MSc Thesis in Marine Technology – Research report – MT54035

Offshore Wind Installation Vessels

Generating insight about the driving factors behind the future design

Casper van Lynden – 4378784

SDPO.21.018.m

July 13, 2021

Offshore Wind Installation Vessels

Generating insight
about the driving factors
behind the future design

Casper van Lynden – 4378784
SDPO.21.018.m
July 13, 2021

To obtain the degree of Master of Science in Marine Technology
at Delft University of Technology

Thesis exam committee:

Dr. ir. R.G. Hekkenberg	TU Delft - Chair
Dr. A.A. Kana	TU Delft - Supervisor
Dr. ir. H. Polinder	TU Delft
Dr. J. Rezaei	TU Delft
Ir. I. van Winsen	Heerema Engineering Solutions - Supervisor
Ir. C.N. Westland	Heerema Engineering Solutions - Supervisor

An electronic version of this thesis is available at https://repository.tudelft.nl/

Preface

There is one certainty in life, the future is uncertain. We are not able to predict the future, but everyone wants to try to predict it as close as possible. Think about the energy transition in which we are replacing conventional energy sources such as oil for solar and wind. What do we need in the near future to support this energy transition at sea? What kind of vessels are necessary to install the utilities for generating this type of energy? How fast is this energy market changing and what kind of impact has this on the vessel lifetime, design, and the investment? That is where this thesis is all about.

The master Marine Technology at TU Delft offers the opportunity to develop as marine engineer in various directions. My personal interests are to perform research in how we could better design vessels for the unknown future. What are the possible future drivers and how do these relate to the vessel design? I got the opportunity at Heerema Engineering Solutions (HES) to dig deeper in this topic, while also touch on a bit of programming and visualizing all the different parameters towards an interpretable output.

Of course this all was not possible without the help of my mentors at the TU Delft and the support of my supervisors and colleagues at HES who gave me the opportunity to work on the methodology and related model. I appreciate the input from Royal IHC regarding the cost model. I am also very grateful for the support from my girlfriend, family, and friends throughout my graduation.

Casper van Lynden

Delft, July 2021

Summary

The world is trying to move towards a more sustainable future [1]. One of the hot and important topics is the transition of conventional energy towards sustainable energy sources. An energy source that plays a major role is offshore wind [2]. To keep up with the increasing installation demand in this sector new offshore wind installation vessels are needed [3]. This fast developing offshore wind market reduces the vessel life time due to the changing vessel requirements. This introduces risks for potential investors [4]. Therefore, there is a need for more certainty and predictability regarding the requirements of the future offshore wind installation vessels. To get more insight in the driving factors behind the future design and therefore reducing risk the following main question is defined:

> *What are the important aspects in the vessel design of offshore wind installation vessels over the next 10-15 years in order to reduce the costs and to be competitive in the offshore wind installation market?*

Currently market reports only give insights in possible developments related to energy producing costs or installation capacity, not to requirements of future offshore wind installation vessels. To translate the market developments towards input variables for future vessel concept designs, the methods 'needs analysis' and 'concept exploration' from the systems engineering framework are applied. When applying the 'needs analysis' the changing turbine power rating, the increasing water depth, and the changing distance from wind farm to port are identified as key developments. As the future in this market is uncertain and very dynamic the 'concept exploration' phase involves both scenario modelling and parametric modelling. Epoch-era analysis is selected as scenario modelling method to capture this uncertain and the fast changing market by generating various future possibilities each posing different vessel requirements. In the parametric model a set of vessels is defined by their length, beam, depth, crane capacity, speed, and transport strategy. This set is used to define ship characteristics (geometry, lightweight, deadweight, stability properties, resistance, power estimation, engine configuration, deck space, crew, and crane properties). These ship characteristics indicate if a vessel meets the requirements and how long it takes to complete a project (transport, installation, and idle time of a vessel). The vessel properties and project time can be translated towards vessel costs which is a measure of the performance of the vessel.

The case study shows that the application of Epoch-era analysis and parametric modelling is capable of generating insights in important aspects for designing future offshore wind installation vessels. In the case study the costs performance of monohull vessels installing monopile foundations is analysed in four different eras. In each of these eras the key uncertainties turbine power rating, water depth, and distance from wind farm to port change over time. This methodology provides an

opportunity to investigate the impact of the fast changing market at the vessel design by showing the vessel performance during its lifetime, while also informing the user about the constraints that are being set for the investigated vessel properties. From the case study it can be concluded that the main dimensions of the vessels are being influenced by the size of the cargo, the necessary vessel stability, and the costs. The needed crane capacity is a function of the expected cargo weight, which increases when the power rating of the turbine or the water depth increases. The implementation of an upgradable crane has been investigated in order to deal with the market uncertainty. An upgradable crane will have an advantage in the short term but will be outperformed by crane capacities that do perfectly fit future needs. In terms of transportation a feeder strategy is not recommended. It has been found that it is preferred to sail at a ship speed of around 7 kts, while using a shuttle strategy.
In real life the selection of the most optimal design might not only rely on the costs of a vessel, but for example also on the total project time. The strength of this method is that it has the flexibility to select different key performance indicators but also provides the opportunity to incorporate the importance of short term against long term goals. It can therefore be tailor-made to a stakeholders strategy. Applying their wishes while analysing many different options results in robust input variables for the concept vessel design.

The current implemented model is a first step, but more steps are needed to further exploit this potential. It would be beneficial to develop new empirical methods that are specifically for offshore wind installation vessels. More accuracy of the estimated installation time can be reached by extending the workability calculation in such way that it also includes possible delays due to bad weather, maintenance, and other unforeseen issues. It is possible to compare different vessel types, cargo types, and supply chains by adding additional parametric models and model components. By adding these possibilities an extended overview of the available strategies for various stakeholders becomes visible. When scaling up this methodology it is advised to investigate data analysis techniques for multi dimensional data.

To conclude, this research shows that the methodology has a lot of potential of generating insight in future offshore wind installation vessels. A base framework has been developed and challenges lay ahead to refine this framework.

Content

1 Introduction

The energy transition is a topic that you experience everywhere as the world is trying to move towards a more sustainable future [1]. The most important development of this dedication is the signed Paris Agreement, meanwhile signed by 197 countries all over the world, in which they agreed that the increase in average temperature worldwide at the end of this century should be less then 2 degrees Celsius compared to 1850-1900 [5]. The energy transition involves the replacement of the conventional energy sources (gas, oil, coal, or nuclear energy) for sustainable energy sources (hydro power, bio energy, geothermal, wind, and solar energy). A sustainable energy source that plays a big role in this energy transition is offshore wind energy [2]. The installation of wind turbines in an offshore environment requires vessels. This research will investigate the impact of the fast changing offshore wind market at the these installation vessels.

This research will be carried out in collaboration with Heerema Engineering Solutions (HES). HES is an engineering company that supports its customers by providing offshore engineering, installation engineering, and automation knowledge. HES is currently shifting its focus to the offshore renewable energy sector and in particular the offshore wind industry. They are interested in the developments of the installation vessels in this market in order to develop knowledge that can be used to support client decisions in the offshore wind market. This also provides HES an overview of the opportunities in the offshore wind market in which their knowledge can be useful.

The problem description and objectives of this research can be read in chapter 2: the problem statement. An overview of the offshore wind industry and in particular the developments that have impact at offshore wind installation vessels are presented in chapter 3. Chapter 4 introduces the current offshore wind installation fleet that is used for installing wind turbines and its foundations and discusses the impact of the market trends at these installation fleet. This chapter also shows the upgrades for the current fleet, vessels on order, and announced concept vessels. Chapter 5 presents the systems engineering methodology that is used during this research. Afterwards, chapter 6 discusses the method that has been used to help predict the possible requirements for future offshore wind installation vessels. In chapter 7 a description of the parametric model used for generating a large amount of concept designs is given. The case study conducted in this research can be found in chapter 8. The conclusion and the discussion are presented in chapters 9 and 10. Finally, an afterword can be found in chapter 11.

What are the important aspects in the design of offshore wind installation vessels over the next 10 to 15 years?

Problem statement 2

The main purpose of this chapter is to introduce the research topic, the gaps identified during the literature review, and the objective of the research. First of all, the importance of the offshore wind market and the gap regarding the design of offshore wind installation vessels identified in this market will be described in section 2.1. Subsequently, the objectives of this research will be given in section 2.2. Then, section 2.3 discusses the main question and the sub questions used as guidance during this research. Finally, the scope is defined in section 2.4.

2.1. Problem description

The global energy sector is moving towards a more sustainable future [1]. An example of this shift is the goal set by the Paris Agreement that limits the global temperature rise to a maximum of 2 degrees Celsius this century compared to the average temperature in 1850-1900 [5]. In order to become more sustainable and accomplish this goal a change in the current global energy landscape is required. This change involves the replacement of conventional for sustainable energy generation methods [6]. A sustainable energy resource that is expected to take a key role in this transformation is offshore wind [2].

In the upcoming years it is therefore expected that the installed amount of offshore wind turbines will increase by 13% per year [7]. In order to keep up with this increasing demand there is a necessity in expanding the current offshore wind installation fleet [8].

Apart from the growing demand in installation capacity there is also a drive to reduce the levelised cost of energy (LCOE) of offshore wind. By reducing the LCOE offshore wind becomes competitive against the conventional and stays competitive against other sustainable generation methods, which is of importance in order to secure future investments [2]. The increasing demand in new offshore wind farms and the drive to reduce the LCOE cause the offshore wind market to evolve. This is visible in the fact that the turbine sizes and weight increase, the distance from the wind farm towards port increases, and the depth at which wind turbines are installed increases [9]. As will be explained in section 4.3 the changing market impacts the vessels used during the installation of offshore wind farms. For example, the increasing demand in installation capacity and the drive for a lower LCOE indicate a need for new and more cost effective vessels. These new vessels need to be capable of handling the harder requirements due to the changing market. In order to get more insight in these aspects the offshore wind installation vessel will be the focus of this research.

A gap that will be identified in section 3.7 is the lack of available methods to predict the future requirements for offshore wind installation vessels. The current forecasting reports available do mainly focus on the costs and the annual installation rate of the offshore wind industry. They do not give a lot of insight about the underlying aspects

that are used to define the forecasts. As it is important for naval architects to know for which requirements the vessels needs to be designed and on which assumptions these predictions are based, it is of importance to provide more information regarding predicting the future requirements for offshore wind installation vessels.
A second gap that will be identified is related to the fast changing offshore wind market. Due to the rapid developments the lifetime after which offshore wind installation vessels receive a refit is reduced to 10 years instead of a more sustainable 25 years, which will be explained in sections 4.3, and 4.4. For designers it is important to find the best design that is not over designed and too expensive, but also not under designed and therefore not capable of performing the required operations when it is delivered to the market [10]. As explained by Doerry there are two design strategies that can be applied when requirements are uncertain over the lifetime of a vessel: a robust design and an modular adaptable design [11], see figure 2.1. At the moment no research has been conducted in the offshore wind market regarding the best design strategy in order to take in to account this fast changing market and prevent over and under designing the installation vessels.

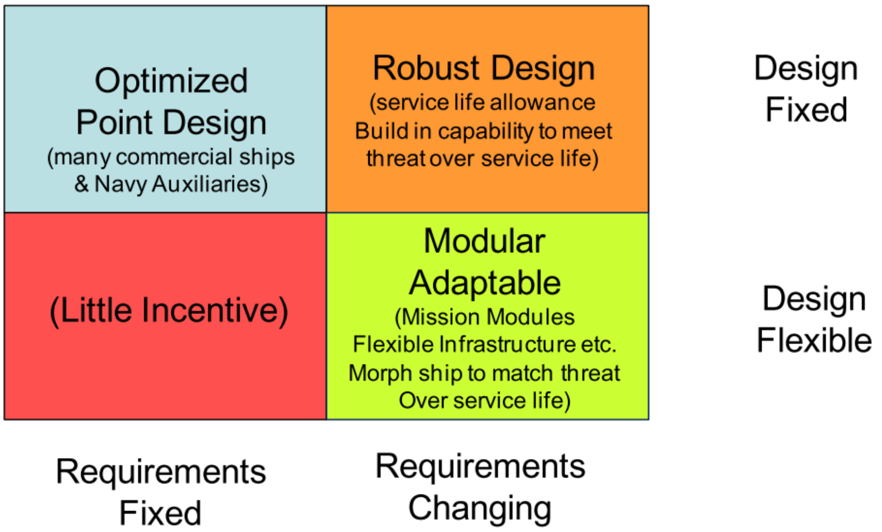

Figure 2.1.: Design strategies [11]

The last gap that will be identified in sections 4.3 and 4.4 relates to the concept development of new offshore wind installation vessels. First of all, there is a limited amount of information publicly available regarding the design choices and process for offshore wind installation vessels. Secondly, the reports and concepts that are available all design from a static scenario, for example one specific wind farm or one specific installation method. Using this method gives no additional insight in the trades off that a ship designer has to make during the design process and the impact of these choices.

2.2. Research objective

The objective of this research is to get a better understanding about the driving factors behind the design of an offshore wind installation vessel over the next 10-15 years to be cost effective and competitive in the fast changing market. Before it is possible to fulfil this main objective the gaps defined in section 2.1 need to be addressed, by solving the following sub objectives:

- The first sub objective is to fulfil the need of a method that can be used in order to determine possible future vessel requirements. This is necessary as the first gap defined indicates that there is a need for better insight in the requirements for the future offshore wind installation vessels in order to prevent over or under designing. Additionally, the second gap mentions the problem of the reduced economical life time of a vessel due to the fast changing market and thus requirements. The method used for predicting possible future situation should therefore also be capable of handling the aspect of a fast changing market.

- A second sub objective is the application of a model that is capable of handling dynamic market inputs. As mentioned by the third gap in section 2.1 the current concept designs are build using a specific wind turbine or a specific field location. More insight can be generated by using a dynamic situation instead of a static situation. Moreover, the concept generation method should be capable of handling not only the selection of the main parameters of the vessel but also the selection of the transportation strategy based on the input variables. It is important that the transportation strategy is involved as the distances that have to be traveled from port towards the installation site increases, which has a big impact at the costs, see section 3.5.

- The third objective is to combine the methods that determine the future vessel requirements and the concept vessels in order to assess the performance of the different concepts that are generated. This assessment needs to be carried out in such a way that the costs and competitiveness of the vessels can be compared.

- The final sub objective is to investigate how the vessel performance and the defined future market situations could provide feedback about the different aspects that are of importance for the future offshore wind installation vessels. By completing this final sub objective an answer can be given to the main objective of this research.

For an overview of the relations between the gaps identified and the sub objectives described above see figure 2.2.

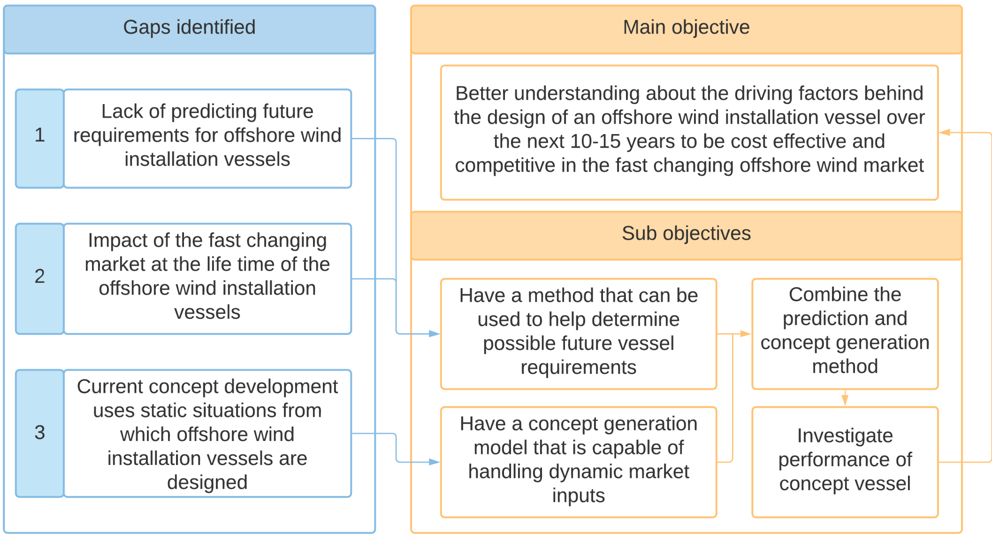

Figure 2.2.: Relation between gaps and objectives

2.3. Research questions

The main objective from section 2.2 is translated into a main question:

> *What are the important aspects in the vessel design of offshore wind installation vessels over the next 10-15 years in order to reduce the costs and to be competitive in the offshore wind installation market?*

In order to guide the research and to be able to answer the main question, the following sub questions are identified based on the sub objectives described in section 2.2:

1. How is the offshore wind industry evolving and what is the impact at the requirements of the current type of installation vessels?
2. How can systems engineering support the designer in defining the important requirements that need to be predicted?
3. Which scenario modelling method can be applied to predict a set of possible future requirements for offshore wind installation vessels?
4. Which method and variables can be used to generate offshore wind installation vessel concept designs?
5. How can the performance of a concept installation vessel being assessed for the different sets of scenarios?
6. How can a combination of scenario modelling and concept design generation provide more insight into future offshore wind installation vessels?

2.4. Scope of the research

The following boundaries are defined for this research:

- The types of operations in the offshore wind industry considered in this research are the installation of foundations and wind turbines.
- This research will only focus at the concept development stage of systems engineering.
- The research will use foundation size and weight, distance from farm to port, and water depth as input parameters for creating the various scenarios.
- A baseline vessel will be selected from the current fleet for the parametric model that is used for generating concept designs.

Market reports give insights in possible developments related to energy costs or installation capacity, not to requirements of future installation vessels

Offshore wind 3

The goal of this chapter is to provide an overview of the offshore wind market and to get an understanding of the developments in the sector that are of importance for offshore wind installation vessels. First of all, section 3.1 introduces the concept of a wind farm as a sustainable energy plant. Then an overview of the different life cycle stages of a wind farm will be given in section 3.2. An involvement of the different stakeholders at each life cycle stage will be given in section 3.3. The importance of the offshore wind industry is explained in section 3.4. The trends in the offshore wind market will be presented in section 3.5. The important technological developments are presented in section 3.6. Insight about the offshore wind market prediction methods is given in section 3.7. Finally, a chapter conclusion is given in section 3.8.

3.1. Offshore wind farm

An offshore wind farm is a sustainable power plant that converts the air flow (wind) in the atmosphere into electrical energy, which is transported via the electrical grid towards its end users [12]. The conversion in the offshore wind farm from kinetic energy towards electrical energy is possible because of the usage of the wind turbine. The wind turbines used in a wind farm need to have a sufficient amount of spacing between each other in order to reduce wake effects on other wind turbines in the field and therefore prevent an efficiency reduction [13]. Therefore, the wind turbines are positioned in an array which gives the offshore wind farm a typical look as can been seen in figure 3.1.

Figure 3.1.: Offshore wind farm grid [14]

An offshore wind farm has two main tasks: the production of electricity and the transportation of the generated electricity towards shore [13].

Production of electrical energy
The wind turbine is the component in the offshore wind farm that is responsible for converting wind into electrical energy. The electrical energy is generated by the lift principle. The wind introduces an airflow over the blades of the wind turbine, which creates lift and causes a rotational motion of the rotor. This rotational motion is transferred towards the generator in the nacelle in order to convert the rotational motion in electrical power [15].
The rotor and the generator in the nacelle that are responsible for generating the electrical energy are located on top of the wind turbine tower. The tower is supported by a foundation that keeps the tower above the water surface. See figure 3.2 for the main components of an offshore wind turbine.

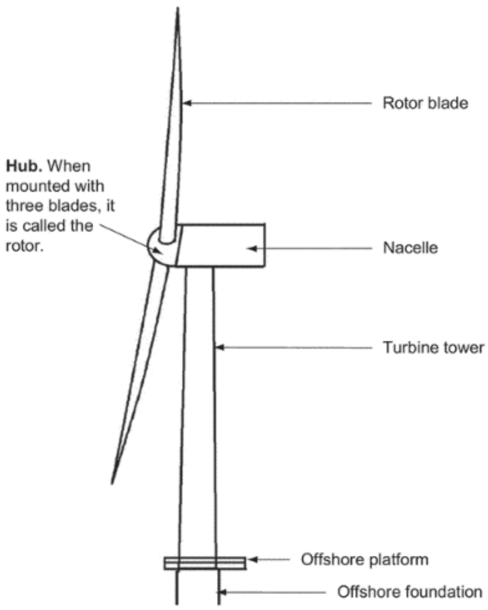

Figure 3.2.: Wind turbine main components [16]

Transportation of electrical energy
After the generation of the electrical energy it has to be transported towards the final user. For the transportation of the energy a couple of components are used. First of all, array power cables are used for the transportation of the electrical power from the turbine to the substation located in the offshore wind farm grid. Secondly, the offshore substation adapts the voltage of the electricity in order to reduce the electrical power loss during the transportation towards shore. Then export power cables are used to transport the energy from the offshore substation towards the onshore substation. Finally, the onshore substation ensures that the provided electrical energy can be used by the users that are connected to the onshore electrical grid [13].

For an overview of the different components and the interconnection between the components, see figure 3.3.

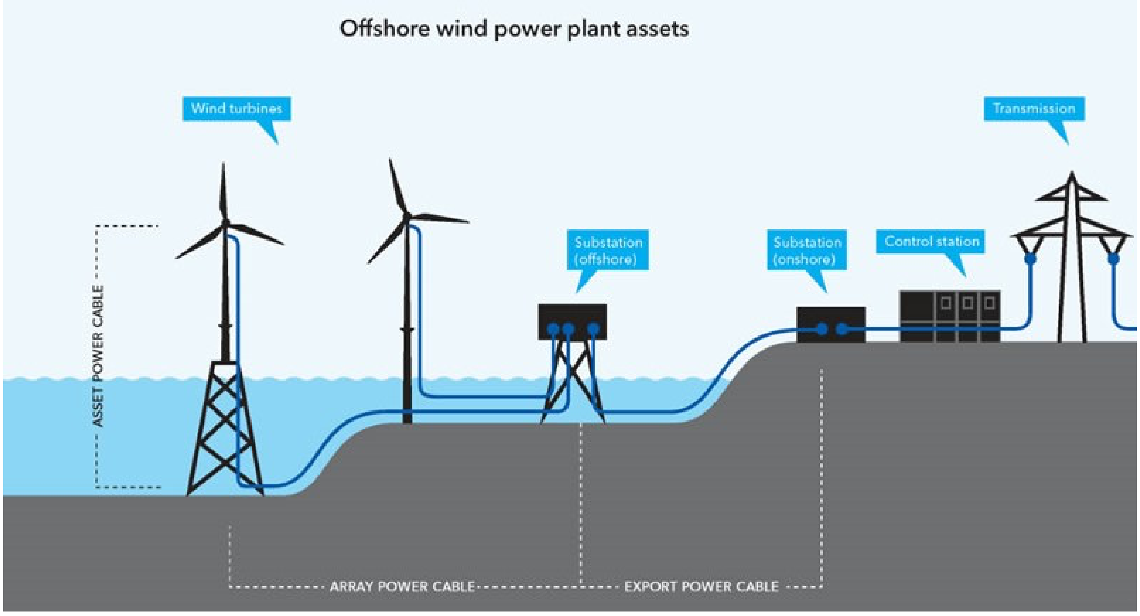

Figure 3.3.: Offshore wind farm main components [17]

3.2. Life cycle

To get better insight in the possible applications of an offshore wind installation vessel during the life time of an offshore wind farm, it is of importance to understand the different processes that take place during the life time of an offshore wind farm. This is important because an overview of the life cycle can generate a better understanding in the different opportunities that arise in the offshore wind market. In general the total development of an offshore wind farm takes around 7 - 10 years [18][19]. The following four main phases in the life cycle can be identified [20][21]:

Project management and development
The project management and development phase involves the necessary procedures and surveys in order to prepare for the approval and installation of the offshore wind farm. Examples of processes involved in this phase are an early feasibility study which will be followed by a more extensive research into financing, site investigation, project approval, tender process, wind farm design, testing, and production.

Installation and commissioning
The installation and commissioning stage is the stage on which this research is focused, as it involves the application of offshore wind installation vessels. In this stage the various wind farm components described in paragraph 3.1 will be transported from their production location towards the site location using vessels. When the components arrive at their location they are installed by an offshore wind installation vessel. Finally, after installing the equipment the commissioning procedures starts in which everything is tested before going to a fully operational stage.

Operation, maintenance, and service
This is the stage in which the offshore wind farm generates electrical power. During this stage it is of importance to keep the offshore wind farm in good condition in order to ensure an optimal generation of electricity. During this stage there are two main activities to be done. First of all the management of the various assets that are necessary for the operation of an offshore wind farm. Think of the required people, equipment, and procedures. Secondly, maintenance is carried out in order to prevent a break down of the wind turbine and service repairs are conducted in case of failure. During this stage, dedicated operation and maintenance vessels are used for transporting the required personnel and equipment.

Decommissioning
A typical offshore wind turbine is designed to have a life time of around 20 years [22]. After reaching the end of its life time a few options are available. First of all the operational life time can possibly be extended by carrying out a risk assessment and replacing the components that do impose a high risk according to the assessment. Secondly, the site can be used to install new turbines. In this situation the foundations and turbines are replaced while the electrical grid of the former wind farm is used. The final option is to fully decommission all the components.

3.3. Stakeholders

The stakeholders are discussed in this section as they provide an overview of the different parties that have an influence at the offshore wind market and the parties that are influenced by the offshore wind industry. Each of these parties has a different point of view at the offshore wind market and therefore different interest. Examples are an interest in a low energy price, interest of earning money, or the interest in a more sustainable installation approach. The main actors are the government, grid operators, wind farm developers, wind turbine manufacturers, wind farm owners, offshore contractors, engineering firms, and end users [23][24].

Government
The government gives vital agreement for the development of the offshore wind farms and is a key actor in the planning of new offshore wind farms. Support is given by assigning wind farm locations and receiving the necessary permits in order to install the wind farm.

Grid operators
The grid operators are responsible for the integration of the wind farm in the national electrical grid. They have to ensure that there is enough capacity to handle additional energy supply from the wind farm.

Wind farm developers
These companies are key players in the development of the offshore wind farm. They carry out the first surveys, determine the feasibility, and define the first concept designs for the wind farm and its components. The wind farm developers will mainly influence the project management & development and the installation & commissioning process.

Wind turbine manufacturers

The manufacturers are responsible for the design and the production of the wind turbines. They will mainly be involved during the installation phase, but also have an influence on the operation and maintenance phase due to the design choices they make.

Wind farm owner

The wind farm owners are responsible for the operation and maintenance (O&M) of the offshore wind farm when the wind farm is running. They will also be responsible for arranging the decommissioning of the offshore wind farm.

Offshore contractors

These are companies that provide services and equipment during installation and maintenance in order to be able to transport, install, and replace components.

Engineering firms

Engineering firms will support the parties mentioned above by giving advice based on the in house knowledge available. As mentioned, the research is carried out in collaboration with HES. HES is an engineering firm that supports various companies in the offshore wind industry. In particular during the concept development, turbine and foundation installation, and the decommissioning phase by applying the in house offshore engineering knowledge.

End users

The end users are the users that do consume the electricity that is produced by the offshore wind farm.

Other stakeholders

Apart from the actors mentioned above there are other stakeholders that influence the process but will not be discussed in detail. Examples are universities, researchers, environmental organizations, sea ports, fishing industry, shipping industry, and other North Sea users [24].

Possible conflicts between stakeholders

Conflicts between the above mentioned stakeholders could arise [24]. First of all you have the parties that favour the installation of the wind farms, for example the government in order to reach its sustainability goal or the engineering farms as this gives them the opportunity to earn money. However, there are also examples of stakeholders that benefit less from the installation of offshore wind farms. An example is the visual pollution for the local community that is caused by the wind farms or the fishing industry that gets less space for their activities.

3.4. Energy demand

The development of the wind industry is of importance in order to decarbonise the global economy and to meet the sustainability targets. It is expected that the wind industry will be one of the key players in this process and will be one of the important sustainable energy resources in 2030 [2], see figure 3.4 for the generation capacity of the various resources. The COVID-19 pandemic does have an impact at the current electricity demand, which has decreased by 6% this year [25]. Moreover, research by DNV-GL indicates that COVID-19 might cause a short-term impact at the installation rate of new renewable production facilities. Although COVID-19 introduces a new market uncertainty, it is expected that the offshore wind market will keep growing in the long term aiming to reach the sustainability targets [26].

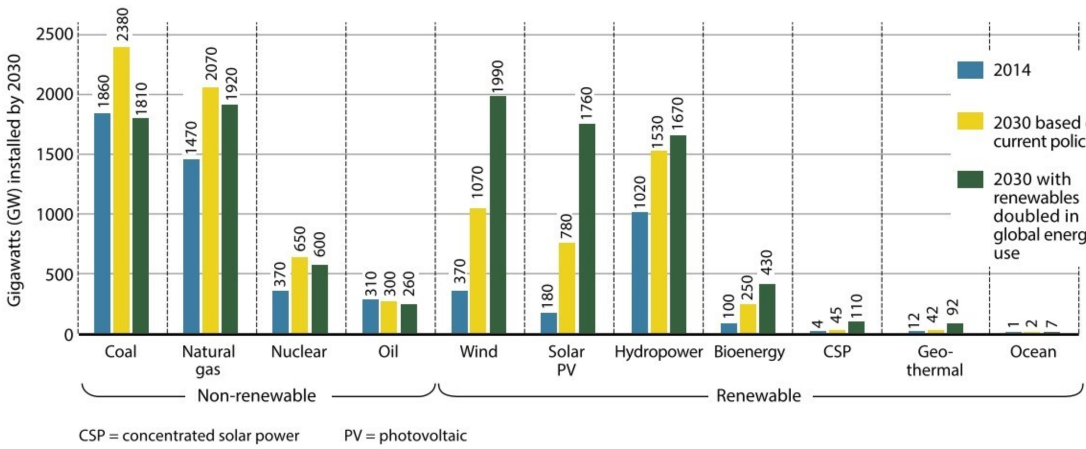

Figure 3.4.: Global Energy mix 2030 [2]

The wind industry includes both wind farms onshore and offshore. The current onshore wind industry has a capacity of 594 GW and is much larger compared to the 28 GW installed capacity of offshore wind farms [27]. However, the growth potential of the offshore wind market is much larger compared to the onshore wind market. This is due to a reduction in the available new sites onshore and the favourable wind conditions offshore which improves the capacity factor of the wind turbine [28]. The capacity factor indicates the ratio between the amount of power that is generated by an energy plant compared to the maximum amount of power it would be able to generate in the same time [29].

The interest in the offshore wind industry is visible in the rapid growth of this industry, between 2010 and 2018 there has been a yearly grow of around 30% in the installed capacity. It is expected that this increase continues as there are already more than 150 new projects scheduled for the upcoming five years [7]. The need to fulfil this demand and comply with the targets set in the Paris Agreement leads to an increase in necessary installation rate. The current installation rate needs to be 6 times larger by 2030 and 10 times larger by 2050 [6], see figure 3.5.

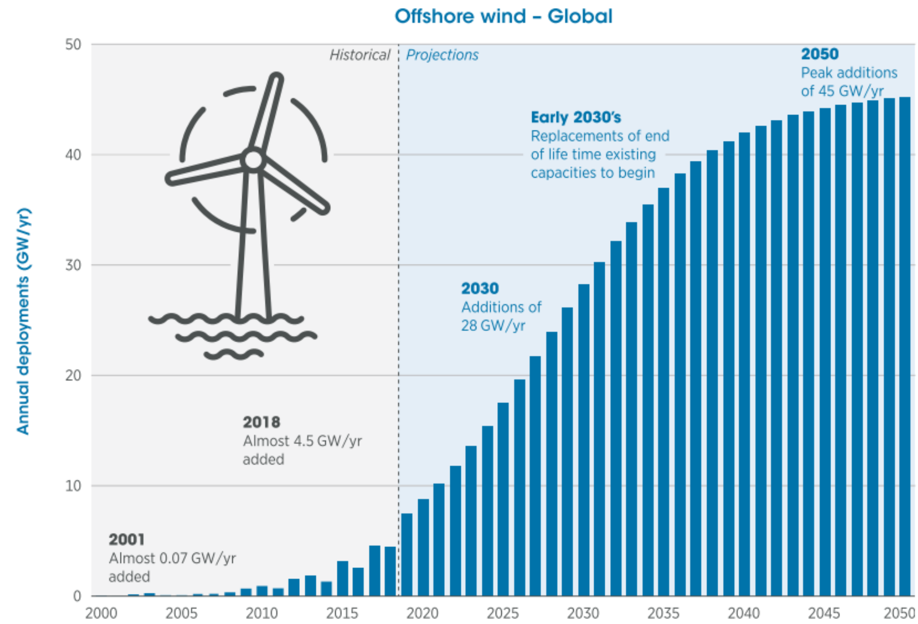

Figure 3.5.: Annual installation rate [6]

The current offshore wind market is mainly taking place in Europe and Asia. Around 84% of the total offshore wind capacity is installed in Europe, while the other 16% is mainly installed in Asia [30]. Over the next 40 years it is expected that the market outside Europe will evolve a lot, especially in various countries in Asia who currently focus on offshore wind, see figure 3.6. These countries are China, Japan, India, Chinese Taipei, Vietnam, the Republic of Korea, Indonesia, and the Philippines.

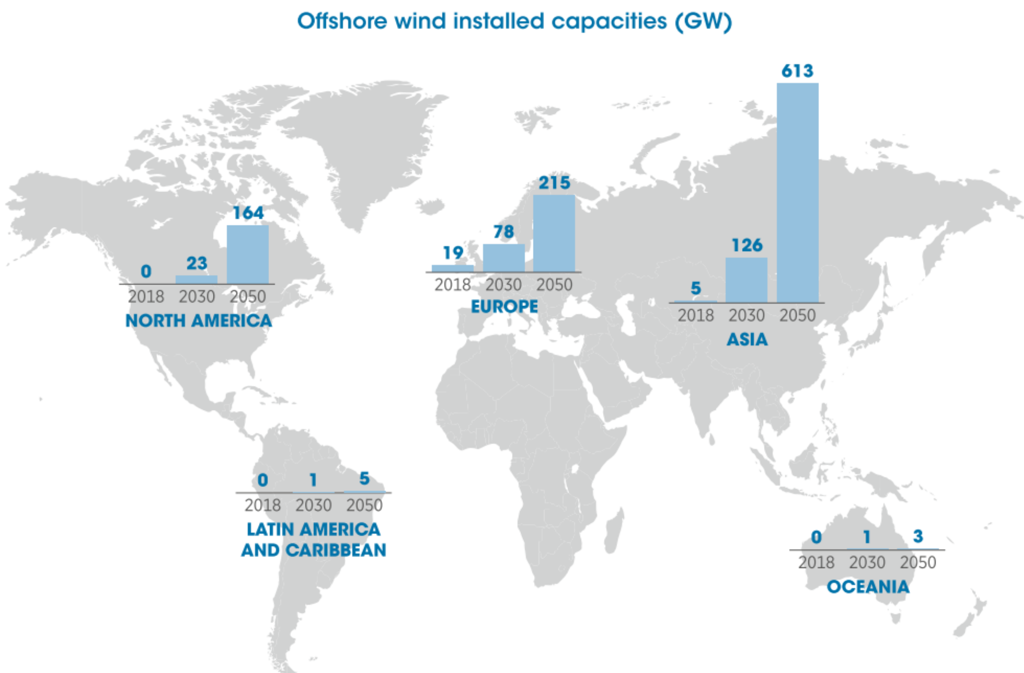

Figure 3.6.: World wide installation capacity [6]

Competitiveness

There are a lot of different energy generation methods available which can be compared based on their costs. The primary metric used is the levelised costs of energy (LCOE). By reducing the LCOE offshore wind becomes a bigger competitor of the conventional energy generation methods [31], see figure 3.7 for a comparison between the LCOE values. It is even essential to reduce the LCOE in order to secure future investments and to keep both public and political support [2]. Therefore, the aim to reduce the LCOE is one of the main factors of the developments in the offshore wind sector [32].

