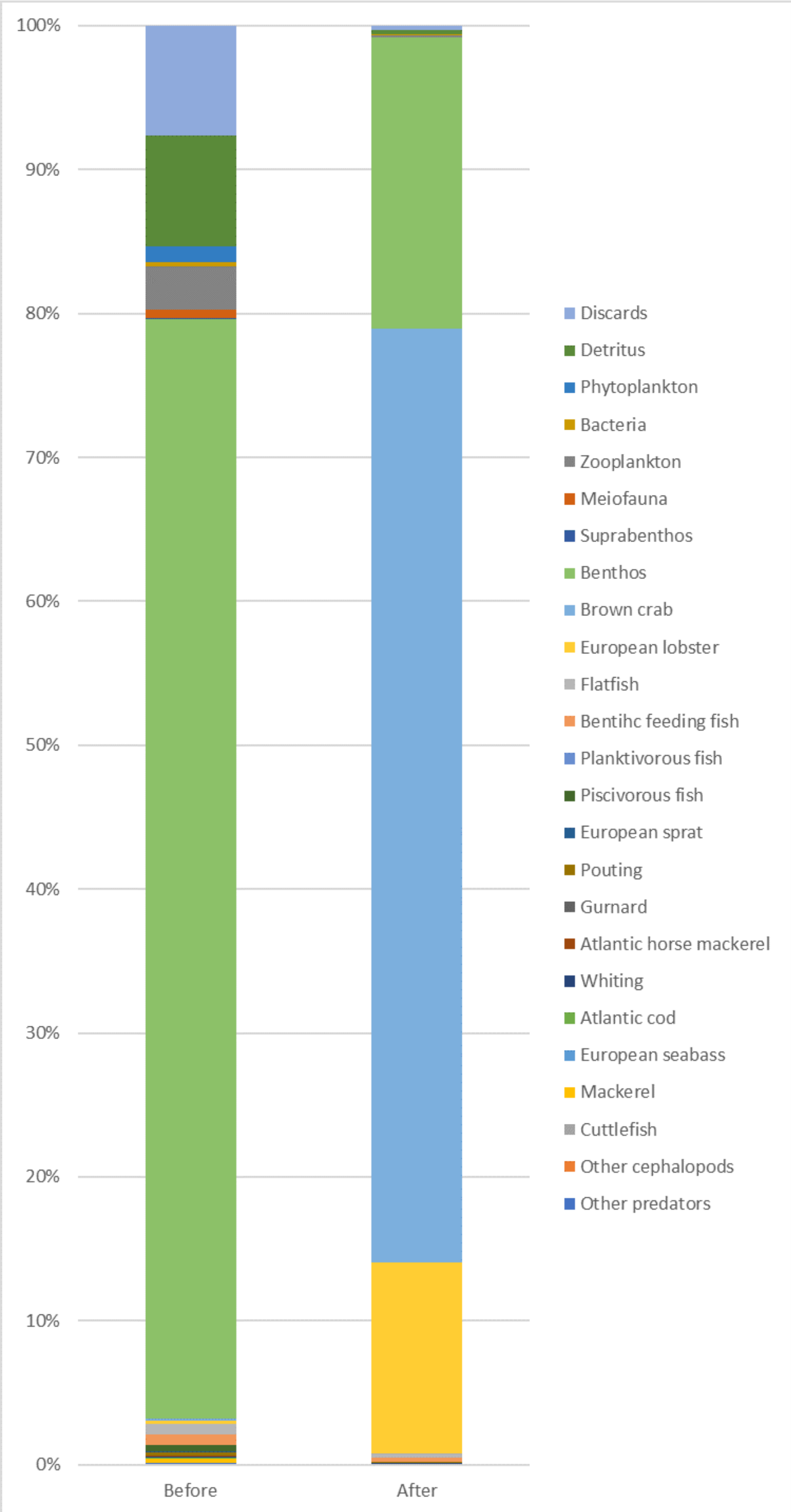


Figure 10.3: Percentage of the biomass of each functional group of the total biomass in the system for the scenarios before and after hard substrate was added.

Table 10.6: Biomass (B) and production (P/B) input of the functional groups in the scenarios before and after the addition of hard substrate, and the percentage the parameter increases.

Functional group	B (t/km ^2)			P/B		
	Before	After	Increase %	Before	After	Increase %
Other predators	0,61	2,37	288,29	0,55	0,55	-0,12
Other cephalopods	0,22	0,64	190,69	4,50	4,50	-0,05
Cuttlefish	0,10	0,27	175,37	4,50	4,50	0,00
Mackerel	1,72	1,23	-28,72	0,60	0,60	0,06
European seabass	0,15	0,01	-93,25	0,53	0,53	-0,11
Atlantic cod	0,24	4,79	1897,26	1,39	1,39	0,00
Whiting	0,57	14,48	2422,94	1,46	1,60	9,49
Atlantic horse mackerel	0,58	0,00	-100,00	1,20	1,20	0,12
Gurnard	0,08	0,30	289,37	0,82	0,82	-0,17
Pouting	1,39	15,42	1006,31	2,20	2,20	0,00
European sprat	0,58	1,40	141,25	2,28	2,28	-0,06
Piscivorous fish	2,60	0,00	-100,00	0,92	0,90	-2,24
Planktivorous fish	0,03	0,00	-100,00	4,00	4,02	0,43
Bentihc feeding fish	4,81	43,40	803,11	2,00	2,00	-0,15
Flatfish	4,97	53,18	970,19	0,74	0,74	0,55
European lobster	1,10	2374,09	215726,61	0,37	0,38	2,66
Brown crab	1,35	11608,94	857281,15	0,55	0,57	2,66
Benthos	499,00	3619,49	625,35	0,77	0,79	2,11
Suprabenthos	0,50	0,00	-100,00	3,00	3,01	0,21
Meiofauna	4,11	7,01	70,77	35,00	35,01	0,03
Zooplankton	19,73	25,86	31,04	8,21	8,18	-0,39
Bacteria	1,57	1,88	20,34	1168,06	1167,49	-0,05
Phytoplankton	7,50	7,50	0,00	286,00	286,00	0,00
Detritus	50,00	54,82	9,64	-	-	-
Discards	50,00	50,00	0,00	-	-	-

Table 10.7: Consumption (Q/B) and Ecotrophic Efficiency (EE) input of the functional groups in the scenarios before and after the addition of hard substrate, and the percentage the parameter increases.

Functional group	Q/B			EE		
	Before	After	Increase %	Before	After	Increase %
Other predators	4,52	4,45	-1,56	0,06	0,06	0,17
Other cephalopods	20,00	19,96	-0,18	0,89	0,92	3,55
Cuttlefish	20,00	19,96	-0,20	0,89	0,89	0,25
Mackerel	1,73	1,73	-0,01	0,63	0,63	0,05
European seabass	3,09	3,08	-0,27	0,44	0,44	0,14
Atlantic cod	4,31	4,31	0,00	0,81	0,83	2,35
Whiting	5,89	6,45	9,51	0,90	0,91	0,09
Atlantic horse mackerel	3,51	3,51	0,06	0,36	0,36	0,07
Gurnard	3,20	3,19	-0,40	0,58	0,58	0,00
Pouting	5,05	5,05	0,00	0,75	0,84	12,58
European sprat	6,00	5,99	-0,13	0,81	0,81	0,07
Piscivorous fish	4,65	4,61	-1,03	0,69	0,65	-4,65
Planktivorous fish	10,19	10,22	0,27	0,98	0,98	0,05
Bentihc feeding fish	8,21	8,13	-0,99	0,76	0,76	0,06
Flatfish	3,39	3,39	-0,22	0,34	0,34	0,05
European lobster	1,85	1,90	2,66	0,99	0,99	0,00
Brown crab	2,77	2,84	2,66	0,93	0,93	0,00
Benthos	2,71	2,77	2,11	0,48	0,47	-2,79
Suprabenthos	10,00	10,02	0,21	0,45	0,45	0,03
Meiofauna	125,00	125,04	0,03	0,99	0,99	0,01
Zooplankton	26,77	26,66	-0,42	0,58	0,59	1,00
Bacteria	2336,12	2334,99	-0,05	0,74	0,74	0,94
Phytoplankton	-	-	-	0,21	0,22	2,41
Detritus	-	-	-	0,94	0,96	2,41
Discards	-	-	-	0,75	0,75	0,00

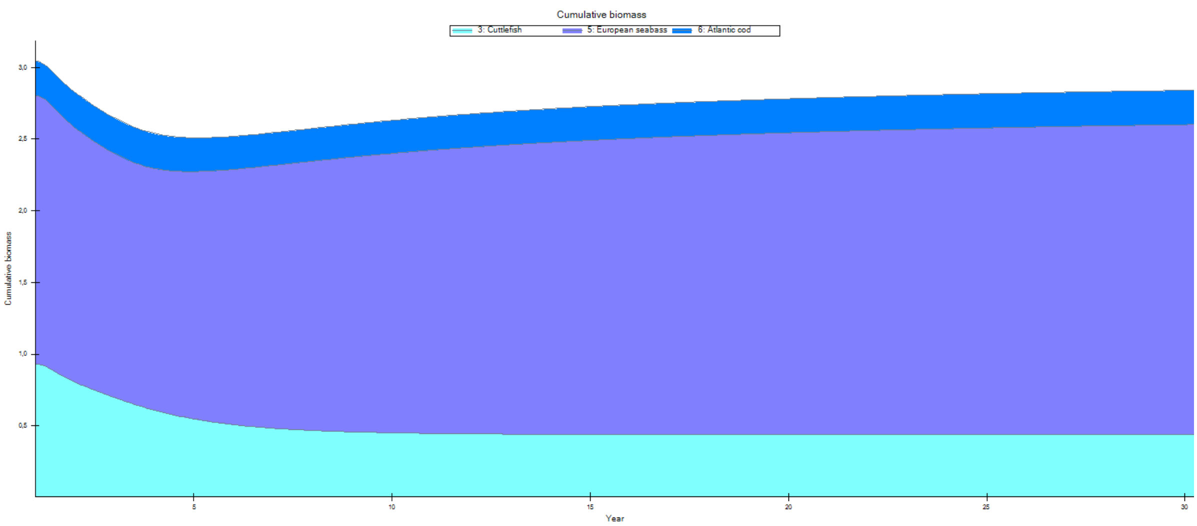


Figure 10.4: Biomass of Atlantic cod, Cuttlefish and European seabass in the scenario without additional hard substrate for the fist 30 years.

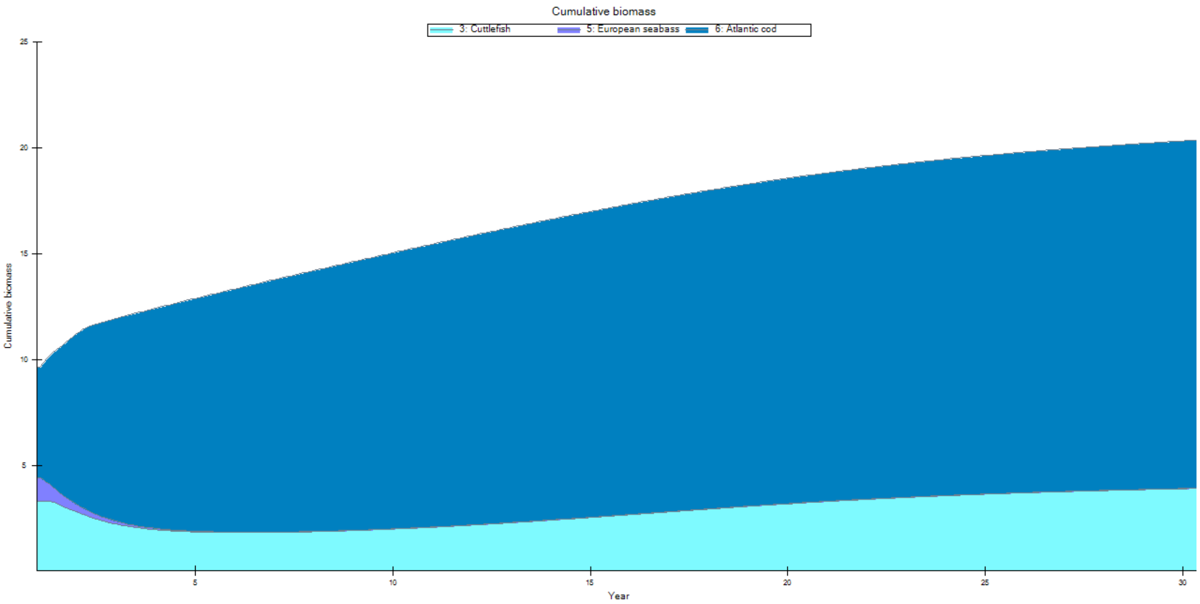


Figure 10.5: Biomass of Atlantic cod, Cuttlefish and European seabass in the scenario with additional hard substrate for the fist 30 years.

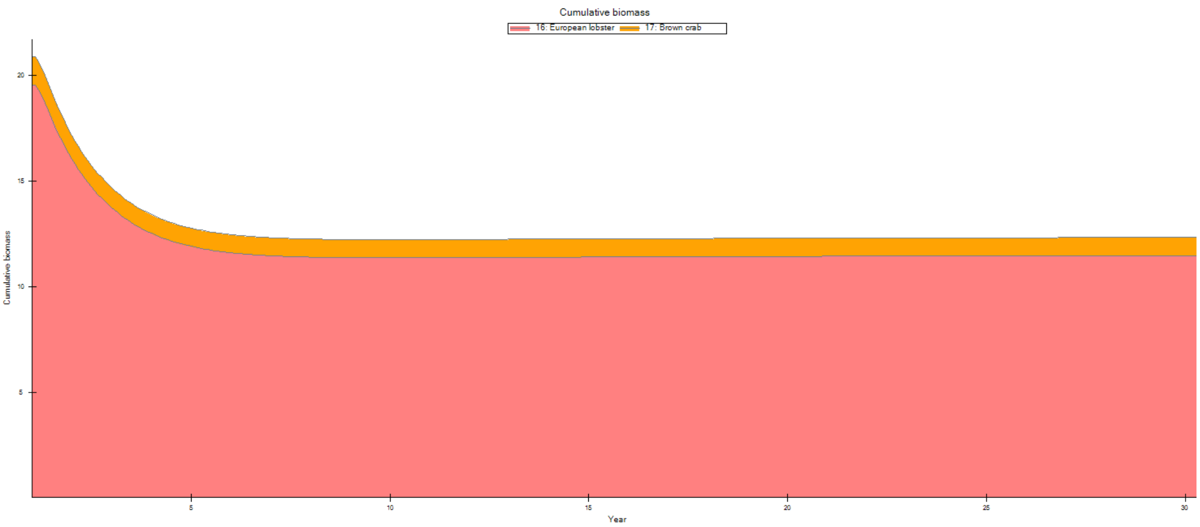


Figure 10.6: Biomass of European Lobster and Brown Crab in the scenario without additional hard substrate for the fist 30 years.

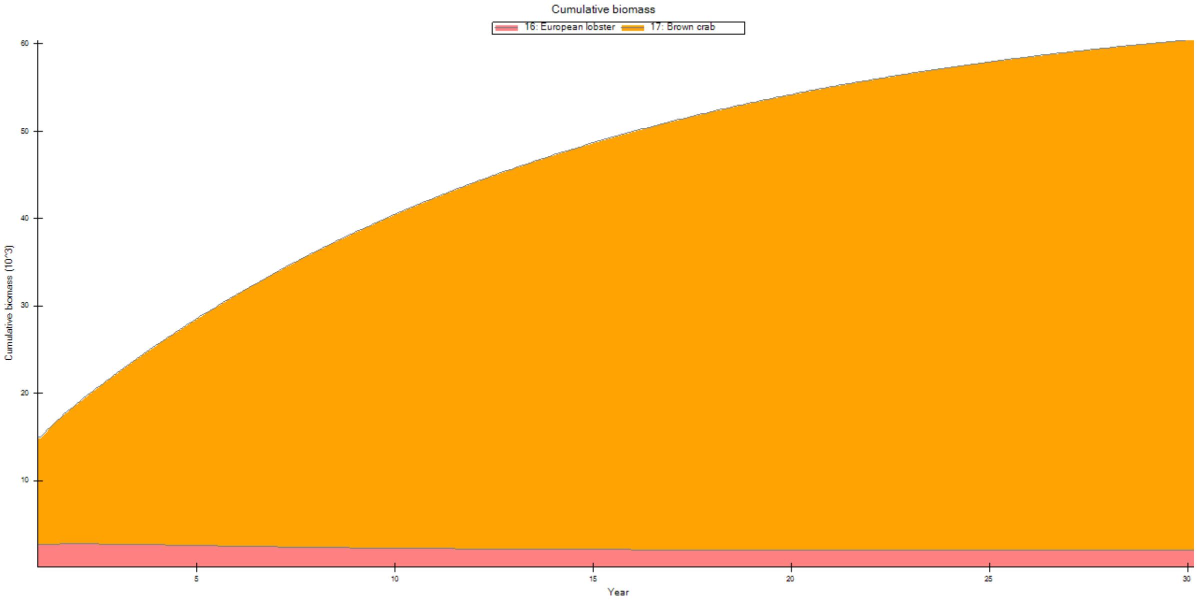


Figure 10.7: Biomass of European Lobster and Brown Crab in the scenario with additional hard substrate for the fist 30 years.

10.4 Fishing mortality situation

The Ecosim model was used to estimate the carrying capacity of the system by estimating the population biomass over a time period of 100 years. This information was used to estimate the maximum sustainable fishing yield the system could endure for our five target species. The landing biomass was increased gradually until the final biomass of the population reached half of its carrying capacity. This was assumed to be the maximum sustainable yield biomass [S. Jennings, M. J. Kaiser, J. D. Reynolds, 2001]. The landing data that satisfied this demand is shown in table 10.8. Landings for the other functional groups were set at 0. The progression of the catch over the first 30 years after implementation of the hard substrate is shown per target species in figures 10.8, 10.9, 10.10, 10.11 and 10.12.

Table 10.8: Landing biomass used to reach a final biomass of half the carrying capacity per target species

Species	Landings [t/km2/year]
Cuttlefish	0,5
European seabass	0,0028
Atlantic cod	1,3
European Lobster	275
Brown Crab	1000

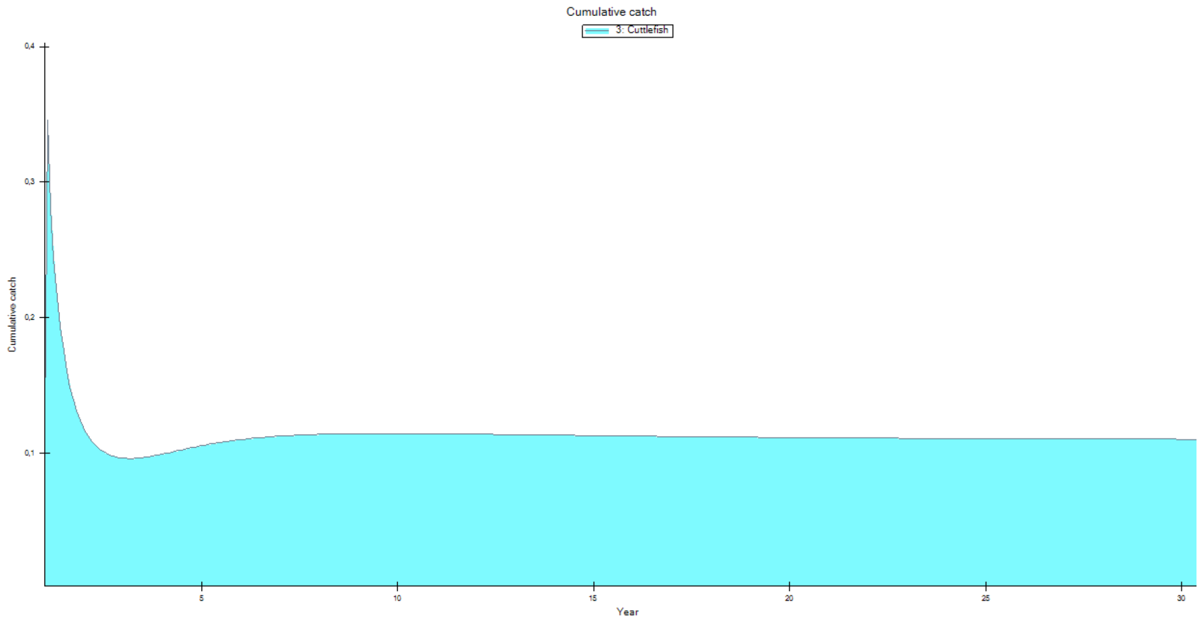


Figure 10.8: Catch biomass of cuttlefish for the fist 30 years after addition of hard substrate.

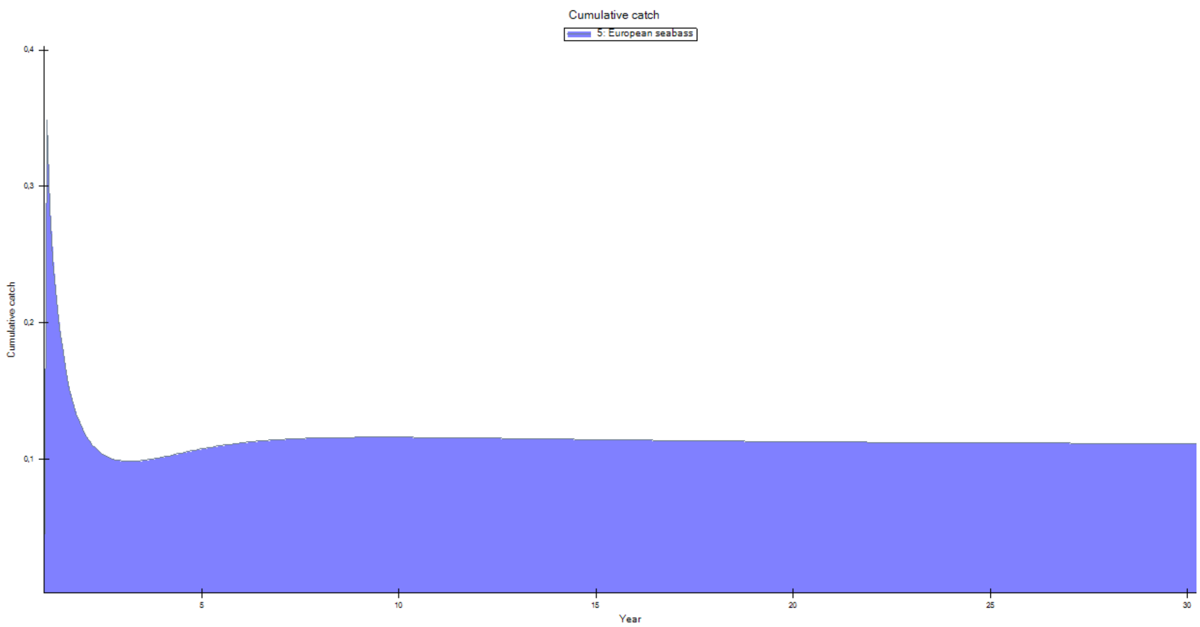


Figure 10.9: Catch biomass of European seabass for the fist 30 years after addition of hard substrate.

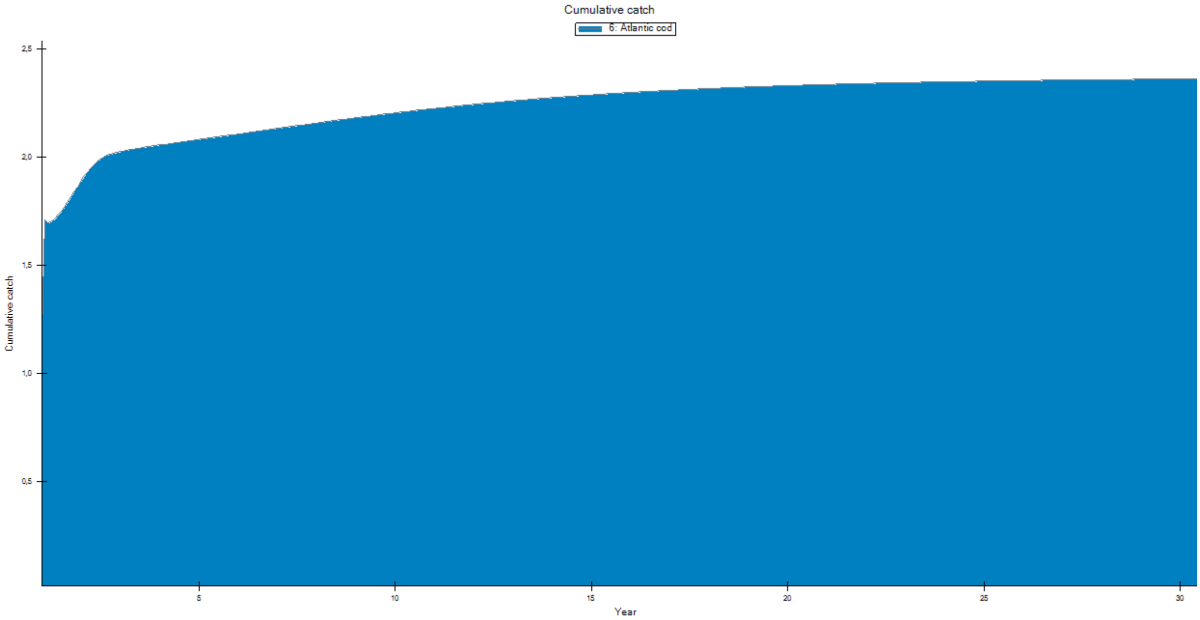


Figure 10.10: Catch biomass of Atlantic cod for the fist 30 years after addition of hard substrate.

