Delft University of Technology

Exploring market uncertainty in early ship design

Simulating the effect of design parameters on vessel performance in an uncertain market

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Report Number: SDPO.20.011.m

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Simulating the effect of design parameters on vessel performance in an uncertain market

by

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to obtain the degree of Master of Science, Marine Technology
at the Delft University of Technology,
Faculty Mechanical, Maritime and Materials Engineering
to be defended publicly on Wednesday June 10, 2020 at 1:00 PM.

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Project duration:	September 11, 2019 – June 10, 2020	
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Abstract

To decrease Europe's harmful emissions, the European Union aims to substantially increase its offshore wind energy capacity. To further develop offshore wind energy, investment in ever-larger construction vessels is necessary. Designing vessels is difficult however, as this market is characterised by a large but seemingly unpredictable growth of market demand, turbine size and distance from shore. Currently a way of dealing with such market uncertainty within the ship design process was found not to exist.

This research aims to develop a method that is able to deal with market uncertainty in early ship design by increasing knowledge when design freedom is still high.

The method uses uncertainty modelling prior to the requirement definition stage by performing global market research, and during the concept design stage by iteratively co-evolving the vessel design and business case in parallel. The method consists of three parts; simulating an expected market from data, modelling multiple vessel designs, and an uncertainty model that evaluates the performance of the vessels in the market.

The case study into offshore wind foundation installation vessels showed that the method can provide valuable insight in the effect of ship parameters like main dimensions, crane size and ship speed on the performance in an uncertain market. These results were used to create an initial design that is expected to perform well in the uncertain market.

The developed method thus provides a way to deal with market uncertainty in the early ship design process.

Preface

Dear reader,

This Thesis has been a learning process every step of the way. The research gave me a glimpse into the vast worlds of data analysis, uncertainty modelling, complex ship design and many more. This experience has sparked my interest for research and I am looking forward to learn so much more in the future.

First of all, I would like to thank Austin Kana for introducing me to the topic and for his guidance. Likewise I want to thank Ko Stroo for his support, knowledge and enthusiasm about my project. I am indebted to Jose Jorge Garcia Agis for his critique, discussions and the amazing stay in Norway.

Furthermore, I would like to thank Hans Hopman for his critique and as chair of the thesis committee, and Frederik Schulte and Jafar Rezaei for being part of the thesis committee.

I also sincerely appreciate the expertise and help from my friends at Ulstein Design & Solutions B.V., and the hospitality, and openness of the employees at Ulstein International and Ulstein Design & Solutions A.S.

Many thanks to my fellow students, PhD's and others with which I have had the pleasure to discuss my research.

Lastly I would like to thank my parents, my girlfriend, my family and my friends for their encouragement, friendship and help.

J.J. Zwaginga
Delft, May 2020

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1 Doubtful situation

Ship design firms find themselves on the border of product and service, only delivering a ship on paper. They sell knowledge, which is famously one of the most difficult businesses to monetize and protect, while also having to deal with competing design firms from all over the world that have lower hourly engineering costs. A designer needs to be able to convince customers that their design has the right range of capabilities to fulfil contracts over several decades. Firms therefore use innovation to improve their ability to develop suitable ship designs which anticipate the future needs accordingly, without becoming overly complex or expensive.

This thesis will focus on creating a method that can be used by an offshore focussed subsidiary of the Norwegian owned group of companies Ulstein Group (from here on referred to as Ulstein); Ulstein Design & Solutions BV (UDSBV). The method should allow them to research what initial designs fit the future market by using their design knowledge and information from the market. During the early design phase, a designer needs to provide the customer with estimated information like price and capability for multiple alternative vessels, which are used to make design decisions. As mentioned by Pruyn [1], vessel owners typically optimize for the economic situation at the start of construction, but should optimize for use. Predicting which design will have the right functionality for a future market is however very difficult. The method aims to solve this by providing a good indication of what design would be of use in a probable future market. This will improve the ability to give information on interesting alternatives and steers decision making toward an initial design that fulfils the need of the customer. To develop the method, a case study is performed for offshore wind foundation installation vessels, as the developments in the offshore wind market makes it especially difficult to define the right vessel requirements.

The offshore wind market is characterised by wind-turbines becoming larger in size and construction occurring further from shore to support the need for increased power production. As it is uncertain how the demand, size and distance from shore will develop, determining an offshore wind foundation installation vessel that has the right size and capabilities for use over multiple decades becomes very difficult. This results in a general reluctance with customers to pay for design and building of vessels. Because of this, as mentioned in to the Offshore Wind Outlook 2019 [2], the installation of offshore wind-farms is said to be one of the bottlenecks for the growth of offshore wind energy generation. Even though offshore wind presents many opportunities for offshore construction companies, as is evident from the renewable energy targets set by the European Union (EU) [3], which is projected to invest a total of 12 billion in offshore wind by 2030 [4]. With the total amount of installed offshore power capacity within the EU even being targeted to rise from 18.5 GW in 2018 up to 150 GW in 2030 and eventually 460 GW in 2050 [5].

To be able to identify the future vessel needs, the projected business case is coupled with the concept design phase. The findings from the method can then be used as reference for developing heavy lifting vessel designs that are effective and competitive in a wide range of probable future scenarios. This enables UDSBV to provide and advise customers with concept designs that take possible changes in the market into account, thus decreasing the uncertainty for the customer. The method should also be able to be used together with, or in addition to, the existing design methods that are being used within Ulstein.

1.1. Research approach

During the start of this thesis it became apparent that the subject of decision making for future uncertainty in ship design is very broad. This made it difficult to direct the research in a certain direction. From literature and current practice, three directions for the research are considered.

- Method: Starting with an existing method or tool used to guide decision making for uncertainty and exploring if the method can also be used for the Ulstein case.
- Literature: Starting with defining where a literature gap exists and determining how the Ulstein case could be used to fill the literature gap.
- Practice: Starting with the problem and proposing a solution from literature that purely satisfies the needs of UDSBV. Either by taking the problem as defined by UDSBV at face value or investigating if there was another underlying problem to be solved.

Due to the limited knowledge available at the start of the thesis, the amount of literature and subsequent methods available were perceived to be very extensive. It was difficult to place research in context and grasp the current state of the art, which made it hard to start from literature. Regarding practice, the designers at Ulstein had a very clear picture of where they would like to gain more insight, but it was not immediately clear what the deliverable should be. The Ulstein Group already had a lot of knowledge on processes for guiding innovation and decision making with the Ulstein Design Process (UDP) and Accelerated Business Development (ABD) respectively. From the state of the art report from the 2018 International Marine Design Conference (IMDC) proceedings [6] it seems however, that these processes are on two different sides of the ship design research field, namely; Complex design methodologies (UDP) and designing for uncertainty (ABD). From these observations, two questions came up that effectively divided the research into a practice side and a literature side: What is the relation between both of the research fields, other literature and current practice within Ulstein? In what way could this thesis benefit UDSBV, without re-inventing knowledge from current practice? These questions together form the first research question. Besides this, a few personal goals for the thesis were also identified; to gain as much insight in the ship design industry as possible and to gain more experience working with data.

It became clear that, with all the available information sources, understanding the problem was a first priority. Ship design, and therefore this thesis, is however characterised by ill-structured or wicked problems [7][8]. Hence this research was initiated by structuring the project so the underlying problem could clearly be defined. Different theories and perspectives to structure scientific research were explored by reading PhD and Masters theses. The Deweyan approach, from a PhD thesis by Bruinessen [9], was eventually selected, as the approach focuses on decoupling theory (literature and university) and practice (knowledge from within company), while structuring the problem and solution definition process. The process is taken from Stompff [10] and is generally used to develop a solution (theory) from a problem (doubtful situation) and eventually testing that theory to see where new gaps occur, effectively creating the possibility to iteratively improve the theory. The approach is used to structure the report and is summarised below and graphically represented in figure 1.1.

1. Doubtful situation (Chapter 1): short problem and background description based on current practice at UDSBV.
2. Problem institution (Chapter 2): discussing the problem and trying to understand it as well as possible using literature and practice.
3. Determination of problem-solution (Chapter 3): describe the final problem, then use literature to propose probable solutions and define the research questions and scope.
4. Reasoning (Chapter 4): evaluate the proposed solutions and choose which one to use and describe the solution as clearly as possible.
5. Experiment (Chapter 5 & 6): implement the solution in practice and evaluate if the solution worked. In this thesis, this is included in the model setup and results chapters.
6. Warranted assertion (Discussion): from the method, a new problem description is determined (recommend further research).

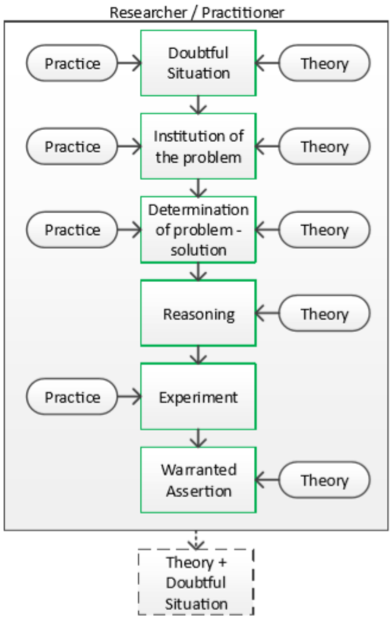

Figure 1.1: Deweyan inquiry as described by Stompff [10]

Besides using the Deweyan approach to structure the research, one main research question and five sub-questions are defined that guide research towards an end-goal. The main research question that the thesis aims to answer is defined out of the problem description in Chapter 2:
How to model the effects of changing business case requirements due to market uncertainty during the early ship design phase, in such a way that the designer can explore the design space?

To guide the research towards answering the main research question, five sub questions are established:

1. *What is the relation between complex design and uncertainty modelling literature and current practice and how can the thesis benefit UDSBV and advance research?*
2. *How can the future market be forecasted while dealing with market uncertainty accordingly?*
3. *How to model the case study using uncertainty modelling and how to implement this in the design process?*
4. *Which scenarios can be modelled to determine the effect of certain design choices on vessel performance in the market?*
5. *Using the method, what is the effect of market changes on the selected design parameters and how sensitive is each to the market.*

2

Institution of the Problem

As described in Chapter 1, Ulstein wants to tackle the problem they have with creating designs for an uncertain market, specifically the offshore wind foundation installation market. To determine the root cause of this problem, it is important to investigate how Ulstein and other design firms currently operate. Besides researching the gap in current practice, literature has been explored to understand the theoretical background of the problem and see what research is applicable. This chapter thus presents the underlying problem by looking at both literature and current practice.

2.1. Problem background

Ship design is an industry which can be described as going through a process characterized by managing decision making [11]. Through experience, design firms gain knowledge (tacit knowledge) that grants them the ability to make the difficult promise that their design, a product of going through the process, will have the desired functionality. The goal of this process is to create designs with verifiable and noticeable added value against fair cost and acceptable risk [12]. The ship design industry is distinguished by constant cost competition between design firms, while participating in highly specialized or cyclical markets with a relatively small amount of work [13]. These characteristics result in a need to be proactive toward change, by constantly improving the ability to provide better designs [14]. Therefore, firms have looked into innovating their design process by focusing more on customer processes, developing analysis tools [15] and improving the management of projects [16]. The goal of such developments is generally to improve their market position or to decrease the cost of their process. Design firms have thus broadened their service portfolio towards more business case centric design [12][17].

With the drive to innovate, many have researched the nature of design. Researchers like Andrews [8] have identified the complex design problem and Singer [18] names the dancing landscape of ship design. Both describe the difficulties that arise in design due to increasingly complex mission statements and conflicting and changing requirements. Designing a ship that fulfils the need of the customer (purpose) accurately, has been identified as the "interpretation objective" by McKenney [19]. The second objective McKenney identified is the "prediction objective", having to predict what design will fit the requirements. The necessary capabilities of a ship (design drivers), which depend on the targeted market segment, together with the customer's requirements will dictate important parts of the design. At the start of the design process, the capabilities to focus on must be decided. The specific effect of each on the design is however not known, especially due to the large amount of uncertainties present during the start of the process. UDSBV's problem shows that the uncertainty due to a changing offshore wind market makes it difficult to substantiate what the result is of certain design choices on the performance of the vessel.

Decision making in ship design under uncertainty has been researched by Garcia Agis [17] (page xvii), he describes uncertainty as being a 'State reflecting the lack, inaccuracy or deficiency of information. Any situation outside pure certainty, independently of the degree of uncertainty.' An example of such an uncertainty is having to deal with a changing market, as the necessary capabilities and economic performance of a ship can change in the future [1]. The designer thus has to deal with uncertainty when making decisions in the process, while being responsible for converging all inputs from stakeholders and integrating everything into a functional design [7] [20]. Decisions made during the early design stage have a large impact on the direction of the process and the eventual performance of the design, since the freedom to make changes will rapidly decrease. As shown in Figure 2.1, a designer is confronted with a lot of uncertainty in early design, the figure distinguishes uncertainty about the market (purpose) and the design (function). Design uncertainty gradually decreases until the design is fixed and the vessel is build. Market uncertainty only slightly decreases over the design process and mainly decreases during the life-cycle (as the market progresses). To improve the design's performance in the market, uncertainty needs to be dealt with in early design, decreasing market uncertainty and increasing knowledge of the problem when design freedom is still high. Four strategies designers can deal with uncertainty are categorized by Thissen & Agusdinata [21] as seen below. As mentioned by Garcia [17], each of these strategies can be of use in the ship design process, however it is most important to know when to use them, which is not always the case in the current design process.

1. Ignore: assuming that the future can be described in terms of past experience. This is basically the same way the human brain works [22] and is the current industry standard in ship design. The uncertainties that may occur in the future are not taken into account explicitly. The designer thus bases decisions on experience and what is believed to be likely to happen, without taking changes into account.
2. Delay: wait or guide the process in such a way until uncertainty has become smaller over time, basically delaying decisions until more aspects become clear.
3. Accept: by accepting that parts of the design will remain uncertain, one could plan for different possibilities and protect the vessel or even exploit the uncertainties.
4. Reduce/Control: trying to gain more knowledge so the amount of uncertainty regarding choices is reduced. Ways to gain more knowledge are; doing research, simulations and analysis. Reducing is named as a cost-effective way of dealing with uncertainty [23], but it displaces cost and time distribution to the start of the design process. As the designer will have to put more hours into research instead of just designing. This is sometimes perceived by customers as extra cost, even though it might save a lot of costs in the long run.

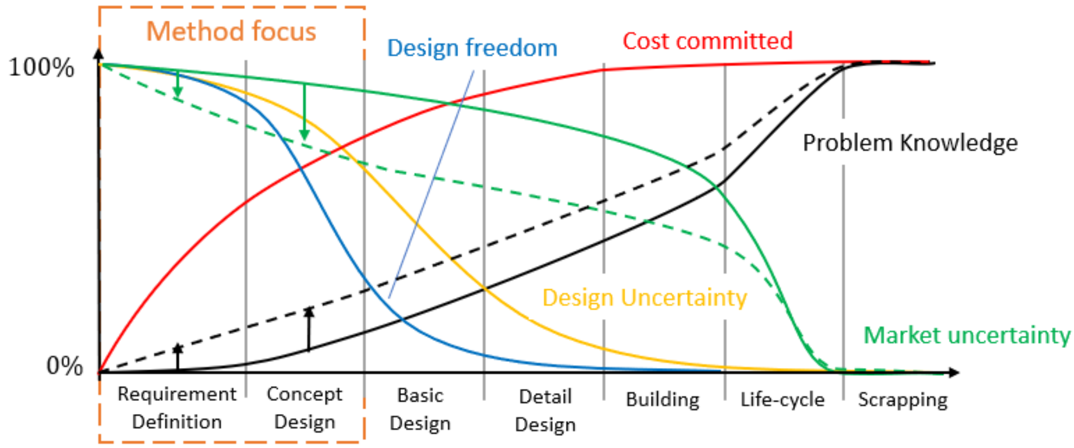

Figure 2.1: Depiction of design freedom over the design process, adapted from Nam and Mavris [24]

As mentioned by the state of the art report from IMDC 2018 [6], two separate research fields are looking into dealing with complexity (complex design methodologies) and uncertainty (designing for uncertainty) respectively. Dealing with complexity is mostly looking at the full design process, while design for uncertainty commonly uses modelling to explore uncertainty. As explained by Patricksson [25], these models can be divided into deterministic (optimizing for one point) and uncertainty modelling (taking change into account stochastically). Many papers have shown the functionality of such models [26][27], but neither seems to couple both research fields and explain where to use uncertainty modelling in a design process. Both research fields might be used to solve the UDSBV problem.

Currently most design processes are arranged around experience, creating a design from a reference ship (evolution). When a designer has no frame of reference for the whole or certain parts of the ship, because of unique requirements or uncertainty, designers might have to invent elements themselves (revolution) [8]. In any design process, both revolution and evolution will occur, but the distribution depends on the knowledge of stakeholders (frame of reference) and the market segment. The purpose of the ship will however always be leading the process, as it dictates the size of the ship and equipment on board. Many researchers therefore divide the design process into two; a definition of function and the creation of a design that fits it [25][9][19]. The description used in this Thesis is based on the concept to knowledge theory (CK-theory) for ship design as explained by Bruinessen [9] and is visualised in Figure 2.2. CK theory has been introduced by Hatchuel & Weil [28] and defines design as a process of going from a concept space with many undecided possibilities to a knowledge space where decisions have been made. Bruinessen [9] explains that shifting between concept to knowledge can happen on four hierarchical levels in ship design; business case, ship, system and component. Designers can choose to evolve or innovate parts of a level but as named by Bruinessen, innovation should ideally be limited to only two levels in parallel. As a design can otherwise quickly become unmanageable, leading to large design iterations, requiring more time and effort. Regarding this thesis, as the offshore wind foundation installation market is uncertain, it could be useful to explore both the business case and ship levels in parallel to visualise their effects.

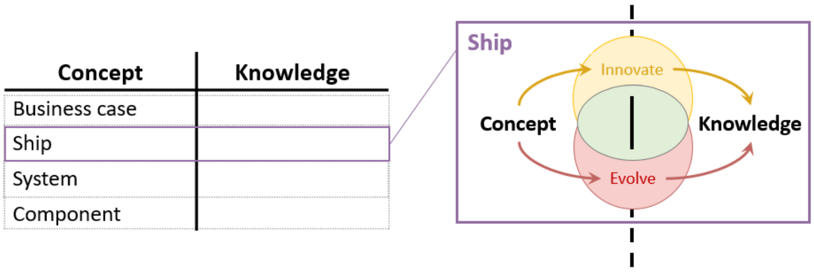

Figure 2.2: Visualisation of design using CK-theory

1. Business case: deciding what the function of the ship will be.
2. Ship: deciding what ship design will have the desired function.
3. Systems: as mechanical and electrical systems also have to be designed, decisions are made what components and connections are needed for the system to work.
4. Components: each component of a system also needs to be designed, like creating a propeller or pump.

As is evident from the hierarchical levels and the objectives of ship design named by McKenney [19], everything starts with finding the purpose (business case) of the ship. Andrews [29] calls this part of the design process requirement elucidation and stresses it's importance. He explains that it is however very difficult to create a clear method for requirement definition in ship design, since each design process starts from a different point with other information and customer expectations [30]. Besides this, difficulties in technical and social interaction [31] make the designer's first objective, 'interpret requirements', even more challenging. This was also recognized as a major challenge by employees at Ulstein. The importance of requirement elucidation is substantiated by the risk that bad requirement interpretation can result in a disconnection between the real and perceived purpose. Which means that a design might fulfil its function (what it was designed for), but not its purpose (need of the user). This disconnect can culminate in expensive refits or overruns in cost and time or it can even result in the design firm and customer splitting ways. An example of a disconnect is given by A. Kana [32], who names the US navy's littoral combat ship project where; "decisions were made about attributes of the design without full understanding of their effect on both solving the problem or their effect on vessel costs". A designer thus has to continuously decide whether the described functional requirements are actually what the customer needs by also looking at the market and using their experience. Or as described by Gaspar [33]; "a correct ship will only be decided on a correct set of requirements." Design processes that do not make a formal distinction between needs and requirements may lead to ineffective design. Exploring the effect of the market uncertainty on requirements in offshore wind would be especially useful in terms of the design process.

Even though the specific design process will differ each project, design firms and researchers have developed design methods that help guide the process. The specific set-up of a design process differs between firms, each created in a way that works best in their company culture and vessel segment. The current practice, relevant for this thesis, at two companies within the Ulstein Group; UDSBV, Ulstein Design & Solutions AS (UDSAS) and the company offering market advice to both, called Ulstein International (UIN), has been researched through interviews. A list of all interviewees can be found in the Appendix D.1. Differences were found in approach between these companies that can be attributed to differences in culture and market segment, but in general the approach of each company from within the Ulstein Group was to be proactive to the market and advise customers with vessel designs that are effective and competitive. At UDSBV, the design process fit well within the CK-theory set-up. As an example, several methods have been created by Ulstein that are used during particular innovative projects that guide innovation (UDP) and requirement research together with a customer (ABD). While for evolution, preliminary designs are created to function as a starting point for evolution and advertisement called "standard designs". The research performed into the current practice at UDSBV can be found in the appendix E.3, the research aimed to answer if the existing methods could be used, but neither was found to be able to provide a quick and clear overview of the market uncertainty found in offshore wind. Regarding the requirement elucidation, some other important observations from interviews and other talks are reviewed below:

1. The early talks with a customer generally turn out more productive when a designer has prepared a more detailed business case, which is the case with the standard designs (having done homework). Even when a customer does not agree with the business case, notes on how the customer thinks the proposal is flawed provide valuable information.
2. The customer should be at the center of the design process, while the designer is equal in dialogue (also mentioned by Andrews [29]). The design is more likely to be built when this is the case, as the customer has been more involved in the process. Besides this it is mentioned that; "It is difficult for our customers to let us look behind their scenes, this only happens when they think of you as a partner. It doesn't work when they still have other design firms in mind."
3. Most interviewees stress the importance of supporting the designer while using and improving their knowledge. As knowledge through experience is one of the greatest assets of a design firm. Initiatives which try to automate parts of the design process, such as the holiship project, might over time result in a loss of knowledge.

One tool which can be particularly useful to reduce the market uncertainty is the use of data analysis. It presents many opportunities, as it can provide a lot of useful insights into the evolution of a market over time or the performance of a vessel. Many design firms are now also beginning to exploit this resource, one of which being UIN as described by Abbasian [34] and Ebrahimi [35]. Trying to create better designs by using databases to get a good view of the historical and current market. One such database describing the offshore wind market, 4COffshore [36], has been made available for this research and it presents an invaluable asset to describe the market uncertainty.

The customer's perspective on uncertainty during the design process is discussed in the work of Garcia Agis [17], who performed a survey among ship owners. He explored what influenced the decision of selecting a specific vessel design, with participants giving different aspects a score from 1 to 5 (with 3=somewhat influential, 4 = very influential and 5 = extremely influential). Uncertainty sources that are believed by customers to have a significant effect on decisions relevant to this thesis can be divided into the categories; context, input, process and model.

- Context: many of the context based sources were unanimously selected as having a large influence on design selections. Factors like; upcoming regulations (4.52), future vessel requirements (4.26), company based financial factors (4.26), future vessel demand (4.13), vessel costs (4.09), vessel day-rates (4.00) and the amount of vessels supplying the market (3.83) are believed by customers to have a significant effect on decisions.
- Input: in regards to clarification of the problem, the targeting of the vessel's operational region (4.26) and clarity of the project scope (4.13) were found to be most influential.
- Model: with respect to the accuracy, quality and reliability of used models, customers found that the models calculating economic performance (4.30) and vessel capability and capacity (4.17) influenced their decision most.

- Process: regarding the process (how the problem is solved), especially the goodness of the fit of the problem solution (how well the design satisfied the customer's expectation) was thought to be very influential (4.26).

2.2. Stakeholders

After having identified the perspective from literature, current practice and even the customers perception of uncertainty in the design process, it is evident that this Thesis deals with many different stakeholders. This section further identifies the stakeholders that could benefit from creating a method as is proposed in this thesis and explores their needs.

Ship owners: One of the most important stakeholders in this project is the eventual ship owner. The way uncertainty is dealt with by a designer makes the difference if a design process will be successful or not. The goal of this Thesis is to explore better ship designs, which are more likely to make money. Due to this, financing and the decision to build a design can be substantiated more clearly, as a ship-specific business case will be produced that is tested against multiple future scenarios. The decision making process between alternatives is improved, argumentation is more clear and fits the customers business case more directly. Ships are therefore developed based on a set of needs rather than requirements defined from gut feeling. Ships that are designed for, and are able to deal with uncertain fluctuating market demand might become the new market standard. This would minimize their financial risk and improve the economic stability of shipping companies, preventing bankruptcy and unemployment.

Ship designers/Ulstein: As the business case is explored in a more comprehensive way, the Ulstein group might be able to boost the quality of their designs and therefore also increase the amount of customers they attract. The method will focus on visualizing the effect of design choices on the financial performance. Designs will therefore become more innovative and standard designs will get better. While in all projects, the research into the business case will result in a better understanding of customer requirements, thus improving the goodness of fit of the solution to the problem. Another positive effect is the subsequent improvement in conversation with the customer. As social interaction is a big influence on the success of a design process [9], which is an important development.

A ship designer can thus use the method to gain a better understanding of the customer perspective or can at least gain an indication of what the ship owner bases his decisions on. This might also help the customer to speak more freely and the designer will be able to understand the customer expectations and needs better. As ship designers are more clear in the creation of the business case, the customer will be encouraged to see the designer as an equal partner. The improved business cases will then also result in better and more innovative designs. While the designer will have to put less time into creation of a business case. So when a ship designer joins a tender, the method can also provide a way to quickly comprehend the business position of a customer. This way, the designer is able to propose a solution that corresponds to a customer better, thus increasing the chance that the solution is chosen. This results in an increase in success for a lower amount of work. Besides this, the aim of the method is to have designers remain a crucial aspect in the process, meaning that they will not become obsolete (designers keep their jobs). Within the method, no customer permission is needed for the use of method, as gaining more knowledge is the designer's choice.

End user/ship contractor: In the offshore wind sector, the end user of an installation vessel is the ship contractor. This company hires the vessel and can be either the project owner or an installation company. When looking at the contractor in terms of the case study; offshore wind installation vessels, the companies that build and operate the offshore wind farms are a major stakeholder. These companies are paid from the moment that the first power comes from the wind-farm, which only happens when the full wind-farm has been completed [37]. Quick and complete installation is therefore key and installation vessels that have the right capability when it is needed are crucial. This could be assured when a vessel has been designed (in part) by using the method created by this thesis.

Ship financing banks: Shipping is such a capital intensive business, that many vessels are largely financed by ship financing institutions. Financing offshore installation vessels has become more difficult in recent years, as they operate on a spot market and their margins are generally low. A way to solve this problem could be to design a ship to have less financial risk. If the shipowner is able to substantiate this, a bank might be more likely to finance. This will also result in a better position for the bank, as a lot of the financial risk assessment that they will normally have to do themselves is already accounted for. When identifying the right risk parameters into the method it might become more attractive for banks to enter the offshore industry, possibly boosting the market. Besides this, the Loan to Value (LTV) ratio might increase, as the perceived risk is lower. This way the liquidity that a ship owner has to put into their ships themselves is lower and they will therefore have the ability to buy more ships and increase their competitive position.

European ship design industry: The method might have an impact on the amount of customers UDSBV attracts, as the ship designers at Ulstein will be more knowledgeable on the aspects that are believed by ship owners to be important influencers during deciding on a ship design. Thus improving Ulstein's competitive position. Due to this, other European ship design firms will want to also gain more knowledge on the business case during the early design phase to provide the same level of service as Ulstein. This is possible because the European ship design industry are very open to innovation to be able to be competitive versus design firms in other countries with lower hourly engineering cost. The European ship design industry as a whole will therefore become more attractive for ship owners. The business case focus will provide new design possibilities that other design firms around the world do not have, thus the European industry will be able to provide better, broader service. While a well researched business case will result in less uncertainty for the customer, thus decreasing the amount of times a customer might pull the plug on a design project.

Ship yards: When a business case is researched in a more substantial way, a shipowner will have more reason to eventually build a ship design. Now it often happens that the ship design is finished, but the customer is eventually not able or willing to build. This has multiple reasons, either no financing is found or the company is not convinced that the ship will perform decently after all. When a better business case is created as part of the design, the customer will feel more confident and banks might be more willing to finance, which will result in more build projects for ship yards as well.

Education and research The method tries to expand knowledge on coupling business case and design. This way it helps researchers gain more insight into the effect of this coupling. It can subsequently be used to educate beginning ship designers on what the effect of a changing business case is on the design. Thus shifting the focus of maritime engineering students toward business-centric design.

2.3. Problem description

Design firms, such as UDSBV deal with cost competition in highly cyclical or specialized markets. This makes it important to deal with market change pro-actively, to provide customers with better designs and improve the competitive position of Ulstein. Designers have to make many decisions while a lot is still uncertain during early design stages, these decisions have a large effect on the vessel performance. One source of uncertainty, which has a large impact on the offshore wind foundation installation segment, is market uncertainty. From literature, four strategies that can be used to deal with uncertainty are categorized. With foundation sizes growing exponentially however, it has proven difficult to substantiate what the correct way of dealing with this uncertainty is. The effect of design choices on the performance of a vessel in such a market is especially unclear, making it difficult to substantiate what decision alternatives the customers has. It is important to implement uncertainty modelling as part of the design process to be able deal with this uncertainty in future projects. The design process is described using CK theory and exploration of the business case and ship design levels in parallel is identified as possible solution. The process of identifying the purpose for which the ship is built, called requirement elucidation, is also identified as the right moment in the design process to explore the effect of market uncertainty. Therefore this Thesis aims to build a method that can be used during the early design stages to quantify uncertainty by modelling the effect of certain design choices on the performance of the ship in this market. Three gaps are explored within this Thesis:

1. It is unclear when to use what way of dealing with uncertainty when confronted with an uncertain market.
2. It is currently difficult to determine the effect of design decisions on the financial performance in an uncertain market.
3. The concept of uncertainty modelling has been proven but has not yet been properly implemented as part of the design process.

Using the doubtful situation and formulated gaps, the main research question and sub questions are formulated as follows:

How to model the effects of changing business case requirements due to market uncertainty during the early ship design phase, in such a way that the designer can explore the design space?

To further guide the research, the following sub questions are established:

1. *What is the relation between complex design and uncertainty modelling literature and current practice and how can the thesis benefit UDSBV and advance research?*

2. *How can the future market be forecasted while dealing with market uncertainty accordingly?*

3. *How to model the case study using uncertainty modelling and how to implement this in the design process?*

4. *Which scenarios can be modelled to determine the effect of certain design choices on vessel performance in the market?*

5. *Using the method, what is the effect of market changes on the selected design parameters and how sensitive is each to the market.*

3

Determination of problem-solution

Regarding a solution to the problem, the ability to explore the business case and the ship design levels could provide a way to deal with market uncertainty. When looking at the design process, this exploration might happen at two moments; at the start (improving project preparation) and during the process (evolving the ship and business case in parallel). The parallel exploration of market and design is shown in Figure 3.1 using the CK-theory from Bruinessen. The market is researched by using the available market data from 4COffshore and is used to create a conceptual description of the future market. The same is done for the ship design, starting with a current vessel design from Ulstein and creating possible concepts from this reference. Using the future market description together with these ship designs, the performance of each in the market can be calculated. As shown on the right of Figure 3.1, the effect of certain design choices in the market might be explored by creating multiple conceptual ship design configurations and reviewing the effect of changing design aspects on the performance in the simulated market.

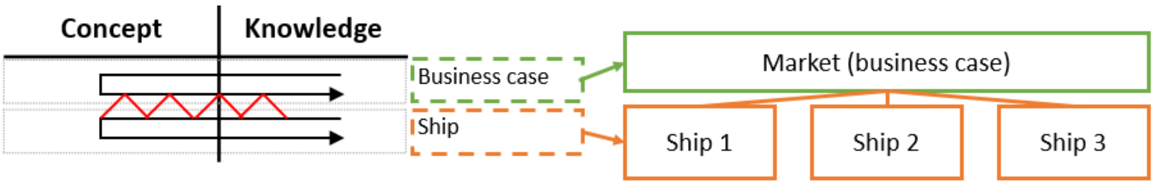

Figure 3.1: General model description

A method needs to be created for use during the ship design process that allows for exploration of the market and ship design needs. The method should quantify uncertainty by approximating the behaviour of vessels in a future market projection. Therefore, both market and vessels need to be simulated realistically as part of the method. The set-up of these simulations is discussed in the next chapters. In this chapter, methods from literature and the way they deal with uncertainty are explored. To determine which method could be useful and to evaluate its performance, a set of requirements is proposed. The most promising methods are researched in more detail by using CK-theory to see if parallel exploration is achievable. Finally, the method to be used is selected based on a set of requirements which have been derived from the literature and current practice research.