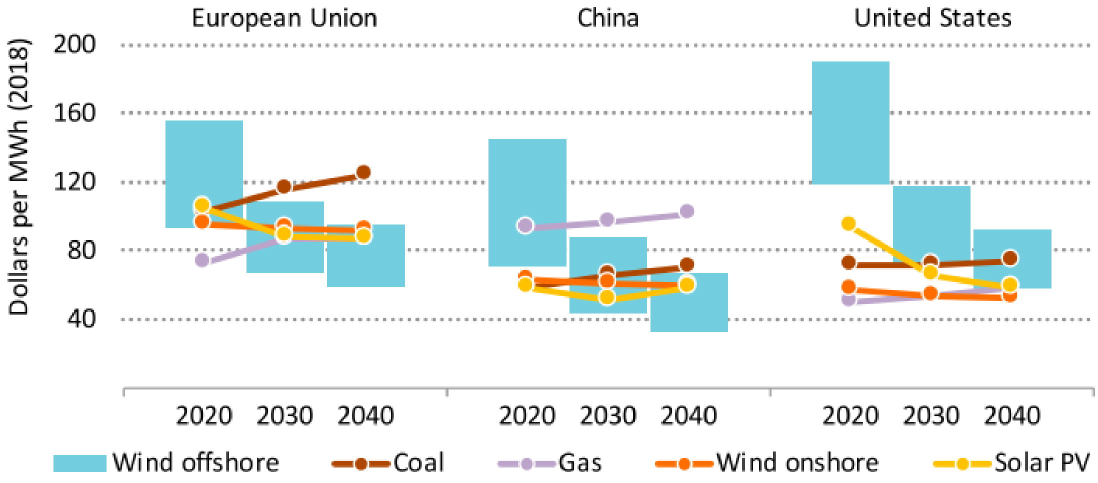

Figure 3.7.: Comparison between LCOE of different energy sources [7]

The LCOE method determines the overall costs and the total amount of electricity produced in its life time in order to get an average costs per unit of energy. By having a standard method for defining the cost different energy generation methods can be compared. For a simplified calculation method of the LCOE see equation 3.1 [33].

$$\frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{1+r}^t}{\sum_{t=1}^{n} \frac{E_t}{1+r}^t} \tag{3.1}$$

I = Investment, M = Operation and maintenance costs, F = Fuel costs, E = Electricity generated, r = Discount rate, t = current year, n = life time

Equation 3.1 shows the various components that are of importance in case of reducing the LCOE. For the offshore wind industry the fuel costs are almost zero as no fuel is used to run the wind turbines. The investment costs of offshore wind farms are high. This indicates that the discount rate has a large influence on the LCOE [33]. In order to reduce the LCOE the industry strives to improve the following aspects:

- **Investment costs**: a reduction improves the LCOE. By improving the installation vessels the 15-20% [9] investment costs due to the installation can be reduced leading to an improved LCOE, see figure 3.8.
- **Operation and maintenance costs**: by reducing the yearly O&M costs the LCOE of offshore wind can be improved. At the end of 2015 the O&M costs were around 20% of the total cost compared to 32% in 2001 [2].

- **Capacity factor**: as explained, the capacity factor is a ratio between its electricity production and the maximum amount of electricity (based on power rating) it could have produced in the same time span [29]. This indicates that a higher capacity factor relates to more energy production and a lower LCOE. An increase in capacity factor has been measured between 2010 and 2018 from an average percentage of 38 toward 43. For 2030 it is expected that the capacity factors of new wind farms will be between 36 and 58% and increase further towards values between 43% and 60% in 2050 due to improved turbine designs [6].

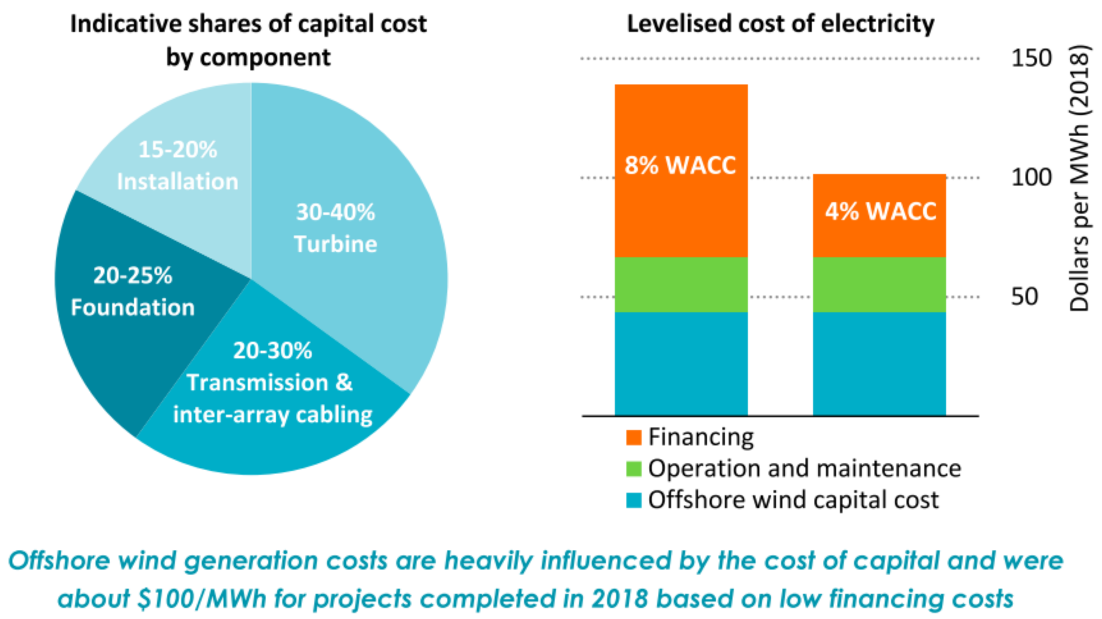

Figure 3.8.: Overview costs offshore wind [7]

3.5. Key trends and future forecasts

Due to the interest in the offshore wind industry and the drive to reduce the LCOE the offshore wind market is changing. From literature the following three main trends in the offshore wind market are identified that have an impact on the installation vessels: increasing turbine sizes, increasing distance from wind farm to port, and increasing water depth.

Increasing turbine size

Since 2014 the offshore wind turbine rating is on average growing by 16% each year. This has led to an average installed turbine rating of 7.1 MW for in Europe in 2019 new installed offshore wind turbines [9]. There are two main reasons that the turbine sizes did increase. First of all, in between 2001 and 2015 manufacturers did start designing wind turbines specifically for the offshore wind industry [2]. A second reason is the importance to improve the energy generation capacity and efficiency of a turbine in order to reduce the LCOE [27]. See figure 3.9 for the growth of the maximum turbine sizes available in recent years.

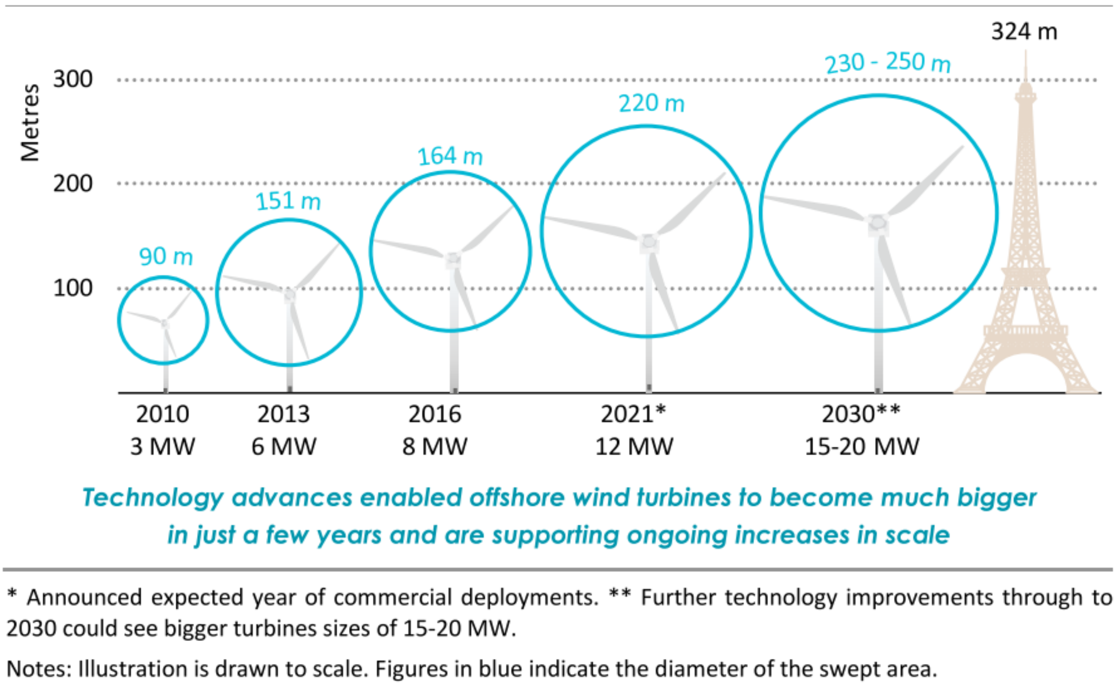

Figure 3.9.: Development offshore wind turbine size [7]

The improved energy generation capacity due to the bigger wind turbines is not the only aspect of the new turbines that help reducing the LCOE. The increasing size also helps to reduce the costs that are faced during the installation and operation of the wind farm. This is based on economy of scale, as around the same amount of installation time and maintenance is required for each individual turbine, while one turbine may have a much higher power rating [27]. It is also visible that the increasing turbine sizes relate to an increase in the installed capacity in an offshore wind farm. See figure 3.10 for the size of the installed wind turbines and the used turbine power rating.
The increasing turbine size introduces a new challenge. Due to the increasing size of the turbine the weight of the components increases, which introduces new vessel requirements for the lifting and transportation stages [34]. It is uncertain what the power rating will be in the next couple of years and what the specifications of these future wind turbines will be. But research regarding the new 15 and 20 MW turbines gives an indication of the increasing mass and height of the various components. The increasing mass and height of the hub may poses challenges for the current fleet of offshore installation vessels and their crane capabilities [35][36]. For a summary of the results, see table 3.1.

Table 3.1.: Forecast weights future wind turbines, based on table published by Hoogendoorn [37] summarizing Peeringa et al. [35] and Gaertner et al. [36]

Power rating	Units	10 MW	15 MW	20 MW
Tower mass	mT	987	1300	1600-1780
Blade mass	mT	41	65	99
nacelle mass	mT	674	1017	1730
Rotor diameter	m	178	240	252
Hub height	m	119	150	168

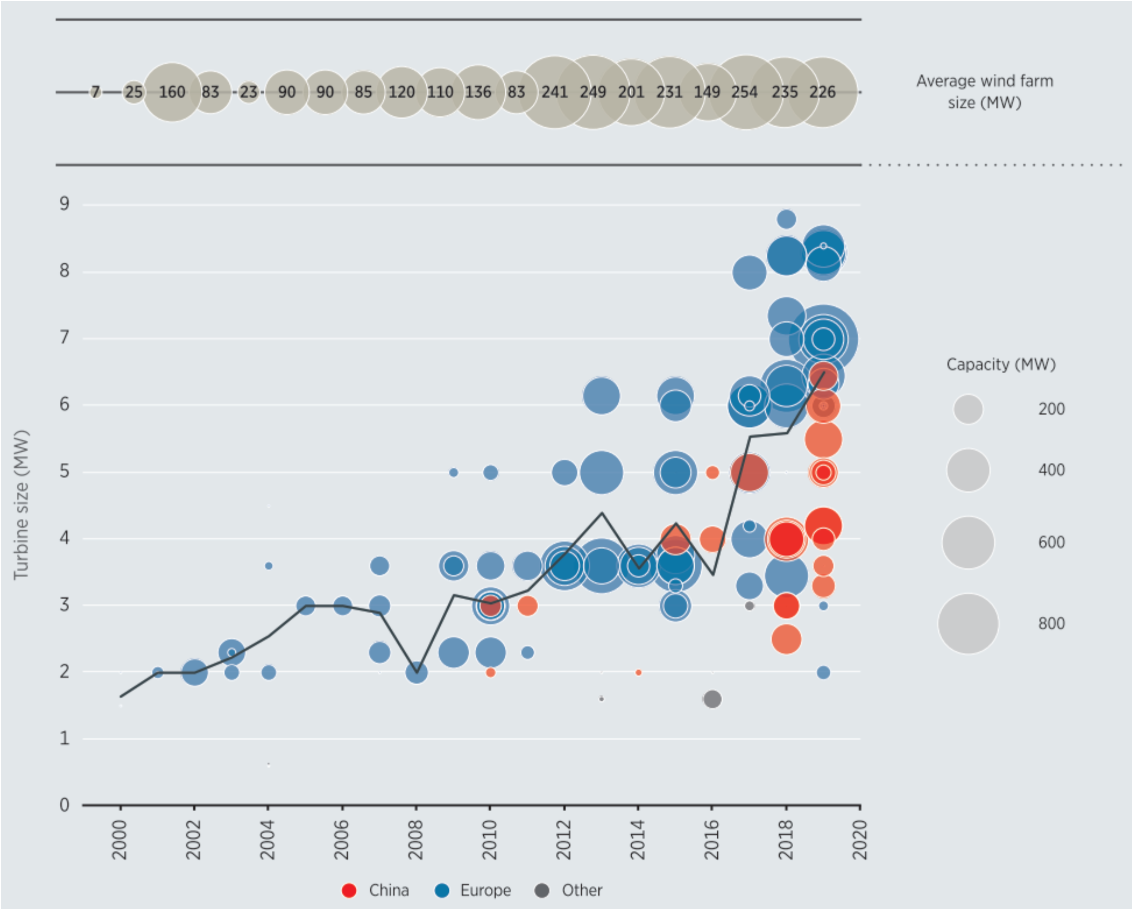

Figure 3.10.: Wind farm size and installed power rating [38]

Increasing distance from wind farm to port

During recent years the location and therefore site circumstances have changed. The trend that is visible is the increasing distance from wind farm towards the nearest port, see figure 3.11. Between 2018 and 2019 the average distance from farm to port in Europe has increased from 35 km towards 59 km [9].

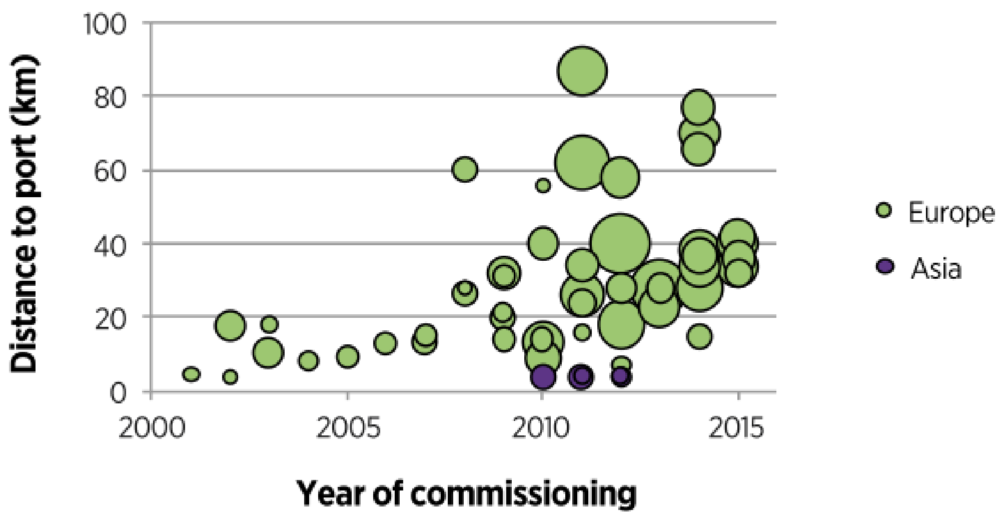

Figure 3.11.: Average distance to shore offshore wind farm [2]

The trend of moving further from the ports can be explained by the reduced availability of sites close to the various ports [9] and the favourable wind conditions further offshore [7]. See figure 3.12 for the trend in which proposed locations move further from ports. The increase in distance introduces extra challenges during installation. First of all, the costs for the transportation and the operation and maintenance will increase when the distances vessels have to travel towards their location increases [38]. As vessels are the most expensive asset during this process it is important to evaluate what the most optimal solutions for their application is in order to reduce the transportation costs [34]. An example is the application of feeder vessels [39]. Additionally, by moving further offshore the environment in which installations have to be carried out becomes harsher. This means that the installation process will become more difficult and that there is a bigger chance on delays during this process as there are less weather windows available, which also increases installation costs. The industry therefore, indicates that it will be beneficial to have an offshore wind installation vessel that is capable to perform installations in harsher environments [34].

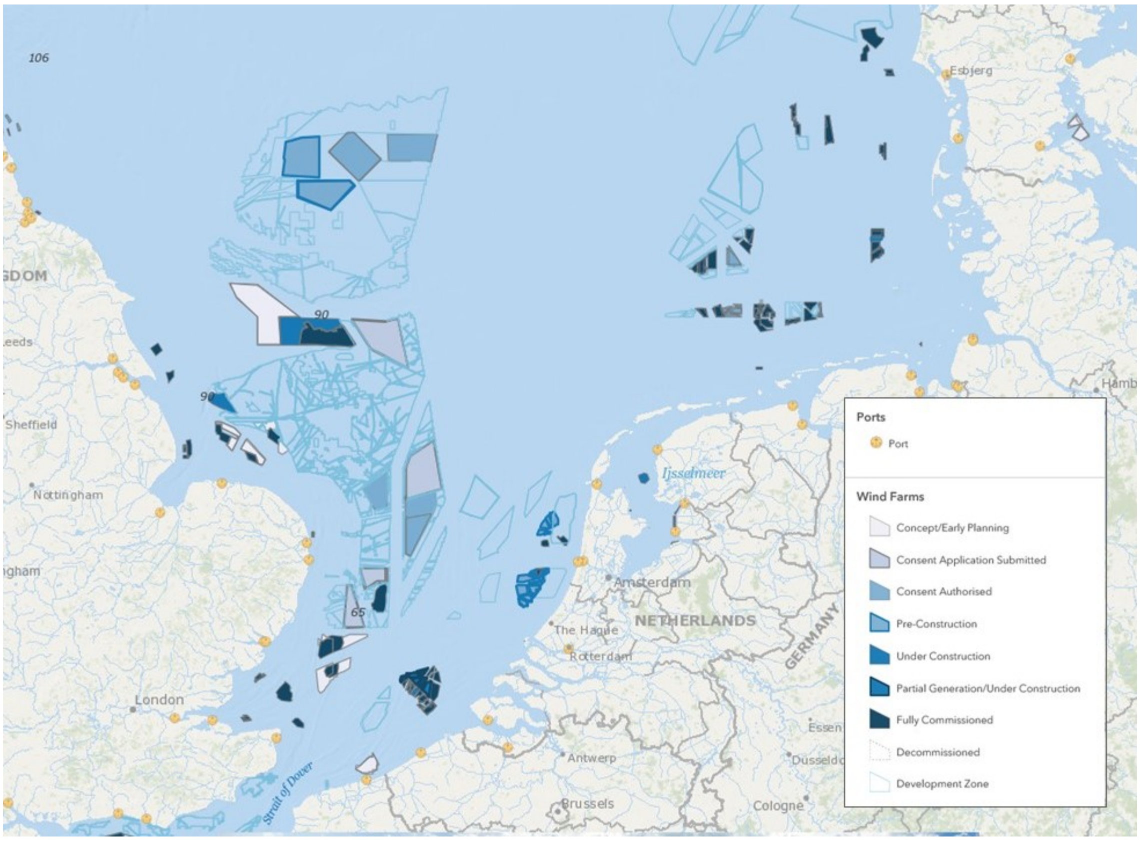

Figure 3.12.: Offshore wind farm locations Europe [40]

Increasing depth at wind farm location

Apart from the increase in distance there is also an increase in water depth in which the wind farms are installed, see figure 3.13. The average water depth of the installed offshore wind farms in Europe in 2019 was 33 meters, which is an increase of 3 meter compared to 2018 [9].

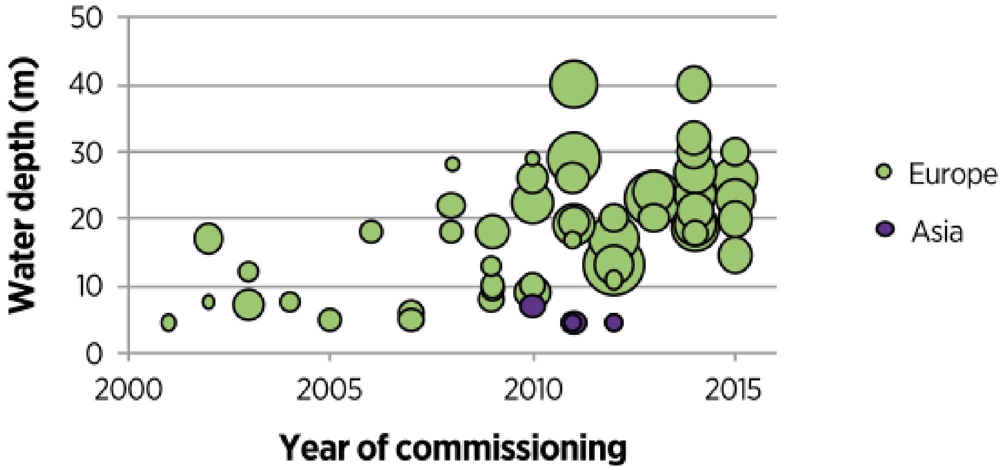

Figure 3.13.: Average water depth offshore wind farm Europe[2]

The increase in water depth may have a future impact on the properties and type of foundation that the vessels will need to install. The properties such as size and weight of the foundation are mainly driven by the water depth. Therefore, it directly impacts the requirements for the installation vessel. Examples are deck space and strength in order to transport the foundation and crane capacity in order to handle the necessary weight [41]. At the moment the monopile is the type of foundation that is used mostly because of its relatively low installation costs and the design improvements. These design improvements have led to the possibility of using the monopile in deeper waters and in combination with larger wind turbines. However, in deeper waters or in areas with a rocky soil the monopile might be facing competition from the jacket type of foundations [32]. An overview of the currently used type of foundation and the max depth at which it is used is given in table 3.2.

Table 3.2.: Foundation types in Europe [9][42][43]

Foundation type	Amount installed	Market share 2019 [%]	Water depth [m]
Monopile	4258	80.98	0-40
Jacket	468	8.90	5 - 80
Gravity base	301	5.72	0 - 30
Tripod	126	2.40	25 - 50
Tripile	80	1.52	40
Spar	6	0.11	Floating > 50
Semi-sub	2	0.04	Floating > 50
Barge	1	0.02	Floating > 50
Others	16	0.30	

3.6. Technological opportunities

The trends mentioned in the previous section introduce challenges and possible deficiencies for the current offshore wind installation fleet. Apart from the trends there are also technological opportunities that may impact the installation vessels. Research by the International Renewable Energy Agency (IRENA) has indicated four technologies which are marked as having a high potential to reduce the LCOE or have the capability to open up new markets. These four technological developments are related to tasks carried out by installation vessels and are: future generation turbines, floating foundations, repowering of sites, and the integration of turbine and foundation installation [6]. A more detailed analysis of the impact of the trends and the technological opportunities at the current offshore wind installation vessels will be carried out in chapter 4.

Future generation turbines

The technological developments in the drive train, the control technologies, and the blade will push the efficiency and reliability of future turbines even more. Therefore, the power capacity increases and the LCOE decreases. As explained in section 3.5 these developments will lead to wind turbines of which the hub heights increase to 150-168 meters in 2030 and of which the mass of the turbines is expected to grow, see table 3.1. The development in size and weight poses threats on the current offshore wind installation vessels as these have to be able to handle these increased sizes and weight.

Floating foundations

Most of the current new build offshore wind farms are located at sites with a maximum depth of 60 meters. This means that these sites are perfectly suited for using fixed foundations. However, there are also a lot of potential areas available in waters exceeding a water depth of 60 meters in which the use of fixed foundations will introduce a lot of technical and economical challenges. A more promising solution for the application of offshore wind in these areas is the application of floating foundations [33]. Additionally, floating wind can reduce the installation costs as specialised vessels such as heavy lift vessels are not necessary to install this type of foundations. Cheaper alternatives such as tugs can be applied in order to reduce installation costs [2]. The current development projects in the floating wind show a lot of progress. However, it is expected that the commercial projects with floating foundations are at least more than five years away [32]. Even though it will take at least five more years before the projects will be commercially interesting, it is important to take this development in consideration as this will mean that sites that were inaccessible before will become available [2]. Possible areas of interest for the floating wind industry are the United States of America and Japan as these countries have deep water regions that are located near areas which are having a high power demand [33].

Repowering of sites

An option during the decommissioning phase is to replace the old turbines and its foundations by new models, as explained in section 3.2. The new models most likely will have a higher power rating compared to the first models installed on site. This results in less wind turbines needed to install in order to reach the same power output, which is also beneficial in reducing the O&M costs. Moreover, as the transmission network is still intact a lot of investment costs are saved. The repowering market is expected to grow from 2030 onward as many offshore wind farms from the first generation will then reach their end of life time [6].

Integrated turbine and foundation installation
A reduction in LCOE can be achieved by moving the installation operations as much as possible towards shore. After the installation onshore a pre-assembled wind turbine or a combined floating foundation and wind turbine can be transported towards site for installation. For this transportation process tugs or customized vessels can be used [6].

3.7. Predicting the future needs

The previous sections show that the offshore wind market has changed during recent years. It indicates that these changes will continue and that there are technological opportunities for further market developments. These changes and opportunities in the offshore wind market have an impact on the vessels used during the installation phase and will be explained more in detail in chapter 4. Due to the changing market there is a lot of uncertainty regarding the future vessel requirements. To get better insight in the current forecasting methods used to predict these necessary future capabilities of offshore installation vessels market reports are selected and analysed. These reports are analysed on the approach and the factors they include to forecast the future of the offshore wind industry, see the subsection below. The high level results of these reports will not be discussed here but are mentioned in the previous sections 3.5 and 3.6. From this analysis it can be concluded that no report does include a specific analysis regarding the development of the vessel requirements. The reports do mainly focus at the costs and annual installation rate.

International Energy Agency
The International Energy Agency (IEA) works together with multiple countries to research the current offshore wind industry and to forecast its future [7].
The development of the installed amount of offshore wind turbine power and the LCOE for the period of 2018-2040 have been forecast in the IEA research. In order to determine the installed capacity in 2030 and 2040, two scenarios are used. A policy scenario and a sustainable development scenario. The policy scenario analysis the current and announced political goals and makes a cautious estimation of their implementation. The sustainable development scenario involves the political goals but also uses the current international agreements in order to assess what the grow in the market should be in order to comply with these agreements [44].
Another aspect of the report involves the analysis of suitable regions for offshore wind. This analysis gives an indication of the possible regions in which offshore wind may develop in the future. The analysis is carried out by first excluding the different areas assigned to for example shipping, military, fishing, oil and gas production, and cables. Then wind data are analysed to determine the potential capacity factor at each location available. Finally, a cost estimation is carried out for each location in order to get a LCOE value. This LCOE value can be used to compare the different regions on their potential.
Additionally, the research briefly addresses the increasing power rating and size of the wind turbines. Moreover it indicates an expected power rating of 15-20 MW and a rotor diameter of 230-250m in 2030, see figure 3.9 which describes the expect maximum turbine sizes in 2021 and 2030. These future values are based on the targets set by the industry.

International Renewable Energy Agency

As an intergovernmental organisation the International Renewable Energy Agency (IRENA) gives support towards countries in the energy transition by providing their expertise about renewable energies [45].

The forecast research published by IRENA involves a forecast of the annual installation rate, the total installed capacity, and the LCOE for 2016-2045 [2]. In order to forecast these variables the research has first determined a central scenario for the LCOE under the assumption that the offshore wind industry will be an important part of the energy mix. This central scenario is based on the different technological developments (wind farm design, turbine, foundations, electrical interconnection, installation, and O&M), the changing site conditions, and other impacts related to financing the projects, and policies. The trend of this LCOE is then validated using the trends that have been seen in the onshore wind industry in the past. Based on the trends of the LCOE a forecast for the annual installation rate is determined. Additionally, a high and a low scenario have been created by increasing/decreasing the costs with 10% compared to the central scenario.

Apart from the forecast the research also addresses the availability of the different sites. It indicates that they expect that the shallow water location will no longer be available after 2040. Moreover, it mentions the low amount of shallow water locations in the USA and Japan and the potential of using floating turbines in these regions.

WindEurope

WindEurope is an organisation that works together with different stakeholders from the offshore wind industry to improve the interest and knowledge in offshore wind worldwide. Stakeholders involved are for example offshore wind farm operators, offshore contractors, classification societies, and universities [46].

WindEurope has forecast the annual installation rate in Europe for 2020-2030 by applying a bottom-up approach [47]. This bottom-up approach indicates that the data have been collected at each individual country. Additionally, information is collected by contacting various national energy associations and stakeholders in the offshore wind industry. Based on the information gathered via the sources above three scenarios have been created, a central scenario, a high scenario, and a low scenario. For each of these scenarios it is indicated what the necessary policies are in order to fulfil them.

Gap between forecast reports and vessel requirements

The research and market forecast mentioned above share a lot of similarities. First of all, it can be concluded that all of the reports do apply a similar forecasting strategy in which they define 2 or 3 scenarios. The central scenario is in all cases based on the current policies and technological developments. A limited amount of information is publicly available regarding the policies and numbers these forecasts are based on.

Additionally, the forecast variables that are mostly focused on are the costs and the expected annual installation rate. All of the reports do indicate the trends related to turbine sizes and changing wind farm site conditions. However, no forecasts are being made regarding these variables. As explained in section 4.3 these variables do have a big impact at the vessel design and need to be known for the designer in order to optimise the design. This indicates that there is a gap between the current

market forecasting reports and the future vessel requirements.
To conclude, the market reports analysed mention that the forecasts are based on the current policies but do not elaborate in detail what these policies are. The important variables for determining the vessel requirements are not being forecasted, only the variables costs and annual installation rate are described.

3.8. Conclusion

From this chapter it can be concluded that the offshore wind market is a market that did grow fast in recent years and is expected to continue growing in the upcoming years. This grow does introduce a need for an increased installation capacity. The large trends in the market that have an impact on the installation process are an increase in turbine size, an increase in distance between offshore wind farm site and port, and an increase in water depth. Apart from the trends some technological opportunities have been identified for the offshore wind market which are the introduction of floating foundations, repowering wind farms, and the installation of integrated turbine and foundation installation. All these developments and opportunities do introduce uncertainties about the future offshore wind market. There are market reports available that do give insights in the possible developments of the offshore wind market under this uncertainty. However, the variables predicted are related to the costs or the necessary installation capacity. The market reports do not give insight in the requirements that are needed for future offshore wind installation vessels, which is the first gap identified in this research.

More insight can be given
in the trade offs
of the ship design when
a dynamic input situation is used

4 Installation vessels

In the previous chapter it is concluded that the offshore wind market is a market that is evolving. It involves a lot of factors that will change in the next couple of years which have an impact at the vessels currently being used during the installation process. To get a better understanding of this impact, the installation process and current installation fleet will first be described in sections 4.1 and 4.2. Afterwards section 4.3 will discuss the impact of the trends presented in section 3.5 at the current offshore wind installation fleet. Section 4.4 will give insight in the current methods used for designing new vessels for the future offshore wind market, by describing the current market prediction and concept development methods. Finally, section 4.5 will give the conclusions of this chapter.

4.1. Offshore wind installation process

A first overview of the actions to be carried out during the manufacturing, installation, and decommissioning of the offshore wind farm are visible in figure 4.1.

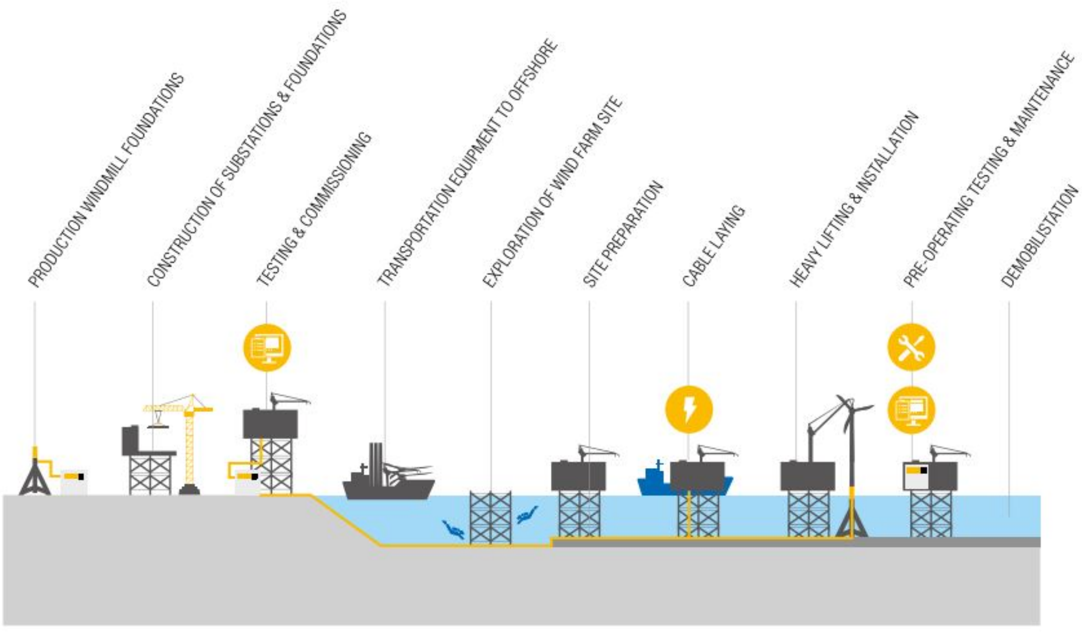

Figure 4.1.: Offshore wind farm installation [48]

Figure 4.1 contains both the onshore and offshore activities. The involvement of offshore contractors starts at the transportation of the different components from the manufacturing site towards the installation site [20]. This research will focus on the transportation and heavy lifting & installation phases as mentioned in figure 4.1.

This involves the transportation of the components and installation of the foundation and the wind turbine. Cable laying and the installation of the substation will not be included as it is not expected that a lot of changes will occur in the requirements for the necessary installation vessels.

Transportation
The foundation and the wind turbine installation phases both require the transportation of components. These components are the foundation, the transition piece, the tower, the nacelle, the hub, and the blades, see figure 3.2. Kaiser and Snyder described different transportation strategies [39]:

- **One installation vessel**: the selected installation vessel is responsible for transporting and installing the components. Therefore, it is expected to sail towards and from the installation site.
- **Multiple installation vessels**: in this situation there are multiple installation vessels working on the same offshore wind farm installation project. As these vessels do work independently on the same project, the installation time reduces.
- **Feeder concept**: this strategy involves an installation vessel that stays at the installation site while another vessel (the feeder vessel) supplies the components from port. The advantage of this method is that costs can be saved as the installation vessel does not need to travel to pick up the components. However, this method does also introduces a risk as the components need to be transferred from the feeder vessel towards the installation vessel.
  Extra care should be taken when applying a feeder for the installation of the wind turbine due to the vulnerability of the nacelle (for example acceleration limits [2]) [49]. Therefore, a self lifting vessel is necessary in order to assure a stable platform when transferring the components from the feeder vessel towards the installation vessel [49].
  The trade off whether or not to apply a feeder concept in general is determined by the carrying capacity and transit speed of the installation vessel, the distance from installation site to shore, and the size of the various components [39].

Foundation installation
The foundation installation method depends on the type of foundation used [50]. A general overview of the installation methods will be given for the monopile, jacket, and floating foundation types, see figure 4.2. These types are selected as these are the most common used type of foundations (table 3.2) or have a big future potential (see section 3.6).