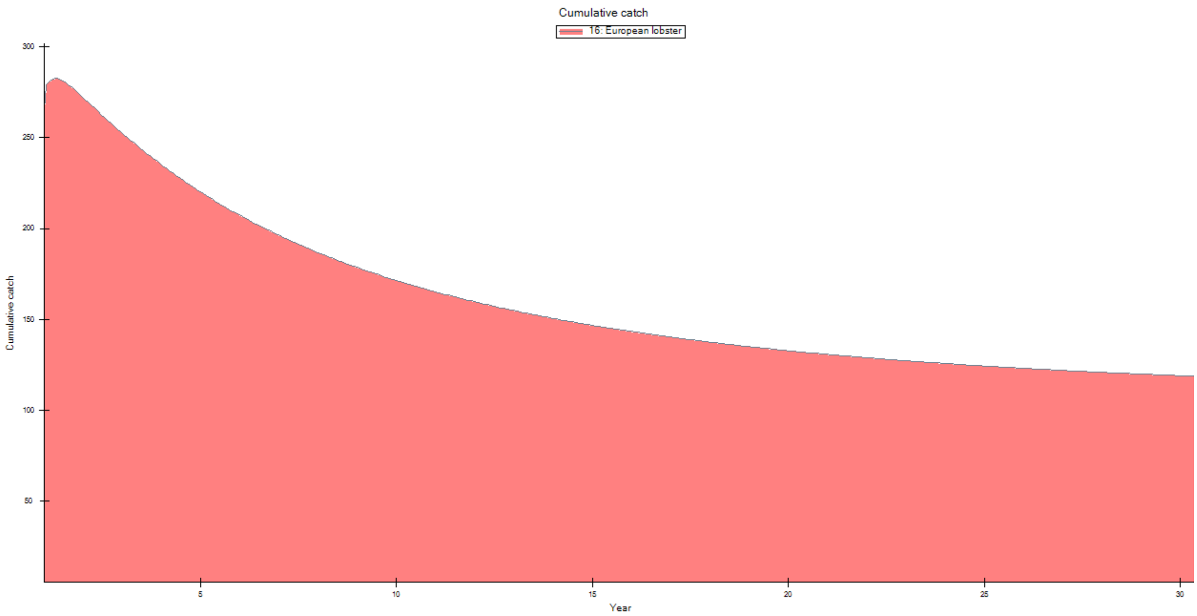


Figure 10.11: Catch biomass of European lobster for the fist 30 years after addition of hard substrate.

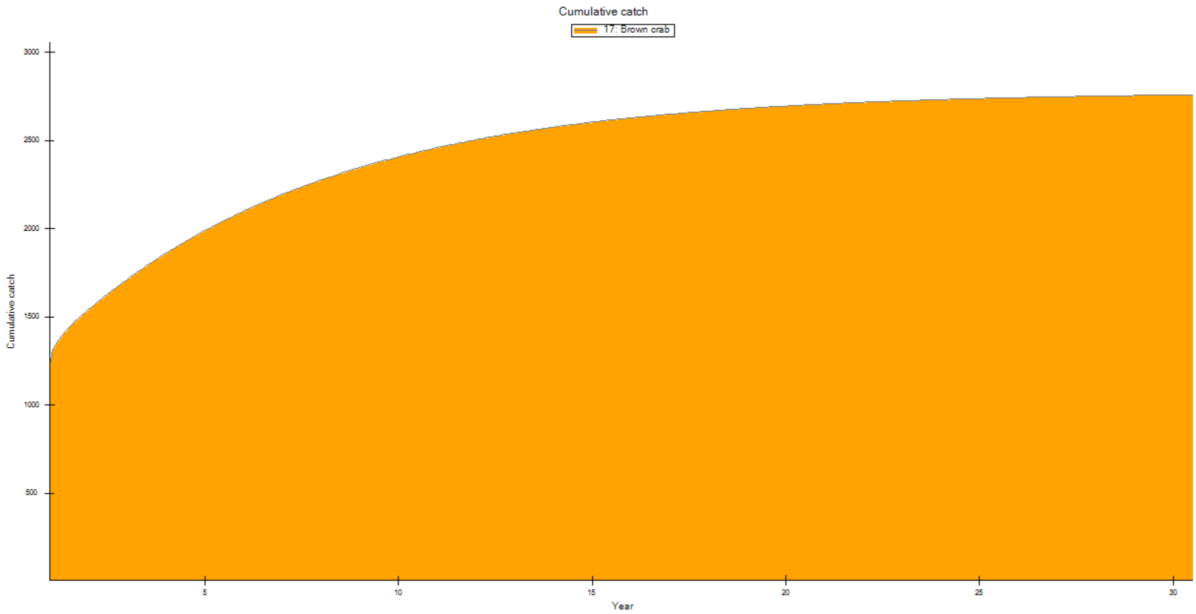


Figure 10.12: Catch biomass of brown crab for the fist 30 years after addition of hard substrate.

10.5 Evaluation of the model

10.5.1 Model validation

Although the use of the EwE model provides very useful information on the potential impact of the addition of hard substrate, the reality will certainly not follow this prediction precisely. In order to confirm whether the results of the model were within the realm of reality, they were compared to other trophic interaction studies. First, as seen in Table 10.1 in Section 10.2.4, trophic levels assigned to the different groups in the model were compared to two other studies, one by Christensen (1992), which also used EwE and the other by Yang (1982), which uses values from preceding literature studies. These values were vital in adjusting the dietary requirements of our model and establishing a realistic range of trophic levels for each organism. For those values that were comparable (some species or groups could not be accounted for), all trophic levels remained within a reasonably close range of each other, while those that deviated most from the other studies were adjusted to establish a smaller range for the final trophic level (also seen in Table 10.1). For example, the starting trophic level of cod was 5,1, whereas the values for Yang and Christensen were 4,4 and 4,0. It is likely that the starting trophic level for cod was higher because it included juvenile cod as well as adult. While this validation process did help to confirm that our trophic level estimates were plausible, it should be noted that the comparison is far from perfect, since the only other studies found date from 1981 and 1982, while the data used for our model date from 2007 and 2017 respectfully. Therefore, large differences regarding the state of fisheries in the North Sea combined with ecological conditions between these years could have a significant effect on this comparison.

In addition to comparing trophic levels, biomass estimates from certain groups in the model were compared to other data to check the accuracy of the final model. The estimated benthic biomass was compared to data obtained by Zintzen (2006) for shipwrecks in the Belgian North Sea. In this study it was found that the hard substrate of a structure can house 6,28 kg/km^2 sessile epifauna. Soft substrate houses 0,074 kg/km^2 infauna. When these values are extrapolated to our design this equals approximately 385 t/km^2 of sessile epifauna and infauna. The total benthic biomass estimated by our model is 3619,49 t/km^2. 21% of this value is accounted for by sessile epifauna and 30% by infauna [S. Mackinson, G. Daskalov, 2007]. This equals 1846 t/km^2. Our estimate is thus 4,8 times as high as can be expected when comparing to the biomass living on shipwrecks, which can be considered adults artificial reef structures. Lindeboom *et al.* (2011) analysed the ecological effects on the Egmond aan Zee OWF, in the Dutch coastal area. In this report the total biomass of blue mussel (*Mytilus edulis*) in the OWF is estimated to be 1257 g ash-free dry weight (AFDW)/m^2. This translates to 4,8 t/km^2 wet weight (AFDW/WW = 0,06, [S. Horn, C. de la Vega, 2016]). In this location there is an approximate hard substrate cover of 0,04%, based on the scour protection around each monopile. Extrapolating this value to the hard substrate cover of our design, this would lead to a biomass of *M. edulis* of 542 t/km^2. Unfortunately no account is given of the percentage of *M. edulis* of the total epifauna, but if we assume this to be 100%, a total benthos biomass of 2582 t/km^2 would be obtained (epifauna is 21% of total benthos, [S. Mackinson, G. Daskalov, 2007]). This would mean that our estimate is 1,4 times higher than the benthos biomass estimated in the Egmond aan Zee OWF. It should be noted however that the *M. edulis* biomass found by Lindeboom *et al.* (2011) was mostly found in the upper layer of the water column, and therefore the increase of hard substrate on the bottom might not lead to the increase calculated here. Nevertheless, based on Lindeboom *et al.* (2011) and Zintzen (2006), we can conclude that the benthic biomass estimated by our model is approximately 1-5 times higher than the estimated biomass of real situations.

Fish biomass estimations have been performed on (artificial) reefs by Whitfield *et al.* (2014) and Brock and Norris (1989) in both North Carolina and Hawaii. These studies provide us with a wide range of 40-2.250 t/km^2 of total fish biomass when modified for a situation with 5% hard substrate. The lower parts of this range is obtained from the studies in North Carolina, where the higher values are found in the Hawaiian reefs. The total fish biomass estimated by our model is 134 t/km^2. This fits well within the range found in literature, considering that a North Sea system would compare better with a reef in North Carolina than Hawaii. Unfortunately no workable biomass estimations of reef systems in the North Sea could be found to further validate the model.

10.5.2 Data sources

All EwE input values were obtained from already existing literature. For almost all functional groups the values were obtained, and when necessary modified, from Mackinson and Daskalov (2007). In some cases, for instance European lobster and European seabass, the functional group desired for our situation was not described by Mackinson and Daskalov (2007). In these cases data was used from Raoux *et al.* (2017). When the data from Raoux *et al.* (2017) was also not sufficient, the most comparable group was chosen to fulfill the role in the food web. In the case of Brown crab for instance, data from the functional group “Large crabs” from Mackinson and Daskalov (2007) was used, even though this group describes several crab species. Since Krone *et al.* (2017) found that 96% of the crabs at a monopile were brown crabs, our focus was solely on this species. It proved however difficult to subtract the data of the brown crab specifically from the functional group of Mackinson and Daskalov (2007). We therefore assumed that the biology of large crab species was comparable enough to regard the data general for all crab species. Additionally, it should be noted that Mackinson and Daskalov (2007) describe the North Sea system as a whole, whereas this report focuses specifically on the Borssele OWF in the southern North Sea. Furthermore, it should be noted that while this report models a "with and without" hard substrate scenario, it is not clear in the sources used whether the data originate from areas in the North Sea exclusively without substrate. This compromises the comparison for obvious reasons. However, because the North Sea benthos is largely dominated by sand, mud, and coarse sediment, rather than larger substrate such as rocks or stones, the data was deemed to be sufficient for a "rough" estimate. In addition, because no EwE models for the specific area of Borssele exist, the data from Mackinson and Daskalov (2007) was assumed to describe the location of this site sufficiently. A more fitting data set would improve the accuracy of the model. This goes for basic input (biomass, productivity and consumption) as well as the dietary data used in the EwE simulation.

When predicting the situation before and after the addition of hard substrate, the results of Raoux *et al.* (2017) were used. These results were projected on the functional groups largely obtained from Mackinson and Daskalov (2007). It should be kept in mind that there is a mismatch in location and time between these two articles. Where Mackinson and Daskalov (2007) describes the entire North Sea system for the years 1973 and 1991, Raoux *et al.* (2017) describes a specific area in the Bay of Seine (France) before and after the construction of the Courseulles-sur-mer OWF. The mismatch between these two articles causes the results of our model to be less realistic compared to a situation where all data would come from the same time period and location. Unfortunately, this data does not exist yet for the location of the Borssele OWF to our knowledge. Therefore, the current model describes the estimated effect of addition of hard substrate to a North Sea system as best as possible with the data that is currently available. Hopefully, as more research on this topic is done in the future, more finely tuned versions of this model will be produced.

The data obtained from Mackinson and Daskalov (2007) describes an average North Sea system. The Borssele OWF is however located in the Dutch delta, which has an above average primary production [L. van den Bogaart, M. Poelman, L. Tonk, S. Neitzel, J. Tjalling van der Wal, J. Coolen, M. Machiels, M. Rozemeijer, I. de Boois, S. Vergouwen, L. van Duren, 2019]. On a yearly average, phytoplankton concentrations are higher in this area compared to the total North Sea. It could therefore be that the potential total biomass of the system is underestimated by the model described in this report. In contrast to this, it should be noted that this EwE model assumes a constant biomass throughout the year. In reality however phytoplankton concentrations are heavily seasonal with strong peaks during bloom periods. Since the availability for consumers is not as constant as assumed in the model, it is likely that the potential biomass of the consumer populations is overestimated by the model. In a reality with peaks of phytoplankton biomass, consumer populations will likely not be able to reach the levels of a situation with a constant average phytoplankton level. Although Ecosim has the function to take seasonality into account, time constraints have prevented this from being included in the model.

Due to the lack of available data, no differentiation between the different kinds of hard substrate (e.g. layer cakes, shipwrecks, and jackets) could be made. In the EwE model it was simply assumed that all kids of structures contributed in equal measure to the effect of hard substrate. In reality, it seems likely that the various structures produce a different effect on biomass, production and consumption of specific functional groups. A Layer Cake could for instance be more beneficial to Atlantic cod than mere stones in the scour protection. These omitted factors would affect the biodiversity and production and consumption rates in the system. It is however at the moment not possible to make judicious assumptions due to the lack of sufficient studies comparing the effect of such structures on the scale of a larger ecosystem.

10.5.3 Data extrapolation

Another critical note on the expectations calculated by Ecosim lies in the extrapolation of the changes in basic input parameters of Raoux *et al.* (2017) to the models described in this report. A linear relation was assumed when projecting the changes found by Raoux *et al.* (2017) to our input for the scenario with added hard substrate. Where the area of Raoux *et al.* (2017) had a coverage of 0,684% hard substrate, our scenario worked with a coverage of 5,22%. It is likely that the linear extrapolation of the increase found in biomass and productivity for the crustacean species caused the growth in the scenario with additional hard substrate to be unrealistically large. Unfortunately Raoux *et al.* (2017) is the only article so far that describes the effect of additional hard substrate in the detail required for such an extrapolation. It is therefore difficult to find a realistic relationship between hard substrate and change in input parameters. The linear extrapolation comes with a number of unrealistic effects. First, in the case of a decrease in a parameter with an increase of hard substrate, the parameter could decrease to a point where it reaches a negative value. In reality the minimum would be zero. In the case of combined functional groups, it is impossible to see whether a parameter in one of the species combined in the group has reached an unrealistic decrease. This could cause an overestimation of a negative impact of hard substrate which causes entire functional groups to disappear from the system. Secondly, parameters are allowed to increase unlimited based only on the addition of hard substrate. In reality, there would be a point where another factor becomes limiting for the growth of the population and additional hard substrate would no longer cause the population to increase. It should also be noted here that for most groups the system is considered closed, which means no migration is assumed. As the Borssele area is relatively small, it is not likely that all the produced individuals will remain in the area, especially when populations begin to reach their limits. In a more refined model, the change of the parameters would thus have a minimum level and a maximum level, making it resemble more of an S-curve than a linear relationship. It is likely that when these additions to the extrapolation could be made, population sizes of European Lobster and Brown Crab would be substantially lower and therefore more realistic. Also this could cause groups that in our scenario disappear to remain present in the system. Additionally, the change in parameters by the addition of hard substrate was estimated solely with the data obtained from one single article. Naturally, additional data to estimate the effect of hard substrate on the system would improve the quality of the model. This lack of data explains for instance the marginal abundance of European seabass in the scenario with additional hard substrate. As European seabass is known to be dependent on hard substrate for prey, it was expected that there would be a positive relationship with its abundance and hard substrate coverage. Raoux *et al.* (2017) found however no such relationship in their research. Additional sources could help to better define the relationship between hard substrate coverage and population biomass of European seabass and other functional groups.

10.5.4 Conclusions

Despite the limitations of the EwE model in providing precise biomass estimates, the consequences of adding hard substrate to a North Sea system become clear. Even though the estimates are subject to the assumptions made where available data was lacking, the tendencies predicted are still of important value. The model shows the potential hard substrate addition can have on North Sea species and their interactions. The most noteworthy estimates with respect to addition of hard substrate of Brown crab (11608,94 t/km2) and European Lobster (2374,09 t/km2), indicate a great opportunity to enhance these fisheries within an OWF. This in contrast with a "before" biomass of 1,35 t/km2 for the former and 1,10 t/km2 for the latter. This result can be further supported with the knowledge that these two species, due to their sessile nature and inherent need for hard substrate, make them the ideal artificial reef fishery in an OWF. Finally, the possible economic benefit through the increase of species shows a broader application for this concept than just an ecological one.

Chapter 11

Economics of Sustainable Fisheries

11.1 Introduction

The economics of future sustainable fisheries along with the financial feasibility are two of the vital elements in the practicality of this concept study. In this chapter a pre-feasibility study has been executed to uncover the strengths and weaknesses of the business opportunities. In more detail, all costs and revenues throughout the lifetime of the sustainable fishery are taken into account resulting in a cash flow analysis that could be used as final investment advise. Both the costs and the revenue are dynamic and influence the project's financial feasibility. Therefore, in order to be as precise as possible, the costs and uncertainty are considered simultaneously in the Program Evaluation and Review Technique (PERT) method. Furthermore, in order to control the uncertainty related to revenue, all the sources of income are analysed with a normal distribution. Finally, a detailed cash flow analysis has been carried out in order to give a clear view on the different financial scenarios.

11.2 Costs

The first step taken in determining the financial feasibility is calculating the costs. All expenditures, which are subdivided in the capital expenditures (CAPEX) and operating expenditures (OPEX), related to the installation and operations of the sustainable fishery are taken into account. Consequently, the CAPEX is divided into six items of which the stones and block reefs account for around 70% of the CAPEX. The costs of the final design of the sustainable fishery, of which the quantities are shown in table 9.1, has been calculated deterministically as well as probabilistically with the PERT method. The costs are analysed per installed item, and an overview of all the costs is given below in figure 11.1.

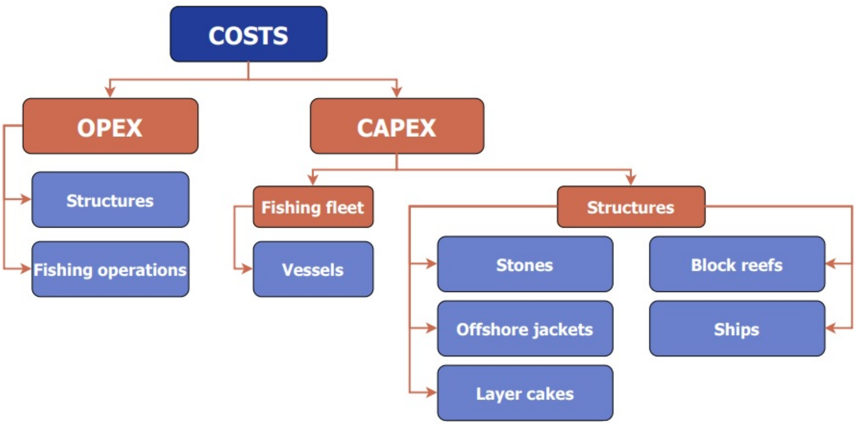


Figure 11.1: Overview of costs items

11.2.1 Deterministic cost estimating

Deterministic cost estimating is the conventional way of budget engineering of construction projects. Where possible this chapter consists of a solid bottom-up calculation which is applied to the cost items shown in figure 11.1. Despite the fact that the bottom-up method is considered to be very accurate, in this case, due to limiting information it is a time-consuming, uncertain and therefore a costly technique. However, in this report, the bottom-up method is used for calculating the 'most likely' factor of the PERT method, see table 11.3. The other two factors of the PERT method; 'optimistic' and 'pessimistic' are calculated with the price ranges of installation activities given in interviews held with different contractors and materials suppliers, which will be explained in chapter 11.2.2. In total there are 6 different structures to be installed, which all consist of different elements. A detailed study into pricing of the elements has been carried out. To summarize, the deterministic price estimation will be the base of the following probabilistic calculation.

Table 11.1: Overview of costs per structure

Cost items	Quantity	Price per unit (most likely)
CAPEX		
Structures		
Stones	5,1 mln ton	26,2 EUR/ton
Offshore jackets	56 pieces	975.000 EUR/piece
Layer cakes	1120 pieces	6.800 EUR/piece
Block reefs	1,57 mln ton	47,8 EUR/ton
Ships	56 pieces	88.392 EUR/piece
Fishing fleet		
Crab vessel	1.0 piece	20.000.000 EUR/piece
Long lines vessel	1.0 piece	10.000.000 EUR/piece

Capital Expenditures

In construction the capital expenditures are the total funds that are needed to construct or acquire the fixed assets. Therefore, it is the most important part of the costs and puts a strain on the budget and therefore the financial feasibility. The CAPEX consists of the following items: structures on the seabed and purchase of a fit for purpose vessel. The most ideal composition of structures on the seabed has been explained in detail in chapter 8. As the information regarding prices supplied by contractors or other sources were quite limiting, an estimation has been made with the broad ranges given. Besides that, as some sources supplied basic figures that could be used in multiple ways, the broad ranges of prices could be sharpened. A detailed elaboration on how the prices have been calculated is given.

First, the biggest item of the construction works are the stones and block reefs which also account for the biggest part of the CAPEX. The stones and block reefs are being installed with a rock dump vessel, the Rockpiper of Boskalis [Boskalis, 2018]. Although limited information is available, some figures could be used to determine the minimum and maximum value. The minimum value has been determined by a bottom-up calculation considering the total amount of stones, the production and day rate of the rock dumping vessel. As the constructions are relatively easy to install, the values needed for this calculation are chosen advantageously but reasonably. The maximum value is chosen by the main values given by Boskalis. The maximum price per ton of Boskalis is 40 EUR, see Appendix L. Together with the total volume of stones, the total value is calculated. Secondly, Layer Cakes are mainly installed for the biodiversity as well as to attract scuba divers. In total, 1120 Layer Cakes are planned to be installed which are clustered in groups of ten pieces. The Layer Cakes, which are being sold on the website for 10.000 EUR, are estimated to cost between 5.000-10.000 EUR because of wholesale discount. The installation will be done with a vessel that could store 100 pieces and could use 2t crane. Third, other significant cost items are the offshore structures and installation of old ships. The offshore structures need to be decommissioned, which is very cost intensive, before they can be installed in the field. The jacket structures need to be lifted and transported with a heavy lift vessel, which is estimated to cost between 300.00-400.000 EUR per day, see Appendix K. The purchase costs of the steel has not been taken into account because the structure owner is expected to support this alternative solution. On the other hand, scrap ships that are disassembled and cleaned in a ship scrap yard need to be paid for because of the steel. The price of the steel, which is taken as an uncertain factor, is between 0,21-0,25 EUR, see Appendix M. After the scrap ship is bought, the vessel will be taken to the offshore wind farm by one or two vessels. At last, the purchase of a new fishing vessel that is fit-for-purpose for in the area has also been taken into account. Two types of fishing vessels are being bought, one long liner and a crab fishing vessel. Regarding second hand prices and the expected size of the vessel, the long-liner is expected to costs around 10 mln EUR [Shipping, b]. The crab and lobster vessels need a much bigger capacity, therefore, the vessel will be much bigger and in the range of 20 mln EUR [Shipping, a]. As the vessels need to be upgraded, the price of the vessel is taken as an uncertain factor in the calculation.

Operational Expenditures

The Operational Expenditures (OPEX) are the expenditures incurred in daily activities such as repairs, maintenance, operations and wages. The OPEX have been divided in variable and fixed annual costs. The fixed costs which do no vary with output mainly consists of the maintenance of the structures on the seabed and the maintenance of the vessels. The variable costs consist of the operating costs that do differ when the output differs. The main variable costs are the expenses related to operating the fishing vessels (e.g. gasoline and wages) in the sustainable fisheries. In total, the fixed operating costs are estimated to be 2%, based on expert knowledge, see Appendix L. The variable costs are estimated to be around 4 mln EUR [UR, 2010]. The subdivided OPEX can be found in the table 11.3 and are taken into account in the financial model.

11.2.2 PERT Method

PERT is a method developed by the US Navy in 1958 and can be used in cost engineering [Hedden, 1987]. Constructing the sustainable fishery so far demands deep research into prices related to installation activities offshore. The deterministic calculation, which has been explained in the previous section, gives a little guidance and often gives the most likely value. However, as mentioned before, contractors or suppliers are not willing or able to give detailed information and therefore the deterministic calculation does not give a clear view of the potential costs burden. Therefore, the PERT method is introduced which also includes maximum (pessimistic) and minimum (optimistic) values.

Regarding the unknown figures of prices and the uncertainty of known prices, the PERT method is most suitable for this project. The PERT method uses an optimistic (a), most likely (m) and pessimistic (b) value (see formulas below). The optimistic and pessimistic value are calculated by the ranges received from the interview. The 'most likely' figure has been calculated in two ways. In case all data need to be calculated the most likely figure was available, the deterministic method has been used. For some items information was missing about the 'most likely' value. In those cases, the most 'likely value' was calculated by taking 25% of the value between the extreme values and adding this value up to the optimistic value. The value of 25% is chosen because of several reasons. Firstly, depicting higher prices does less damage than low prices. Secondly, the field lay-out is chosen in such a way that production offshore is higher than regular projects of contractors. Thirdly, the technical design is accompanied with less strict requirements. At last, there is no strict deadline on the works, so the contractor could make use of the calm periods within the vessel schedule. In the end, combining the bottom-up quantity calculation and the three-point calculation, the weighted average (E) and standard deviation (SD) is to be determined. As all cost items are considered to be independent, the weighted average can be added.

$$E = \frac{a + 4m + b}{6} \tag{11.1}$$

$$SD = \frac{b - a}{6} \quad (11.2)$$

Based on the PERT method an estimation has been made of all the cost items. From the information gained in interviews the most optimistic value was given as well as the most pessimistic. However, as prices are most of the time confidential, most companies give higher standard market values than low values. Therefore, we assumed the 'most likely' value resulting from a multiplication of 130% by optimistic. The three values are used to fit a PERT distribution for Monte Carlo simulations.

Table 11.2: Overview of CAPEX and OPEX

Cost items	Optimistic	Most likely	Pessimistic	Weighted average	Standard deviation
CAPEX (mln)					
Structures					
Stones	103,3	134,0	205,4	140,7	17,0
Offshore jackets	42,0	54,6	84,0	57,4	7,0
Layer cakes	5,9	7,6	11,5	8,0	0,93
Block reefs	62,9	75,1	103,5	77,8	5,0
Ships	4,9	5,0	5,3	5,0	0,065
Fishing fleet					
Crab vessel	18,0	20,0	26,0	20,7	1,33
Long line vessel	9,0	10.0	13,0	10,3	0,67
OPEX (mln/year)					
Structures		5,291			
Fishing operations		4,0			

11.2.3 Monte Carlo analysis - costs

The Monte Carlo analysis is a risk management technique that is used to analyze the impact of risks and therefore uncertainties in the project's financial feasibility. In this case a Monte Carlo has been executed with 1000 simulations. The weighted averages and weighted standards per cost item are acquired from the table above, see table 11.3. The total sum can be calculated resulting in the PERT distribution figures that can be used for the Monte Carlo simulation. The probability density function results from a Monte Carlo simulation.