1. The method should be able to visualise and explore the effects of a range of different future scenarios on the design. The method becomes two sided;
   (a) Handling input from market data with a designer selecting important parameters and a probability interval.
   (b) Calculating the performance of designs based on this business case input.
2. Handle co-evolution of business case and ship design in parallel, enabling exploration of design choices in an uncertain market.
3. The method can be integrated in current practice, quantifying and dealing with uncertainty. While keeping the designer at the centre of the process.

4. The method should be able to be used at the start of and during the design process.
5. To make sure the method will perform properly, it should be based on one or multiple existing methods, which have been shown to work in similar settings.
6. Be able to also take flexibility and changeability of a design into account.
7. The method should be quick and easy to use, to stimulate exploration during and before the process.

3.1. Current methods dealing with uncertainty

To define in what way already existing methods from complex design methodology and uncertainty modelling could be used to solve the problem, the uncertainty categories as defined by Thissen & Agusdinata [21] are used to classify in what way these deal with uncertainty. Investigating these might provide insight into what tools there are to deal with uncertainty. To be sure to keep the amount of methods reviewed to a minimum, only methods relevant to the problem will be discussed. Each is explored under their respective categories.

3.1.1. Ignore

Over the years many optimization methods have been created that rely on a designer setting a single goal to optimize for [25]. Most of these ignore the uncertainty around the customer requirements and market and optimize a vessel design within a limited context. These kinds of models are called deterministic and often maximize or minimize certain performance attributes to satisfy design requirements. Most of these performance parameters, or measures of merit, are based on economic criteria like Net Present Value (NPV) or Discounted Cash Flow (DCF). These present the value of a ship or the expected value of an investment and are commonly used to compare alternatives. Both of these values use a discount rate and predicted cash flows as estimated by the user, not accounting for uncertainty. This is also the downside to deterministic methods, as they optimize for only a small amount of cases. As mentioned by Patricksson [25], these deterministic methods are therefore not able to handle uncertainty in future contexts, effectively ignoring uncertainty altogether. The different deterministic tools make use of mathematical models and select performance parameters that could still be interesting for the Ulstein case however. McDonald for example [38] creates a tool with the ability to rapidly explore a large number of radically differing alternative conceptual ship designs. Moreover, concepts like DCF and mathematical models will be of use in this thesis. In their literature reviews, Patricksson and McDonald mention a range of different deterministic ship design approaches, that can be used as reference:

- Optimization based approaches: models using Operations Research, which use an objective function to optimize for and constraints to make sure the model converges. Used by Erikstad [39], who selects optional functionality using available contracts, and Balland [40], who minimizes the cost of machinery for emission reduction. This includes multi-objective optimization, as used by Balland and as used in the CJob Accelerated Concept Design program by de Winter [41].
- Concept exploration based approaches as used by McDonald. Another concept exploration method that allows the designer to interactively adjust criteria while exploring the design space is created by Van Oers [42].
- Artificial Intelligence Based Approaches using genetic algorithms to think of design solutions. Used by Bagheri and Ghassemi [43] to optimize the hull shape based on displacement constraints that guarantee sea-keeping performance.

3.1.2. Delay

Some of the more common design processes dealing with complexity used in ship design deal with uncertainty by delaying it. The following can be described:

1. Concurrent design: is based on the system engineering procedure, it generates much of the "hard information" early in the process, having a few critical activities working in parallel instead of designing iteratively. The method aims to decrease design time by working in parallel and delaying certain decisions until these teams have formulated more information on the selected critical activities [11].
2. Set based design: this is a design method currently used by the US Navy, it was introduced in ship design by a research group from the University of Michigan. Singer [18], describes the goal of the method

as handling the increased information content during conceptual design. It follows a comparable approach as concurrent design but delays more of the decisions until trade-offs are better understood. It couples multiple computational tools and incorporates users into the design process.

3. Probe and learn: using probing (testing a first concept) of the design and then looking at what comes out, to learn something about what to do with the final design. Also compared to the wait-and-see method used in process engineering for companies engaging in mass-production activities [44].

4. Real options: take advantage of potentials or opportunities and avoid the risk to make decisions [45]. The theory is based on the financial option theory, but now uses realistic options. It first determines a large range of possible design solutions and then evaluates them using "measures of merit". Basically valuing flexible strategies in an uncertain world. By defining all options and evaluating their value, you know what decisions to make in what situation. An example of such options are the two economic options; call option, to buy an asset in the future, or put option, sell asset in future. The method is said to prepare for the future, by examining what the options are, but essentially delays uncertainty until later.

Especially real options theory could be of use in terms of this Thesis. The theory has been used in shipping to manage freight rate risk [46] and might also be used in the case study. Erikstad & Rehn [45] mention the method to be able to deal with future uncertainty, but don't specify how it could be used specifically. An application of real options analysis (ROA) to naval ship design has been presented by Knight & Singer [47]. They use ROA to express the value of flexibility in naval ship design focusing on naval application, leaving out markets and cash flows. In terms of this Thesis, a lot of options would have to be identified and evaluated using measures of merit. This way, a ship owner will know what decisions to make in what situation. Thus substantiating that making a design flexible is useful for different market scenarios. This does present the ship owner with a strategy and effectively delays the decisions until later. The designer will however not get a chance to explore the ship and business case in parallel, as real options typically focusses on evaluating market related options and researching the value of flexibility. In terms of CK-theory, as visualised in Figure 3.2, the business case is explored first, going from concept to knowledge. A flexible strategy is then determined which can be used during the ship design in both concept and knowledge space.

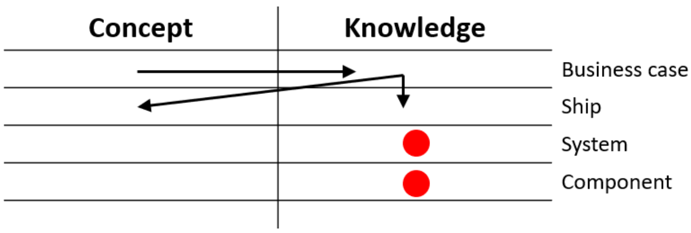

Figure 3.2: CK-theory visualisation of real options theory

Useful aspects of this theory are the identification of risk, design features and measures of merit. There is however little parallel co-evolution of ship design and business case, as the real options theory mostly substantiates that the design should be flexible.

3.1.3. Accept

Methods that accept uncertainty are aware that parts of the design and parts of the operation of the vessel will stay uncertain. By identifying these uncertainties and preparing for them, a designer effectively accepts uncertainty while trying to protect the vessel against them. When this is done in the right way, a ship owner might be able to even exploit some uncertainties. Examples of methods doing this are optimization tools for future uncertainty (like Markov decision processes and fuzzy decision making) and making sure a design is value robust.

Value robustness

When a ship is value robust it will be able to create value even though it faces uncertainty. Two ways of being "value robust" are distinguished:

- Active: adapting a ship to uncertainty by changing aspects of it during its lifetime. Also referred to as changeability. In practice this manifests itself as a refit of equipment or the whole ship, to be able to service a new business case due to changed market demand. Rehn [48] presents a very extensive review of changeability and ship design.
- Passive: while the business case might change, no changes to the ship are made. Designers account for this by using either safety margins, to account for uncertainty during use, or design margins, to account for changes in the requirements or the engineering. Garcia Agis [17] further divides safety margin into market margin, which can be used to account for changes in the market, and life-cycle margin, accounting for unforeseen future events and system degradation. Another way to increase value robustness passively is by increasing the resilience, which means designing the ship to be flexible. This way the vessel is able to deal with change and will be able to keep operating during these periods. An example of this is a shipping company keeping a large diverse fleet to ensure flexibility, as the bad performance of some ships is compensated by other ships.

Value robustness is visualised well in the matrix taxonomy Figure 3.3 as provided by Doerry [49]. The matrix presents that when dealing with changing requirements (uncertainty) a design can either be fixed, being passively value robust (robust design) or the design can be flexible in dealing with changing requirements during its lifetime, resulting in active (modular adaptable) value robustness. The Figure also shows that when dealing with fixed requirements, the design can be optimized for a certain point (deterministic optimization). This will however only be the case for a few ship types.

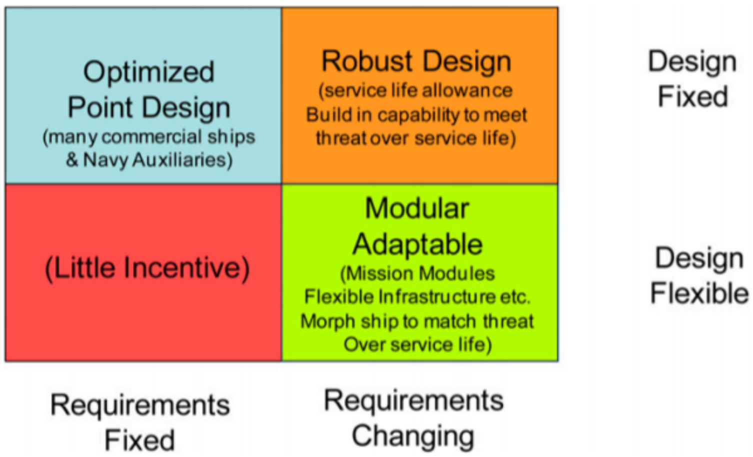

Figure 3.3: Matrix visualisation of models dealing with uncertainty by Doerry [49]

Using value robustness, a vessel will be able to create value even though it faces uncertainty. This could be a response to uncertainty but it doesn't provide a design process. This becomes evident when looking at the matrix taxonomy by Doerry, as a designer can choose how to respond to uncertainty, by either making a flexible or changeable design. When looking at the theory in terms of CK-theory, value robustness can be visualised as done in Figure 3.4. It is shown that only ship design is explored, while the business case is not co-evolved. The designer will accept the uncertainty and use it to determine whether to design the ship to be flexible by using margins [17] or by designing a ship to be changeable by exploring refit possibilities or modularity [48]. From interviews, this way of dealing with uncertainty is currently one of the main measures taken by Ulstein to deal with uncertainty. As the business case is not explored by the method, it remains unknown for the designer what the specific effects of the uncertainty are on the design. It also can't be used as a separate method, but it can provide performance parameters in terms of changeability or flexibility.

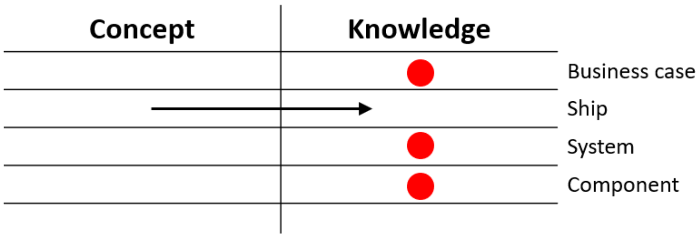

Figure 3.4: CK-theory visualisation of value robustness

Stochastic programming

Some models that accept uncertainty make use of comparable techniques as deterministic optimization, also using measures of merit, but take uncertainty into account by "simulating" multiple futures. Stochastic programming models uncertainty by using a probability range (with upper and lower bound). These methods have their roots in probability modelling and can also use different deterministic optimization theories that are adapted to be able to handle probability distributions. One of the methods; robust stochastic programming is used by Patricksson [25] to explore what engine should be selected when faced with sulphur emission regulation, by minimizing cost. The method works by first deciding on input data and running a simulation, the input is then changed to deal with the random events that happened during the simulation. Going through this two stage program results in considering all possible scenarios and optimizing for each. By considering all scenarios, the method gives a clear view of uncertainty as there is no flaw of averages as is argued by Neufville & Scholtes [50]. Meaning that everything is averaged and the possible outliers (which might be the most extreme cases) are discarded. The method can definitely be used in terms of this thesis, as the designer gains a view of uncertainty and how to deal with it. Patricksson does however explain that his method only looks at fuel uncertainty and needs to be expanded to include expert opinion. Another way to model probability density is to use fuzzy programming, as it models uncertainty in a way that is more similar to human decision making. It uses fuzzy decision, which works using a normal distribution of what a value might be, while also describing a median value called crip. Brefort [27] uses a type-2 fuzzy logic method to incorporate human intelligence into the early design phase, trying to handle linguistic uncertainty (communication & human knowledge related uncertainties). He eventually optimizes the design of a planing craft, by incorporating expert opinion into the optimization process.

Both stochastic programming models can be used to model the case study in this thesis accordingly. When looking in terms of CK-theory in Figure 3.5, the models seem to be able to explore the business case to an extent, by researching how to stochastically model uncertainty which is used to eventually guide the ship design process. Most examples however use fixed business case input at the start of the process. Meaning that a case is selected and the design is varied until it deals with that case accordingly. The tools are therefore primarily used in decision support roles as they optimize and explore designs for a single point, since changing constraints is more extensive. Changing inputs does also affect the outcome substantially, so it might be challenging to compare cases. This means that the effect of a changing business case on the design is difficult to explore, as the probability distribution is fixed and can not be easily changed by the designer. The methods do however explore the fixed cases well, which is something that would be useful for this thesis.

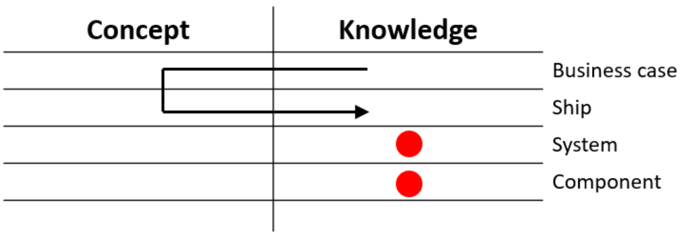

Figure 3.5: CK-theory visualisation of stochastic programming

Dynamic optimization

Dynamic optimization splits a big complex problem into smaller, simpler problems. It examines the immediate static decision and evaluates the consequences of all subsequent decisions. This is done by using backward induction, effectively evaluating each decision one by one backwards from an end point. Markov Decision Processes (MDP) is an example of this dynamic programming. As named by Strom [51], it is crucial to understand the strategic, tactical and operational aspects when designing in a complex system while dealing with uncertainty. Strom uses a MDP based method called design-strategy planning, which produces a framework that integrates life-cycle strategies in the early stages of a design process. MDP's model an agent making decisions based on simulated behaviour of the operational environment, for every environmental change the agent will respond and is rewarded. It does however assume there is certainty about the current state, meaning that the decision maker has perfect information about the present. Partially observable Markov decision processes (POMDPs) deal with this by implementing a belief state, so the agent needs to either improve information or make a decision based on imperfect information [52]. A version of MDP that is used within ship design is the Ship Centric MDP as described by Niese and Singer [53], it analyses uncertain sequential decision making problems. Examples of the use of MDP's within ship design are summarised as follows:

- Ship evacuation patterns estimation model for use during early stage design by Kana & Droste [54] and Joustra [55].
- Evaluation of a ships changeability under uncertain disturbances like environment, market, politics and technological changes for ballast water systems [53].
- Planning lifecycle compliance for ballast water treatment systems [26]
- Choosing an engine, while taking possible regulation into account by Kana& Harrison [56].
- Strom et al. [51] looked into designing offshore support vessels for a specific strategy by using MDP to determine what functionalities an Offshore Support Vessel (OSV) should be designed with. The design variables where limited to accommodation, crane capacity, light well intervention, ROV, cable laying equipment and moon pool capabilities.

One of the articles that is particularly close to this thesis subject is the research by Strom et al. [51], who looked at designing offshore support vessels (OSV) for a specific strategy (business case), by using MDP to determine what systems the OSV should be designed with. The design variables used by Strom were however limited to system related parameters, not looking at the dimensions of the ship. Niese [53], who used MDP for assessing the effect of changeability on a ship design, names some pros and cons for the use of MDP which are summarised below. He does not argue whether MDP is better than other techniques though. Niese also names that for MDP's it is important to examine if performance merits (performance parameters) result from positives or merely a lack of negatives. As a design that is selected based on a small amount of constraints may be best for this set-up but isn't good in reality. Besides that, there is a need to expand MDP modelling to use hundreds of initial design alternatives (scale-ability).

- MDP is well-suited for decision making where changeability is viewed as a means to manage uncertainty.
- MDP is more focused on determining what option to select at what time, versus real options analysis, where the option itself is valued.
- MDP is less appropriate when uncertainty cannot be characterized using probabilities.
- Curse of dimensionality, because the state and action spaces can be infinitely large, the space needs to be bounded. But even when bounded, the memory storage is huge.
- MDP exhibits limited ability to reuse portions of the solution when modifying a scenario. Epoch-Era analysis is however capable of reusing single epochs for different scenarios.

The case as explained by Strom et al. [51] shows that evolution of two levels (system and business case) is possible, while Strom uses value robustness in parallel with MDP to show the value of changeability. Therefore MDP could be a very useful method to try and model the effects of different decisions on the ship design. The method also has the ability for the designer to set up their own parametric range to see the effect of other decisions. Even being able to review changes in the business case during the design process. A way to deal with a large amount of future possibilities is using Monte Carlo simulations as discussed by Kana & Harrison [56]. When looking at MDP in terms of the CK-theory disposition in figure 3.6, the co-evolution of ship design and business case is certainly possible.

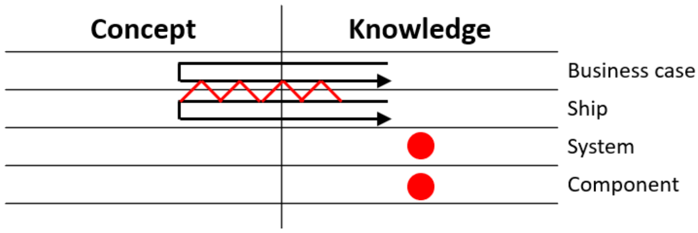

Figure 3.6: CK-theory visualisation of MDP and Epoch Era

3.1.4. Reduce and Control

When reducing uncertainty, one can either increase their knowledge or follow a structured way to go through the decision process. Especially increasing knowledge is useful when trying to make a good decision during the early design phase. Methods that reduce uncertainty create knowledge and structure it. The reaction of increasing knowledge is very psychological, as the confidence of a person goes up and perceived uncertainty is decreased when faced with a problem whilst having a large amount of information. As explained by Platt and Huettel [57], this doesn't mean that the results increase to the same extent. They demonstrated with an experiment that people become more confident with more information but perform worse. Indicating that there could be an optimum amount of useful information versus the increase of confidence. Garcia Agis [17] proposes that cost of information can be used as a metric to find the optimum amount of information versus cost ratio. An example of this principle is the amount of CFD calculations, for the first few someone will gain a lot of knowledge, while additional calculation will cost the same but reveal less. Another negative aspect of information, is that it can quickly become too substantial. This is something that the method needs to deal with accordingly, as it will create information and the designer will generate knowledge by researching certain scenarios using the method. In terms of relevant methods reducing uncertainty, a designer has the following at their disposal; research, scenario planning (epoch era), Management & organisational tools, simulation & prototyping, data analytics and communication. Besides using the method to increase knowledge, market analysis (data analytics) is going to play a role in this thesis. The more relevant tools will be discussed in more detail below.

Management & Organisational tools

Another research field that deals with reducing uncertainty is management and organisation. Some useful strategies from this research field are summarised below.

- Combination of Enterprise Performance Management (EPM); which explores how to take advantage of opportunities, and Enterprise Risk Management (ERM); which evaluates the impact of decisions on business.
- Combination of Dependence Structure Matrix (DSM) and Dependence Mapping Matrix (DMM), Garcia Agis et al. [58] names that DMM can be used to map functional requirements onto design variables and map how they may change the design.
- Porter 5 forces: Can be used to analyse competition and see where profit can be made [59].
- Performance benchmarking: By determining performance parameters that the design will be tested for early on, expectations are quantified.
- Vertical integration to reduce uncertainty: As cooperation with different companies will result in uncertainty on what to expect, vertical integration might reduce this uncertainty [60].
- SWOT analysis: Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis can be used for better decision making. As it provides an overview how the strengths and weaknesses from your company connect to the opportunities and threats in the market. This way the firm can pro-actively work to improve its position in the market [61].
- PEST: is used to evaluate external factors like the effect of Political, Economical, Social and Technological changes on the company [62].
- TELOS or technological-feasibility: Evaluate resource availability for a project or if a project is technically feasible to see if some economic profitability can be gained [63].

- Probability management: To arrange a common language to be used for R&D, where the probability distribution of random variables in the business are communicated actively. By providing information in a range (low to high), uncertainty is visualised and reduced [64].

Scenario planning: Epoch-Era analysis (EEA)
Scenario planning helps to control uncertainty by creating scenario's of multiple possible futures and evaluating the performance of a design or action. It limits the amount of scenarios to a few feasible ones and sets out to understand how to act in each. Epoch-Era Analysis (EEA) is a version of scenario planning, but it divides time into epochs for which some design requirements are determined. Multiple epochs are then collected in design era's, which provide information on the requirements that the ship should be able to cope with over its life-cycle. The model can be used to explore what design would perform best in one or many different scenarios. The method is used by Gaspar [65] to look into the design of an Anchor Handling Tug Suply vessel. Gaspar also uses epoch-era analysis to create a value robust design, thus combining both reducing and accepting uncertainty [33]. Gaspar & Erikstad [66] explain that the method is very useful to explore market uncertainty. The model they use is however still highly theoretical and they name that it is important to have more information to base the model on. It is therefore unclear if the method is able to use database information accordingly. The method is used as part of the Responsive Systems Comparison (RSC) methodology, which is used to structure ill-structured design problems [7]. Thus showing that it can be used in context of a design process as well. A designer can define epochs, era's and parameters themselves, thus being able to use the method during the process. When looking at the method in terms of CK-theory, figure 3.6 can also be used to visualise EEA. The main difference is that EEA explores scenario's while MDP is mainly used to evaluate decisions. This makes EEA less useful as the designer will have to imagine possible future scenarios in terms of epochs already, while limiting these to only a few scenario parameters. When combining the two shortcomings however, a database could be created that inputs future scenarios. But it seems this has not been done before for EEA.

3.2. Evaluation of solutions

The most promising methods are compared in terms of the method requirements below in Table 3.1. It is clear that multiple methods could be used to solve the problem, each providing valuable information, but especially MDP and EEA seem to be good options. Regarding EEA, database input and easy use need to be addressed before the method can be used. MDP seems to agree with all requirements set, but one aspect which isn't explored is the implementation of preliminary market research. This is why the addition of a market analysis tool and visualisations seems to be important. MDP also has the advantage that researchers familiar with MDP are directly involved with this thesis. Therefore MDP is selected to create an optimization model. A few challenges still remain, as the limited ability to reuse portions of the solution and huge memory storage will have to be dealt with. This could be managed by using other methods like the division of the future into epochs and era's, the implementation of value robust designs and the measures of merit from real options. The method will therefore likely be a combination of multiple methods.

Table 3.1: Possible solutions versus method requirements

	1: Database input	**2: Co-evolution**	**3: Uncertainty**	**4: Before & during**	**5: Similar uses**	**6: Design for**	**7: Easy/no customer**
Real options	Unknown	No	Delay	No	No	Decision	Yes
Value robustness	No	No	Accept	No	No	Scenario	Yes
Robust stochastic	Yes	No	Accept	No	Yes	Probability	No
Fuzzy	Yes	No	Accept	No	No	Probability	No
MDP	Yes	Yes	Accept	Yes	Yes	Decision	Yes
Epoch Era	Semi	Yes	Reduce	Yes	Yes	Scenario	Semi

4
Reasoning

In the previous chapter, it was found that the offshore wind market and vessel configurations need to be simulated to be able to explore the market and designs in parallel. Therefore, the offshore wind market, the Ulstein vessel designs, and the chosen uncertainty modelling method are investigated in more detail in this chapter. This information is then used to determine how the method should be set-up. The chapter is divided into three parts that discuss relevant information regarding the market simulation, the vessel configurations, and the uncertainty modelling algorithm.

4.1. Offshore wind foundation installation market

Besides being an uncertain market, the case study into offshore wind foundation installation presents a unique opportunity to contribute to decreasing carbon emissions. This section is used to form an understanding of the sector in which offshore wind foundation installation vessels operate. Besides a short review of the market background, the supply and demand sides of the offshore wind foundation installation segment are also discussed. The supply side are the vessels with the capability of installing the offshore wind foundations, while the demand side are the planned offshore wind farms and the aspects that effect the installation both technically and economically. Besides using literature, the information in this chapter has also been complemented by following the offshore wind transport and logistics course at the DOB Academy in Delft.

4.1.1. Offshore wind market background

To make sure health and environmental impact of energy-related emissions are limited, the amount of renewable energy needs to be increased substantially. One of the most promising renewable energy sources to do this is offshore wind energy. Although its current share in the global electricity supply is just 0.3%, offshore wind is a young market that has become an increasingly attractive renewable energy source. With a capacity factor (ratio of average output versus maximum rated output) equal to gas and coal power and low energy variability compared to solar, it; "has the potential to become a mainstay of the world's power supply" [2]. The development of offshore wind turbines began after a series of European wide studies found that the potential amount of energy from offshore wind is significantly higher than onshore sources [67]. Besides this, in many central European waters, depth only increases slowly with large distance from shore, thus providing a good basis for bottom mounted offshore wind turbines. Because of this, research projects like the "Structural and economic optimisation of bottom-mounted offshore wind energy converters" project (Opti-OWECS), were initiated to explore economic and structural possibilities for offshore wind turbines. To make the offshore wind economically feasible [68], the project found that due to high development costs, turbines with

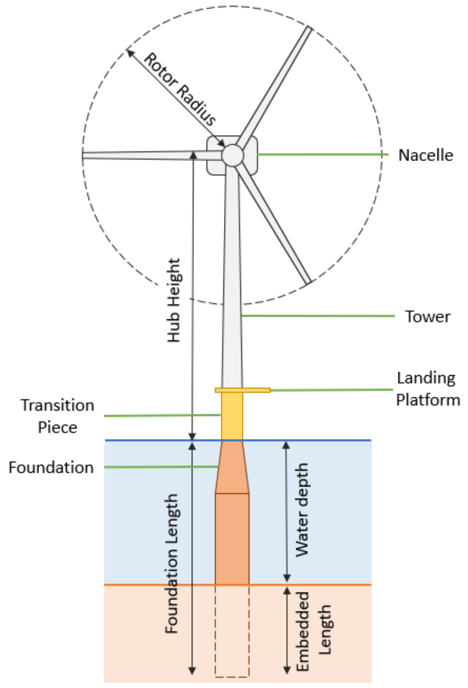

Figure 4.1: General offshore turbine set-up

higher capacity than onshore turbines were needed and large amounts of turbines had to be combined in offshore wind farms. Because of this, several projects began to build and explore the potential of offshore wind, gradually decreasing cost by increasing scale [69].

Nowadays, offshore wind has come a long way, with the levelized cost of energy (LCOE) of offshore wind gradually decreasing towards the LCOE of onshore wind and it is projected to eventually get to a point where its LCOE can be compared to fossil fuels [70]. Before this will be the case however, a scale increase in offshore wind has to be initiated. The necessary growth is luckily supported politically as is evident from the European commission [3] offshore wind targets of 150 GW for 2030 and 460 GW for 2050 [5]. In the process of designing and installing an offshore wind farm, multiple parties are involved; an association that coordinates build locations, companies building the turbines, corporations installing farms and firms that operate offshore wind farms. Two phases can be distinguished during wind farm design as explained by Giebel & Hasager [71];

1. Choice of sites by national authority, exclusion zones, etc. The authority then opens applications for companies.
2. Companies willing to buy the permit answer the tenders. The authority reviews proposals and rewards the lowest bid for price per produced kWh (as is the case in Denmark). The goal of this price per produced kWh is to decrease the LCOE of offshore wind over time.

The way of writing tenders can differ between countries. After bidding, the detail design of the wind farm starts and the project will subsequently go through; strategic planning, environmental investigation (EIA), removing obstacles, foundation placement and turbine construction. During the strategic planning, the offshore wind farm designer has to choose the type and the amount of turbines that fit the location best. Responsibility for the design and installation depends on the contract type used. Two contract types are characterised [37]:

- Engineering, Procurement, Construction & Installation EPC(I) contract: single point of contact for the owner, contractor is responsible for design and installation and hands over a working facility (turn-key). Risks are mostly transferred to the contractor.
- Design & Build contract: single point of contact for the owner, contractor is responsible for design but owner is more involved in the design and installation process. Risks are shared between owner and contractor.

In general, an offshore wind turbine design consists of the parts described in Figure 4.1. Besides this, the essential installation vessel capabilities will also depend on the characteristics of the part that is installed. The heaviest part of the turbine being the foundation and the transition piece, while the tower, the nacelle and the blades require installation on great height. As the case study focusses on foundation installation vessels, mainly foundations are discussed. However, different aspects of the installation could also be included in the method in future versions.

Offshore wind foundation types
The choice of foundation affects which installation vessel might be best, as turbine size and distance to shore might decrease the installation efficiency of certain ships. Due to the size and power increase of turbines [72] the size and weight of foundations have also increased. This has put more strain on the installation process, as current installation vessels might not be able to handle the increasingly larger and heavier foundations. The type of foundation chosen might differ between wind farms as this is also dependent on the depth and the distance to shore. Both fixed and floating foundations have been developed to exploit the power capacity offshore as well as possible. The most common foundation types are defined in table 4.1.

Construction costs
Construction cost of each part of the installation process will differ for each project. An example cost distribution is shown in Figure 4.2 for turbines using grounded foundations at different water depths as discussed by Maienza [76]. Many costs like the transportation of turbines to the installation location will also increase. The costs presented are therefore not necessarily fixed, but fluctuate substantially. The eventual cost of a wind farm is therefore mostly expressed in price per kWh, which could be a good measure of merit during modelling.

	Foundation	Max depth [73][74]	Market share (2018) [75]
fixed	monopile	50-60m	81.71%
	jacket	30-80m	8.02%
	gravity based	20m	5.99%
	tripod	25-50m	2.51%
	tripile	25-50m	1.59%
Floating	Spar	>120m	0.12%
	Semi-Sub	>50m	0.04%
	Barge	>50m	0.02%
	TLP	>50m	0.00%

Table 4.1: Foundations max depth and current market share

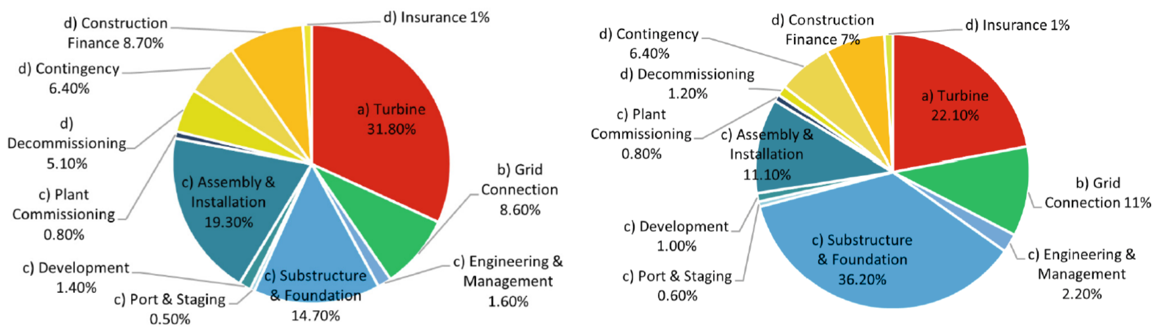

Figure 4.2: Capital costs for a grounded offshore wind turbine in shallow water (left) and deep water (right) [76].

As seen in Table 4.1, only a very small amount of the current offshore wind market uses floating foundations. This is because these are still much more expensive when compared to proven concepts like grounded foundations [77]. Figure 4.3 shows the expected cost development of conventional fixed and floating foundations. In light of this Thesis, it is therefore assumed that an installation vessel would preferably have the capability of installing grounded foundations. It could however be interesting to use the method to gain an idea what effect the future changes with regard to floating foundations might have on installation vessel design.