- **Monopile**: after transportation the monopile is up-ended at the installation site and placed at the seabed using a crane and a gripping tool. The monopile is secured by driving it into the seabed using a hammer [51]. The installation of monopiles is currently carried out by jack-up vessels or floating vessels [20].

- **Jacket**: the installation of jackets involves a pre-piling phase in which a set of piles are installed at the seafloor. After the pre-piling phase the jacket is lifted from the deck and installed over the piles pre-installed and secured by grouting the two components together. Both jack-up vessels and floating vessels can be used for this operation [20].

- **Floating**: wind turbines using floating foundations are pre-assembled near shore and then towed towards their installation location [50].

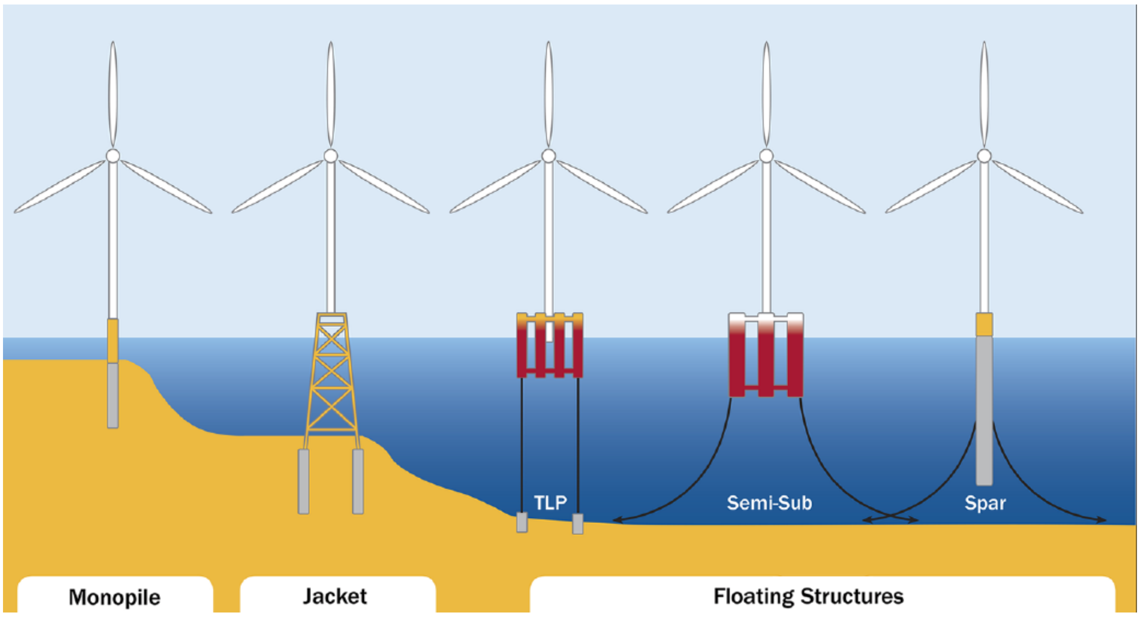

Figure 4.2.: Foundation types [52]

Additionally, the installation of the transition piece is carried out during foundation installation phase. This involves the transportation of the transition piece and the installation using a crane [20].
The important vessel requirements during the foundation installation phase as described by Kaiser and Snyder are the water depth at which the vessel can operate and its crane capacity in order to handle the weight of the foundation. The maximum lifting height is not indicated as limiting factor as the foundation only need to be lifted slightly above the main deck of the vessel [39].

Wind turbine installation

The installation process of the wind turbines can vary due to the degree of pre-installation. At the moment the general approach is to transport the tower, nacelle, and blades as separate parts towards the installation site. The components are then installed in the following sequence [20]:

1. **Tower**: the pre-installed tower is lifted and installed at the transition piece.

2. **Nacelle**: the nacelle and the hub are together installed at the top of the tower.

3. **Blades**: finally, the blades are separately installed and connected to the hub.

The method described above is currently the preferred method in the offshore wind sector. It should be remarked that there are more installation sequences available differentiating on the amount of pre-installation of the components [20][39]. An interesting installation sequence for the future offshore wind market is the installation of fully onshore assembled wind turbines as this reduces the amount of lifts offshore [20]. Moreover, it has the potential to reduce the LCOE as work will be shifted towards shore locations, as explained in section 3.6.
The vessel types currently used for the installation of the turbines are jack-up vessels [49]. The current market has not used heavy lift vessel a lot for the installation of wind turbines because of the motions that do occur during the lifting operations at the heights at which the turbines need to be installed [39]. However, it is mentioned that an improvement in installation time can be achieved when floating vessels can be used for installing wind turbines [20].
The vessel characteristics that are indicated to be important during this installation phase are the cargo carrying capacity of the vessel that determines the amount of components it can carry, the maximum lifting height which impacts the maximum hub height of the turbine it can install, the crane capacity which relates to the weight of the turbine, and the water depth at which the vessel can operate [39].

4.2. Current installation fleet

The current offshore wind installation fleet can be characterised by the following two main types of vessels: the jack-up vessels (used for installing wind turbines and foundation) and floating heavy lift vessels (used for installing foundations) [50].

Jack-up vessels
Jack-up vessels are characterised by the capability of lifting their hull out of the water, see figure 4.3. This is possible due to a set of legs which are being placed at the sea floor in order to lift the vessel [50]. Within the jack-up vessel fleet a distinction can be made between self-propelled and non-propelled type of vessels [39]. In recent years the jack-up fleet has evolved towards vessels that are self-propelled, have an efficient hull shape in order to reduce the resistance, and have an optimised deck area in order to transport as many components as possible [50].

Figure 4.3.: Jack-up vessel Pacific Osprey [53]

Examples of current state of the art jack-up vessels used for the offshore wind industry are the Pacific Orca, the Vole au vent, and the Aeolus. For their capabilities, see table 4.1. To put the numbers in perspective, the crane capacity of the Pacific Orca is sufficient to install a nacelle having a weight of 500 tonne at a hub height of around 120 meter. Moreover, the deck area is sufficient to carry twelve offshore wind turbines having a rating of 3.6 MW [54]. When the rating increases, the amount of turbines that can be carried decreases.
The vessels mentioned in table 4.1 indicate the current capabilities of the fleet and help identify whether or not the current fleet is capable of installing the growing offshore wind turbines.

Table 4.1.: Specifications state of the art offshore wind jack-up vessels

	Unit	Pacific Orca [55]	Vole au vent [56]	Aeolus [57]
Owner		SPO	Jan de Nul	Van Oord
Year built		2012	2013	2014
Length overall	[m]	160.9	169.3	139.4
Breadth overall	[m]	49.0	60.0	44.5
Draught	[m]	6.0	7.5	8.6
Speed	[kts]	13.0	12.0	10.5
Maximum water depth	[m]	60	50	40
Hook height above deck	[m]	97	115	109
Maximum lifting capacity[1]	[mT]	1,200	1,500	1,600
Cargo area	[m^2]	4,300	3,535	3,775
Cargo capacity	[mT]	8,400	6,500	5,955

[1] Max lifting capacity is lower at max hook height

See figure 4.4 and 4.5 to get better insight in the spread of lifting and transportation (deck area) capacity in the jack-up fleet.

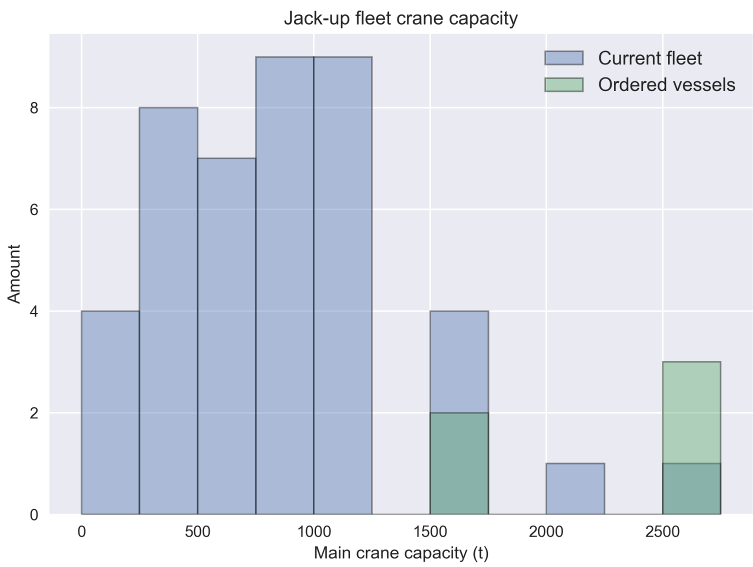

Figure 4.4.: Jack-up fleet main crane capacity

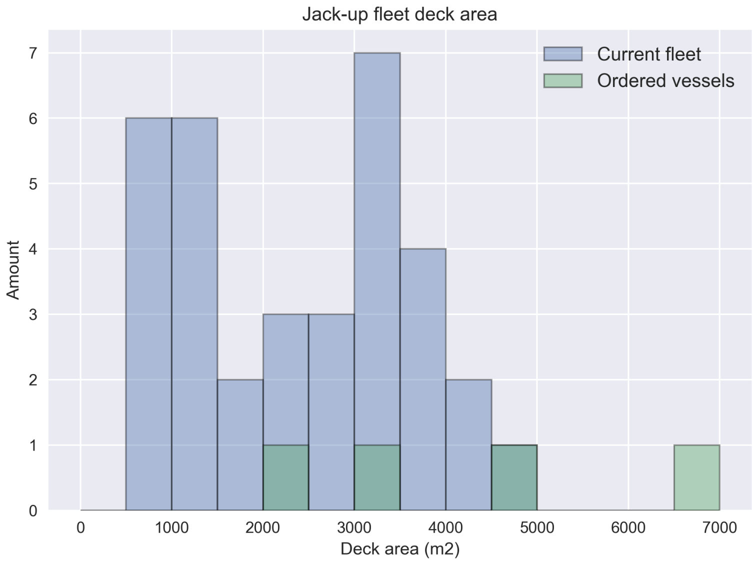

Figure 4.5.: Jack-up fleet deck area

Floating heavy lift vessels

Another type of vessel that is used in the offshore wind industry are floating heavy lift vessels. Most of these vessels have served the offshore oil and gas industry, but are recently also serving the offshore wind industry [50]. These vessels do not have the capabilities to lift themselves out of the water, but are equipped with high capacity cranes. The installation of wind turbines is seldom carried out by heavy lift vessels. These types of vessels are more often used to install the foundations, substation, or a fully pre-assembled wind turbine [39]. Four types of heavy lift vessels can be distinguished within the offshore wind industry [58]:

- **Barges**: a barge is a vessel type that is used both for offshore installation and transportation. Generally these types of vessels do not have a propulsion system on board and therefore require a tug. In case of offshore installation a crane can be installed permanently or temporally in order to carry out the required lifting operations [50].

- **Monohull vessels**: these are vessel types that have a single hull and are self-propelled. A crane is installed at the deck of the vessel to provide the heavy lift capabilities.

- **Semi-submersibles**: a semi-submersible vessel is a vessel that is capable of submerging itself which can be used during lifting operations. For an example of a semi-submersible vessel, see the Sleipnir in figure 4.6.

- **Sheerlegs**: a sheerleg is a vessel that has a similar hull shape as a barge at which a heavy lift crane is installed. A big difference between the barge and a sheerleg, is that the crane of a sheerleg cannot rotate separately from the vessel [41].

Figure 4.6.: Heavy lift vessel Sleipnir [59]

Examples of heavy lift vessels that are currently state of the art vessels in the offshore wind market are the Seaway Strashnov, the Asian Hercules III, and the Sleipnir. For the technical specifications and capabilities of these vessels, see table 4.2.

Table 4.2.: Specifications state of the art offshore wind floating heavy-lift vessels

	Unit	Seaway Strashnov [60][61][62]	Asian Hercules III [63][64]	Sleipnir [65]
Owner		Seaway 7	Boskalis	Heerema
Year built		2010	2015	2019
Vessel type		Monohull	Sheerleg	Semi-submersible
Length overall	[m]	183.0	106.4	220.0
Breadth overall	[m]	47.0	52.0	102.0
Draught	[m]	8.5	5.5	12.0
Speed	[kts]	12	7	10.0
Hook height above deck[1]	[m]	130.2	120	165
Maximum lifting capacity[2]	[mT]	5,000	5,000	10,000
Cargo area	[m^2]	3,950	-	12,000
Cargo capacity	[mT]	14,228	5,041	20,000

[1] For the Oleg Strashnov and Sleipnir it indicates height above water level
[2] Only the max capacity of one main crane is included in case of multiple installed

In order to get a better insight in the lifting capabilities of the overall floating heavy lift fleet, see figure 4.7. From this figure it can be concluded that the floating heavy lift vessels do outperform the current jack-up fleet in terms of lifting capacity. However, it should be remarked that the installation of the wind turbines is a challenging task for floating heavy lift vessels due to the introduced motions [49].

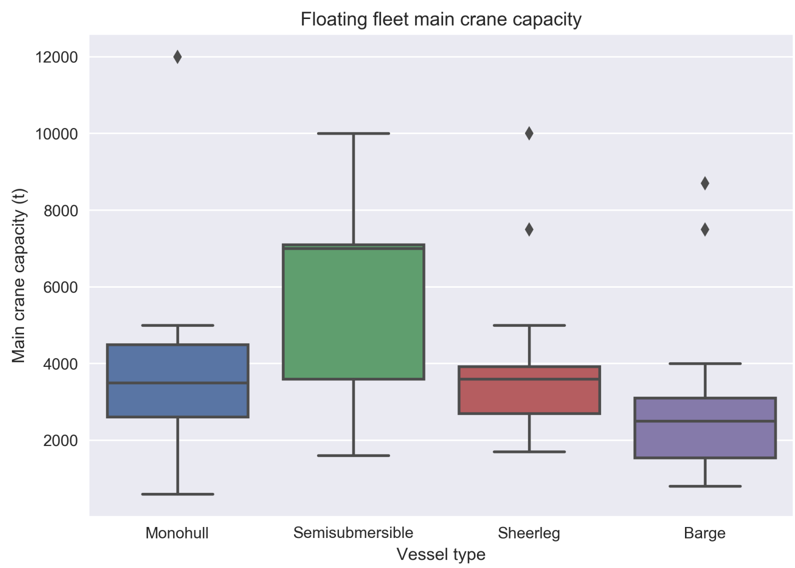

Figure 4.7.: Floating fleet main crane capacity, data based on [66]

4.3. Impact of the changing offshore wind market on the installation fleet

The trends and technological developments in the offshore wind industry described in section 3.5 and 3.6 do introduce new requirements for the offshore wind installation fleet. It can be concluded that the currently announced future requirements tend to be higher than the current capabilities of the fleet, which indicates the need for new vessels in the future. Moreover, vessels already received upgrades 4 to 8 years after they were built due to the fast changing market. See the subsections below for a more in depth analysis of the impact of the trends at the current fleet.

Impact of increasing component size and weight

The increasing turbine sizes and increasing water depth at which the wind farms are installed do increase both the size and the weight of the various components, as explained in section 3.5.

An example is the increasing weight of the monopile foundations. In 2002 monopiles having a weight between 180 and 230 tonnes are used for the installation of the Horns Rev field in Denmark (2.0 MW turbines, water depth 6-14 meters [67]). The monopiles used in 2016 for the installation of the Galloper wind farm (6.3 MW turbines, water depth 27-36 meters [68]) had a much bigger weight of up to 2,000 tonnes [69]. The current fleet of jack-up vessels is not capable of installing these 2,000 tonnes monopiles, see table 4.1. The heavy lift vessels, however have the lifting capabilities of handling these weights, see table 4.2. In order to be able to handle these increasing weights various jack-up vessels have performed upgrades. An example is the Aeolus, which has received a crane update in 2018 from 900 towards 1,600 tonnes [70]. It should be remarked that the Aeolus is built in 2014 and already needed a crane update after 4 years in service to keep up with the unexpected market developments, while in general a more sustainable life time for a vessel is around 25

years [10].
Another aspect that introduces a big challenge for the future installation vessels is the height at which the nacelle need to be installed [71]. This installation height increases due to the increase in hub height and the increase in water depth and may pose problems for the current jack-up fleet, see figure 4.8. The current hub heights for the introduced 10 MW turbines is around 119 meter, while future 20 MW turbines may reach hub heights of around 168 meter, see table 3.1. The current maximum hook height above deck of the various jack-up vessels that carry out these operations is 115 meter, see table 4.1. As the current jack-up fleet is designed to install at max 6 to 10 MW turbines new vessels or upgrades are necessary to account for these increasing heights [20]. There might be a point in the future when floating vessels become more interesting for the installation of nacelles as these do not have dependency on the water depth [71] or will be capable of installing the nacelles faster compared to jack-up vessels [20].

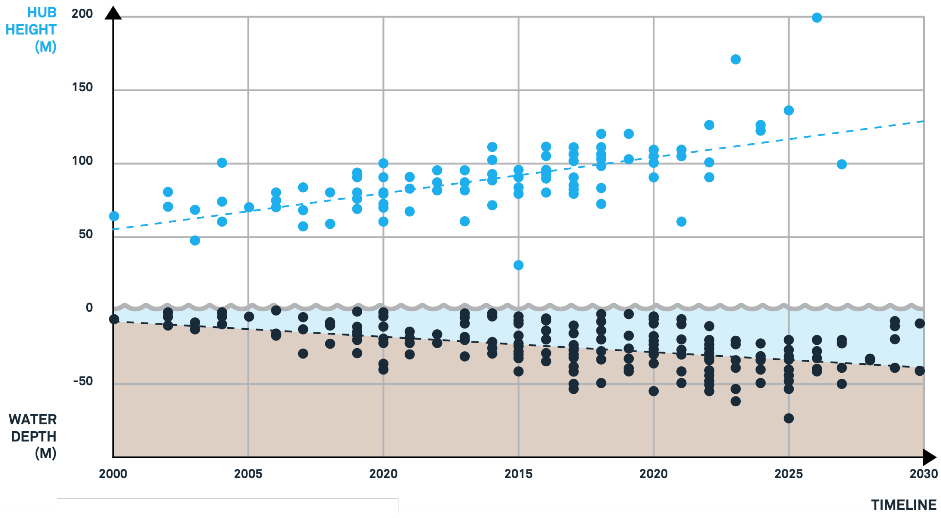

Figure 4.8.: Trends of hub height and water depth [71]

Because of the increasing weight of the foundations and the limitations in lifting capacity for the current jack-up fleet a shift is going on in the type of installation vessels used for installing the foundations. In previous years the foundation and wind turbine installation were performed by jack-ups. However, in recent years floating vessels have become more interesting. First of all, these are capable of lifting the heavier components. Moreover, they save time as there is no need to jack up the vessel and therefore are more cost effective and reduce the LCOE [20].

Impact of increasing distance from offshore wind farm to port
In recent years the distance from the installation site towards ports have increased. This means that the installation costs will increase and that various transportation strategies and vessels specifications for these strategies need to be reconsidered in order to stay cost effective [38]. The possible transportation strategies are presented in section 4.1.
As mentioned before, the choice between these transportation strategies is a combination between the distance, transit speed of the vessel, and its carrying capacity, see section 4.1. The carrying capacity is dependent on both the area available for

transporting the cargo and the size of the component. The Pacific Osprey, see figure 4.3, that has similar specifications as the Pacific Orca is originally designed to carry twelve 3.2 MW turbines. This vessel built in 2012, already received a crane update in 2020 in order to install and transport turbines of 12 MW. However, the amount of 12 MW turbines it is capable to transport is reduced to 3, because of the increasing size of these turbines [72].

Reducing the LCOE

The offshore wind market is trying to reduce the LCOE as much as possible to be competitive with other energy sources. As explained the LCOE can be lowered by lowering the installation costs by having a vessel that is being cost effective.
An opportunity mentioned in section 3.6 is the installation of pre-installed wind turbines in order to reduce the amount of lifts and offshore working hours. This opportunity introduces new types of vessels that are purposely build for this task. An example is a concept by Huisman Equipment, the Wind Turbine Shuttle. The design focuses on improving the installation efficiency by having a vessel that is capable of fast transport and installation. Therefore the design involves the transportation of two fully-assembled wind turbines at high speed, and a design that has favourable motion characteristics for the installation process [73].

Figure 4.9.: Wind turbine shuttle [73]

The drive to reduce the LCOE also leads to the fact that owners are pushing towards more efficient vessels. Research shows that the most optimal vessel in terms of costs is a vessel that is perfectly fit for the specific foundation, turbine, site conditions, water depth, and soil conditions. In order to stay competitive in the whole offshore wind industry and potential other offshore industry, owners prefer a vessel that is as efficient as possible, but still has some flexibility [49].

Demand and supply
The current offshore wind installation fleet consists out of approximately 137 vessels of which 82 vessels are jack-up vessels and 55 vessels are heavy lift vessels. Around 61% of the installation fleet is based in Europe while the other 39% of the fleet is based in Asia, mainly China. At the moment there are 16 jack-up vessel under constructions of which 8 will be delivered towards the Chinese market, 4 towards the European Market, 3 towards Japan, and 1 towards the US [8].
The current supply in the European market is sufficient. Worldwide there are only 9 vessels that have the capability of installing turbines exceeding a power rating of 10 MW. Only 4 vessels are capable of installing the 12 MW turbine model announced [74]. In order to keep up with this increasing demand, it is necessary that more vessels are built or upgraded in such a way that they can handle these sizes [8][20].

4.4. Current concept development process

The two previous sections describe the need for new and upgraded vessels. The goal of this section is to get a better understanding of the announced and performed vessel upgrades, the ordered vessels, and the requirements on which these are based. In order to accomplish this goal announced upgrades of the current fleet, new vessels, new concepts, and published design reports will be discussed.

Upgrades for the current fleet
The fast changing market causes a situation in which current vessels are not capable of meeting the requirements for installing the new wind turbines, as explained in section 4.3. In order to be able to install these new wind turbines some vessels in the fleet do receive crane updates in terms of lifting capacity and height. It should again be remarked that the problem of not reaching a more sustainable lifetime of 25 years due to the fast developments in the market is a general problem in the offshore wind industry [10]. See the examples below for some vessels that received an upgrade or will receive an upgrade:

Aeolus
The Aeolus of Van Oord received a crane update in 2018 just 4 years after its launch to increase the lifting capacity from 900 to 1,600 tonnes [70].

Blue Tern
This vessel is acquired as the Seafox 5 by Fred. Olsen Windcarrier [75]. The Seafox 5 is originally built in 2012 and received a crane upgrade in 2018 to extend the boom length to have the capability of installing 6.0 MW turbines in Germany at the wind farm Merkur [76].

Brave Tern
The Brave Tern, a vessel operated by Fred. Olsen Windcarrier and built in 2013 will receive a crane upgrade in 2022. This new crane will improve the lifting capacity from 800 to 1,600 tonnes. The maximum hook height increases to 165 meter above deck at which it will be capable of lifting 400 tonnes. This prepares the vessel for the hub heights required for the future 12 MW turbines [77].

Pacific Osprey
A vessel operated by SPO and built in 2013 received a crane update in 2020 resulting in a lifting capacity of 1,200 tonnes and a lifting height of 132 meters above the deck. This gives the vessel the capability of installing the recently announced 10, 11, and 12 MW turbines [72].

Ordered and concept vessels
As the current fleet is struggling with installing the new announced 12 MW turbines, new vessels are ordered that are able to handle these new turbine sizes more efficient [78]. The new vessels that enter the market and the wide spread of concept vessels that are announced can be separated in the following four segments: floating vessels, jack-up vessels, vessels for installing pre-assembled wind turbines, and equipment.

Floating vessel - Alfa lift
Floating vessels that are specifically built for the installation of offshore wind foundations and component transportation are entering the market. An example is the Alfa lift from OHT.
The Alfa lift is a vessel that is expected to be operational in 2021 and is specifically built for installing offshore wind turbine foundations, see figure 4.10. It combines a semi-submersible vessel design with a large crane of 3,000 tonnes and an available deck area of 10,000 m^2. This gives the vessel the opportunity to transport and install up to eleven monopiles and transition pieces each having a weight of 2,000 and 400 tonnes. Moreover, it provides the vessel with flexibility in ways that it is also capable to operate in the oil and gas industry and the heavy transportation market [79].

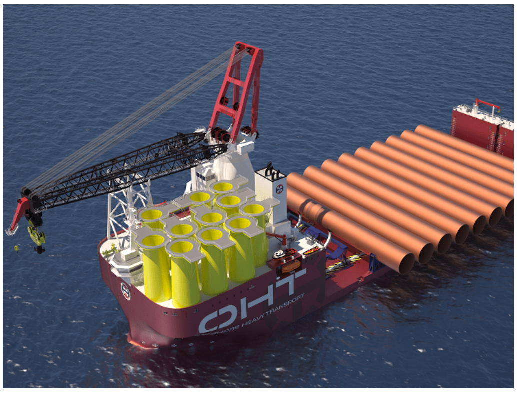

Figure 4.10.: Alfa lift [79]

Jack-up vessel - Voltaire
The design of the current operating jack-up vessels has improved to handle the new increased turbine sizes. An example of a future jack-up vessel is the Voltaire ordered by Jan de Nul.
This vessel, designed to install both foundations and wind turbines is scheduled to be delivered in 2022, see figure 4.11. The vessel is designed in such a way that it can work in deeper waters of up to 80 meters, can lift the turbines to higher heights of 165 meter above water level, and is capable of handling weights of 3,000 tonnes [80]. These specifications are a large increase when comparing this vessel with the current state of the art vessels described in table 4.1.

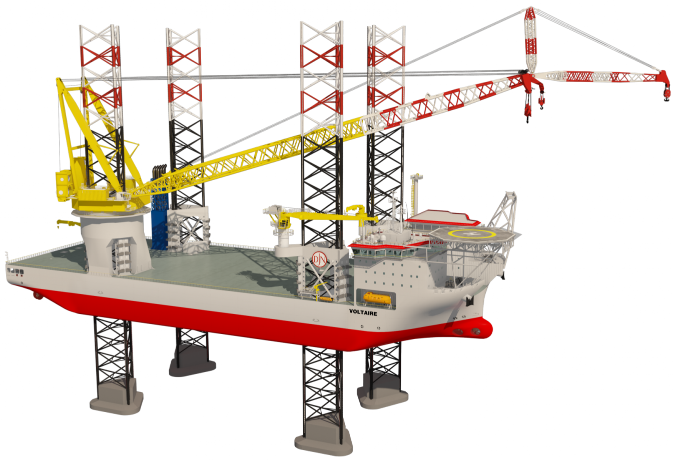

Figure 4.11.: Voltaire [81]

Vessel for pre-assembled wind turbines - Wind Turbine Shuttle

More vessel concepts are being published that have the capability of installing fully pre-assembled wind turbines. An example of a concept that has these capabilities is the Wind Turbine Shuttle by Huisman Equipment that has been introduced earlier in this report, see figure 4.9.
As explained the Wind Turbine Shuttle is capable of installing and transporting two fully assembled wind turbines. By reducing the amounts of lift offshore and having a transit speed of 14 knots it is capable of increasing the installation efficiency [73].

Equipment - Offshoretronic

Various types of equipment are introduced in the offshore wind market in order to increase the efficiency of the lifting operations and the installation process in general. An example is an add on developed by Offshoretronic.
Offshoretronic has developed an add on for one of their vessels which gives the vessel the flexibility of both installing and transporting foundations (without add-on) and fully-assembled wind turbines (with add-on, see figure 4.12) [82].

Figure 4.12.: Concept design offshoretronic [82]

Research in future offshore wind installation vessels
Only a limited amount of information is publicly available regarding research about future offshore wind installation vessels.
A first research is carried out under project LEANWIND. This project has the goal to reduce the life cycle costs of an offshore wind farm and is a collaboration between European industry and various academical partners [34]. The design approach used in this report is the design spiral. However, the design spiral approach does not contain a requirement definition phase [83]. Therefore, four different wind farm sites are determined in this research based on the input of the various industry partners. At each of these sites a suitable foundation type and wind turbine is selected, which together define the requirements for the future vessels [49]. Based on these requirements, the current fleet, and the current known technological developments three concepts have been generated [34]:

- **FTIJ**: a jack-up specialised for the transport and installation of foundations
- **WTIJ**: a wind turbine installation and transportation jack-up
- **FTIV**: a floating vessel for the transportation and installation of foundations

Another approach that is being used to define new concepts for the offshore wind installation market is to design a vessel for a specific installation method. Examples are two reports that describe solutions for the installation of fully-assembled wind turbines in order to have a more efficient installation process [37][84]. Both reports indicate that an expected size and weight for future offshore wind turbines is selected for which the vessel is designed. The final design proposed by Hoogendoorn involves a semi-submersible with an adapted aft on which two cranes are installed, see figure 4.13. Krishnakanth proposes to use a small waterplane area twin hull (SWATH) vessel for the installation of fully assembled wind turbines.

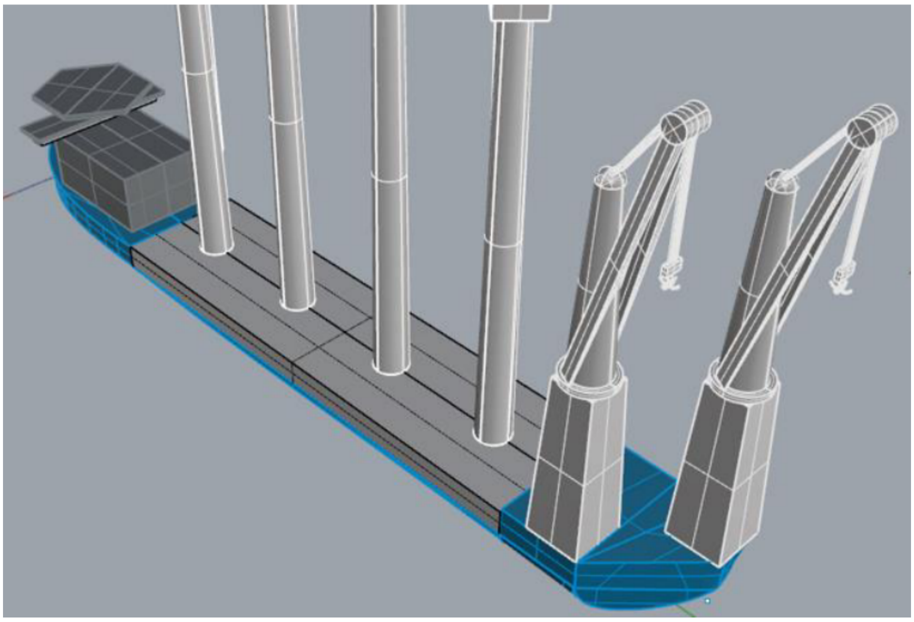

Figure 4.13.: Parallelogram wind turbine installation vessel [37]

4.5. Conclusion

In this chapter the current offshore wind installation fleet is discussed and the impact of the changing offshore wind market at these vessels. By combining the findings in this chapter and chapter 3 an answer on the first sub question can be given: *How is the offshore wind industry evolving and what is the impact at the requirements of the current type of installation vessels?* From sections 3.5 and 3.6 it can be concluded that the offshore wind industry has changed in recent years and is expected to change further in the next years. Apart from future technological opportunities such as floating wind turbines and fully pre-assembled wind turbines these changes are visible in the increasing turbine sizes and the increasing distance from wind farm to port. In recent years the power rating of the wind turbines has increased from a maximum of 3 MW in 2010 towards 12MW in 2021. The impact of this increase is that the hub heights at which the components need to be installed by the installation vessel increases to a height of 119 meters. At the moment there are only 4 vessels capable of installing the announced wind turbines having a power rating of 12 MW. The increase in distance from wind farm to port indicates that the installation vessels need to travel larger distances, which increases the installation costs. Additionally, the increasing component size cause a decreasing transportation efficiency as less components can be carried in one trip.
From the analysis in this chapter it can be concluded that the current offshore wind fleet needs to be expanded because of the increasing demand for more installation capacity and the harder requirements because of the wind turbine developments. The changes in the offshore wind market are going at such a pace that the life time for vessels reduces from 25 to 10 years or even less. At the moment there are no clear guidelines available for designers to face this problem. This is a gap in the literature which need to be solved in order to prevent under and over designing the vessels. It can be concluded that the design reports available use as starting point a static situation. They choose one specific wind farm or one specific installation method. However, more insight can be given in the trade offs in the ship design when a dynamic input situation is used.

The approach of this research follows the first two stages of the concept development phase of systems engineering

Methodology 5

From the problem definition it can be concluded that the focus of this research is to create a framework that provides the ship designer a better insight in the impact of the changing market on the future design of offshore wind vessels. It is of importance to select a design approach that contains both an analysis of possible future vessel requirements and vessel concepts. A commonly used design approach is the ship design spiral, which visualizes the design process. However, this method only describes how the design process should be, not what the requirements for the vessel should be [83]. An approach that does take into account the requirement definition and concept designs in its design approach is systems engineering [83]. This method is very suitable to get more insight in the future aspects of wind turbine installation vessels.
This chapter will introduce systems engineering and describes how systems engineering will be applied in this research. First of all, the systems engineering process will be described in section 5.1. Afterwards section 5.2 will give the implementation for systems engineering in this research. Section 5.3 discusses the conclusion of this chapter.

5.1. Systems engineering process

In order to get a better understanding of the requirements of the vessel design systems engineering uses a system thinking approach. This is an approach that solves problems by taking a holistic approach, it sees problems as a component of a bigger system and investigates the relationships within this system [83]. By investigating the system the objectives of the vessels are discovered. These objectives are then used to define the necessary vessel functions and the environment in which the vessel should be capable to carry these out. This is used as input for the vessel requirements.
In systems engineering approach three main parts can be identified [85], see figure 5.1:

- **Concept development**: In this phase the problem is analysed using the systems thinking approach. This results in system functional specifications (a set of requirements for the design in order to comply with the needs) and defined system concepts.
- **Engineering development**: This phase ensures a proper transformation from concept design towards a feasible detailed design that meets all the requirements. Resulting in the system production specifications and the production system.
- **Post development**: Involves the production, the commissioning, the operation, and the support of the final design. By delivering the installed operational system and its operations and maintenance documentation as output.

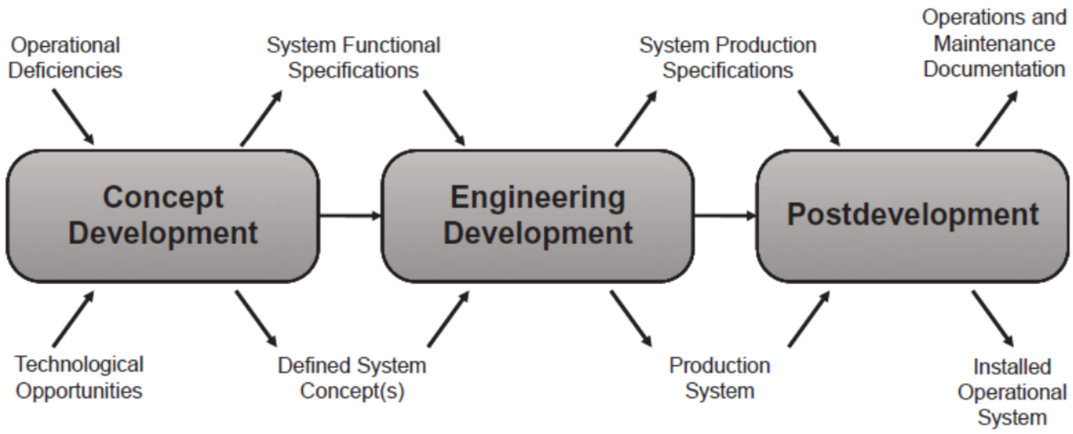

Figure 5.1.: Systems engineering process [85]

In this research the focus will be on the first stage of systems engineering, the concept development stage. It will only focus on this stage because it meets the goals defined in this research. First of all, it is capable of handling the changes in the offshore wind market as inputs. Secondly, the output of this stage is a set of functional specifications which can be used in combination with the input to analyse the impact of the market changes at the installation vessel requirements.