The input values of the PERT method are retrieved from the table 11.3 which are based on the bottom-up and PERT method calculation. The mean has been calculated by adding up all the means together. The standard deviation used in the model has been calculated by taking the square root of each figures separately followed by the root of the sum.

$$\sigma = \frac{4(b - a)}{c - a} + 1 \quad (11.3)$$

$$\beta = \frac{4(c - b)}{c - a} + 1 \quad (11.4)$$

Table 11.3: Input values PERT model

Parameter	Symbol	Value
Optimistic	a	459,76
Most likely	m	540,90
Pessimistic	b	811,35
Mean	E	572,45
Standard deviation	σ	58,60
Alpha	α	1,92
Beta	β	4,08

The PERT method makes use of a skewed distribution. As calculated costs figures more easily increase than decrease, the skewness is more to the left. The mean value is 572,45 mln EUR meaning that the price will be this value with 50%.

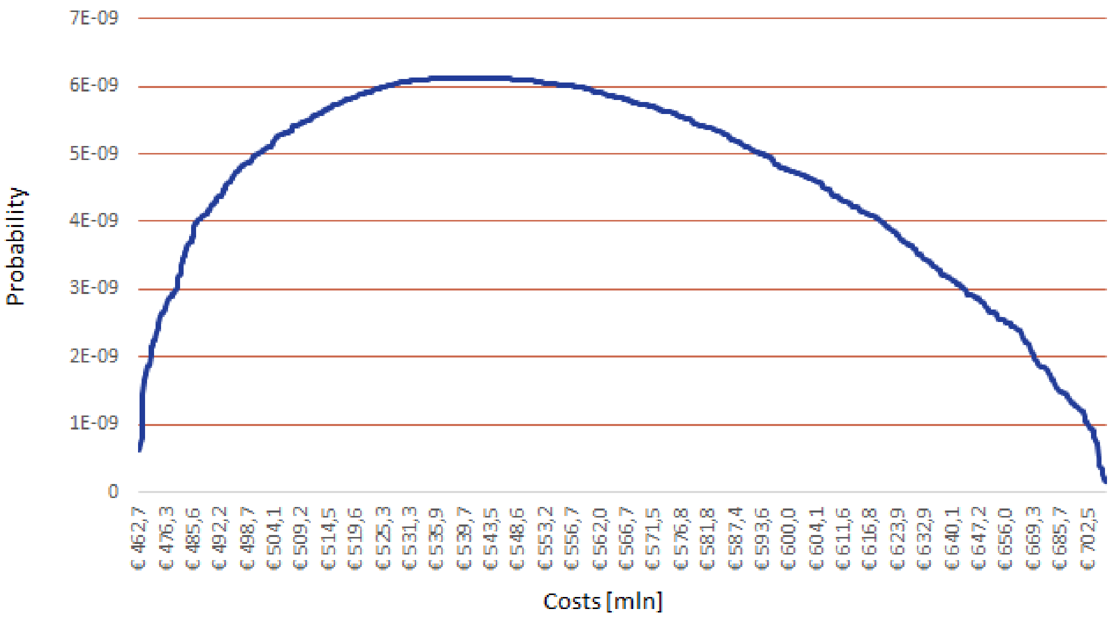


Figure 11.2: PDF costs

11.3 Income

The revenue gained during the project's life span of 25 years has been subdivided in the following categories: research institutes, tourist activities and commercial fishing. The research institutes are expected to be interested because of research purposes and therefore also contribute to the project. Secondly, the project is expected to gain huge interest of sport fishing and diving as biodiversity and the total biomass has increased significantly in the field. At last, the most important sources of revenue will be commercial fishing in which a few species have been selected, as described in chapter 5.

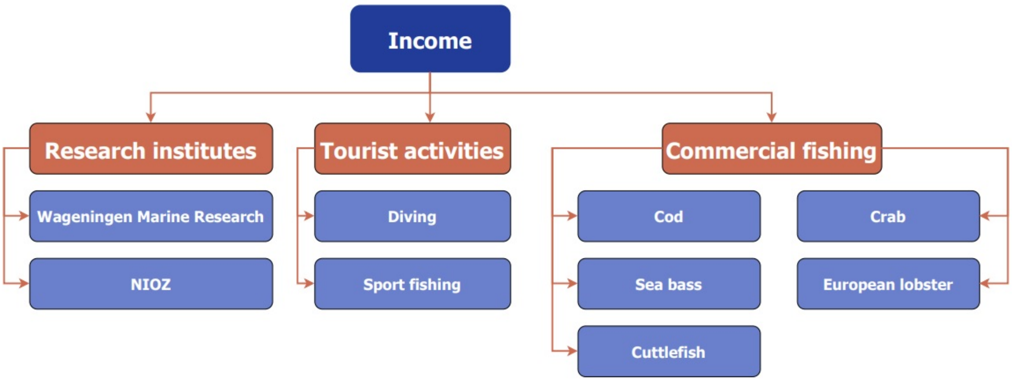


Figure 11.3: Overview of revenue sources

11.3.1 Commercial fishing

Commercial fishing will account for the biggest part of the income stream which is therefore considered highly important. The sustainable fishery mainly aims on fostering 5 species in the area. The expected biomass has been calculated with the EwE model, see chapter 10.

Table 11.4: Expected catchings biomass in first 5 years [ton]

Fish species	Year 1	Year 2	Year 3	Year 4	Year 5
Cod	212	219	221	223	226
Sea bass	0,28	0,25	0,23	0,22	0,21
Cuttlefish	11	11	12	12	12
Crab	154.259	174.206	191.452	206.339	219.174
European lobster	29.217	27.127	25.305	23.741	22.401

Next to the fact that the income of the project depends on the total available landings, the market price of the landings is also relevant. As prices of some species might be seasonally dependent and differ throughout the year, the prices of the last 5 years (2015-2019) have been taken into account. The prices considered are collected from all fish markets in the Netherlands and are recorded by the Dutch Ministry of Agriculture, Nature and Food Quality each month [EUMOFA, 2019]. The data of all Dutch fish auctions have been taken into account as these might give the most trustworthy values possible. Furthermore, the weighted average of the price has been taken into account as supply and demand of certain fish species is highly volatile. Based on these data, the average, variance and standard deviation of the fish prices through the period of 5 years have been calculated. See an overview of the values per specie below [Fletcher and Clark, 2002].

Table 11.5: Landing prices of main fish species in 2015-2019

Fish species	Mean Price [EUR/ton]	Std dev. σ	Variance σ^2
Specie A - Cod	3.210	600	360.000
Specie B - Sea bass	12.776	2.900	8.410.000
Specie C - Cuttlefish	2.007	1.200	1.440.000
Specie D - Crab	1.474	1.800	3.240.000
Specie E - European lobster	16.296	8.600	73.960.000

The total income from fisheries has been calculated by multiplying the biomass by the weighted average fish price assuming that the market price remains constant. As the price of the landings fluctuate throughout the year, an income stream has been calculated in which price and probability of the price have been integrated. Consequently, with a normal distribution, the probable revenue of the project over 25 years has been calculated including the depreciation factor. In more detail, all the distributions of the fish prices are considered to be independent normal distributions. Therefore, all distributions can be summed up together, resulting in a probability density function, see figure 11.4.

11.3.2 Tourist activities

Next to the commercial fisheries income stream there is a huge potential for tourist activities in the sustainable fishery area. The activities considered in this part are sport fishing and diving. Although the number tourists activity in the Netherlands is thriving only inland tourists are taken into account. Any future changes in quantities are interests of tourists are unknown and therefore not taken into account.

Sport fishing

The Dutch sport fishing accounts for more than 1.1 million recreational fishers in marine or fresh waters in 2017 [Hammen, 2019]. The total number of marine sport fisherman in 2017 was 529.000 [Hammen, 2019]. In order to estimate the yearly catches of this group, an online survey (50.000 households) was conducted in the research of Hammen. The result of the survey showed that 1.213 marine fish trips were recorded. Extrapolating this value to the total population of more than 17 million [CBS, 2019], a total of 414397 fish trips have been executed in the Netherlands. The catches during a fishing trip are calculated to be between 1-5 cod, which have a size of 46,6 cm and a gutted weight of 1,36 kg which comes down to approximately 2 kg per fish [FAO, 2001].

The total fishing activity in the area is difficult to estimate. Therefore, a rough estimation of 10.000 certificates will be sold in the area, which is 2.5% of the total fish trips. In practice, this comes down to 1 full vessel with cod fishermen sailing to the area each day. The total catches of biomass are 60 tonnes, which are taken into account in the biomass analysis. As the normal cod price, shown in table 11.5, is 3,21 EUR, the yield per catch needs to be higher when sport fishing is done in the area. In case the revenue will not be higher, this activity will be prohibited. As the gutted weight is 1,36 EUR and the average number of catches is 3, the minimum price needs to be 20 EUR per certificate.

Diving

Although diving has the reputation in the Netherlands of being an uncommon sport, there are 300.000 scuba divers of which 14.000 are a member of the Dutch association for divers (NOB) [onderwatersport bond, 2018]. Diving will be a very interesting activity to do for tourists and local people. There will be plenty of structures such as jackets and shipwrecks to explore. Furthermore, there are also shipwrecks already present in the area. All these structures might attract sea life and are therefore interesting for all kinds of scuba diving. Although it seems to be hard to acquire data regarding scuba divers, a percentage of 5% of the total scuba diving community is expected to go diving in the area each year. A certificate for a diving trip in the area will cost 10 EUR. It is a extremely rough calculation in which tourists are not included. At last, there are no disadvantages to diving activity in the area. Thus, it will not have influence on the ecosystem or the total biomass.

Table 11.6: Revenue tourist activities

Tourist activities	Quantity	Mean Price [EUR]	Std dev. σ	Variance σ^2
Sport fishing	10.000	20	1	1
Diving	15.000	15	3	9

11.3.3 Research institutes

Wageningen University Research (WUR) & Wageningen Marine Research (WMR)

The goal of the sustainable fishery operator is to manage the area as well as possible. With all the technology in place, it could be an interesting location for research institutes such as NIOZ and the WUR. As there is still a lot of knowledge to gain about the sea, the Dutch government could be interested as well. As the WUR receives millions in subsidies from the Dutch government as well as from other businesses and the project might add value to Wageningen Marine Research, a total value of 500.000 EUR subsidy is estimated [WUR, 2018].

NIOZ

The Royal Netherlands Institute for Sea Research (NIOZ) is the oceanographic institute for the Netherlands and performs and promotes applied marine research. The organisation has its own North Sea Centre of Expertise that is doing research in the fields of: habitat conditions, seabirds & fish, carrying capacity and seaweed farming. All these extremely relevant topics in this project might in fact reinforce each other. In more detail, NIOZ gets the possibility to do research in the field and even influence the design or use of certain material. In return, the sustainable fishery operator has the possibility to make use of the knowledge to improve the system.

Table 11.7: Research institutes

Research institutes	Quantity	Mean Price [EUR]	Std dev. σ	Variance σ^2
WUR/WMR	1	500.000	50.000	2.500.000.000
NIOZ	1	100.000	20.000	400.000.000

11.3.4 Monte Carlo analysis - income

For the analysis of the income, a Monte Carlo simulation (1000 simulations) has been carried out with a normal distribution. The input values of the simulation can be found in table 11.9.

Table 11.8: Input values revenues

Input	Value [mln EUR]
Mean	13.248
Standard deviation	2.158

The sum of all the revenues are presented in a normal distribution in which all the standard deviations are calculated by the general rules of adding normal distributions. The simulation shows a mean of 13.248 mln EUR with a minimum extreme value of 6.632 mln EUR and a maximum extreme value of 17.666 mln EUR.

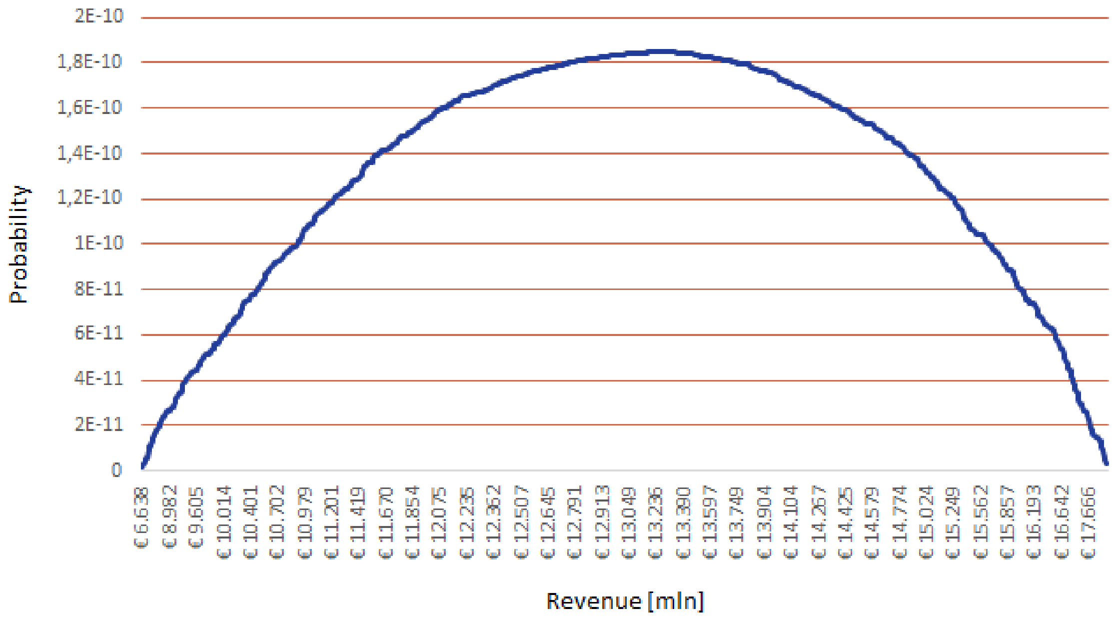


Figure 11.4: PDF revenue

11.4 Cash flow analysis

In the cash flow analysis of the sustainable fishery all the costs and revenues are considered over a lifespan of 25 years. Counting starts when the first capital expenditures have been done, which takes approximately 2 years. The cash flows have been summed up including a deflation factor, see table 11.9. The cash flow consists of income and costs, the CAPEX are subdivided equally over the first 2 years of the project. The revenue is spread over year 3-25. When the revenue is gained, the operational costs also come into play.

Subsequently, the total revenues, CAPEX and OPEX are summarized in the pre-tax cash flows including a deflation factor. Thereafter, in order to calculate the post-tax cash flows, the assets are depreciated and the OPEX and revenues are subjected to tax. In the end, a net cash flow has been calculated with a rate of 18%. The future cash flows including the depreciation and tax rate are depicted in the graph below, see table 11.9.

Table 11.9: Input values cash flow analysis

Parameter	Value [%]
Inflation	2
Corporate taks rate	17
Depreciation	18

Below in table 11.10, the input values and the results in both before and after tax deduction are shown. As reference a NPV 7% is given in order to show the results of a potential investment.

Table 11.10: Economics of sustainable fishery

Parameter	Unit	Value
Input values		
CAPEX	[mln EUR]	319,9
Variable annual OPEX	[mln EUR/year]	4,0
Fixed annual OPEX	[mln EUR/year]	5,79
Revenue before tax		
NPV 7%	[mln EUR]	4.502
Pay-out time	[year]	3
IRR	[%]	77,48
Revenue after tax		
NPV 7%	[mln EUR]	3.715
Pay-out time	[year]	3
IRR	[%]	69,90

Furthermore, below in the cash flow analysis 11.5 three line graphs are added, each showing the Net Present Value (NPV) compared to other investment opportunities with different IRR rates (3%, 7% and 10%). As shown in the graph, the NPV of 3% has the highest value. This value could give a clear view to investors what the future result will be compared to other investments with different IRR values. As the NPV of 10% still gives a high positive value of 3.000 mln EUR, the investment is considered to be highly profitable.

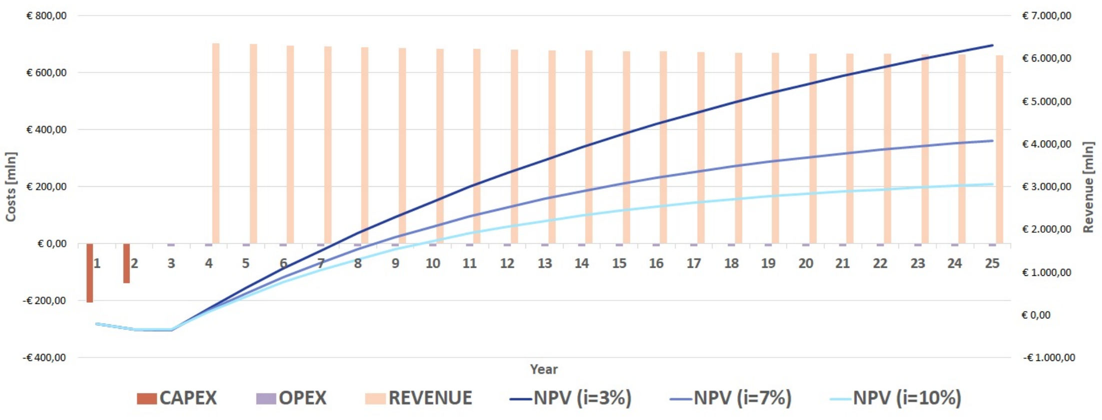


Figure 11.5: Cashflow analysis

11.5 Conclusion

In this chapter, all the financial flows in the project of the sustainable fishery have been considered. The costs consist of CAPEX in the first 2 years after which the OPEX remains the only costs throughout the lifetime. The revenues of the project consist of commercial fishing, tourist activities and research institutes of which the commercial fishing accounts for the main part of the costs. The cash flow analysis shows a final NPV result at year 25 of values between approximately 3000 and 6000 mln EUR for discount rates of 3% to 10%. Therefore, the results of the economics prove to be extremely profitable with an Internal Rate of Return (IRR) after tax of 69,90%.

Chapter 12

Fish-as-a-Service

12.1 Introduction

In the chapters Stakeholders and Economics of sustainable fisheries, the need arose for a different system within OWFs. Unfortunately, based on literature and interviews, it becomes apparent that wind farm clients are not interested in participating in the fishing industry. Nonetheless, letting fishing ships roam free in an OWF without clear instruction on safety behaviour may become a high risk, dangerous problem. On top of that, insuring the wind farms will become too costly. For that reason, there is a need for a different, updated system. This system should create new opportunities where the fishing and offshore wind industries can come together and cooperate. There are already calls to give room to innovative projects or projects that make use of multi-functional use of the space. There are also pilots running that stimulate the growth of oyster banks in offshore wind farms [kamer, 2019]. One other solution that might bring about this cooperation is the Fish-as-a-Service concept.

12.2 Problem analysis

First, a brief overview of the principal challenges will be briefly explained. In order to revive the current state of the ecosystem, large investment costs are necessary. The cost for dumping the rocks, placing the layer cakes and sinking jacket systems from old oil and gas platforms are immense. Any investors, banks or other investment companies would want a guarantee of a certain return on their investment. This means that a solid business case will be required, showing the feasibility, complexity, and duration of the project with cash flows. Next, offshore wind farm operators are fearful that the safety of wind parks will become an issue. If there are not any strict regulations around ancillary activities such as fishing, insurance companies will charge immense fees when insuring the wind parks. Therefore, there should be strict regulation and instruction regarding the permitted fishing methods. Another point is the monitorization of the local ecosystem. For nature organisations continuing enhancing biodiversity and maintaining the local population of predatory fish is vital. If fishing finally gets permitted in the area, then the fish stocks need to be monitored. There is a crucial difference between the fish stocks the fishing industry prefers and the fish stocks that marine biologists opt for. Economically speaking, the fish stocks of the target fish should be kept where the S-curve has the highest slope angle. Here the growth of that particular fish species is the highest meaning the return on biomass is most effective.

As was brought to light in the chapter stakeholder analysis, both fishermen and scientists want more data, and thus research in OWFs is required. From interviews with NIOZ, it becomes clear that currently researchers have to spend a fortune on ships, permits and crew before they get the possibility to execute some field work in these OWFs. These regulations are often based on a standard safety protocol from offshore maintenance work. One example of this work might be when divers need to perform maintenance on certain oil pipes on the bottom of the sea. These current safety regulations are too strict for researchers.

12.3 Product-Service System: Farming as a Service

A Product-Service System (PSS), which is considered by many as a excellent vehicle to enhance competitiveness and foster sustainability simultaneously [Tukker, 2004], consists of 'tangible products and intangible services designed and combined so that they are jointly capable of fulfilling specific customer needs' [U Tischner, 2002]. The PSS has been subdivided in three main categories: product-oriented services, use-oriented services, result-oriented services [Tukker, 2004].

A practical example of a Product-Service System is the Farming as a Service (FaaS) which pretends to be promising tool in developing agricultural countries [C Mitchell, 2018]. India in particular is a good candidate for such a concept, especially since its population is growing while the efficiency and productivity of its agriculture is lagging behind when compared to other countries at the same socio-economic level. To cover the potential in the business, FaaS provides affordable technologies for efficient farming as it transfers fixed costs into variable costs. The services are available on a subscription or pay-per-use basis in three broad categories: farm management solutions, production assistance and access to markets [C Mitchell, 2018]. Those categories will be explained in further detail below.

12.3.1 Farm management solutions

The first category in the FaaS model, farm management solutions, offers information sharing by cloud computing technology, analytical and precision farming tools. In other words, the farmer could use the wisdom of the sector as well as other farmers which in the end will lead to more successful decision-making by making use of data of fellow farmers. Furthermore, information sharing also contributes to the degree of involvement of other parties such as governments, corporations, financial institutions, advisory bodies and nature conservationists.

12.3.2 Production assistance

Production assistance contributes to on-farm decision-making by offering resources to aid production. Those resources involve equipment rental, labour services and utility services. Equipment rental consists of traditional products or innovative tools such as aerial spraying drones. Labour and utility services are the basic needs such as electricity or water that are needed to run a farm.

12.3.3 Access to markets-platforms

Digital trading platforms are platforms that connect farmers with suppliers of agricultural products such as: seeds, fertilisers and other agrochemicals. Such digital trading platforms create freedom for the farmers to choose economically. Next to the fact that farmers can buy products, they could also sell their products via B2C e-commerce market-platforms.

12.4 Fish-as-a-Service

Within the possible options of a Product-Service System, the Fish-as-a-Service concept can be considered to be pay-per-service unit which is a part of the result-oriented service [Tukker, 2004]. This model is a pay per fish model as the fishermen are buying certificates to enter the field on a regular basis. In other words, the fishermen can always decide to quit buying certificates.

The Fish-as-a-Service concept is based on the farming as a service model. However, there are some significant differences between those two. First, the sea is a much more difficult and dynamic system to interact with than agriculture ground. Second, the organizational structure of properties, dependencies and distribution of responsibilities are different. At last, number of involved stakeholders is significantly higher.

In this concept there is next to the offshore wind farm owner a fishery manager/owner who together with the offshore wind exploiter determines the policy regarding fishing in a wind farm. The policy which is described in the following sections treats topics such as: management of the area, fishing techniques and market places. Basically, the fishery owner ensures that there is enough fish available and determines the amount that can be caught. Consequently there are fishermen that want to fish in the area, but the owner determines the allowable vessel requirements. One of the earning models is that the fishermen need to pay per use when entering the field. In this case the owner has the urge to guarantee enough fish each day. Another business model is that the owner also owns the vessels that are allowed. In this case the fishermen are employees of the owner.

12.4.1 Fishery management solutions

Currently the sea bottom is low on biodiversity and biomass with monopiles and scour protection in a grid shape. In order to help the area grow towards a well-balanced, biodiverse ecosystem, a thoughtful management plan needs to be made that gives space to all necessary elements in the system throughout their lifetime. In fact, the plan needs to be thought through to a further stage. Technology needs to be involved to keep track of innovation and make well-substantiated choices. Therefore, in this section the basic state and monitoring technique are described followed by data-driven decision making and the question how to guarantee the safety of the area with the aid of technology.

Monitoring the state of nature

The cornerstone of the whole concept is connecting theory and practice and thereby strengthening both parts. The goal is to get more knowledge concerning the relationship between ecological circumstances, marine fouling to offshore structures and the quantity and type of fish species. Therefore, to cover the first goal, measurement equipment has been installed over the whole water column measuring the basic parameters such as chlorophyll, phosphorus and nitrogen. Next to the ecological base parameters, the sea conditions such as current and wave heights will also be measured. To research the second goal, practical research will be executed by divers who bring marine fouling to the lab on a regular basis to find out what the relations are between substrate materials and marine fouling species. For the last goal, radar systems that are usually used on fishing vessels will be installed on offshore jackets on the seabed or monopiles to monitor the size and movement of schools of fish. By installing these systems, a holistic view of the entire ecosystem and its human interactions can be acquired.

Data-driven decision making fishery management

All the data derived from the three types of research mentioned in the previous section 12.4.1 are being stored in a cloud. With all this data further research is being conducted in order to find answers to questions regarding the productivity of the area and the carrying capacity of the North Sea.

From all target fish species a random selection will be chosen to chip fish and consequently track them. Some of the target species are more likely to migrate and will therefore be chipped with higher quality trackers that have the ability to send signals to receivers on a greater distance. This type of research is especially important for species that are seasonally dependent on their food and therefore must follow their prey's migration patterns rather than staying in one place.