4.1.2. Demand: Market developments

Demand for installation vessels is directly dependent on the way the offshore wind market evolves. It is important for vessel owners that the vessels designed and built today will continue to find work in the future. Many different agencies and firms therefore present forecasts that give an overview of the probable market developments. The international energy agency (IEA) [2] publishes the Offshore Wind Outlook report annually, which presents a range of market opportunities within the offshore wind energy field. In the report published in 2019, the IEA indicates the following:

- In the next 5 years, 150 new offshore wind projects are scheduled to be completed.
- The technical potential of offshore wind is enormous. With fixed offshore turbines having a potential of 1.5 times the current global electricity demand and floating offshore potentially producing the global demand 11 times over.
- Offshore wind has a high capacity factor (average output relative to maximum rate) and fluctuates with a narrower band than solar (20% versus 40% fluctuation).
- Offshore wind is set to be competitive with fossil fuels within the decade, being projected to decline by 60% by 2040. Besides this, Offshore wind has a high value to the system, as power output increases in winter.
- Capacity credit (guaranteed energy when needed) of offshore wind is much higher than onshore wind and solar.

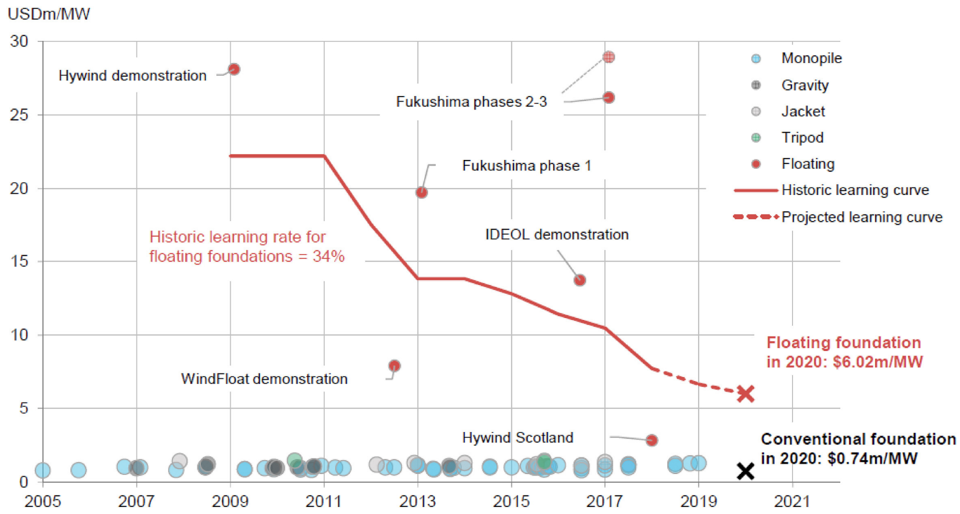

Figure 4.3: Capital cost comparison between fixed and floating offshore wind foundations [77]

- There are many synergies with offshore oil and gas activities, thus having a good secondary market for heavy lift vessels (HLV). With offshore market construction and maintenance presenting a market opportunity of $400 billion or more in Europe and China over the next two decades.
- Offshore wind can be used to produce zero-carbon fuels like hydrogen, thus it is also able to be used in shipping, heating and others. Thus increasing the market potential for offshore wind.

Another market opportunity presents itself due to the design lifetime of offshore wind farms being typically around 20 to 25 years [78]. This means that after a wave of installations, a vessel will encounter a cyclical wave of decommissioning and re-installation 20 to 25 years after. Thus presenting another large business opportunity in the coming decades. This information can be used in an eventual market analysis, as water depth at such a location is fixed, while probably only increasing the turbine size. These forecasts are however not set in stone, with the IEA recognizing a few challenges that could slow the growth of offshore wind. One of the most important challenges named is the crucial development of efficient supply chains to decrease LCOE the offshore wind. They explain that this is primarily dependent on the investment in construction and support vessels, recognizing that future uncertainty hinders this investment. This is exactly what this thesis aims to solve, by incentivizing the heavy lifting industry to invest by decreasing uncertainty. This problem was also recognized by employees at UDSBV, naming one of the main reasons for haltering investment in offshore installation vessels being uncertainty.

Market developments can generally be analysed by looking at data from multiple sources like 4COffshore [36], WindEurope [75] and the Offshore Wind Outlook 2019 [2]. An example of this is given in Figure 4.4, where the foundation types for current and planned wind farms (year on horizontal axis) are set against the depth of a wind farm (vertical axis, logarithmic scale). A key takeaway would be that the demand for the planned wind farms in the coming decade is focused on grounded foundations. This trend is also recognized by many market analysis reports, but one thing that becomes clear, is that their projections differ slightly each month. Data which is consistent however, are databases that record planned and current wind farms. This information is very useful to predict trends within the market and therefore provides a good basis for this thesis. To make sure the method stays up to date with market developments, users should be able to update a database. As explained, UDSBV has a subscription to the 4COffshore database, which is a market research organisation specifically targeting the offshore energy market. Using the database as input, the market analysis part can be automated, but to make sure the right relationships are taken from the database, the market reports are used as a guideline. To analyse the market properly, the range of values and relationships below are selected as they might prove to be interesting.

- Water depth: above a certain water depth the European market will have to switch from using monopiles to other solutions. This will result in other demanded capabilities for a vessel design.
- Distance from shore: Increasing distance from shore has an impact on the VOYEX of a vessel design, maybe making it more economical to increase ship speed and decrease installation time.

- Foundation type: The market percentage for a foundation type might make it attractive to design a ship with a second or third foundation type in mind.
- Installed MW per turbine: this value might be used to forecast the trend in increase in foundation size for the coming years. Thus being useful to determine deck size.
- Number of turbines: This parameter could be used to determine the amount of projected work there is within a contract.
- Depth versus foundation type: with innovation, foundation types like monopiles might be able to be installed in larger depths, thus making it less likely to make the switch to other foundation solutions.
- (Estimated) Year of completion and status: To be able to analyse a trend, the year of completion and status of a farm are needed. Luckily 4COffshore also includes future proposed wind farms and it updates the state of a farm when construction begins.
- Geo-Region: Since the scope is initially limited to the European market and 4COffshore also includes Asian and American wind farms, the data should be filtered.
- Developers and Owners: This data could help the designer gain an idea of the bigger players in the field and how market share is distributed.

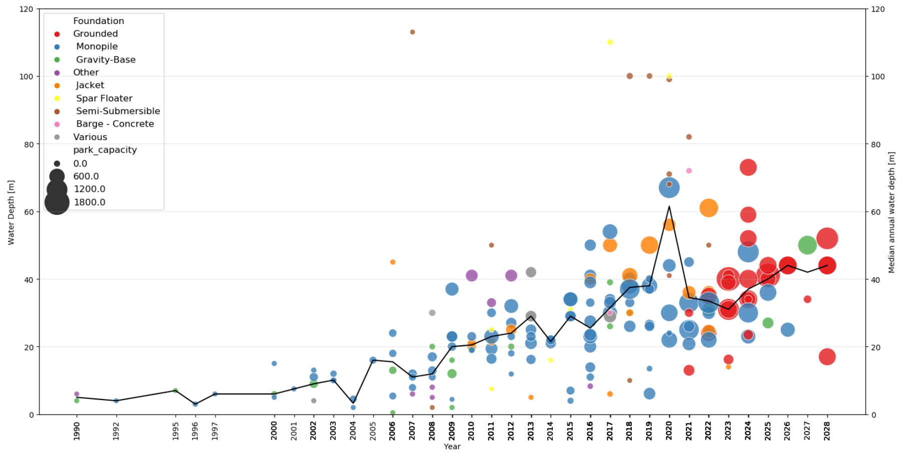

Figure 4.4: Water depth and chosen foundation types for current and projected wind farms from 4COffshore [36]

4.1.3. Supply: Installation vessels

Supply of installation vessels for the offshore market is directly dependent on the current fleet and ships on the orderbook. As the vessels that are currently being designed or built will be able to supply the market within two to three years. Another aspect to keep in mind is that the market is very comparable to the capabilities asked in the offshore oil & gas market. And since most the projections for the oil & gas market suggest a downturn development [79], companies from this market may choose to refit their vessels for use in the offshore wind installation market instead. As refitting takes a much shorter time than new building, this also has a large effect on supply. Even though this makes the possible supply relatively large, currently only about 50 heavy lifting vessels have enough crane capacity to handle upcoming offshore wind turbine installations, world wide. Only some vessels currently used within offshore wind installation have specifically been built for this purpose, while others were refit. This is because of the changing market, since purpose built vessels risk either being too large and too expensive or too small and having too little crane capacity and deck area to deal with the rapid development of wind turbine sizes. With no end in sight and wind turbines having grown nearly four times as large as they where two decades ago [72], only vessels that are able to deal with the market uncertainty in the coming years will have a great prospect. Therefore it is important to research the capabilities that are needed within the offshore wind foundation market.

The capabilities of an offshore wind installation vessel are very specific and are directly dependent on the development of the offshore wind market. The foundation type and size affect the required deck space and crane capacity, while wind farm distance from shore and water depth might affect the vessel performance. Besides this, the vessel owner might only charter the vessel (sub-contracting) for the installation or could be contracted for the full design and installation (as part of a PCI(E) contract or design and build contract). This difference in perspective can affect the vessel purpose. The installation contractor will want to have the farm installed as fast and as inexpensive as possible, decreasing the cost per installed MW. While a charterer prefers to decrease vessel cost to increase their own profit, while improving vessel capability to increase the amount contracts that the vessel might get. Heavy lifting vessels are used for two phases in the installation; the foundation placement and the turbine construction. To increase installation speed, the time spent on each turbine should be as low as possible. The time-window during which farms can be installed is very dependent on the weather however, with different vessel types being able to deal with different kinds of sea state (workability). While this might also affect the speed with which a turbine is installed.

For the transport of turbine parts to the installation site, a logistical strategy is determined. This strategy depends on the location of the manufacturing site and the capability of an installation vessel. Three different transport strategies are explained below. Depending on the strategy, either one or multiple vessels might be used. In the last decades different combinations of vessels where employed that would perform different parts of the installation process. Optimizing such a combination of vessels in terms of availability and cost has been researched by Siljan & Hansen [80] by modelling current vessels and then minimizing for charter cost. The most commonly used vessel configurations, including wind turbine installation vessels (WTIV), heavy lifting cargo vessels (HLCV) and semi submersible crane vessels (SSCV) and their capabilities are discussed in Table 4.2.

- Transiting: direct transport from manufacturing site to wind farm site
- Feeding: transport from manufacturing site to a mobilisation port first to then transport to the installation site. Necessary when the manufacturing site cannot be reached directly because it might not be located next to water.
- Sea feeding: transport from manufacturing site to a mobilisation location on sea to then either install directly (direct sea feeding) or transport toward mobilisation port and then use a feeder vessel. This might be necessary when a vessel does not have enough cargo capacity, but the crane is used for installation.

Table 4.2: Most common vessel type and configuration for offshore wind foundation installation [81]

Type	Configuration	Relative seastate	Cargo	Propulsion	Estimated dayrate	note
Jackup	WTIV	high	Medium	8-12kts	$150-250+k	jacks: max depth & payload
	Jackup barge	medium	Medium	4kts	$100-180k	jacks: max depth & payload
Monohull	HLCV/Cargo	medium	Large	15kts	$150-250k	rarely used to install turbine
	Sheerleg	low	No	4+kts	$80-100k	
	Pipelayer/crane	low	No	14kts	$80-100k	cargo feeder needed
	Crane barge	low	No	4+kts	$80-100k	cargo feeder needed
	Crane vessel	low	Medium	4+kts	$80-100k	
Semi-submersible	SSCV	high	Low	10+kts	$150-250+k	needs cargo feeder (low volume & large depth)

It is clear that many factors will influence the wind farm designer's decision of what installation vessel is used. Besides factors like workability, transition speed and day rate, the availability of a vessel during the installation dates is also important as the fleet size is limited. To get an idea which combinations of vessel types have been used to install wind-farms, the data from Arántegui et al., is used [72]. The data presented in Figure 4.5 provides the installation vessels used for both the foundation and turbine installation phase. As part of this Thesis, the vessels where categorized in the vessel configurations named above. The red line in the "Average days per foundation" and "Average wind turbines in project" represent the average value over all 82 evaluated projects.

Beside vessel type, other market factors will also affect the overall performance of the installation vessels. The figure therefore primarily provides competitive information on the average days per configuration, how many of the projects have been done by a configuration and how many wind turbines the vessel at least has to place to be competitive. The current average installation times have decreased from 5.52 days to 2.56 days from 2000 to 2018. Information like this could be used to benchmark a design against current practice. Charter costs also depend on cargo capacity, since some of the configurations also provide their own cargo carrying capability, while it needs to be chartered separately for others. Regarding multiple vessels, when looking in

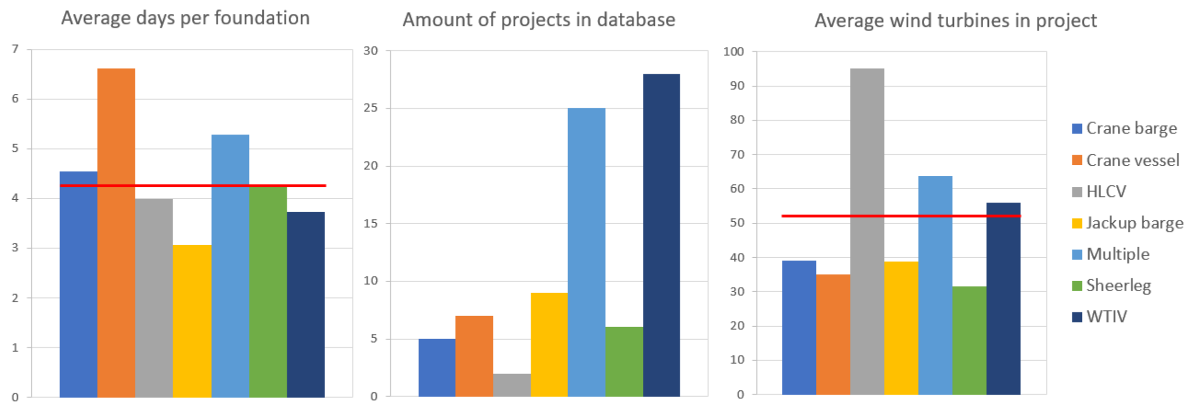

Figure 4.5: Performance of most common vessel configurations for 82 project completed in the period 2000-2018, data from [72]

terms of total costs, the use of vessels greatly depends on the combined day-rate in conjunction with completion time, as a longer completion time with a significantly lower day-rate will still result in less installation costs. As shown in the amount of projects completed by different vessel types, over the last couple decades, especially combinations of vessels and WTIV vessels have been used for a large percentage of installation projects. Recently however, a trend can be seen of installation companies switching to HLCV's. Evidence of this trend can be found in a recent series of design contracts; DEME, Jan de Nul and Royal Boskalis. The switch toward HLVC's can be explained by the vessels providing a full package of cargo capacity, lift capacity and speed into one vessel. Besides this, by optimizing a single purpose built vessel, instead of using changing combinations of vessels, the installation becomes more profitable for the vessel owner and due to optimization, the LCOE of offshore wind energy decreases further. The case-study therefore focusses on optimizing the capabilities of an existing HLCV mono-hull Ulstein design. Besides charter cost and payload, the lift capacity plays an important role in foundation installation, as the crane should be able to handle the weight of a monopile. For example, according to Van Oord, the foundation weight of the next wind turbine generation of 12MW will at least be 2000 tons. When looking at the current fleet capacity of monohull type installation vessels as taken from the Ulstein vessel database, only 39 ships can do this, of which only 8 are based in Europe. While 8 more ships are currently on order. A summary of interesting aspects to research is given below.

- Operability: Depending on the operability, a vessel can continue installation work during certain sea-states. Especially in Europe, where weather can be very disruptive to operations, good operability is key for shorter installation times. Operability is greater for certain vessel types like jack-ups or for vessels with better DP capabilities.
- Crane capacity: The crane capacity will influence the vessel income directly, too small and the ship might be out of business in a few years (having to be refit due to foundation size increase), while being too big results in a ship that might be too expensive for contracts during the first few years.
- Length, Breadth and Depth: The dimensions of the ship will determine a lot of the ship's capabilities, like deck area, resistance and other factors.
- Free deck-space: For the installation vessel itself, being able to transport foundations, free deck-space might be crucial, with more space resulting in less round trips and faster installation.
- Design speed: When a ship needs to transport itself or foundations from the harbour toward the wind farm, the ship's speed should not be too great as the engine will be very expensive and can't be too slow as installation time will increase.
- Project crew accommodation: Certain projects will ask for a large amount of people on-sight. When a vessel is not capable of accommodating enough crew, a second crew-vessel might need to be chartered.
- Secondary business: When a ship is designed with a backup market into mind, possibly performing other tasks in the offshore wind farm, financial risk might be minimized.

4.2. Ship Model

A lot of aspects within a ship are related, its therefore important to gain an understanding of what these relationships and their effects on each other are. These are visualised in Figure 4.6 below. The inputs from the optimization model in green are; LBD (Length, Breadth and Depth), Crane Capacity (CC) and Ship speed (V_s). These values can be tweaked by the optimization method, but within a feasibility range given by criteria. The data from the model projection and databases in yellow are; Foundation weight/size, Seastate, Waterdepth and distance to shore. These values are subject to the projected change over the lifetime of the vessel. Data and optimization parameters are scaled and new values are calculated in the ship model. The output values are; OPEX, CAPEX, VOYEX, Revenue or profit, Charter rate and Cost per MW. The rest of the ship model parameters are to be calculated, while being bounded by upper and lower bound feasibility criteria to limit the amount of simulations. The visualisation presents an overview of the relations in the model and the exact set-up will be discussed later.

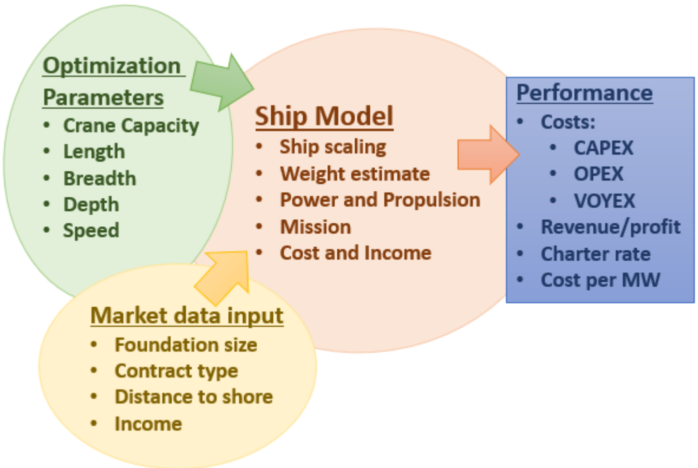

Figure 4.6: Model relationships

The ship model should be able to create multiple designs that are realistic enough for the purpose of performance testing. This is where UDSBV's design knowledge and previous designs as reference are very valuable. As UDSBV has set out to create standard designs that cover the full installation market, shown in Figure 4.7, they have also designed a conceptual foundation installation vessel called the HX118. The outcome of this research will thus be of use to determine the optimal scaling of this vessel. Therefore, as a lot of design information is available, the choice is made to use the HX118 design as basis for scaling and optimize it's capability as part of the case study.

Figure 4.7: Ulstein standard designs covering the full wind farm installation process

Ulstein HX-vessels
Besides the HX118, different scaled versions of this HLCV have also been designed and built. These vessels are perfect references for the creation of a ship model that needs to be able to create a large range of scaled vessel designs. The main parameters of the existing HX118 and the HX104 designs are shown in Table 4.3. The main dimensions are chosen in such a way that the vessel has large deck area with enough stability for lifting operations and payload transport. As found in the market research and mentioned by UDSBV supervisor ir. J.D.Stroo, the stability, deck size, crane capacity and vessel speed will affect the financial performance of such a vessel greatly. The model will test different configurations by creating different combinations of the input parameters by varying each inside a selected range, by for example testing different crane sizes from 2000 until 6000 tons. The model then calculates the capability of each configuration to be able to test the performance in the market.

Table 4.3: Reference vessels main dimensions

	HX104	HX118
L	185.4	193.2
B	36	49
D	12.6	15.4
V_s	14	13
CC	2000	3000-5000

4.3. Uncertainty model

The uncertainty modelling methods MDP and EEA are discussed in more detail in this section. The primary goal is to become more familiar with their application and use this understanding during the set-up of the method.

4.3.1. Markov Decision processes

To explain the working of the Markov Decision Process (MDP), the Markov Chain transition principle can be used. This principle is used to describe the behaviour of a system. It is visualised using an example of a system of two states as shown in Figure 4.8. For an agent starting at state A, the probability is 20% that it stays in that state and 80% that it moves to state B. The same thing is done for state B and the probability can then be calculated how likely the system will be in state A or B after some time. This is done by multiplying a start state (with start state = 1) with the transition matrix as shown in Figure 4.8.

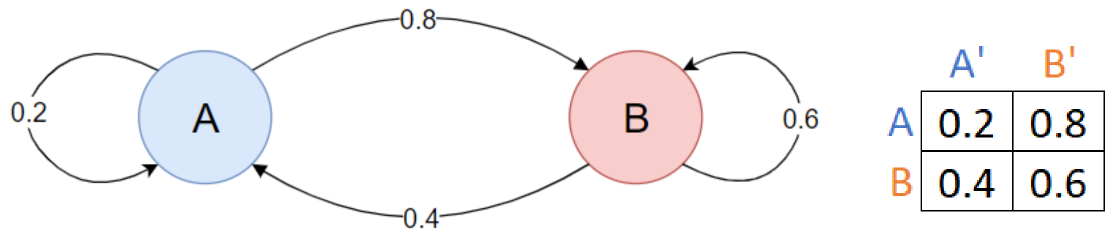

Figure 4.8: Markov chain visualisation (left) and transition matrix T (right)

Markov decision processes
The book Artificial intelligence: A modern Approach, written by Russel & Norvig [52] is used to understand the basics of MDP. The eventual goal of an MDP is to determine the best choice or policy when dealing with uncertainty (mitigating risk using probability). The Markov Decision Process uses the Markov transition principle as described for the Markov chain above, but it simulates an environment of states that an agent can move inside using actions. MDP adds rewards to each state and tries to maximize the total utility gained from the rewards. This can be visualised as a matrix, where each box represents a state and moving between boxes is seen as an action of either moving up, down, left or right in the matrix (when there is no box for an action, the state remains the same). As shown in the left side of Figure 4.9, an action to go up to state B has a probability (or risk) that the action is performed as expected, or the agent might be moved to one of the sides, going to state C or staying in A. When looking at this principle in an environment, an agent might make a series of actions from the start to reach the exit. There are multiple states and two exits (terminal states),

one with a positive reward of 1 and another with a negative reward of 1. As shown in the two matrices to the right of Figure 4.9, each state gives the agent a negative reward, thus prompting it to move to an exit to avoid collecting a large negative reward.

Figure 4.9: MDP explanation, left: Markov transition principle for MDP and right: two reward distributions with corresponding policies

One can determine the utility that an agent receives over the process using Equation 4.1, adding the rewards together with a discount rate γ with a value between 0 or 1. The discount rate represents the human preference for current rewards versus future rewards. When the discount value is 1, there is no preference. Another possibility is the addition of a finite time-frame by limiting the amount of steps $N \neq \infty$. The MDP optimizes the utility each time-frame and defines the best policy for each state. A policy provides the agent with the best possible move during each state, while taking the probabilities of the action not doing what is expected into account. An optimal policy will eventually provide the largest expected utility. The middle matrix in Figure 4.9 shows the optimal policy in every state for a continuous reward of -0.04 and the right matrix shows the optimal policy for a continuous reward of -1.7. Because the increased negative reward is larger than the exit value, the agent is advised to move to the closest exit. Different algorithms can be used to optimise a policy, such as the value iteration algorithm. This algorithm calculates the utility of a state by using all surrounding states and probabilities and is given by the Bellman Equation 4.2. It starts each utility with a value of 0 and iteratively updates all utilities in the matrix until all the values converge.

$$U(s) = \sum \gamma^1 R(s_1) + ... + \gamma^N R(s_N) \tag{4.1}$$

$$U(s) = R(s) + \gamma \max \sum P(s'|s,a) U(s') \tag{4.2}$$

MDP is named by Russel & Norvig [52] to be one of the only methods to be able to deal with risk. This is shown in Figure 4.9 when for a small negative reward for staying in a state, the agent would rather take the long way around to avoid the exit with a strong negative value. When the negative reward for staying is increased substantially, the agent however heads for the nearest exit, even though it is negative. This can be seen as an increase in risk for not making a decision, where an agent would eventually even take a loss now to make sure future (larger) loss is avoided. MDP basically mimics the human decision process, dealing with both the risk and the reward. The behaviour of the agent is however very dependent on the input values.

When looking at modelling the case study using MDP, a range of parameters need to be defined; actions $A(s)$, rewards $R(s)$, probability transition model $P(s'|s,a)$, amount of steps N, discount rates γ and a set of states $[s_0,...,s_N]$. When looking at literature, a great example is found of how to set up an actions vector in the article by Strom [51], who uses MDP for exploring what systems can be used in a ship. For each state, the agent can choose a combination of state variables. Strom does name that due to the amount of variables, a large amount of combinations is possible. He limits the amount of combinations by adding feasibility, stability and free-board criteria. To decrease the runtime of the case study, the amount of variable actions can also be limited and feasibility criteria can be added. The uncertainty in market state and technical requirements is presented in terms of stochastically changing values where the state has a low or high uncertainty over each epoch (each new state is called an epoch during which the transition model might change).

Within the case study, a way which could be used to project market trends from the business case could be to convert the data to a Monte Carlo distribution. Kana et al. [56] use the same method in combination with MDP to define a mean uncertainty with a standard deviation over different epochs within the MDP model.

4.3.2. Epoch-Era Analysis

Epoch-Era Analysis (EEA) was originally created in aerospace engineering by as a part of a PhD thesis by Ross [82]. Ross researched multi-attribute tradespace exploration (MATE) for aerospace engineering systems. EEA is a decomposition of possible futures into scenarios. Both short term uncertainties (using epochs) and long term uncertainties (using era's) can be used. This makes the EEA special, no clear algorithm to solve for an optimum is defined, multiple designs are being tested versus all random epoch distributions. The analysis is basically a concept exploration approach which deals with multiple uncertain scenario's. The computing time of EEA quickly gets very large however as an era space needs to be defined that increases in size according to the amount of epoch variables that can change each epoch and their range. Schaffner et al. [83] showed that with growing number of eras, the problem can become computationally infeasible very quickly using equation 4.3. Where E is an epoch variable, E_{level} is the amount of epoch levels and E_{length} is the epoch length.

$$E = 5 \quad E_{level} = 3 \quad E_{length} = 10 \qquad Epochs = 3^5 = 243 \qquad Era_{space} = 243^{10} \approx 10^{24} \tag{4.3}$$

Curry & Ross use big-data to try and solve this problem [84] and introduce interactive EEA (IEEA). IEEA adds the designer into the Epoch-Era process to explore the trade-space for aerospace designs. They name that this has many positive effects on the design process, as it improves designer insight and the stakeholder has more confidence in the solution. Their analysis focuses on testing the resilience and flexibility of multiple designs. This could be of use for the optimization model, as long as the computation time can be decreased and the projection model can be used as input. A way in which this could be done is by increasing the uncertainty interval over time. The uncertainty then represents the variability in data. At the start, the interval is small and only a few epochs will vary, while towards the end of the vessel's life-cycle, the full variability is used. This would effectively divide the era space in half. The IEEA process, is described by Curry & Ross using Figure 4.10. The design formulation step is the creation of many different designs to be checked, therefore it doesn't necessarily optimize designs but it checks their performance under uncertainty. The result of an EEA is shown as the performance of each design during an epoch versus two multi-objective functions (cost and utility). As is done more often, a Pareto front is then used to find the design that performs best for both objectives. This is explored below as a way to visualize the performance of different designs of the optimization model.

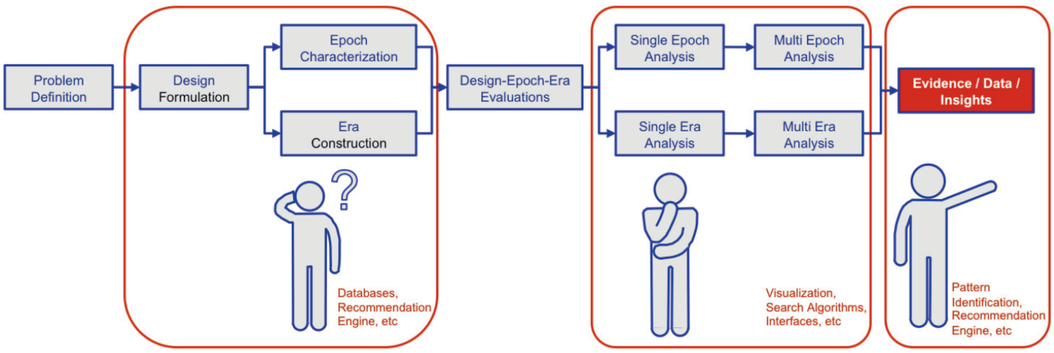

Figure 4.10: Interactive Epoch-Era Analysis with human-in-loop analysis setup from [84]

4.4. Proposed model and scenarios

To be able to deal with the database input and visualise the projected business case clearly, a projection model needs to be created. This model has to read the values from the wind farm database as discussed above. Using these values, the model needs to be able to extrapolate and visualise data trends. The designer then needs to be able to interactively change the probability interval to a range that seems probable. The market set-up can be verified by using recent reports on offshore wind energy as reference. As explained, a ship modelling tool is used to vary different parameters, creating new designs. The capability of each configuration is used to calculate the performance in the market which is built from the extrapolated trends. The uncertainty modelling methods are then used to explore the uncertain market. The method will therefore effectively consist of three parts; a market, a ship model and an uncertainty modelling method. All three are programmed in Python, as this programming language has the required capabilities. Using the method, different interesting relationships found from the market research, are eventually examined to see their effect on vessel performance. Before checking performance, the set-up of each model is explained in more detail in the following chapter.

5

Method set-up

In this chapter, the method set-up is explained in more detail, by discussing the market simulation, ship model and the uncertainty modelling. The method mainly consists of an implementation of a model that can be used to explore the market and ship design at two design stages. Figure 5.1 shows how the method fits in the design process. The method aims to decrease market uncertainty and increase knowledge during the early design stages; requirement definition and concept design. The effect of a changing market on different design configurations is explored by modelling the performance of multiple vessel designs in a simulated market. During or before the requirement definition stage, the designer can use the model to perform global research into the market and the effect of certain design parameters. This way they can advice a customer with better initial designs. During the concept design stage, the model can be used to check whether iterations still fit the projected market. As was found from researching current practice, like many design firms, UDSBV uses an iterative ship design method comparable to the ship design spiral [85]. By implementing a step into the process where market and ship design are re-alligned using the model, the market and ship design are therefore iteratively co-evolved. As more becomes known about the design and the chosen market, assumptions can be improved and new design solutions and market scenarios can also be modelled.

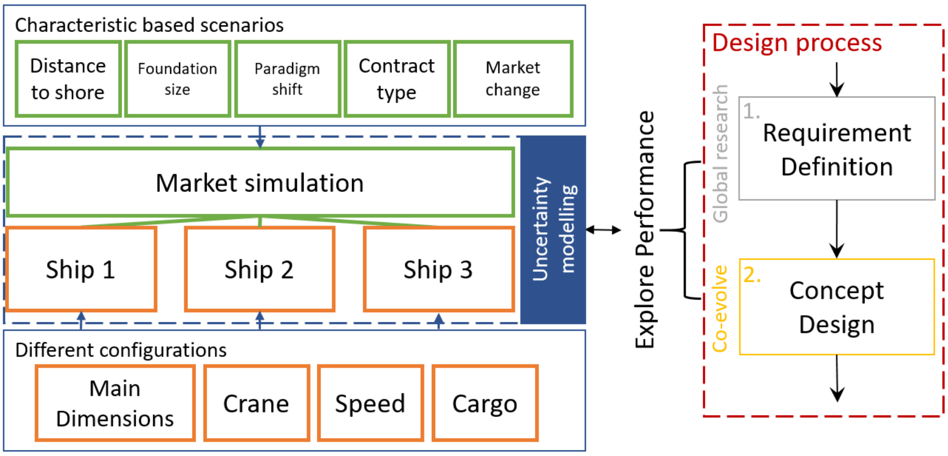

Figure 5.1: Visualisation of scenario's

The model itself consists of three parts; the market simulation, ship model and uncertainty model. The market and ship model use supply and demand side characteristics as input to create a projected market and relevant ship configurations. The uncertainty model then evaluates and visualizes the performance of the vessels within the market. Each run, the user can change aspects on both the market and vessel sides to explore the design space. For the case study into offshore wind foundation installation vessels, global research is performed. The goal being to prove that the method is able to provide valuable insights about what the effect of certain design choices is on the performance of the vessel. Several of the supply and demand characteristics, defined for the offshore wind foundation installation market, are used as shown in the figure and will be discussed in the results chapter.