Concept development
The concept development phase consists out of three separate stages, the needs analysis, the concept exploration, and the concept definition stage [85], see figure 5.2:

- **Needs analysis**: the input values for the needs analysis are operational deficiencies (for example the growing wind turbines that impose a deficiency for the current installation fleet) and technological opportunities (for example the introduction of floating wind turbines). These inputs are used to define the system operational effectiveness (the objectives that the design should accomplish) and system capabilities (it is feasible that there is a system that accomplishes the objectives).

- **Concept exploration**: In the concept exploration phase the output of the needs analysis, the operational effectiveness, is used as input to explore possible concepts that provide a solution for the defined problem (for example various vessel designs that all meet the objectives). Based on the concept exploration a set of candidates that solve the problem will be given as output. Additionally, the operational effectiveness input will be used to create more detailed set of requirements by involving the requirements of subsystems (for example the requirements for the crane on the vessel instead of the general objective that the vessel should be able to lift cargo).

- **Concept definition**: This phase of the concept development is about the analysis of the different candidates from the concept exploration phase. A set of defined functional specifications will be used to give an insight in the performance of each candidate. The performance assessment makes it possible to select the most suitable candidate for this problem.

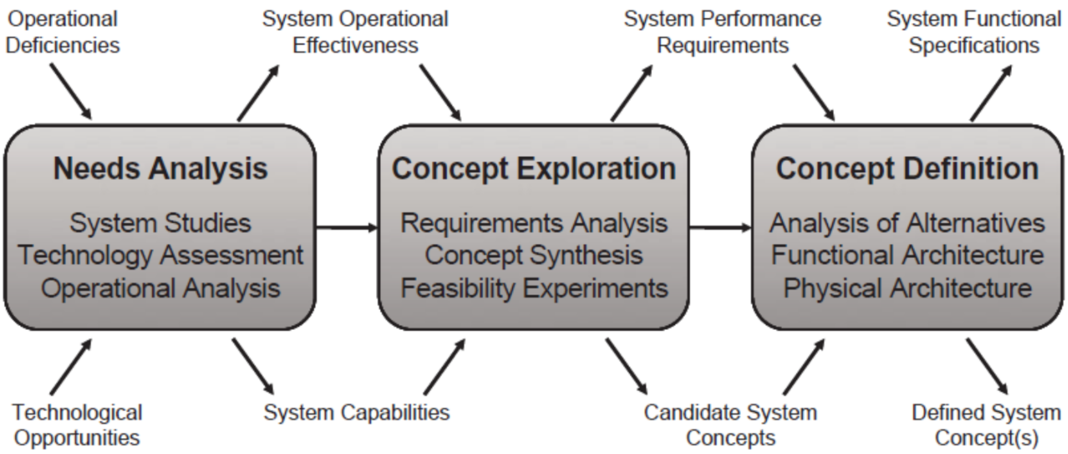

Figure 5.2.: Concept development process [85]

5.2. Research approach

The approach of this research will follow the first two stages of concept development mentioned in section 5.1. The offshore wind market is the driving factor behind the operational deficiencies and technological opportunities due to the developments mentioned in section 3.5 and 3.6. These development are the increasing turbine size, the increase in distance between wind farm site and port, the increasing water depth at site location, the possible introduction of floating foundations, and the introduction of integrated turbine and foundation installation. In the needs analysis, these developments will be used to define the methodology to predict future requirements, a key performance indicator (KPI) depending on the selected stakeholder, and a baseline design for the parametric model. Using a baseline design can poses restriction on the exploration of the design space, as only a limited space around this baseline design will be explored. Therefore, a pre-concept exploration will be conduced in order to select the baseline design. During the concept exploration stage the selected scenario modelling method, Epoch-era analysis, is used to predict a set of possible requirements which change over time. Additionally, a parametric model is used to generate a set of concept vessel designs. Finally, the similarities and differences between the concept designs for each set of future needs are analysed. The goal of this analysis is to generate more insight in the impact of the changing offshore wind market at the installation vessel design. For a schematic overview of the research approach, see figure 5.3. For a more detailed description about the method selected for predicting the future requirements see chapter 6. A description of the parametric model is available in chapter 7.

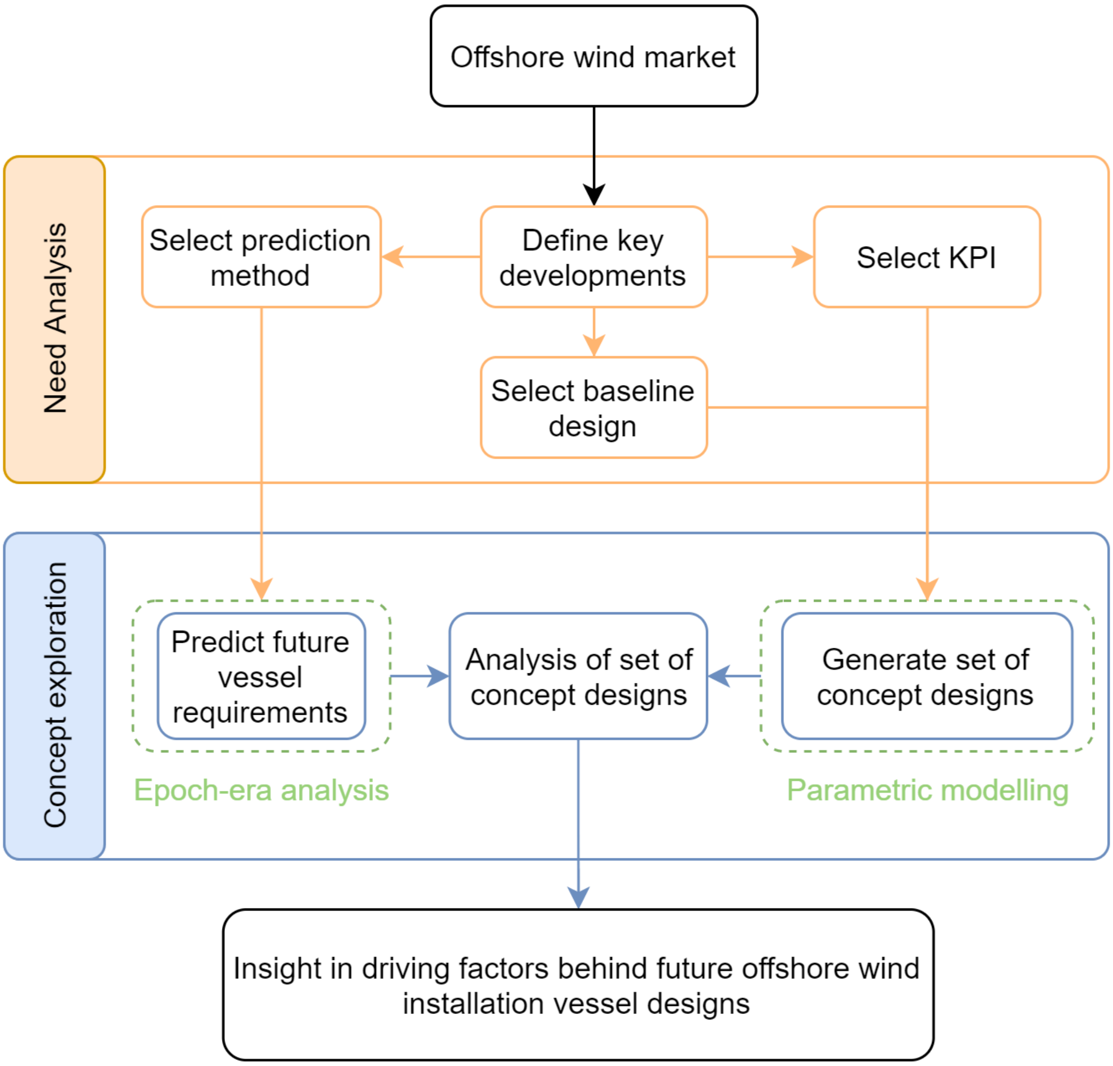

Figure 5.3.: Research approach

5.3. Conclusion

This chapter provides an answer on the following sub question: *How can systems engineering support the designer in defining the important requirements that need to be predicted?* The system thinking approach that is involved in systems engineering forces the designer to take a holistic approach when investigating the offshore wind market. By investigating the offshore wind market and the way installation vessels interact with this market using the systems engineering method, the needs of the offshore wind market can be identified. These needs are related to a set of objectives that the offshore wind installation vessels will need to accomplish. The objectives that need to be fulfilled can be translated into the important requirements for the offshore wind installation vessels.

Epoch-era analysis is selected as scenario generation method to be applied in this research

Predicting requirements 6

The purpose of this chapter is to select a method to help determine possible future requirements for offshore wind installation vessels. First of all, the difference between forecasting and scenario modelling, two types of future prediction, are discussed in section 6.1. Secondly, the different steps for scenario generation will be given in section 6.2. Then, the main variables and their corresponding level of uncertainty are described in section 6.3. Section 6.4 will include an overview of various scenario modelling methods and the choice for the scenario modelling method that will be applied in this research. The application of the chosen scenario modelling method is described in 6.5. Finally, a conclusion of the chapter is given in section 6.6

6.1. Forecasting and scenario modelling

The future can be characterised as being uncertain, it is not possible to predict the future for one hundred percent correctly. However, there are methods available that can help predicting future events in order to aid the decision making process [86]. There are two main types of prediction methods that can be characterised:

- **Forecasting** is applied in regions where the probability of future events can be determined based on historical data. In this type of scenario modelling it is assumed that the behaviour structure of the system stays similar over the next years. Therefore, the goal of forecasting is to use historical events to predict the most likely future [87].
- **Scenario generation** operates in areas where the behaviour structure of a system does change and no statistical data is available to define probabilities for future events [87]. The aim of this method is to construct a set of possible futures that are relevant for the strategical decision to make [88]

The region in which forecasting (F) and scenario generation (S) do operate are made visible by Van der Heijden [87], see figure 6.1. Figure 6.1 shows that when trying to predict further in the future, uncertainty increases and predetermined events decreases. It shows that forecasting can be used best for short-term prediction, while the strengths of scenario generation relates to the long-term prediction. Finally, an area is defined after which predicting the future will not provide any beneficial information (H).

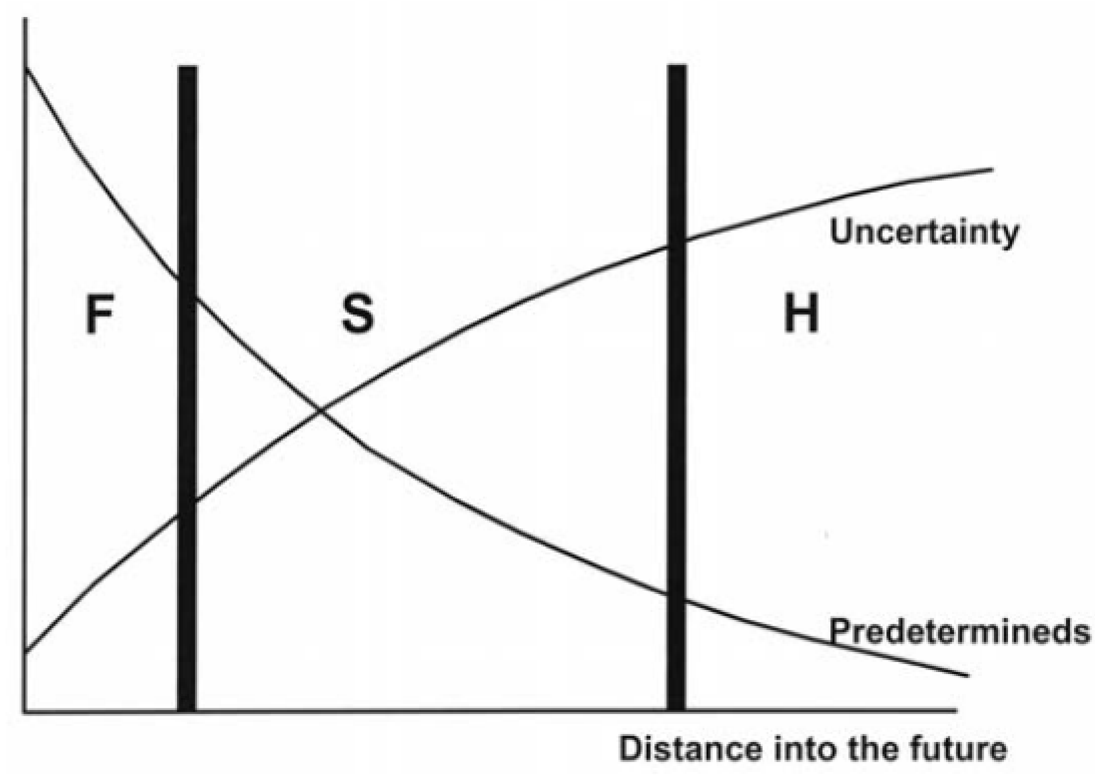

Figure 6.1.: Forecasting and scenarios [87]

One of the sub goals of this research is to get a better understanding of the future requirements of the offshore wind installation vessels. As explained in sections 3.4 and 3.5 the offshore wind market can be defined as a complex market due to the many technological, political, and regional changes that take place. Van der Heijden mentions that when the complexity of a market or system increases, the time in which the structural behaviour can be assumed to be constant reduces [87]. So, forecasting becomes less applicable as this method assumes a constant structural behaviour. Additionally, another sub goal is to better inform the naval architect in order to prevent under and over designing the vessel. Scenario generation can support this goal as it provides insights for future strategies and design choices. This is possible because this method creates an overview of different possible scenarios which can be used to test various aspects of strategic decisions such as robustness, effectiveness, and reliability [89].
To conclude, scenario generation will be used in this research to predict the future offshore wind market in which the offshore wind installation vessels have to operate, as this method best aligns with the sub goals defined in section 2.2.

6.2. Scenario modelling approach

There are different descriptions available for the process of generating scenarios. An abstract description based on the definition by Mißler-Behr is given by Kosow and Gaßner [89] and will be used in this research as guideline for building different scenarios, see figure 6.2.

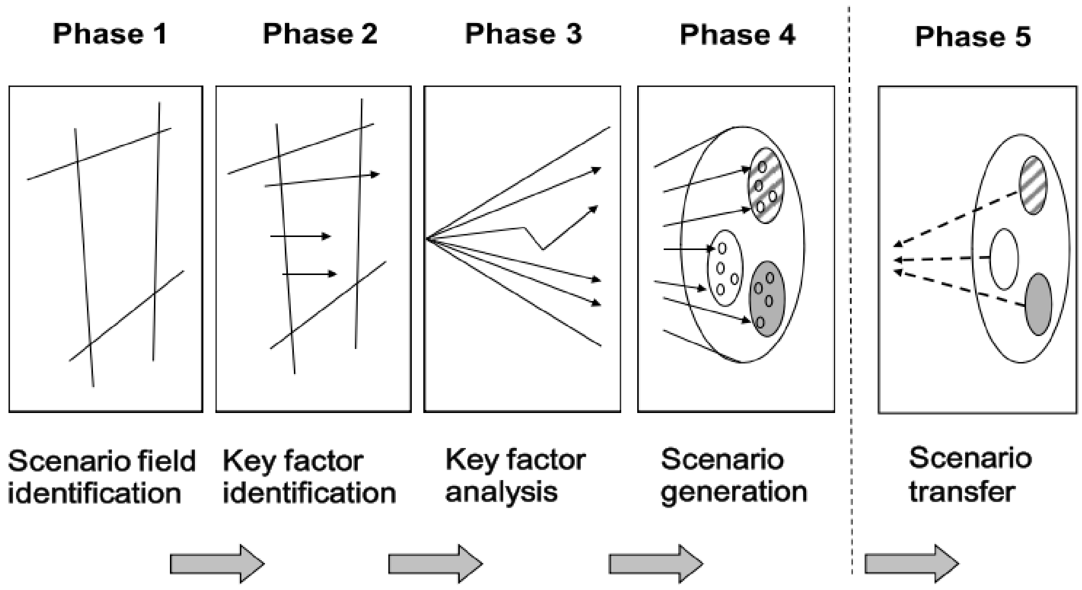

Figure 6.2.: Steps scenario generation [89]

The approach follows the following steps [89]:

1. **Scenario field identification** is the step in which the purpose of the scenario modelling is determined. In this research the purpose is to get more insight in the design aspects of the future offshore wind installation vessels in order to be competitive and cost effective in the offshore wind market, as defined in section 2.2.

2. **Key factor identification** involves the selection of a set of key factors such as variables, trends, or developments that have the biggest likelihood to influence the future and can be used during the process of generating scenarios. The key factors that are selected for the scenario modelling are turbine size, distance from wind farm site to port, and water depth, see sections 3.5 and 3.6.

3. **Key factor analysis** concerns the analysis and definition of the possible values that the selected key factors can have in the future. A high level analysis of these key factors is presented in section 6.3.

4. **Scenario generation** is the step in which a scenario generation method is selected based on the characteristics of the input values and the objective of this research. Afterwards it is combined with the boundaries and key factor variable ranges defined in the previous steps to generate a set of scenarios. The selection of the scenario generation method will be addressed in section 6.4, and its application in section 6.5.

5. **Scenario transfer** is the last phase in which the created scenarios will be used for the assessment of the performance of different vessel designs, see section 6.5. The execution and results of this steps will be discussed in detail during the case study in chapter 8.

6.3. Key factor analysis

The key parameters that will be used as input for the scenario modelling method are selected from the trends and technical developments defined in section 3.5. The selected variables are:

- Turbine size and weight
- Distance from offshore wind farm to port
- Water depth at offshore wind farm location

These variables are selected as they tend to be varying over the next years and are related to the different vessel requirements such as crane capacity, crane height, vessel stability, and transit speed [49][41]. During the key factor analysis the possible range and therefore uncertainty of each input variable will be determined. The uncertainty definition as published by Marchau et al. [90] will be used in this research, see figure 6.3.
In a situation in which the future is perfectly known it is labeled as complete certainty. Level 1 indicates a situation in which the future is clear enough and no prediction method is necessary. Level 2 describes an uncertainty in which the future can be described using probabilistic data, which are being used in forecasting methods. Level 3 indicates an uncertainty in which there is a bounded set of options which cannot be given an probability. Level 4 relates to deep uncertainty and is split in to level 4a (many options but the bounds can be guessed) and 4b (many options but there is a lack of knowledge to determine a bounded region). The last level indicates total ignorance of the uncertainty.

	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future	Alternate futures (with probabilities)	A few plausible futures	Many plausible futures	Unknown future	
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	
Weights (W)		A single set of weights	Several sets of weights, with a probability attached to each set	A limited range weights	A wide range of weights	Unknown weights; know we don't know	

Figure 6.3.: Levels of uncertainty [90]

Turbine size and weight
In recent years an increase in maximum turbine size has taken place, from 3 MW in 2010 towards 12 MW in 2021 [7]. As discussed in section 3.5 it is expected that this increase will continue towards 15-20 MW in 2030. However, as figure 3.9 indicates, the exact power rating and size at that time will depend on the technological developments. As mentioned by Rosenberg technological development is a process in which a lot of uncertainty is involved and in which development time

can vary a lot between different innovations [91]. There are researches available that do assign probability to these technological developments. An example is a research by Kana et al. in which probability is used to assess if a container vessel should switch towards LNG under the uncertainty of possible future regulation [92]. Another example is a research by Zwaginga in which probability is used to model the uncertainty in the offshore wind foundation installation market [93]. In this research there will not be given probabilistic values to the technological developments. This choice has been made as it gives designers the opportunity to involve out of the box situation that can be helpful for future strategies and design choices. In this research a bound will be defined for this variable and it will be modeled as a level 3 uncertainty.

Distance from offshore wind farm to port

The distance from offshore wind farm to port depends on the selected location of the wind farms, and the ports that can be used by the installation vessels.
The selection of the wind farm location is carried out by the national authority [94], while taking in consideration other sea users as defined in the maritime spatial planning (MSP) [95]. These MSPs can vary over time and therefore introduces uncertainty about future locations. An example is the MSP of the Dutch government, which will be revised once every 6 years [96]. As indicated in section 3.4 offshore wind will become one of the important sustainable resources in the future. Many countries are expanding their plans of installing offshore wind farms, which introduce new site locations [7].
Policy can have an impact at the distance from offshore wind farm to port as well. An example is the Jones Act in the USA. This law prevents installation vessels built outside the USA to pick-up materials in a USA port, which means that a feeder concept has to be used or the vessel has to use ports in surrounding countries [97][98]. Finally, as mentioned in section 3.6 the introduction of floating foundations will open up even more accessible locations for offshore wind which introduces additional options regarding the distance towards port.
To conclude, there are many aspects that determine the distance from the offshore wind farm to port, all adding uncertainty. This uncertainty is so high that no small set of options can be defined, therefore this variable is defined to be level 4.

Water depth

As mentioned in section 3.5 the average water depth at which wind farms are installed is growing during recent years. However, figure 3.13 shows that there is a wide spread around this average, which indicates that there are a lot of different water depth options. These set of options will possibly grow even further with the introduction of floating wind turbines that do not have the water depth limitations that fixed foundations have, see table 3.2. It should be remarked that technological developments have impact on these limitations and could push the water depths even further. To conclude, for fixed foundations it is possible to define a bound of water depths. But the options within this bound are still endless. Therefore, this variable can be identified as level 4.

6.4. Selection scenario modelling method

The purpose of the application of scenario modelling in this research is to get a better understanding of the possible future requirements offshore wind vessels will face. To accomplish this goal, the scenario modelling method applied should comply with the following requirements:

- It should be capable of handling non-probabilistic input variables (uncertainty of level 3 and higher)
- It should be capable of handling dynamic uncertainties over time because of the changing market
- The method should explore the uncertainty space to get a better understanding of the possible future changes in the market.
- The output should aim for a robust main vessel
- The output must be able to assess flexible vessel equipment such as a crane

Various methods are available that can be used to generate future scenarios. Examples of possible methods that can be applied in this research are listed below [90][99]:

- Epoch-era analysis (EEA)
- Engineering option analysis (EOA)
- Info-gap decision theory (IG)
- Markov decision process (MDP)
- Robust decision making (RDM)
- Real option analysis (ROA)

Out of the above mentioned methods RDM and EEA are selected for further analysis regarding the applicability in this research. EOA is not selected as the main purpose of this method is to assess the implementation of flexibility over the lifetime of a design instead of aiming for a robust design in the first place. The info gap method is not applied as this method handles very high levels of uncertainty related to level 4b. When applying this method a risk is taken that the outcomes are not adding information to the objective defined. Finally, MDP and ROA are not selected as these two methods do not comply with the requirement of non-probabilistic input variables [90]. For a comparison between RDM and EEA see the following subsections.

Robust decision making
RDM is a method that uses various processes and computational tools to define a myriad set of scenarios which are used to stress test a set of proposed designs [90] in order to select a robust design. An example of this method in the maritime industry is a research by Terün, that applies RDM in order to get more insight in a robust ultra large container vessels design for alternative fuel types [100].

Epoch-era analysis

EEA creates different scenarios by constructing different time lines (era's) using a set of different short term time lines (epoch's) that are connected to each other. By applying this method EEA involves both short and long term uncertainties in the generation of different scenario's [101]. Gasper et al. did apply EEA in the maritime industry to design an Anchor Handling Tug Supply vessel [102].

Scenario method used in this research

An comparison between EEA and RDM has been carried out by Moallemi[101]. The main difference identified between the two methods are:

- **Goal of the method**: The goal of RDM is to get more insight in the most robust design over a variety of scenarios. A second aim of RDM is the analysis of potential weaknesses in the proposed designs, by stress testing these designs. EEA on the other hand has as goal to find an optimal design that provides the most robust performance over its lifetime while facing dynamic uncertainties, such as changing requirements. Additionally, EEA is also being used for assessing the impact of adding flexibility in the design.
  To conclude EEA focuses more at finding an optimal robust design while RDM does focus more at robustness and identifying possible threats of a design.

- **Handling uncertainty**: The main difference between EEA and RDM is that EEA uses short and long term uncertainties which makes it possible to have dynamic uncertainties over the life time of the design. RDM on the other hand only has a fixed uncertainty space during the life time of the design. Moreover, there is a difference in the levels of uncertainty these models do handle. RDM can handle level 4b uncertainties, while EEA handles situations in which parameters have probabilistic inputs (level 2) or bounded inputs (level 3 and 4a).

- **Experts opinion**: Both methods involve stages where the opinion of the designer is used. RDM uses this opinion in the first step of the process where the objectives, a set of design solutions, and uncertainty variables are selected. EEA uses the opinion of the designer when selecting the range of the input variables for the system and during the construction of the various era's by defining so called consistency rules [102].

When comparing the differences of the methods and the objective of this research EEA is selected as method to be applied in this research. First of all both methods are capable meeting the requirements regarding the ability of handling non-probabilistic input variables, the exploration of the uncertainty space, and an output that focus on robustness. However, a difference between the two methods occurs regarding the handling of dynamic uncertainty over time and the possibility of having a flexible concept design. EEA is capable of accomplishing these two objectives, while RDM is not. The fulfilment of these two objectives is of importance to cope with the dynamical aspect of the offshore wind market.

6.5. Application of Epoch-era analysis

The EEA method is selected as scenario generation method in this research. By combining the scenario modelling approach provided in section 6.2 and the EEA steps described by Curry and Ross [103] the following necessary EEA steps are identified for this research.

- **Defining epochs**: values will be assigned to the identified key uncertainties in order to indicate the state of that uncertainty in a specific epoch. For example the amount of MW of an offshore wind turbine.
- **Generating eras**: in this phase various potential epoch combinations will be analysed in order to define various eras. This analysis and construction of various eras can be conducted using statistical models or knowledge from experts [104].
- **Epoch and era analysis**: analyse the performance of the generated designs in the various epochs and eras. There are two forms of analysis that can be applied [103]:
  - Single: analyse the design in a specified epoch or era
  - Multi: use a set of epochs or eras to analyse the proposed designs

The application of the above mentioned process is visualized in figure 6.4. In this example two key uncertainty factors power rating turbine, and distance to farm are given together with a set of states. The combination of the states of the two uncertainty factors generate 9 unique epochs, which are labeled in figure 6.4. By combining the various epochs a set of eras can be generated, see eras 1, 2, and 3 in figure 6.4.

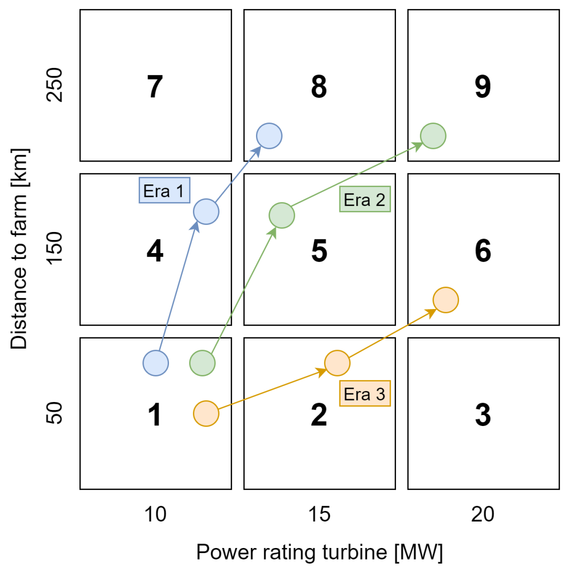

Figure 6.4.: Epoch to eras - Based on a figure by Gaspar et al [105]

During the analysis the performance of the vessels will be assessed in the defined epochs and eras in order to assess the vessel performance in the changing environment.

This assessment is based on the costs of the vessel in each epoch. In order to determine the performance of the vessels over a certain era, the costs in each epoch is added together to determine the total costs of a vessel over a whole era [102], see equation 6.1.

$$C_{era} = C_{epoch\,1} + C_{epoch\,2} + C_{epoch\,3} \tag{6.1}$$

where: $C_{'name'}$ = Costs of component 'name' [€]

6.6. Conclusion

The information discussed in this chapter answers the following sub question *Which scenario modelling method can be applied to predict a set of possible future requirements for offshore wind installation vessels?* During this chapter advantages and disadvantages of various scenario modelling methods have been compared. After this comparison it has been concluded that EEA will be used as scenario modelling method in this research. Another sub question that is partially answered in this chapter is the following: *How can the performance of a concept installation vessel being assessed for the different sets of scenarios?* In this chapter it is shown that a scoring system that is based on the costs can be used to assess the performance of the concept designs.

This framework is capable of generating many offshore wind installation vessel concept designs

Model

7

This chapter will introduce the model that is being proposed as part of the methodology to provide insight in the future offshore wind installation vessels. One of the goals of this chapter is to provide insights in the generation of a set of vessel designs, which helps answering the following sub question: *Which method and variables can be used to generate offshore wind installation vessel concept designs?* Another goal is to elaborate on the answer given in chapter 6 concerning the following sub question: *How can the performance of a concept installation vessel being assessed for the different sets of scenarios?* In order to answer these sub questions the model structure and input variables are first discussed in section 7.1. The following sections 7.2 till 7.7 discuss the various components of the model. Finally, section 7.8 gives an answer on the two sub questions. The verification and validation tests of the various sub components in the model can be found in appendix A.

7.1. Model structure and input variables

The main purpose of the concept exploration phase is to transform the scenario characteristics from the scenario model, such as power rating and water depth towards a set of good performing vessels in terms of costs using a parametric model. The variables that are used to perform the above mentioned step are summarized in table 7.1.

Table 7.1.: Source of chapter pictures

Model level	Variables
Scenario model	Power rating turbine
	Water depth
	Distance to port
	Amount of cargo
	Region
Exploration model	Length, Beam, Depth
	Crane capacity
	Ship speed
	Transport strategy

The model used in the concept exploration phase consists of two stages, a preparation stage and an exploration stage, see figure 7.1. In the preparation stage the turbine power rating and the water depth are used to determine the cargo properties. These cargo properties are of utmost importance for the parametric model as these define the objects that the offshore wind installation vessels should be able to handle. For more details regarding the definition of the cargo properties see section 7.2.

The exploration stage consists out of a beforehand determined set of input variables, a parametric model that translates the design variables towards vessel performance, and a module for analysing the vessel performance.

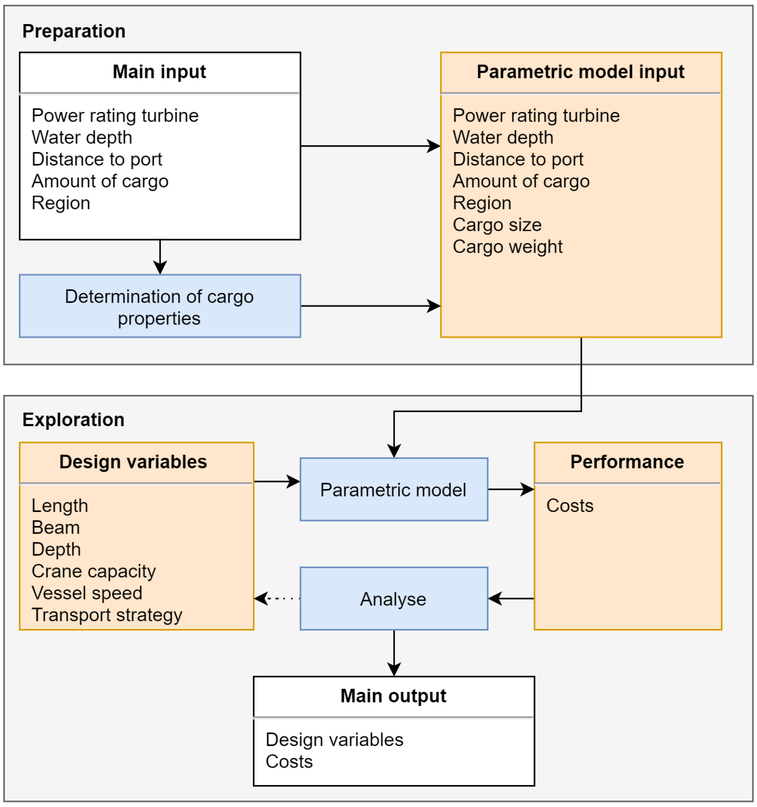

Figure 7.1.: Overview model

An overview of the parametric model as defined in figure 7.1 is given in figure 7.2. As mentioned before, the goal of the parametric model is to determine the performance of the different vessel designs in each scenario. This performance will have to be assessed based on the costs related to building and operating the specific vessel design in a certain scenario. To determine the vessels costs the following necessary sub components are identified:

- **Ship model**: to specify the ship properties necessary for the other sub components, see section 7.3
- **Mission constraints**: assess if the vessel can carry out the project, see section 7.4
- **Transport**: determines the necessary transport time of the vessels used in the project, see section 7.5
- **Operability**: defines the installation time and idle time of the vessels involved, see section 7.6
- **Cost calculations**: a module that determines the vessel build costs, general operational costs, and voyage expensive costs related to the project based on the operational profile (transport, installation, and idle time) of the vessel, see section 7.7.

- **Analyse**: this component analyses the results from the parametric model in order to select the vessel having the lowest costs according to the equation also described in section 7.7.

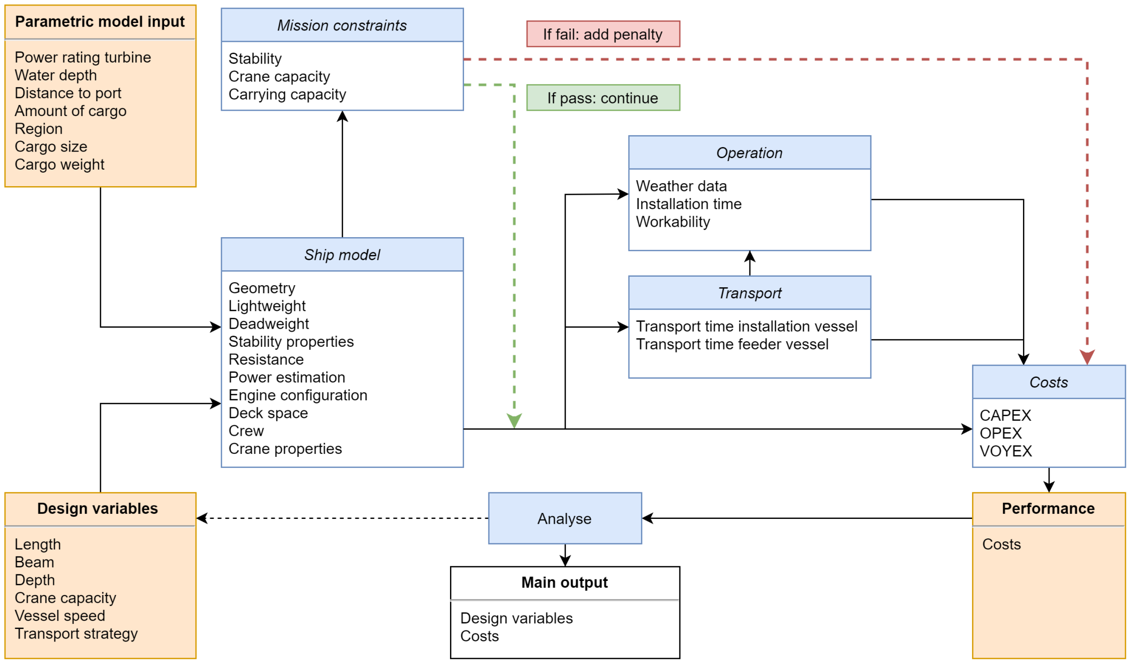

Figure 7.2.: Overview parametric model

7.2. Cargo properties

The main goal of the preparation stage is to transform the power rating and the water depth towards cargo size and weight. In the case study monopiles will be used as cargo, and therefore this section will focus on the monopile properties. Other cargo types have not been implemented in this model. First of all the length of the monopile is determined based on the water depth, see equation 7.1. This equation is a linear trend line that is based on a data set published by Negro et al. [106].

$$L_{monopile} = 1.65 \cdot T_{water} + 21.3 \tag{7.1}$$

where: $L_{monopile}$ = Length monopile [m], and T_{water} = Water depth [m]

The width of the monopile on deck depends on the power rating of the turbine and an additional width to incorporate the seafastening, see equation 7.2. In this equation a value of 1.25 is used as ratio between the turbine power rating and the monopile diameter [107].

$$B_{monopile} = \frac{P_{turbine}}{1.25} + B_{add} \tag{7.2}$$

where: $B_{monopile}$ = Monopile width on deck [m], and $P_{turbine}$ = Turbine power rating [MW] B_{add} = Additional width sea fastening [m]

After determining the length and width of the monopile on the deck, the weight can be determined by assuming an average wall thickness of 100 mm [108] and applying equations 7.3, 7.4 and 7.5.

$$A_{monopile} = \pi \cdot (r^2_{monopile} - r^2_{monopile-wallthickness}) \tag{7.3}$$

$$V_{monopile} = A_{monopile} \cdot L_{monopile} \tag{7.4}$$

$$W_{monopile} = V_{monopile} \cdot \rho_{steel} \tag{7.5}$$

where: $A_{monopile}$ = Surface area top of monopile [m^2], $r_{monopile}$ = Radius monopile [m], $V_{monopile}$ = Volume monopile [m^3], $L_{monopile}$ = Length monopile [m], $W_{monopile}$ = Weight monopile [mT], and ρ_{steel} = Density steel [mT/m^3]

7.3. Ship model

This is a model component that defines vessel characteristics such as: geometry, lightweight, deadweight, stability, resistance, power estimation, engine configuration, deck space, crew, and crane. In order to assure that plausible input variables are used when generating the set of vessels, the Aegir a Heerema Marine Contractors (HMC) vessel is used as reference vessel.