Poaching

In the scenario of a sustainable fishery there are only fishing vessels allowed in the area that fulfill the requirements. Poaching might become a serious problem if it becomes apparent that the area has productive catch numbers. As any activity of these poaching vessels increases the risk for damages or failures, it is a top priority preventing these vessels from entering the area. Fisheries patrols with patrol vessels could be a solution to this potential issue. However, as 24/7 patrol vessels are highly expensive with high variable costs and do not have a high success rate, some form of a 'hands off' technology will likely be a better solution. Protecting the area by aid of technological solutions could be done by: adding trackers to certain fish, checking movements in the area constantly and installing infra-red cameras on monopiles.

12.4.2 Fishing assistance

The strict requirements concerning fishing activities create room for new policies in the fishing industry. The urge to monitor and control fishing activities in the field gives the opportunity to get a fresh view on the fishing industry. The fishing industry could make use of the offshore wind projects by innovating their fleet and improving their landing products. Below, per item has been explained what the measure will look like, what the benefits are and why the measure has been taken.

Controlled fishing activities

The most important reason for offshore wind operators not allowing fishing activities in the offshore wind farm is the risk accompanied with fishing methods such as bottom trawling. Besides that, as these activities take place underwater it is hard to control and check the extent of the damage and the people involved in case of an accident. Therefore, the only fishing activities allowed in the area will be methods that in worst case could not cause any damage to the vital core activities of the OWFs. This includes methods such as long lines, nets or cage fishing. However, in order to make the fishermen more aware of the exact location of there hooks and to prove that the activities taking place in the area concerning fishing do not entail increased risks, all boats, hooks, nets and cages would be fitted with location trackers that can be monitored continuously.

Data-driven decision making in fishing activities

The goal of intensifying fishery management activities is to create a well-balanced nature-based biodiverse ecosystem in which fishing activities have been taken into account. The second goal is to fish as efficiently as possible with the least effort and reduce the number of bycatch. Therefore, the data resulting from the continuously fish tracking mentioned in section 12.4.1 is to be used efficiently for fishing on the right locations, abundant fish and e.g. seasonally dependent species. This will lead to a substantial increase in the catch per unit effort and a target species strategy, which in the end will be better for all parties involved. To summarize, the data processing that is associated with monitoring and data accumulation will lead to optimisation and innovation in the expectations of behaviour of schools of fish. In addition, the fishing tactics could also be analyzed and eventually be reconsidered.

In practice, the data accumulated for the general fishery management will be transferred to the fishermen. The vessels will also monitor activities, including total catches per species and the quality and size of the fish. All these data will be sent to the cloud, which in the end could use the data for processing and important predictions.

Eco-friendly fishing activities

Eco-friendly is a broad understanding, especially in the context of fishing activities. Therefore, a little more explanation on how to use eco-friendly in the perspective of fishing activities could be helpful. At first, the lobster and crab cages will be equipped with sensors that measure the activity in the cages so these will only be harvested when needed. Second, fishing gear that disturbs the ecosystem (especially benthos) or creates bycatch will be prohibited. This means that harvesting of target species should be done using long lines, traps, or nets, which implement innovative designs, such as "gates," which release non-target or bycatch species. At last, the vessels allowed in the fishery are to be equipped with a stunning machine for fish before the fish is cleaned [N. Anders, 2019].

Furthermore, as it is already in the name, sustainability is one of the core values of the sustainable fishery. Although the marine industry and therefore the fishing industry is, compared to other sectors lacking behind in transforming to CO2 neutral transport activities, this project will only allow CO2 neutral fishing vessels.

12.4.3 Access to markets-platforms

Having invested in the total supply chain of the fishing industry gives the possibility to fully control the final product. As a result, introducing certificates are a possibility to promote the product. Furthermore, being sure about the quality and guaranteeing the quality creates the opportunity to sell the fish without a market place.

Certificates

The use of sustainable certificate labelling in an OWF under the Fish-as-a-service concept can potentially attract consumers and open access to markets. For example, the Marine Stewardship Council, which assigns MSC certified labels to commercially fished species, ensures that the fish within their supply chain are traceable and harvested in a sustainable manner. An OWF under a Fish-as-a-Service management system should follow suit, perhaps even devising its own sustainable certificate system.

The goal is to create a certificate that guarantees product quality regarding all the activities related to the sustainable fishery. This includes activities related to the installation of the artificial reef to interaction with the consumer. The main focus points are the sustainability of fish stocks, local catch, CO2 emissions and eco- and welfare-friendly fishing and cleaning methods.

Digitize selling process

The process of selling landings from the fishermen to the fish traders traditionally goes via the fish markets that are present in Dutch fishing towns. However, this process takes time, adds a middle man and therefore, costs money for both the fishermen and the fish trader. The process is needed for traders as the quality of fish might differ throughout the year or due to storage techniques on board. Because the process of tracking both the fish and fishermen, making use of standard vessels, standard sailing procedures and fish certificates, the quality of the fish will meet the new higher standard. Therefore, a vessel with a track record, would rather get the confidence of a trader who, therefore, tend to be quicker in purchasing the product. At the moment, there are already initiatives with selling fish while the vessel is still in production [vissersbond,]. This digital market could give the potential for fishermen to sell to export markets directly and therefore increase their sells.

Part 4

Conclusion

Chapter 13

Discussion

The overall discussion of this project is defined by the substantiation through the discussion points of each discipline. Chapter 13 continues in on how the approach of each subject-oriented problem could have lead to such outcomes. To explain a bit more, one might for instance ask whether the stakeholder analysis led to a correct explanation on how the different parties are involved. Therefore, the stakeholder analysis will be discussed in the first place.
Secondly, a thorough discussion on the biomass estimates and the notion about attraction vs. production is presented. As a logical consequence, different potential concepts can be brought up to advance the biological potential.
In the design phase one has considered sustainable and effective structural solutions for the problem, more elaboration is made on how the technical input could have been improved. Financial remarks conclude chapter 13.

13.1 Stakeholders

Although the stakeholder analysis has been thorough, the main discussion point is the actual validity of the input. To clarify, the majority of the input data used, is obtained from long-term policy plans, annual reports, or company websites. Nonetheless, without the possibility for the commissioned process manager to verify the reaction of the spokesman in a personal interview, there is considerably less room for the actual validation of the interviewee's response. While one can argue that lying in a process is permitted and sometimes even necessary or inevitable [de Bruijn, 2010], the actual stance of the actor becomes much more apparent in a personal meeting than one would ever find on a company website. The main reason that some stakeholders were not personally interviewed was a combination between the MDP's fixed time duration and the overall accessibility of some of the actors. For example, critical actors such as the NWEA and TenneT were not interviewed. In addition, the genuine opinion of those actors remains debatable. Notably, critical information regarding the views of the different actors was obtained via expert advice from prominent professors of Wageningen Economic Research and Wageningen University and Research. These experts are specialized in sustainable fisheries, policy management, and fisheries economics. Besides those two organisations, co-operation with the knowledge institute Royal Netherlands Institute for Sea Research (NIOZ) and contractors, such as Seaway Heavy Lifting and Royal Boskalis, proved invaluable in the data collection process. Arguably, information was acquired that could not be gained from the actors themselves.

13.2 Biology

13.2.1 Biomass estimates

As was the key purpose of this report's biomass analysis, the final result in Chapter 10 presented Table 10.6 to show the final biomass estimates for the Borssele OWF before and after hard substrate was added. In this section, results of the table are discussed.

Of noteworthy mention are two rather unexpected results presented in Table 10.6, namely, the large increase in the Flatfish functional group and the biomass decrease in European seabass. The large increase in Flatfish is rather counterintuitive, since it is known that Flatfish species tend to dominate areas lacking hard substrate. However, there are two possible explanations for this. First, the model categorizes Flatfish into a very large group of species, and second, the potential OWF described in this project covers a large area, which is not completely covered with hard substrate. In addition to that, the overall biomass in the system, including the prey items for Flatfish, increase with the addition of hard substrate. This likely enables the Flatfish biomass to increase. Rather puzzling in the model is the decrease in European seabass, which would only be expected to benefit from such a scenario.

As mentioned previously, European Lobster and Brown Crab have the most impressive biomass increase with the addition of hard substrate. This can be expected, since these are the species most dependent on artificial and/or natural reefs for shelter. This concept will be further discussed in the following subsection. The two reef dependent species are therefore the species of greatest economic interest in this report and likely have the greatest success in a bio-enhanced OWF.

Another expected result from the model is the stable or even decrease in biomass for the pelagic species. More mobile, pelagic fish species will be less dependent on artificial reefs for recruitment and production, so the fact that the model reflects this is reasonable. For example, species such as Mackerel, Atlantic Horse Mackerel, and European Sprat all have negligible changes in biomass, with Mackerel even having a slight decrease (1,72 t/km2 and 1,23 t/km2).

Demersal fish species from the cod family, such as Atlantic cod, Whiting, and Pouting, all show an increase in biomass. This is also to be expected, since these demersal species also tend to be reef dependent. Interestingly, Atlantic cod, one of the target species of this report, has the lowest increase (from 0,24 t/km2 to 4,79 t/km2) compared to Whiting (0,57 t/km2 to 14,48 t/km2) and Pouting (1,39 t/km2 to 15,42 t/km2). This unexpected difference in biomass increase among fish species with similar reef dependency reflect the need to explore other potential fisheries rather than those that have been primarily fished in the past. The North Sea's dynamic state due to both natural and human pressures, means that fisheries will also change. Therefore, changes in species assemblages will require humans to target alternative species and adapt.

13.2.2 Attraction vs production

One key assumption of this report is the notion that wind parks, along with the combination of hard substrate and other artificial reef additions, will create critical recruitment habitat for fished species, increase stocks, and thereby the overall carrying capacity of the ecosystem. However, the alternative is that artificial reefs will simply act as aggregation devices, attracting fish to them and increasing their vulnerability to fishing with no population replacement, thus damaging the fishery itself. This is termed the attraction-production debate and has long been discussed with evidence to support both positions [H. Pickering, D. Whitmarsh, 1996], [J. Wilson, 2001], [C.W. Osenburg, 2002], [J.A. Smith, 2016], [S. Wright, C. Lynam, D. Righton, J. Metcalfe, E. Hunter, A. Riley, L. Garcia, P. Posen, K. Hyder, 2018]. In this report, it is important to note that the Ecopath model used does make the production assumption, as the model treats the area of interest as a closed area, and it is assumed that the addition of hard substrate before and after is correlated with higher production. In addition, the model assumes attraction in the beginning because we do not start with a population of zero. Experts have claimed that simply high fish densities, recruitment, and high catch rates are not enough evidence to show production enhancement has occurred [J.A. Bohnsack, 1989]. Instead, merely a redistribution of species takes place or there is a migration where one population moves to another more favorable site [J.J. Polovina, 1990]. Pickering and Whitmarsh state that the species most likely to benefit from artificial reefs are demersal, habitat limited, and reef obligatory species. This is demonstrated in the example of Brown crab in the model, as a significant increase particularly for this species is seen in the before and after situation (with and without hard substrate). In contrast, species exhibiting attraction behavior will tend to be pelagic, mobile, and only partially reef dependent [J.A. Bohnsack, 1989] [H. Pickering, D. Whitmarsh, 1996]. As seen in the previous section, these relationships seem to be largely corroborated by the model results. In order to ensure that artificial reefs within wind parks create production enhancement rather than simply an attraction scenario, it is vital that structural designs directly serve the target species requirements as well as said species' different life history stages. For example, in the case of the European Lobster, the optimal crevice size for shelter changes with age. Shelter material also changes. In the larval pelagic stage, European Lobster occupy the water column and then burrow into sand substrate. Therefore, as the attraction-production discussion continues, research should continue to identify precisely what design characteristics for artificial reefs are connected to production enhancement and recruitment. In addition, for such models as the one mentioned in this report, it would greatly improve such studies to include quantitative assessment methods for determining the impact artificial reefs really have on fish stocks [C.W. Osenburg, 2002].

13.2.3 Stock enhancement

One concept that was not considered in the biological analysis, but may be worthy for future consideration is the practice of stock enhancement. Stock enhancement efforts have been applied in fisheries management for a range of species. The concept of stock enhancement can be used for several purposes, for instance to compensate for recruitment overfishing or to replenish vulnerable stocks. Here we are discussing the possibilities of enhancing the stocks of the economically interesting species of the Borssele system with the idea of maximising fisheries productivity. For European lobster and Atlantic cod, both target species discussed in this report, attempts have been made to improve capture through stock enhancement with varied success.

In the case of cod, attempts to enhance stocks have been made in Norway since the 19th century [S. Tilseth, T. Nosho, K. Freeman, 1994, T.S. Kristiansen, 1999, S. Mustafa, S. Saad, R.A. Rahman, 2003]. These attempts have however not yet shown an increase in capture numbers, despite a wide range of release ages and sites. Explanations for the lack of success are mostly given to be a restriction of the population size by prey availability. It is believed that the capacity of the local resources in the attempted release sites do not allow for further stock enhancement [S. Mustafa, S. Saad, R.A. Rahman, 2003]. Although these results appear to be discouraging to attempt stock enhancement, the ecological capacity in the Borssele OWF may very well be more suitable to increase cod stocks, compared to the Norwegian fjords. It should however also be noted that the OWF is a very open system. Although Atlantic cod is known to live a rather stationary life, it remains debatable whether the release of juveniles in an open sea system will yield in an increased catch rate. Since no successful cases of Atlantic cod stock enhancements are known, and the Borssele OWF is an open system, it is not advised to attempt stock enhancement for this species with an economic intention. Since the location varies substantially from the Norwegian test location, it might however be considered to attempt a study to the possibility at the location, in order to implement stock enhancement at a later stage.

European lobster fisheries have been shown to benefit from the release of juveniles. A stocking experiment done in Norway in the period 1990-1994 resulted in an improved fisheries with 43% of the landings comprising of previously released lobster. After 5 to 8 years the released individuals started to contribute to the fisheries [A.L. Agnalt, G.I.V.D. Meeren, H. Jorstad, H. Naeass, E. Farestveit, E. Norstvold, T. Svasand, E. Korsoen, I. Ydstebo, 1999]. However, economically speaking , lobster stock enhancement is not yet successful. Since large amounts of juveniles are needed due to a high mortality rate, and cost of juveniles is high, cost-effectiveness of lobster stock enhancement is low [S. Mustafa, S. Saad, R.A. Rahman, 2003]. Using older individuals of approximately 1 year, effectiveness of stock enhancement was shown to increase [S. Mustafa, S. Saad, R.A. Rahman, 2003]. Although so far no economically successful stock enhancement project exists, the method has been shown to work. In order to increase the lobster catch in the Borssele OWF, this method might be useful when costs of juveniles to release is reduced. What impacts the biological input might then have on the technical solution is encountered in the next section.

13.3 Technical

13.3.1 Environmental parameters

Important parameters such as the North Sea current velocity, significant wave height and the accompanying wave period can be disputed. A 10 year return period is assumed in the determination of these important parameters. With an offshore wind farm constructed with a design lifetime of 25 years, one could argue the fairness of the use of these values. However, graphs show differences between 10-year and 25-year values that are not as significant that it might cause large size increments of the bio-enhancing objects on the seabed [H.J. Riezebos, 2015]. Other environmental parameters such as among others sand waves, do make the design a challenge though.

The presence of sand waves has made designing in this location a challenge. Although the sandy bed is dynamic, in preliminary calculations they are assumed to be static, because the migration speed is very slow. When looking in the order of years, it is yet unclear how the hard substrate will behave with regards to the change of the seabed. It is assumed in this project, that the hard substrate will simply move with the sandy bottom when it settles, and it will be completely buried when the seabed rises again.

Sand wave heights are in the order of meters. However, the slopes of the sand waves themselves are in reality not flat, even though they are assumed to be in this report. The sand waves themselves contain smaller sand ripples, which are in the order of decimeters. It is not clear whether these ripples would have had an impact on the hard substrate at all. In this report, it has been assumed that the ripples do not impact the structural integrity of the hard substrate. Because the sizes of these ripples are relatively small.

13.3.2 Structural elements

A number of structural elements have been assessed in this report. Of those structural elements considered, four were deemed most suitable, namely: stones, block reefs, sunken ships and sunken jackets. However, there are possibly many different materials or structures existing which could act as a hard substrate, which may have been overlooked here.

The calculation process behind the required stone sizes is a relatively complex process, because the effects of flow and waves have to be combined. The theory and formulas behind the calculation process has been backed by the book "Introduction to Bed, Bank and Shore protections" by Schiereck [Gerrit J. Schiereck, 2016c]. The specific approach used in this report may differ from other existing reports done on bed protection in the North Sea. Although the methods in this report could be challenged, the results show relative confidence in the accuracy of the results when comparing to other reports, most notably the report assessing the scour protection around mono-piles in the Borssele area [G. van Velzen, H.J. Riezebos, N. Bruinsma, 2016].

In the calculation process, it is important to choose which parameters should be taken into account. For example, the threshold of motion parameter, flow velocity, significant wave height and peak period are parameters that impact the outcomes of the results heavily. The calculation process in this report shows that it's chosen that the hard substrate cannot move. However, sea conditions are not completely predictable, higher waves are likely to occur than the significant wave height used in this project indicates. Also, a significant wave height with a 1 in 10 year occurrence has been used, while the lifetime of the structure is, as earlier mentioned, 25 years. Some stones are therefore likely to move a little bit, but this is not problematic. Whether the right parameters have been used are theoretically up for debate.

The block reefs have been treated as if they were stones. The calculations used in this project are designed to work for heterogeneous stones (stones with varying diameters). Block reefs are homogeneous rectangular blocks. The behaviour of the blocks regarding loads may differ significantly from regular stones because of its shape and homogeneity. Whether the differences are favourable or not is not known.

13.4 Financial

The financial analysis shows a high value for the Internal Rate of Return. A value that is expected to be too high because of the limiting methods available to calculate the total potential biomass. However, the financial feasibility comes down to both the costs and the revenue during the lifespan of 25 years.

13.4.1 Costs

The costs of the project consists of the CAPEX and the OPEX. The CAPEX has been subdivided in the 5 structure elements such as: stones, block reefs, offshore jackets, layer cakes and scrap vessels. Furthermore, the purchase price of both a crab vessel and a long liner have also been included. The OPEX are the operational and maintenance costs during the life time of the project of both the structures and fishing vessels.

The calculation of the installation and purchasing costs of the structures is based on interviews with experts from for example offshore contractors. As the figures mentioned in interviews have not been double checked and these were given with broad ranges, the prices could change in practice. Therefore, the precision of both the total prices per item and the total price in general could be questioned. Even the uncertainty ranges given with the price calculation needs to be verified as those are estimated based on the information received from interviews. At last, the OPEX figure of 2% need to be reconsidered as this value is chosen on the safe side.

13.4.2 Revenue

The potential revenue sources of the project has been subdivided in the following three categories: commercial fishing, research institutes and tourist activities. First, the commercial fishing consists of the revenue from catching from five target species. The market prices of the last five years of those species has been taken into account. The total amount of revenue originated from the research institutes has been estimated based on the expected importance for the research institutes. The exact figure could be totally different as the awareness of importance might even rise. At last the revenue coming from tourist activities has been based on the size of the current market and the attraction the area will have to this market. However, it is unclear how the tourists are going to react and if they are interested.

For all categories, the assumption has been made that supply and demand is in balance, regardless of the quantity and price. In case of the quantities of catchings of certain fish species, the market price will change as these quantities are flooding the markets. In case the feasibility will be considered on a more detailed level, these factors are to be taken into consideration for all revenue categories. In parallel, other markets such as export markets need to be analyzed as well so that the seller is not only dependent on the Dutch market.

All findings and possibly doubtful outcomes in the biological, technical and financial approach were highlighted throughout this chapter. The next chapter gives a more general view on the outcome of this project. To continue on that, several recommendations will be provided on how one could counter this problem more in more detail.

Chapter 14

Conclusion and recommendations

14.1 Conclusion

The stakeholder analysis resulted in many applicable solution spaces. All of the solutions carried a wide spread support and are likely to trigger the engagement of the actors in the process. The Fish-as-a-Service concept was considered the most interesting for further exploration, as it resolves several issues that so far halted the advancement towards multi-use purpose OWFs. It offers solutions for concerns of the actors such as safety concerns, unsustainable fisheries, high initial investment costs and job security. Additionally, five animal species were selected which were regarded to have high potential to form the basis of the fisheries in the area. The selected species are the European Lobster, Brown crab, Atlantic cod, European seabass and Cuttlefish. This selection was made on their economic viability, potential to be sustainably harvested, natural suitability to the region and previously proven success to adapt to an OWF. The results from the stakeholder analysis and the species selection formed the foundation of the program of requirements.

Based on the program of requirements and boundary conditions and the currently available concepts and possibilities of habitat enrichment, three preliminary designs were made. Of these designs, the second did not appear to be technically feasible at the water depth in the Borssele OWF. The third design was expected to yield the highest biomass and biodiversity in the area. Therefore, this design was used as the basis for the biomass estimations and the economical analysis. This design applies block reefs as hard substrate in deeper levels, while stones are applied in shallower levels. A geometrically closed granular filter layer is applied under the stones and reef blocks in order to prevent erosion under the hard substrate. Layered cakes are added to increase the diversity and complexity of the substrate. Also, jackets and shipwrecks can be added to increase the vertical range of hard substrate and create more complexity.

An estimate of the potential biomass production in the area was provided using an Ecopath with Ecosim model. From the comparison of the system with and without the addition of hard substrate as described in the design, an increase in total biomass from 653 to 17.887 t/km^2 was estimated. The largest increases were found in European lobster (2.157.265%) and Brown crab (857.281%). Also, the target species Atlantic cod and Cuttlefish showed increases in biomass when hard substrate was added (respectively 1897% and 175%). Surprisingly, European seabass appeared to decrease by 93% when substrate was added. Other species that showed high increases based on the model were Whiting (2423%), Pouting (1006%) and Flatfish (970%). Although the model showed certain limits leading to unrealistic predictions, the tendency of consequences of the addition of hard substrate became clear. An analysis of the financial flows in the project predicted a final NPV result at year 25 between approximately 3 and 6 bln EUR. This further indicates the potential profitability of the Fish-as-a-Service concept, integrated in OWFs. Besides the financial profitability, the biomass and productivity of the system would clearly benefit from the addition of hard substrate. From this report it can therefore be concluded that the execution of the proposed design would be of great benefit in both an economical and ecological sense.

14.2 Recommendations

Although this report provides a thorough account on the possibilities of a sustainable multi-purpose OWF, many questions remain to be answered. In the process of data collection and analysis, assumptions had to be made repeatedly. Although this is inherent in the preliminary phase of such innovative projects, it does cause the results presented to be less valid. Furthermore, time limitation has been a continuous constraint during the process. Therefore, a large number of questions remain unaccounted for. A number of recommendations are formulated to improve the validity of the results for future research on this topic. It is hoped by the writers of this report, that through these recommendations, the barriers hindering the implementation of this concept will be removed. Furthermore, a number of interesting additions that are not included in this report, but could be of benefit towards the sustainable integration of seafood production within OWFs are formulated as topics for future studies.

14.2.1 Stakeholders

1. More interviews with actors such as the network operator Tennet and the wind energy union NWEA should be done, in order to directly obtain their vision while also precisely pinpointing their main concerns. This should be done instead of just using policy plans or annual reports. Also, it should be investigated how the client (usually big investment companies) reacts to the new profit motive that comes with the Fish-as-a-Service concept.

2. A pilot should prove the Fish-as-a-Service concept, by securing more hard data. This takes away part of the uncertainty around the concept and therefore to a large extent the concerns of stakeholders (mainly network operators and the clients of OWFs).

3. Clear safety regulations should be agreed upon between the actors, in order to tailor the Fish-as-a-Service concept to future OWFs.

4. Unbiased information should be included from knowledge institutes in future negotiation, ones that fishermen, nature organisations, and network operators trust. This would improve the overall process. Indeed, this has been done in the actual negotiation around the Noordzee Akkoord. Here, the Koninklijke Nederlandse Akademie van Wetenschappen takes this role [de Kruif, 2019].

14.2.2 Biological

1. In order to improve the biomass estimates made by the EwE model, current limitations in, for instance, migration and seasonality have to be removed. This will create more realistic estimates and would therefore strengthen the economic analysis which is of vital importance for the business case.

2. More surveys for the abundance of functional ecosystem groups and species have to be done in OWFs or artificial reef structures in the North Sea to improve the available data. Moreover, these surveys have to be performed in such a manner that they can be compared to situations without artificial structures. This would be a major step towards a better understanding of the impact of the presence of an OWF or artificial reef on the North Sea system.

3. The possibility of expanding the fisheries in the area to more species than the five selected target species has to be investigated. It was found that species such as Pouting and Whiting can benefit immensely from the addition of hard substrate in terms of abundance. Sustainable fishing practices, preferably without the need for bottom trawling could be a great benefit towards a stronger business model.

14.2.3 Technical

1. The effect of ripples on a structure resting on the seabed should be researched. This could be done by placing a sample of hard substrate and by observing the long term effects.

2. Depositing the block reefs may cause a number of blocks to break due to impact stresses. Whether this has a big impact on the structural integrity should be studied further.

3. Dropping stones and block reefs causes an extra impact load once they reach the bed. The effect of this force on the filter layers should be studied further, it is unclear whether it will have a big impact on the integrity of the structure.

4. The flow of waves and currents should be studied in detail. Stones are dropped from a certain height, the flow influences on the exact location in which it will land (see chapter 13 in [Gerrit J. Schiereck, 2016c]).

14.2.4 Financial

1. The revenue originating from commercial fishing is based on figures from the EwE model. These figures are high enough that the revenue of the sustainable fishery almost meets the revenue of the whole Dutch fishing industry. Next to the fact that these values are questionable, the extra fish might cause a change in demand and supply curves causing a decrease in the prices of the selected fish species. On the assumption that the figures are more or less valid, the Dutch fish market will not be able to consume the species itself. Therefore, the potential of new markets in neighbouring countries or even worldwide need to be explored.

2. The base figures of the costs have been obtained from interviews with employees of contractors. As the values are mostly given in broad ranges, there is room for improvement and thereby reduce the uncertainty. The figures should be updated with costs from databases or costs at which the contractor would execute the works.

