OFFSHORE WIND INSTALLATION VESSELS - GENERATING INSIGHT ABOUT THE DRIVING FACTORS BEHIND THE FUTURE DESIGN

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SUMMARY

To reach the sustainable targets and to reduce the investment risk, there is a need for more certainty and predictability regarding the requirements of the future offshore wind installation vessels. To capture the fast changing offshore wind market and its impact on vessel requirements, this paper generates scenarios using Epoch-era analysis. A parametric model is created to determine the performance of a set of vessels defined by their length, beam, depth, crane capacity, speed, and transport strategy in the different scenarios. The strength of combining Epoch-era analysis and parametric modelling is that the performance criteria and input variables can be tailor-made to a stakeholders strategy resulting in robust input variables for the concept vessel design.

NOMENCLATURE

ρi	Density of i (mT/m^3)
∇	Displacement (m^3)
a_{ii}	Added mass ii (kg or kg · m^2)
B	Beam vessel (m)
B_{add}	Additional width seafastening (m)
BM	Metacentric radius (m)
$B_{monopile}$	Beam monopile on deck (m)
CAPEX	Capital expenses (€)
C_b	Block coefficient (-)
C_i	Costs of i (€)
c_{ii}	Spring constant ii (N/m)
C_m	Mid ship coefficient (-)
C_p	Prismatic coefficient (-)
C_{wp}	Waterplane area coefficient (-)
DAF	Dynamic amplification factor (-)
DNV-GL	Det Norske Veritas and Germanische Lloyd
DP	Dynamic positioning
E	Electricity generated (MW)
EEA	Epoch-era analysis
F	Fuel costs (€)
GM	Metacentric height (m)
HMC	Heerema Marine Contractors
Hp	Horsepower
H_s	Significant wave height
I	Investment (€)
ICLL	International Convention on Load Lines
I_{ii}	Mass moment of inertia (kg·m^2)
IMCA	International Marine Contractors Association
KB	Vertical center of buoyancy (m)
Kg	Kilogram
kN	Kilonewton
KPI	Key performance indicator
Kts	Knots
kW	Kilowatt
L	Length vessel (m)
LCOE	Levelized cost of energy
Lmonopile	Length monopile (m)
LNG	Liquefied natural gas
M	Operation and maintenance cost (€)
m_v	Mass vessel (kg)
m	Meter
mT	Metric tonnes
n	Life time (years)
N_{trips}	Number of trips (-)
$N_{turbines}$	Number of turbines (-)
OPEX	Operational expenses (€)
P_i	Power of i (MW)
$P_{turbine}$	Turbine power rating (MW)
R	Discount rate (-)
S_i	Score in era i (-)
SW_i	Score weighting era i (-)
t	Current year
T	Draught vessel (m)
T_{ii}	Natural period ii (s)
$T_{installation}$	Total installation time (days)
T_p	Wave peak period (s)
$T_{per\ turbine}$	Installation time per turbine (days)
$t_{project}$	Total project time (days)
$T_{sailing}$	Time sailing (days)
T_{water}	Water depth (m)
$V_{monopile}$	Volume monopile (m^3)
VOYEX	Voyage expenses (€)
V_s	Ship speed (km/days)
W_i	Weight of i (mT)
$X_{offshore\ wind\ farm}$	Distance farm and port (km)

1. INTRODUCTION

The world is trying to move towards a more sustainable future (DNV-GL, 2018a). One of the challenges is the transition of conventional to sustainable energy sources. In order to decarbonize the global economy, it is expected that the wind industry will be one of the important sustainable energy resources in 2030 (IRENA, 2016a). What is needed 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 does this have on the vessel lifetime, design, and the investment? The goal of this paper is to provide a method to support stakeholders in their strategic ship design choices by generating more insight in the future offshore wind installation vessels.

2. OFFSHORE WIND MARKET

2.1 INCREASING MARKET

The interest in the offshore wind market is visible in the rapid growth; between 2010 and 2018 there has been a yearly growth of around 30% in the installed capacity. To comply with the targets set in 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), the current installation rate needs to be 6 times larger by 2030 and 10 times larger by 2050 (IRENA, 2019). To keep up with this increasing installation demand new offshore wind installation vessels are needed (offshoreWIND.biz, 2021).

2.2 DRIVING FACTOR: LCOE

The levelized costs of energy (LCOE) is the primary metric used to compare energy generation methods. The LCOE method determines the overall costs and the total amount of electricity produced in its lifetime, to get the average costs per unit of energy. For a calculation method of the LCOE see equation below (IRENA, 2016b):

$$LCOE = (\sum^{n}_{t=1} (I_t + M_t + F_t / (1 + r)^t)) / (\sum^{n}_{t=1} E_t / (1+r)^t)$$

Reducing the LCOE is essential to secure future investments in offshore wind and to keep both public and political support (IRENA, 2016a). The aim to reduce the LCOE is even one of the main factors of the developments in the offshore wind sector at the moment (BVG Associates, 2019) to be an even bigger competitor of the conventional energy generation methods. By improving the installation vessels, the 15-20% investment costs due to the installation can be reduced leading to an improved LCOE.

2.3 KEY DEVELOPMENTS OFFSHORE WIND

Due to the interest in the offshore wind industry and the drive to reduce the LCOE the offshore wind market is changing fast. The following three main trends are identified that have an impact on the installation vessels.