Geometry
In the geometry module different geometry characteristics of the vessel are determined. These characteristic are necessary as these will be used as input for other components in this model.

Draft, freeboard, and displacement
The first characteristic is the vessel draft. In this research two different drafts are used, the draft during transit and the draft during lifting. The draft in these two situations is defined as a percentage of the selected vessel depth. During this research it is assumed that the trim of the vessels is zero. It is assessed whether or not the vessel has enough freeboard available to comply with the freeboard regulations according to the ICLL 1966 [109]. If a certain draft does not provide enough freeboard, the draft is adapted in such a way that the vessel does comply with the freeboard constraint. Based on the main dimensions of the vessel and the vessel draft, the displacement in the transit and lifting condition is calculated using the relation described in equation 7.6

$$\nabla = L \cdot B \cdot T \cdot C_b \tag{7.6}$$

where: ∇ = Displacement [m^3], L = Vessel length [m], B = Vessel beam [m], T = Vessel draft [m], and C_b = Block coefficient [-]

Hull characteristics
In order to calculate the vessel resistance an indication of the mid ship, waterplane area, and prismatic coefficient are required. Empirical methods are used to estimate these necessary coefficients, see equations 7.7 [110], 7.8 [111], and 7.9 [112]. The calculation of the resistances will be described later in this chapter.

$$C_m = \frac{1}{1 + (1 - C_b)^{3.5}} \tag{7.7}$$

$$C_{wp} = \frac{1 + 2 \cdot C_b}{3} \tag{7.8}$$

$$C_p = \frac{\nabla}{L \cdot B \cdot T \cdot C_m} \tag{7.9}$$

where: C_m = Midship coefficient [-], C_b = Block coefficient [-], C_{wp} = Waterplane coefficient [-], ∇ = Vessel displacement [m^3], L = Vessel length [m], B = Vessel beam [m], and T = Vessel draft [m]

The wetted area of the vessel design is calculated using the approach described by Holtrop and Mennen [113]. For the longitudinal location of buoyancy a fixed number is selected based on the reference vessel Aegir.

Vessel components
Apart from the main dimensions information regarding accommodation, deck, and bow size are of importance. First of all, to assess the transport capabilities of the vessel. Secondly, to determine the wind area of the vessel for resistance during transport and for counteracting external wind force during DP situations. The sizes of these various components are based on the dimensions of these components on the Aegir and are scaled with the vessel length and the crane capacity. The application of the accommodation size in the calculation of the resistance, external wind force, and carrying capacity will be discussed later in this chapter.

Lightweight and deadweight
The calculation of the lightweight services two purposes. As part of the vessel costs, because the vessel costs are very much related to the weight of the ship and its components [114]. Secondly, to estimate the amount of weight the vessel can carry as cargo.
A first insight in the vessel lightweight can be generated using the vessel length, beam, and depth. However a more accurate result can be found by for example estimating the weight separately [114]. In this research the choice has been made to use a more accurate estimation of the vessel weight and related costs by splitting the various weight components of the vessel. Input data for this approach has been based on data provided by Royal IHC [115]. Using the provided data the following weight components are identified:

- Hull
- Outfit
- HVAC
- Accommodation
- Electrical systems
- Machinery

Based on the input data from Royal IHC and the ship design variables length, beam, depth, person on board, and installed power a weight estimation of the various components is calculated. All the components together form the lightweight of the vessel, see equation 7.10.

$$Lightweight = W_{Hull} + W_{Outfit} + W_{HVAC} + W_{Accommodation} + W_{Electricalsystems} + W_{Machinery} \tag{7.10}$$

where: $W_{'name'}$ = Weight of component 'name' [mT]

The second purpose of the determining the vessel lightweight is to calculate the weight the vessel can carry (deadweight). The deadweight is calculated using equation 7.11, in which the displacement is the maximum displacement during transit condition.

$$Deadweight = \nabla \cdot \rho_{water} - Ligthweight \tag{7.11}$$

where: ∇ = Displacement [m^3], and ρ_{water} = density water [mT/m^3]

Stability

Sufficient stability of the vessel is necessary to keep it floating up right, during both sailing and installation. Due to the importance of the stability for these type of vessels and the need for determining a detailed GZ curve an approach has been selected that involves the application of the software DAVE [116]. DAVE is a program that can be used to determine the stability of the vessel by using a mesh of the hull and the COG of the various vessel and monopile components.

Hull shape

For this research a basis hull shape is being used to create a variety of desired hull shapes. The hull of the Aegir is used as basis for the mesh that is being scaled towards the various desired vessel dimensions. For the used mesh, see figure 7.3.

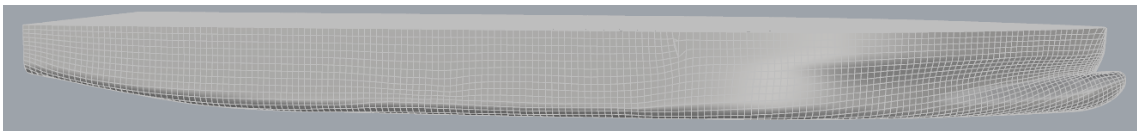

Figure 7.3.: Mesh of hull shape

Center of gravity

The center of gravity of the vessel is an important input value for determining the stability of the vessel. In this research the center of gravity of the lightweight, the crane, the anti heel tanks, the wing tanks, the center tanks, and the load has been taken into account, see figure 7.4. The center of gravity location of the various components is based on the Aegir and scaled according to the size of the vessel design. The vertical center of gravity (VCG) of the lightweight and tanks are scaled using the depth of the vessel. It is assumed that the transverse center of gravity (TCG) of the lightweight and the center tank is zero. The transfers location of gravity for the wing and heel tanks is assumed to scale with the width of the vessel. The size of the crane is not scaled. Therefore, the center of gravity of the crane and the load is only moved in order to assure that the bottom of the crane is placed on the deck of the vessel.

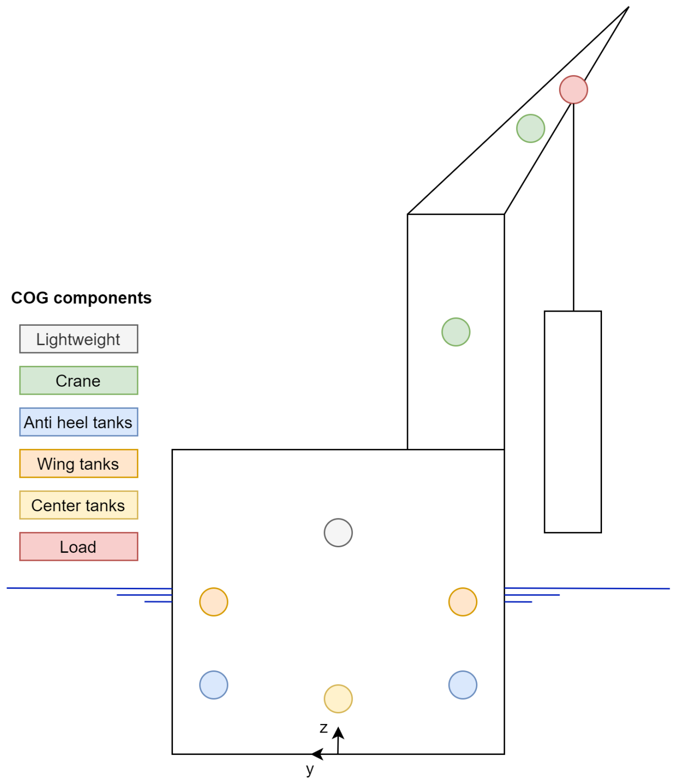

Figure 7.4.: Center of gravity of vessel components

Ballast
Ballast is used to influence the heel and the draft of the vessel during transit and lifting. The ballast system of the vessel is modeled out of three compartments, the anti heel tanks, the wing tanks, and the center tanks, see figure 7.5. The capacity of the various tanks are scaled based on the length, width, and depth of the vessel. The anti heel tanks are a type of tank in which a port side and a starboard side ballast tank are connected. The amount of water in these tanks cannot be changed, only the distribution of the water over the two tanks. The other tank types, the wing and center tanks can be filled.

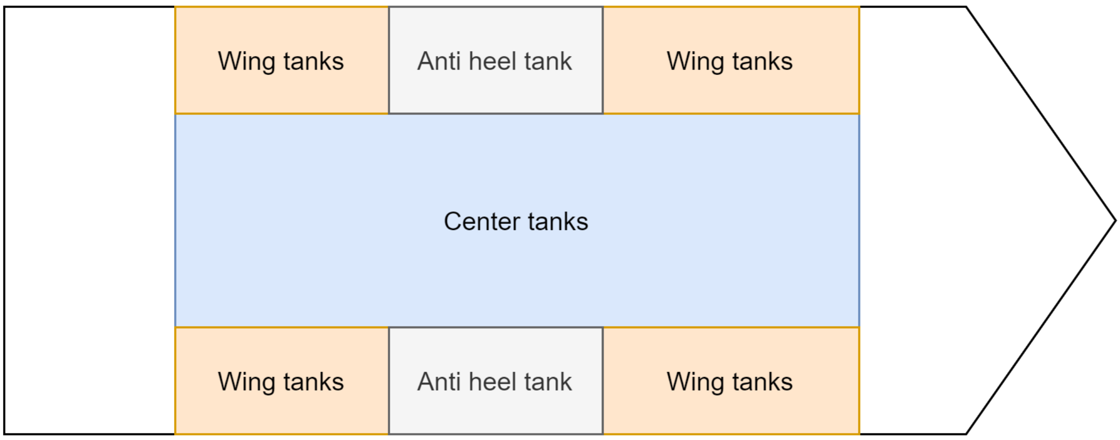

Figure 7.5.: Ballast tanks

The ballast process is carried out in two stages. In the first stage an attempt is made

to bring the vessel to a position in which the heel is zero. The second stage uses ballast to bring the vessel to the required draft.
The first step in reducing the heel of the vessel is the application of the anti heel tanks. Equation 7.12 is used to determine the combined TCG of the anti heel tanks. This required TCG indicates the distribution of weight between the two tanks, see equation 7.13, and 7.14.

$$TCG_{heel} = -\frac{TCG_{ship} \cdot W_{ship} + TCG_{load} \cdot W_{load}}{W_{heel\,tanks}} \tag{7.12}$$

$$W_{heel\,port} = \frac{TCG_{heel\,tanks} \cdot W_{heel\,tanks} - TCG_{heel\,starboard} \cdot W_{heel\,tanks}}{TCG_{heel\,port} - TCG_{heel\,starboard}} \tag{7.13}$$

$$W_{heel\,starboard} = W_{heel\,tanks} - W_{heel\,port} \tag{7.14}$$

where: $TCG_{'name'}$ = Transfers center of gravity of 'name' [m], and $W_{'name'}$ = Weight of component 'name' [mT]

If adapting the anti heel tanks does not bring the heel of the vessel to zero degrees, the wing tanks will be used in accordance with equation 7.15. If the vessel still experiences heel after using the full capacity of the available tanks the vessel will find an equilibrium in which it experiences heel.

$$W_{wing\,port} = \frac{-TCG_{ship} \cdot W_{ship} - TCG_{heel\,tanks} \cdot W_{heel\,tanks} - TCG_{load} \cdot W_{load}}{TCG_{wing\,port}} \tag{7.15}$$

where: $TCG_{'name'}$ = Transfers center of gravity of 'name' [m], and $W_{'name'}$ = Weight of component 'name' [mT]

For the next stage the wing tanks and the central tanks are used. First of all the required additional weight is determined to bring the vessel to the selected draft using equation 7.16.

$$W_{required\,for\,draft} = \nabla \cdot \rho_{water} - W_{ship} - W_{heel\,tanks} - W_{wing\,tanks} - W_{load} \tag{7.16}$$

where: ∇ = Displacement [m^3], ρ_{water} = Density water [mT/m^3], and $W_{'name'}$ = Weight of component 'name' [mT]

The first tanks used for drafting the vessel, are the wing tanks. In order to bring the vessel to its required draft without introducing a new heel, it is of importance to fill the wing tanks in such a way that the total TCG of the vessel stays zero. Therefore, both port and starboard side will be filled with the same amount of ballast. The available ballast in these tanks after the heeling stage is determined using equation 7.17.

$$W_{wing\,available} = 2 \cdot (W_{wing\,max} - W_{wing\,port}) \tag{7.17}$$

where: $W_{'name'}$ = Weight of component 'name' [mT]

The center tanks of the vessel will be used if additional ballast is required after having fully loaded the wing tanks. Finally, the new TCG and VCG of the vessel is determined based on the defined ballasting plan which is used for calculating the stability.

Stability calculations
As mentioned above the software package DAVE is used to assess the stability of the vessel designs. DAVE is used to calculate the carene table for the lifting and transit draft. Additionally, the program is use to determine the GZ curves of the vessel. The carene table is created by 'cutting' the vessel at different drafts and calculating hydrostatic properties of the vessel at this draft. It provides for example information regarding the vertical center of buoyancy (KB) and the metacentric radius (BM). These two measurements can be combined with the center of gravity of the vessel to determine the metacentric height, which is used as an indication of the initial stability of the vessel. See equation 7.18 for the calculation of the metacentric height [117].

$$GM = KB + BM - KG \tag{7.18}$$

where: GM = metacentric height [m], KB = vertical center of buoyancy [m], BM = metacentric radius [m], and KG = vertical center of gravity [m]

The GZ curve is an indication of the righting moment of the vessel at various heel angles. The points that form the GZ curve are calculated by forcing an angle to the vessel, see figure 7.6. At each angle the necessary moment is calculated to reach a static equilibrium with the buoyancy and gravity force. By repeating this procedure for multiple angles the GZ curve is created.

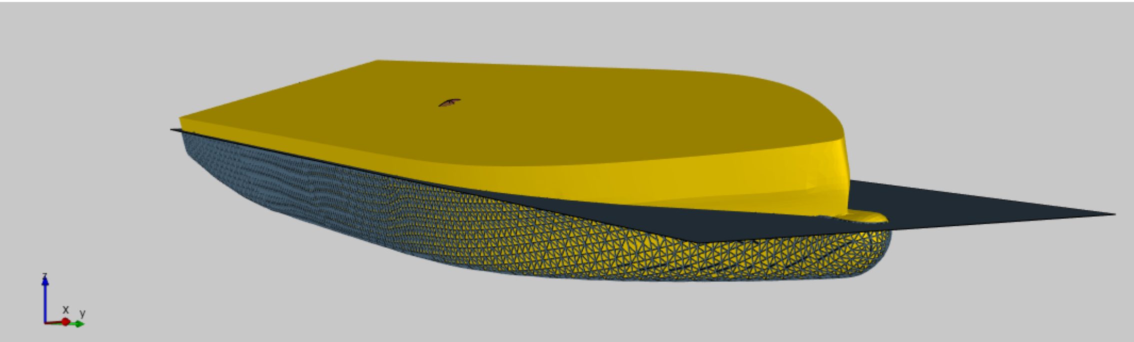

Figure 7.6.: GZ curve calculation - Forced rotation

Resistance and propulsion
The resistance of the vessels is calculated in order to assess the fuel expenses during transit. As mentioned by Larsson and Raven [118] resistance calculation in early design stages should be rapid and should assists in exploring a set of main dimensions for the vessel designs. The method that fits this situation best is the application of empirical models, as these are able to give a fast and a reasonable estimation of the resistance. The empirical method used for determining the resistance in this research is the method published by Holtrop and Mennen [113]. In order to get an estimation of the power consumption the calculated resistance is transformed into required power generation by the main engines. The efficiency ratios of the different components on the drive train are used to transform the resistance towards required power, see equations 7.19, 7.20, and 7.21 [119].

$$P_E = R \cdot V_s \tag{7.19}$$

$$P_P = \frac{P_E}{\eta_o \cdot \eta_R \cdot \eta_H} \tag{7.20}$$

$$P_B = \frac{P_P}{\eta_s \cdot \eta_{GB}} \tag{7.21}$$

where: P_E = Effective towing power [kW], R = Resistance [kN], V_s = Speed [m/s], P_p = Propeller power [kW], η_o = open water efficiency: 0.6 [-], η_r = Relative rotative efficiency: 1.0 [-], η_H = hull efficiency: 1.0 [-], P_B = Brake power [kW], η_s = Shaft efficiency: 0.99 [-] and $\eta_G B$ = Gearbox efficiency: 0.98 [-]

Installed power and engine configuration

The current fleet of offshore wind installation vessels uses a dynamic positioning (DP) system to keep position during the installation operation. It is assumed that the installed power on board of these type of vessels is determined by a combination of required propulsion power and its hotel load, see equation 7.22.

$$P_{installed} = max(P_{DP}, P_{propulsion}) + P_{hotel} \tag{7.22}$$

where: $P_{'name'}$ = Power of component 'name' [kW]

The required propulsion power is defined as the maximum of the power necessary during transport and DP operation. The calculation regarding the transport power is discussed, in the section above. The necessary force from the DP system is calculated using the DP guidelines described in the DNV-GL standard [120] and multiplied by two to guarantee redundancy. In case of a sailing condition, the sailing speed is used to transform the force towards engine capacity. However, a DP situation is a stationary situation in which the vessel speed is zero. Therefore, a fixed force/power ratio of 13 kg/hp ≈ 0.17 kN/kW is applied in accordance with the DP capability guidelines of IMCA [121]. The hotel load is based on the reference vessel and fixed in this research.
For the engine configuration a fixed specific fuel consumption is selected for all three operational profiles (transit, installation, and idle).

Deck space

The deck space layout is based on vessels that are currently active and build for the offshore wind installation market, such as the Orion, Alfa lift, and Les Alizés [122][79][123]. Common characteristics between these vessels are the accommodation/bridge area that is located at the bow of the vessel, the crane which is placed at the side of the vessel, and the availability of a flat deck spanning a big part of the vessel. Using these common characteristics the following four different area types are identified for the modelled vessels. The bow, the accommodation/bridge, the cargo deck, and the crane. For the various areas and their length and beam definitions, see figure 7.7

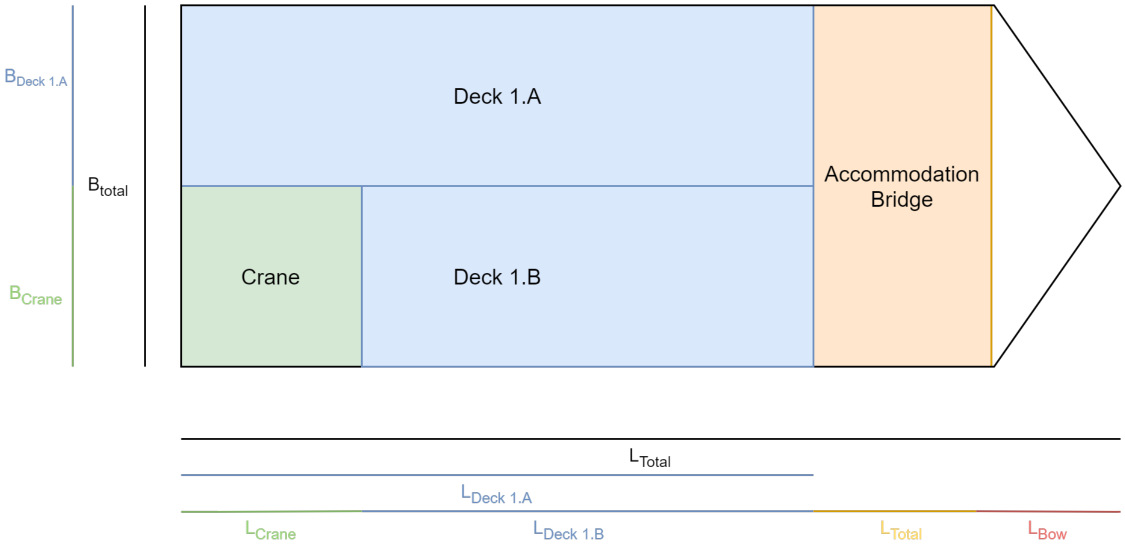

Figure 7.7.: Deck space

As seen in figure 7.7 there are two decks 1.A and 1.B defined. Both decks are on the same level, which makes it possible to place cargo over the common edge of deck 1.A and 1.B. The reason these two decks are split is related to the calculation of the amount of monopiles that can be loaded on the vessel. For the details regarding loading the vessel, see section 7.4.

Crew

Determining the maximum crew on board of the vessel provides insight in the accommodation size of the vessel [115]. Therefore, current fleet data has been used to research possible relations between vessel dimensions and crew on board. No significant correlations have been found between vessel dimensions and crew on board. In order to assess whether the vessels equipment has an impact on the maximum crew on board a relation between the crew and crane capacity is considered. Again no clear relation has been found. Therefore, the choice is made to define a fixed amount of crew for all vessels.

Crane

In this research a crane is used as the mission equipment that is responsible for carrying out the installation operation from the vessel. In this model there are two different strategies available with respect to the crane; a fixed crane and a changeable crane.

In case of a fixed crane the crane capacity is constant over the life time of a vessel. The capacity will be determined by the model input variables that are selected.

In the second situation the vessel is capable of upgrading its crane during its lifetime. In this situation the model will check the required crane capacities during the various scenarios the vessel will face. If a crane upgrade is required the crane capacity will be increased and additional costs will be added. For the details regarding the additional costs, see section 7.7. The crane capacity will never be decreased during its lifetime.

7.4. Mission constraints

In order to ensure that the created vessel is capable to accomplish its mission of installing components for the offshore wind farm, a set of constraints has been defined. These are related to the vessel stability during transit and lifting, the capability of transporting the cargo, and constraints regarding the equipment in order to be able to handle and install the offshore wind farm components.

Stability
The assessment of this stability is based on DNV-GL regulations [124] [125][126] and will be assessed using the following three criteria:

- GM during transit should be larger than 0.15 m
- GM during lifting should be larger than 0.15 m
- Dynamic stability in case of loss of load should comply the regulations, see equation 7.23

The dynamic stability is calculated using the vessels initial heel during lifting and the corresponding GZ curve after the load has been lost. See figure 7.8 for the initial heel angle (intersection of GZ_1 with the horizontal x-axis) and the GZ curve after losing the load.

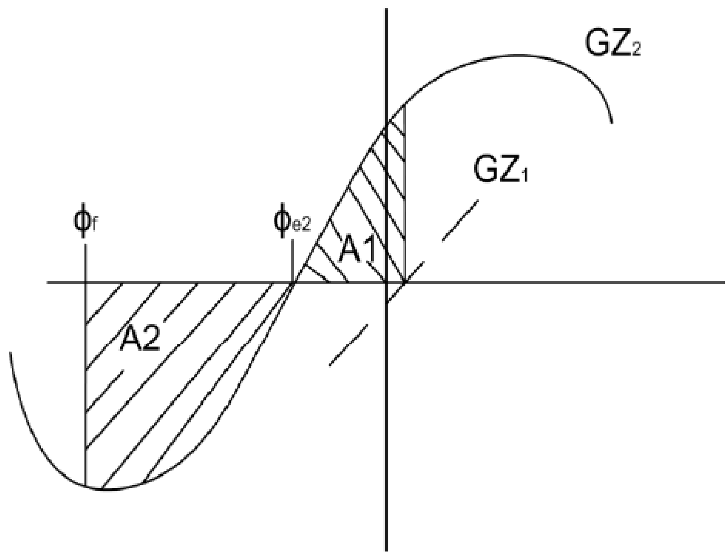

Figure 7.8.: Loss of load

When the vessel loses its load the vessel will start rotating until a new equilibrium has been found (ϕ_{e2}). According to the DNV-GL regulations [125] there should be enough dynamic stability to counter act the rotational energy due to the loss of load. A situation that provides enough dynamic stability can be identified using equation 7.23.

$$A_2 >= 1.4 \cdot A_1 \tag{7.23}$$

The area A_1 provides an indication of the amount of energy that is being released due to the loss of load, while the area A_2 corresponds to the vessels capability to counteract this energy in order to keep the vessel upright. The angle ϕ_f used to provide a lower bound for A_2 is defined as the minimum of the angle at which the deck of the vessel is flooding or the angle at which the vessel loses stability.

Carrying capacity

In case of a transport strategy where the installation vessel carries the offshore wind turbine components, it should be ensured that the vessel is capable of carrying these components. The maximum carrying capacity is determined by calculating the limiting factor of space and weight:

- The vessel should have enough deck space available
- The deadweight of the vessel should be sufficient

Firstly, the carrying capacity based on space is determined by comparing the available deck width and deck length with the cargo size. In this calculation it is assumed that the cargo size includes the sea fastening necessary to attach the cargo to the deck. As visible in section 7.3 the deck space is split in part 1.A and part 1.B, due to the crane equipment installed at the vessel deck. Due to this non square deck size (see figure 7.7) the following calculation steps are applied in combination with equations 7.24, 7.25 and 7.26:

1. First the amount of cargo that fits on deck 1.A is calculated
2. Then the amount of cargo that fits on deck 1.B is calculated
3. Finally, it is assessed whether additional cargo can be placed over the common edge of deck 1.A and deck 1.B

$$N_{cargo\,l} = L_{deck}/L_{cargo} \tag{7.24}$$
$$N_{cargo\,b} = B_{deck}/B_{cargo} \tag{7.25}$$
$$N_{cargo\,space} = N_{cargo\,l} \cdot N_{cargo\,b} \tag{7.26}$$

where: N = Number of cargo [-], L = Length [m], and B = Beam [m]

In this calculation it is assumed that the cargo is placed in the longitudinal direction of the vessel as visible in figure 7.9.

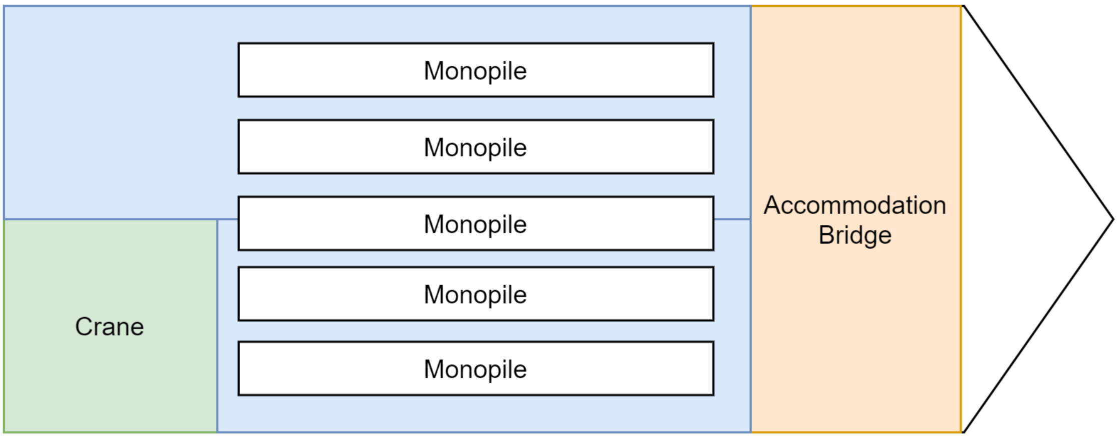

Figure 7.9.: Deck space loaded

Secondly, it is assessed how many cargo the vessel can carry based on the cargo weight and the vessel deadweight using equation 7.27

$$N_{cargo\,weight} = \frac{Deadweight}{W_{cargo}} \tag{7.27}$$

where: N = Number of cargo [-], and W_{cargo} = Cargo weight [mT]

The results of the carrying capacity equations are all rounded down to an integer value. Based on the rounded values the limiting factor is determined, which also determines the carrying capacity of the vessel.

Mission equipment - Crane capacity
In order to ensure that the vessel can install the offshore wind turbine components a constraint to the required crane capacity is introduced. This constraint involves the static and an estimation of the dynamic loads by using a dynamic amplification factor (DAF) [127], see equation 7.28.

$$Crane\ capacity >= DAF \cdot W_{cargo} \tag{7.28}$$

where: DAF = Dynamic amplification factor [-], and W_{cargo} = Cargo weight [mT]

7.5. Transport

The transport module defines the time in which the vessel is in transit between the offshore wind field and shore. As mentioned in section 4.1 various transport strategies are available that could possibly have an impact at the vessel design. In order to asses this potential impact, the model calculates the transport time for the following two transport strategies:

Installation vessel only - Shuttle strategy
In this situation the installation vessel is responsible for both the transport and the installation of the components. The total time the vessel will be in transit during

one project is determined using equation 7.29 below. It is assumed that the vessel will always end in the port it did start its project.

$$T_{sailing} = \frac{x_{total}}{V_s} = \frac{N_{trips} \cdot x_{offshorewindfarm} \cdot 2}{V_s} = \frac{\frac{N_{cargo}}{C_{cap}} \cdot x_{offshorewindfarm} \cdot 2}{V_s} \quad (7.29)$$

where: $T_{sailing}$ = Time sailing [days], $x_{'name'}$ = Distance 'name' [km], V_s = Speed [km/day], $N_{'name'}$ = number of 'name' [-], and C_cap = Carrying capacity per trip [-]

Installation vessel and feeder vessel - feeder strategy

In this situation additional feeder vessels are added to the fleet. The purpose of these feeder vessels is to transport all the components while the installation vessel will stay in the field till installation is completed. A minimum of two vessels will be added as one of the feeder vessels will always have to be along side the installation vessel. This is due to the fact that the application of a feeder vessel does not pose any restrictions regarding the deck size of the installation vessel. Therefore, it can not be guaranteed that the installation vessel can carry all the components provided by the feeder vessel. In this research a feeder vessel combination consists out of one barge and two tugs. The total transport time of the feeder vessels is calculated by equation 7.29 above, using the feeder vessel characteristics.

7.6. Operation

The operational module defines the installation time and the possible idle time of the vessel. These two time periods combined with the transport time described in section 7.5 determine the total project duration and the operational profile of the vessels in the project.

Installation time

The installation time is described as the time to install the offshore wind farm components and the time to wait on good weather. An operability analysis indicates the maximum weather limits in which the vessel is capable to work. An additional workability analysis uses the results from the operability analysis to determine how often the vessel can work during a certain period. The operability and workability analysis are normally conducted using the wave spectrum and the vessel response amplitude operators (RAOs). However, during the early stages of the vessel design it is time consuming and challenging due to lack of data to generate vessel RAOs [128][129]. Therefore, an estimation of the workability has been made based on the vessels heave, roll, pitch period, a $HsTp^2$ limit, and environmental data. The surge, sway, and yaw motion components are not considered as it is assumed that these are being counteracted using the vessels DP system. The various steps taken to calculate the installation time are discussed below. For an overview of this method, see figure 7.10.

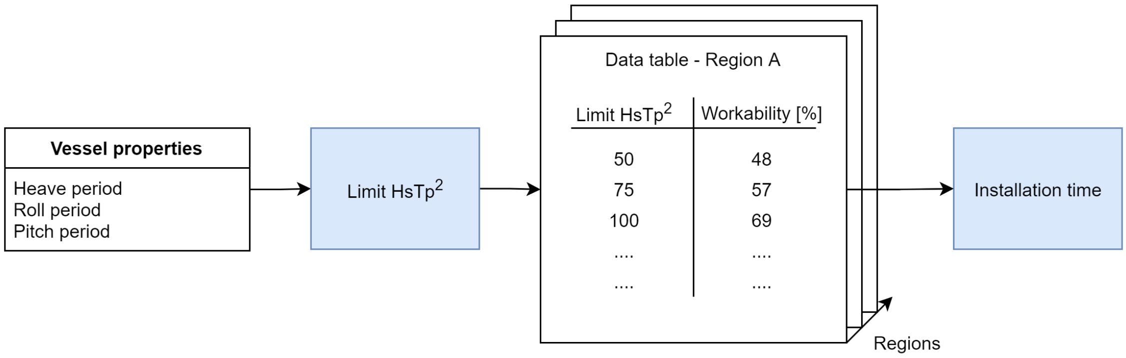

Figure 7.10.: Installation time calculation

The first step in this method is to calculate the natural period of the vessel for heave, roll, and pitch. An approximation of these periods is calculation using the equations 7.30, 7.31, and 7.32 [130].

$$T_{heave} = 2\pi \cdot \sqrt{\frac{m + a_{zz}}{c_{zz}}} \approx 2\pi \cdot \sqrt{\frac{m + 0.5 \cdot \pi \cdot \rho \cdot \frac{B}{2}^2 \cdot L}{\rho \cdot g \cdot A_{wl}}} \tag{7.30}$$

$$T_{roll} = 2\pi \cdot \sqrt{\frac{I_{xx} + a_{\phi\phi}}{c_{\phi\phi}}} \approx 2\pi \cdot \sqrt{\frac{k_{\phi\phi}^2}{g \cdot GM}} \tag{7.31}$$

$$T_{pitch} = 2\pi \cdot \sqrt{\frac{I_{yy} + a_{\theta\theta}}{c_{\theta\theta}}} \approx 2\pi \cdot \sqrt{\frac{(0.32L)^2}{g \cdot GM_L}} \tag{7.32}$$

where: $T_{'name'}$ = Natural period of 'name' [s], m = Mass [kg], $a_{'name'}$ = Added mass 'name' [kg or kg$\cdot m^2$], $c_{'name'}$ = Spring constant 'name' [N/m], ρ = Density water [kg/m^3], B = Vessel beam [m], L = Vessel length [m], g = Gravity constant [m/s^2], A_{wl} = Waterline area [m^2], $I_{'name'}$ = Mass moment of inertia [kg $\cdot m^2$], GM = Metacentric height [m], and $k_{\phi\phi}$ = Radius of gyration [m]

The various natural periods need to be translated into a HsTp^2 limit. Based on project experience within HES a feasible HsTp^2 limit for the Aegir is selected [131]. The limit selected for the Aegir, combined with its vessel properties, is used to scale the limit for the generated vessels, using equation 7.33. In order to incorporate the effect of all three natural periods, the weighted average of these natural periods is used for the scaling, see equation 7.34. At the moment an equal weight for all three natural periods has been applied.

$$HsTp^2limit = \frac{HsTp^2_{Aegir}}{T_{average\ field} - T_{average\ Aegir}} \cdot (T_{average\ field} - T_{average\ vessel\ design}) \tag{7.33}$$

$$T_{average\ vessel\ design} = \frac{T_{heave} \cdot w_1 + T_{roll} \cdot w_2 + T_{pitch} \cdot w_3}{w_1 + w_2 + w_3} \tag{7.34}$$

where: $T_{'name'}$ = Natural period of 'name' [s], and w_{number} = Weight of each natural period [-]

Based on the HsTp^2 limit and the Hs (significant wave height) and Tp (wave period) data from the offshore wind farm location an estimation of the workability can be made. See figure 7.11 for an indication of the effect of changing the limit. The limit is visualized by the lines in the figure. All the data points above the line indicate the region in which working is not feasible, while the data points below the line indicate situations in which installation is possible.

$$Workability = \frac{number\ of\ data\ points <= HsTp^2\ limit}{number\ of\ data\ points} \cdot 100 \tag{7.35}$$

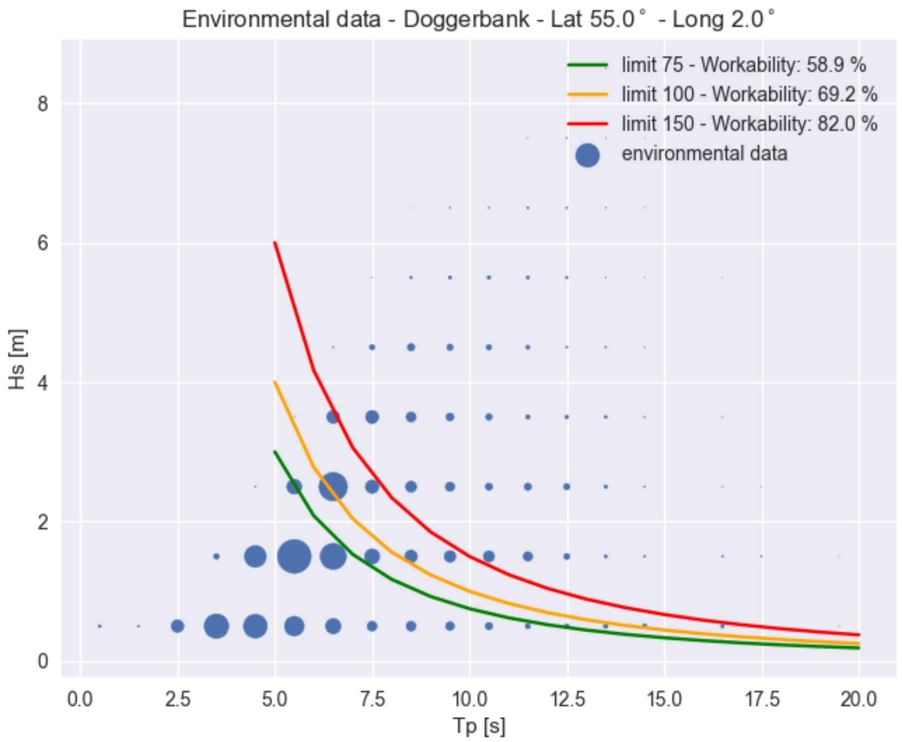

Figure 7.11.: Workability

Finally, the relation described by equation 7.36 is used to transform the workability towards the installation time necessary for a specific project. During this calculation it is assumed that the necessary time for installing a wind turbine having a 100% workability is 1 day [132].

$$T_{installation} = \frac{T_{per_turbine} \cdot N_{Turbines}}{Workability} \tag{7.36}$$

where: $T_{installation}$ = Total installation time [days], $T_{per\ turbine}$ = Installation time per turbine [days], and $N_{Turbines}$ = Amount of turbines [-]

Idle time

When the installation vessel is responsible for both installation and transport of the cargo the vessel will not experience idle time, as it does not have to wait for other vessels. For a typical modelled timeline see figure 7.12.