3. In this research the location was already chosen while there are many new offshore wind farms planned to be built. Besides, the offshore structures that are planned to be decommissioned in the near future could also be considered. Combining these activities could lead to a huge benefit in planning and therefore costs as for example the offshore decommissioning vessel could be used when there is a lot of room in the vessel schedule or rock dump vessels can be used for rock berm installation when they are rock dumping the scour protection of the monopiles.

4. Regarding the stakeholder analysis, there are possibilities in making use of the transition fund of the North Sea for the installation of structures on the seabed. Therefore a Cost Benefit Analysis for the contractor and government might possibly result in the desired outcome.

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Appendix A

Actor Scan

Actors	Repetitive character	Interests	Problem perception	Goals/ Objectives	Important resources	Replaceability	Dependency	Critical Actor	Type of Power	Level of Power
Ministry of Infrastructure and Water State	High	- Ecological healthy resilient sea; - finding a balance between energy transition, nature recovery and food supply; - invest in competitive Blue Economy.	The lack of space makes it difficult to find balance between stakeholders.	Agreeing with as many actors as possible on a new Noordzeeakkoord 2030.	Funding and authority	Low	High	Yes	Diffuse Power	High
Ministry of Agriculture, Nature and Food C	High	- Restructuring of the current fishing fleet; - renewal and innovation possibilities for current fishign fleet; - describing the social-cultural importance of the fishing industry/communities; - meet nature2000 requirements set by EU.	Both political responsible for fishery and to comply with Nature2000 areas, but the current fishing industry does more harm than good	Satisfying the fishing industry and agreeing on a Noordzeeakkoord.	Funding and authority	Low	High	Yes	Diffuse Power	High
VisNed	Low	- Job security; - striving for fair fishing legislation; - enough fishing grounds in the near future; - fishing ships should be able to fish in offshore wind parks; - green deal fishery for a clean ocean.	- Fishing grounds are diminishing; - no job security for future generations; - science is on the hand of the politicians and against the fishing sector; - there is a lack of transparency in funding around offshore wind parks.	Securing enough fishing grounds for future generations to preserve a profitable fishing industry.	Practical knowledge on bottom trawling and ability to mobilize work force.	High	Medium	No	Diffuse Power	Low
Nederlandse Vissersbond	Low	- Unification of the fishing industry; - spatial planning: fishing ships should be able to fish in offshore wind parks.	Fierce discussion within the fishing sector itself leads to unwanted fragmentation of the sector, weakening the negotiation position of the fishing industry as a whole.	Securing enough fishing grounds for future generations to still make fishing profitable.	Pratical knowldge on fishery in general and able to mobilize a work force	Medium	Medium	No	Diffuse Power	Medium
Branche Organisatie Zeehavens	Medium	- Safeguarding the negotiation position of Dutch sea ports	Overbuilding the North Sea with offshore windfarms leads to intensifying shipping routes and in the worse case, completely blocking certain shipping routes.	Striving for the least amount of hinder for shipping from multi-purpose offshore wind parks.	Sector is significantly contributing to Dutch economy	Medium	Low	No	Blocking Power	Low
Port of Rotterdam	Medium	- Strengthening the competitive position of the Port of Rotterdam	Overbuilding the North Sea with offshore windfarms leads to intensifying shipping routes and in the worse case, completely blocking certain shipping routes. Meaning future expansion of the port will be troublesome.	Becoming the most sustainable port in the world.	Economic power house for The Netherlands	Medium	Medium	No	Blocking Power	High
NWEA	Medium	- Promoting policies and legislation in favor of offshore wind; - expanding the offshore wind industry.	- Approving fishing in offshore wind parks results in a safety breach, curtailing the current high safety standard. - In turn, the higher risk results in higher insurance fees that will dwindle profit margins.	- Offshore wind energy should be become the most important energy source in the future, meaning many more offshore wind parks need to be build resulting in a higher revenue for companies in the sector.	Knowledge on developing offshore wind parks and powerful relations	Low	High	Yes	Production Power	High
Energie Beheer Nederland	Medium	- Protecting the current position of the Dutch Oil and Gas sector.	Environmental organisations are negatively and unfairly influencing the public opinion regarding fossil fuels	Promoting innovation and circularity in the sector in order to make fossil gas the key facilitator in the energy transition, resulting in a larger revenue for the sector.	Knowlegde on oil and gas infrastructure and powerful relations	Medium	Medium	No	Production Power	High
NOGEPA	Low	- Advocating the use of fossil gas for the energy transition	Environmental organisations are negatively and unfairly influencing the public opiniun regarding fossil fuels	Finding a economical-friendly solution for the obsolete oil and gas infrastructure, so that future oil and gas extraction in the North Sea can still continue, producing a larger profit margin for the sector.	Knowledge on oil and gas infrastructure and members give massive contribution to GDP The Netherlands	Medium	Medium	No	Production Power	Medium
TenneT	High	- A coordinated roll-out of North Sea Wind Power Hubs facilitates an accelerated deployment of large scale offshore wind in the North Sea	The large roll-out of offshore wind parks should in all likelihood be mostly focussed further offshore.	Ensuring an international coordinated roll-out with power hubs on the North Sea	Expert knowledge on operating wind farm	Low	High	Yes	Production Power	High

Actors	Repetitive character	Interests	Problem perception	Goals/ Objectives	Important resources	Replaceability	Dependency	Critical Actor	Type of Power	Level of Power
Stichting Noordzee	Medium	- More affordable research excursions in Dutch Offshore wind parks; - revive the currently overfished North Sea.	- Current fishing techniques are destroying the North Sea and the sea doesn't get the possibility to recover; - research expeditions within offshore wind farms are outrageously expensive, so there is little to no possibility to monitor what ifs happening in those parks; - the shipping and fishing industry contributes massively to (plastic) population in the North Sea, more than 50% of the waste that is found on beaches comes from these two industries.	- 30% of the Dutch North Sea should become a marine protected area; - in 2020 there should be 50% less waste floating in the sea; - making the shrimp, flounder and pelagic fisheries more sustainable; - the required energy transition of offshore wind should be used as a lever for the enhancement of the North Sea nature.	Expert knowledge on ecological value of the North Sea, ability to mobilize protest, strong relations with other stakeholders	Low	High	Yes	Diffuse Power	Medium
WWF	Low	- Safeguarding the top predators in the food pyramid; - protecting local flora and fauna in the North Sea.	Current fishing techniques are destroying the North Sea and the sea doesn't get the possibility to recover.	- Banning destructive fishing methods; - in 2030 is 30% of the areas that WWF-NL protects well controlled by a sustainable approach; - in 2030 will sustainable fishery be implemented in 30% of the area where WWF-Nl currently focusses on.	Ability to mobilize protest	Medium	Low	No	Blocking Power	Low
Greenpeace	Low	- Increase the number of marine protected areas; - decrease the extraction of fossil fuels.	Oil and gas companies aren't taking the responsibility to remove the old infrastructure in a environmental friendly way.	- 40% of the North Sea should be laballed a marine protected area; - in the other 60%, only sustainable fishing should be allowed.	Ability to mobilize protest	Medium	Low	No	Blocking Power	Low
Vogelbescherming Nederland	Medium	- Boost seabird populations by reviving the fish stocks in the North Sea; - protect current bird population; - more research on the effect of offshore wind parks; - advocating the use of sustainable energy, even wind energy.	An increase in the construction of offshore wind farms results in a significant surge of fatal collision between birds and wind turbines and decrease the surface of their habitat.	- Valuable birds area should be kept free from offshore windparks - Maximum mitigation of the effects should be top priority in other areas.	Ability to mobilize protest, kwowledge on bird habitats and migrating behaviour, strong lobby in The Hague	Medium	Low	No	Blocking Power	Medium
Stichting Natuur en Millieu	Low	-Advocating the use of sustainable energy such as wind energy - increase the number of marine protected areas; - revive the currently overfished North Sea.	The extraction of fossil fuels from the North Sea is detrimental for the climate and should be called to a halt immediately.	- Offshore wind parks should function as delivery rooms for underwater nature. - preserve and build support for wind energy.	Strong relations with other stakeholders, ability to mobilize protest	High	Low	No	Blocking Power	Low

Appendix B

SWOT/TOWS

Internal		
	Strengths	**Weaknesses**
	1. The ministries possess legal power (permits) 2. Government core value is serving the people and therefore should give the people/organisation the reasonable possibility to make use of mothers nature 3. Government supports sustainable initiatives by funding, especially innovation related to the blue economy concept. 4. The government recently made agreements with OWF owners to allow shipping in the OWF. 5. Government issues permissions for research and exploration of new gas and oil fields 6. Stable plan that is future proof with a life span of 25 years 7. Contractors, energy companies, operator reacts re-actively to (new) legislation of the ministries drawn up by the government. 8. The government aims to construct future OWF close to shore, decreasing the construction costs. 9. Multi-purpose solution enables more effective use of the sea surface area 10. The ministries made agreement with the oil and gas companies that they have to decommission old oil and gas infrastructure. 11. The price of electronics, for example security hardware, is ever decreasing, while the possibilities for the usage of technology are becoming basically limitless.	1. The ecological data and specific research on a fully enhanced North Sea biotope is missing. 2. Internal governmental bodies, such as the different ministries, have slight different interests 3. Fish stocks take long time to fully recover. 4. Huge gap between the financial power of the different stakeholders involved. 5. Extreme sea conditions in the North Sea 6. Time spent offshore is extremely costly. 7. Wind farms are valuable investment and investors want a return on their investment promptly. 8. Offshore safety regulations are extremely high in comparison to fishery industry. 9. Initiative requires large investment cost in the beginning of the project. 10. The bottom of the North Sea is highly dynamic (Sand waves). 11. The currently the North Sea is overfished, meaning many fish stocks are significantly lower than half a century ago 12. Definite research regarding the effects of OWFs on the local flora and fauna is largely missing
External		
Opportunities	**SO**	**WO**
1. Currently offshore wind farms, especially the ones close to the coast, raise a lot of resistance of the public. 2. North Sea is a nutrient rich sea with relatively shallow waters 3. EU supports the increase of biodiversity and biomass. 4. Many fish and crustaceans aren't too picky on the type of hard substrate for their biotope. 5. Potential investments from the European Union for sustainable fisheries/initiatives 6. Environmentalist groups supports sustainable fisheries 7. Fishing industry is looking for new opportunities to secure the future 8. Government can make a deal with the oil and gas industry for the financial settlement of re-using out of production oil and gas platforms 9. No real time pressure on jacket decommissioning and installation companies 10. Enhancing an area in the North Sea meets the requirements for Green investing, attracting investment companies. 11. Other countries are struggling with the same spatial planning and fishery problem. 12. The Dutch fishing industry is overall an innovative industry 13. Many new OWF will be constructed in the new future, potentially as one large energy hub. 14. Recently the OWF the CPB published an article stating the massive C02 impact the construction of a OWF has. 15. Opportunities to boost tourism sector: Diving, recreational fishing, etc. 16. The gas industry is still a highly profitable industry 17. 500 old oil and gas platforms will be decommissioned in the upcoming decades. 18. In the near future it becomes mandatory for the owners of offshore wind farm to prove their farms support biodiversity. 19. Climate change and nature preservation is becoming a major concern of the public. 20. A large portion of the target fish and crustaceans are territorial and therefore are likely to stay in the wind farms.	- Multi-purpose use in combination with sustainable fishing might give a positive effect on the image of offshore wind companies [S9, O1, O3, O19] - Reduce decommissioning costs by reusing out of service oil and gas platforms as hard substrate. [S4, S6, O4, O8, O9, O16, O17] - Creating a fish-as-a-service system enables room for less economical strong parties such as fishermen and research institutes [S2, S3, S9, O6, O7] - Together with the Dutch favourable investment conditions for sustainable initiatives and the innovative Dutch fishing industry new technologies might be developed for alternative and productive fishing methods and/or aquaculture. [S3, S6, O3, O5, O6, O7, O10, O11, O12] - Reducing decommissioning and installation costs by making use of the not booked period of offshore vessels [S10, O1, O7, O8] - Using the new system, fishermen obtain job security for the next 25 years [S2, S6, O6] - Knowledge could be transferred to foreign countries, resulting in a strong export product [S3, S11, O2, O5, O11, O13] - Ministries can indirectly draw up new laws requiring the reduction of the environmental impact in the construction of OWF by, for example, implementing seaweed or crustacean farms in OWFs [S1, S3, S9, O1, O14, O15] - Parts of the OWF can be used for commercial fishing, while other might be used for diving and recreational fishing activities. [S2, S9, O11, O15]	- Aquaculture system in the North Sea might prove difficult due to the rough sea conditions, however possibilities for sustainable fishing methods with long lines might still proof profitable. [W5, W10, O6, O12, O20] - By boosting the biodiversity in offshore wind farms, for example by biotope enhancement, the nature organisations will change their view on those farms and become a less opposing party [W6, W7, W11, O1, O13, O14, O18, O19] - Research on the ecological development in the area, that is currently close to non-existent, can give researchers a better idea on area enhancing projects in the future. [W1, W4, O2, O6, O13, O18] - Part of the revenue from the extraction of new gas fields can be transferred into a transition fund that subsequently pays for the increase in insurance fees. [W4, W6, W9, O16] - Successfully implementation a fish-as-a-service concept in the North Sea with her rough sea conditions, will likely result in successful implementation in other regions. [W5, W8, W10, O11, O13, O18, O19] - Creating a fish-as-a-service concept takes the large lump sum investment costs away from the fishermen. [W4, W9, O3, O5, O7, O10, O15] - Fish stocks of top predators in the North Sea are still relatively low compared to the high times [W3, W7, W9, W11, O2, O7, O15, O20] - In the earlier phase of the process, the fishing industry can focus on fish and crustaceans that grow and multiply faster. [W3, W7, W9, O2, O7, O12] - Using regular stones as hard substrate can significantly lower the investment costs [W4, W5, W6, W9, W10, O2, O4, O18, O20] - Even though a portion of the fish species is not constantly present in the wind farms, still a significant part of the territorial fish can be harvested throughout the year. [W1, W11, O20] - Start with a pilot focussing on target species which can later be expanded to a larger scale [W1, W3, W4, W9, O2, O3, O5] - The recovery of fish stocks will have a positive effect on populations of local sea bird and marine mammals [W3, W11, O1, O2, O15, O18, O19]
Threats	**ST**	**WT**
1. Offshore wind operators are inclined to block the process of making the OWF multi-purpose, due to safety concerns. 2. Fishing might conflict with the maintenance of the OWF. (Loss of access) 3. Little to no interest for operators. 4. Insurance premiums for OWF become extremely high 5. Nature preservationists negatively and publicly oppose sinking old oil and gas platforms and ships as a whole 6. Fishermen refuse the restrictions regarding safety that come along with the new way of fishing 7. Safety regarding fishing activity with present fishing vessels and equipment is hard to control and thereby hard to ensure 8. Fishes migrate and therefore there is no guarantee that fish stay in the area as assumed in the biological analysis 9. Fishermen might be reluctant to invest in innovative fishing methods, due to the conflict around pulse fishing 10. Implementing a fishing industry in a OWF requires an area both suitable for the exploitation of wind energy and fishing conditions. 11. (illegal) fishing is hard to control and can easily lead to overfishing. 12. OWF clients stick to their demand that no large offshore constructions are placed in a radius of 500m around their wind turbines. 13. Fishermen lost confidence in scientific community due to large absence of data 14. Bio-enhancing OWF might result in even more collisions with sea birds.	- The government has the possibility to use their legal power to force offshore wind operators to share the nutrient-rich area [S1, S2, S4, T1] - Sinking an old decommissioned offshore construction might be less impactful on the environment, compared to removing it completely and thereafter it will be on land. [S1, S2, S3, S7, S10, T5] - Creating a fish-as-a-service system means a high level of control over fishing regulations for the area[S9, T9, T11] - Using a fish-as-a-service system enables the option that fishing ships and bypassing cargo vessels, using the farm, should be in the possession of a GPS coupled to security software. [S11, T1, T2, T4, T6, T7] - Building a OWF closer to shore in shallower water is, in general, more beneficial for biomass production [S8, T10]	- Creating a multi-purpose wind farm whereby the interests of all government bodies are included, might result in wide support for the fish-as-a-service concept [W2, W3,W11, T9] - The slow development time of a sustainable fishery creates an opening for a gradual learning curve, meaning as the fishing activity in the area slowly increases, the operating company has plenty of time to calmly adjust the safety measures. [W3, W8, T7] - The jacket construction, in contrast to the top sides of the oil and gas platforms, contain almost no toxic materials. [W10, T5, T12] - Due to the likely substantial increase in fish stocks, the fishermen are less likely to refuse the terms regarding safety legislation, as there might be a significant risk for them that they will be banned from the area completely [W11, T6, T9] - The high safety standard that comes with the fish-as-a-service concept in combination with the already strict offshore safety regulations largely prevents serious accidents in the farm. [W8, T4, T6] - Additional data obtained from research that was enabled due to the fish-as-a-service, provides hard proof on the impact of, for instance, OWFs on the sea life. [W1, W12, T13] - Early studies show that seabirds tend to avoid OWFs on the whole. [W12,T14]

Appendix C

Stakeholder Engagement

Actors	Area of influence/interest	Engage or disengage	(Dis)Engage approach	Offer them: (SWOT/TOWS)	Take away their concerns (SWOT/TOWS)	Frequency
Ministry of Infrastructure and Water State	- Legal power in the form of permits - Dutch government owns land North Sea - Possibility to provide funding for sustainable projects.	Engage	Empower	Participation in a process that shapes a balance between the nature, energy and food transition, that simultaneously forms a potential export product fully in-line with the blue economy concept.		Very frequent
Ministry of Agriculture, Nature and Food Quality	- Legal power in the form of permits - Dutch government owns land North Sea - Possibility to provide funding for sustainable projects.	Engage	Empower	The integration of a sustainable fishing industry in OWFs provides an opportunity to possibly end the heated discussion around the future of the Dutch fishing fleet.		Very frequent
VisNed	- Practical knowledge on bottom trawling - Ability to mobilize work force.	Disengage	Inform		The fish-as-a-service system provides a minimum of 25 years of job security, that due to a transition fund initiative requires marginal upfront investment costs.	Less frequent
Nederlandse Vissersbond	- Practical knowledge on fishery in general - Able to mobilize a work force	Engage	Involve	Fish-as-a-service brings a profitable convenience to compose and reconcile the fishing industry while at the same time establishing a positive public image that shows the progressiveness of the sector.		Frequent
Branche Organisatie Zeehavens	- Contributes significantly to Dutch economy	Disengage	Consult		Bio-enhancing a OWF area for the fish-as-a-service concept will likely limit the focus to augmenting the sea floor, in general with the use of smaller rocks. In addition with the strict safety regulations and extensive spatial planning within the OWF, this won't obstruct any future policy changes to possibly establish shipping routes in the area. Overall marginalizing the impact on the shipping routes and therefore the numerous sea ports.	Less frequent
Port of Rotterdam	- True economic power house for The Netherlands	Engage	Involve	Involvement in a fish-as-a-service concept that is directly linked to the blue economy theory might result in opportunities to become an even more sustainable port. For instance, a possibility for a natural form of carbon capture leading to indirect CO_2 reduction of the port.		Less frequent
NWEA	- Knowledge on developing offshore wind farms - Powerful relations	Engage	Empower	The positive image for the offshore wind sector that comes with the multi-purpose use of OWF might result in less protest around future OWF and possibly shorten the application time for permits, saving considerable money in the long run.		Very frequent
Energie Beheer Nederland	- Knowledge on oil and gas infrastructure - Powerful relations	Engage	Collaborate	An initiative for a transition fund sets up the possibility for a perfect pretext for the environmental-friendly course the industry is taking. Consequently, the extraction of fossil fuels in the North Sea can continue in exchange for a minor percentage of the profit margin.		Frequent

Actors	Area of influence/interest	Engage or disengage	(Dis)Engage approach	Offer them: SWOT/TOWS	Take away their concerns (SWOT/TOWS)	Frequency
NOGEPA	- Knowledge on oil and gas infrastructure - Members give massive contribution to GDP The Netherlands	Engage	Collaborate	Sinking parts of the obsolete rigs brings a possible financially attractive solution for the tumult around the topic of old platforms, that currently impends the future extraction of gas in the North Sea.		Frequent
TenneT	- Expert Knowledge on operating wind farm	Engage	Empower	The fish-as-a-service concepts provides a multi-purpose solution for OWFs that eliminates the main argument for formation of a giant energy hub on the North Sea, at relatively limited additional risk.		Very frequent
Stichting Noordzee	- Expert knowledge on ecological value of the North Sea, - Ability to mobilize protest - Strong relations with other stakeholders	Engage	Collaborate	Besides the fact that the bio-enhancing OWF that comes with the fish-as-a-service concept has a productive effect on the bio-diversity, the concept also creates room for less economical strong parties such as research institutes to perform field research in the OWF.		Very frequent
WWF	- Ability to mobilize protest	Disengage	Inform		The core value in the fish-as-a-service concept is sustainable fishery, bottom-disruptive techniques are not allowed in the OWF. Moreover, the data-driven approach enables closely monitored control over the fish stocks.	Occasionally
Greenpeace	- Ability to mobilize protest	Disengage	Inform		Obsolete oil and gas rigs will be dismantled, whereby the non-toxic jacket construction, after having executed an environmental impact analysis, can be sunk in an OWF. Similar to the concept extensively tested concept of rigs-2-reefs.	Occasionally
Vogelbescherming Nederland	- Ability to mobilize protest - Knowledge on bird habitats and migrating behaviour - Strong lobby in The Hague	Disengage	Inform		A bio-productive North Sea will result in more food, especially for the larger solitary seabirds living on open sea. Moreover, exploratory research shows that the majority of sea birds tend to avoid OWFs completely.	Less frequent
Stichting Natuur en Millieu	- Strong relations with other stakeholders - Ability to mobilize protest	Disengage	Inform		Offshore wind farms will bio-enhance barren sea bottom into productive biotopes that will function as delivery rooms for the underwater nature. Further, the offshore wind sector on the North Sea can continue the planned expansion in the process to a sustainable energy transition.	Occasionally

Appendix D

Program of requirements and boundary conditions

	Program of Requirements					
NUMBER	Boundary conditions (BC)		Requirements (R)			
	Physical (P)	**Legal (L)**	**Functional (F): (how should the system perform according to the owner?)**	**Operational (O): (from user's perspective)**	**Remarks/additions**	**Structural (S)**
1	The effective workable wind farm area, including the wind turbines, amounts 112.6 km^2.	Offshore construction elements may not contain or emit toxic or contaminating chemicals, such as mercury, lead paint and asbestos which will lead to a burden for the marine environment.	Existing wind turbines may not be loaded and/or affected by the implementation of structures for the bio-enhanced fishery system.	A loose rock revetment should have for the adult life stage a crack/opening width of 11 cm for providing shelter. Crevice spacing should be 6.5 cm apart.	A lobster can be up to 0.50 m. The harvestable size is 85 mm CL.	Structural elements may not be covered by sand waves.
2	Pipelines, cables and their 1000 meter wide maintenance zones are excluded from parcels I and II.	The noise standardization (see figure 6.2) for the purpose of the protection of marine fauna has to be maintained.	The buried depth of the cables and pipelines in the wind farm area should not be increased or decreased by the deployment of elements for sea ranching.	One is obliged to choose for the construction material a.o. concrete, steel with a minimized environmental impact (reduced environmental burden).		Overturning of structural elements due to the forces exerted by sand waves is not allowed.
3	The water depth at Low Astronomical Tide (LAT) ranging between 14 – 40 m and the design maintenance vessel draught are the governing parameters that determine the design height of the biostructures.	Mitigating measures for the underwater sounds have to be undertaken during the construction of the sea ranching system.	A reused decommisioning offshore structure element has to be provided with holes to enhance the biodiversity.	European lobster require temperature range of 1-25 C.		Stability of the existing wind farm foundations should not be compromised by the construction of the integrated multi-trophic aquaculture system.
4	The development of an integrated sea ranching system in the Borssele Wind Farm is bordered by the Belgian Economic zone including its offshore wind farm zones in the southwest and it is bordered by the 12 mile nautical zone and sand extraction areas in the southeast.	Bottom trawling vessels and transport ships, especially larger than 24 meter (exception for maintenance vessels), are not allowed to sail in between the wind turbines.		European lobster require salinity range 28-35 ppt.		The structures should be stable enough to withstand loads caused by flow velocities resulting from dominant sea currents and orbital significant wave motion.
5	A safety zone is located between the Belgian Wind Farm Zone and the Borssele Wind Farm Zone and this 500 m wide zone is applied at both sides of the international border.	Navigation of transport vessels through the designated shipping corridor should not be significantly hampered by the construction activities.		European lobster cannot tolerate current speeds of 0.6 m/s.		The shear forces, normal forces and bending moments that occur in the sea ranching structures should not exceed the resistances of shear force, normal force and bending moment respectively. Material dimensions and properties determine the structural resistance.
6	The galvanic anode, which functions as corrosion protection of submerged steel structures, may consist of alloys from Aluminium, Magnesium and/or at most 5% of its own weight from other metals.			Atlantic cod require a temperature of 2-20 degrees, a maximum of 11 degrees is optimal.	Temperature and prey abundance determine cod dispersal, there is no clear preference for substrate	Failure such as tear, wear, abrasion due to limitations on characteristics of the construction material, should be minimized as such that the structure's lifetime failure probability is minimized.
7	The water temperature in the Borssele Wind Farm varies approximately within 2 and 20 degrees Celcius.			Atlantic cod lives at a depth range of 10-200 m on the continental shelf		The stress distribution due to the landing impact during dumping or placement of the structural elements should not excessively exceed their stress capacity.
8	The salinity level in the Borssele Wind Farm amounts up to 33 - 34.5 g salt in 1 kg of water.			Juvenile atlantic cod require vertical structures as shelter	e.g. vegetation, corals, artifical 3D structures	Constructability of the designed solution is guaranteed for its specified location.
9	The design flow velocity of the current(s) at Borssele I+II is 1.1 m/s.			European seabass requires a temperature range of 8-24 degrees	Just like cod, temeperature and prey abundance determine the presence of seabass	The allowable coverage of the area by hard substrate is less then or equal to 5.2 %. Higher coverage causes too severe drops in biomass of species depended on soft substrate or predated on by species benefiting form hard substrate
10	In the Borssele wind farm area, the migration speed of a sand wave with a 90% non-exceedance rate is equal to 1.9 m/year, meaning that only 10% of sand waves will migrate faster than this rate (Hasselaar et al., 2015).			European seabass lives at a range of 10-100 m depth		Rocks and boulders of varying sizes are preferred by the European lobster and Brown crab, so these species require rocks of varying crevice size to account for all life stages as juveniles in particular tend to rely on them for shelter.
11	In the Borssele wind farm area, the significant wave height Hs is 6.6, 7.2, 7.66 m for return periods of 10, 25 and 50 years respectively.			European seabass prefers clear waters over turbid waters	They are therefore often found at places with more currents	Atlantic cod and European seabass prefer hard, complex substrate of various height and rugosity for sand wave and juvenile protection.
12				Adult North sea crab tolerates a temperature range of 5-31 degrees, 5-8 is the optimum, temperatures above 15 degrees are only tolerated for shorter periods		
13				Adult North Sea crab requires a salinity of > 17 PSU		
14				Adult north Sea crab lives at a depth of 6-40 meters		
15				North Sea crab cannot tollerate current speeds of more than 1,5m/s		
16				Adults North Sea crab prefer sandy bottoms over hard substate, but rocks may be present		
17				Juvenile North Sea crab require crevices to hide in untill they reach approximately 70cm with	Competition with lobster for crevices is often won by the lobster	
18				Adults North Sea crab (>70cm) prefers hard objects to press their back against		
19				Cuttlefish require depth between 0-100m		
20				Cuttlefish require salinity range of 18-40 psu		
21				Cuttelfish require sandy/muddy substrate for burying and shelter	Seagrass may be limiting factor for juvenile recruitment	