5.1. Market model

A simulation of the market should provide an up to date overview of the current market and expected trends. These trends should be able to cover the projected market demand for at least the economic lifetime of a vessel. The data from 4COffshore [36] is perfect for this, as it can be used to gain an impression of what the market looks like now and even includes planned wind-farm projects up to five years in advance. To deal with projecting trends, the data science research field is studied, which aims to create clear and useful overviews out of large datasets. To read and analyse data, a processing program is built using the programming language Python. The database file that the projection tool uses is written to be updated using a "database reader". This way, previous versions of the database can also be researched to see in what way trends have changed over time. Before projecting future trends, the data needs to be visualised however.

5.1.1. Data visualisation

The tool loads 23 different data-points of all wind-farms from the database (columns include data like distance to shore, build year, capex per wind-farm and much more). The tool is originally limited to just monopiles, but could easily be expanded to other foundations later. To create an overview of the market, the relationships that were deemed interesting from the case study have been explored. Besides this, a unique opportunity was presented by UDSBV to help prepare a meeting, where market knowledge was shared with two customers working in the offshore wind foundation installation market. From the meeting, the parties agreed on the validity of the market overview and therefore the program's capability to visualise is assumed to be validated. Besides this, the meeting preparation showed which relationships are currently of interest to the industry, thus explaining what graphs should at least be represented. One exemplary overview, used in the presentation, showing the growth in turbine capacity over time is presented in Figure 5.2.

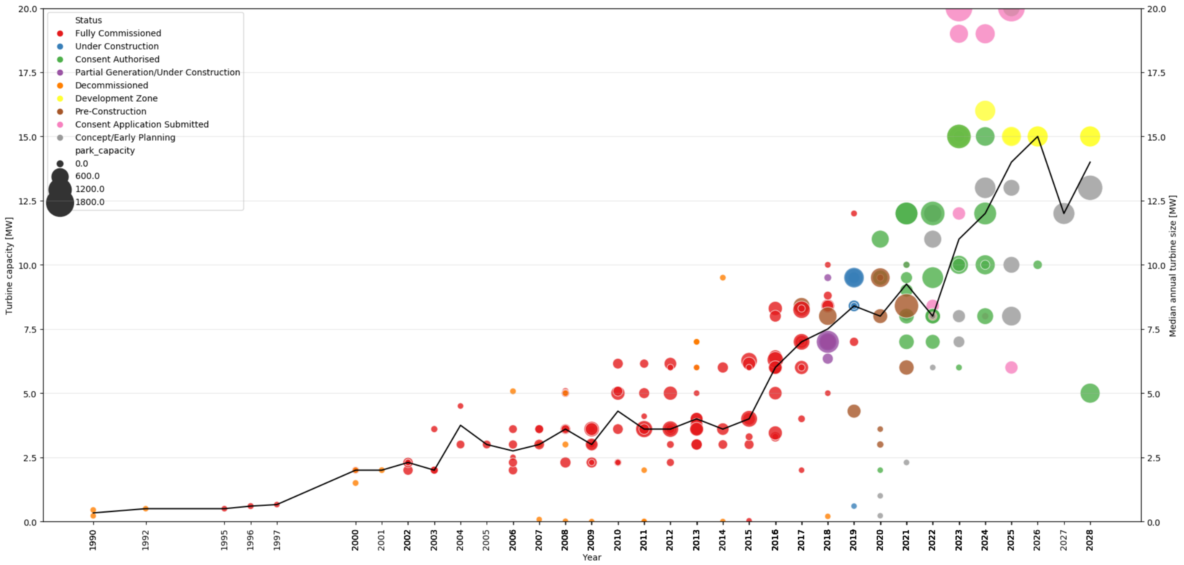

Figure 5.2: Exemplary market overview created using the data visualisation tool.

5.1.2. Forecasting trends

As the market simulation needs to be able to project probable trends and analyse large amounts of data, research fields like data science were researched. One way of data analytics that seemed promising is the use of machine learning algorithms to forecast trends [86]. An example being the estimation of daily and seasonal power usage trends by Contreras [87], using an Arima algorithm. This algorithm takes the first, second or third order differences of time-series data and tries to find a frequently re-occuring trend within the differential signals. The algorithm learns from previous data and can then be used to predict future power usage by using the trends it learned. A check to see whether such a machine learning algorithm could be used to predict future trends in foundation size was performed using an Arima python extension [88]. Unfortunately, the sample size proved too small and differencing did not show re-occurence.

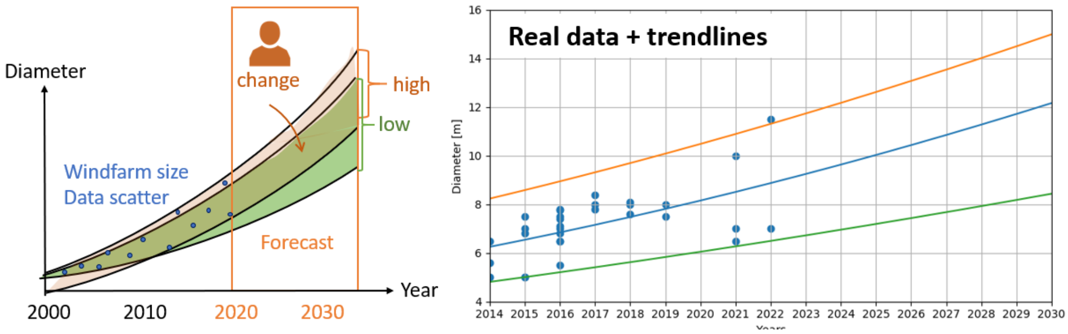

Figure 5.3: Forecast of market trend using extrapolation from data scatter and example of principle with real data.

Besides machine learning, other forecasting algorithms where also researched but were found to be too extensive for the purpose of this Thesis. Therefore, a new trend prediction method is proposed, one which uses the human cognitive ability as described by Barr [89], who explains that humans are particularly good at seeing relationships. As shown in Figure 5.3, the prediction method first extrapolates a trend from data and then gives the designer the opportunity to shift the trend line into a prediction they want to research. Choosing to look at a broader market with smaller size or a narrower market with larger foundation sizes.

To estimate the development of the foundation market, the foundation size and weight and the turbine capacity need to be included in the forecast. A wind turbine foundation is designed to be able to deal with many different kind of loads; permanent loads (mass of turbine and pressure), variable loads (vessel impact), environmental loads (wind, wave and ice) and extreme loads (like accidents, deformation and abnormal operation). A first estimate of monopile geometry is often made using rules of thumb, but geometry can also be estimated using data regression from previous projects as is shown by Negro et al [90], who perform a preliminary estimation of main dimensions for monopiles. Along the same line, to estimate foundation size growth, a correlation study is performed as part of this Thesis using the 4COffshore database. To be able to correctly judge the relationships found in the study, turbine foundation design has been researched in more detail using the wind energy handbook [91], internal knowledge from UDSBV and lectures from the TUDelft Offshore Wind Support Structures course [92].

The database correlation is analysed by using Spearman's Rank coefficient as described by Gauthier [93]. All columns are graphed against each other to visualise if the data points are grouped or scattered and then a Spearman correlation coefficient is added. The $r_{spearman}$ is calculated using Equation 5.2 and is a measure of how well the relationship between two lists $r_x \& r_y$ of values can be described using a monotonic function. Which is a function that either only increases or decreases but can have a variable slope. It uses the ranking order of each list and performs a Pearson correlation over these ranks first. The Pearson correlation, on the other hand, is a measure of the linear correlation between two lists of values $x \& y$ as calculated using Equation 5.1.

$$r_{pearson} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2}\sqrt{\sum(y_i - \bar{y})^2}} \tag{5.1}$$

$$r_{spearman} = \frac{cov(r_X, r_Y)}{\sigma_{rX} \sigma_{rY}} = \frac{\sum(r_{xi} - \bar{r_x})(r_{yi} - \bar{r_y})}{\sqrt{\sum(r_{xi} - \bar{r_x})^2}\sqrt{\sum(r_{yi} - \bar{r_y})^2}} \tag{5.2}$$

The spearman correlation coefficient for turbine, foundation and environmental parameters is shown in Table 5.1. The total length of the monopile is the embedded length plus the water-depth. The embedded length is dependent on soil type, as the soil acts as flexible medium while it needs to fix the pile in place. This results in the effective depth of the pile being decreased. The soil type for monopiles in the north sea, is shown to be mainly sand [94], so the effect of soil type is assumed to scale equally for the monopiles from the database. The embedded surface area of the monopile supports loads due to friction and needs to be dimensioned in such a way that variable loads (like blade passing frequency) cannot excite the pile's natural frequency. From the correlation study, foundation length is mainly correlated to waterdepth, no good correlations were found for embedded length however. Foundation length is therefore assumed to depend primarily on water depth and is constrained to $50m$, which is the maximum depth for monopiles [73] and a recurring maximum depth in the European market [95], which is targeted for the case study. The turbine parameters, which dictate important loads that are used to design foundation geometry, mainly correlate with foundation diameter. Foundation weight is physically calculated using Equation 5.3, which assumes the foundation as a hollow steel cylinder with a tapered end, with diameter D_{Fo} and length L_{Fo}. Wall thickness t is determined using Equation 5.4 from API [96] with an adapted slenderness ratio. This adaption was made by UDSBV after discussions with monopile manufacturer SIF about future monopile design. The depth-constrained length regression and the physical estimation for weight and regular data fits are shown in Figure 5.4.

$$W_{Fo} = W_{Fo_l} + W_{Fo_t} \rightarrow W_{Fo_l} = \pi \cdot L_{Fo_l} \cdot \rho_{Fo} \left(\left(\frac{D_{Fo}}{2} \right)^2 - \left(\frac{D_{Fo}}{2} - t \right)^2 \right) \tag{5.3}$$

$$t = 6.35 \cdot 10^{-3} + \frac{D_{Fo}}{120} \tag{5.4}$$

Table 5.1: Spearman correlation coefficient for mono-pile data from 4COffshore 05-03-2020

	Foundation dimensions			Environment	Turbine		
	Foundation Length [m]	Foundation Diameter [m]	Foundation Weight [tons]	Water Depth [m]	Hub Height [m]	Turbine Capacity [MW]	Rotor Radius [m]
Foundation Length [m]	1	0.84	0.89	**0.87**	0.61	0.62	0.71
Foundation Diameter [m]	0.84	1	0.91	0.82	**0.86**	**0.85**	**0.89**
Foundation Weight [tons]	0.89	**0.91**	1	0.84	0.74	0.75	0.81
Water Depth [m]	**0.87**	0.82	0.84	1	0.59	0.61	0.65
Hub Height [m]	0.61	**0.86**	0.74	0.59	1	0.9	0.94
Turbine Capacity [MW]	0.62	**0.85**	0.75	0.61	0.9	1	0.96
Rotor Radius [m]	0.71	**0.89**	0.81	0.65	0.94	0.96	1

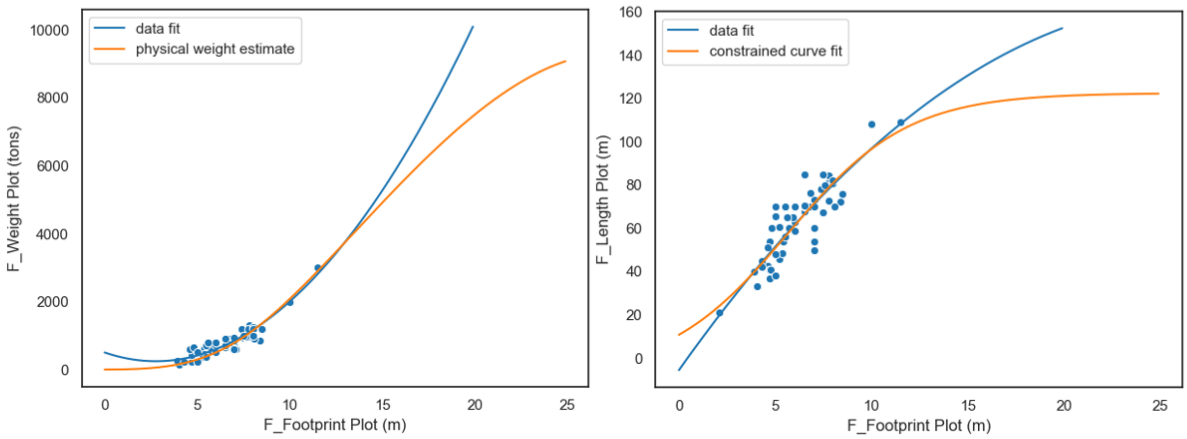

Figure 5.4: Comparison between data fits and constrained length and physical weight estimate.

The diameter is found to also correlate well with time ($r_s = 0.86$), and because other values can be approximated well from diameter, it is used to forecast foundation size growth. A lower and upper bound per time step δT is determined to account for outliers and represent the market uncertainty, effectively creating a range in which contracts might occur each year. These are created by normalizing all points versus the mean trend-line and using the negative and positive points respectively to interpolate the bounds. The designer can change the direction and slope of the mean and bound trend-lines by changing the polynomial coefficients of each line.

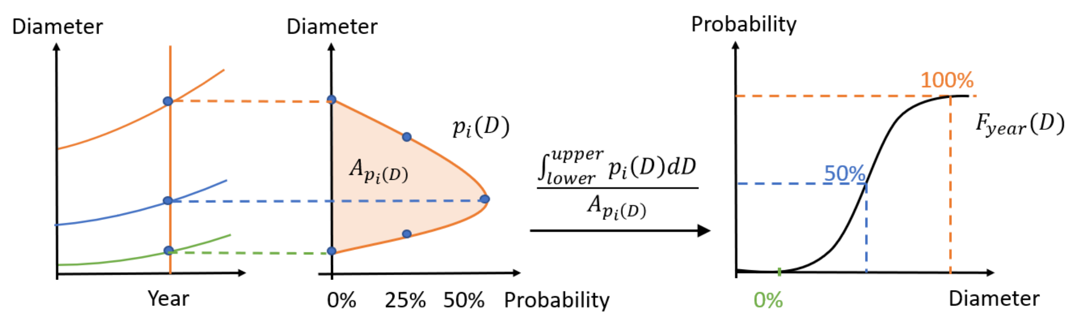

Figure 5.5: Use of forecasted trendlines, transformation into probability density.

To use the forecast, a probability density function $p_i(D_{Fo})$ is created using the mean and the upper and lower bounds for each year. It was researched if normal or gaussian distributions could be used, but it didn't seem possible to create asymmetric distributions while controlling the location of the mean. This is very important however, as a massive outlier would be able to shift the mean toward unrealistic values. Therefore, a probability distribution function was built that could do this, which is visualised in Figure 5.5. Five points at important percentiles are created by using a discrete probability mass function. The points are then interpolated, thus creating function $p_i(D_{Fo})$ out of the mean and bound values for each year, where D_{Fo} represents the diameter of the foundation. The cumulative probability function $F_{year}(D_{Fo})$ in Equation 5.5 is created by integrating the probability density function and normalizing it by dividing by the area under the curve. The function can now be used to determine the probability between two diameters points and it is used to create probability matrix T_{config}. This matrix is used to store the cumulative probability data for a range of diameters $[d_0...d_n]$ for multiple years $[y_1...y_n]$. This way, the market is simulated using a stochastic description regarding the development foundation size over time. An rough example of such a matrix for multiple years is shown in Table B.2 the appendix. In the actual model the diameter range step size is chosen to be 0.01m.

$$F_{year}(D_{Fo}) = \frac{1}{A_{p_i(D_{Fo})}} \int_{d_0}^{d_n} p_i(D_{Fo}) dD_{Fo} \quad \rightarrow \quad p_{d,y} = F_y(D_{Fo}) \quad \rightarrow \quad T_{config} = \begin{bmatrix} p_{d_1,y_1} & \cdots & p_{d_n,y_1} \\ \cdots & \cdots & \cdots \\ p_{d_1,y_n} & \cdots & p_{d_n,y_n} \end{bmatrix} \tag{5.5}$$

5.2. Modelling ship configurations

To simulate variations of ship design configurations, multiple designs have to be created that have realistic values. The UDSBV vessel designs are therefore used as reference for the modelling. A few main parameters that dictate the general capability of a vessel are used as input for creating scaled conceptual vessel designs. As explained in Section 4.2, the ship model is divided into several modules which will be explained in more detail in this section. The advantages of using modules is that each can be verified and validated separately, can be changed to fit a new case or can be upgraded. Overall the ship model has been divided into five modules:

1. Scaling
2. Weight estimate
3. Power and Propulsion
4. Mission
5. Cost and income

The input is created by taking a range for each design parameter. Going from a lower value to an upper value with a given step size. A program is written that creates combinations of all values as input for the model. This way, the designer could either fix a parameter to a single value or research multiple configurations as is shown in Figure 5.6.

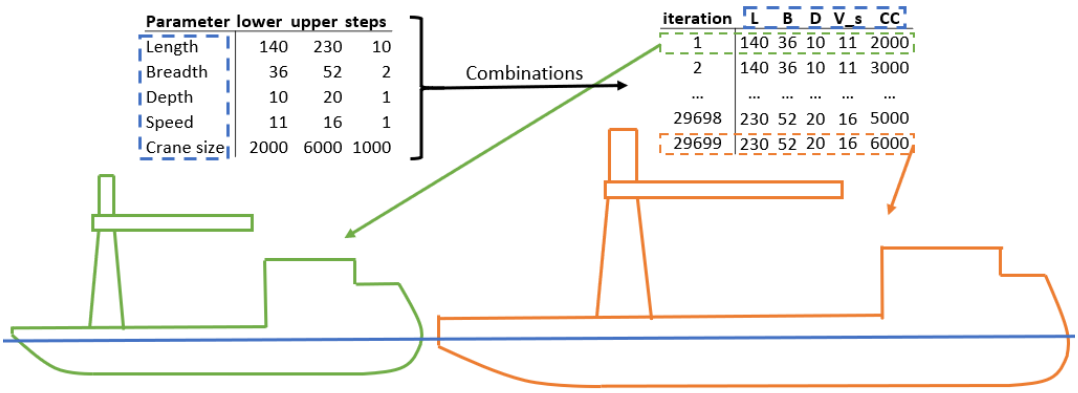

Figure 5.6: Visualisation of input data

Verification and Validation
It is important to check whether the models and their behaviour can be trusted. In modelling, this is usually done by verification (checking internal consistency) and validation (justification of knowledge claims). As the model is very large and uses a stochastic market description, it becomes very difficult to properly validate each aspect. Therefore the validation square methodology, as proposed by Pedersen [97], is used. This article explains that model validation can consist of empirical validation to test internal consistency and test external relevance by using example problems. They propose validating a method on four terms; looking at theoretical structure and performance and empirical structure and performance.

Besides looking at theoretical and empirical validation, the sensitivity of each module and the total model need to be verified as explained by Ye & Hill [98]. This can be done by looking at the effect of certain parameters on the output of a mathematical model and checking its behaviour, called a sensitivity analysis. Therefore a local sensitivity analysis is performed for each module and a global sensitivity analysis is done for the entire model. In this chapter, besides explaining the working of each module, the local sensitivity (verification) and internal relevance (validation) are also addressed. While the global sensitivity is checked as part of the next chapter by going through example problems. As mentioned by Ye & Hill a verification and validity study should examine all values in a model. Due to the size and complexity of the model and limited time, the verification and validity study is restricted to only a few relevant values. A summary of the verification and validation study that is performed locally and globally is added to the appendix. The values mentioned are only a selection of the total study, but are sufficient to show how the validation and verification has been performed.

5.2.1. Scaling
A scaling function is created that estimates some values that are used by the other modules, based on input of the main parameters. A combination of books by Birk [99] and Papanikolaou [100] have been used to determine important coefficients for the scaling. As the vessels are assumed to be equipped with an Ulstein X-bow, no bulb area is assumed. Draught T is scaled using input vessel depth and, as no pitch is assumed, this is also taken to be the aft and forward draught. Two different types of draught are of importance; the design draught (used for resistance and power estimations) and the maximum draught (used for installation stability calculation). In reality, the design draught is based on an average of the most common loading conditions. For this estimation however, the design draught is taken as a percentage of the maximum draught which has been determined together with UDSBV. The maximum draught is estimated calculating the minimum freeboard by using the international load-line convention and subtracting this value from the depth input.

The longitudinal centre of buoyancy in percentage from the ships centre (negative is aft) is determined using a method from the Guldhammer and Harvald method as described by Kristensen and Lützen [101]. The midship coefficient C_M is estimated using a regression equation from Jensen [102], prismatic coefficient C_P and waterplane area coefficient C_{WP} are estimated using Equations 5.6 from Papanikolaou [100].

$$l_{CB} = -(0.44Fr_{design} - 0.094) \quad C_M = \frac{1}{1+(1-C_B)^{3.5}} \quad C_P = \frac{C_B}{C_M} \quad C_{WP} = C_P^{2/3} + 0.05 \tag{5.6}$$

The block coefficient C_B is a value that is used as an input by many of the used estimation methods and therefore needs to be approximated as well as possible. Multiple theoretical estimations where researched, eventually using Katsoulis' exponential equation for optimum block coefficient [103] shown in Equation 5.7. This equation was found to be useful, as it recognizes the relation between main dimensions L, B, T and ship speed V_s (in knots), while providing a scaling factor f that can be used to fit the outcome to the reference vessels. The necessity of calibrating the equation is also mentioned by Katsoulis in a critique of his own method in 2016. Calibration was done using two of UDSBV's reference vessels and can be found in the appendix. It was found that the equation overestimates the effect of certain parameters however, which resulted in large vessel cost discrepancies. To improve the estimation, the exponents were also calibrated using the reference vessels.

$$C_B = 0.8217 f_k \cdot L^{0.42} \cdot B^{-0.3072} \cdot T^{0.1721} \cdot V_s^{-0.6135} \rightarrow C_B = 0.8217 f_k \cdot L^{a_k} \cdot B^{b_k} \cdot T^{c_k} \cdot V_s^{d_k} \tag{5.7}$$

The wetted surface S is determined using Equation 5.8, the half angle of the waterline entrance i_E and its exponent a are given by Equations 5.9 and 5.10, the run length L_R needed for exponent a is given by Equation 5.11. All of these values are determined using Holtrop and Mennen [104][105].

$$c_{23} = 0.453 + 0.4425C_B - 0.2862C_M - 0.003467\frac{B}{T} + 0.3696C_{WP}$$

$$S = L_{WL}(2T+B)\sqrt{C_M}\left[0.615989c_{23} + 0.111439C_M^3 + 0.000571111C_{stern} + 0.245357\frac{c_{23}}{C_M}\right] + 3.45538A_T + \frac{A_{BT}}{C_B}(1.4660538 + \frac{0.5839497}{C_M}) \tag{5.8}$$

$$i_E = 1 + 89e^a \tag{5.9}$$

$$a = -\left[(\frac{L_{WL}}{B})^{0.80856}(1-C_{WP})^{0.30484}\,[1 - C_P - 0.0225l_{CB}]^{0.6367}\,(\frac{L_R}{B})^{0.34574}(\frac{100V}{L_{WL}^3})^{0.16302}\right] \tag{5.10}$$

$$L_R = L_{WL}(1 - C_P + \frac{0.06C_P l_{CB}}{4C_P - 1}) \tag{5.11}$$

The equations have been verified using empirical examples from Birk [99] and Holtrop and Mennen [105]. The internal validation for the scaling module can be found in the appendix. Sensitivity of the scaling module was checked performing two tests; the draught should increase for larger depth and wetted surface should increase for volume increase. The wetted surface scatter is a result of the block coefficient calibration. These tests are presented in Figure 5.7. As expected, the design draught increases linearly with depth and wetted surface increases with an increase in displacement.

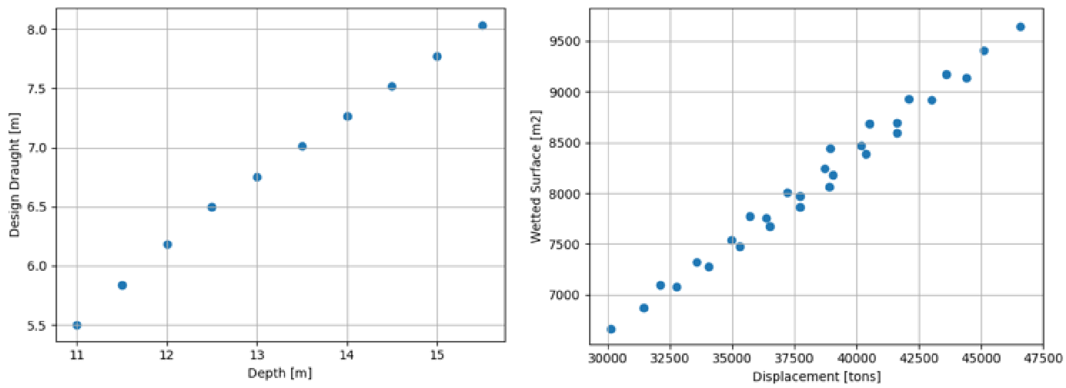

Figure 5.7: Development of Vessel depth versus design draught and displacement versus wetted surface for different configurations.

5.2.2. Weight estimate

As Aalberts [106] explains, satisfactory weight estimation in an early design phase can be done by dividing weight into multiple weight groups. The chosen weight groups are based on Ulstein internal protocol, so separate results can be validated easily against reference vessels. Scaling vertical centre of gravity (VCG) of each weight group is done using vessel depth, as equal ship types show a relation between depth and VCG, as named by Papanikolaou [100]. Each weight group is scaled using values that are influential for that weight group:

- Hull weight: scaled using length, breadth, depth and block coefficient as hull shape mostly determines the amount of structural steel needed.
- Main engine weight: scaled using installed power.
- Crane weight: scaled using crane capacity
- Equipment for crew and passengers weight: scaled using amount of persons on board.
- Machinery weight: scaled using installed power
- Common systems (like electricity cabling) weight: scaled with installed power.
- Sailing equipment (navigation and mooring) weight: scaled with ship length as mooring weights are often scaled with length.

During research at UIN in Norway, it was mentioned that using a database of reference vessels could provide good weight estimation as shown by Ebrahimi. To research if a weight regression could also be done for heavy lifting vessels, a database was created using UDSBV projects including 13 offshore vessels with known weights having a crane capacity larger then 900 tons. The Construction Vessel Base from IHS Markit [107] was used to do the same for 15 complementary vessels. Both databases were used to check whether scaling with depth or other parameters would show correlation. As the information is property of UDSBV, it was chosen not to publish this information. Unfortunately, in the limited time, there was a lack of correlation, which could be attributed to the limited amount of offshore vessels to regress over. More importantly, it seems over-dimensioning of the hull for different cargo, extra mission equipment and/or crane capacity seems to result in little relation between vessels. This is an interesting direction for new research. For now it was chosen to keep using scaling from reference vessel. Using the reference values, each separate and total weight and VCG are validated. A few tests are run to verify behaviour of the module, these are visualised in Figure 5.8

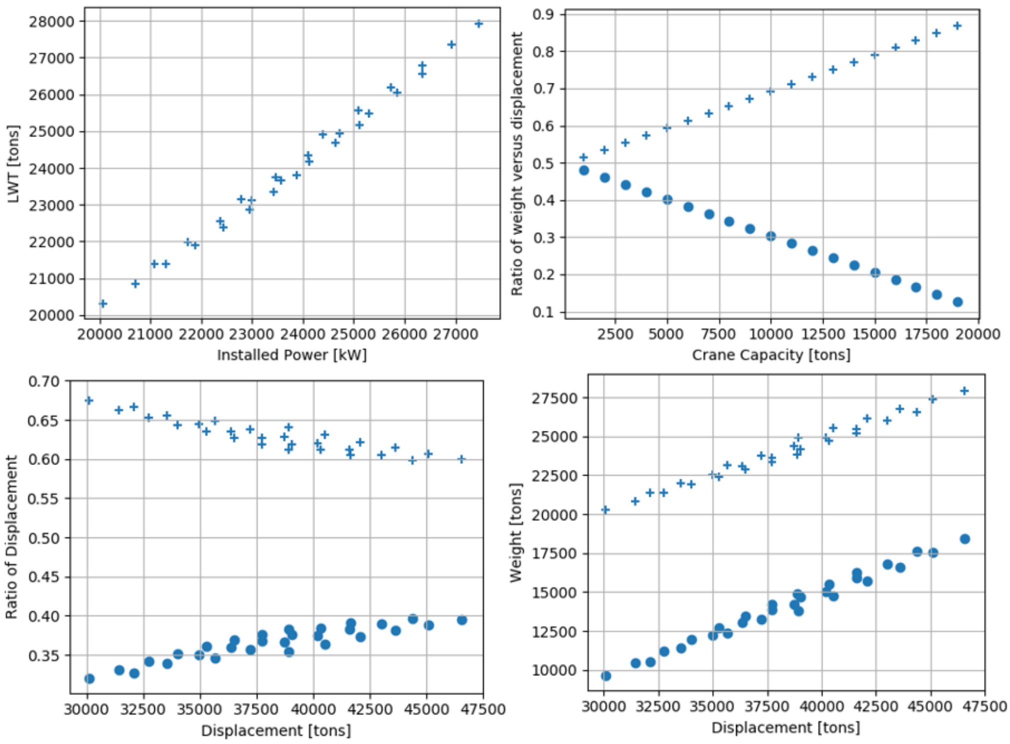

Figure 5.8: Weight test results, plus sign is LWT and dots are deadweight

and discussed going clockwise from the top left. In the first figure, lightweight should increase with installed power, as both the propulsion and generators increase in size. In the second figure, the LWT should increase and the deadweight should decrease when only changing crane capacity. This is seen to be true, as the ratio LWT/displacement increases for larger crane sizes and the ratio DWT/displacement decreases. In the bottom right, the LWT and DWT both increase as the vessel increases in size. The last figure shows that the ratio of DWT versus LWT increases however, which could be realistic as the increase in volume should enable a larger cargo capacity. The rate of increase can be read from the lower right figure, which shows that for each 1000 tons of displacement, the DWT increases with 800 tons. More research could be done to see if this is a typical value.

5.2.3. Power and propulsion

The installed power and size of thrusters have a large effect on capability and cost. Using the scaled hull shape, the resistance is estimated using Holtrop and Mennen's method as described by Birk [99]. The method is verified using example values from Birk and Holtrop & Mennen. The outcome has also been validated using tank-test resistance data from Marin that was available for one of the reference vessels in two different draughts. From this validation it became clear that a residual resistance term needed to be added to approximate resistance correctly, the result can be seen below in Figure 5.9.

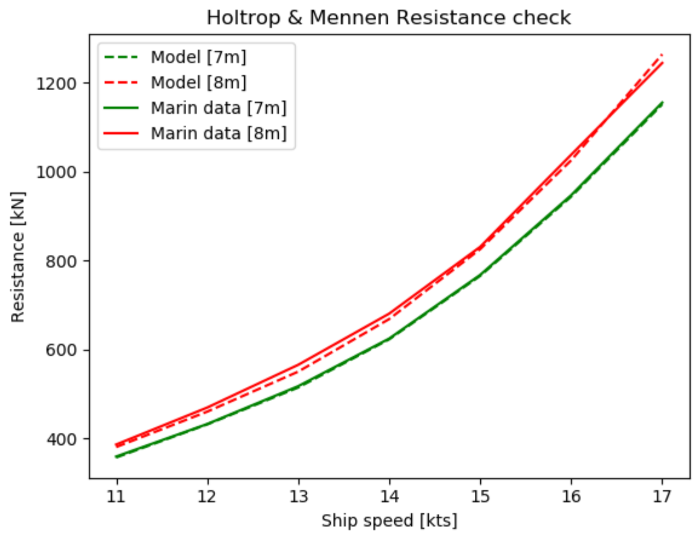

Figure 5.9: Holtrop and Mennen resistance validation

The resistance is then used to determine the necessary propulsion power using the book by Klein Woud & Stapersma [108]. The thrust coefficient as required by the ship $K_{T,ship}$ for different advance ratio values J, is determined using values as determined from Holtrop [105]. It is assumed two propellers describe the propulsive capacity for heavy lifting vessels accordingly (HLCV commonly have more thrusters, but no method as established as Holtrop and Mennen was found that describe more than two propellers). The propulsion power is then estimated by intersecting the thrust coefficient of a Wageningen B-Series propeller with the ship's thrust coefficient in an open water diagram. The torque and thrust coefficient and open water efficiency for the Wageningen B-series are calculated using the B-series polynomials as described by Oosterveld & van Oossanen [109].