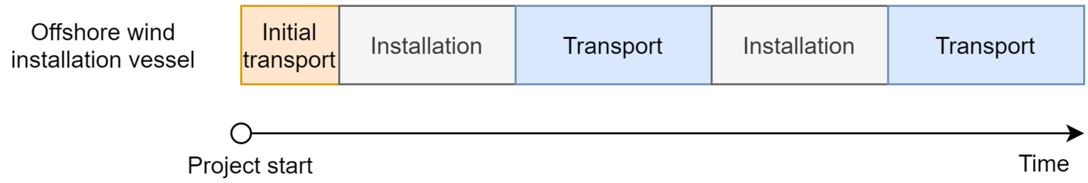

Figure 7.12.: Normal project stages

In case of a strategy in which a feeder vessel is used, it may occur that some of the vessels used experience idle time as they have to wait for the other vessels to complete their tasks. The application of a feeder vessel is modelled in such way that the installation vessel will never experience idle time. This indicates that there will always be enough feeder vessels available to supply the installation vessel. The feeder vessels however, can experience idle time, see figure 7.13 for a timeline example.

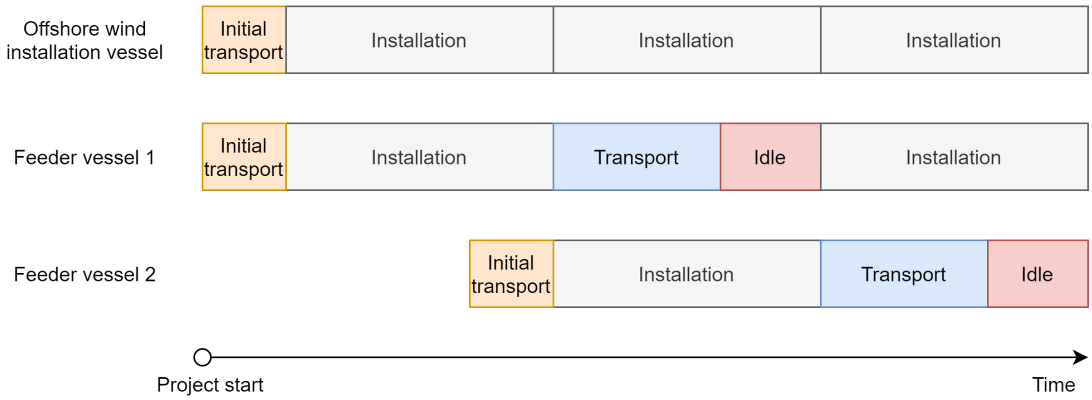

Figure 7.13.: Idle time during early stages of the project

It should be remarked that it is assumed that at least 2 feeder vessels combinations are necessary as the installation vessel is not required to carry a component at all. Therefore, a feeder vessel needs to stay along side the installation vessel during the whole installation procedure, while another feeder vessel is picking up new components. Moreover, the additional risks of offshore transfer lifts and time involved having a feeder vessel along side the installation vessel is not included [39].

7.7. Costs

The costs is the KPI that is being used to assess the performance of the vessel designs. As indicated by Stopford [133] there are many different methods used in the industry to define the vessel costs. The choice has been made to use a definition in which the vessel costs is split in the following three main categories:

- **Capital expenses**: costs related to financing and building the vessel
- **Operational expenses**: yearly returning costs to keep operating
- **Voyage expenses**: costs related to each offshore wind installation project

Capital expenses

The capital expenses (CAPEX) related to the vessel designs are determined using equation 7.37.

$$C_{capital} = \frac{C_{build}}{vessel\,lifetime} \tag{7.37}$$

where: $C_{capital}$ = Capital costs per year [€/year], and C_{build} = Build costs [€]

It should be remarked that the described definition of capital costs and therefore also this research does not include periodic docking costs, and also excludes the financing structure and related costs when building a new vessel. The vessel lifetime is set to a fixed value, while the total build costs of the vessel is defined according to equation 7.38.

$$\begin{aligned} C_{Vessel\,newbuild} = C_{Hull} + C_{Outfit} + C_{HVAC} + C_{Accommodation} \\ + C_{Electrical\,installation} + C_{Machinery} + C_{Mission\,equipment} \end{aligned} \tag{7.38}$$

where: $C_{'name'}$ = costs of component 'name' [€]

As mentioned before, the costs of the vessel is closely related to the weight of different vessel components [114]. Therefore, the build cost of the vessel is estimated using the weight of the various components determined under the subsection lightweight and deadweight. These weights are multiplied by costs ratios that are determined in collaboration with Royal IHC [115]. The only exception are the costs of the mission equipment. These costs are based and scaled using the installed crane capacity. The approach in this research additionally, involves the possibility to investigate the impact of a changing crane. This impact is measured by the costs of the vessel which will increase due to a crane upgrade according to equation 7.39.

$$C_{additional\,crane\,upgrade} = \frac{c_{crane\,upgrade} \cdot capacity\,added}{vessel\,lifetime - time\,passed} \tag{7.39}$$

where: $C_{'name'}$ = costs of component 'name' [€], and $c_{crane\,upgrade}$ = ratio of crane capacity and costs [€/mT]

Operational expenses

The operational expenses (OPEX) are costs that run during the whole year. The total operational expenses per year can be calculated applying equation 7.40.

$$\begin{aligned} C_{operational} = C_{crew} + C_{Repair\,and\,maintenance} + C_{Stores\,and\,lub} + C_{Insurance} \\ + C_{Administration} \end{aligned} \tag{7.40}$$

where: $C_{'name'}$ = costs of component 'name' [€]

The operational cost components are scaled based on various vessel properties. The crew costs are scaled with the amount of crew on board. The costs related to repair and maintenance, and stores and lubrication are scaled using the installed power on board. Finally, the insurance and administration costs are determined based on the estimated new build price of the vessel.

Voyage expenses

The voyage expenses (VOYEX) that are modelled in this research are the fuel costs, the port call costs, and the costs of using additional vessels in case of a feeder strategy, see equation 7.41.

$$C_{voyage} = C_{Fuel} + C_{Port} + C_{Additional\ vessel} \tag{7.41}$$

where: $C_{'name'}$ = costs of component 'name' [€]

The fuel costs of the vessels is related to the amount of power that is being required in a certain time period. An insight in the power requirements of the vessel during the project is given by the operational profile. Three different situations in the operational profile are defined, the transit, installation, and idle stage. For each of these stages the required power, engine efficiency, and time is determined to calculate to total fuel expenses, see equation 7.42 [119].

$$\begin{aligned} C_{fuel} = c_{fuel} \cdot (sfc_{transport} \cdot t_{transport} \cdot P_{transport} \\ +sfc_{installation} \cdot t_{installation} \cdot P_{installation} \\ +sfc_{idle} \cdot t_{idle} \cdot P_{idle}) \end{aligned} \tag{7.42}$$

where: C_{fuel} = Fuel costs [€], c_{fuel} = Ratio of fuel and costs [€/g], $sfc_{'name'}$ = Specific fuel consumption during situation 'name' [g/kWh], $t_{'name'}$ = Time in each situation 'name' [hours], and $P_{'name'}$ = Power consumption during 'name' [kW]

The price of the port calls is currently modelled as the price per port call in Rotterdam port [134]. The expenses related to the additional vessel are based on the day rate of the vessels and the time the vessels are being used during the project. In this research the day rate will be based on the amount of feeder sets that are being used. One feeder set consists out of a barge and two tugs. When combining the day rate and the total time of vessel deployment the costs can be calculated using equation 7.43.

$$C_{additional\ vessel} = c_{additional\ vessel} \cdot (t_{transport} + t_{idle}) \tag{7.43}$$

where: $C_{additional\ vessel}$ = Total costs additional vessel [€], $c_{additional\ vessel}$ = day rate of vessel [€/day] and $t_{'name'}$ = Time in each situation 'name' [days]

Total costs

The total costs are defined as costs per project. In order to add all cost items together the CAPEX and OPEX costs per year are transformed towards costs per project, see equation 7.44.

$$C_{total} = \frac{C_{CAPEX}}{365} \cdot t_{project} + \frac{C_{OPEX}}{365} \cdot t_{project} + C_{VOYEX} \tag{7.44}$$

where: $C_{'name'}$ = Costs of component 'name' [€], and $t_{project}$ = Project time [days]

The purpose of the methodology is to find the vessel with the lowest costs possible. This indicates that the model is trying to minimize equation 7.44.

7.8. Conclusion

The chapter does provide an overview of the variables and shows that a framework is built that is capable of generating many offshore wind installation vessel designs. By providing this overview an answer has been given on the following sub question: *Which method and variables can be used to generate offshore wind installation vessel concept designs?* The conclusion of chapter 6 provides the first part of the answer on the following sub question *How can the performance of a concept installation vessel being assessed for the different sets of scenarios?* It concludes that costs can be applied to assess the various installation vessels. The current chapter provides the second part as it does elaborate on how these costs can be defined, by calculating the CAPEX, OPEX, and VOYEX.

The case study shows that a combination of scenario modelling and concept design generation gives specific inputs for future vessel designs

8 Case study

The goal of this chapter is to answer the following defined sub question: *'How can a combination of scenario modelling and concept design generation provide more insight into future offshore wind installation vessels'*, see section 2.3. Insight required for answering this question will be generated by performing a case study regarding future offshore wind installation vessels. In this case study the various steps in the methodology presented in chapter 5 are carried out. In section 8.1 epochs and eras are defined for this specific case study. A description of the concept vessel design space is given in section 8.2. The epochs, eras, and generated concept vessel are analysed in section 8.3. Section 8.4 provides insight in the exploration opportunities of various epochs and eras. Finally, an answer on the sub question is given in section 8.5.

8.1. Defining epochs and eras

The first stage of concept exploration involves generating various scenarios in order to define a set of operational needs for the vessel. In this case study the scenarios will be generated using the scenario method and approach described in chapter 6. This involves first defining a set of short-term epochs, after which these will be combined into different long-term eras.

Epochs

The key uncertainties in the offshore wind market are identified to be the power rating of the offshore wind turbine, the water depth at the wind farm location, and the distance between the wind farm location and the closest port, see section 3.5. For each of these key uncertainties three states are defined based on available market reports [2] [7] and advice from a Heerema Marine Contractor (HMC) business analyst [135]. The first state represents the current market average, while the third state represents an extreme value. The second stage is an average between the first and the third. For the selected values, see table 8.1.

Table 8.1.: Input variable for epoch generation

Input variable	Unit	Values
Turbine power rating	MW	10, 15, 20
Water depth	m	30, 45, 60
Distance to farm	km	50, 150, 250

First of all, this case study assumes that the vessel only installs monopile type foundations. The installation of the turbine is not considered in this case study. A fixed number of 100 monopiles is set as cargo amount. Finally, the Doggerbank in the North sea is selected as region. The weather properties in this region influences the workability at the installation site.

Eras

The epochs defined above are combined together to generate four different eras. All of these eras will start with the same epoch that describes the averages of the current offshore wind market. The four different eras are selected in such a way, that the impact of a single uncertainty and a combination of uncertainties at the vessel design can be investigated. See below the four defined eras:

1. **Power rating turbine**: in this era the power rating of the turbines will increase over the years while the other variables are fixed
2. **Water depth**: only the water depth changes over time
3. **Distance to farm**: this timeline only investigates the impact of a changing distance to farm
4. **All variables**: in this era the impact of increasing all variables at each time step is investigated

Impact on cargo properties

The eras 1, 2, and 4 introduce changing cargo properties over time. Era 3 does not involve changing cargo properties as it is defined that the distance to farm does not influence the design of the monopile. The cargo properties in the various scenarios are determined using the described method in section 7.2, see table 8.2 for the properties.

Table 8.2.: Cargo properties per era

Era	Cargo property	Unit	Epoch 1	Epoch 2	Epoch 3
1	Length x width	m	71 x 9	71 x 13	71 x 17
	Weight	mT	1429	2133	2850
2	Length x width	m	71 x 9	96 x 9	121 x 9
	Weight	mT	1429	1912	2429
4	Length x width	m	71 x 9	96 x 13	121 x 17
	Weight	mT	1429	2879	4844

8.2. Concept vessel design space

During the second phase of this case study, the parametric model for monohull vessels described in chapter 7 is applied. In order to run this model it is necessary to define a range of values for the length, beam, depth, crane capacity, speed and transport strategy. These values are determined based on the properties of the current monohull offshore wind installation vessels. For the min, mean, and max values of the current fleet per necessary input variable, see table 8.3.

Table 8.3.: Main parameters fleet

	Length	Beam	Depth	Crane capacity	Speed
Unit	m	m	m	mT	kts
Min	144	27	13	600	5
Mean	192	42	15	3275	10
Max	237	56	18	5000	15

In this research the goal is to explore the concept vessel design space for vessels that perform best in terms of low costs. The current fleet main parameters give an indication of the design space that needs to be considered. The minimum values of the current fleet is used as guideline for the minimum values for the parametric model. As it is expected that the market evolves further the maximum input values of the parametric model will be higher compared to the current fleet. Therefore, an additional 10% is added to the maximum values of length, beam, and depth. Moreover, an additional 20% is added to the crane capacity. For the resulting input values and the amount of steps, see table 8.4. The transport strategy has two different input variables. A shuttle strategy represents a situation in which the installation vessel sails and transports the cargo. A feeder strategy corresponds to a situation in which a feeder concept is being used to transport the cargo.

Table 8.4.: Input parameters

	Length	Beam	Depth	Crane capacity	Speed	Transport strategy
Unit	m	m	m	mT	kts	[-]
Min	140	30	12	1000	5	Shuttle
Max	260	60	20	6000	15	Feeder
Step size	15	5	2	1000	2	-
Amount of steps	9	7	5	6	6	-

Having this input values a total of 22680 vessel combinations is generated. More variables can be added, but this will result in a rapidly growing amount of vessel combinations. If this set of vessels gives an area of interest it is possible to conduct a more detailed analysis in or around this specific area.

8.3. Performance analysis

In the last stage of the case study the performance of the different vessel designs in the selected epochs and eras will be assessed based on the defined cost function, see 8.1.

$$C_{total} = \frac{C_{CAPEX}}{365} \cdot t_{project} + \frac{C_{OPEX}}{365} \cdot t_{project} + C_{VOYEX} \tag{8.1}$$

where: $C_{'name'}$ = costs of component 'name' [€], and $t_{project}$ = project time [days]

A vessel will perform better if the costs are reduced, as this provide a reduction in LCOE. The performance of the vessels in combination with the eras will be used to investigate possible driving factors. For the findings in this case study, see the following subsections.

General trends in all eras

During the analysis of the selected eras a set of general trends is visible, see the following paragraphs.

Performance over time

One of the strong points of the application of EEA is the possibility to investigate the vessel performance over time. In order to visualize this performance a visualization technique called parallel coordinate plots is applied. The combination of EEA and parallel coordinate plots has been applied before by Gasper and Ross [104] [102]. See figure 8.1 for a visualization of the era in which the water depth increases over time.

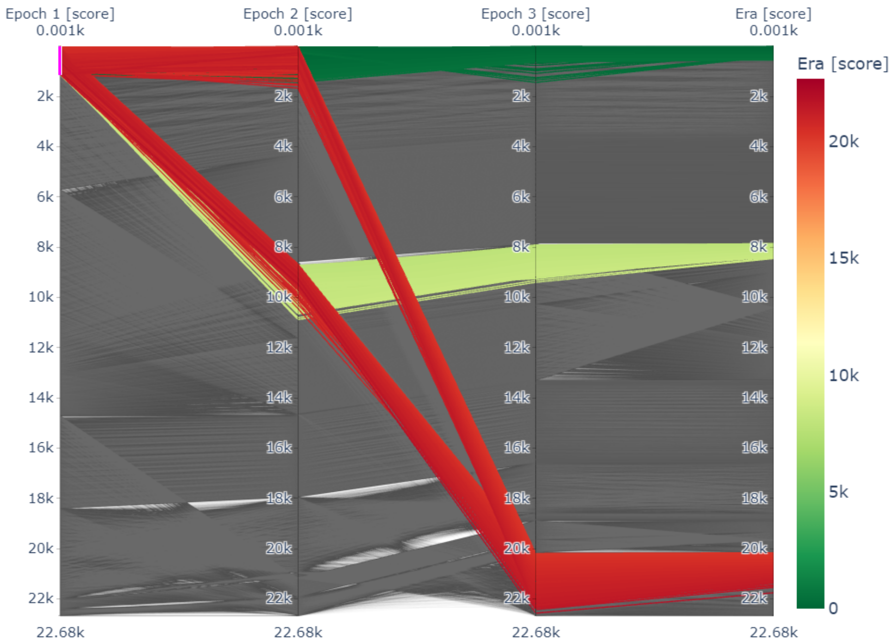

Figure 8.1.: Performance changes over time (era- water depth)

In figure 8.1 four axis are visible each indicating the performance of the created vessel designs in the selected epoch and corresponding era. In this figure each vessel has received a score in each epoch and era based on its costs. The vessel with the lowest costs will receive a score of 1, the vessel with the second lowest cost will receive a score of 2, etc. A low score (which corresponds to the point highest on the axis) therefore relates to vessels that do perform good in that specific epoch or over the era. In order to emphasize the impact of the changing market at the vessel design the best 5% of the vessels are being highlighted in the figure. It can be seen that a part of the top 5% performing vessels at the beginning of the era, start to perform much worse due to the changing requirements. Moreover, they will not be able to recover from a 'bad' performing scenario in order to end in the top 5% of the overall era. This indicates the importance of this analysis, in order to explore designs that will be robust over its lifetime.

Vessel characteristics
Over all eras there are general trends visible in the main dimensions of the vessels. The vessel length and beam share the behaviour visible in figure 8.2.

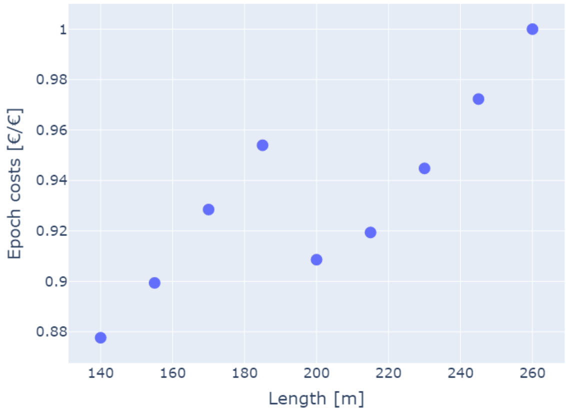

Figure 8.2.: Impact of vessel length at the costs

Figure 8.2 shows a positive correlation between the era costs and the vessel length. However, in this figure it is visible that a drop occurs around a vessel length of 200 meter. This decline of era costs can be related to the vessels deck space and cargo length. In this example the cargo length is 71 meter. By increasing the vessel to a length of 200 meter, it becomes possible to place two monopiles behind each other on the deck and therefore increase the carrying capacity. Further increasing the length will only increase the costs until the moment an additional set of monopiles can be placed on the deck. This increase in carrying capacity makes the vessel more efficient and therefore reduces the costs. See figure 8.3 for the visualisation of these two situations.

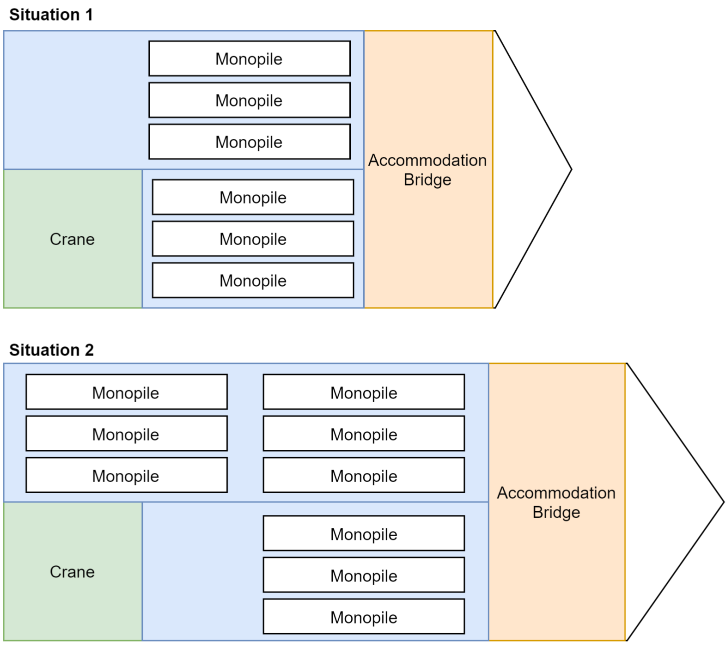

Figure 8.3.: Impact of vessel length at carrying capacity

The vessel beam and cost relation share the same properties as the vessel length and cost relation. This is due to the fact that a certain increase in beam will improve the carrying capacity of the vessel. In addition to this another trend regarding the beam can be found. In all epochs the vessel designs with a low beam face higher epoch costs, see figure 8.4.

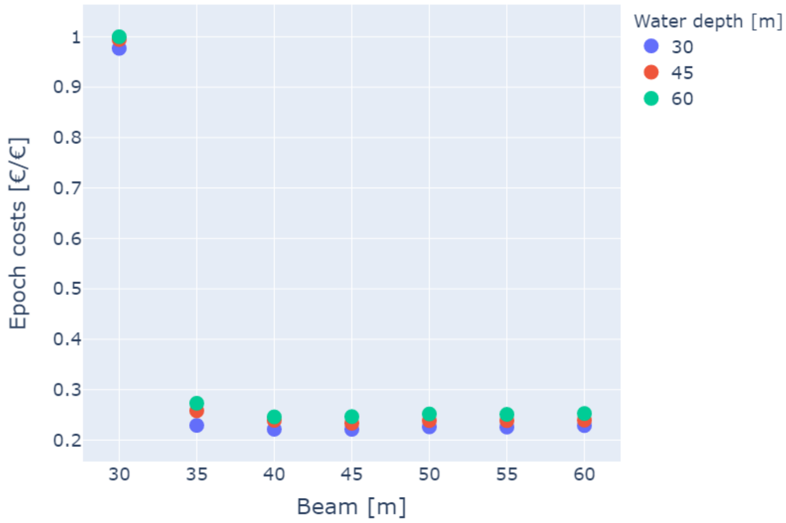

Figure 8.4.: Impact of vessel beam at the costs

The increase in vessel costs at these lower beams is due to the fact that these vessels receive a cost penalty as they do not comply with the stability constraints. Therefore, these vessels are not capable of carrying out these specific epochs and eras.
When investigating the results regarding the vessel depth it is visible that the lower depth of 12 meter is mostly the favourable depth in the selected eras, see figure 8.5.

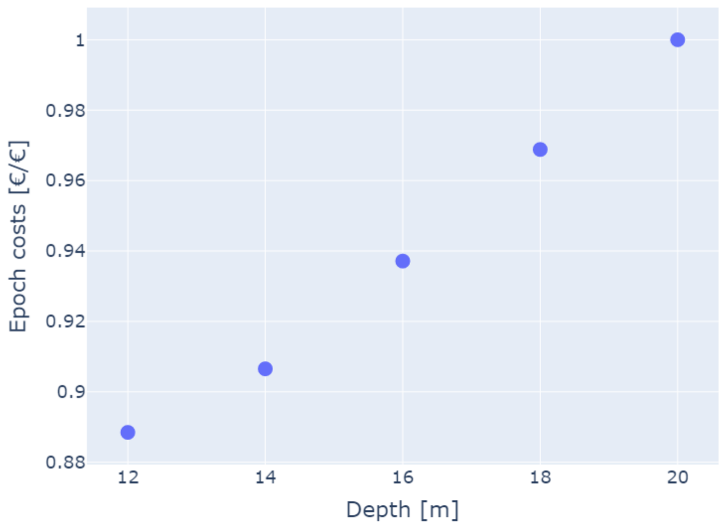

Figure 8.5.: Impact of vessel beam at the costs

The higher depths increase the vessel costs due to its impact at the build and fuel costs.

Application of feeder vessel strategy
In the currently defined eras the feeder vessel concept is never the best strategy due to higher costs. However, the model shows that an increase in distance and cargo size does decrease the difference in costs between the two transport strategies. In order to get a better insight in this behaviour additional distances have been added of 350, 450, and 550 km, in a situation in which the vessel needs to handle a monopile for a 15 MW turbine at a water depth of 60 meters. Figure 8.6 shows the costs of the two transport strategies, in case of changing distance.

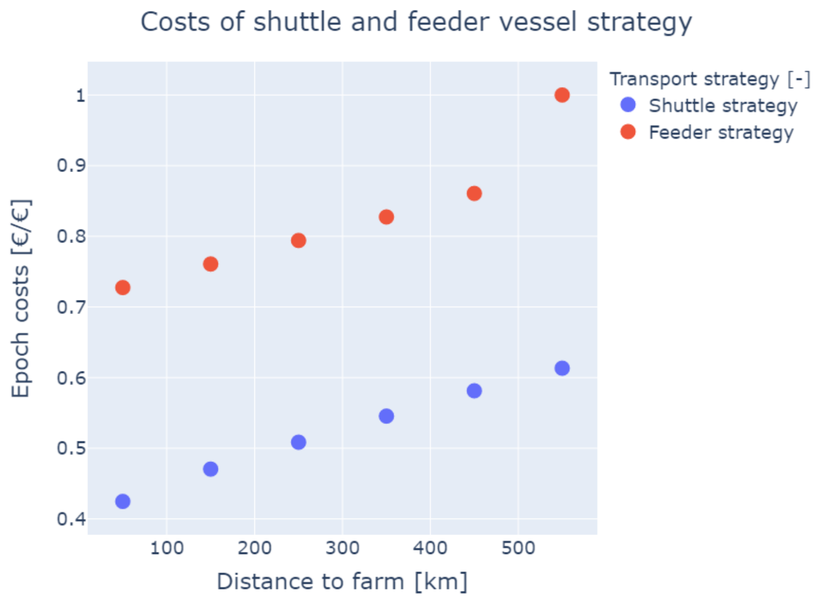

Figure 8.6.: Transport strategy comparison

From this figure it can be seen that in this specific epoch it is not favourable to have a feeder vessel at a distance between 50 - 550 km. At a distance above 450 km the costs of the feeder vessel strategy even increases significantly compared to the other distances due to the introduction of an additional feeder vessel. This additional feeder vessel prevents that the installation vessel experiences idle time.

Application of changeable crane
Due to the fast changing offshore market it is interesting to investigate the application of having a changeable crane. The current scenario and parametric modelling methodology provides an opportunity to upgrade vessels during its lifetime. By upgrading the crane later in the lifetime of the vessel the initial investment costs are lower which reduces investment risk related to the uncertainties in the market. However, the costs will be higher when a crane upgrade is carried out. As mentioned in 7.3 the crane will be upgraded if additional crane capacity is required due to the cargo it should be able to handle. The performance of the vessels having a changeable crane in the changing water depth era are visible in figure 8.7. It should be noted that only the feasible vessels are included in this figure and the vessels with changeable crane that are in the top 5% in epoch 1 are highlighted.

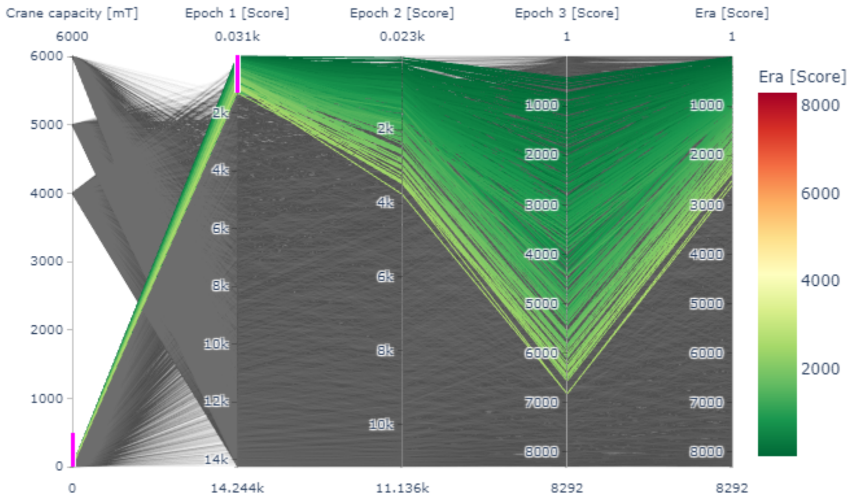

Figure 8.7.: Performance of vessels having a changeable crane

Figure 8.7 shows that the vessels having a crane that does change over time (indicated with a capacity of 0 mT in this figure) does outperform all vessels in the first scenario and then slowly starts to perform worse compared to the other vessels. This is expected, as the vessel will have a benefit in the beginning as the crane perfectly fits the necessary capacity. However, in later stages the vessels with a fixed and changeable crane share the same specifications. The performance of the vessel with a changeable crane will be worse in these situations as the capabilities are the same but the vessel is more expensive due to the upgrades. In order to get a better overview of this behaviour, a single hull with different crane capacities is selected and shown in figure 8.8.

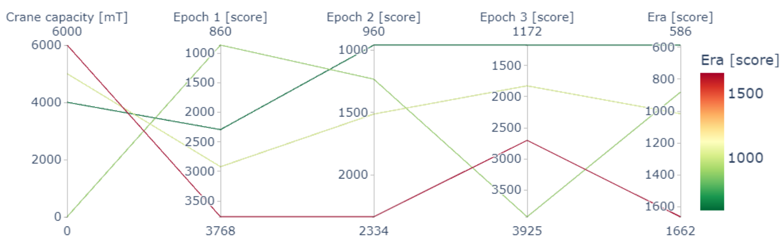

Figure 8.8.: Detailed performance of vessel having a changeable crane (Length: 185 m, Beam: 50 m, Depth: 14m, Speed: 9 kts, Transport strategy: shuttle

The vessel in figure 8.8 clearly shows the performance difference between a vessel having a fixed crane and a changeable crane. It can be seen that in the end the performance of the fixed crane under the current upgrading costs is performing better. A small sensitivity test has been conducted. In case of upgrades costs that equal the costs of installing an original crane, the fixed vessel still outperforms the vessel with the changeable crane in the end. This is due to the fact that the investment takes place at a later stage and therefore needs to be payed back in a smaller amount of time.

Era - Power rating turbine

Apart from the mentioned trends, the changing power rating of the offshore wind turbines causes changes in the requirements for the crane capacity due to the increasing weight of the monopile from 1429 to 2850 mT. This results in a required crane capacity of 2000 mT in the first epoch, 3000 mT in the second, and in the last situation a crane of 4000 mT. Figure 8.9 shows the impact of the increasing weight at the performance of vessels having a different crane capacity.

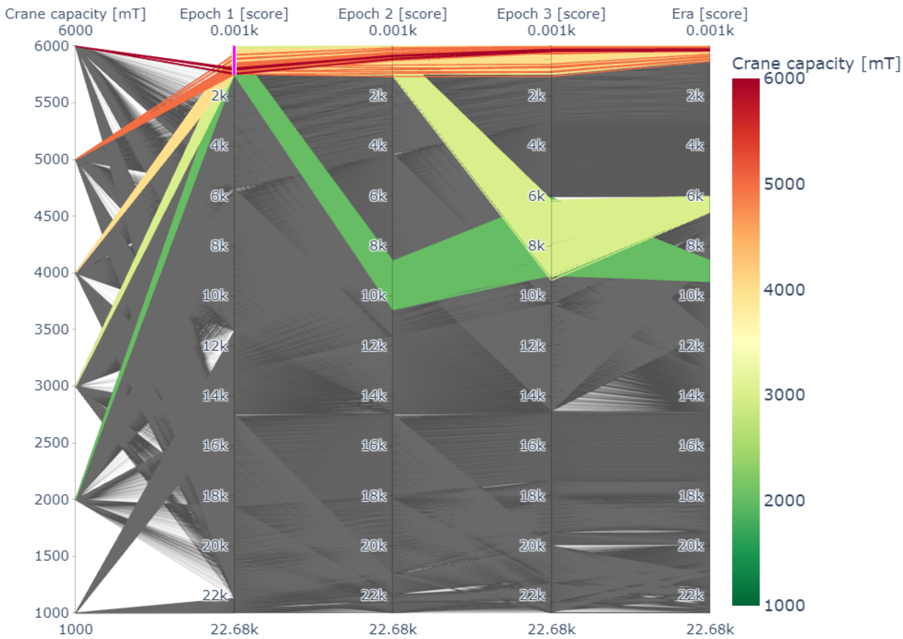

Figure 8.9.: Era power turbine rating impact at crane capacity

In figure 8.9 it can be seen that the vessels with a crane capacity of 2000 mT are in the top 5% best performing vessel in epoch 1, but are suddenly performing much worse in epoch 2. This is due to the increasing cargo weight which makes it impossible for these vessels to perform the required lifts with the crane installed. The same behaviour occurs with the 3000 mT cranes after the second epoch. This indicates that the last situation the vessel will encounter sets a constraint for the minimum required crane capacity, as the vessel should be capable of carrying out all the tasks. Additionally, in comparison to the other eras larger beams are performing better. This behaviour can be related to the fact that the increasing power rating increases the diameter of the monopile. Having a wider deck gives the vessel the possibility of carrying more monopiles. The preference for an increased beam is also visible in figure 8.10.