Appendix E

Drag coefficients for different types of objects

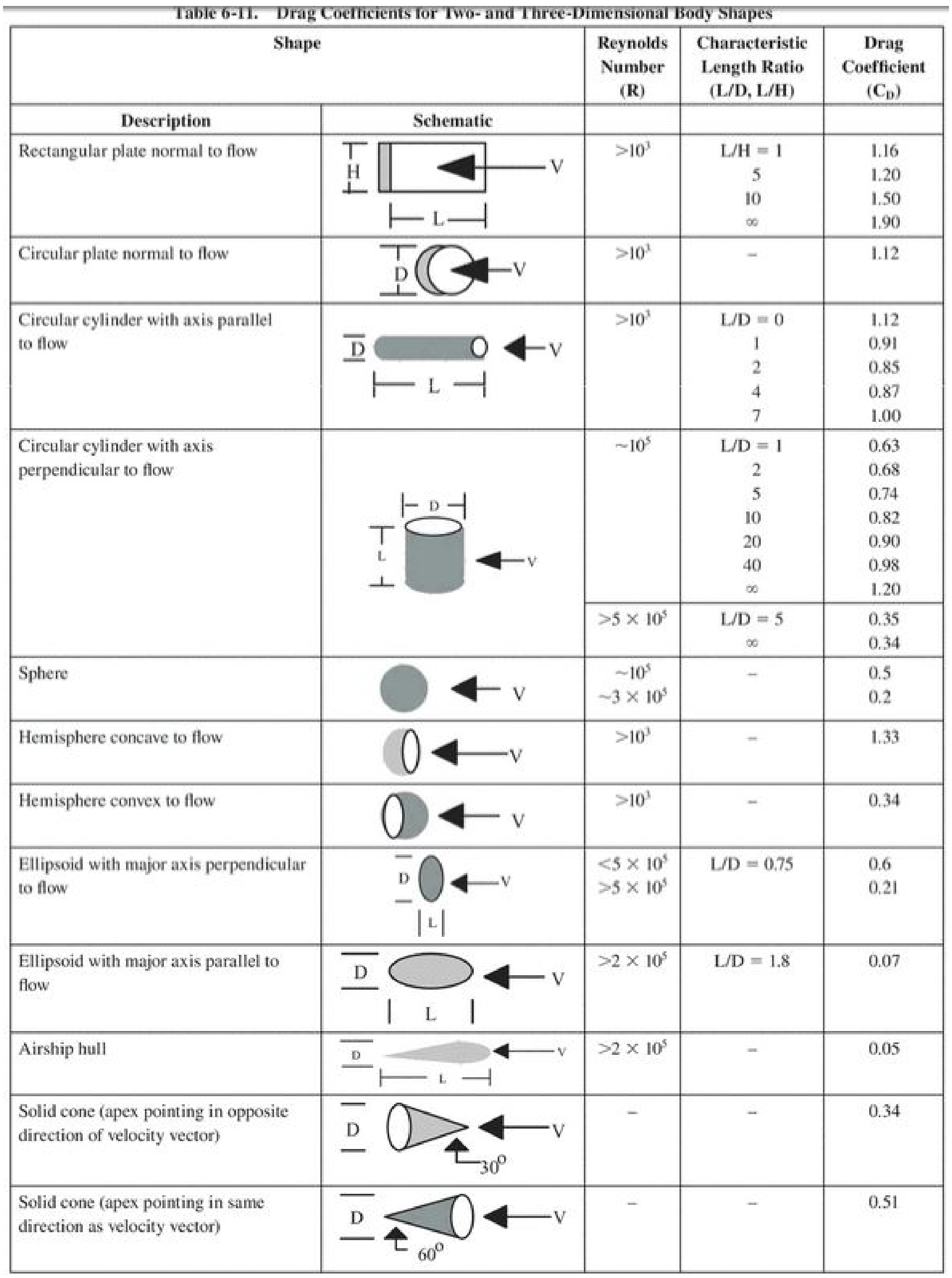

Table 6-11. Drag Coefficients for Two- and Three-Dimensional Body Shapes

Shape: Description	Shape: Schematic	Reynolds Number (R)	Characteristic Length Ratio (L/D, L/H)	Drag Coefficient (C_D)
Rectangular plate normal to flow		$>10^3$	L/H = 1 5 10 ∞	1.16 1.20 1.50 1.90
Circular plate normal to flow		$>10^3$	–	1.12
Circular cylinder with axis parallel to flow		$>10^3$	L/D = 0 1 2 4 7	1.12 0.91 0.85 0.87 1.00
Circular cylinder with axis perpendicular to flow		$\sim 10^5$	L/D = 1 2 5 10 20 40 ∞	0.63 0.68 0.74 0.82 0.90 0.98 1.20
		$>5 \times 10^5$	L/D = 5 ∞	0.35 0.34
Sphere		$\sim 10^5$ $\sim 3 \times 10^5$	–	0.5 0.2
Hemisphere concave to flow		$>10^3$	–	1.33
Hemisphere convex to flow		$>10^3$	–	0.34
Ellipsoid with major axis perpendicular to flow		$<5 \times 10^5$ $>5 \times 10^5$	L/D = 0.75	0.6 0.21
Ellipsoid with major axis parallel to flow		$>2 \times 10^5$	L/D = 1.8	0.07
Airship hull		$>2 \times 10^5$	–	0.05
Solid cone (apex pointing in opposite direction of velocity vector)		–	–	0.34
Solid cone (apex pointing in same direction as velocity vector)		–	–	0.51

Figure E.1: Varying shapes and their corresponding drag coefficients [R.E. Randall, 1997]

Appendix F

Cone penetration diagram of Borssele I+II

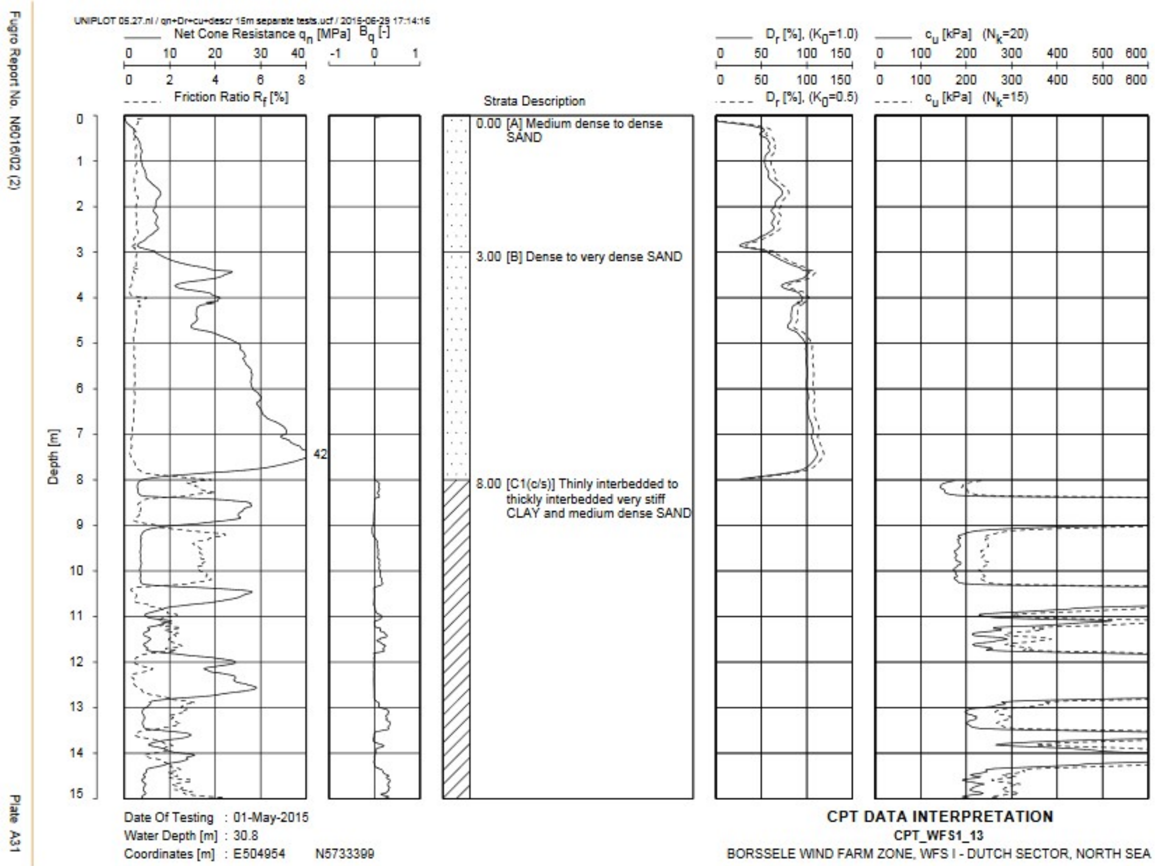

Figure F.1: Cone resistance diagram of the yellow-marked sample [R. Hasselaar, 2015] (see figure 6.2).

Appendix G

Calculation of the Biohut units

G.0.1 Overturning

Firstly, the overturning of a Biohut is addressed. Overturning is caused by an imbalance between the drag force F_D, which is initiated by the current, and the submerged (net) weight of the structure F_G. A moment equilibrium around point O shows whether stabilizing measures have to be taken.

Figure G.1 shows the sketch in which the dimensions l = b = 0.5 m and h = 0.4 m. The Biohut is symmetric when seen from a top view. A moment equilibrium around point O checks whether the Biohut is overturning or not.

$$\Sigma M|_o = f_D \cdot \frac{h^2}{2} - F_G \cdot \frac{b}{2} = 0$$

Where:

$$f_D = \frac{1}{2}\rho u_c^2 (C_D + C'_D)\frac{1}{[}H]$$

$$F_G = (V_{s,total}\rho_s + V_{shells}\rho_{sh}) \cdot g$$

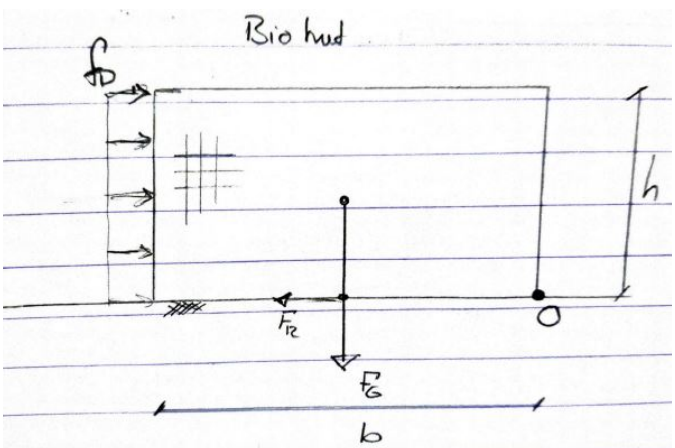

Figure G.1: Schematization of the forces on one Biohut unit.

The static and dynamic drag coefficients, C_D andC'_D respectively, are dependent on the shape of the structure and the Reynolds number [M.Z. Voorendt, W.F. Molenaar, 2019]. The Reynolds number is calculated with the following formula:

$$Re = \frac{u_c D}{\nu} \tag{G.1}$$

In which:
Re = Reynolds value [-]
u_c = the critical value for the flow velocity at h = 0.4 m in [m/s]
ν = kinematic viscosity 10^{-6} m/s
D = measure of length depending on geometry
The width of one Biohut object is considered in this case to be equal to D [m].

The horizontal water motion at seabed level $\hat{u}_b$ is the critical velocity u_c and it equals 1.88 m/s. From this it follows that Re = $\frac{1.88 \cdot 0.5}{10^{-6}}$ = 940000, which indicates that the flow is turbulent.

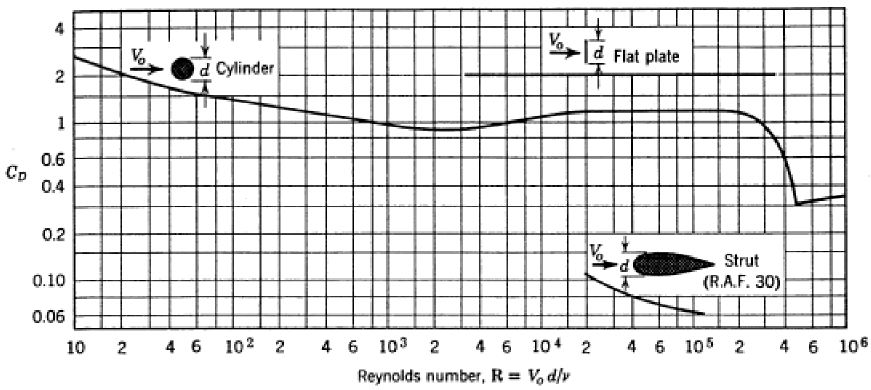

Figure G.2: The static drag coefficient as function of the structural shape and the Reynolds number

For a flat plate, a static drag coefficient $C_D = 2$ is found, the maximum dynamic drag coefficient C'_D is approximately $0.5 \cdot C_D = 1$. The density of salty water is 1025 kg/m^3 and the lifting coefficient for parallel approaching flow is zero, so the drag force per m becomes:

$$f_D = \frac{1}{2} \cdot 1025 \cdot (2+1) \cdot \frac{1.88^2}{0.4} \approx 20 \text{ kN/m}$$

Given the assumption that shells are aggregated inside an interior fence that is 60% of the dimensions of the exterior fence, one can determine the total mass:

$$m = 7800 \cdot 0.01[0.4 \cdot (2 \cdot 0.5^2 + 4 \cdot 0.4 \cdot 0.5)] + 7800 \cdot 0.01[0.4 \cdot (2 \cdot 0.3^2 + 4 \cdot 0.24 \cdot 0.3)] + 800 \cdot 0.24 \cdot 0.3^2 = 40.56 + 14.6 + 17.28 = 72.44kg$$

The gravitational force is:

$$F_G = 10 \cdot 72.44 = 724.4N \approx 0.7kN$$

An overturning stability check results in a net moment of:

$$M|_o = 20 \cdot \frac{0.4^2}{2} - 0.72 \cdot \frac{0.5}{2} = 1.42kNm(+)$$

Hence one Biohut unit will not be stable for overturning. The Biohut units may be placed after one another (in a row) to maintain stability. Three Biohut units decrease the overturning moment as the moment becomes:

$$M|_o = 20 \cdot \frac{0.4^2}{2} - 0.72 \cdot 1.25 - 0.72 \cdot 0.75 - 0.72 \cdot \frac{0.5}{2} = 0.02kNm(-)$$

(It is negative because it is a restoring moment)

G.0.2 Horizontal sliding

Horizontal sliding is checked by a horizontal force equilibrium. Figure G.1 presents the forces that are exerted on one object.
The friction force F_R is calculated with the friction coefficient of steel sliding against sandy soil:

$$F_R = F_G \cdot \mu_R = 724.4 \cdot \frac{0.4}{2} = 0.145kN$$

The friction coefficient is reduced since the objects are submerged, submerged objects are less resistant against driving forces (think of a human sitting on the bottom of a swimming pool and being influenced by forces).

$$\Sigma F_[H] = f_D \cdot 0.4 - 0.145 = 8 - 0.145 > 0$$

A horizontal force equilibrium shows a horizontal instability. In short, 56 bio huts are needed to acquire horizontal stability against sliding. Therefore one should better opt for an other solution for sea ranching.

Appendix H

Calculation of the hang culture configuration

The design flow velocity at subsurface level which is normative for the drag force is equal to $u_D = 1.1 m/s$. For design purposes, this load is assumed to be quasi-static, while in reality the velocity is irregularly changing over time. In this situation, only two-dimensional cases are considered. Thus a static cable analysis is performed. Figure H.1 provides a free body diagram for a subsurface buoy in a current. For static equilibrium, the sum of forces and moments must be zero:

By summing the forces at the attachment point below "G", one finds:

The horizontal tensile force in the cable to be equal to the drag force:

$$T[H] = F_D \tag{H.1}$$

Where the drag force is:

$$F_D = \frac{1}{2}\rho_w(C_D + C'_D)A_N u_D^2 \tag{H.2}$$

Where rho_w is the seawater density, C_D is the drag coefficient and A_N is the area projected on the plane normal to the flow. The vertical component of the tensile force is determined to be:

$$T_V = F_B - W - F_L \tag{H.3}$$

Where:

$$Thebouyantforce : F_B = submergedvolume \cdot rho_w \cdot g \tag{H.4}$$

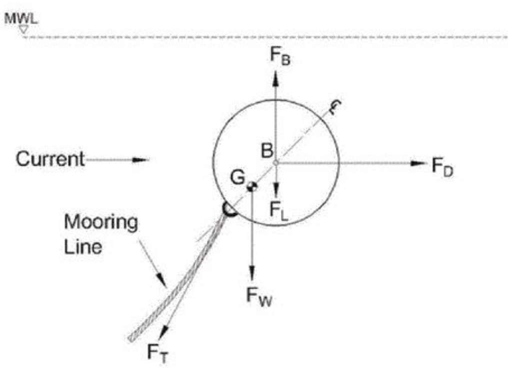

Figure H.1: Free-body diagram of a moored subsurface buoy in a current [R.E. Randall, 1997]

The lifting force is expressed by equation H.5.

$$F_L = \frac{1}{2}\rho_w(C_L + C'_L)A_L u_D^2 \tag{H.5}$$

A spherical buoy with a diameter D = 1000 mm is used for the following computations. The weight of the buoy W is determined with the submerged weight of the cable and the bouyant force, see equation H.6.

$$q_s ds = F_B - W \tag{H.6}$$

Hence, the bouyant force = $\frac{\pi D^3}{6} \cdot 1025 \cdot 9.81 = 5264.92N$ and the immersed weight of the cable $q_s ds = 40 \cdot 1150 \cdot \pi 0.05^2 = 361.28N$ determine the weight of the buoy to be at least (maximum depth of 40 m is assumed):

$$W = 5264.92 - 361.28 = 4903.63N$$

Straight flow (inclination angle $\alpha = 0°$) uses a lift coefficient C_L=0, the drag coefficient C_D of a sphere however is equal to 0.5, since there is turbulent flow (Re > 10^5), see Appendix E. The dynamic drag coefficient C'_D and the dynamic lifting coefficient C'_L can be assumed to be equal in this preliminary design.

Vortex shedding is an oscillating flow that takes place behind an object, in this case as a buoy. Eddies are developed and the oscillation frequencies of vortex shedding f_s behind the buoy is assumed to be larger than the natural frequency f_n (one expects no resonance), the dynamic drag coefficient is therefore at most $C'_D \approx 0.5C_D = 0.25$ [M.Z. Voorendt, W.F. Molenaar, 2019].

For The tensile force T is determined by its components:

$$T = \sqrt{T[H]^2 + T_V^2} \tag{H.7}$$

θ is the angle between the long line and the anchor at seabed and this angle θ is determined with:

$$\theta = \tan^{-1}\frac{T_V}{T[H]} \tag{H.8}$$

Given all this information, one finds the drag force, lift force, $T[H]$ and T_V to be:

$T[H] = F_D = \frac{1}{2} \cdot 1025 \cdot 0.75 \cdot (0.5 \cdot 1.0)1.1^2 = 232.55N$ (Half of the sphere is assumed to be below water and susceptible to drag)

$F_L = \frac{1}{2} \cdot 1025 \cdot 0.25 \cdot (1.0 \cdot 1.0)1.1^2 = 155.03N$

$T_V = 5264.92 - 361.28 - 155.03 = 4748.6N$

Hence the angle θ can be found to be:

$$\theta = \tan^{-1}\frac{4748.6}{232.55} \approx 87°$$

The horizontal component of the tension at the anchor equals the buoys drag force so: $T_{HA} = 232.55N$. The vertical component of this tensile force at the anchor level is: $T_{VA} = 232.55\tan 87 = 4437.3N$. Recall that the used cable has a length of 40 meter. The tension of the cable at the anchor is then: $T_A = \frac{232.55}{\cos 87} = 4443.4N$.

The cable at the interface with the buoy experiences a tensile force T_B. Its vertical component T_{VB} equals the sum of the immersed weight of the cable $q_s ds$ and T_{VA}:

$T_{VB} = 40 \cdot 4.90363 + 4.4373 = 200.58kN \approx T_B$ because the horizontal component $T[H]$ is relatively very small compared to the vertical component T_V.

Lastly, the tensile resistance is checked with the tension force in the cable at the buoy since $T_B > T_A$: This tensile stress is:

$$t_B = \frac{T_B}{50^2\pi} = 25.54N/mm^2.$$

An unity check yields: $\frac{25.54}{75} \approx 0.34 \ < \ 1.0.$

Appendix I

Design calculations

This appendix focuses on the calculation process behind determining the required stone sizes which will act as a hard substrate. Essentially, it is similar to placing a bed protection. Therefore, the construction will be treated as such. Since the location is offshore with relatively shallow depths, both the influence of waves and currents will be present on the erosion of the seabed. The shear stress on the bed caused by the current (flow) is calculated using formula (I.1). The bed shear stress caused by waves is calculated using formula (I.2).

$$\tau_b = \rho_w u_*^2 \text{ with } u_* = \bar{u}\sqrt{g}/C \tag{I.1}$$

$$\hat{\tau}_w = \frac{1}{2}\rho_w c_f \hat{u}_b^2 \text{ with } \hat{u}_b = \frac{\omega a}{\sinh kh} \tag{I.2}$$

The total shear force is calculated by adding the results of both equations together. Eventually, the required stone size will be calculated using the Shield's approach as shown in formula (I.3).

$$d_{n50} = \frac{\hat{\tau}_w + \tau_b}{\psi_c(\rho_s - \rho_w)g} \tag{I.3}$$

In which ψ_c is the critical mobility parameter which determines the threshold of motion for sediment particles. Since the rocks have to remain in its place during its lifetime, this value is set to 0.03. ρ_s and ρ_w are the density of the stones and seawater respectively. These values are set to 2650 kg/m^3 and 1025 kg/m^3 respectively. The design current speed $\bar{u}$ is equal to 1.1 m/s. The horizontal orbital

motion at the bed as a result of wave action $\hat{u}_b$ is dependent on the radial frequency of the wave ω, the wave number k, the wave amplitude a and the local water depth h. To calculate the contribution of the

current, one needs to determine the Chézy value C, which is a smoothness coefficient dependent on the bed material, in this case the protective stone layer. The Chézy value can only be used in uniform flow, which is assumed in this case. This value is calculated using (I.4). To calculate the contribution of the wave action, one needs to calculate the friction coefficient c_f over a rough bed. This value is calculated using (I.5).

$$C = 18 \log \frac{12h}{2d_{n50}} \tag{I.4}$$

$$c_f = 0.237 \left(\frac{a}{\sinh(kh) 2d_{n50}} \right)^{-0.52} \quad \text{with } c_{f,max} = 0.3 \tag{I.5}$$

The required stone size diameter parameter d_{n50} is present in τ_b and $\hat{\tau}_w$. Therefore, a complex iterative process is required in order to exactly know the required stone size for the bed protection. The step-by-step process is explained below:

1. Assume a Chézy value and a stone size. This can be a wild guess.
2. Calculate the shear stress caused by the current τ_b based on the initially guessed Chézy value. See (I.1).
3. Calculate c_f based on the initially guessed d_{n50} and thereby the shear stress caused by the waves $\hat{\tau}_w$. See (I.2).
4. Add both shear stresses together.
5. Calculate the new stone size based on (I.3). This value will be used again in step 3.
6. Calculate the new Chézy parameter based on (I.4) and using the stone diameter calculated in step 5. This value will be used again in step 2.
7. Repeat steps 2-6 until the stone size doesn't change anymore through new iterations.

The stone size depends on the water depth as well, since the influence of the waves on the stones is dependent on the water depth. The wave number k is calculated using the wave dispersion relation:

$$\omega^2 = \left(\frac{2\pi}{T}\right)^2 = gk\tanh(kh) \tag{I.6}$$

The stone mass is calculated using formula (I.7).

$$M = d_{n50}^3 \rho_s \tag{I.7}$$

The end results are shown in table I.1.