Table 5.2: Wind and wave statistics

P	H_s	V_w	V_c	$1-P$	T_p
2.5	0.66	1.4	0.75	97.5	3.4637088
5	0.79	2.19	0.75	95	3.895625042
10	1	3.3	0.75	90	4.4706024
20	1.35	4.95	0.75	80	5.259666225
30	1.7	6.21	0.75	70	5.812328962
40	1.9	7.48	0.75	60	6.328340198
50	2.3	8.74	0.75	50	6.801990125
60	2.6	10.01	0.75	40	7.24323895
70	3	11.39	0.75	30	7.684410074
80	3.5	13.11	0.75	20	8.183098996
90	4.2	15.53	0.75	10	8.799643025
95	4.9	17.6	0.75	5	9.2596152
97.5	5.3	19.32	0.75	2.5	9.602636314
98	5.6	19.9	0.75	2	9.7114548
98.5	5.8	20.59	0.75	1.5	9.836934626
99	6.1	21.51	0.75	1	9.99816814

Besides estimating propulsive power from resistance, installed power is estimated using environmental wind, wave and current loads calculated using the DNV-GL DP standard [110]. The resulting force that will occur at least 90% of the time using environmental data taken from Table 5.2 is related to the amount of thruster power that is needed using a thruster power to force relationship as given by Bulten & Suijkerbuijk [111]. It is assumed that all vessel configurations at least need DP2, being able to still perform operations even when one full DP system fails thus needing twice the propulsion power, which results in installed power Equation 5.12. The equation represents the maximum power balance scenario for the vessel, which is the sum installation power (based on crane capacity), accommodation power and DP2 power.

$$P_{inst} = 2 \cdot P_{DP} + PoB \cdot 7 + \frac{CC}{4} \tag{5.12}$$

The propulsion power is validated using example values but is found to underestimate the power for the reference vessels, the propulsion power estimate was changed because of global verification and is discussed in the results chapter. The resistance and propulsion power are also locally verified, as shown in Figure 5.10. The resistance tests are discussed first, the frictional resistance at the top right is verified to increase for an increase in wetted surface. Secondly the wave resistance is shown to increase exponentially for an increase in ship speed. Then starting on the bottom left, only the propulsion power should increase exponentially for larger speeds, while the DP power stays equal, as it is not dependent on the vessel speed. The DP power does however slightly decrease, as the current force is dependent on hull shape and the C_B calibration slightly decreases for larger speeds.

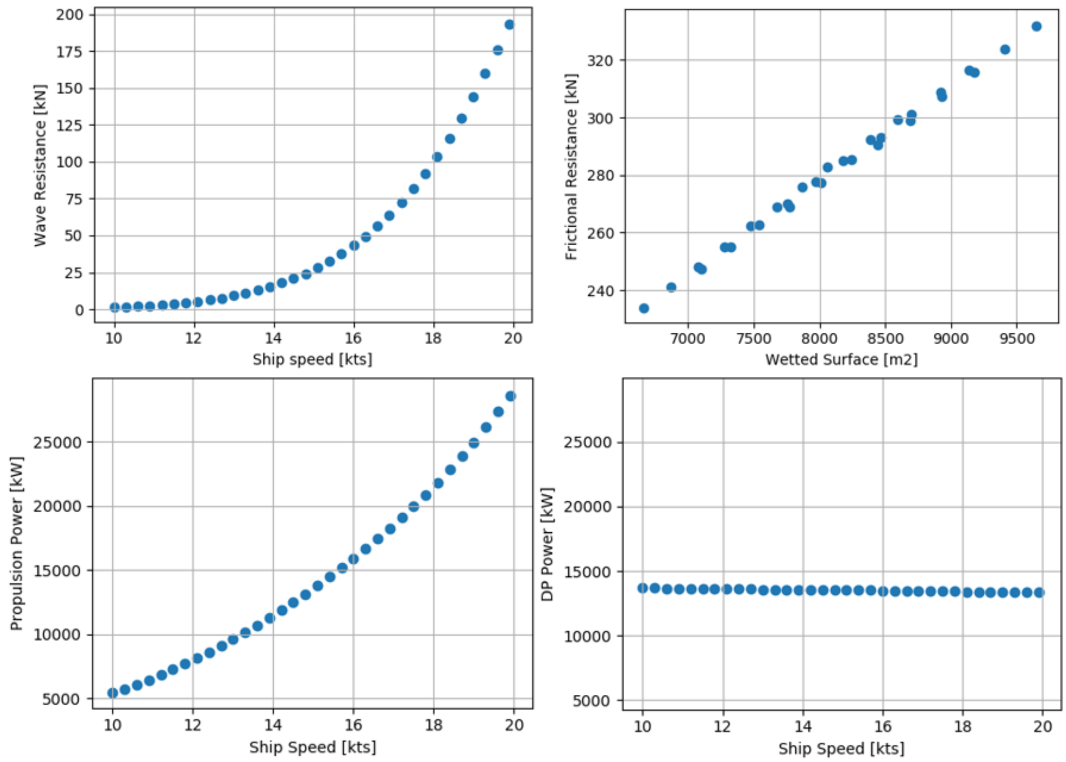

Figure 5.10: Resistance and Propulsion test results

5.2.4. Mission

The mission module is used to couple the market with the configuration. In terms of the offshore wind foundation installation, this is the transport and installation of foundations by the vessel. The amount of foundations with a certain weight, length and diameter that can be placed by a configuration is dependent on multiple factors, which are explained below. Using these factors, the maximum amount of foundations are determined and used as constraint.

- Deck area and foundation length: The maximum amount of foundations constrained by deck area is calculated using Equation 5.13. It is assumed the same amount of foundations and transition pieces needs to be carried, the TP size plus sea fastening is taken as $1.1D_{Fo}$. When the foundation length is larger than the deck length, foundations might be placed sideways, as no regulation was found limiting the load sticking out from the sides. The only constraint in foundation length could be the feeding harbour entrance size. Luckily, a database was created internally at Ulstein that could be used to show what harbours that a design might not be able to enter. However as a start, only longitudinal placement is taken into account and is constrained using Equation 5.14.

- Deck strength: As the structural weight is scaled from reference, the deck strength is assumed to comply initially.
- Crane Capacity: The crane capacity constraints whether a monopile can actually be installed. Besides this, the crane moment is typically determined at a boom length of 30 meters and results in a decrease in crane capacity at larger boom lengths. This also decreases the amount of cargo for higher foundation weights, as the area that can be reached with maximum crane capacity is lower than the full deck area. To increase installation capability, foundations might be moved toward this area for installation. But initially it is assumed that this is not possible, thus limiting the cargo capacity.
- Stability: the stability effects both the cargo and installation and is explained in more detail below.
- Sea fastening size: It is assumed that between each foundation and transition piece, 10% of the foundation diameter is required for sea-fastening.

$$N_{Fo,Deck} = \frac{A_{Deck} - L_{Fo}B}{1.1D_{Fo}} \quad \rightarrow \quad A_{Deck} = L_{Deck}B - A_{crane} \tag{5.13}$$

$$N_{Fo,L} = \begin{cases} 0 & if L_{Fo} > L_{Deck} \\ \infty & else \end{cases} \tag{5.14}$$

Stability constraint

As one of the most important constraint is the stability of the vessel, this will be explained in more detail. Stability is estimated using geometric metacentric height rewritten to the height of the centre of gravity $KG = KM - GM$. The GM value is based on Equation 5.16 taken from Harenberg [112], who mentions the equation being a stability rule that was internally developed at Jumbo based on experience. The importance of such an equation is apparent as heavy lifting vessels also have to satisfy a lot of stability criteria, like the loss of hook load criterion. This criterion signifies the event when a crane load breaks off and the vessel rolls back towards the ballasted side. When the righting arm is not large enough in the individually ballasted case, the vessel might capsize after load loss. It is assumed the GM equation also takes criteria like these into account, as it was created for installation vessels. The keel to metacentric height value KM is determined using Equation 5.15 from Papanikolaou [100]. The KM calculation is validated by using hydrostatic reports of two reference vessels.

$$KM = B \cdot (C_1 C_2 \frac{B}{T} C_M^{-\frac{2}{3}} + \frac{0.9 - 0.36C_M}{B/T}) \tag{5.15}$$

$$GM = 1 + 1.5 \cdot \frac{W_{load}}{1800} \tag{5.16}$$

The maximum posible KG is then calculated by solving a moment balance Equation 5.17 for N_{Fo}. The first part of the equation is the centre of gravity for each pile $\left(\frac{N_{KG}}{N_{Fo}} + D\right)$ and mass of the stored foundations W_{Fo}. The N_{KG} is determined using Equations 5.18, using the amount of foundations that fit in width $N_{Fo,B}$ and the amount of layers of foundations l_{Fo}. The second value is the centre and mass of the unloaded vessel. The ballast mass value is equal to $W_{bal} = DWT - N_{tot} \cdot (W_{Fo} + W_{tp})$ and is multiplied by the location of ballast tanks represented by ratio x versus depth. The fourth value represents the weight and location of one foundation that is hoisted by the crane. The last value is the weight and height of transition pieces.

$$KM - GM = \frac{\left(\left(\frac{N_{KG}}{N_{Fo}} + D\right) N_{Fo} W_{Fo} + LWT \cdot KG + x_{bal} W_{bal} D + N_{Fo} W_{TP} \left(D + VCG_{TP}\right)\right)}{\Delta} \tag{5.17}$$

$$N_{KG} = N_{Fo}\left(l_{Fo} - 0.5\right) - N_{Fo,B}\left(\frac{\left(l_{Fo} - 1\right) l_{Fo}}{2}\right) \quad l_{Fo} = floor\left(\frac{N_{Fo} + N_{Fo,B} - 1}{N_{Fo,B}}\right) \quad N_{Fo,B} = floor\left(\frac{0.9B}{1.1D_{Fo}}\right) \tag{5.18}$$

Constrained amount of foundations on deck

The amount of foundations that fit on deck are calculated for all diameters that might occur in the market for the selected period. The way this works for the weight criterion is shown in Figure 5.11. The equation $DWT = N \cdot (W_{Fo} + W_{TP})$ calculates how many piles N with weight $(W_{Fo} + W_{TP})$ fit on board for the cargo DWT. Depending on the size D_{Fo} of a monopile, the monopile weight (W_{Fo}) and transition piece (W_{TP}) weight increase to a fraction of the DWT, shown as a constraint on the right. When the weight passes this point, zero piles will fit on deck, while a one or more will fit before the intersection. The amount of monopiles on deck therefore depends on the weight to DWT fraction. When the fraction is not exactly a round number, a portion of the DWT is not used for transport and is therefore non-used, which is also shown flipped in Figure 5.12. Each of the criterion equations calculates amount of piles on deck for a range of diameters and the minimum amount of piles is used as capability to calculate income and cost of installation.

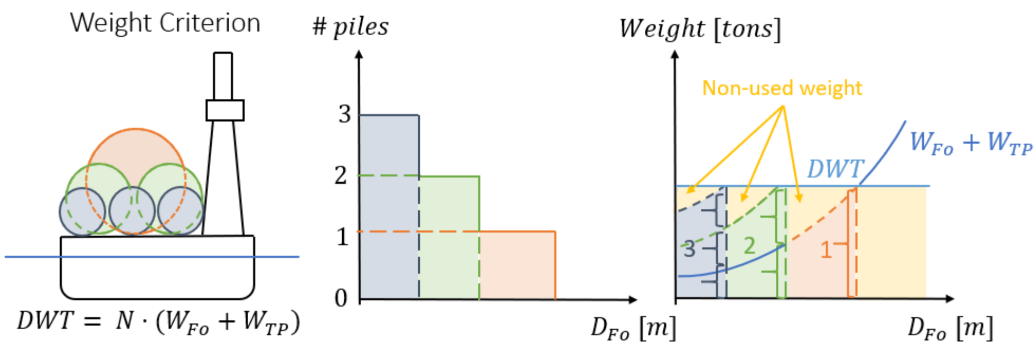

Figure 5.11: Set-up and functioning of the Weight criterion

The monopiles on deck are validated by comparing how many 2000 tons monopiles fit on deck versus the amount UDSBV has calculated can fit for the HX104 and HX118 and has been included in the appendix. The module is verified by checking whether all criteria are obeyed as shown in Figure 5.12. An example for the HX118 with a lower breadth (of 36 meters) showing all constraints ('criterion') that directly lower the amount of monopiles on deck with dashed lines. At the start, the deadweight is the primary constraint for the amount of piles. Above $9m$ diameter, the lowered breadth results in a lower stability, so the pink line (lift stability) also becomes a direct constraint when size (VCG of the piles) and weight of the monopiles increase. Two depths are shown in the ballast figure, one without and one with stability problems. The figure shows the amount of weight that is not used for piles and needs to stay between 0 weight and deadweight. The sawtooth shape occurs because full monopiles are assumed, so each sawtooth is the amount of weight that is just not enough for a new pile. After 9m diameter, the stability constraint kicks in and an amount of ballast is needed which decreases the amount of piles that can be transported. Just before 12 meter diameter, the crane capacity criterion cuts off the amount of piles because the piles become too heavy for the vessel's 3000 ton crane. This is also seen in the non-used weight chart, because no piles are carried, the total DWT becomes non-used weight.

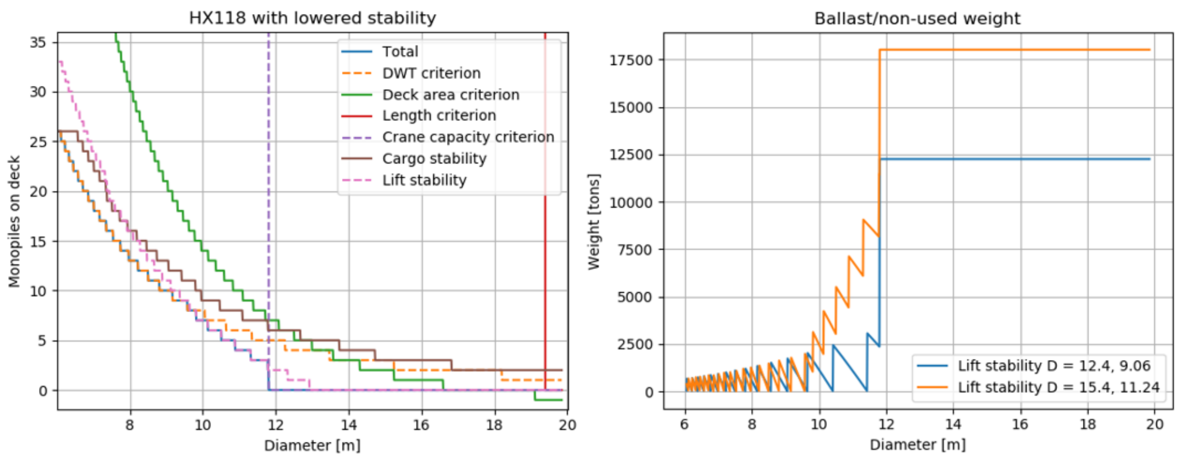

Figure 5.12: Stability and monopiles on board check

5.2.5. Cost and income

As mentioned by Aalbers [106] it is possible to estimate building and operational costs with relative simple means. Using his article together with Stopford's ship finance book [113] and internal research from Ulstein, the capital cost (CAPEX), operational cost (OPEX) and voyage cost (VOYEX) are determined. The parameters which affect each cost category and their equations are given below:

- CAPEX: most influenced by build cost, as the loan, depreciation and interest rates are set as a percentage of the investment in the ship.
- OPEX: also influenced by build cost as insurance, stores and maintenance are estimated as part of the ship's investment. Another aspect that greatly influences OPEX is the amount of crew, this is initially fixed.
- VOYEX: the voyage expenses are based on the amount of trips and the installed power as this dictates the fuel use and port fees paid.

$$CAPEX = Loan_{interest} + Loan_{repayment} + Equity_{return} \tag{5.19}$$

$$OPEX = Crew_{wage} + maintenance + stores\&supplies + insurance + management_{overhead} \tag{5.20}$$

$$VOYEX = Port_{charges} + C_{Fuel} \tag{5.21}$$

$$C_{Fuel} = trips_{yr} \left(P_{inst} \cdot t_{tot} \cdot sfc \cdot Perc_{use}\right) C_{fuel,tonne} \tag{5.22}$$

The amount of trips is dictated by the amount of foundations that a ship can take and how many are installed each year. The amount that fit on board is given by the mission module. The amount of installed foundations $N_{Fo,yr}(yr)$ each year is calculated using equation 5.24, where n_{fo} is the amount of foundations that can fit on deck and t_{pfo} is the amount of time per foundation in hours. The amount of time each part of the mission (sailing, in harbour and installation) will take is calculated using equation 5.23. The times in hours for each part are given in Table B.1 in the appendix and are based on internal research. The amount of trips the vessel makes each year is calculated using equation 5.25. To validate the result, the amount of days installation per monopile has been compared against the values discussed in the case study chapter.

$$t_{tot} = t_{sail} + t_{harbour} + t_{inst} = \frac{2dts}{V_s} + (t_{Fo,load} \cdot N_{Fo} + t_{Vessel,dock}) + N_{Fo} \cdot t_{Fo,inst} \tag{5.23}$$

$$N_{Fo,yr} = \frac{Oper_{days}}{t_{pfo,days}} \quad \rightarrow \quad t_{pfo,days} = \frac{1}{24}\left(\left(\frac{t_{tot}}{N_{Fo}}\right)\frac{1}{\eta_{work}}\right) \tag{5.24}$$

$$trips_{yr} = ceil\left(\frac{N_{Fo,yr}}{N_{Fo}}\right) \tag{5.25}$$

The newbuilding cost for the ship is estimated using Equation 5.26 which uses a cost table that has been estimated from experience. There are five parameters dictating cost: steel weight, propulsion power, ship length, crane capacity and amount of crew. The first two are calculated in their respective modules, while ship length and crane capacity are input values. The amount of crew is more difficult, as only a part of the crew needs to be on board for the vessels operation and the remaining accommodation is often filled by other stakeholders that need to be on location for the installation process. Looking at comparable vessels, the amount of accommodation capacity differs substantially from 100 till 400, which does not provide information on crew size. This value was initially fixed for all configurations but can be changed by the user.

$$\begin{aligned} NewbuildCost = {} & C_{class}(Lwl) + C_{steel}(W_{steel}) + C_{propulsion}(P_B, P_{DP}) + C_{gen}(P_B) + C_{electric-system}(P_B, P_{DP}) \\ & + C_{accomodation}(Crew) + C_{systems}(CC) + C_{Crane}(CC) \end{aligned} \tag{5.26}$$

The cost and income module is effectively the creation of a measure of merit. Besides determining a negative reward in the shape of cost, two income models need to be created, representing different contract types. One based on charter rate, where ships are rewarded that can do more contracts and another based on installation, where ships are rewarded by the amount and size of monopiles they install. The charter revenue is calculated by determining the percentage that a vessel can sail contracts (no extra reward for monopile size) times the operational days in a year as shown in 5.27. The installation revenue is found by multiplying the monopile size and the amount of these that is placed by the vessel. The income and cost are calculated for each amount of monopiles that might be transported and installed as calculated by the mission module.

This results in multiple vectors with cost and revenue values for different scenarios (state). As mentioned by Aalbers, these values are then used to determine the expected cashflow for each scenario as part of the uncertainty modelling explained below. Instead of just profit, it was chosen to use the return on investment, as it presents a more realistic picture.

$$R_{charter} = Perc_{contr} * Oper_{days} * R_{charter} \tag{5.27}$$
$$R_{install} = N_{MW,yr} * R_{MW} \tag{5.28}$$

The assumptions in the model are included in an assumption database which can be found in the appendix. Users can use this file to adjust the initials assumptions or read notes on each. The costs are validated by looking at internal data available for the two reference values. Verification of the module is done by looking at the development of the time charter value versus crane capacity and vessel size (displacement) in Figure 5.13.

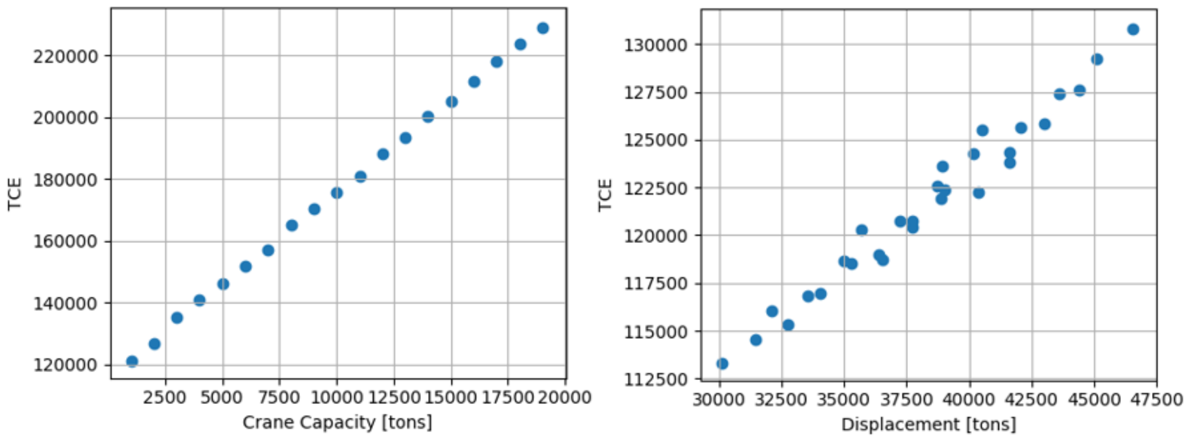

Figure 5.13: Time charter equivalent value for varying crane size and displacement

5.2.6. Feasibility criteria

As not all vessel configurations might be feasible, as also done by Strom [51], a few feasibility criteria are used to limit the amount of calculations. As mentioned by Papanikolaou [100], the use of Holtrop and Mennen is limited to the range of values in Equation 5.29. After discussing with UDSBV, the $\frac{L}{B}$ ratio limit is lowered from 3.9 to 3, as they guaranteed that Holtrop and Mennen still holds and the new ratio enables interesting new designs for research. The power estimation, using B-series polynomials is also limited to certain values as shown in Equation 5.30.

$$Fr \leq 0.45 \quad 0.55 < C_P \leq 0.85 \quad 3.9 < \frac{L}{B} \leq 9.5 \tag{5.29}$$
$$0.3 < \frac{A_E}{A_O} \leq 1.05 \quad 0.5 < \frac{P}{D} \leq 1.4 \tag{5.30}$$

When the vessel cannot take any monopiles, the configuration is also skipped. It is found that the model is effectively constrained by these feasibility criteria. The global behaviour of the model within the constraints is researched in chapter 6.

5.3. Uncertainty modelling

The point where both the market and ship configurations come together is the mission module. The amount of piles on deck can be determined for different "cut-off diameters". These cut-off points can be linked to the cumulative probability density matrix from the market simulation. By reading the corresponding cumulative probability and calculating the difference between two cut-off points, the probability that a contract during such a period will result in a certain amount of piles on deck is found. This process is visualised in Figure 5.14, where the amount of foundations on deck will decrease over time. For each time step, the occurrence of contracts can be calculated for example, in 2030 about 85% of contracts will result in 3 piles on deck, while this is only 40% in 2040 and 5% of the time no piles will be transported. For each vessel, the amount of piles that might be transported for certain diameters differs. Using this characteristic with the cost and income module, vectors for cost, revenue and profit can be created for a range of piles on deck $[N_{Fo_1}...N_{Fo_n}]$.

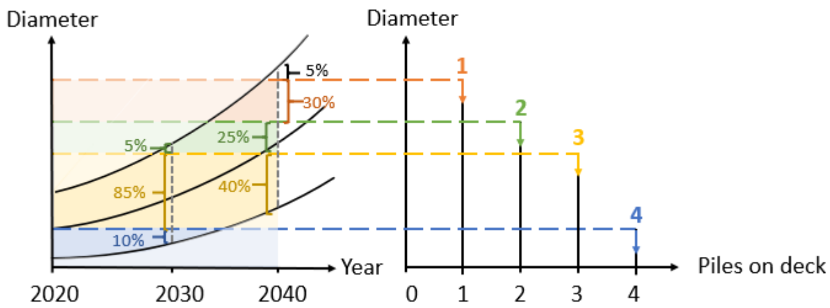

Figure 5.14: Visualisation of market and ship model coupling, values are simplified

The uncertainty modelling now needs to calculate the performance of each vessel in the market. Based on the initial scenarios, two main aspects need to be modelled; the yearly and the total market performance. As learned from literature, it is important to define a measure of merit that can be used to quantify performance, this will be discussed next.

5.3.1. Measure of merit

Many different ways exist of measuring financial performance of a product. In general these methods are based on fixed assumptions, using the expected return and cost to provide an expected income. As this Thesis deals with uncertainty however, expected value is used in another way. Expected value uses the probability that each income will occur and it calculates the mean value that the investment will bring. This can be done for multiple investments and the total expected value will present the best choice. As shown by Sheskin [114], Markov chains and decision processes are very useful to calculate these kinds of finances for managerial decisions. As vessels are regularly expressed in monetary value, discount rates also need to be included. This rate describes both the depreciation and the possible interest rate gained by other investments. Because of this, a discounted Markov Chain with Rewards (MCR) with a finite horizon from Sheskin is selected for use. The expected value at the start of a configuration's lifecycle $V(0)$ is calculated using Equation 5.31 below. The expected value for each year can also be calculated separately. The salvage value V_T is the remaining value of a configuration at year T. The probability matrices $[P_1...P_T]$ are created using probability matrix T_{config} from the mission module, which represents the probability of how many contracts that allow a vessel to transport a certain amount of piles occurs each year. The reward vector q can be chosen to be anything like cost, revenue or profit. The expected value for each vessel is given as a vector for each amount of piles on deck can then be multiplied by the probability of occurrence in the very first year to get one performance value.

$$V(0) = q + \alpha P_1 \cdot q + \alpha^2 P_1 P_2 \cdot q + ... + \alpha^T P_1 \cdot ... \cdot P_T \cdot V_T \tag{5.31}$$

$$T_{config} = \begin{bmatrix} p_{d_1,y_1} & ... & p_{d_n,y_1} \\ ... & ... & ... \\ p_{d_1,y_n} & ... & p_{d_n,y_n} \end{bmatrix} \rightarrow P_1 = \begin{bmatrix} p_{d_1,y_1} & ... & p_{d_n,y_1} \\ ... & ... & ... \\ p_{d_1,y_1} & ... & p_{d_n,y_1} \end{bmatrix}, P_T = \begin{bmatrix} p_{d_1,y_n} & ... & p_{d_n,y_n} \\ ... & ... & ... \\ p_{d_1,y_n} & ... & p_{d_n,y_n} \end{bmatrix} \tag{5.32}$$

Besides financial performance, several other values are also calculated that might be of more interest. One of which is the percentage of contracts that a vessel is able to complete. Another is the amount of foundations that a vessel is able to complete over its lifetime, by multiplying the pile vector with each probability matrix. The expected cost of the vessel can then be used to calculate the cost per pile and also presents the needed charter cost. The behaviour of the uncertainty model is verified using Figure 5.15 by looking at the expected value of the vessel, which has been calculated for different crane sizes for a charter contract for the HX118 vessel not including scrap value. On the left, the cash flow each year is shown, as expected, larger cranes can earn money a lot longer than others due to size, but have lower profit due to higher cost. On the right, the expected profit is calculated, showing a decrease the older the vessel gets, eventually converging to zero. The expected value presents the best vessel to choose at different moments, the 6000 ton crane barely outperforming the 7000 ton crane in 2020. When looking at return on investment however, the 6000 ton crane would definitely be better. The expected value at the starting year of an economic life-cycle (2020 in Figure 5.15) is used in the rest of the report to measure vessel performance. Because profit does not include the investment cost however, the expected return on investment is used instead. This value is calculated by dividing the expected profit by the newbuild cost.

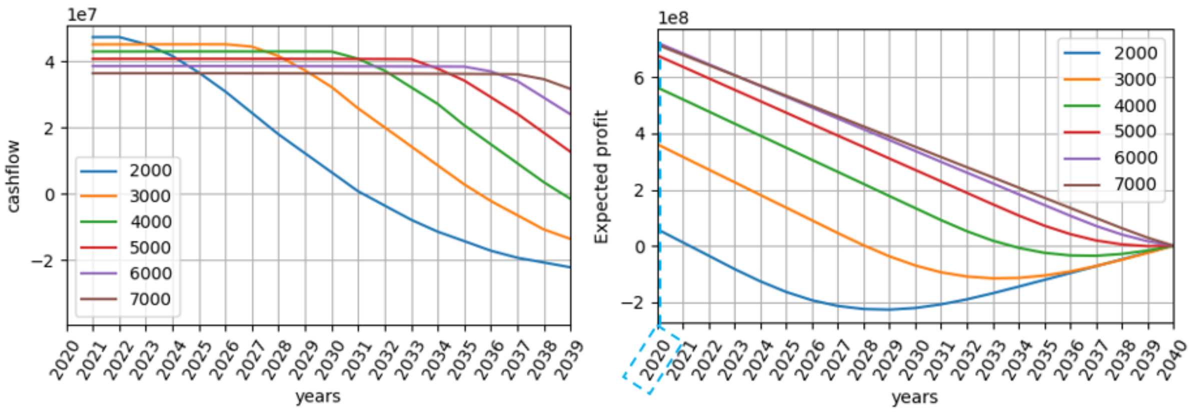

Figure 5.15: Profit and cash flow development for the HX118 with different crane sizes

6

Global verification and Case study findings

In this chapter, the model is discussed in its entirety. The modules have been coupled and are used to investigate the case study. The global verification and validation is discussed first before showing the findings. The verification is done by looking at the global behaviour of the model by changing only single parameters [115]. The model is validated by checking the external relevance by using a few example problems, thus completing Pedersen's validation square [97]. As a result of the validation and verification study, several parts of the the model were improved. More in depth research was also performed to gain confidence in assumptions regarding stability, resistance and scaling.

The method consists of two steps, using modelling during requirement definition, globally researching vessel design performance in the uncertain market, and concept design, co-evolving ship and market in parallel. In this Thesis, global research is performed for the case study to show that the model can be used to increase knowledge at the start of the process. The findings are used to create an initial design for UDSBV. The next step is for the designers to use the model within the design process together with a customer to co-evolve ship and market levels toward a conceptual vessel design.

6.1. Global verification and external relevance

In this section the global verification and validation are discussed. The external relevance of the model is validated by looking at the behaviour of the HX118 reference vessel in two different markets. The global behaviour is verified by researching the effect of changing main parameters on the design's performance. As a result of these tests, several changes were made in the model to improve model behaviour. Some of the more relevant changes are addressed in their respective paragraph. Aspects that have been explored more extensively to improve model confidence as a result of verification are discussed at the end of this section.

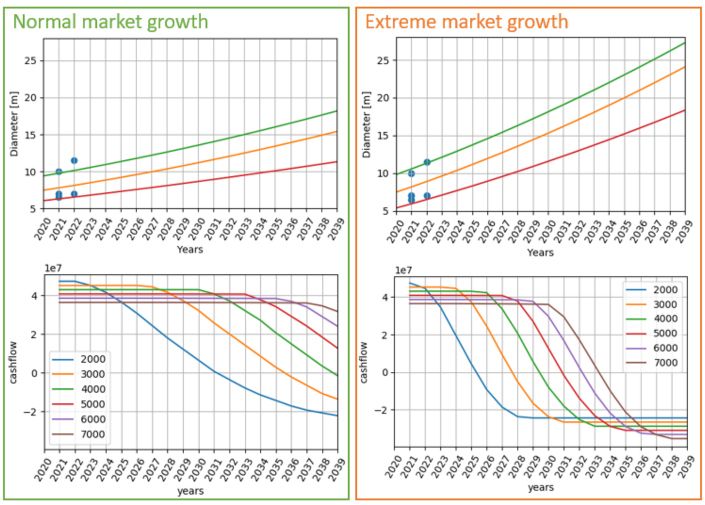

Figure 6.1: Cashflow in probable market (left) and cashflow in market with large increase in monopile size and low uncertainty (right)

6.1.1. External relevance

To see if the market indeed has the desired effect on the model performance, two exemplary problems are tested. For the first test, a market is created that increases very fast, starting out with 10 years of large but achievable sizes and then increasing very fast as shown in Figure 6.1. The cash-flow diagram is made again for different crane sizes using this market to show that the larger cranes become too small rather quickly. Seeing both side by side, the effect of the market is evident, from the moment the sizes start to increase rapidly, all vessels lose cash-flow as expected.