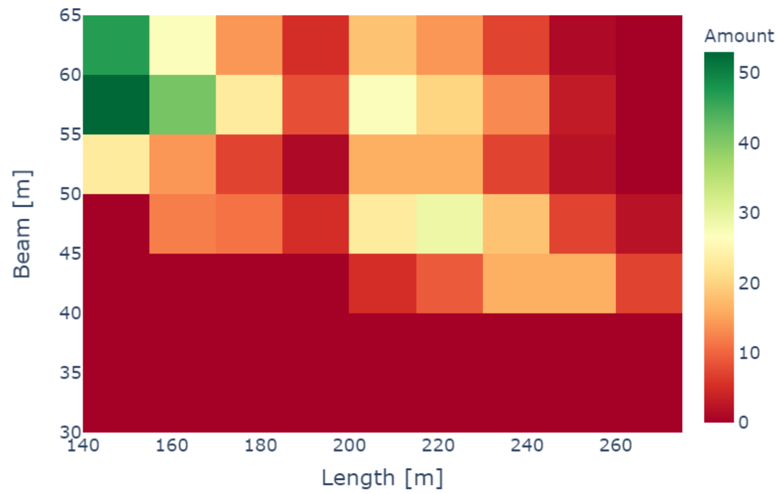

Figure 8.10.: Era power turbine rating impact at beam and length. Transport strategy: shuttle

Figure 8.10 shows the distribution in this era of the top 5% vessels. The more green a square is the more vessels are present in that specific beam length combination. As mentioned above, it is visible that at a lower length, it is best to increase the beam of the vessel in order to improve the carrying capacity.

Era - Water depth

In addition to the general behaviour mentioned above, the increasing water depth sets a bound to the crane capacity and the vessel length. The crane capacity requirements set in this era is 3000 mT. The impact at the length of the vessel over time is visualized in figure 8.11.

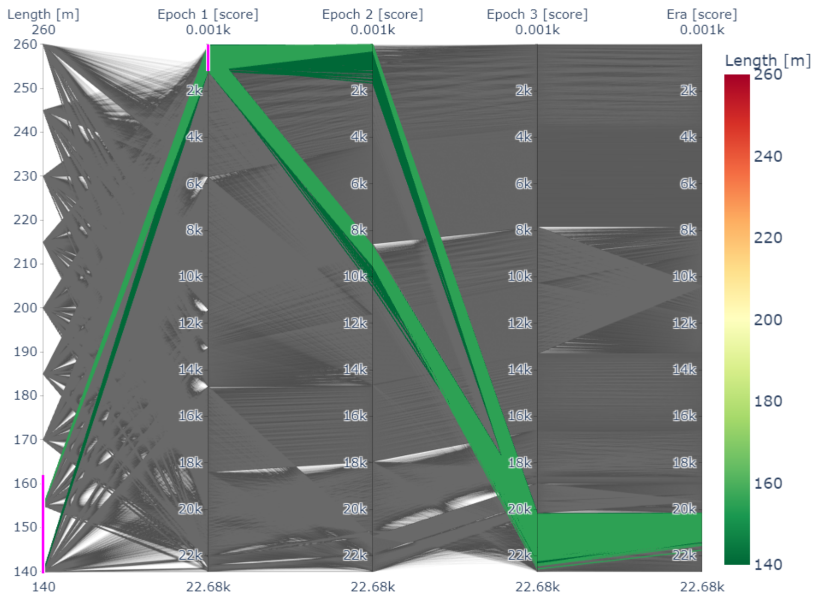

Figure 8.11.: Era water depth impact at vessel length

In figure 8.11 the vessel having lengths of 140 and 155 meters in combination with the best 5% vessel in epoch 1 are highlighted. It can be seen that the vessels are capable of dealing with a monopile length of 96 m in epoch 2. When the monopile length increases to 121 m in epoch 3 the vessels start to perform much worse because of the lack of deck length. Due to the fact that the deck length is not sufficient the vessels will not be able to transport the components and carry out its mission. The limit posed in the third epoch is also visible as a red area in the multi dimensional histogram in figure 8.12, which is based on the top 5% vessel in terms of costs.

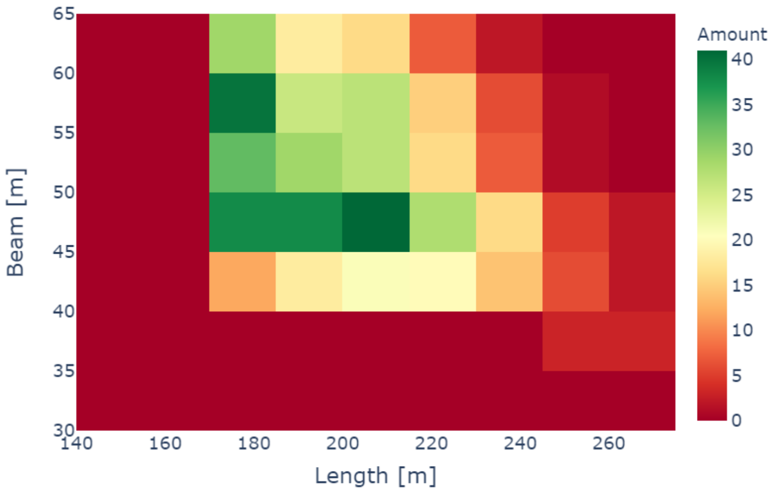

Figure 8.12.: Era water depth impact at beam and length. Transport strategy: shuttle

In addition to the length constraint figure 8.12 also shows the beam constraint, by the red blocks at the bottom of the figure. This beam constraint is due to the lack of stability the vessel experiences withholding it from successfully carrying out its mission.

Era - Distance to farm

Changing the distance to farm does not result in changes to the preferred vessel designs over time in terms of vessel dimensions or crane capacity. However, it does have an impact on the optimal vessel speed. In figure 8.13 the lowest costs per speed and distance is visualized, while excluding the impact of the transport strategy. The trend visible in this figure, is that when the distance to the offshore wind farm increase the optimal vessel speed increases as well. This trend can be explained by the fact that the vessel speed is a variable that can be used to find the perfect balance between the fuel costs and the project time. An increase in speed will reduce the project time while it does increase the fuel costs. A reduction in project time will result in a reduction of the OPEX and CAPEX costs.

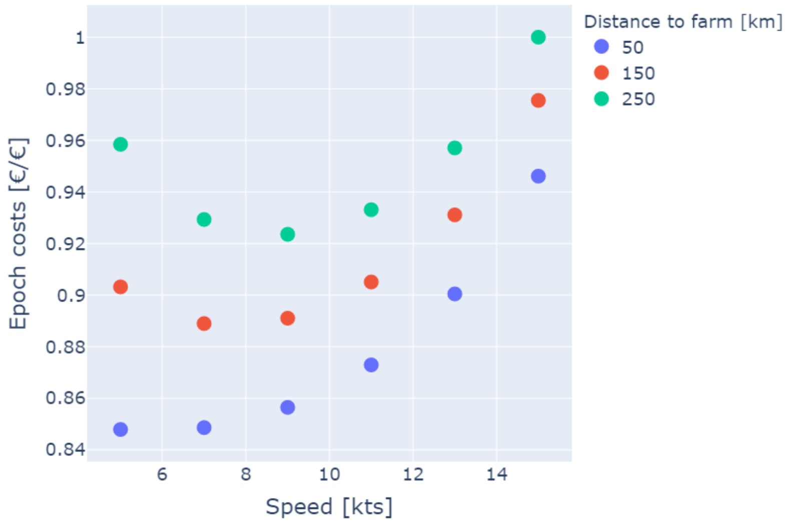

Figure 8.13.: Vessel speed at different farm distances

In terms of main dimensions, the vessel is preferred to be as short as possible while having a beam between 45 - 55 meters, as visible in figure 8.14. As mentioned before, the beam/length preference does not change over time due to increasing distance.

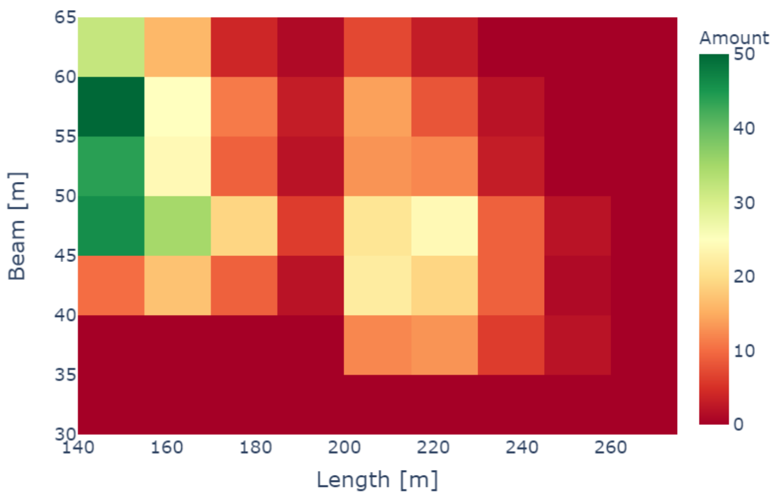

Figure 8.14.: Era distance impact at beam and length. Transport strategy: shuttle vessel

Era - All variables

In this era it becomes visible that the boundaries of the vessel input variables are being reached. Due to the increasing cargo weight in combination and an assigned dynamic amplification factor of 1.1 a crane capacity of 6000 mT is required. Moreover, a combined impact of the previous eras are visible when looking at the preferred beam length combinations. It can be seen that the model prefers a wider beam, while the length has a constraint due to the length of the monopiles, see figure 8.15.

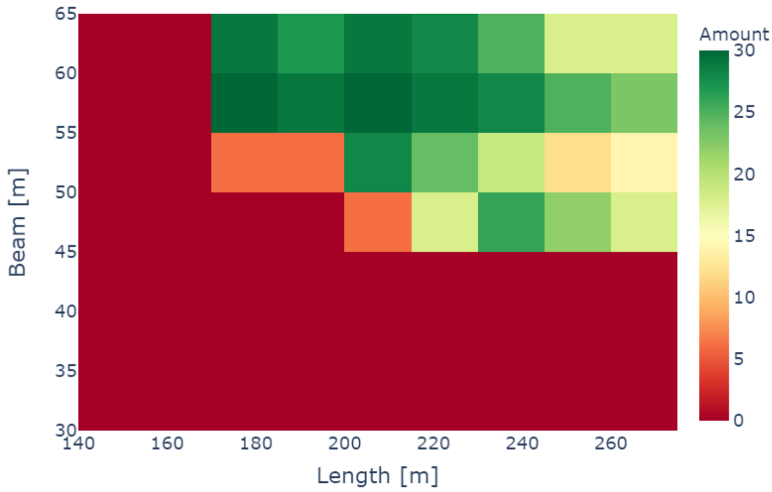

Figure 8.15.: Era all increasing impact at beam and length. Transport strategy: shuttle vessel

Sensitivity
In order to test the sensitivity of the model to the various costs components a small sensitivity test is carried out in addition to the small test early in this case study. In this methodology, the performance of the vessels is determined by calculating the three main cost components, the CAPEX, VOYEX, and OPEX over a project. In this sensitivity analysis, these three components are each altered by 10% in order to investigate if this impacts the previous findings. An example is given in figure 8.16 in which the CAPEX has been varied.

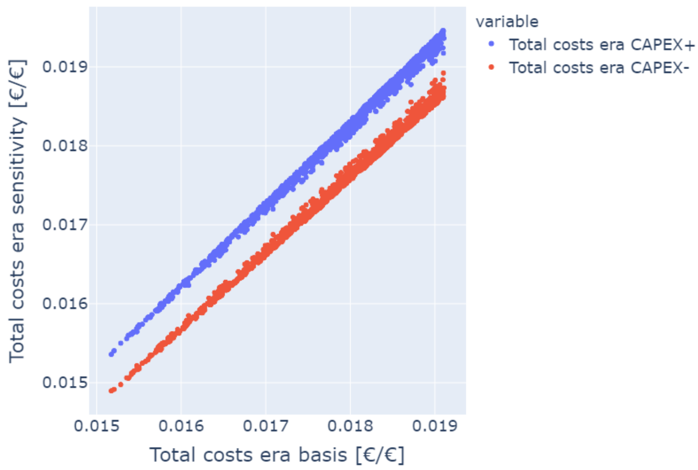

Figure 8.16.: CAPEX sensitivity

In this figure it is visible that the main trends are similar. The best vessel and the trends visible in the basis scenario are still the same in the scenario in which the CAPEX is changed. However, it is also visible that when the costs increases some small variations occurs. Additionally, it should be remarked that the cargo properties have a big impact at the results. An example is the cargo weight, which mainly dictates the required mission equipment. This effect is also visible during the various epochs, in which the required crane capacity changes due to the changing vessel weight.

Future offshore wind installation vessel

When providing advise regarding the future offshore wind installation vessel all defined eras should be taken in consideration. The analysis above shows the results in each epoch or era individually. In this analysis the score from each era will be combined in order to investigate the most robust and best performing vessel. The eras are combined by summing the scores in each era individually, while each era has a weight of 1, see equation 8.2.

$$
\begin{aligned}
Score_{Eras\ combined} = (&Score_{Era\ 1} \cdot Weight\ score_1 \\
&+ Score_{Era\ 2} \cdot Weight\ score_2 \\
&+ Score_{Era\ 3} \cdot Weight\ score_3 \\
&+ Score_{Era\ 4} \cdot Weight\ score_4) \\
/(Weight\ score_1 + Weight\ score_2 &+ Weight\ score_3 + Weight\ score_4)
\end{aligned} \tag{8.2}
$$

First of all, it should be remarked that only the feasible vessels over all eras are considered in order to have a vessel that is robust and can perform in a variety of different situations. In terms of vessel depth, crane capacity, vessel speed, and transport strategy similar trends are visible as the ones mentioned in the previous subsections. This indicates that the preferred vessel depth is around 12 meters. The crane capacity is set by the minimum required capacity during all the eras, which equals a capacity of 6000 mT. Moreover, the optimal vessel speed is around 7-9 kts. Finally, it can be concluded that using a feeder vessel is not advised when considering all eras combined. When investigating the preferred length and beam of the vessel it is visible that the previous trends are combined, see figure 8.17.

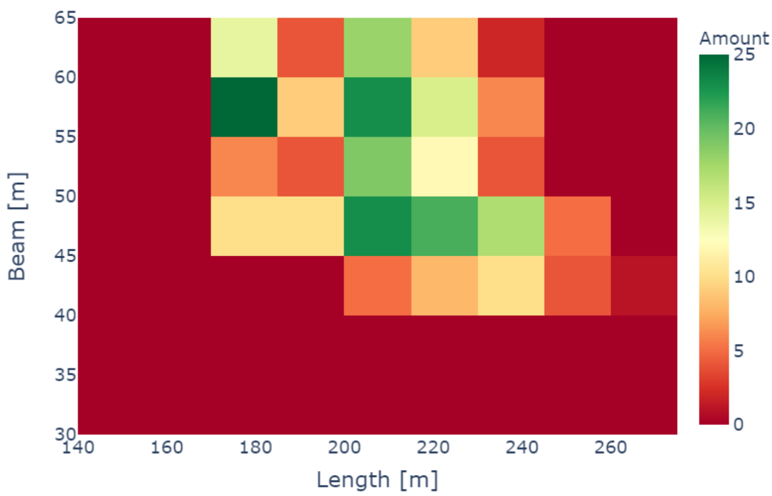

Figure 8.17.: All eras impact at beam and length

In figure 8.17 it is visible that there are three preferred combinations, a vessel length of 170 meters and a beam of 55 meters and a vessel length of 200 meters with a beam of 45 or 55 meters. The results of these findings are compared with the currently announced vessels, or just launched vessels. For their vessel dimensions and mission equipment, see table 8.5.

Table 8.5.: Newbuilds offshore wind installation market [122] [123] [136]

Name	Company	Length	Beam	Depth	Crane capacity
		m	m	m	mT
Orion	DEME	217	49	17	5000
Les Alizés	Jan de Nul	237	52	16	5000
Stella Synergy	Jumbo	185	36	13	2500

When comparing the findings from combining the eras with the currently build vessels, it is visible that the vessels in general are longer than the one of the advised length of 170 meters. This can be explained due to the fact that this case study only discusses the installation of monopile vessels, while the vessels currently being build show application in which they install jackets and transport transition pieces as well. Another reason of this can be due to the behaviour visible in figure 8.18.

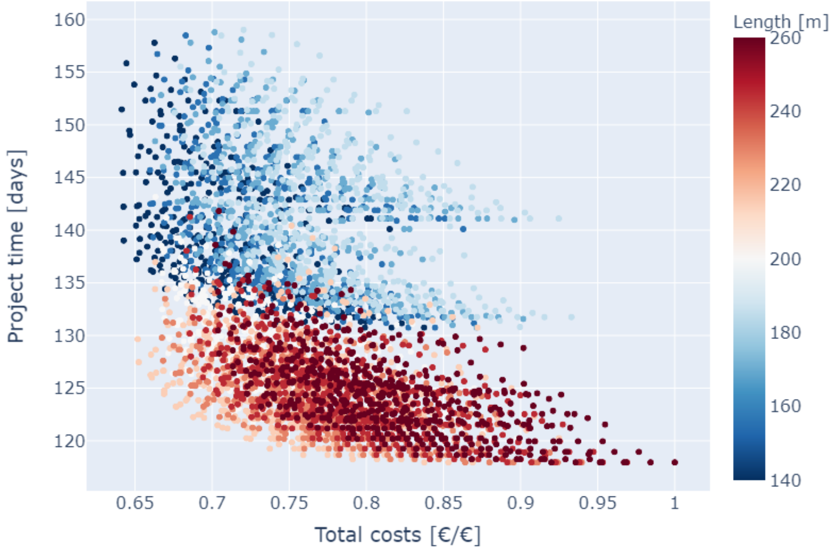

Figure 8.18.: Project time versus project costs

In this research the main focus is to lower the LCOE of the offshore wind industry by reducing the costs. Figure 8.18 shows that if a vessel has the lowest costs it does not necessary means that the project time is the shortest as well. The longer vessels of 215 meters, orange in the figure, provide an advantage in terms of project time. For a vessel owner it might be better to balance the vessel design based on costs and project time as this gives the owner the possibility to deploy its vessel in another project.

In terms of crane capacity it is visible that the advised crane capacity of 6000 mT is above the capacity of the Orion, Les Alizés, and Stella Synergy. The mission equipment can have an impact at whether or not the vessel is capable of carrying out the operations. The 2500 mT crane capacity of the Stella Synergy is sufficient to install the foundations and will outperform the vessels having a higher crane capacity in the current market. As it is expected that the 2500 mT crane capacity will not be sufficient to meet the necessary requirements set by the developing offshore wind market, the Orion and Alizés will outperform the Stella Synergy in future markets.

8.4. Exploration opportunities

The combination of EEA and parametric modelling gives the possibility to investigate many different scenarios, concept vessel designs, and key performance indicators. In the current case study the costs have been selected as single objective, but for other studies multi objective criteria can be applied. This is of use as it provides additional insight in possible trade-offs that have to be made by the stakeholder. For example the trade-off between lower project cost and higher project time. The flexibility of the selection of these performance criteria and the input for the scenarios provides many exploration opportunities. It makes it possible for a stakeholder to define a setup in order to get insight in the vessel designs that best fits their strategy. But the degree of flexibility also results in a lot of information that is being generated. In order to get an overview of the information a dashboard has been created that provides the stakeholder a methodology in which it becomes possible to interact with the information generated by the model. In the created dashboard it is possible to define a set of epochs that together define an era, see figure 8.19.

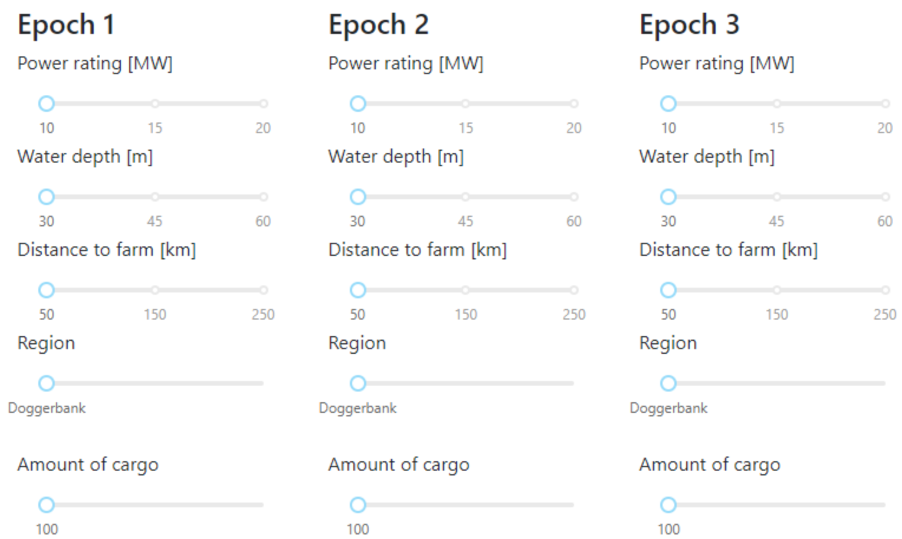

Figure 8.19.: Dashboard inputs

When the epochs and era are defined a single objective can be specified in order to investigate the impact of the vessel design at this objective. The relation between the vessel design and the selected objective will be visualized as vessel performance over time, see figure 8.20.

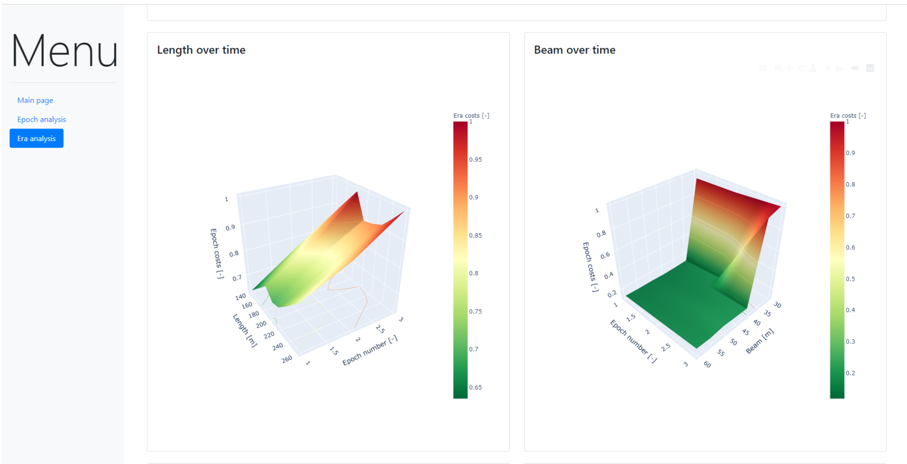

Figure 8.20.: Dashboard example graphs

A second objective can be selected in the dashboard to get insight in the relation between two performance criteria and to visualize possible trade-offs as a pareto front. The dashboard is very valuable in this methodology as it provides an easy and structured way of investigating the information generated. Based on the wishes of the stakeholder the dashboard can be altered and expanded in such a way that it provides the information that is of importance for the stakeholder to make its decision.

8.5. Conclusion

The purpose of the case study is to answer the sub question *'How can a combination of scenario modelling and concept design generation provide more insight into future offshore wind installation vessels'*. From the applied case study it can be concluded that the combination of a scenario modelling method and a parametric model does provide the possibility to get insights in the future offshore wind installation vessels. By applying a scoring system in combination with variety of visualization techniques more insight in the future vessel properties can be found. The main advantage of the combination of these two methods is that it is possible to investigate the impact of the changing market at the vessel design. This is due to the fact that it provides an opportunity to test a big amount of vessel designs that can be tested in a big amount of scenarios that vary over time.

The application of Epoch-era analysis and parametric modelling is capable of generating insights in important aspects for designing future offshore wind installation vessels

Choices have to be made in the balance between the vessel capabilities and costs. The method provides insights in the results of those choices

9 Conclusion

The main objective of this research is to answer the following main question.

> *What are the important aspects in the vessel design of offshore wind installation vessels over the next 10-15 years in order to reduce the costs and to be competitive in the offshore wind installation market?*

In order to answer this main question an approach has been developed that involves the application of Epoch-era analysis and parametric modelling in a systems engineering framework. It can be concluded that this methodology is capable of generating insights in the important aspects of the future offshore wind installation vessels. For the answer on the sub questions asked in section 2.3, see the conclusions of chapters 4, 5, 6, 7, and 8.

Offshore wind market
An important aspect regarding the vessel design is the future offshore wind market in which the vessel has to be able to operate. It defines the future vessel requirements and therefore the future vessel design. During this research the power rating of the offshore wind turbines, the water depth, and the distance from wind farm to port have been identified as the three key uncertainties for future offshore wind parks.

Vessel main dimensions
The vessel main dimensions in this research are defined as its length, beam, and depth. During this research it is visible that an aspect influencing these main dimensions is the size of the cargo. When the water depth increases, the length of the monopile foundations will increase as well. This increase in length does pose length constraints to the vessel, as it should still be able to transport the cargo to its final location. Additionally, it is visible that when the power rating of the turbine increases, the cargo width increases as well. This causes vessels having a larger beam of 50-55 meter to become more favourable over vessels with a lower beam of 40-45 meters. Besides the impact of the cargo size, the case study conducted shows an additional constraint regarding the required beam. The lower beam of 30 meters is never feasible, and a beam of 35 meters is almost never feasible. At these lower beams, the installation vessel does not comply with the required amount of stability. Finally, the case study also shows that the model is balancing the vessel size and carrying capacity. A reduction in vessel size gives lower investment costs but also reduces the carrying capacity which increase the project time.

Crane capacity
Another important design aspect is related to the mission equipment needed during the installation operation. In this case study defined as the crane. The required crane capacity is determined by the weight of the cargo the vessel should be able

to handle. When increasing the power rating of the turbine or the water depth an increase in cargo weight is visible. Based on the Epoch-era analysis it can be concluded that it is important to select a crane capacity that will be capable of handling all cargo it is facing during its lifetime. Additionally, an analysis has been conducted regarding changing the crane of the vessel during its lifetime. The case study in this research shows that the application of a changeable vessel will generally not outperform a vessel having a fixed crane that is perfectly fit for the offshore wind market. It does shows that it will outperform vessels that have installed a crane with a higher capacity then necessary. This shows the possibility of reducing investment risks due to the uncertainty of the required crane capacity in the future.

Strategy
Various strategies can be applied when transporting the cargo from port towards the installation site. From the defined case study it can be concluded that the distance from farm to port has an impact at the optimal sailing speed. At smaller distances a lower speed of around 7 knots is preferred. When the distance does increase, it is advised to increase the speed of the vessel accordingly. A same trend is visible with the size of the cargo. When the cargo size increases, the carrying capacity of a vessel reduces, and therefore the amount of trips it needs to sail increases as well. In order to properly balance the project time and the fuel consumption, it is advised to increase the vessel speed. In addition, an extra transportation strategy is investigated. This transport strategy uses a set of feeder vessel that transport the cargo while the installation vessel stays at its location. From the analysis it is visible that for the defined eras it is not advised to use a feeder concept.

Overall
The findings described above give an indication of the important aspects in the future vessel design of offshore wind installation vessels. It can be seen that the findings all relate to the two main tasks of an offshore wind installation vessel. First of all, it should be able to transport the cargo to its location. Afterwards it should have the proper equipment to install the cargo in an efficient way. The best vessel for these two tasks in the future offshore wind market is a vessel that has the best balance between the vessel costs and the efficiency in which the vessel is carrying out its tasks.


The methodology shows
potential but could be
optimized further in detail

Discussion 10

This research shows the potential of applying epoch era analysis and parametric modelling in order to get insight in future offshore wind installation vessels. This potential can be exploited even further by conducting additional research.

Parametric model

Empirical methods

In order to be able to generate many different vessel designs various empirical methods are being used to estimate vessel properties such as various shape coefficients, weight, and resistance of the vessel. The current research uses empirical methods that are available and that fit as best as possible in order to predict the related vessel properties of the monohull offshore wind installation vessels. However, these empirical methods are originally not developed for heavy lift vessels, but for merchant vessels transporting goods. It will benefit this research if more empirical methods are available that are designed specifically for heavy lift vessels and therefore produces even more accurate vessels and results.

Workability

Another area of interest for future work is related to the workability of a vessel. The methodology used in this research estimates the workability of the vessel based on the natural periods of the vessels. In future work it would be of interest to investigate the application of a vessel response analysis in combination with parametric modelling. Additionally, the installation of an offshore wind farm does not involve one wind turbine, but many wind turbines and is a repetitive process. Due to the time span of a project the workability estimation of a vessel during the whole project due to for example bad weather, maintenance, and other unforeseen issues becomes a challenge. It would be interesting to investigate this challenge and to generate insights how these relate to the vessel design, or even to the fleet that needs to be applied during the installation to improve efficiency.

Vessel types

An additional subject for future work is related to the type of vessels that are modelled. In the current methodology the focus is only on the application of monohull vessels. In the current offshore wind installation market, it is visible that apart from monohull vessels also jack-up vessels and semi-submersibles are used. The advantage of the current methodology is that it is possible to add these type of vessels or other new designs by developing a new parametric model in the current framework. It would be beneficial to be able to compare the performance of these types of vessels in order to investigate their strengths within the offshore wind installation market.

Scenario model

Cargo types

The case study in this research involves the handling of monopile foundations in order to present the advantages of this methodology. However, in the offshore wind market additional types of cargo are being transported and installed. In order to get an even better overview of future offshore wind installation vessels it is of interest to apply this analysis to other cargo types. For example, the jacket foundation types, as these type of structures may take a bigger market share in the future. Apart from the foundation installation it is of interest to also include the installation of the tower and the turbine as cargo types. This provides the researcher the opportunity to investigate the impact of the various cargo types at the vessel design. Moreover, it can be used to generate better insights in trade-offs that have to be made regarding having a vessel that is capable installing both the foundation and the turbine, or a vessel that focus on one part of the installation process.

Supply chain

The installation of an offshore wind installation farm is a complex logistical process due to the amount of wind turbines that need to be installed. Different researches have been conducted regarding optimizing this logistical process and the supply chain related to the installation of an offshore wind installation farm. For future work it would be interesting to extend the methodology presented in this report with more logistical aspects in order to involve additional complex logistical solutions. By adding more logistical options, it becomes possible to investigate the impact of the supply chain at the vessel design.

Analysis techniques

The advantage of the application of epoch era analysis is that there are many situations that can be tested. The disadvantage of this is that this methodology generates large amount of data that needs to be filtered and analysed. Currently, only a small set of eras have been manually generated to investigate the impact at the vessel design. However, when scaling the amount of epochs in an era, and the amount of eras the analysis will become more challenging. This methodology can therefore benefit from future research that applies data analysis techniques to analysis the vast amount of multi dimensional data that is being generated using this methodology.

The selection of many different views did result in a methodology to give input in future offshore wind installation vessel concept designs

11 Afterword

This master thesis is the final project before finishing my Marine Technology master at Delft University of Technology. In this chapter I would like to lead you through the various challenges, learning moments, and achievements during this master thesis.
At the start of this research the following question was formulated in collaboration with TU Delft and HES: *'What is the offshore wind installation vessel of the future?'* It is a question that is very relevant in today's offshore wind industry due to the uncertainty that this market is facing. But it is also a question that is very open and therefore has many different research directions. It has been a challenge to translate this towards a specific scope for this research.
The many options made it challenging to find a good balance in the necessary detail level. During this process I have learned when it is important to take a step back in order to have an overview. But also when it is of importance to add necessary details to the various sub components of the project.
The COVID-19 situation did also introduce some challenges in this master thesis. Due to the regulations it was not possible to work in the office most of the time. This made it more difficult to get in touch with various colleagues and receive input for my research. Even though this situation introduces some additional challenges I am very grateful with the good communication between me and my supervisors.
During this master thesis I have been able to identify the important aspects in the offshore wind market in order to select a research direction and methodology that is relevant for the current offshore wind industry.
My research has been performed in collaboration with the TU Delft and HES. Each of them had their own wishes and requirements for this project. During the past months I have learned that it is important to do a proper scoping in the various wishes in order to define a project that is feasible to execute within the time frame available. By clearly defining the wishes and goals it becomes possible to get the best possible outcome for all parties involved.
At the TU Delft I have learned about all the technical subjects during the various courses and projects. This master thesis provided me insights in the combination of technical aspects in a changing market. I am now even more interested in how we could best create concept vessel designs for the future.
I got various new insights during this research. Not only technical aspects but also a lot about the whole research process. It has given me the possibility to further explore the various topics in the maritime industry. I am grateful that HES provides me the opportunity to continue this journey together!

Bibliography

[1] DNV GL, "Energy Transition Outlook 2018: Power Supply, Forecast to 2050," no. September, p. 96, 2018.

[2] IRENA, *Innovation Outlook: Offshore Wind*. 2016, ISBN: 9789295111356. [Online]. Available: https://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf.

[3] offshoreWIND.biz, *With 15 mw wind turbines on horizon installation fleet lags behind*, [Online; accessed June 26, 2021]. [Online]. Available: https://www.offshorewind.biz/2021/05/05/with-15-mw-wind-turbines-on-horizon-installation-fleet-lags-behind-report/.

[4] O. McDonald, "Economen: 'Nederlandse investeerder bang voor duurzame projecten'," *Het Financieele Dagblad*, p. 13, Jun. 24, 2021.

[5] United Nations Climate Change, *The paris agreement*, [Online; accessed December 5, 2020], 2015. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[6] IRENA, *Future of Wind: Deployment, investment, technology, grid integration and socio-economic aspects*. 2019, pp. 1–88, ISBN: 9789292601553. [Online]. Available: https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf.

[7] IEA, "Offshore Wind Outlook 2019: World Energy Outlook Special Report," *International Energy Association*, p. 98, 2019.

[8] Global Wind Energy council, *Gwec market intelligence releases global offshore wind turbine installation vessel database*, [Online; accessed November 28, 2020], 2020. [Online]. Available: https://gwec.net/gwec-market-intelligence-releases-global-offshore-wind-turbine-installation-database/.

[9] WindEurope, "Offshore wind in Europe," *Refocus*, vol. 3, no. 2, pp. 14–17, 2019, ISSN: 14710846. DOI: 10.1016/s1471-0846(02)80021-x. [Online]. Available: https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2019.pdf.

[10] Ulstein, *Securing your future in offshore wind*, [Online; accessed November 30, 2020], 2019. [Online]. Available: https://ulstein.com/news/2019/securing-your-future-in-offshore-wind.

[11] N. H. Doerry, "Institutionalizing Modular Adaptable Ship technologies," *Journal of Ship Production and Design*, vol. 30, no. 3, pp. 126–141, 2014, ISSN: 21582874. DOI: 10.5957/JSPD.30.3.130038.

[12] A. W. E. Association, *Basics of wind energy*, [Online; accessed October 1, 2020], 2020. [Online]. Available: https://www.awea.org/wind-101/basics-of-wind-energy.

[13] N. Chong and L. Ran, *Offshore Wind Farms - Technologies, Design and Operation*. Woodhead Publishing - Elsevier, 2016, ISBN: 9780081007808.

[14] Recharge news, *Denmark maps seas for future offshore wind farms and energy islands*, [Online; accessed September 30, 2020], 2020. [Online]. Available: https://www.rechargenews.com/wind/denmark-maps-seas-for-future-offshore-wind-farms-and-energy-islands/2-1-821629.

[15] U. D. of Energy, *How a wind turbine works*, [Online; accessed October 2, 2020], 2014. [Online]. Available: https://www.energy.gov/articles/how-wind-turbine-works#:~:text=Wind%5C%20turbines%5C%20operate%5C%20on%5C%20a,a%5C%20generator%5C%20to%5C%20create%5C%20electricity..

[16] K. Thomsen, *Offshore wind - A comprehensive guide to succesful offshore wind farm installation 2nd edition*. London: Academic Press, 2014, ISBN: 9780124104228.