Table I.1: Minimum required d_{n50} for each water depth in m

[redacted]		
20	0.463	263
21	0.420	196
22	0.368	132
23	0.339	103
24	0.301	73
25	0.270	52
26	0.242	38
27	0.219	28
28	0.200	21
29	0.182	16
30	0.167	12
31	0.154	9.7
32	0.143	7.7
33	0.126	5.3
34	0.117	4.3
35	0.110	3.5

I.1 Preliminary design 1

In this design, the default hard substrate are stones, or simply a bed protection. Based on table I.1, corresponding stone classes are listed per meter of depth based on the Eurocode EN13383. The stone diameter is expressed as the nominal diameter. The corresponding stone class according to EN13383 with the nominal diameter and minimum dumping amount is shown in table I.2.

Table I.2: Required stone class per m depth

20	HM_A300-1000	59	59	88	1325
21	HM_A300-1000	59	59	88	1325
22	LM_A60-300	38	59	57	950
23	LM_A40-200	34	59	52	850
24	LM_A15-300	31	31	46	700
25	LM_A15-300	31	31	46	700
26	LM_A15-300	31	31	46	700
27	LM_A15-300	31	31	46	700
28	LM_A10-60	21	21	32	550
29	LM_A10-60	21	21	32	550
30	LM_A5-40	17	21	25	500
31	LM_A5-40	17	21	25	500
32	LM_A5-40	17	21	25	500
33	CP90/250	12.8	12.8	20	300
34	CP90/250	12.8	12.8	20	300
35	CP90/250	12.8	12.8	20	300

It might be more convenient to limit the amount of stone classes needed, in order to make the supplying process more simple (and possible cheaper). This is the reason why the parameter d_{n50}, pr (pr = practical) is introduced. Now there are only four different stone classes necessary instead of seven.

Filter layer:
A geometrically closed granular filter layer under the stones is necessary in order to prevent erosion under the hard substrate. This is to prevent the risk of the stones sinking into the soft sand. The soft seabed is made of sand with $d_{50} = 0.25$ mm. The filter layer consists of relatively small layers of sediment in which the following criterion applies:

$$d_{50F} = 3 \text{ to } \ 5 * d_{50B} \tag{I.8}$$

It means that the d_{50} of the higher layer should be 3 to 5 times larger than the lower layer. The results of each stone class are presented in tables I.3 until I.6. Note that $d_{50} = d_{n50}/0.84$.

Table I.3: Overview of top and filter layers ($d_{n50} = 59$ cm).

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	HM_A300-1000	702	88
Filter layer 1	CP90/250	152	20
Filter layer 2	Coarse gravel	30	10
Filter layer 3	Fine gravel	6.1	5
Filter layer 4	Very coarse sand	1.2	5
Base layer	Medium sand	0.25	-

Table I.4: Overview of top and filter layers (d_{n50} = 31 cm).

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	LM_A15-300	369	46
Filter layer 1	CP45/125	76	20
Filter layer 2	Medium gravel	15	5
Filter layer 3	Very fine gravel	3.0	5
Filter layer 4	Coarse sand	0.6	5
Base layer	Medium sand	0.25	-

Table I.5: Overview of top and filter layers (d_{n50} = 21 cm).

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	LM_A10-60	250	32
Filter layer 1	Very coarse gravel	50	10
Filter layer 2	Medium gravel	10	5
Filter layer 3	Very fine gravel	2.0	5
Filter layer 4	Medium sand	0.4	5
Base layer	Medium sand	0.25	-

Table I.6: Overview of top and filter layers (d_{n50} = 12.8 cm).

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	CP90/250	152	20
Filter layer 1	Coarse gravel	31	10
Filter layer 2	Fine gravel	6.1	5
Filter layer 3	Very coarse sand	1.2	5
Base layer	Medium sand	0.25	-

The side views of a strip of hard substrate is provided in figures I.1 until I.4.

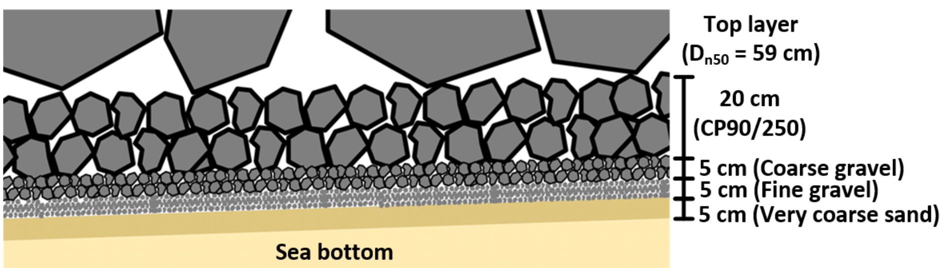

Figure I.1: Side view of a stone strip with top layer: d_{n50} = 59 cm

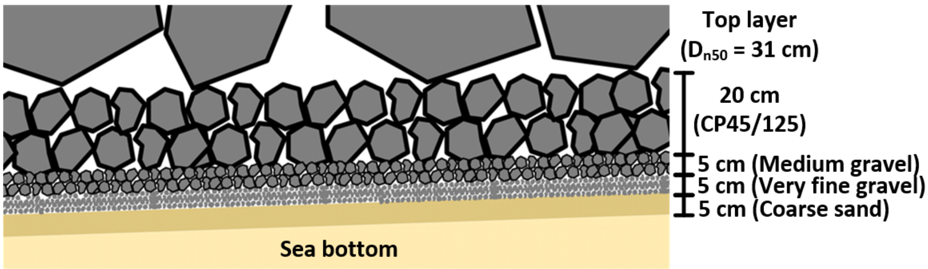

Figure I.2: Side view of a stone strip with top layer: $d_{n50} = 31$ cm

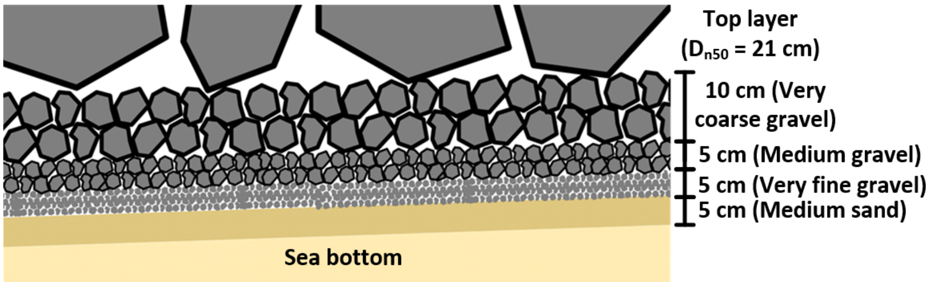

Figure I.3: Side view of a stone strip with top layer: $d_{n50} = 21$ cm

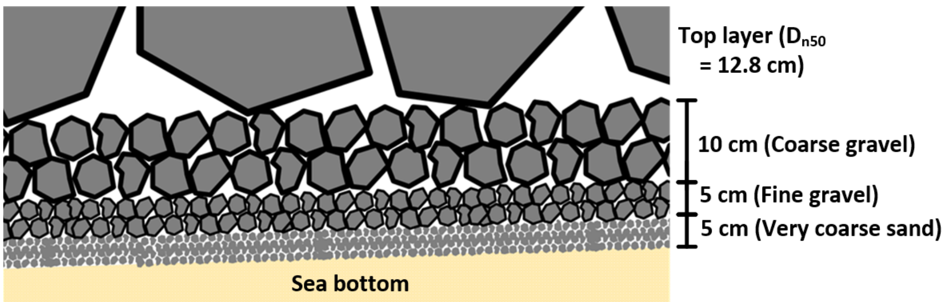

Figure I.4: Side view of a stone strip with top layer: $d_{n50} = 12.8$ cm

The total stone mass required to meet this demand can be calculated based on the given dumping quantity, expressed in kg/m^2. The amount of a particular stone class required is determined based on percentages of the total area of hard substrate (which is about 5.6 km^2). For example, stone class HM$_A$300-1000 is applied at depths which are shallower than 24 m (LAT). The percentage of strips with this stone class are equated with the percentage of the total area which elevates higher than 24 m (LAT). This is also the same percentage of hard substrate which lies at these elevations. The area of hard substrate is then multiplied with the required dumping quantity which is provided in the last column of table I.2. The results are shown in table I.7.

Table I.7: Required top layer tonnage.

Top layer class	Area %	Area [km^2]	Stone quantity [tons]
HM_A300-1000	15.75	0.89	1,174,895
LM_A15-300	19.83	1.12	781,262
LM_A10-60	43.76	2.46	1,354,616
CP90/250	20.66	1.16	348,888
Total	100	5.63	**3,659,660**

For the filter layer, the same calculation process takes place. The minimum dumping quantity of small sediment particles are not mentioned in EN13383. For smaller stone classes, a dumping quantity of 300 kg/m^2 is required for a layer of 20 cm. Based on this norm, it is assumed that the dumping quantity for smaller sediments is 75 kg/m^2 per 5 cm thickness. The results are shown in table I.8.

Table I.8: Required filter layer tonnage.

Top layer class	Area [km^2]	Filter thickness [cm]	Stone quantity [tons]
HM_A300-1000	0.89	40	532,028
LM_A15-300	1.12	35	585,946
LM_A10-60	2.46	25	923,602
CP90/250	1.16	20	348,888
Total	5.63	-	**2,390,464**

Total stone quantity: 3,659,660 + 2,390,464 = **6,050,124 tons**

Layer cake:

A cluster of 10 layer cakes is applied in every km^2. The total area is 112.6 km^2, therefore 1120 layer cakes are needed. Each layer cake has a minimum weight of 1364 kg, it is for this reason safe to assume that a layer cake is able to withstand any tough sea conditions.

I.2 Preliminary design 2

In this design, the default hard substrate are block reefs, which will be considered as monolithic hollow stones. To determine the required Concrete Masonry Unit (CMU) size, the required mass of a stone from table I.1 is equated to the required mass of the CMU. Products from the company EMCON have been referenced as available CMU sizes. The heavyweight class of CMU is preferred since higher weights are more able to withstand tougher sea conditions. Sizes and weights of available blocks are given in this case. However, the minimum dumping quantity is based on a few rough assumptions. First of all, the layer will consists of two layers of stones to accommodate a decent cover. Secondly, the stones are assumed to fit perfectly into each other on the sea bottom. Note that this will likely never be the case, it is just assumed to be able to quantify a minimum dumping amount. This amount is calculated as follows:

$$\text{Min. dumping} = \text{CMU's per m}^2 * \text{Weight} = \frac{1}{L * B} * 2 * \text{Weight} \tag{I.9}$$

In which L and B are the two longest sides, since it's more likely that a block will fall on its side with the biggest area. The results are shown in table I.9.

Table I.9: Required block reef class per m depth.

Depth [m]	Size [mm]	Weight [kg]	Min. dumping [kg/m^2]
20	N/A	N/A	N/A
21	N/A	N/A	N/A
22	N/A	N/A	N/A
23	N/A	N/A	N/A
24	N/A	N/A	N/A
25	N/A	N/A	N/A
26	N/A	N/A	N/A
27	400x300x200	30	500
28	390x190x190	21	567
29	390x140x190	16	432
30	390x90x190	13	351
31	390x90x190	13	351
32	390x90x190	13	351
33	390x90x190	13	351
34	390x90x190	13	351
35	390x90x190	13	351

Based on the information in table I.9, it can be concluded that no block reef class exists which can withstand the sea conditions at elevations shallower than 27 m depth (LAT). When block reefs are applied at shallower depths, the risk of stones moving too much increases, which presents a danger to the hard substrate on a larger scale (scour). Since shallower depths also require hard substrate for biological reasons, this design is therefore technically unfavourable.

I.3 Preliminary design 3

The last preliminary design assesses block reefs as a hard substrate on deeper levels, while stones as applied as a hard substrate on shallower levels. In design 2, it has been concluded that block reefs are technically unfavourable at depths shallower than 27 m (LAT). For this concept, block reefs as a hard substrate will be applied at water depths deeper than 27 m, while stones will be applied at depths shallower than 27 m. By combining table I.2 and I.9, a new design can be made.

Table I.10: Required stone/CMU class per m depth

Depth [m]	Stone/CMU class	Min. dumping [kg/m^2]
20	HM_A300-1000	1325
21	HM_A300-1000	1325
22	HM_A300-1000	950
23	HM_A300-1000	850
24	LM_A15-300	700
25	LM_A15-300	700
26	LM_A15-300	700
27	400x300x200	500
28	390x190x190	567
29	390x140x190	432
30	390x90x190	351
31	390x90x190	351
32	390x90x190	351
33	390x90x190	351
34	390x90x190	351
35	390x90x190	351

Based on this table, it can be concluded that two different stone classes are necessary as top layers while there are four different classes of CMU covering the deeper parts of the sea.

Filter layer:

A geometrically closed granular filter layer under the stones and block reefs are necessary in order to prevent erosion under the hard substrate, just like in preliminary design 1. The soft seabed is made of sand with $d_{50} = 0.25$ mm. The filter layer consists of relatively small layers of sediment in which the following criterion applies:

$$d_{50F} = 3 \text{ to } 5 * d_{50B} \tag{I.10}$$

For the stones, the same results as presented for design 1 apply. For block reefs, however, there is an extra condition that needs to be met. The stones of the first filter layer cannot pass through the holes in the CMU blocks (see figure I.5).

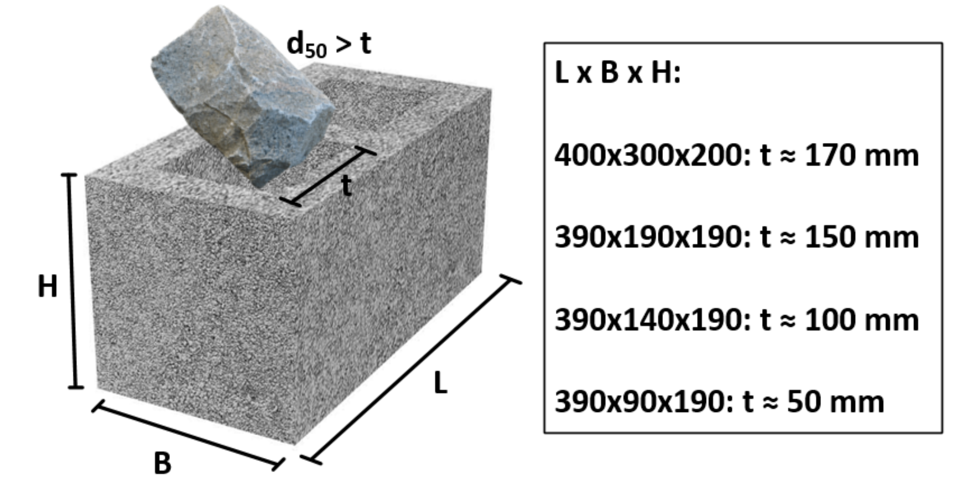

Figure I.5: Illustration of a stone which cannot pass the CMU block

Based on figure I.5, the first layer of the filter layer should have a d_{50} higher than the smallest t of the CMU block. Once this stone size is determined, the same calculations apply as in design 1, namely that the d_{50} of the higher layer should be 3 to 5 times larger than the lower layer. The results of each stone class are presented in tables I.3 and I.4, but also I.11 until I.14, which are presented below. Note that $d_{50} = d_{n50}/0.84$.

Table I.11: Overview of top and filter layers (400x300x200)

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	400x300x200	-	Min. 2 blocks
Filter layer 1	LM_A5-40	202	25
Filter layer 2	Very coarse gravel	40	10
Filter layer 3	Medium gravel	8.1	5
Filter layer 4	Very coarse sand	1.6	5
Filter layer 5	Medium sand	0.32	5
Base layer	Medium sand	0.25	-

Table I.12: Overview of top and filter layers (390x190x190)

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	390x190x190	-	Min. 2 blocks
Filter layer 1	CP90/250	152	20
Filter layer 2	Coarse gravel	30	10
Filter layer 3	Fine gravel	6.1	5
Filter layer 4	Very coarse sand	1.2	5
Base layer	Medium sand	0.25	-

Table I.13: Overview of top and filter layers (390x140x190)

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	390x140x190	-	Min. 2 blocks
Filter layer 1	CP63/180	107	20
Filter layer 2	Coarse gravel	21	10
Filter layer 3	Fine gravel	4.3	5
Filter layer 4	Coarse sand	0.86	5
Base layer	Medium sand	0.25	-

Table I.14: Overview of top and filter layers (390x90x190)

Layer	Sediment type	d_{50} [mm]	Layer thickness [cm]
Top layer	390x90x190	-	Min. 2 blocks
Filter layer 1	CP45/125	76	20
Filter layer 2	Medium gravel	15	10
Filter layer 3	Very fine gravel	3.0	5
Filter layer 4	Coarse sand	0.61	5
Base layer	Medium sand	0.25	-

The side views of a strip of hard substrate are provided in figure I.6 until I.11.

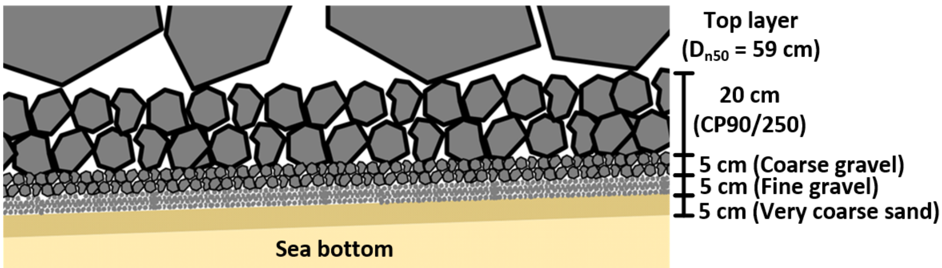

Figure I.6: Side view of a stone strip with top layer: $d_{n50} = 59$ cm

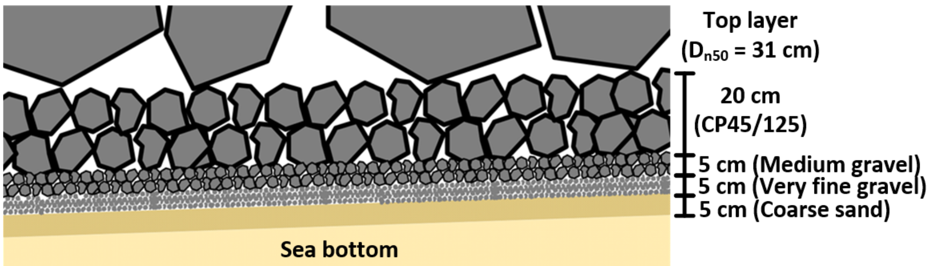

Figure I.7: Side view of a stone strip with top layer: $d_{n50} = 31$ cm

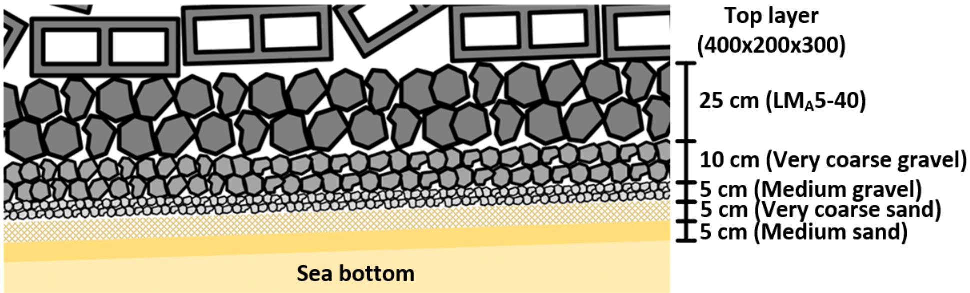

Figure I.8: Side view of a block reef strip with top layer: 400x200x300 mm

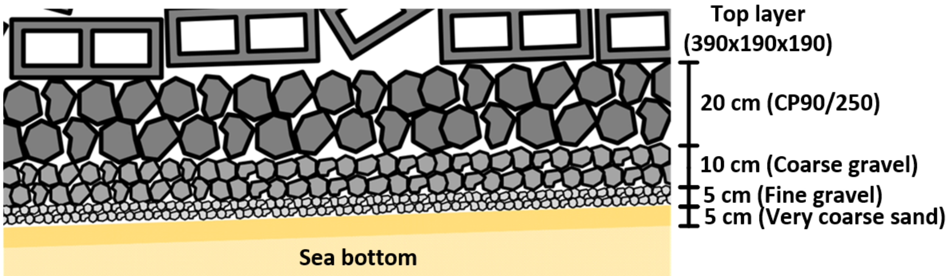

Figure I.9: Side view of a block reef strip with top layer: 390x190x190 mm

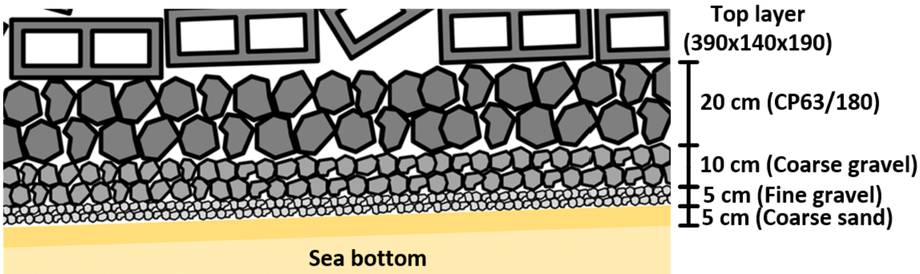

Figure I.10: Side view of a block reef strip with top layer: 390x140x190 mm

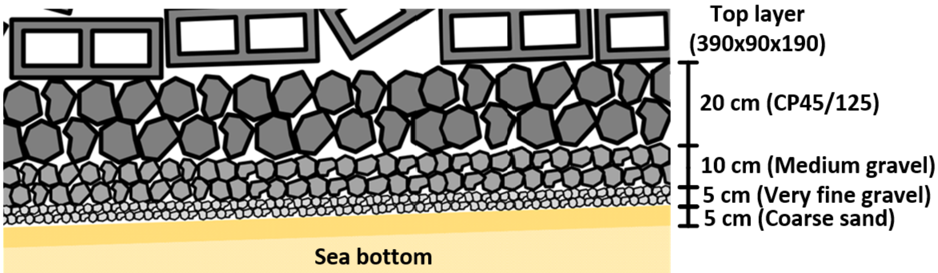

Figure I.11: Side view of a block reef strip with top layer: 390x90x190 mm

In the same way as in design 1, the total material mass required can be calculated. The results are shown in table I.15.

Table I.15: Required top layer tonnage

Top layer class	Area %	Area km^2	Stone quantity [tons]
HM_A300-1000	15.75	0.89	1,174,895
LM_A15-300	14.02	0.79	552,552
400x300x200	5.80	0.33	163,364
390x190x190	7.67	0.43	244,700
390x140x190	8.64	0.49	210,042
390x90x190	48.11	2.71	950,551
Total CMU	70.23	3.95	1,568,656
Total	100	5.63	**3,296,103**

Similar to design 1, it is assumed that the dumping quantity for smaller sediments is 75 kg/m^2 per 5 cm thickness. The results are shown in table I.16.

Table I.16: Required filter layer tonnage

Top layer class	Area km^2	Filter thickness [cm]	Stone quantity [tons]
HM_A300-1000	0.89	40	532,028
LM_A15-300	0.79	35	414,414
400x300x200	0.33	50	285,887
390x190x190	0.43	40	258,941
390x140x190	0.49	40	291,724
390x90x190	2.71	40	1,624,873
Total	5.63	-	**3,407,868**

Total stone quantity: 3,296,103 + 3,407,868 = **6,703,971 tons**

Layer cake:

A cluster of 10 layer cakes is applied in every km^2. The total area is 112.6 km^2, therefore 1120 layer cakes are needed. Each layer cake has a minimum weight of 1364 kg, it is for this reason safe to assume that a layer cake is able to withstand any tough sea conditions.

A summary of the results of each preliminary design is presented in table I.17.