Historical market

The second test is a check to see if the model is able to evaluate the performance of vessels in an existing market. This is done by simulating the market of the last 20 years and determining the performance of MV Fairplayer. The information for this test comes from work by Harenberg from 2016 [112], who describes a performance improvement of MV Fairplayer based on operability, and Stavenuiter from 2009 [116], who describes the offshore wind market. The general expectation is that smaller vessels, that have been dominating the market, indeed perform well in the replicated market. Even though MV Fairplayer wasn't used to install offshore wind foundations, the goal is to check if the model indeed shows that the work from Harenberg, looking at stability improvement, would indeed have enabled MV Fairplayer to perform well within the market.

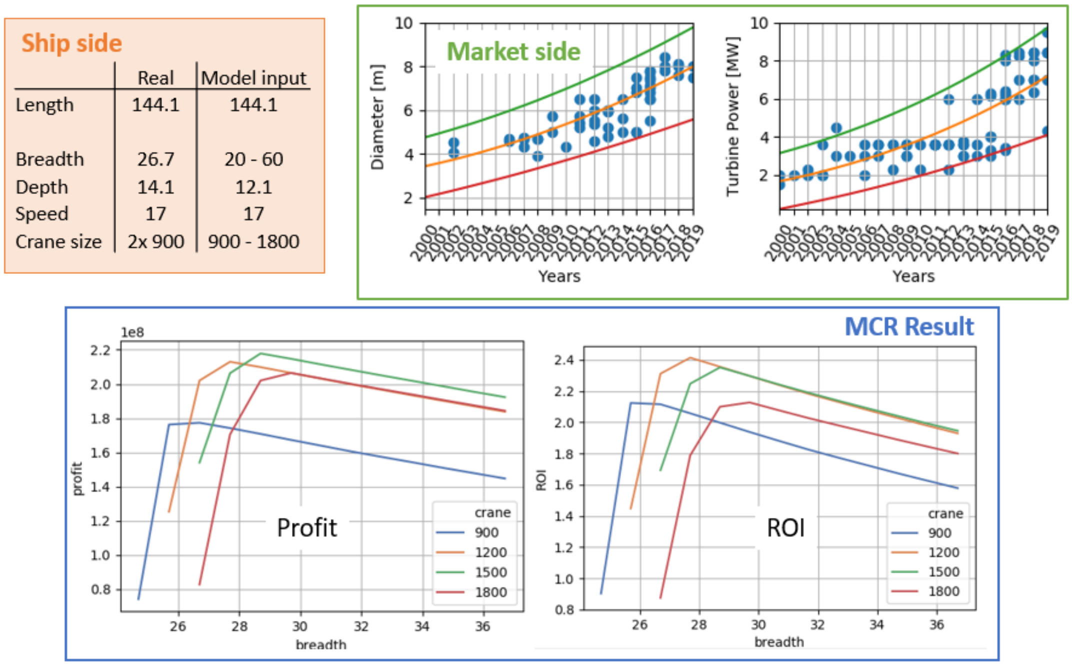

Figure 6.2: Past market performance

Using the method, MV Fairplayer is simulated in the ship model for different crane sizes and breadth range. The depth is slightly decreased because design draught is over-estimated by the model. The market simulation has been fit to market data (blue dots) in such a way that both diameter and turbine power are approximated as well as possible. As expected, the results show that the lower the vessel size, the higher the profit. Which can be accounted to a decrease in cost for smaller vessels. The breadth simulated from 20 to 60 meters has been constrained by the feasibility constraints to 24 to 36 meters for a vessel of 144.1 meters in length. There does seem to be a minimum breadth for different crane sizes, which occurs due to the stability constraint. As the Fairplayer has not one but two 900ton cranes, the model has difficulty exactly approximating its capability. What can be established from the results however, is that the breadth for a 900 ton crane is feasible. While larger total crane capacity will result in more profit and return on investment (ROI). The two cranes are cheaper and smaller than any larger single crane, thus the model predicts the vessel to indeed perform well within the market. Besides this, the stability improvement research by Harenberg would have extended the profit and ROI curve to the left, thus increasing overall return on investment. The method is therefore assumed to give realistic estimations.

6.1.2. Global verification

The model was verified globally by changing single values and researching if the behaviour of the coupled model could be. Many variables and assumptions were varied which resulted in small improvements. In this section one of the more influential improvements found from the global verification is discussed. When checking the behaviour of the HX118 design to changing distance to shore for multiple speeds, it was found that there was a clear cut off that occurred due to a large increase in installation power, as seen in Figure 6.3.

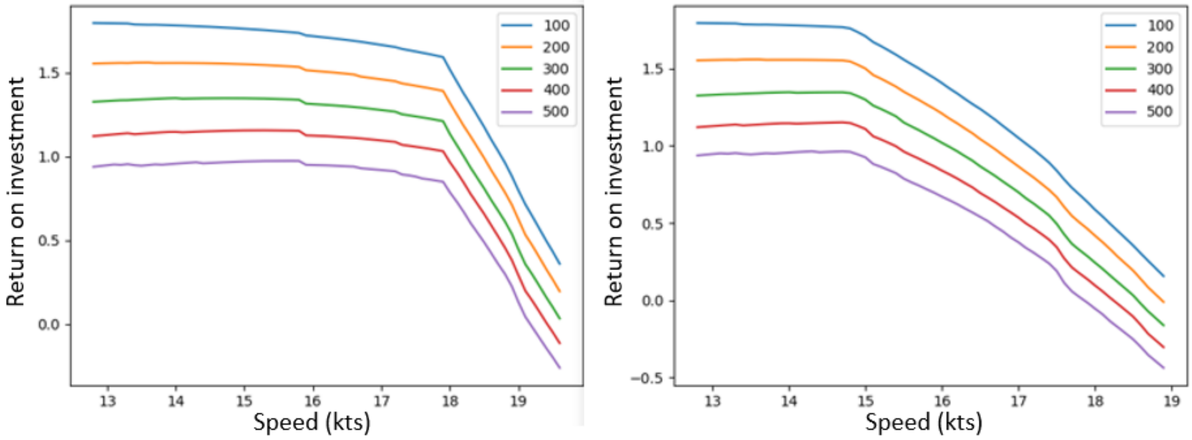

Figure 6.3: Cut-off due to DP2 assumption in left figure, improved assumption on the right

For each step, the propulsion power was found to increase substantially while the installed power remained equal, as it was only based on DP. The rule followed was: installed power needs to be at least as large as the largest power balance on board. In general the installed power is therefore mostly twice the DP power (due to DP2 requirement), together with crane power and accommodation power. It was assumed that whenever propulsion power (P_B) went over this threshold, the propulsion power became the dominant factor in the power balance. Because of this however, the installed power remains mostly constant while P_B becomes very big. Thus meaning that the propulsion thrusters increase until being equal to the full installed power. This is unrealistic, as the propulsion thrusters are not the only thrusters on board. Therefore a new assumption is made that increases the power balance by checking whether the total sources, where all sources used at once, are equal or larger then the DP2 case. If this is the case (because of significant P_B increase), this total power is increased using the total power balance.

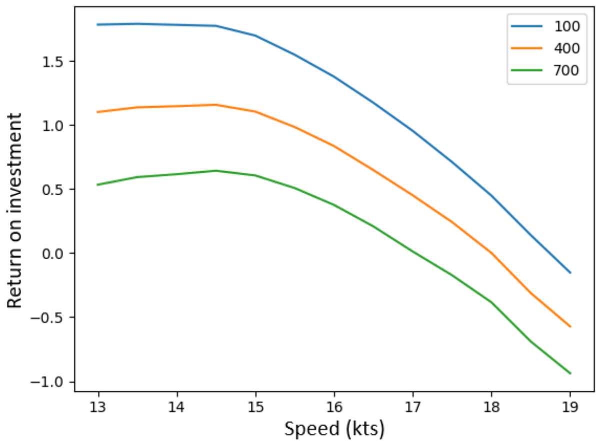

Figure 6.4: Showing the use of the new assumption for installation contract. Distance to shore in kilometre in legend, speed step size is smaller than Figure 6.3.

6.1.3. Model confidence improvement

During the validation and verification study, small parts of the model were tweaked to improve behaviour. Besides changing assumptions and values however, some aspects have been researched in more depth to validate theoretical structure [97]. Research into the theory of three modules are discussed below; resistance and propulsion, mission and scaling.

Power and Propulsion module

Resistance and propulsion are important attributes within ship design as they influence aspects like power speed and transit time. Because the model uses Holtrop and Mennen to approximate these values, it was validated against reality using tank test data. However, as tank test data was not available for all reference values, the research used hydrostatic reports to calibrate the ship model. Differences were found in resistance and propulsion results from the tank test and hydrostatic equivalent. One reason was that the Marin tank test used other displacement and wetted surface values than the Ulstein hydrostatics reports. As seen in Figure 5.9, when using the Marin values, the resistance estimation came close to the Marin test resistance. When using the hydrostatics report values instead, the calculated resistance is slightly lower than the test values. The propulsion power however, is found to be consistently higher for lower resistance values. This is shown in Figure 6.5, where the estimated resistance is lower for equal speeds, but propulsion for those resistance values is higher. Implementation of residual resistance or increased efficiency to calibrate the curves was decided against. Residual resistance based on velocity would for example be a polynomial, which would become negative for velocity lower than 10 knots. Furthermore, the shaft efficiency had to be much larger than 100%. As the power does seem to scale well proportional to both draft and velocity, it is assumed that the original suffices as first indication. However, as maritime engineers commonly choose a fixed thruster size (azimuth thrusters are generally provided with a design power), the propulsion power will be rounded toward that number. Besides that, the under-prediction of resistance might result in the financial performance of the vessel being overly positive. The sensitivity of the model to a lower power estimate can be checked by looking at the financial performance of a equal vessel outfitted with two different engines. Doing this, lifetime cost was found to scale linearly with power (3.5mln per 1000kW), so the results won't be affected as long as the difference in resistance remains constant.

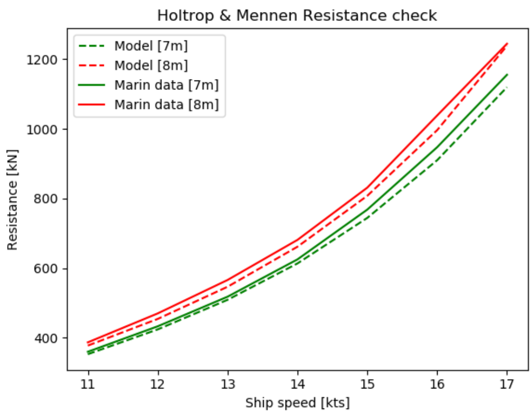

Figure 6.5: Resistance estimation using hydrostatics report versus tank test values (left) and propulsion power difference (right)

Mission module

One of the most important aspects for heavy lifting cargo vessels (HLCV), is the lift capability. From experience ir. J.D.Stroo mentioned three criteria that commonly limit cargo and lifting capability of such vessels; loss of hookload, deck edge submergence and weather criteria. These criteria were also cross-referenced from literature [112] and regulation. As the model creates multiple designs with different combinations of parameters, the behaviour of stability when changing single design parameters was investigated. In literature no references were found that discuss the behaviour of stability for geometrically scaled vessel designs however. To perform the research, a model was created that calculates KN-curves out of main dimensions for a simplified box shape vessel shown in Figure 6.6. This model was verified using Delfship, as is shown in the appendix. To validate the model, the reference vessels were simulated and their KN-curves were compared.

It was found that the area until the deck submergence angle is approximated well. But the remaining area under the GZ-curve is found to be flawed and became worse for larger draught (area until $1rad$ is important for hookload and rollback). The curves could be calibrated by summing the GZ area over ship length and using simplified shapes to approximate bow and stern. As the tests became too extensive however, the research was abandoned. The criteria were instead accounted for by using environmental loads in the DP calculation, adding a workability percentage and using the Jumbo GM-criterion, which takes increased hookload into account.

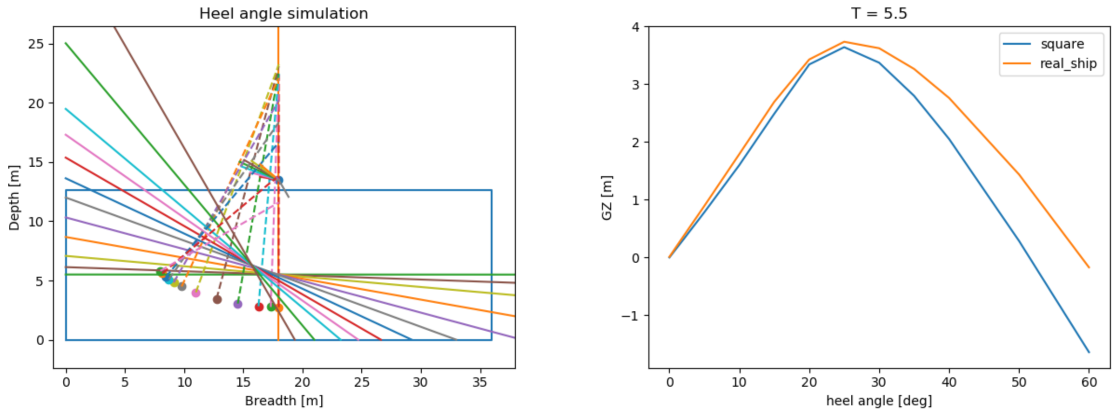

Figure 6.6: Stability for scaled vessels research

Besides stability, the remaining criteria in the mission module are length, deck area, deadweight and crane capacity. Some tests where performed to investigate if the criteria constrained the amount of piles properly. Checking weight in the stability criterion, it was found that the moment equation forced the ballast weight to be negative when $KM - GM$ becomes too large, because the equation solves for this value. However as the final number of piles also takes a weight criterion into account, it was found this did not affect the results.

Scaling module

The block coefficient and draught directly influence aspects like cargo capacity, stability and resistance. Normally these values are determined later in the design process when load targets and hull shape are designed. However, because this Thesis tries to model multiple scaled vessel designs in the early design stage, the values need to be approximated. In ship design, reference vessels are commonly used to estimate initial values. Therefore, the calibration of the Katsoulis equation was checked against other heavy lifting vessels and was found to correctly estimate C_B for most. Some vessel designs were overestimated, but these were found to have different capabilities than the HX-vessels. It was also researched if the design draught estimation could be improved, but as the model deals with changing cargo loads it was difficult to determine design draught this way. It is found the percentage of maximum draught does not directly approximate real vessels but the error is small enough for an initial assumption.

6.2. Case study findings

With the model verified and validated to an acceptable level, it is used to perform a global research for the case study. The goal of the global research is to gain more knowledge of the market and the performance of different design configurations within. Before the research, the model was validated with UDSBV. The knowledge is then used to create an initial design that fits the market. The case study is performed for offshore wind foundation installation, which is a rapidly evolving, uncertain market. The recent paradigm shift from jack-up toward heavy lifting vessels and the necessary investment in larger construction vessels as named by the IEA [2] shows the need for highly efficient heavy lifting cargo vessels. As the fleet is still small however, determining optimum vessel size and crane capacity is still uncharted territory. The initial design resulting from the case study can function as a starting point for concept design at UDSBV. Thus showing that the method can indeed provide interesting insights and can be used to deal with market uncertainty in the early ship design process. The market characteristics that were found during market research are used for the market simulation and the creation of vessel designs. The demand characteristics that are researched are the effects of; increasing distance to shore, foundation size increase, difference in contract types and a paradigm shift toward monopiles without transition piece are simulated. Multiple different vessel configurations are created by varying supply characteristics like; main dimensions (Length, Breadth, Depth), crane size, vessel speed and cargo capacity.

A large amount of vessel configurations is created for the study (about 30.000 configurations on average), the initial selection of input parameters is shown in Table 6.1. From this large amount of data, the effect of a single design parameter and combinations of parameters both need to be analysed. To do this, different ways of visualization were researched to improve readability of the results. Figure 6.7 serves as an example where only the depth and crane size are changed and the return on investment for each configuration is plot on the y-axis. As the amount of points is still small, coloured lines can be used to show the actual effect of changing crane size for different depths in the left and right bottom figures. For a large amount of points, the data becomes unreadable in a point cloud or a coloured line graph. A box-plot can sometimes provide a good overview of the data, but to improve readability, median, mean and maximum visualisations are used. A designer might for example only be interested in the best performing parameter (maximum) or only wants to see the general performance of a certain design parameter. The way the median and maximum lines are set-up is explained by looking at the original data; these lines follow either the maximum points or the box-plot median. As shown in the two plots in Figure 6.7, maximum shading follows the two (or less if not available) nearest points below and median shading includes the two below and two above. Whenever the shaded area is very large, the difference with the closest values is very high and might be erroneous. For larger ranges and more parameters, the maximum and median line descriptions enable the creation of coloured maximum and median lines, comparable to the left and right bottom figures in Figure 6.7.

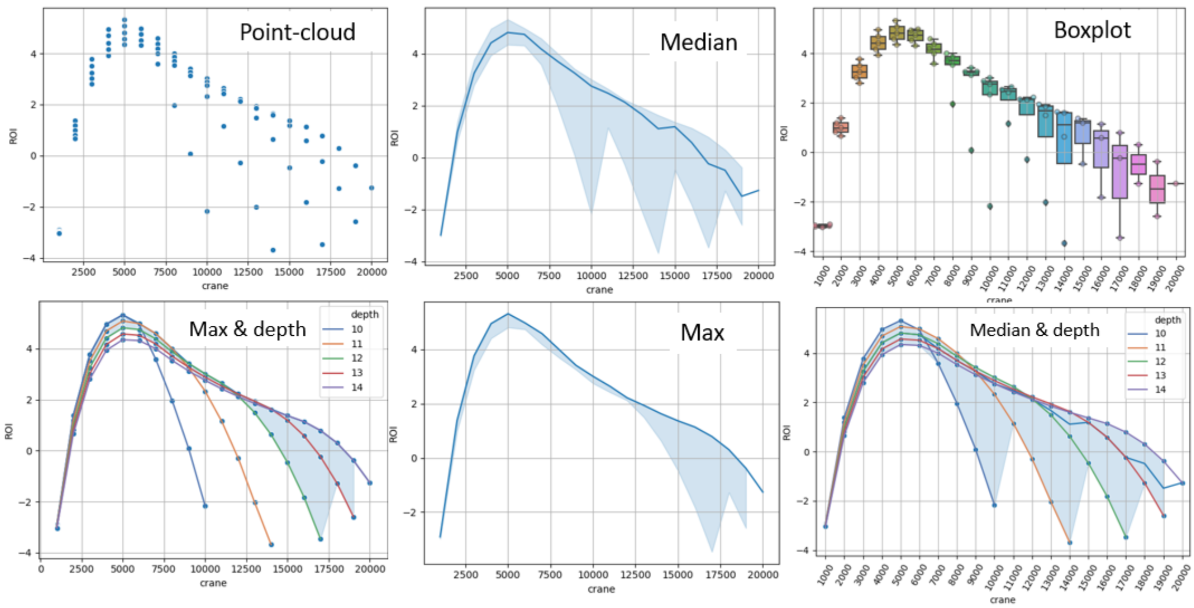

Figure 6.7: Set-up of visualisations

Table 6.1: Case study vessel input

	Lower	Upper	Stepsize
Length [m]	140	270	10
Breadth [m]	36	57	3
Depth [m]	10	19	1
Crane Capacity [tons]	3000	9000	1000
Speed [kts]	11	15	1

6.2.1. Effect of different market projections

To start the global research, three different future markets are researched, each is based on real current market data and is constructed together with Ir. J.D.Stroo from UDSBV. The first market in Figure 6.8 assumes that turbine and diameter size growth is not limited. The second market in Figure 6.9 assumes that there will be a tipping point in the market. The last market in Figure 6.10 assumes that there is no growth after the windfarms that are currently planned. Other values approximated using the market simulation like weight and length are included in the appendix. The second market was deemed as the most likely market by UDSBV as they mentioned that several speakers at the WindEurope Offshore 2019 conference explained turbines would only grow towards a maximum economic size. Regarding the outliers with 19MW of turbine power above the curve, these were found to be unrealistic assumptions from the 4COffshore database [36], as Siemens Gamesa have only recently presented a maximum turbine size of 14 to 15MW that will be commercially available around 2024 [117].

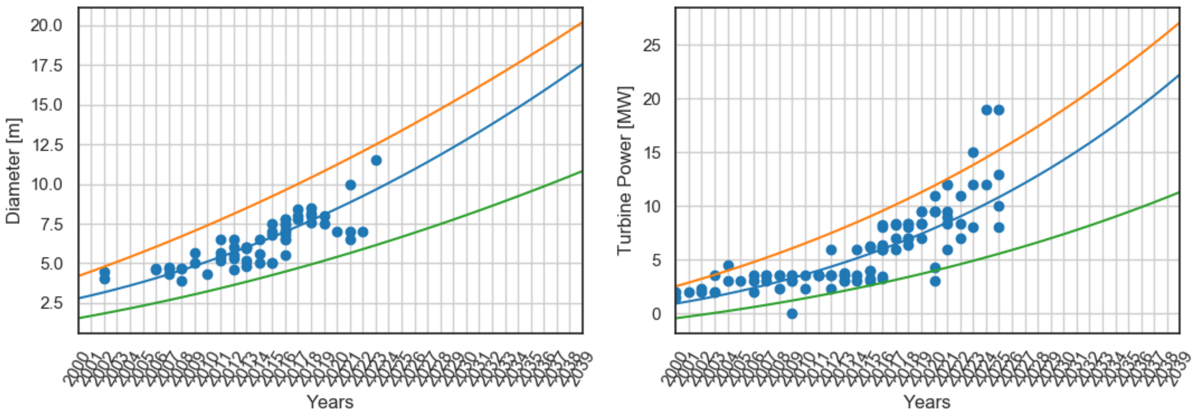

Figure 6.8: Visualisation of non-bound future market

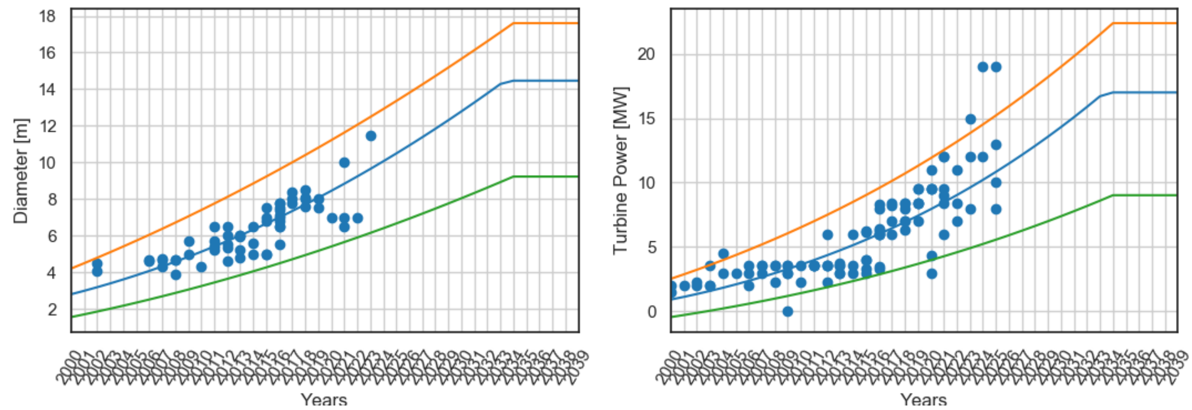

Figure 6.9: Visualisation of future market bound at the mean turbine size of 17MW

The different market projections are run using an installation contract, which rewards the amount and size of piles placed. In Figure 6.11, the results for the three markets are plot together for different parameters. The point where the maximum return on investment occurs is shown using a yellow circle. Vessel speed is not included in the figure as it did not show interesting results (most optimal speed around 13kts for each market), and it will be discussed in more detail later. It is also important to note that the return of investment and profit shown in all results are merely measures of merit. Even though more return seems to be expected in a bound market, the difference in return with an unbound market cannot be taken for granted. There are many

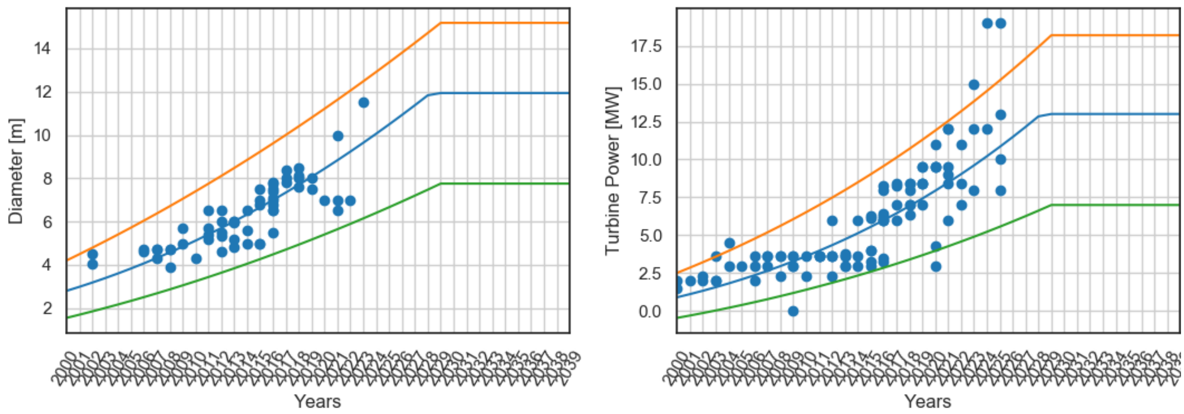

Figure 6.10: Visualisation of future market bound at the mean turbine size of 13MW

factors, like success rate of the shipping company, which will effect the eventual size of return. The measure of merit does however show which vessel is more likely to be rewarded within each market.

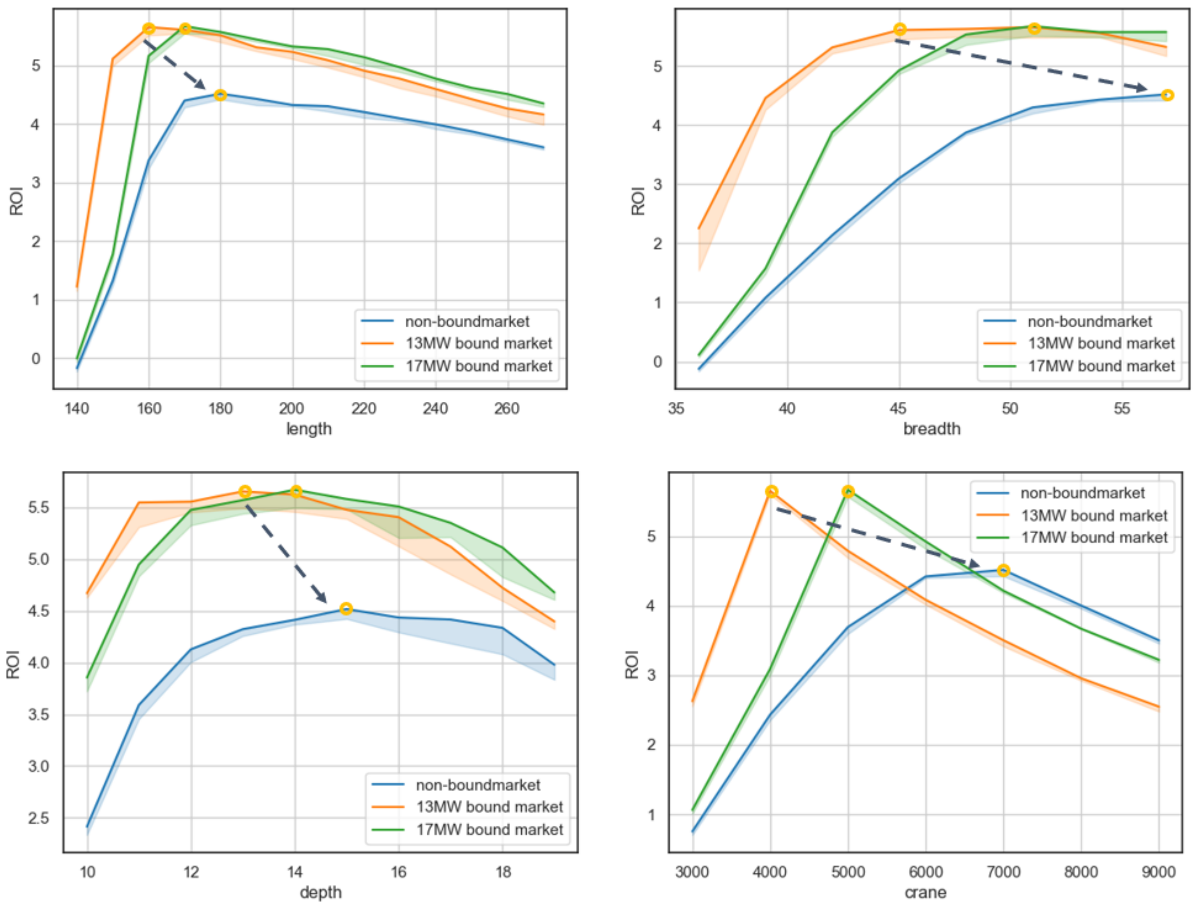

Figure 6.11: Results of three different future market projections

For each dimension, the bound markets show that smaller values are preferred. Which makes sense, because the bounded monopile size remains relatively small, so increased vessel capability is less important, while the lower vessel cost results in a larger return. The bound markets effectively show an optimized vessel for the foundation size, especially looking at the sharp peaks in the length and crane plots. These occur because the vessels that are most optimal for the constrained sizes get a higher reward and shift upwards, while configurations in front of the optimum point do not increase. Regarding the unbound market, as the market does not converge toward one size, the curves are broader. This means that certain ranges of main dimensions seems to be rewarded. It is important to note that, since the lines consist of multiple different configurations, a combination of a 40m breadth and 7000 ton crane might not necessarily be possible. This can be researched by looking in the output files, or can be plot by using coloured lines for crane capacity versus other parameters like in Figure 6.12. As the selection of crane capacity is an important factor in the offshore market, the return on investment for different crane sizes and size parameters is shown. What becomes clear is that different crane sizes perform better for different vessel sizes, larger cranes needing larger vessels. The breadth seems to be affected most, which can be explained because breadth influences stability greatly. The vessel length increases only slightly with foundation length and the curve seems equal for larger crane sizes. This is probably the point where foundation length is constrained by water-depth. In general the smallest size vessel that has the right capability for the market is most optimal, but from this point onward the curves are rather flat. Especially the breadth curve is rather flat after the point where stability is large enough. Optimal vessel depth also increases for larger foundations sizes, as depth mainly determines the available cargo weight. The stability decreases for larger depth and the optimal point is located between these weight and cargo criteria. Vessels with larger depth also need to be larger in size, as the feasibility criteria filter out vessels with insufficient stability.

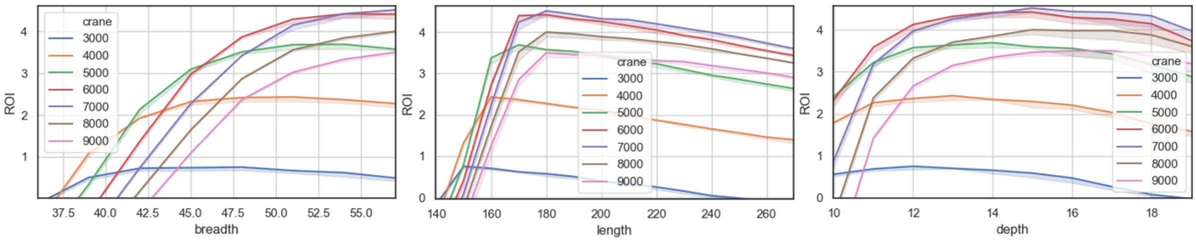

Figure 6.12: Effect of different crane sizes on different optimal design parameters for the non-bound market

6.2.2. Effect of contract type

Using the non-bound market, the effect of different contracts rewarding either vessel capability (charter) or amount installed (installation) is researched. Figure 6.13 shows the revenue (orange), cost (green) and profit (blue) for the maximum and mean for different deck area's. The profit curves do not always correspond to the area between revenue and cost, because the figures show the mean and maximum profit, which might not necessarily be connected to the maximum cost and revenue curves. The visible differences in revenue between charter and installation contracts can be explained by the different reward inputs. The installation reward is input per megawatt and the charter is created using a set daily income. To improve readability, the height of the reward values are chosen in such a way that the revenue lines of both contact types are as close together as possible. To improve readability, the deck area are rounded to thousands.