[17] DNV GL, *Dnv gl's latest guidance on project certification of wind power plants*, [Online; accessed September 30, 2020], 2019. [Online]. Available: https://www.dnvgl.com/energy/feature-articles/project-certification.html.

[18] Roland Berger, "Offshore Wind Toward 2020," no. April, pp. 1–25, 2013. [Online]. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj69euqqZTtAhUuNOwKHcW8CEcQFjAAegQIARAC&url=https%3A%2F%2Fwww.rolandberger.com%2Fpublications%2Fpublication_pdf%2Froland_berger_offshore_wind_study_20130506_1_.pdf&usg=AOvVaw1uj94qWrpLnSPTaITZfqBu.

[19] WindEurope, "Wind energy in Europe: Outlook to 2020," no. September 2017, 2017. [Online]. Available: https://windeurope.org/about-wind/reports/wind-energy-in-europe-outlook-to-2020/#download.

[20] BVG Associates, "A Guide to an Offshore Wind Farm Updated and extended," Tech. Rep. January, 2019, pp. 1–70. DOI: 10.1016/S0029-5493(00)00422-2. [Online]. Available: https://www.thecrownestate.co.uk/media/2860/guide-to-offshore-wind-farm-2019.pdf.

[21] G. Gerdes, T. Albrecht, and S. Zeelenberg, "Case Study: European Offshore Wind Farms - A Survey for the Analysis of the Experiences and Lessons Learnt by Developers of Offshore Wind Farms," p. 158, 2010.

[22] DNV GL, "DNVGL-ST-0262: Lifetime extension of wind turbines," *Standard*, no. March, 2016. [Online]. Available: https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-03/DNVGL-ST-0262.pdf.

[23] J. G. Dedecca, R. A. Hakvoort, and J. R. Ortt, "Market strategies for offshore wind in Europe: A development and diffusion perspective," *Renewable and Sustainable Energy Reviews*, vol. 66, pp. 286–296, 2016, ISSN: 18790690. DOI: 10.1016/j.rser.2016.08.007. [Online]. Available: http://dx.doi.org/10.1016/j.rser.2016.08.007.

[24] F. H. Seeverens, "The effects of 30+ GW offshore wind energy in the Netherlands in 2030 - 2050," [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%5C%3A0cd93bb6-6f8b-4580-8ba5-ca975b4667fc.

[25] DNV GL, "Energy Transition Outlook 2020 Executive Summary," 2020. [Online]. Available: https://eto.dnvgl.com/2020.

[26] ——, "Energy Transition Outlook 2020 Power and Supply Use," no. September, 2020. [Online]. Available: https://eto.dnvgl.com/2020.

[27] IRENA, *Renewable Capacity Statistics 2020*. 2020, p. 66, ISBN: 978-92-9260-239-0. [Online]. Available: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Statistics_2020.pdf.

[28] P. Hevia-Koch and H. Klinge Jacobsen, "Comparing offshore and onshore wind development considering acceptance costs," *Energy Policy*, vol. 125, no. February 2018, pp. 9–19, 2019, ISSN: 03014215. DOI: 10.1016/j.enpol.2018.10.019. [Online]. Available: https://doi.org/10.1016/j.enpol.2018.10.019.

[29] J. Morales Pedraza, *Current Status and Perspective in the Use of Coal for Electricity Generation in the North America Region*. 2019, pp. 211–257, ISBN: 9780128148891. DOI: 10.1016/b978-0-12-814889-1.00004-8.

[30] M. deCastro, S. Salvador, M. Gómez-Gesteira, X. Costoya, D. Carvalho, F. J. Sanz-Larruga, and L. Gimeno, "Europe, China and the United States: Three different approaches to the development of offshore wind energy," *Renewable and Sustainable Energy Reviews*, vol. 109, no. February, pp. 55–70, 2019, ISSN: 18790690. DOI: 10.1016/j.rser.2019.04.025. [Online]. Available: https://doi.org/10.1016/j.rser.2019.04.025.

[31] C. Bjerkseter and A. Agotnes, "Levelised costs of energy for offshore floating wind turbine concepts," Tech. Rep., 2013. [Online]. Available: https://nmbu.brage.unit.no/nmbu-xmlui/bitstream/handle/11250/189073/Bjerkseter%2C%20C.%20%26%20%C3%85gotnes%2C%20A.%20%282013%29%20-%20Levelised%20Costs%20of%20Energy%20for%20Offshore%20Floating%20Wind%20Turbine%20Concepts.pdf?sequence=1&isAllowed=y.

[32] BVG Associates, "Global offshore wind market report 2019," Tech. Rep., 2019, p. 106. [Online]. Available: https://www.4subsea.com/wp-content/uploads/2020/01/Offshore-Wind-market-report-2019-Norwep.pdf.

[33] IRENA, *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*, June. 2016, p. 112, ISBN: 9789295111974. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Power_to_Change_2016.pdf.

[34] Leanwind, "Driving Cost Reductions in Offshore Wind," no. 614020, 2017. [Online]. Available: http://www.leanwind.eu/.

[35] J. Peeringa, R. Brood, O. Ceyhan, W. Engels, G. de Winkel, and G. D. Winkel, "Upwind 20MW Wind Turbine Pre-Design: Blade design and control," *ECN-E–11-017 December*, no. December, pp. 1–53, 2011.

[36] E. Gaertner, J. Rinker, L. Sethuraman, F. Zahle, B. Anderson, G. E. Barter, N. J. Abbas, F. Meng, P. Bortolotti, W. Skrzypinski, G. N. Scott, R. Feil, H. Bredmose, K. Dykes, M. Shields, C. Allen, and A. Viselli, "IEA Wind TCP Task 37: Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine," pp. 1–44, 2020. [Online]. Available: https://www.osti.gov/biblio/1603478%0Ahttps://www.osti.gov/servlets/purl/1603478.

[37] G. Hoogendoorn, "Design in principle for flexible fully assembled wind turbine installation," 2020. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%5C%3A911fb7ee-cb23-4e05-96c7-7b4cd8e5bb4f?collection=education.

[38] IRENA, *Renewable Power Generation Costs in 2018*. 2019, p. 160, ISBN: 978-92-9260-040-2. DOI: 10.1007/SpringerReference{_}7300. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf.

[39] M. J. Kaiser and B. Snyder, "Offshore wind energy installation and decommissioning cost estimation in the U.S. outer continental shelf," no. November, p. 340, 2010.

[40] 4COffshore, *Global offshore renewable map*, [Online; accessed November 23, 2020], 2020. [Online]. Available: https://www.4coffshore.com/offshorewind/.

[41] S. Livaniou, S. Iordanis, P. Anaxagorou, B. Mocanu, R. Sykes, J. Goormachtigh, J. M. Christensen, J. T. Kristensen, and M. Antrobus, "Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments," no. 614020, p. 107, 2015.

[42] M. D. Esteban, J. S. López-Gutiérrez, and V. Negro, "Gravity-based foundations in the offshore wind sector," *Journal of Marine Science and Engineering*, vol. 7, no. 3, 2019, ISSN: 20771312. DOI: 10.3390/jmse7030064.

[43] Tube tradefair, *Fa 09 tripods, jackets and tripiles: Innovative tube systems for offshore wind energy systems*, [Online; accessed November 23, 2020], 2018. [Online]. Available: https://www.tube-tradefair.com/en/Press/Press_material/Archive_Press_releases_for_Tube/FA_09_Tripods,_Jackets_and_Tripiles_Innovative_Tube_Systems_for_Offshore_Wind_Energy_Systems.

[44] H. Kato, "World Energy Model 2002," no. October, 2020. [Online]. Available: https://iea.blob.core.windows.net/assets/fa87681d-73bd-4719-b1e5-69670512b614/WEM_Documentation_WEO2020.pdf.

[45] IRENA, *About irena*, [Online; accessed November 30, 2020], 2020. [Online]. Available: https://irena.org/aboutirenav.

[46] WindEurope, *About us - windeurope*, [Online; accessed November 30, 2020], 2020. [Online]. Available: https://windeurope.org/about-us/.

[47] A. Nghiem and I. Pineda, "Wind energy in Europe: Scenarios for 2030," *Wind Europe*, no. September, p. 32, 2017. [Online]. Available: https://windeurope.org/wp-content/uploads/files/about-wind/reports/Wind-energy-in-Europe-Scenarios-for-2030.pdf.

[48] Energyst, *Offshore wind*, [Online; accessed October 1, 2020], 2020. [Online]. Available: https://www.energyst.com/solutions/offshore-wind/.

[49] A. Attari, G. Okuyemi, J. Goormachtigh, J. M. Christensen, J. T. Kristensen, and J. K. Nielsen, "Novel vessels and equipment," *Report by Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments (LEANWIND), Work Package 3 - Deliverable 3.1*, no. 614020, 2014.

[50] Douglas-Westwood, "Assessment of vessel requirements for the U.S. offshore wind sector," no. September, 2013.

[51] M. Wittingen, "Offshore Wind Turbine Monopile Foun- dation Installation with a Dynamic Posi- tioned Vessel," 2018. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid:9a6f1edb-e780-4184-8b6c-2b346714c680/datastream/OBJ/download.

[52] H. Bailey, K. L. Brookes, and P. M. Thompson, "Assessing environmental impacts of offshore wind farms: Lessons learned and recommendations for the future," *Aquatic Biosystems*, vol. 10, no. 1, pp. 1–13, 2014, ISSN: 20469063. DOI: 10.1186/2046-9063-10-8.

[53] DNV GL, *Fresh breeze for offshore wind farms*, [Online; accessed November 27, 2020], 2018. [Online]. Available: https://www.dnvgl.com/expert-story/maritime-impact/Fresh-breeze-for-offshore-wind-farms.html.

[54] Knud E. Hansen, *Cadeler - pacific orca & pacific osprey*, [Online; accessed November 28, 2020], 2017. [Online]. Available: https://www.knudehansen.com/wp-content/uploads/2017/10/Cadeler-Pacific-Orca-Pacific-Osprey-07086_10073.pdf.

[55] Swire Pacific offshore, *Technical specifications - pacific orca*, [Online; accessed November 28, 2020], 2018. [Online]. Available: https://www.swireblueocean.com/media/1179/o-class-technical-specifications_orca.pdf.

[56] Jan de Nul, *Vol au vent - offshore jack-up installation vessel*, [Online; accessed November 28, 2020], 2020. [Online]. Available: https://www.jandenul.com/sites/default/files/2020-10/Vole%20au%20vent%20%28EN%29_0.pdf.

[57] Van Oord, *Offshore installation vessel aeolus*, [Online; accessed November 28, 2020], 2018. [Online]. Available: https://www.vanoord.com/sites/default/files/leaflet_aeolus.pdf.

[58] D. Ahn, S. C. Shin, S. Y. Kim, H. Kharoufi, and H. C. Kim, "Comparative evaluation of different offshore wind turbine installation vessels for Korean west–south wind farm," *International Journal of Naval Architecture and Ocean Engineering*, vol. 9, no. 1, pp. 45–54, 2017, ISSN: 20926790. DOI: 10.1016/j.ijnaoe.2016.07.004. [Online]. Available: http://dx.doi.org/10.1016/j.ijnaoe.2016.07.004.

[59] Project cargo journal, *Sleipnir installs first jacket of hollandse kust offshore substation*, [Online; accessed November 27, 2020], 2020. [Online]. Available: https://www.projectcargojournal.com/offshore/2020/09/11/sleipnir-installs-first-jacket-of-hollandse-kust-offshore-substation/.

[60] Seaway Heavy Lifting, *Equipment factsheet*, [Online; accessed December 7, 2020], 2015. [Online]. Available: https://www.seawayheavylifting.com.cy/uploads/media/SHL084_Equipment_Factsheet_DEF_WT_LOW.pdf.

[61] IHC, *Oleg strashnov heavy lift vessel*, [Online; accessed December 7, 2020], 2015. [Online]. Available: https://www.royalihc.com/-/media/royalihc/image-carousel/products/product-images/offshore/heavy-lift-and-wind-farm-installation/heavy-lift-vessel/leaflet_royal_ihc_heavy_lift_vessel_oleg_strashnov.pdf.

[62] DNV GL, *Seaway oleg strashnov*, [Online; accessed December 7, 2020], 2020. [Online]. Available: https://vesselregister.dnvgl.com/VesselRegister/vesseldetails.html?vesselid=26865.

[63] RoyalBoskalis Westminster, *Equipment sheet - asian hercules iii*, [Online; accessed November 28, 2020], 2015. [Online]. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwid2cPkq6btAhVQLewKHUh6BE0QFjAMegQIARAC&url=https%3A%2F%2Fboskalis.com%2Fdownload-center%2Fdownload%2FeyJmaWxlVWlkIjoxM%20jQ2MSwicmVmZXJlbmNlVWlkIjowfQ%253D%253D%2F2ae20ae55c4cc28cda1e%20a8faec8788c66278729d.html&usg=AOvVaw3VdinKYFVoDivJUZ3262S5.

[64] Offshore Energy, *Asian hercules iii 'largest heavy-lift sheerlegs of its kind' named in singapore*, [Online; accessed November 28, 2020], 2015. [Online]. Available: https://www.offshore-energy.biz/asian-hercules-iii-largest-heavy-lift-sheerlegs-of-its-kind-named-in-singapore/.

[65] H. M. Contractors, *Fleet - sleipnir*, [Online; accessed October 22, 2020], 2020. [Online]. Available: https://hmc.heerema.com/fleet/sleipnir/.

[66] Spinergie, *Offshore wind fleet main technical specifications*, [Online; accessed November 30, 2020], 2020.

[67] Vattenfall, *Powerplants: Horns rev*, [Online; accessed November 28, 2020], 2020. [Online]. Available: https://powerplants.vattenfall.com/horns-rev.

[68] Galloper wind farm ltd., *About galloper*, [Online; accessed November 28, 2020], 2020. [Online]. Available: http://www.galloperwindfarm.com/about/.

[69] Offshorewind.biz, *Installation vessels reaching the limits and beyond*, [Online; accessed November 28, 2020], 2017. [Online]. Available: https://www.offshorewind.biz/2017/03/27/installation-vessels-reaching-the-limit-and-beyond/.

[70] Van Oord, *Aeolus fitted impressive new crane*, [Online; accessed November 28, 2020], 2018. [Online]. Available: https://www.vanoord.com/news/2018-aeolus-fitted-impressive-new-crane.

[71] TWD, *Offshore wind - installation engineering the future*, [Online; accessed November 28, 2020], 2019. [Online]. Available: https://twd.nl/wp-content/uploads/2019/10/Whitepaper-Offshore-Wind-Online.pdf.

[72] SWZMaritime, *Pacific osprey sets sail with upgraded crane*, [Online; accessed November 28, 2020], 2020. [Online]. Available: https://www.swzmaritime.nl/news/2020/06/05/pacific-ospreys-sets-sail-with-upgraded-crane/?gdpr=accept.

[73] H. Equipment, *Wind turbine shuttle*, [Online; accessed October 22, 2020], 2020. [Online]. Available: https://www.huismanequipment.com/en/products/renewables/offshore_wind/wind_turbine_shuttle.

[74] P. C. Journal, *Rystad: Shortage of installation vessels as early as 2025*, [Online; accessed December 7, 2020], 2020. [Online]. Available: https://www.projectcargojournal.com/offshore/2020/11/26/rystad-shortage-of-installation-vessels-as-early-as-2025/#:~:text=The%20global%20wind%20turbine%20installation,after%202025%2C%20reports%20Rystad%20Energy.&text=Rystad%20Energy%20expects%20installation%20vessel,than%20today%27s%20figure%20by%202030..

[75] Fred. Olsen Windcarrier, *Blue tern - ready for your most challenging installation*, [Online; accessed November 30, 2020], 2020. [Online]. Available: https://windcarrier.com/fleet-blue-tern.

[76] DAMEN, *Jack-up vessel seafox 5 departs damen verolme rotterdam ready for the next generation of wind turbines*, [Online; accessed November 30, 2020], 2018. [Online]. Available: https://www.damen.com/en/news/2018/02/jack_up_seafox_5_departs_damen_verolme_rotterdam_ready_for_the_next_generation_of_wind_turbines.

[77] Fred. Olsen Windcarrier, *Brave tern - highest crane in the market*, [Online; accessed November 30, 2020], 2020. [Online]. Available: https://windcarrier.com/newcrane.

[78] Riviera, *New class of installation vessels to handle 'super-sized' wind turbines*, [Online; accessed November 30, 2020], 2020. [Online]. Available: https://www.rivieramm.com/news-content-hub/news-content-hub/new-class-of-installation-vessels-to-handle-lsquosuper-sizedrsquo-wind-turbines-58478.

[79] OHT, *Mv alfa lift*, [Online; accessed October 23, 2020], 2020. [Online]. Available: https://www.oht.no/fleet/alfa-lift-design-vessel/?gclid=EAIaIQobChMIioTU_KfK7AIVjteyCh0rVwI0EAAYASAAEgKnHfD_BwE.

[80] Navingocareer, *Jan de nul bestelt 3e offshore jack-up schip de "voltaire"*, [Online; accessed November 5, 2020], 2019. [Online]. Available: https://www.navingocareer.com/jan-de-nul-bestelt-3e-offshore-jack-up-schip-de-voltaire/.

[81] J. de NUl, *Offshore jack-up installatieschepen*, [Online; accessed November 3, 2020], 2020. [Online]. Available: https://www.jandenul.com/nl/vloot/navires-dinstallation-autoelevateurs.

[82] Offshoretronic, *Large cost-savings for offshore wind with our new add-on concept*, [Online; accessed October 22, 2020], 2020. [Online]. Available: https://offshoretronic.tech/.

[83] H. Hopman, "Design Spiral & Systems Engineering MT44035 Design of Complex Specials," no. April, 2018.

[84] R. Krishnakanth, "Concept design of an installation vessel to install fully assembled next generation offshore wind energy turbines," 2014. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A2024b8f8-56a3-4bd5-a62f-8e1227d7eff4.

[85] Alexander Kossiakoff, William N. Sweet, Samuel J. Seymour, Steven M. Biemer, *Systems Engineering Principles and Practice 2nd edition*. 2011, p. 528, ISBN: 9781118001011.

[86] Shell, “Scenarios : An Explorer ’ s Guide,” *Shell Intenational BV*, p. 98, 2008. [Online]. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Scenarios+:+An+Explorer's+Guide#0.

[87] K. Van der Heijden, *Scenarios The Art of Strategic Conversation 2nd Edition Kees van der Heijden*. 2005, p. 356, ISBN: 0-470–02368-6.

[88] R. J. Lempert, S. W. Popper, and B. S. C., *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis.* 4. 2005, vol. 4, pp. 522–525, ISBN: 0833032755. DOI: 10.5465/amle.2005.19086797.

[89] H. Kosow and R. Gaßner, *Methods of Future and Scenario Analysis - Overview, assessment, and selection criteria*, May 2014. 2008, p. 124, ISBN: 9783941374034.

[90] V. Marchau, W. Walker, P. Bloemen, and S. Popper, *Decision Making Under Deep Uncertainty. From Theory to Practice*. 2019, p. 408, ISBN: 9783030052515.

[91] N. Rosenberg, *Uncertainty and technological change*, February 1996. 1996, pp. 17–34, ISBN: 9780080505022. DOI: 10.1016/b978-0-7506-7009-8.50004-5.

[92] A. A. Kana and B. M. Harrison, “A Monte Carlo approach to the ship-centric Markov decision process for analyzing decisions over converting a containership to LNG power,” *Ocean Engineering*, vol. 130, no. December 2016, pp. 40–48, 2017, ISSN: 00298018. DOI: 10.1016/j.oceaneng.2016.11.042. [Online]. Available: http://dx.doi.org/10.1016/j.oceaneng.2016.11.042.

[93] J. J. Zwaginga, “Exploring market uncertainty in early ship design,” 2020. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A80dc5052-6fa8-4fdd-81d8-1828a15fdfb5.

[94] G. Giebel and C. Bay Hasager, “Chapter 19: An Overview of Offshore Wind Farm Design,” *MARE-WINT: New Materials and Reliability in Offshore Wind Turbine Technology*, pp. 1–432, 2016. DOI: 10.1007/978-3-319-39095-6.

[95] K. Freeman, C. Frost, G. Hundleby, A. Roberts, B. Valpy, H. Holttinen, L. Ramírez, and I. Pineda, “Our Energy Our Future,” 2019. [Online]. Available: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf.

[96] European MSP Platform, *Msp netherlands*, [Online; accessed November 26, 2020], 2020. [Online]. Available: https://www.msp-platform.eu/countries/netherlands.

[97] B. C. Papavizas, “Clarifying The Jones Act For Offshore Wind,” no. June, 2011. [Online]. Available: https://www.winston.com/images/content/8/6/v2/862/Windpower-Papavizas.pdf.

[98] offshoreWIND.biz, *The jones act in us offshoe wind: Challenge or opportunity?* [Online; accessed November 26, 2020], 2019. [Online]. Available: https://www.offshorewind.biz/2019/04/15/jones-act-us-offshore-wind-challenge-opportunity/.

[99] A. J. Keith and D. K. Ahner, “A survey of decision making and optimization under uncertainty,” *Annals of Operations Research*, 2019, ISSN: 15729338. DOI: 10.1007/s10479-019-03431-8. [Online]. Available: https://doi.org/10.1007/s10479-019-03431-8.

[100] K. Terün, "Assessing Alternative Fuel Types for ULCVs in Face of Uncertainty," 2020. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A84f29960-87fd-427b-bc9d-96b46f4bfe3c?collection=education.

[101] E. A. Moallemi, S. Elsawah, and M. J. Ryan, "Robust decision making and Epoch–Era analysis: A comparison of two robustness frameworks for decision-making under uncertainty," *Technological Forecasting and Social Change*, vol. 151, no. January 2018, p. 119 797, 2020, ISSN: 00401625. DOI: 10.1016/j.techfore.2019.119797. [Online]. Available: https://doi.org/10.1016/j.techfore.2019.119797.

[102] H. M. Gaspar, S. O. Erikstad, and A. M. Ross, "Handling temporal complexity in the design of non-transport ships using Epoch-Era Analysis," *Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering*, vol. 154, no. PART A3, pp. 109–119, 2012, ISSN: 14798751. DOI: 10.3940/rina.ijme.2012.a3.230.

[103] M. D. Curry and A. M. Ross, "Considerations for an extended framework for interactive epoch-era analysis," *Procedia Computer Science*, vol. 44, no. C, pp. 454–465, 2015, ISSN: 18770509. DOI: 10.1016/j.procs.2015.03.029. [Online]. Available: http://dx.doi.org/10.1016/j.procs.2015.03.029.

[104] M. D. Curry, C. F. Rehn, A. M. Ross, and D. H. Rhodes, "Designing for system value sustainment using interactive epoch-era analysis: A case study from commercial offshore ships," *Disciplinary Convergence in Systems Engineering Research*, pp. 267–280, 2017. DOI: 10.1007/978-3-319-62217-0{_}19.

[105] H. M. Gaspar, P. O. Brett, S. O. Erikstad, and A. M. Ross, "Quantifying value robustness of OSV designs taking into consideration medium to long term stakeholders' expectations," *12th International Marine Design Conference (IMDC)*, vol. 2, pp. 247–259, 2015.

[106] V. Negro, J. S. López-Gutiérrez, M. D. Esteban, P. Alberdi, M. Imaz, and J. M. Serraclara, "Monopiles in offshore wind: Preliminary estimate of main dimensions," *Ocean Engineering*, vol. 133, no. December 2016, pp. 253–261, 2017, ISSN: 00298018. DOI: 10.1016/j.oceaneng.2017.02.011. [Online]. Available: http://dx.doi.org/10.1016/j.oceaneng.2017.02.011.

[107] M. Ottolini, *Monopile dimensions*, personal communication, [Meeting May 18, 2021].

[108] W. N. Wandji, A. Natarajan, N. Dimitrov, and T. Buhl, "Design of monopiles for multi-megawatt wind turbines at 50 m water depth," *European Wind Energy Association Annual Conference and Exhibition 2015, EWEA 2015 - Scientific Proceedings*, pp. 8–12, 2015.

[109] I. maritime organization, *International convention on load lines, 1966 and protocol of 1988, as amended*, 2016.

[110] H. Schneekluth and V. Bertram, *Ship Design for Efficiency and Economy*, second. Butterworth-Heinemann, 1998, ISBN: 0750641339.

[111] A. Papanikolaou, *Ship Design - Methodologies of Preliminary design*. Dordrecht: Springer Netherlands, 2014, ISBN: 978-94-017-8750-5. DOI: 10.1007/978-94-017-8751-2. [Online]. Available: http://link.springer.com/10.1007/978-94-017-8751-2.

[112] J. S. L. jr and J. R. Paulling, *The Geometry of Ships*, first, ser. The Principles of Naval Architecture. The Society of Naval Architects and Marine Engineers, 2009, ISBN: 0-939773-67-8.

[113] J. Holtrop and G.G.J. Mennen, "An Approximate Power Prediction Method," *International Shipbuilding Progress*, vol. 29, no. 335, 1982. [Online]. Available: http://resolver.tudelft.nl/uuid:ee370fed-4b4f-4a70-af77-e14c3e692fd4.

[114] A. Aalbers, "Evaluation of ship design alternatives," TU Delft, Delft, Tech. Rep., 2000, p. 15. [Online]. Available: http://resolver.tudelft.nl/uuid:9e3944df-8212-48f3-ae85-2f0e71cbe4b3.

[115] K. Runge, *Monohull vessel costs*, personal communication, [Meeting February 5, 2021].

[116] Ruben de Bruin, *Dave*, [Online; accessed March 10, 2020], 2020. [Online]. Available: https://www.open-ocean.org/.

[117] C. S. More and J. R. Paulling, *Intact stability*, first, ser. The Principles of Naval Architecture. The Society of Naval Architects and Marine Engineers, 2010, ISBN: 978-0-939773-74-9.

[118] H. C. R. Lars Larsson and R. Paulling, *Ship Resistance and flow*, first, ser. The Principles of Naval Architecture. The Society of Naval Architects and Marine Engineers, 2010, ISBN: 978-0-939773-76-3.

[119] H. J. K. Woud and D. Stapersma, *Design of Propulsion and Electric Power Generations Systems*. IMarEST, 2003, ISBN: 9781902536477.

[120] DNV GL, "DNVGL-ST-0111: Assessment of station keeping capability of dynamic positioning vessels," no. July, pp. 1–75, 2018. [Online]. Available: https://rules.dnv.com/docs/pdf/DNV/ST/2018-03/DNVGL-ST-0111.pdf.

[121] IMCA, "IMCA M140 - DP Capability Plots," no. June, 2000. [Online]. Available: https://eti.pg.edu.pl/documents/176634/32506864/imcam140.pdf.

[122] DEME, *Orion*, [Online; accessed May 31, 2021]. [Online]. Available: https://www.deme-group.com/technologies/orion.

[123] J. de Nul, *Les alizés*, [Online; accessed May 31, 2021]. [Online]. Available: https://www.jandenul.com/sites/default/files/2020-10/Les%5C%20Aliz%5C%C3%5C%A9s%5C%20%5C%28EN%5C%29.pdf.

[124] DNV GL, "Part 3 Hull - Chapter 15 Stability," no. July, pp. 1–19, 2019. [Online]. Available: https://rules.dnv.com/docs/pdf/DNV/RU-SHIP/2019-07/DNVGL-RU-SHIP-Pt3Ch15.pdf.

[125] ——, "Part 5 Ship types - Chapter 10 Vessels for special operations," no. October, 2015. [Online]. Available: https://rules.dnv.com/docs/pdf/DNV/RU-SHIP/2015-10/DNVGL-RU-SHIP-Pt5Ch10.pdf.

[126] ——, “Part 5 Ship types - Chapter 10 Vessels for special operations,” no. January, 2021. [Online]. Available: https://rules.dnv.com/docs/pdf/DNV/RU-SHIP/2021-01/DNVGL-RU-SHIP-Pt5Ch10.pdf.

[127] ——, “Lifting Operations - DNV-OS-H205,” Tech. Rep. April, 2014, pp. 1–45. [Online]. Available: https://rules.dnv.com/docs/pdf/DNVPM/codes/docs/2014-04/OS-H205.pdf.

[128] J. Journée and W. Massie, *Offshore Hydromechanics*. TU Delft, 2008. [Online]. Available: https://ocw.tudelft.nl/wp-content/uploads/OffshoreHydromechanics_Journee_Massie.pdf.

[129] J. J. Jensen, A. E. Mansour, and A. S. Olsen, “Estimation of ship motions using closed-form expressions,” *Ocean Engineering*, vol. 31, no. 1, pp. 61–85, 2004, ISSN: 00298018. DOI: 10.1016/S0029-8018(03)00108-2.

[130] J. Pinkster, *Bewegen en Sturen II Manoevreren*. TU Delft, 2006.

[131] I. van Winsen and C. Westland, *Hstp2 limit*, personal communication.

[132] Boskalis, *Offshore wind farm monopile installation veja mate*, [Online; accessed May 31, 2021]. [Online]. Available: https://boskalis.com/about-us/projects/detail/offshore-wind-farm-monopile-installation-veja-mate.html.

[133] M. Stopford, *Maritime Economics*. Taylor and Francis e-Library, 2009, ISBN: 9780429239540.

[134] P. of Rotterdam, *General terms and conditions - including port tariffs*, [Online; accessed June 1, 2021]. [Online]. Available: https://www.portofrotterdam.com/sites/default/files/general-terms-and-conditions-including-port-tariffs-2021.pdf?token=3xBWl9f_.

[135] M. Ottolini, *Offshore wind market future prospects*, personal communication, [Meeting May 18, 2021].

[136] Jumbo, *Stella synergy*, [Online; accessed May 31, 2021]. [Online]. Available: https://www.jumbomaritime.nl/en/offshore/offshore-fleet/meet-stella-synergy/.

[137] Raconteur, *What is the future of offshore wind*, [Online; accessed December 8, 2020], 2019. [Online]. Available: https://www.raconteur.net/energy/renewable-energy/offshore-wind-energy/.

[138] 7Pace, *Understand, design, build: The world’s simplest problem solving framework*, [Online; accessed December 8, 2020], 2019. [Online]. Available: https://www.7pace.com/blog/problem-solving-framework.

[139] OffshoreWIND.biz, *Windfloat atlantic launch a new era for offshore wind and the blue economy*, [Online; accessed December 8, 2020], 2019. [Online]. Available: https://www.offshorewind.biz/2019/10/22/windfloat-atlantic-launch-a-new-era-for-offshore-wind-and-the-blue-economy/.

[140] Heerema Marine Contractors, *Heerema’s dp3 vessel aegir installs first offshore wind turbine*, [Online; accessed December 8, 2020], 2018. [Online]. Available: https://hmc.heerema.com/news-media/news/heeremas-dp3-vessel-aegir-installs-first-offshore-wind-turbine/.

[141] Qursytec, *About us*, [Online; accessed December 8, 2020], 2020. [Online]. Available: https://www.qursytec.com/about-us/.

[142] Pyramid analytics, *Comprehensive forecasting with pyramid*, [Online; accessed December 8, 2020], 2020. [Online]. Available: https://www.pyramidanalytics.com/blog/details/blog-comprehensive-forecasting-with-pyramid.

[143] Pixabay, *Diverse kleuren laserlichten*, [Online; accessed June 7, 2021], 2017. [Online]. Available: https://www.pexels.com/nl-nl/foto/diverse-kleuren-laserlichten-417458/.

[144] Peter Leahy, *Windmolen fotografie*, [Online; accessed June 7, 2021], 2017. [Online]. Available: https://www.pexels.com/nl-nl/foto/windmolenfotografie-603764/.

[145] FOX, *Groene neon waterpas op metalen beugel in donkere kamer*, [Online; accessed June 7, 2021], 2020. [Online]. Available: https://www.pexels.com/nl-nl/foto/groene-neon-waterpas-op-metalen-beugel-in-donkere-kamer-3829224/.

[146] Rodolfo Clix, *Vijf gloeilampen licht*, [Online; accessed June 7, 2021], 2018. [Online]. Available: https://www.pexels.com/nl-nl/foto/vijf-gloeilamplichten-1036936/.

[147] Gabriel Peter, *Timelapse fotografie uit waterfontein*, [Online; accessed June 7, 2021], 2017. [Online]. Available: https://www.pexels.com/nl-nl/foto/timelapse-fotografie-uit-waterfontein-719396.

Nomenclature

BM	Metacentric radius
CAPEX	Capital Expenditures
COG	Center of gravity
COVID-19	Coronavirus
DAF	Dynamic amplification factor
DAVE	Design Analysis Visualization Engineering
DNV-GL	Det Norske Veritas and Germanische Lloyd
DP	Dynamic positioning
EEA	Epoch-era analysis
EOA	Engineering option analysis
FTIJ	Foundation Transport and Installation Jack-up
FTIV	Foundation Transport and Installation Vessel
GM	Metacentric height
GW	Gigawatts
H_s	Significant wave height
HES	Heerema Engineering Solutions
HMC	Heerema Marine Contractors
ICLL	International Convention on Load Lines
IEA	International Energy Agency
IG	Info-gap decision theory
IMCA	International Marine Contractors Association
IRENA	International Renewable Energy Agency
KB	Vertical center of buoyancy
km	Kilometer

kN	kilonewton
KPIs	Key performance indicators
Kts	Knots
kW	kilowatt
LCOE	Levelised cost of energy
LEANWIND	Logistic Efficiencies and Naval Architecture for Wind Installations with Novel Developments
LNG	Liquefied natural gas
m	Meter
m^2	Square meter
MDP	Markov decision process
MSc	Master of Science
MSP	Maritime spatial planning
mT	metric Tonnes
MW	Megawatt
MWh	Megawatt hour
O&M	Operation and Maintance
OHT	Offshore Heavy Transport
OPEX	Operating Expenditures
RAO	Response amplitude operator
RDM	Robust decision making
ROA	Real option analysis
SPO	Swire Pacific Offshore
SWATH	Small Waterplane Area Twin Hull
T_p	Wave period
TCG	Transverse center of gravity
TLP	Tension leg platform
TU	University of Technology
US	United States

USA	United States of America
VCG	Vertical center of gravity
VOYEX	Voyage Expenditures
WACC	Weighted average cost of capital
WTIJ	Wind Turbine Transport and Installation Jack-up
yr	Year

A Verification and validation

During this research various verification and validation test have been carried out in order to justify the applied methodologies in the model framework. The various components and the related test are summarized below.

Geometry

- Relation between depth and draft
- Check implementation of maximum draft
- Relation between displacement and LBT
- Relation between wetted surface and LBT
- Validation to ensure values approach reference

Lightweight and deadweight

- Check implementation of various vessel weight components
- Relation between vessel dimensions and lightweight
- Check implementation deadweight calculation
- Validation to ensure values approach reference

Stability

- Relation between COG and GM
- Check impact of COG change at GZ curve
- Validation using reference carene table and stability booklet

Resistance

- Compare implemented method with results from Holtrop and Mennen [113]
- Relation between speed and resistance
- Validation to ensure values approach reference

Installed power

- Impact of vessel dimensions at installed power
- Validation with fleet data

Mission constraints

- Check various fail/pass options stability constraint
- Check impact of varying cargo size at carrying capacity
- Check impact of cargo weight at crane capacity constraint

Transport

- Relation between carrying capacity and transport time
- Relation between transport time and distance
- Relation between transport time and feeder vessel strategy

Workability

- Impact of $HsTp^2$ limit at workability
- Impact of VCG at workability

Costs

- Check implementation of various vessel cost components
- Relation crane capacity and equipement costs
- Relation between OPEX and project time
- Relation between speed and fuel costs
- Relation between port costs and port calls
- Relation between additional vessel costs and feeder strategy

B Sources chapter pictures

The following table B.1 includes the references of the pictures used at the beginning of each chapter.

Table B.1.: Source of chapter pictures

Chapter	Source
Front page	[137]
2	[138]
3	[139]
4	[140]
5	[141]
6	[142]
7	[143]
8	[144]
Conclusion	[145]
Discussion	[146]
Afterword	[147]

Have a look inside and make the journey
in search for the future offshore wind
installation vessels