Table I.17: Summary of concepts

Preliminary design	1	2	3
No. of element types	3	3	4
Stone quantity (excl. filter) [tons]	3,659,660	N/A	1,727,447
Filter quantity [tons]	2,390,464	Unknown	3,407,868
Stone quantity (incl. filter) [tons]	6,050,124	Unknown	5,135,315
Block reef quantity [tons]	N/A	Unknown	1,568,656
Total quantity (excl. layer cake) [tons]	6,050,124	Unknown	6,703,971
Layer cake quantity	1120	1120	1120
Ship/Jacket quantity	112	112	112
Technical feasibility	Yes	No	Yes

Appendix J

3D sketches of the final design

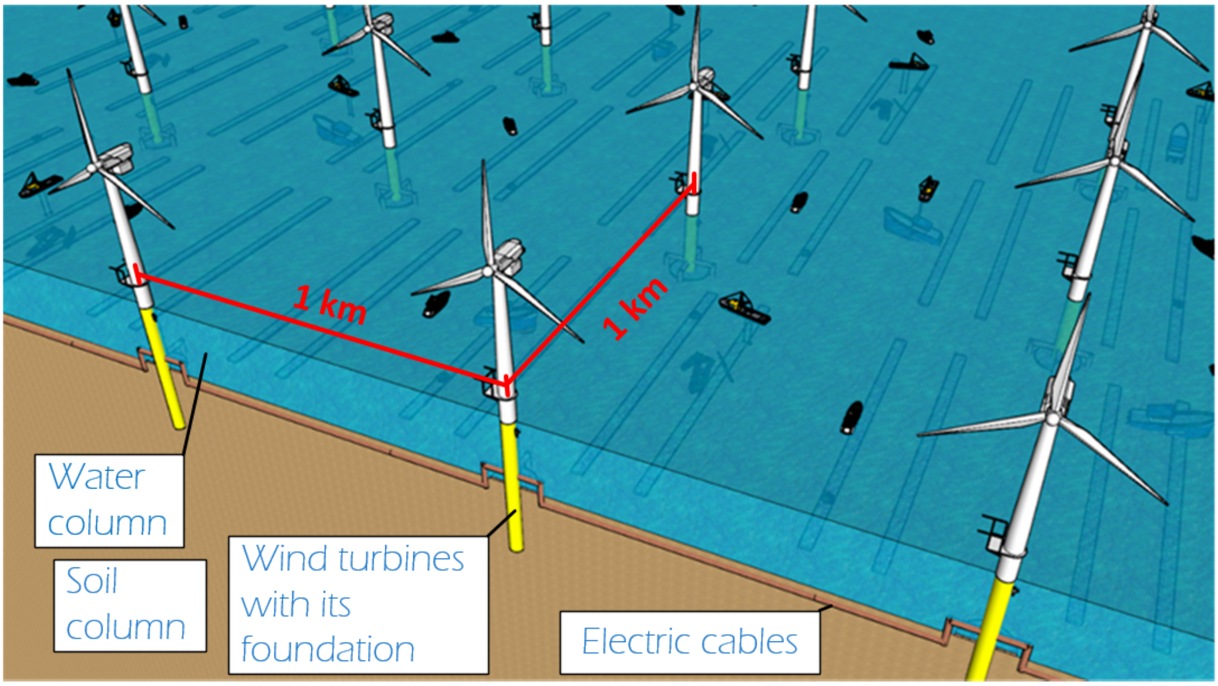

Figure J.1: 3D view of the final design (not to scale)

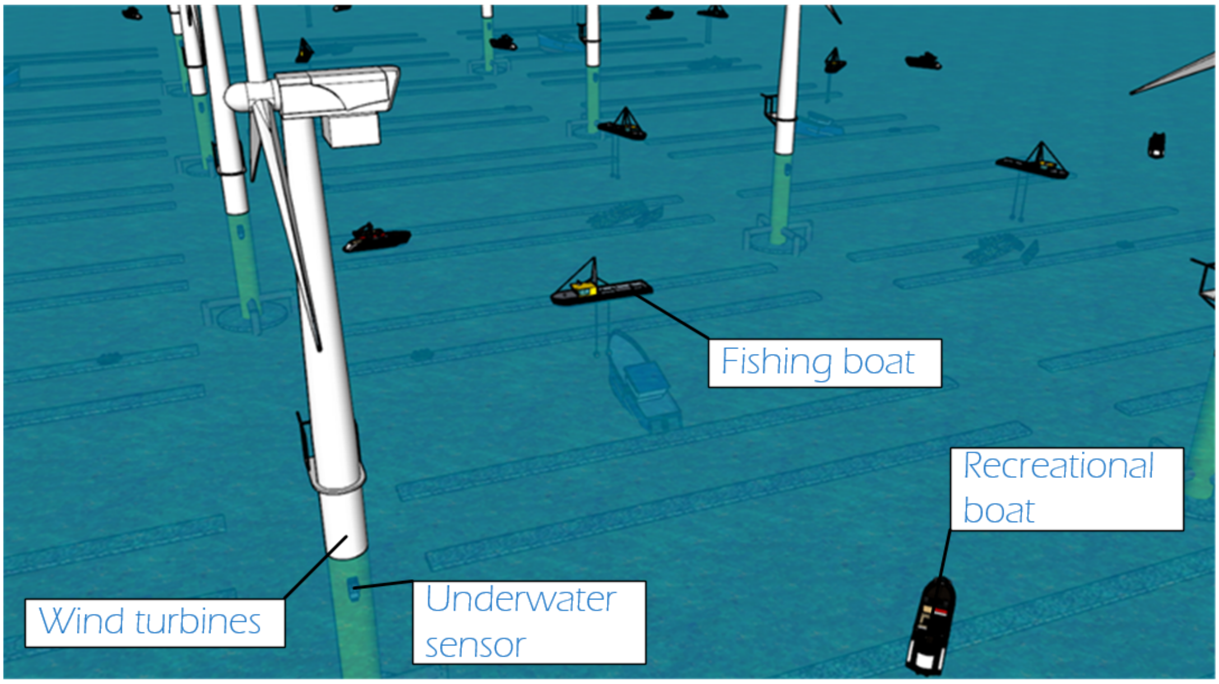

Figure J.2: Birds-eye view of the final design (not to scale)

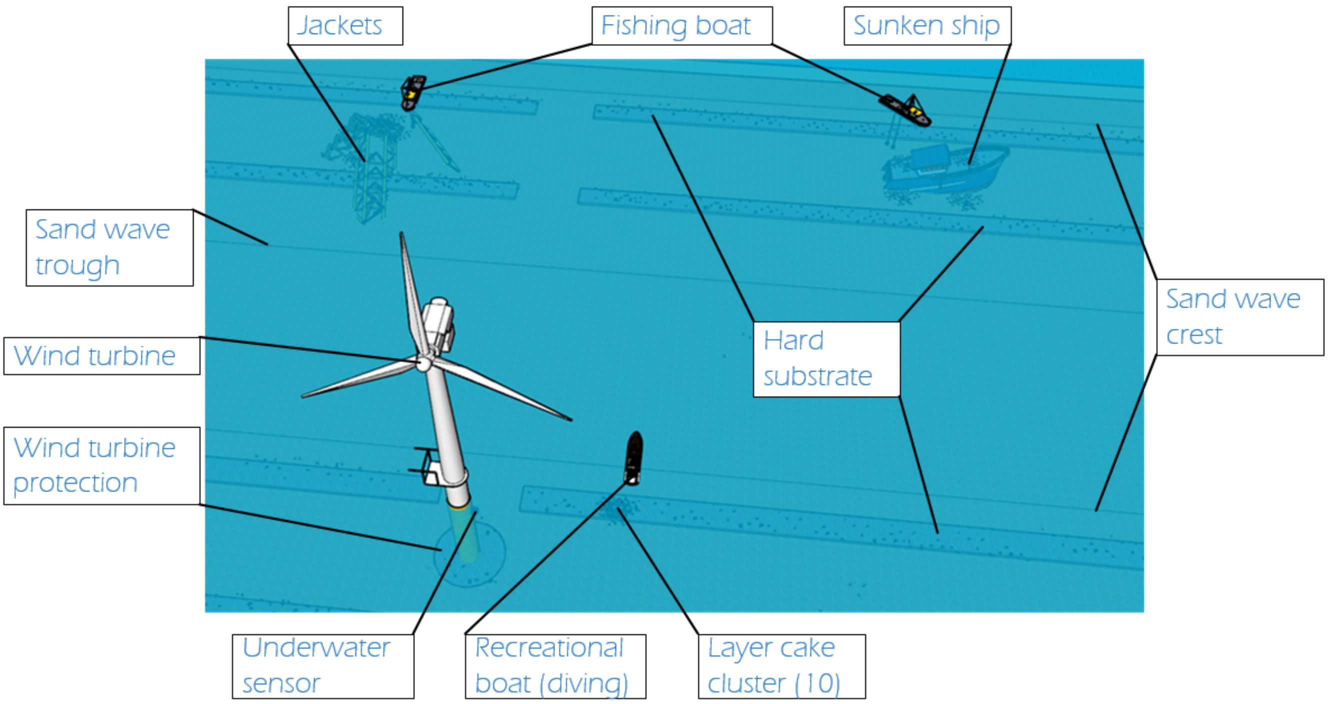

Figure J.3: 3D view of the final design (to scale)

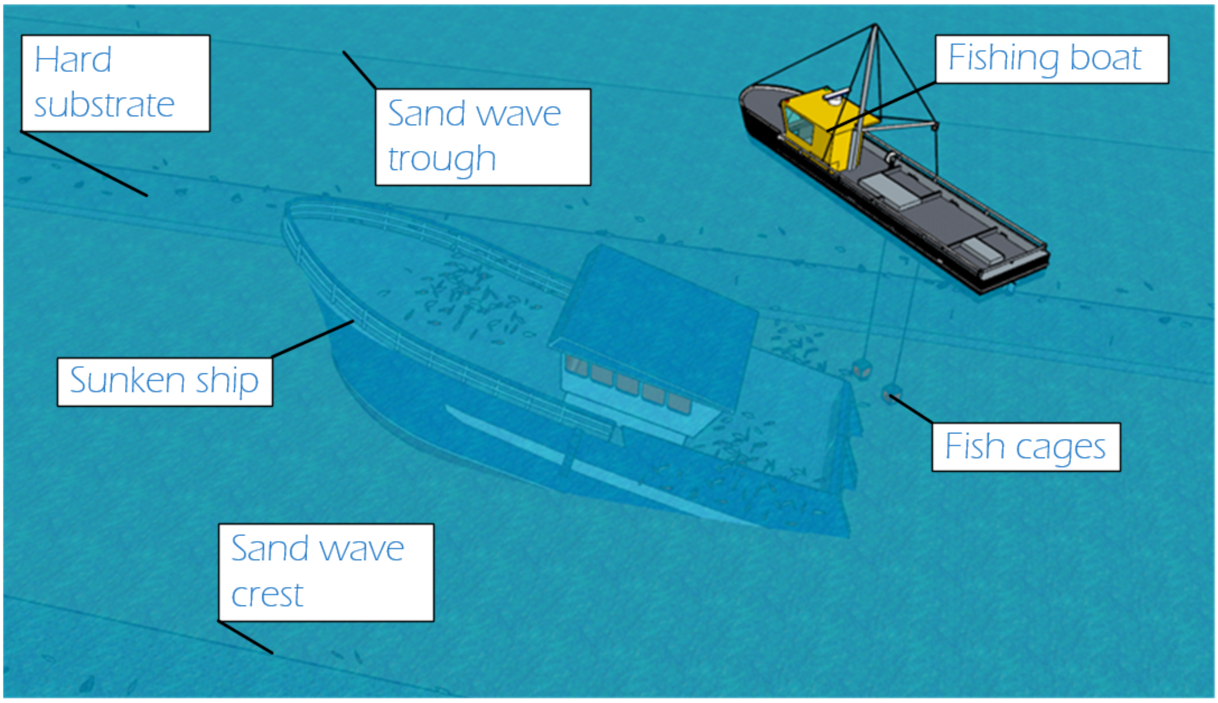

Figure J.4: 3D view of a sunken ship

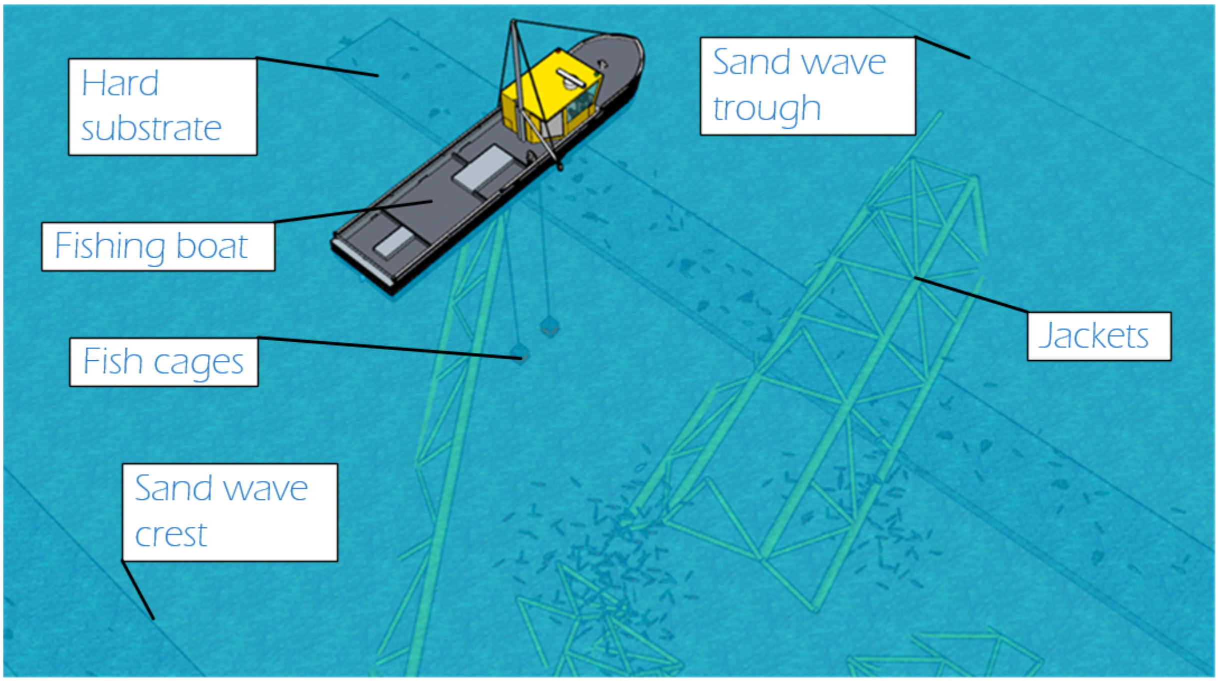

Figure J.5: 3D view of a sunken jacket construction

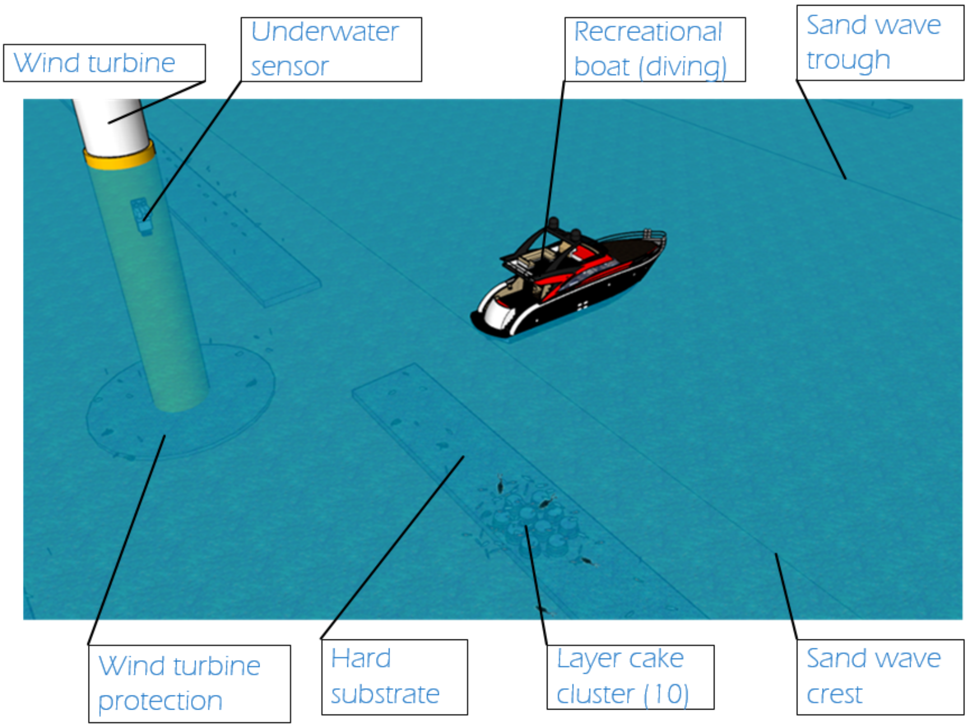

Figure J.6: 3D view of a layer cake patch

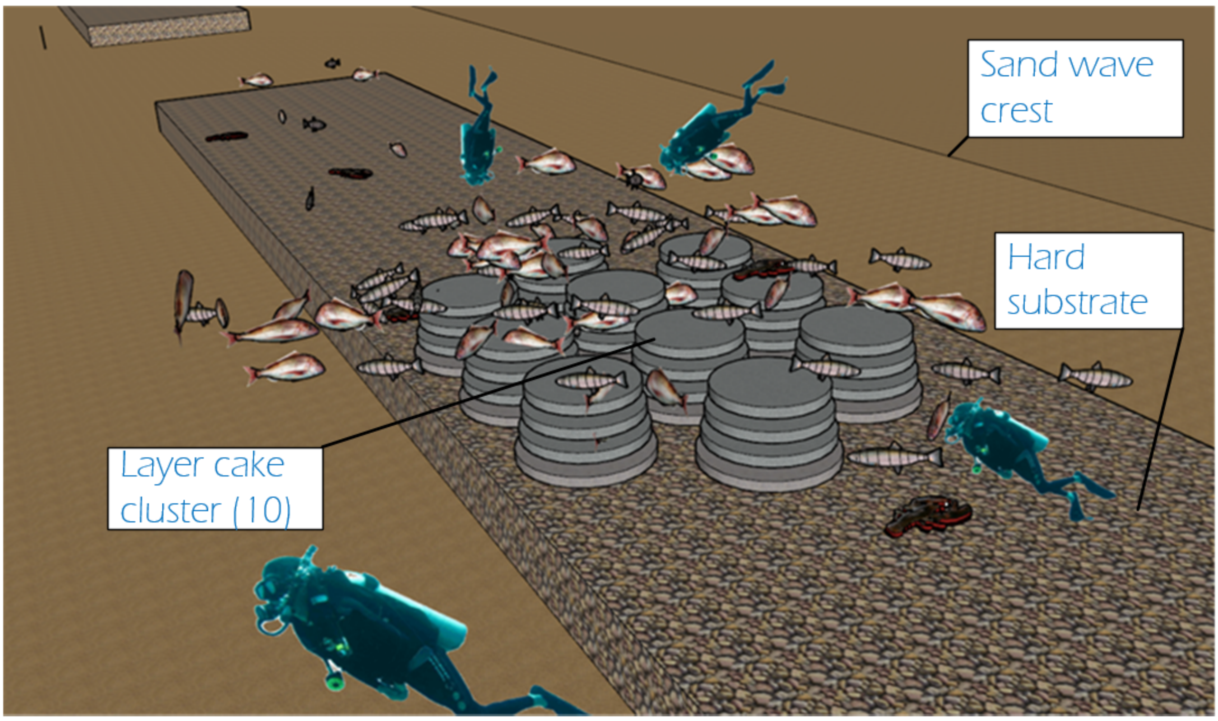

Figure J.7: close-up view of a layer cake patch

Appendix K

Interview with Arnoud Bosch and Michael Osseweijer from Seaway Heavy Lifting on the 6th December 2019

Meeting Seaway Heavy Lifting

Date: 06-12-2019
Location: Zoetermeer, main office Seaway Heavy Lifting
Invites: All
Time: 11.00 - 12.00
Present: Kije, Sebastiaan, Kamal, Chris, Arnoud Bosch (SHL)
Absent: None

Questions:

1. The latest development of reusing offshore constructions on the North Sea is to decommission them and place them on the seabed. Did SHL have involvement in decommissioning and reusing plans of offshore platforms or similar projects?

Not specifically mentioned, deinstallation projects that have been mentioned were:

- Shell 2011
- ST1

SHL has involvement in decommissioning, often however, decommissioned elements are brought back to shore and reused for other purposes. 98 - 99% of the offshore elements is reused. These elements yield a lot of money. Decommissioning costs are for the biggest part paid by the government, taxpayer (the average dutchman) pays 70%.

2. Did SHL ever decommission an offshore platform? What did the works look like in general and for SHL in particular?
2.1 Which vessel was used?

Shear lag vessels/barges are often used:

- Rambiz II
- Shear lag are mainly used for short distances

A shear lag vessel has a crane in the shape of an A-frame on their deck. Yudin/ Strashnov crane vessels can be used, but crane vessels from other subcontractors as well.

2.2 What are the experiences of such a project timewise?

- With or without cargo, vessel speed stays the same.
- Dayrates:
  - Little jacket (300 tons crane, 50 men aboard) is about 30000 - 40000 eu (with a factor 10 for larger vessels).
- Workability in the summer season (April - September) is 70-80% and in the winter season (January - February) it is 20-30%
- Jackets are cut down to 3 to 4 m below the seabed. Clay can be removed by a cutter/brace. Sand can be removed with an air lift tool. Sometimes, when piles are filled with grout, they need to be cut from the outside.
- Tolerance of 2 years for removing an offshore platform. This decreases the pressure on such a project, but the profit margin becomes less. For example, ST1-platform is removed within 10 days.

2.3 Are there differences in decommissioning procedures when considering two offshore structures of different age?

Older platforms have dirtier topside elements. Asbestos is abolished since 1989. Back in the days, offshore platforms use two main support frames. 2000 - 3000 tons topside could be uplifted in one go. MSF consisted of container elements. Back in the days, smaller platforms, less lifting capacity. The latter has now increased.

Older offshore platforms are often more expensive:

- They consists of more elements.
- Top side consists of more box elements.
- More asbestos.

Mass topside is about as much as the mass of the jacket structure.
2.4 What critical factors are involved when cutting the offshore platform modules? Think of steel grade, joints and other material characteristics. The topside elements

of gas platforms are relatively cleaner than those of oil rigs. Topside although contain traces of lead, chrome and chemicals that are difficult to quantify. Risks:

- Possible corrosion: many surveys have to be done on beforehand.

- Centre of gravity is often unknown
- Mass of structure is often unknown
- NDE (Non-destructive evaluation) needs to be done.
- Hyrogen cracking, welds are possibly broken.
- Material risks: asbestos may be present in the materials.

Fatigue is an important factor.
Corrosion continues under water.

3. *What are the key figures of the vessels of SHL?*

3.1 (Production) rates of the equipment used for a decommissioning job?

200-400 t a day for each vessel (time independent). Helicopter, ship estimated costs: 20.000 eu/day and 25.000 eu/day respectively. One hour of offshore work is more expensive than one hour of onshore work.

3.2 Transport speed loaded vessel?

Same as the vessel speed without cargo (difference is marginal), this depends on the type of vessel and hydrologic conditions.

3.3 Workability of the equipment? (Wave, current, wind‘, frequency)

A significant wave height of $H_s = 2.5$ m is mentioned. This however often depends on the deep water wave frequency as well.

3.4 Risk change per job?

Stability (geotechnical, structural) depends on job and size of offshore element.

The Northern part of the North Sea has an other marine life than the Southern part. Transportation of offshore elements has therefore strict rules.

3.5 What is the maximum height of a construction during lifting?

This depends on the equipment that is used. 2000 - 3000 tons can be lifted up in one go.

3.6 Are there any restrictions in lifting a construction to the seabed (20-40m water depth)

An average vessel has only 5 km of lifting wire and 24 disks instead of 48, so less capacity is present. Lifting block is normally used above the water surface. It can be used below water surface as well: but with less voltage so there is less capacity.

Tipping the jacket is only possible for depths shallower than 50 m. *4. Would SHL be*

interested in contributing to construction of artificial reefs?
4.1 Which activities could SHL execute? No comments.

5. As SHL is most probably responsible for what they are lifting, they might also be involved in the mechanical stability of the construction. Is it also possible to transport such a construction in parts? (only the crew cabin of a offshore platform or the jacket structure) It is possible to cut the jacketed structure into smaller elements (e.g. of 30 tons).

Mitigating measures are often not taking into account while decommissioning offshore frames.

500 offshore platforms will be dismantled the upcoming decades.

Dismantling is executed in the following order:

Dredging → cutting with a diamond wire/burner → uplifting → placing on crane vessel deck or on a separate barge.

A separate barge costs extra money.

Other remarks: The use of expired monopiles or/and wind turbines are serious options:

- **Repowering of old wind parks is a possible option because of their useful location.**

London array wind farm uses 2000 installed wind turbines and will soon be repowered.

Idea of Arnoud Bosch: old decommissioned wind turbines and foundations for hard substrate (?).

Structural characteristics is not guaranteed after its design lifetime.

Stakeholders:

Contractors and offshore clients are often careful about the use of their name.

Offshore parties often avoid the media.

Goodwill knock-off effect is hard to predict.

Expansion on renewables is however very important, especially for the attractiveness of young professionals.

Appendix L

Interview with Maarten Nijman (Tender Manager) and Sicco Dommerholt (Project Engineer) from Boskalis on the 4th December 2019

The meeting at Boskalis was an interactive sessions. We started with a presentation after which every discipline spoke with the specialists of Boskalis, in this particular interview the discussion with a project engineer specialized in rock dumping was written down.

1 What are the costs of rock dumping activities and what will be the most cost-efficient way of rock dumping? (for example: dumping in long lanes or squares) Boskalis executes rock dumping works with several types of contracts. As rock dumping is a cost intense activity many clients try to cut corners in certain ways. However the production of rock dump vessel is around 600-700 ton per hour (not precisely). Dayrates are around 125.000 euro although this figure is not fully clear because not all costs are included in the figure. The price to buy stones in Norway are between 8-9 euro. To summarize, Boskalis generally executes rock dumping works for 20-40 euro per ton.

2 Rock dumping to protect the cable from external threats involves detailed surveying, in what way does surveying influence the production of the operation? In other words, if a detailed survey is not needed, to what extent will the productivity increase? Surveying is time intense activity but no surveying is not an option because why should the contractor dump the rocks if there is no control?

3 What would be the potential costs of decommissioning of offshore platforms (with a Dockwise vessels) of a certain size and to what degree will these costs be reduced when the structure is installed on the seabed? Decommissioning is not an activity that can be executed with the Dockwise vessels.

4 What are the values of the OPEX related to the CAPEX for such constructions? In principle Boskalis designs for example scour protection in such a way that there are no repairs needed, besides that, it also depends on the type of contract that Boskalis signed with the client. In case the client is the developer and designs the field themselves, Boskalis not responsible and just installs what is requested by the client. However, there might be storms ones in x years that requires some repairs in a few parts of the field, therefore a value of 1-2% would be a reasonable assumption to be made by the developer.

Appendix M

Interview with site worker from Scheepssloperij NL on the 14th January 2020

Dear employee of the scheepssloperij NL, I am a student of the TU Delft and together with some other student I am doing research on a project to enhance the biodiversity. Therefore we are investigating the possibility to install old vessels on the sea bed. Therefore, we are looking for scrap vessel prices and what the process contains

What kind of vessel do you scrap?

We scrap all kind of vessels. We are mainly focusing on 150 to 200 t vessels which are the inland vessels.

What is the process of scrapping?

The process of scrapping a vessel depends mainly on the degree of cleaning the steel. As you want to put the steel on the seabed the steel most probably need to meet certain ISO standards. Keeping in mind your purpose of the steel, the vessel needs to be fully scrapped while not all vessels can be used as some materials are to expensive to clean and will go immediately into the incinerator.

What are the prices of the scrap steel?

As mentioned in the other questions, the price of the scrap steel depends on the degree of cleanness of the steel. However we use a general value of 0,21-0,25 euro per kg as selling price. So If you want to buy the scrap steel this will be the costs. Off course the transport to sea is not included.