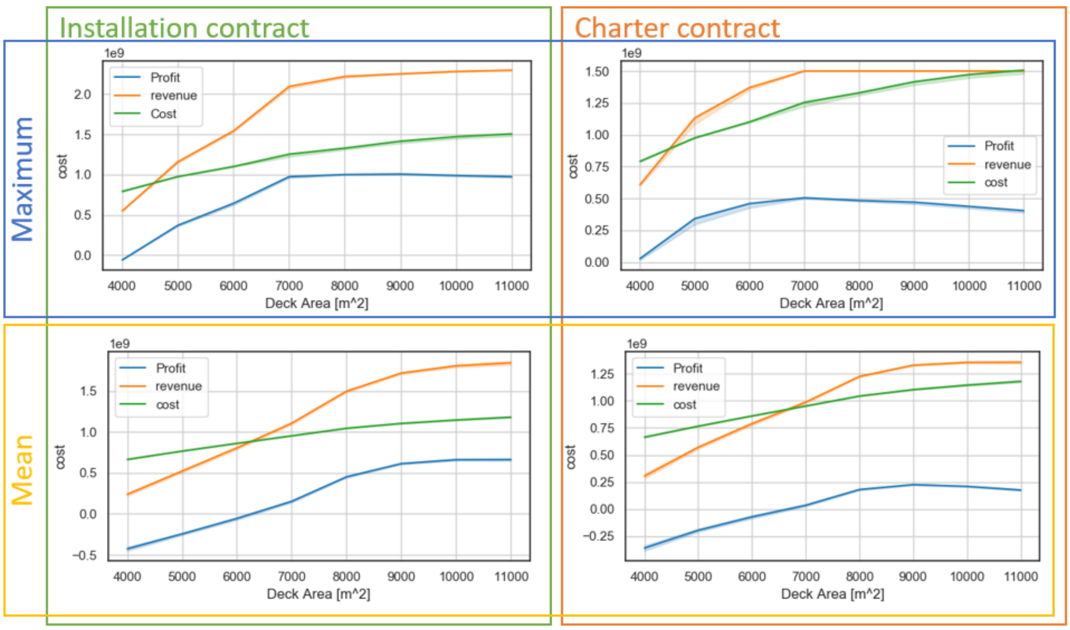

Figure 6.13: Set-up of profit and difference between mean and maximum for different deck area sizes

As the charter revenue is set to be dependent on the possible amount of days operating, the larger vessels will eventually reach a maximum revenue, because the size of crane and main dimensions make it possible to work all contracts in the proposed market. Because the costs keep gradually increasing for larger cargo space however, the profit decreases, thus showing a maximum profit peak around 6000 to 8000 m^2 deck area. The cost development for the installation contract is equal to the charter contract while the revenue curve flattens more gradually. This happens because the installation contract is based on the amount of MW placed by the vessel, which does not seem to increase linearly with vessel size. The installation revenue is monotonic, always increasing, but some other market or design parameter limits its growth. The profit therefore still decreases for larger cargo space, but the maximum profit peak still occurs later than the charter contract and remains constant after 7000 m^2.

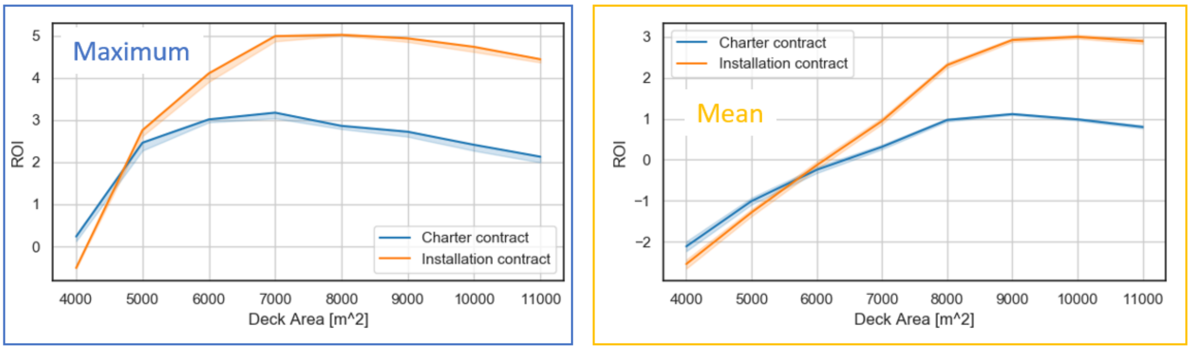

Figure 6.14: Maximum and mean return of investment for deck area

Looking at the return on investment, which includes investment cost, provides a better indication. The deck area does however differ dependent on looking at either the maximum or mean. As mentioned, the choice whether to look at either one, depends on the goal of the designer. Since the general effect (mean) of a contract type on deck area is to shift the curve to the right. While the highest return on investment (maximum) will be around 6000 to 7000 m^2 for the charter and around 7000 to 9000 m^2 for the installation contract. When looking at ROI versus profit, the maximum peak thus shifts to the left, because the cost of larger vessels will decrease the ROI. The mean results shows the general behaviour of the dataset. The amount of feasible smaller vessels versus larger vessels seems to be lower (probably due to chosen parameter range). Most smaller vessels also do not perform well in the market, due to the large foundation sizes, thus lowering the mean and shifting the mean to the right.

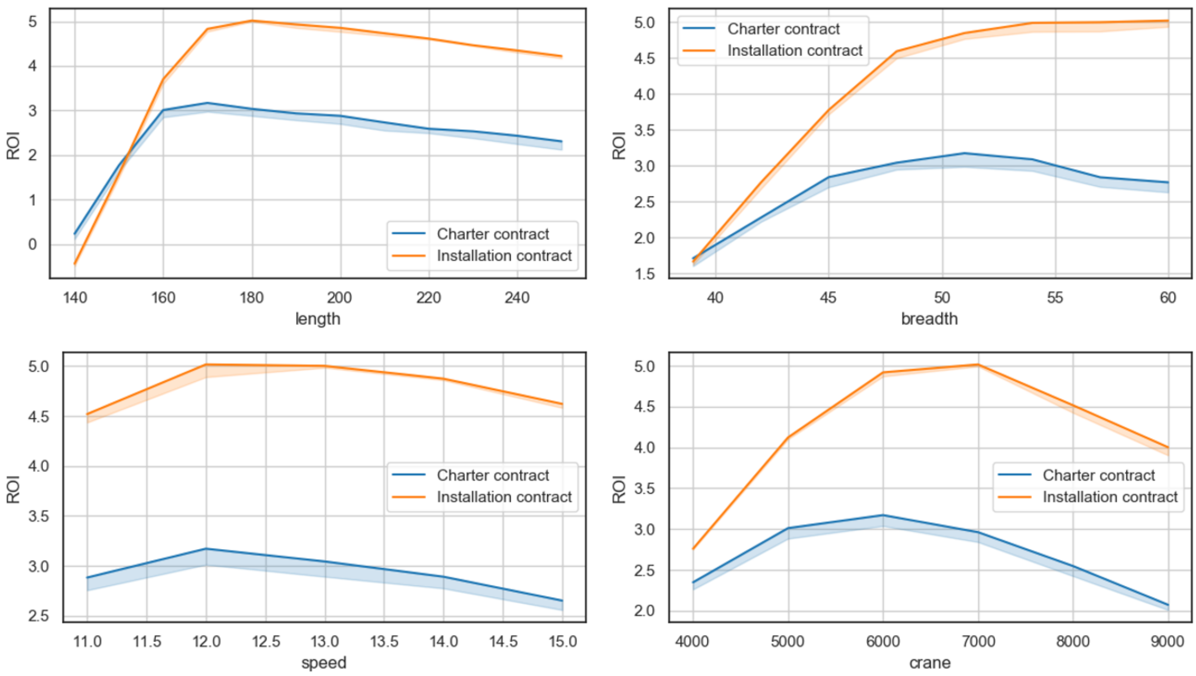

Figure 6.15: Effect of different contract types on design parameters

Looking at the design parameters in Figure 6.15a charter contracts typically reward smaller vessels which cost less, so the income is increased. While installation type contracts reward based on decreasing placement cost by improving placement efficiency. This is evident in the speed and crane capacity figures, where a charter contract is more optimal for lower cost solutions. The optimal speed is fairly broad for the installation contract however, while a peak is clearly visible at $12kts$ for the charter contract. The crane capacity figure shows how 6000 and 7000 ton cranes perform well with an installation contract, while the peak is broader and shifted to the left toward 5000 to 7000 ton cranes for the charter contract. Besides a single input for income, it is also interesting to look at the minimum charter cost and minimum cost per MW. The installation cost provides an interesting perspective, as it calculates the cost per MW, an installation company could use it to estimate which vessel design can be used to decrease the levelized cost of energy (LCOE) fastest. An example of minimum charter and installation cost for different configuration types is shown in Figure 6.16, the figures are equal independent of income input. The figures show that to decrease cost per MW (pilecost), larger deck area (curve flattens) and smaller $\frac{L}{B}$ ratio with the right crane sizes are needed. While for charter cost, there seems to be an optimum deck area and $\frac{L}{B}$ ratio should be as low as possible.

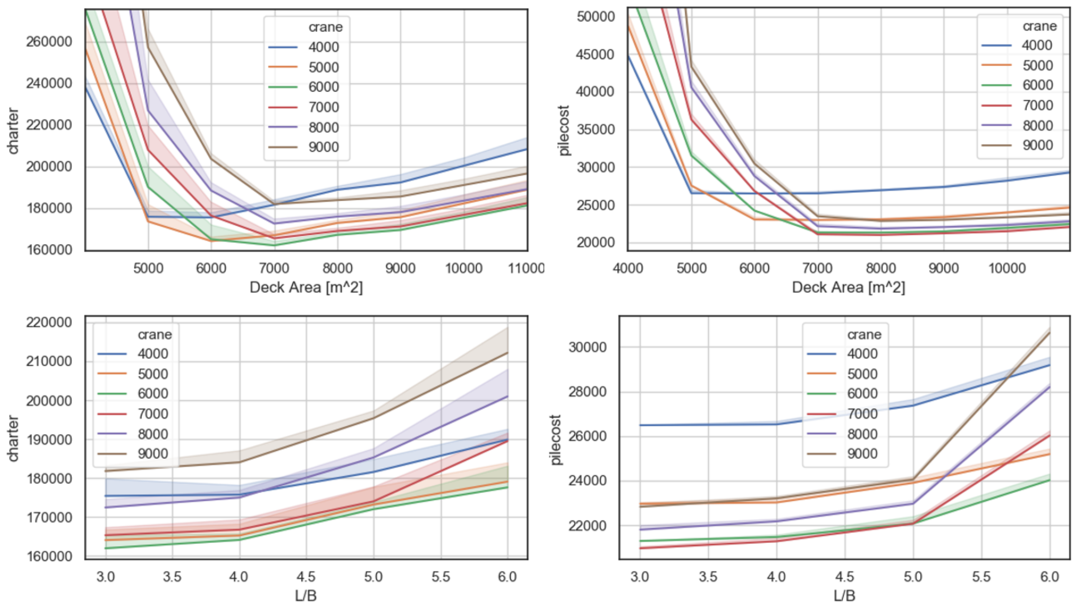

Figure 6.16: Minimum costs for charter and installation contracts

6.2.3. Effect of increased distance to shore

In Figure 6.17, the average distance from shore to installation site is increased to see whether the distance favours different configurations. An installation contract is used for income, as it rewards increased placement. Starting with the effect of increasing distance to shore on speed on the bottom right. The model assumes that the vessel will only have to sail within Europe and these distances are already rather short. The 60km represents the average distance to shore for the last two years as calculated from 4COffshore [36]. The return on investment is based on a relatively high reward of 40.000 euro's per MW placed. This value would reflect an increase in cost for a contract that is further away but for closer contracts the reward asked per MW is much lower. As is expected, an increase in distance does decrease the overall return on investment, because fuel use increases and the income decreases due to longer transit times. The ship speed curve shows optimal speed peaks for increased distance to shore as increasing ship speed decreases transit time progressively for larger distances. The curve remains relatively flat however, because the transit time decrease is still small when compared to installation and loading times and can be expensive to increase. As the curve is rather flat over the three optimal values, the impact of increased vessel speed on return on investment is assumed to be small.

Depth on the top right of Figure 6.17 seems to be greatly affected by increasing distance. The larger the distance to shore, the better a larger depth becomes, while the curve also seems to flatten for these values. This could be explained by an increase in cargo capacity as deadweight increases because of larger depth. The figure thus shows that an increase in distance results in a reward for vessels with larger cargo capacity, this is

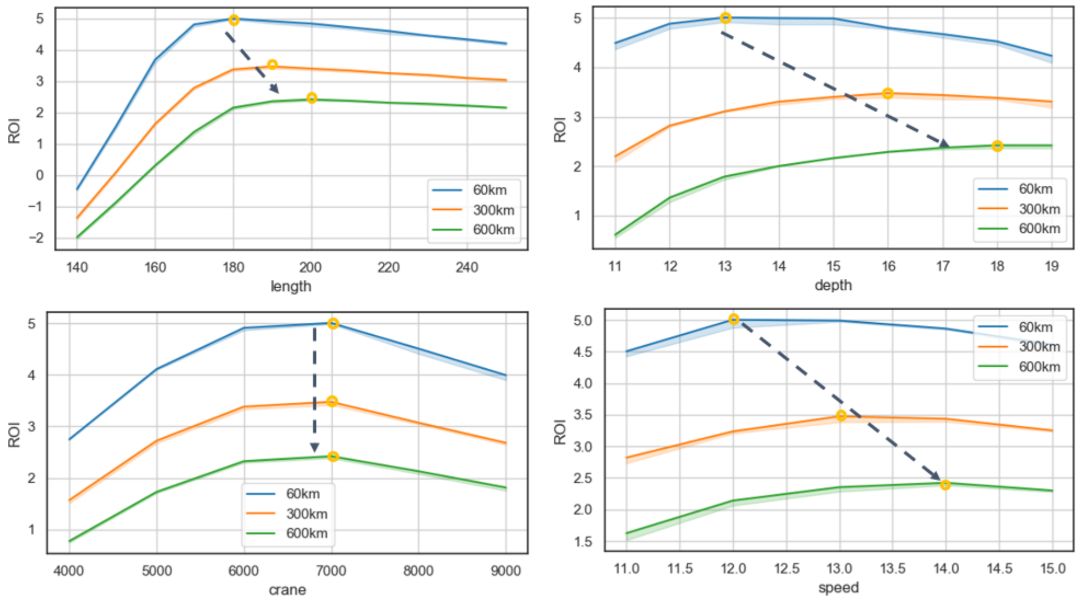

Figure 6.17: Maximum return on investment for increasing distance to shore

also shown in Figure C.4 in the appendix, showing the effect of increased distance from shore on deck area. Besides a decreased ROI, the crane capacity curve does not show changes. The increase in length is a little more difficult to explain, but it probably also has something to do with increasing the cargo capacity without affecting stability, while minimally increasing the resistance (as frictional resistance and wave resistance increase only slightly for increased depth). The curve does also seem to flatten for larger distances from shore, but this could be an effect of the overall return decreasing.

6.2.4. Paradigm shift

Changes in the market are not limited to just a growth in size, technical developments might change the state of the art in the coming years. One such development, that UDSBV wanted to research, is the monopile without transition piece. This development is seen in several planned wind-farms in the 4COffshore database [36]. The transition piece is normally a cylindrical part of about 20 meters in length, that includes a landing platform and ladder. The turbine tower is then secured on top. The new design extends the foundation with about 20 meters and places a smaller landing platform with ladder on top [118]. The increase in length results in an increase in foundation weight, a decrease in transition piece weight and a necessary increase in crane tip height. Again using the non-bound market provides the results shown in Figure 6.18. Results for the 17MW-bound markets show equal behaviour and are found in the appendix C.5.

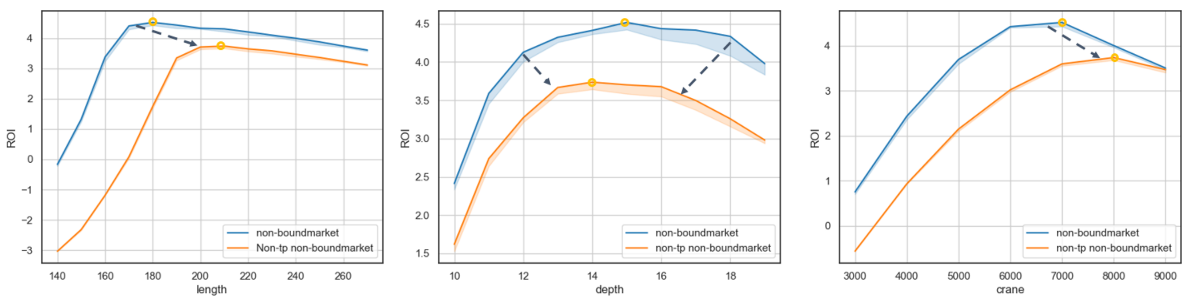

Figure 6.18: Effect of development of monopiles without transition piece

As expected, the optimal vessel and crane size increase for the increased foundation length and weight. The vessel depth peak also becomes narrower, because the vessel needs more installation stability (right side) and cargo weight (left side). From an installation perspective, for larger foundations, the TP-less monopile seems like a bad idea. As the monopile size increase directly affects stability and carrying capability, thus decreasing the overall return on investment. As there are some projects that use the technology however, it could be taken into account during concept design.

6.3. Result discussion

The results from the global research can now be used to decide what initial design would be able to perform well within the future market. The results are discussed to decide how the findings might be used. In Table 6.2, the most optimal vessel design range per category is summarised. The findings and application of each category is discussed in more detail below.

Three different markets

Starting with the three different markets, the 13MW bound seems to underestimate sizes that have already been announced [117] and is neglected. The 17MW bound and non-bound markets are used to estimate a design range as the 17MW bound market is more realistic according to UDSBV and the non-bound shows what would happen if this tipping point does not occur. As the breadth peak is outside of the range, a new simulation was run with larger values which is shown in Figure 6.19.

- Optimal length only slightly increases for larger foundation size as it primarily seems to scale with foundation length, increased vessel length also only slightly decreases return on investment.
- As long as a vessel is guaranteed to have adequate cargo weight and installation stability (to support the chosen crane size), the choice of depth and breadth is less crucial as these curves are generally broad.
- In case of a tipping point market, its better to have an optimal or larger than optimal crane capacity.
- The optimal vessel speed is not affected by

Contract type

Looking at contract type, the most optimal 'charter contract vessels' are the lowest cost vessels that still have the capability to perform most contracts. On the other hand, 'Installation contract vessels' are only slightly larger and are optimized for installation efficiency. It is assumed that the initial vessel design has to perform both roles, but this could be changed after consulting with a customer.

- Charter contracts favour smaller vessels to decrease cost, but the optimum parameters for installation contracts do overlap. This makes it possible to create a vessel that would perform well for both contract types.
- The optimum vessels (maximum) are generally smaller, while larger vessels perform better on average (mean). This means that smaller vessels are more prone to stability and weight issues when confronted with larger markets.
- For both contract types, to decrease cost, the $\frac{L}{B}$ ratio should be as low as possible. Besides this, a deck area of around $7000m^2$ seems to be most optimal. Such a deck area is equivalent to a HX-vessel of $180m$ in length and $51m$ in width.
- Installation costs per MW could be used to decrease the LCOE of wind turbines.

Distance to shore increase

The increase in distance to shore is found to influence vessel performance. Initially the vessel is assumed to only have to transit from shore to the installation site, which has been around 60km on average in the last two years according to the 4COffshore database [36]. In reality, the vessels will have to transit from a feeder port toward the installation site, thus significantly increasing average sailing distance and affecting the vessel size. Studying 4COffshore's online map, showing all wind-farm locations, most are located within 300km from a port. It is therefore decided to take 300km as average distance in a new simulation combined with the breadth increase shown in Figure 6.19.

- Crane capacity is not affected by increased distance from shore.
- For increased distance to shore, from deck area, breadth and depth curves, higher cargo capacity becomes more important.
- Optimum speed does increase for larger average distances, but as the curve is relatively flat the impact on return is small. Higher fuel use however has a large impact on return, so vessel owners should consider increasing price for larger distances if this is not already done.
- As the length curve is rather flat, length selection is less crucial after a certain point.

Paradigm shift

Monopiles without transition piece do not seem to be profitable from an installation perspective. This could results in the development not occurring, as the wind-farm owners will have to pay for the installation cost increase. The choice could however be made to start out with a smaller length vessel with enough breadth for stability, and refit the ship by increasing length when the paradigm shift does occur.

- Optimal length and crane increase proportional to the development increasing foundation length and weight.
- The depth and breadth range narrows due to necessary increase in stability and cargo weight.
- The development might be a bad idea in terms of placement cost, because the financial effect on installation vessels seems to be large. This might result in the development not happening.

New simulation

From the discussion it is found that a new simulation with a larger breadth range needs to be performed to gain a better indication of the optimal vessel size for 300km average distance to shore. The simulation is shown in Figure 6.19. The top two figures show the return on investment for breadth and depth and different crane sizes. The bottom two figures show the optimum breadth for the charter and installation contracts. When comparing the results from Figure 6.17, the optimum shifts right a little but does not change much. the optimum breadth occurs slightly outside of the old range, but the curves is still flat enough to pick any value within a certain range.

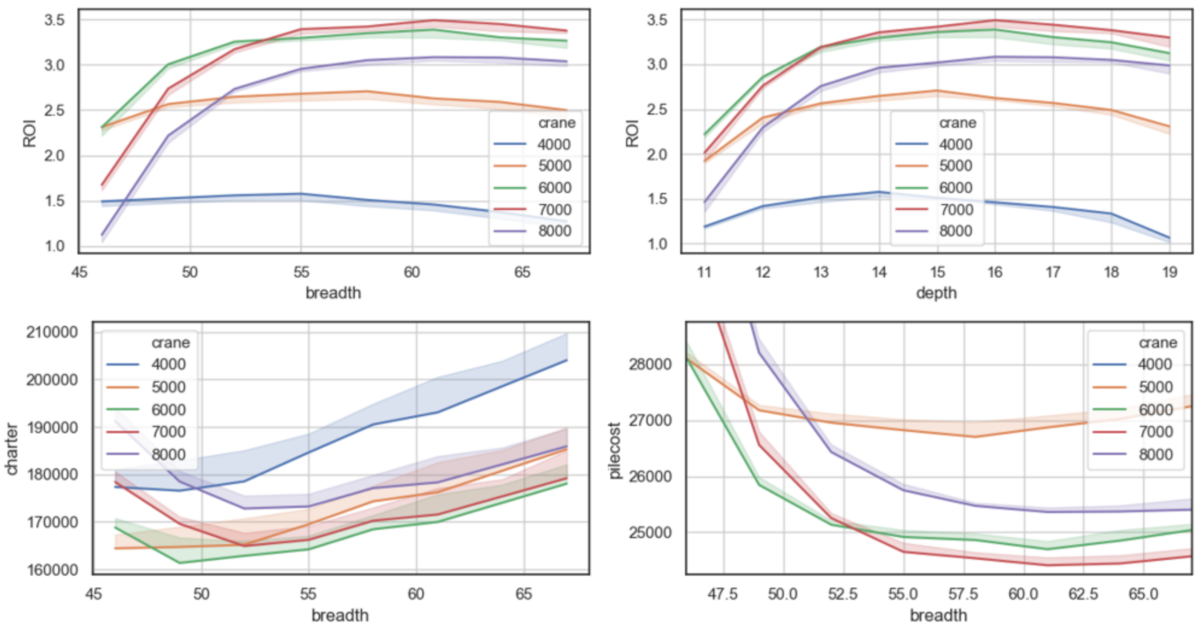

Figure 6.19: Results for an increased breadth range and average transit distance of 300km

Initial design

Using the findings and the optimum vessel range from the table the initial vessel design is determined and shown in Table 6.2. The vessel is selected to perform well for the aspects below.

- The average transit distance is around 300km
- The 17MW-bound and non-bound markets together are used to project the future
- The design is able to perform well for both charter and installation contracts.
- The vessel is should be able to participate in a market with monopiles without transition pieces, but the paradigm shift should not dictate choices.
- Breadth should be large enough so the vessel for a refit in length when the monopile without transition piece paradigm does become dominant.

The initial design from has been visualised by UDSBV in Figure 6.20. The next step of the method is to use the model as part of the design process.

Table 6.2: Optimal design ranges and initial design proposal

Category	Length	Breadth	Depth	Crane Capacity	Speed
Expected markets overall	170-190	51-57	14-15	5000-6000	13
13MW-bound	150-190	51-57	10-15	4000	13
17MW-bound	160-200	51-61	12-16	5000	13
non-bound	170-200	55-65	14-15	6000-7000	13
Contract type	170-190	51-55	13-15	6000-7000	12-13
Shore distance	180-190	51-60	14-17	6000-7000	13-14
TP-less piles	190-210	54-60	13-16	7000-8000	12-13
New simulation	180-200	55-65	14-18	7000-8000	12-13
Initial design parameters	**190**	**55**	**14**	**6000**	**13**

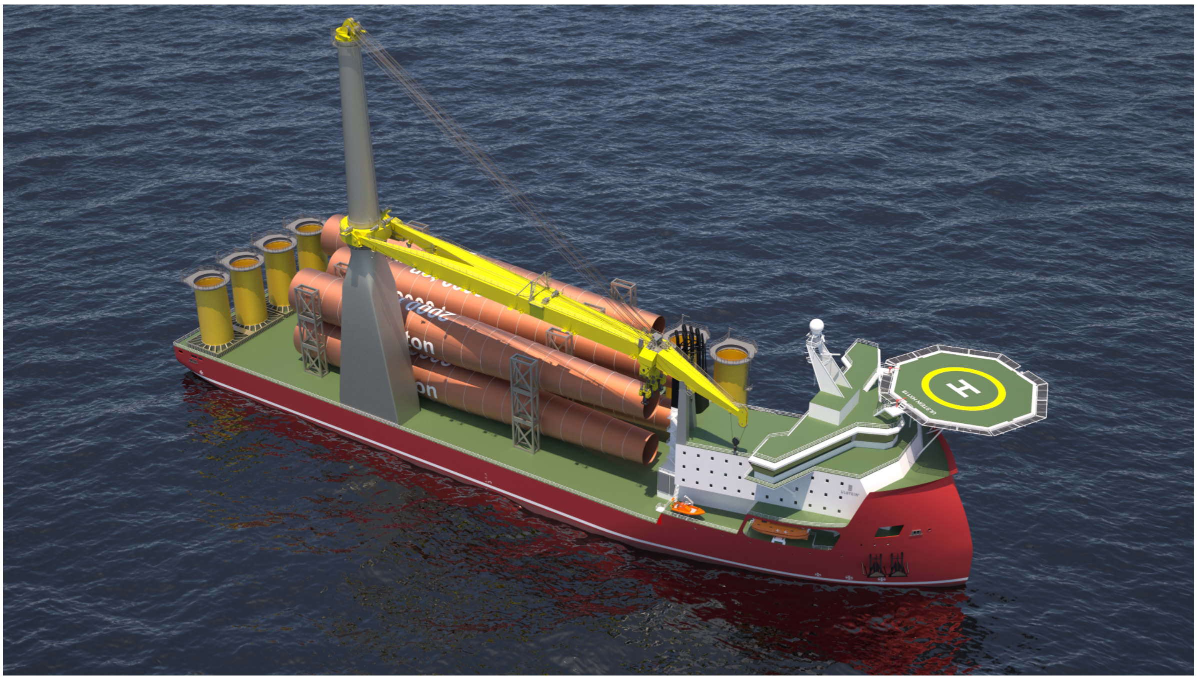

Figure 6.20: Initial design visualisation

7 Discussion and Conclusion

7.1. Discussion

The objective of this Thesis is to model the effects of changing business case requirements due to market uncertainty during the early ship design phase, in such a way that the designer can explore the design space at the start and during the design process. This first chapter discusses the findings and their significance by going through the research questions. The implications of the research and the limitations are then discussed. The main research question was formulated as follows:
How to model the effects of changing business case requirements due to future uncertainty during early ship design, in such a way that the designer can explore the design space?

To answer this research question, five subquestions were defined. Each of these five is explored separately in the paragraphs below.
1. What is the relation between complex design and uncertainty modelling literature and current practice and how can the thesis benefit UDSBV and advance research?
Both complex design and uncertainty modelling literature try to deal with the uncertainty found in the design process. Uncertainty modelling and complex design methodologies are generally differentiated by their approach. Uncertainty modelling tries to model the uncertainty itself, while complex design looks at how the design process can be set up to deal with uncertainty. From literature, four ways of dealing with uncertainty are found: ignore, delay, accept and reduce and control. Current practice is however found to mainly ignore uncertainty. This makes it difficult to deal with the uncertainty found in changing markets like the offshore wind foundation installation market in the design process. Therefore this thesis proposes to couple both the complex design and uncertainty modelling research fields and create a way that can help ship design firms like UDSBV to deal with the market uncertainty found in the offshore wind market and advance research.

2. How can the future market be forecasted while dealing with market uncertainty accordingly?
During the early design phase, a lot is still unknown about the vessel and its purpose. The Thesis describes ship design using concept to knowledge (CK)-theory, going from a conceptual space, where a lot is still undecided, towards a knowledge space, where decisions have been made. Going from concept to knowledge can happen at 4 different hierarchical levels; the market, ship, systems and component levels. As described by literature, the design process is improved by exploring two of these levels in parallel [9]. By researching ship and market levels, and including an existing method that is shown to properly deal with uncertainty, the effect of each level can be researched accordingly. The market level can be researched by forecasting the market using data analysis, using the 4COffshore wind-farm database as input. A stochastic extrapolation with a lower and upper bound is created to simulate market uncertainty.

3. How to model the case study using uncertainty modelling and how to implement this in the design process?
The parallel exploration should take place before and during the early design phase. Besides forecasting the market, the performance of different vessel configurations needs to be tested. The effect of an uncertain market on the ship design and the other way around can then be modelled using uncertainty modelling. To couple the levels, two existing uncertainty modelling methods were chosen that provide the right capability

for use in parallel exploration. The first being Epoch Era analysis, which reduces uncertainty by researching the effect of designs in different scenarios. The second is Markov Decision Processes, which accepts uncertainty and evaluates design decisions. Parts from other complex design and uncertainty modelling methods are also used however. This information together with two models that simulate the market and ship configurations are used to perform the case study research into offshore wind foundation installation vessels.

4. Which scenarios can be modelled to determine the effect of certain design choices on vessel performance in the market?
Scenarios consist of multiple market characteristics that are found by performing research into the offshore wind foundation installation market. On the vessel side, aspects like crane size, cargo capacity, vessel speed and main dimensions are selected, while on the market side the increasing distance from shore, foundation size, contract type and technical development looking into monopiles without transition piece are chosen. Initial research into the case study is performed by simulating changes in the four market characteristics and checking the performance of different vessel configurations in these markets.

5. Using the method, what is the effect of market changes on the selected design parameters and how sensitive is each to the market.
Using the method, research into the case study is performed and the results show that the method can be used during requirement definition and concept design. It is found that the more uncertain a market, the wider the range of possible design parameters. The different probable markets provide insight into which size and capability would be necessary for different expected markets. In general the smallest vessel still capable of competing in the market will have the highest return on investment. This capability is determined by the foundation size, since markets with higher estimated foundation size are shown to reward increasingly larger vessel sizes. The research into the effect of increased distance from shore demonstrated that larger average transit distance affects vessel design parameters. This shows that if wind farms are placed further from shore, vessel size (especially cargo capacity) needs to increase. The different contract types, which target capability and placement efficiency respectively, show how the method can take the effect of company strategy on vessel design into account. Charter contracts reward smaller, low cost vessels with enough capability, while for installation contracts, an optimum vessel size range exists where the amount of MW placed is most cost efficient. With the development of monopiles without transition piece, the installation vessel would need to increase in size and crane capacity. Many more of these developments, like the shift toward jacket or floating type foundations can be researched using the model.

Using this information, an initial vessel design is created for the offshore wind foundation installation market. The research was the basis for an UDSBV standard design that is shown in Figure 6.20. The method can thus be used by a designer to explore the design space more efficiently, decreasing their uncertainty and giving an indication what the effect of a changing market would be on the performance of their design. This answer is in agreement with the main question of the research.

7.1.1. Implications

Regarding the implication of this research for ship design, the method provides a clear improvement when compared to the original way of dealing with market uncertainty in ship design. Current practice effectively ignores changes in the market [1], resulting in some design decisions being made without fully understanding their effect on solving the problem or their effect on vessel costs [32]. To research this effect early in the design process, the new method uses uncertainty modelling, this methodology has been proven to be able to provide valuable insights by several researchers [119] [66]. The method decreases market uncertainty and increases knowledge when design freedom is still high [24]. In this way, the vessel can be designed with the right purpose in mind, in such a way that good performance in the future market is more likely. This was shown to be especially important in offshore wind, where uncertainty comes from the seemingly unpredictable growth of market demand, turbine size and distance from shore [2]. By decreasing this market uncertainty using the proposed method, an initial design was created together with UDSBV that is likely to perform well in the future market. The next step is to use this method during a real design process, iteratively improving assumptions and co-evolving design solutions and market scenarios. This decreases the customer's perception of market uncertainty and increases their confidence in the design solution. In this way, despite uncertainty, the investment by ship owners in the ever-larger construction vessels needed for further offshore wind energy development could be ensured [2].

7.1.2. Limitations

Like all studies, the method created in this thesis also has potential limitations. These limitations are addressed in three categories; methodological limitations, data validity and research limitations.

Methodological limitations

Regarding the methodological limitations, the lack of uncertainty modelling methods that simulate future market scenarios out of data to decrease market uncertainty, illustrates the need for the creation of a new method. As there were many other uncertainty modelling methods found from literature, this new method was created by combining several existing methods. It uses EEA like scenarios to describe the future market and an evaluation method comparable to MDP to define which configurations perform well within this market. Even though this proved to be able to solve the market uncertainty problem, using a single uncertainty modelling method might have have resulted in less extensive research and might provide different potentials. This could be investigated in future research.

Data validity

With regard to validity of the input data, the wind-farm database was found to sometimes include overestimations, these values might be able to affect the market validity. Besides this, 4COffshore was also found to sometimes change the layout of the database, which has resulted in the model not being able to update in several instances. It was therefore found to be important to always check and update values before use and it is deemed preferable to create an own database version. Besides this, as the model extrapolates from the database, the market data used in the model is only a projection. However, by investigating input data, discussing input with experienced individuals and by using an uncertainty range, the impact of errors from the input values is decreased.

To ensure confidence in the model, validation & verification (V&V) was performed. The initial limitation for this was that no V&V methods could be found for models dealing with uncertainty. Instead, two methods from literature were used to V&V separate modules (local) and the coupled model (global); the validation square [97] and verification using a sensitivity study [98]. For local V&V of the ship model, the methods could be followed properly by using test data, references and checking sensitivity of single values. Checking global model behaviour proved more difficult as model assumptions can affect each other. Because a model will always need assumptions to approximate reality, for both local and global V&V, it was found that two or more iterations should be performed to make sure the assumptions are good enough. When a method or model is created for use by others, it is also crucial to always V&V the method together with someone that has experience within the fields modelled. For instance, after the initial validation of the method, UDSBV still found several assumptions that had to be improved before they agreed on the validity of the case study results. Especially models that deal with uncertainty, will always show behaviour that may need extra explanation. Besides the validation square and sensitivity methods, it is thus found to be very important to be able to explain assumptions and behaviour. As this was possible for the case study, the V&V analysis is proven to be acceptable.

Research limitations

As the method has been developed for UDSBV, the research might not be applicable to other design firms and could be subject to biases. The model has also become fairly large and complex and has been written in a programming language that might not be familiar to all of its users. Without UDSBV the research would however not have been possible, due to their design experience and the data and knowledge they had regarding the vessel and the market.

Regarding the extent of the research, besides the four simulations run for the case study, more market categories were meant to be investigated. However, due to time constraints, parts of the research could not be completed. Besides this, as only one case study performed, the method is initially limited to this market. The research that was completed does however prove that the insights gained using the method are valuable. One of the next steps is therefore to also use the method in other market segments.

7.1.3. Recommendations

The last step of the Deweyan approach is to write a warranted assertion, to recommend further research. The method created has been shown to provide insight into the effect of design decisions in an uncertain market. The method has however not been used during the concept design stage yet, being able to test the method in a real design process would provide valuable insights. To make use by UDSBV employees easier, a graphical user interface (GUI) still has to be created. After completion of a GUI, letting UDSBV employees explore model behaviour will also provide valuable input on how to improve the method set-up. Besides making the model ready for use and using it during the process, several other recommendations were identified during the research. Two categories are identified; expansion of current research, recommending future directions for research, and further development of the model, recommending research to improve the modelling.

Expansion of current research

Multiple research directions could be explored using the method, in this section the directions that were identified during the research are discussed in more detail.

<u>Changeability</u>: The method was set-up in such a way that it could be used to investigate both flexible and changeable vessel designs. The current method however only explores flexibility, as it rewards vessel configurations that perform well without refitting. The programming into this direction of changeability has also nearly been finished, but it could not be verified and validated in time. Changeability exploration would allow the designer to investigate whether refitting a vessel, increasing vessel length or crane size, could be a good strategy. This could help the designer gain valuable insights into whether active or passive value robustness is a better strategy. This research direction would also advance literature [49] as the effect of choosing to deal with uncertainty using active or passive value robustness can be investigated.

<u>Market strategy</u>: Other strategic choices like a market switch to capitalize on market opportunity could also be researched. One such market opportunity presents itself in decommissioning of offshore wind foundations. Because the design lifetime of offshore wind farms are typically around 20 to 25 years [78], a vessel will encounter a cyclical wave of decommissioning and re-installation 20 to 25 years after installation. This decommissioning market is graphed beside the installation market with trend-lines in Figure 7.1 and is created using the wind-farm lifetime as given by 4COffshore [36]. A small vessel that is optimal for smaller foundation size installation could corner this market and switch toward cheap decommissioning of these piles right after. This is easily modelled by creating two or more sets of market simulations and using their reward vectors per configuration (either cost, revenue or profit) in combination with the corresponding probability matrices $[P_1...P_T]$. Each market simulation is set to be an action, as is the case for the installation market versus decommissioning market scenario. Here, the MDP evaluates whether it would be smart for a vessel to switch toward the decommissioning market when the ship might not find any contracts in the installation market.

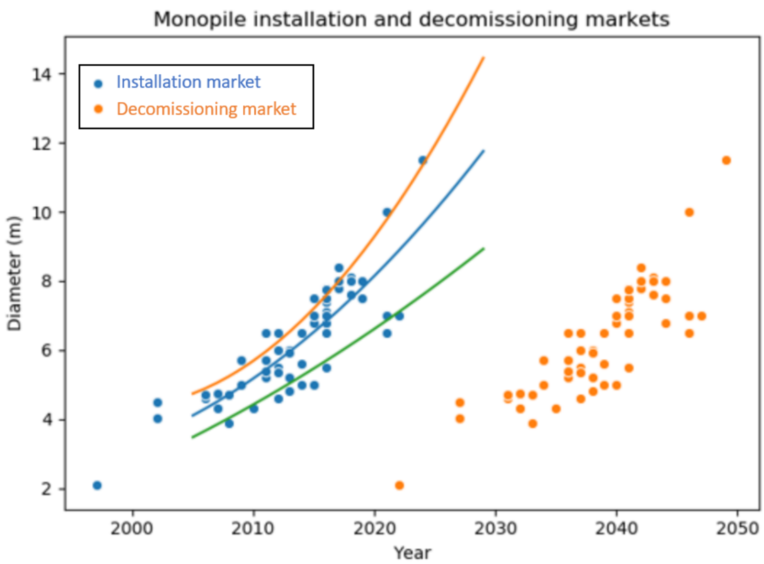

Figure 7.1: Visualisation of decommissioning and installation markets

Offshore wind developments: Beside the monopile without transition piece development, other technical developments within the offshore wind foundation market could also be investigated. One such paradigm shift could be the switch from monopiles toward jackets or floating foundation types. The method can be used to optimize vessel size. This can be modelled by adding a new market trend that projects the growth of other foundation types by researching which vessel configuration performs well for both cases.

Adding competitive market simulation: The effect of competition could be included in the model by including multiple vessels within the market simulation. By researching how the market reacts to saturation and competition, a design could be created that is able to exploit market developments like these.

Other markets: By changing the modules to fit other markets and vessel types, the method could also be used to perform case studies into other markets. UDSBV has already shown interest to use the method for the initial design of other vessel types. During stay in Norway, designers were also interviewed to investigate using the method in segments targeted by UDSAS. Several market like fishing, cruise and offshore support, were identified as possible segment.

Further development of the model
Several research directions were found that could improve the modelling, these would make for interesting side projects.

Multi objective optimization: Because the method researches what the optimal design is from several simulations, multi objective optimization methods could also be included. This would improve decision making between different categories. It was already found that a Pareto front, graphing two objective functions on each axis for multiple designs, could easily be made using the results. By identifying the Pareto front between multiple datasets, the most flexible design can be determined mathematically instead of having the designer decide themselves.

Workability: No literature was found that estimates workability during the early design process, as the hull geometry is not yet fully known. Even at later design stages, workability is still difficult to quantify due to the difficulty of simulating dynamic behaviour during lift. Because of this, the model assumes a fixed workability for all designs. However, when workability can be estimated early in the design process, vessels that can operate under harsher conditions would be rewarded and could be highlighted using the method. As the model uses environmental data to determine DP power, a simplified way of estimating workability could already be implemented by increasing or decreasing the statistical occurrence factor, affecting the environmental load that the DP needs to endure and thus increasing or decreasing installed power.

Estimation improvements: During the research, it was found that a lot is still unknown about estimating design parameters for heavy lift vessels. Therefore, three different directions to improve the estimations in the model are proposed, all of these concern heavy lifting vessels.

- The stability research mentioned in section 6.1.3 could be continued. By researching the effect of changing single parameters on stability, the effect of a design parameter on heavy lift vessel capability might be improved. The dynamic stability could also be included in this research by exploring the effect of changing single vessel design parameters on vessel motion.
- The estimation process of scale coefficients like C_B and draught of heavy lift vessels for modelling purposes could be investigated in more depth.
- Researching weight estimation methods for offshore heavy lifting vessels.

7.2. Conclusion

As part of this Thesis, a method is created that can be used by a designer to deal with market uncertainty during early ship design. It enables the designer to explore the design space by modelling the effect of design decisions on vessel performance in a changing market. The method reduces market uncertainty by increasing knowledge at the start of the process, when design freedom is still high. The method uses modelling during or before the requirement definition stage, by performing global research into the market, and during the concept design stage, by iteratively co-evolving the vessel design and business case in parallel. The model expands on existing research by implementing uncertainty modelling within the ship design process to deal with market uncertainty. The method consists of three parts; simulating an expected market from data, modelling multiple vessel designs, and an uncertainty model that evaluates the performance of the vessels in the market. The model was locally and globally validated and verified by using test data, reference vessels and expert opinion and is found to be able to correctly model the uncertain market and vessel designs. A case study into offshore wind foundation installation vessels showed that the method can provide valuable insight into what vessel characteristics are likely to perform well in different market scenarios. Because the method has been created for broader use, consisting of multiple modules, it can be changed to investigate more scenarios and other market segments. The method thus provides UDSBV with a way to deal with market uncertainty during early ship design.

A

Validation & Verification

A.1. GZ validation

The simulated GZ curve for a shape approximating one of the Ulstein reference vessels has been validated using Delfship and is shown below.

Righting levers

Heeling angle	Draft	Trim	Displacement	KN sin(ø)	VCG sin(ø)	GG' sin(ø)	TCG cos(ø)	GZ	Area
(Degr.)	(m)	(m)	(tonnes)	(m)	(m)	(m)	(m)	(m)	(mrad)
0.0° (CL)	5.500	0.000	37626.9	0.000	0.000	0.000	0.000	0.000	0.000
2.0° (PS)	5.500	0.000	37626.9	0.782	0.470	0.000	0.000	0.311	0.005
5.0° (PS)	5.500	0.000	37626.9	1.958	1.175	0.000	0.000	0.783	0.034
10.0° (PS)	5.500	0.000	37626.9	3.940	2.341	0.000	0.000	1.600	0.138
15.0° (PS)	5.500	0.000	37626.9	5.976	3.489	0.000	0.000	2.488	0.315
20.0° (PS)	5.454	0.000	37626.9	7.951	4.610	0.000	0.000	3.341	0.573
30.0° (PS)	4.980	0.000	37626.9	10.111	6.740	0.000	0.000	3.371	1.183
40.0° (PS)	4.382	0.000	37626.9	10.717	8.665	0.000	0.000	2.052	1.670
50.0° (PS)	3.576	0.000	37626.9	10.614	10.326	0.000	0.000	0.288	1.877
60.0° (PS)	2.341	0.000	37626.9	10.036	11.674	0.000	0.000	-1.638	1.881

phi	GZ
0.01	0.001554
2.00	0.311245
5.00	0.782791
10.00	1.599582
15.00	2.487582
20.00	3.340867
30.00	3.371185
40.00	2.051728
50.00	0.287820
60.00	-1.637747

Figure A.1: Stability validation

A.2. Verification and Validation

Summary of verification and validation mentioned in the report.

- Scaling
  - Validation:
    - Tested that estimation approximates reference vessels (done for CB and displacement)
    - Scaling coefficients are checked using Holtrop and Mennen exemplary problems
  - Verification.
    - Draught should increase for larger depth
    - Wet surface should increase for volume increase
- Weight estimate
  - Validation: Checked that weight estimates approximate real reference vessels
  - Verification:
    - LWT increase for larger engine, larger vessel
    - DWT decrease
    - DWT cargo should be lower than DWT lift
- Resistance:

  - Validation: using tank tests to show that resistance approximates reality
  - Verification:
    - Increased wet surface = increased frictional resistance
    - Increased speed = increased wave resistance

- Power and propulsion
  - Validation: installed power, DP power and propulsion power should approximate real reference values
  - Verification:
    - Increasing DP power or propulsion power = increase in installed power
    - Increase in ship size = increase in both propulsion, DP and installed power
    - Increase in ship speed = only increase in propulsion power

- Mission
  - Validation:
    - check with hydrostatics files if stability values (KMt) approximate reality
    - check if amount of piles on deck approximate UDSBV estimates
  - Verification:
    - Stability decrease for depth increase
    - When stability = 0 no piles able to load
    - Lift stability should be lower than cargo stability
    - Criteria check:
      - Dwt: Ballast weight, dwt cannot be negative
      - Length: decklength should decrease for smaller ship length
      - Max TP: TP should equal amount of monopiles
      - Crane capacity should limit max pile

- Cost and income: measure of merit.
  - Validation:
    - Costs: should approximate UDSBV estimate
  - Verification:
    - Time charter cost should increase for:
      - Higher speed
      - Larger piles placed
      - Larger vessel
      - Larger crane
    - Income should increase
      - Charter: with increased ability (contract percentage) income should increase
      - Per MW: when more piles are placed
      - ROI: ratio income versus investment
    - Cost & income over time:
      - Check effect of smaller vessel in small market (first 10 years)
      - Check effect of larger vessel in larger market (last 10 years)

Total sensitivity: All modules working together

- Market check:
  - One really high market: contract percentage, Income and cost should be zero for vessels (as they don't have any contracts)

- Ship model check:
  - Main parameters; see if effect is logical

B
Ship model

B.1. Monopile installation times

Table B.1: Monopile installation times from UDSBV internal research

Monopile	[h]
Harbour	
Docking	1
Loading provisions	2
Loading foundation	2
Loading TP	2
Docking	1
Variable	
Transit	distance/speed
WoW	operability
On-site	
Positioning	1
Rigging	1
Lift Foundation & Hammer	1
Pilling	5
Survey	1
Remove Hammer	1
Rigging	1
Lift TP	3
Positioning	1

B.2. Cumulative matrix example

Table B.2: Cummulative configuration matrix example

	Diameter [m]						
Year	6	7	8	9	10	11	12
2020	0.00	0.13	0.44	0.77	0.98	1.00	1.00
2021	0.00	0.07	0.34	0.66	0.92	1.00	1.00
2022	0.00	0.03	0.24	0.55	0.84	0.99	1.00
2023	0.00	0.01	0.17	0.44	0.74	0.95	1.00
2024	0.00	0.00	0.10	0.34	0.63	0.88	1.00

C
Results

C.1. Market plots; Weight, length and wall thickness

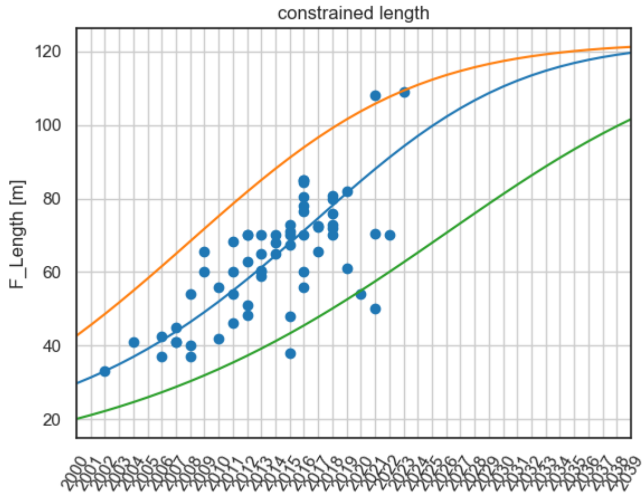

Figure C.1: Constrained length in non-bound market simulation

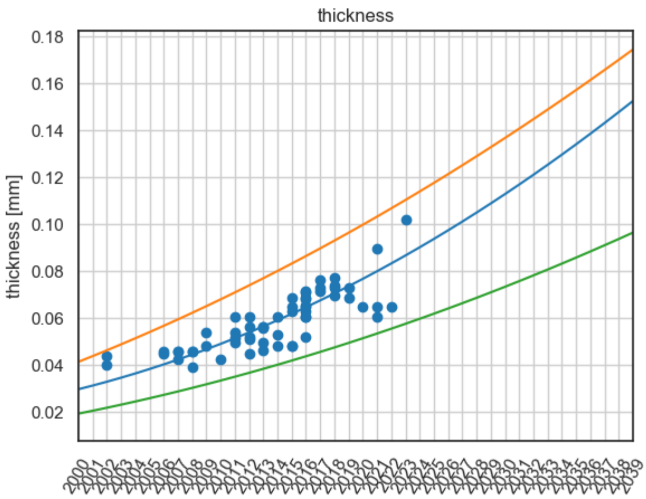

Figure C.2: Foundation wall thickness in non-bound market simulation

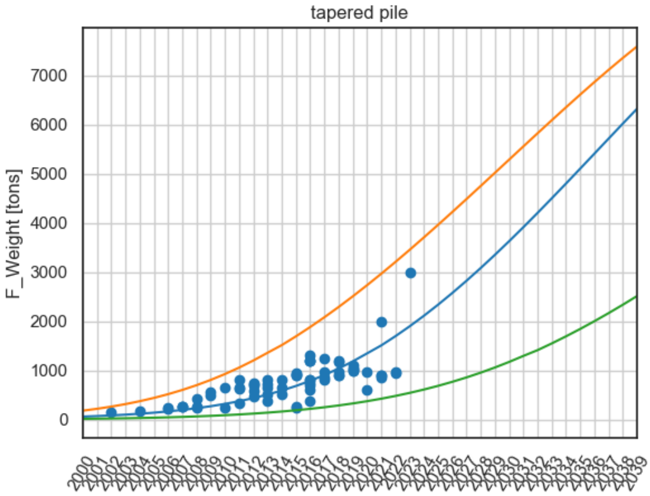

Figure C.3: Tapered weight in non-bound market simulation

C.2. Increased distance to shore, deck area

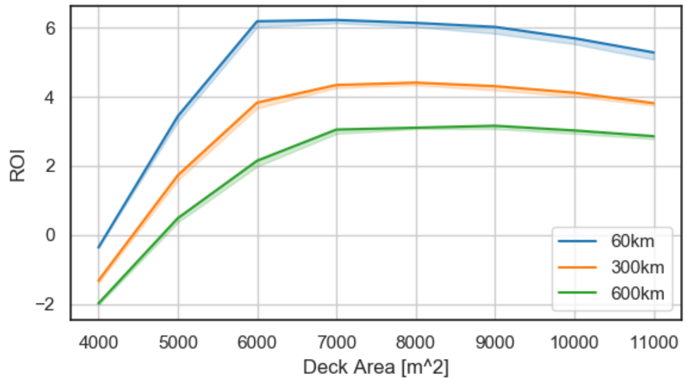

Figure C.4: Increase in optimum cargo area for larger distance from shore

C.3. Paradigm shift 17MW-bound results

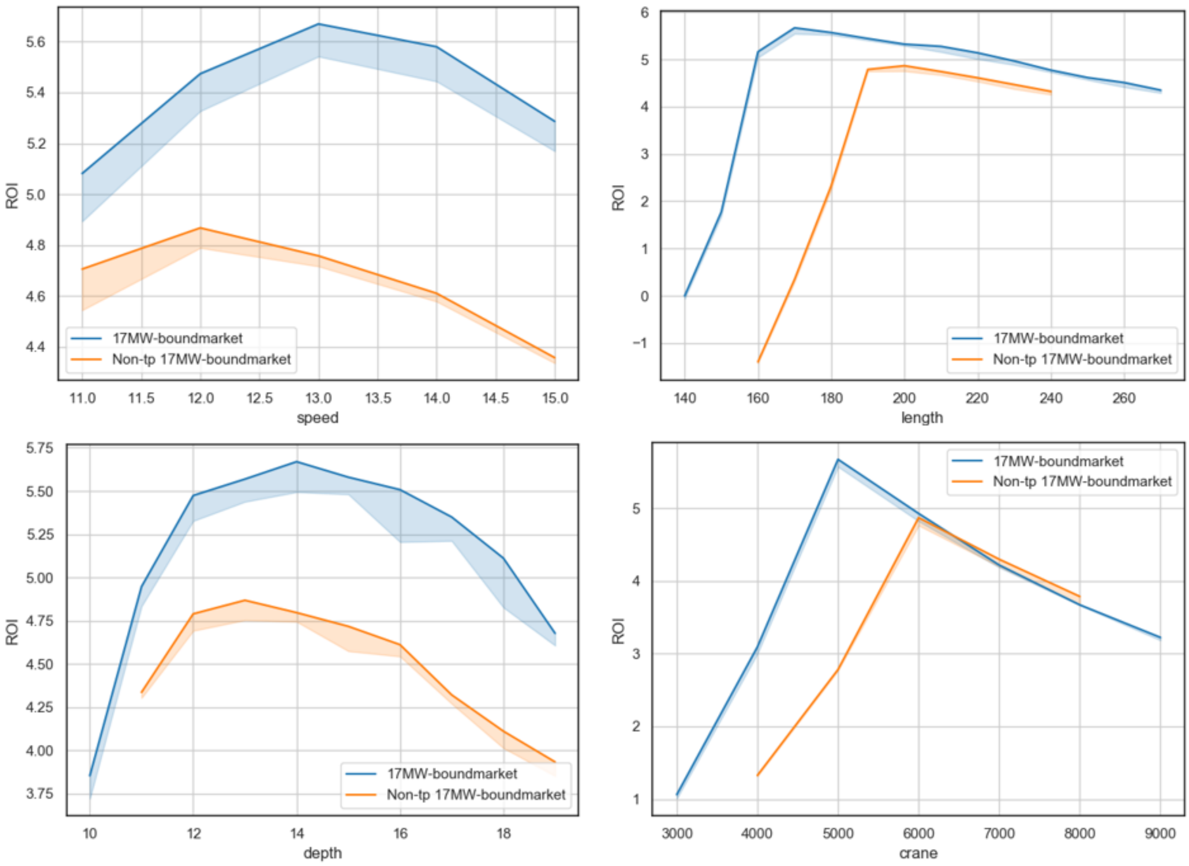

Figure C.5: Effect of paradigm shift toward monopiles without transition piece in the 17MW bound market

D

Information

D.1. Interviewees

During the course of this thesis many employees of the Ulstein group have been interviewed to gain an understanding of current practice. In this section, persons that have been formally interviewed and their interview subject are listed. Besides the people named, many more have been approached informally.
UDSBV

- Ko Stroo: Product Manager at Ulstein Design & Solutions B.V.
- Nick Wessels: Marketing & Sale at Ulstein Design & Solutions B.V.
- Edwin van Leeuwen: Managing Director at Ulstein Design & Solutions B.V.
- Bart Daman: Manager Naval Architecture at Ulstein Design & Solutions B.V.

UDN:

- Per Olaf Brett: Deputy Managing Director at Ulstein International AS
- Jose Jorge Garcia Agis: Senior Business Analyst at Ulstein International AS
- Ali Ebrahimi: Senior Business Analyst at Ulstein International AS

UDSAS:

- Erwin Jager: Sales Manager at Ulstein Design & Solutions AS
- Terje Våge: Head of Naval Architecture at Ulstein Design & Solutions
- Torill Muren: Senior Naval Architect at Ulstein Design & Solutions

Outside Ulstein

- Ties van Bruinessen: Project Manager Design (Naval Architecture) at Oceanco

E

Confidential Appendix

This section of the appendix is withheld from the repository due to confidentiality. The section headers are included so references still work.

E.1. Scaling

E.2. Holtrop and Mennen Checks

E.3. Research summary: current practice at UDSBV

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List of Symbols

Symbol	Unit	Description
Δ	[tonne]	Displacement
η_{work}	[%]	workability of the vessel (fixed)
$\frac{A_E}{A_O}$	[-]	Propeller Expanded area ratio
$\frac{L}{B}$	[-]	ratio length over breadth
$\frac{P}{D}$	[-]	pitch diameter ratio
ρ_{Fo}	$[kg/m^3]$	Density of foundation material
A_{p_i}	[-]	Area under probability density curve
a_k	[-]	katsoulis length exponent
B	[m]	Vessel breadht
b_k	[-]	katsoulis breadth exponent
$C_{accomodation}$	[mln eur]	cost of accomodation
C_{class}	[mln eur]	class certification costs
C_{crane}	[mln eur]	cost of the crane
$C_{electric-system}$	[mln eur]	cost of electric system
$C_{fuel,tonne}$	[eur/tonne]	fuel cost per tonne
C_{fuel}	[mln eur]	total fuel cost
C_{gen}	[mln eur]	cost of power generators
C_{prop}	[mln eur]	cost of propulsion thrusters
C_{steel}	[mln eur]	cost of steel structure
$C_{systems}$	[mln eur]	cost of systems
C_{WP}	[-]	waterplane area coefficient
C_B	[-]	Block coefficient
c_k	[-]	katsoulis draught exponent
C_M	[-]	Midship section coefficient
C_P	[-]	Prismatic coefficent
CC	[tonne]	Crane Capacity
$Crew$	[#]	Amount of crew on board (fixed)
D	[m]	Vessel depth
D_{Fo}	[m]	foundation diameter
d_k	[-]	katsoulis speed exponent
dts	[km]	transit distance
$F_{year}(D)$	[-]	Cumulative probability function
f_k	[-]	katsoulis scaling factor
Fr_{design}	[-]	Froude number for design speed
GM	[m]	geometric metacentric height
h_{crane}	[m]	height of cranetip
H_s	[m]	significant wave height
i_E	[-]	half angle of waterline entrance
J	[-]	propeller advance ratio
$K_{T,ship}$	[-]	thrust coefficient of vessel design
KG	[m]	centre of gravity height from keel
KM	[m]	metacentric height from keel
L	[m]	Vessel length
l_{CB}	[-]	longitudinal centre of buoyancy
l_{Fo}	[#]	amount of foundation layers
L_{Fo}	[m]	Foundation length
L_{WL}	[m]	Waterline length

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Symbol	**Unit**	**Description**
L_R	[m]	run length
$Loan_interest$	[%]	interest rate for loan
$N_{Fo,B}$	[#]	amount of foundations placed in width
$N_{Fo_{yr}}$	[#]	Amount of foundations placed in a year
N_{Fo}	[#]	amount of foundations fit on board
N_{KG}	[m]	centre of gravity of stack of foundations
$N_{MW,yr}$	[#]	amount of megawatts placed in a year
$Oper_{days}$	[days]	amount of days operating
P	[-]	propability matrix for a single year
P_{DP}	[MW]	Dynamic positioning power
P_{inst}	[MW]	installed power
P_B	[MW]	Propulsion power
p_i	[-]	Probability density function
$Perc_{contr}$	[%]	amount of available contracts from uncertainty modelling
PoB	[#]	Amount of crew
$Port_{charges}$	[mln eur]	port charges
q	[eur]	reward vector
$r_{pearson}$	[-]	pearson rank coefficient
$r_{spearman}$	[-]	spearman rank coefficient
S	$[m^2]$	wetted surface
sfc	[g/kwh]	specific fuel consumption
t	[m]	Foundation wall thickness
T	[m]	Draught
T_{config}	[-]	Diameter occurrence probability matrix (transition matrix)
T_{des}	[m]	Vessel design draught
$t_{Fo,inst}$	[h]	installation time per foundation
$t_{Fo,load}$	[h]	in port loading time per foundation
t_{inst}	[h]	time spent installing
T_{max}	[m]	Maximum vessel draught
$t_{pfo,days}$	[days]	total installation days per foundation
t_{port}	[h]	time spent in port
t_{sail}	[h]	time spent sailing to installation site
t_{tot}	[h]	total time spent on mission
$t_{Vessel,dock}$	[h]	time spent docking and loading supplies in port
T_p	[s]	wave period
$trips_{yr}$	[#]	amount of trips per year
V	[mln eur]	expected value
V_c	[m/s]	current speed
V_s	[kts]	Vessel Speed
V_T	[mln eur]	salvage value
V_w	[m/s]	wind speed
VCG	[m]	Vertical Centre of Gravity
VCG_{TP}	[m]	centre of gravity of transition pieces
W_{bal}	[tonne]	ballast weight
W_{Fo_s}	[tonne]	Foundation weight of straight part
W_{Fo_t}	[tonne]	Foundation weight of tapered part
W_{Fo}	[tonne]	foundation weight
W_{load}	[tonne]	one foundation load weight
W_{steel}	[tonne]	Vessel steelweight
W_{TP}	[tonne]	transition piece weight
x_{bal}	[-]	ratio vertical centre of gravity of ballast weight versus depth

List of Acronyms

Acronym	**Description**
ABD	Accelerated Business Development
CAPEX	Capital Expences
CFD	Computational Fluid Dynamics
CK	Concept to Knowledge
DCF	Discounted Cashflow
DMM	Dependence Mapping Matrix
DP	Dynamic Positioning
DP2	Dynamic Positioning system redundancy class 2
DSM	Dependence Structure Matrix
DWT	Deadweight
EEA	Epoch Era Analysis
EIA	Environmental Impact Assessment
EPCI	Engineering, Procurement, Construction & Installation
EPM	Enterprise Performance Management
ERM	Enterprise Risk Management
EU	European Union
GUI	Graphical User Interface
GZ	Righting arm at VCG
HLCV	Heavy Lift Cargo Vessel
HLV	Heavy Lift Vessels
IEA	International Energy Agency
IEEA	Interactive Epoch Era Analysis
IMDC	International Marine Design Conference
KN	Righting arm at keel
LCOE	Levelized Cost of Energy
LTV	Loan to Value ratio
LWT	Lightweight
MATE	Multi-Attribute Tradespace Exploration
MCR	Markov Chain with Rewards
MDP	Markov Decision Process
NPV	Net Present Value
OPEX	Operational Expences
Opti-OWECS	Optimisation of Bottom-Mounted Offshore Wind Energy Conversion System
OSV	Offshore Support Vessel
PEST	Political, Economical, Social and Technological
POMDP	Partially Observable Markov Decision Process
R&D	Research and Development
ROA	Real Options Analysis
ROI	Return on Investment
ROV	Remotely Operated Vehicle
RSC	Responsive Systems Comparison
SSCV	Semi Submersible Crane Vessel
SWOT	Strengths, Weaknesses, Opportunities and Threats
TELOS	Technological Feasibility
TLP	Tension-Leg Platform
TP	Transition Piece
UDP	Ulstein Design Process

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Acronym	**Description**
UDSAS	Ulstein Design & Solutions A.S.
UDSBV	Ulstein Design & Solutions B.V.
UIN	Ulstein International A.S.
Ulstein	Ulstein Group
US	United States
V&V	Validation and Verification
VCG	Vertical Centre of Gravity
VOYEX	Voyage Expences
WTIV	Wind Turbine Installation Vessels