- **Increasing turbine size**
  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. The increasing height also influences the current fleet of offshore installation vessels and their crane capabilities (LEANWIND, 2017).
- **Increasing distance from farm to port**
  The costs for the transportation, the operation, and maintenance will increase when the distances vessels have to travel towards their location increases (IRENA, 2020). As vessels are the most expensive asset during this process it is important to evaluate what the most optimal solutions for their application is (LEANWIND, 2017). Another aspect is that the environment in which installations have to be carried out becomes harsher when moving further from shore (LEANWIND, 2017).
- **Increasing depth at location**
  The increase in water depth has an impact on the size, weight, and type of foundation. 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 to handle the necessary weight (LEANWIND, 2015).

2.4 IMPACT ON THE INSTALLATION FLEET

The current offshore wind installation fleet can be characterized by the following two main types of vessels (Douglas - Westwood, 2013):

- **Jack-up vessels** (used for installing wind turbines and foundations): vessels are characterized by the capability of lifting their hull out of the water providing a stable platform. 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 optimized deck area in order to transport as many components as possible (Douglas - Westwood, 2013).
- **Floating heavy lift vessels** (used for installing foundations): Most of these vessels have served the offshore oil and gas industry, but are recently also serving the offshore wind industry (Douglas - Westwood, 2013). These vessels are equipped with high capacity cranes. These types of vessels are more often used to install the foundations, substation, or a fully pre-assembled wind turbine (Kaiser & Snyder, 2011).

The fast changing offshore wind market causes a situation in which current vessels are not capable of meeting the new requirements. In order to be able to install the new wind turbines some vessels in the fleet receive crane updates in terms of lifting capacity and height. The problem of not reaching a lifetime of 25 years due to the fast developments in the market is a general problem in the offshore wind industry (ULSTEIN, 2019). This introduces risks for potential investors, which reduces the amount of investments (McDonald, 2021). Therefore, there is a need for more certainty and predictability regarding the requirements of the future offshore wind installation vessels.

To get a better insight in the current forecasting methods used to predict the necessary future capabilities of offshore installation vessels, market reports are selected (IEA, 2019) (IRENA, 2016a) (WindEurope, 2017). These reports are analysed on the approach and the factors they include to forecast. From this analysis it can be concluded that these reports do not include a specific analysis regarding the development of the vessel requirements. The reports primarily focus on the energy costs and annual installation rate.

3. METHOD

3.1 SYSTEMS ENGINEERING

The focus of this research is to create a framework that provides better insight in the impact of the changing market on the future design of offshore wind vessels. It is important to select a design approach that contains both an analysis of possible future vessel requirements and vessel concepts. In this paper a system engineering design approach is chosen as it includes both a requirement definition and design phase (Hopman, 2018).

This paper follows the first two stages of concept development: 'needs analysis' and 'concept exploration'. This results in system requirements (a set of requirements for the design in order to comply with the needs) and candidate system concepts (Kossiakoff, et al., 2011).

- **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) (Kossiakoff, et al., 2011).
- **Concept exploration**: In this phase the output of the needs analysis 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). The operational effectiveness input is used to create a 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).

3.2 APPROACH

In the needs analysis the developments in the market are used to define a method to predict future requirements, key performance indicators (KPI) depending on the selected stakeholder, and a baseline design for the parametric model. During the concept exploration stage the selected scenario modelling method, Epoch-era analysis (EEA), is used to predict a set of possible requirements which changes 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. For a schematic overview of the research approach, see Figure 1.

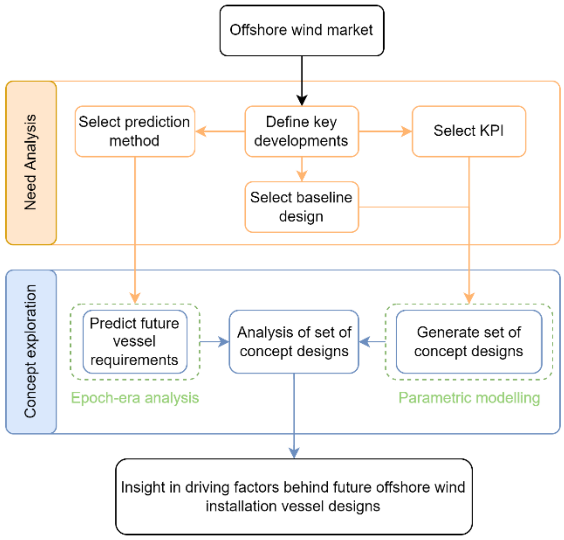

Figure 1. Overview of the approach

4. PREDICTING REQUIREMENTS

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 (Shell, 2008). 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. It is assumed that the behaviour structure of the system stays similar over the next years. The goal of forecasting is to use historical events to predict the most likely future (Van der Heijden, 2005).
- **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 (Van der Heijden, 2005). The aim of this method is to construct a set of possible futures that are relevant for the strategical decision to make (Lempert, et al., 2003).

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 (Van der Heijden, 2005). The combination of an offshore wind market that faces a lot of developments and technological opportunities that impact the structural behaviour of the market and the long term prediction needed, favour the application of scenario generation over forecasting. Scenario generation creates an overview of different scenarios which can be used to test various aspects of strategic decisions such as robustness, effectiveness, and reliability (Kosow & Gaβner, 2008).

There are various scenario modelling methods available. In recent years some of these scenario modelling methods have been applied in the maritime industry. Kana and Harrison applied a Markov decision process to assess if a container vessel should switch towards LNG under the uncertainty of possible future regulation (Kana and Harrison, 2017). Zwaginga et al. also applied a Markov decision process to develop a method to explore market uncertainty in early ship design, which has been used to model uncertainty in the offshore wind foundation installation market (Zwaginga et al., 2021). Robust decision making has been applied as scenario generation method by Terün in order to get more insight in a robust ultra large container vessel design for alternative fuel types (Terün, 2020). Gaspar et al. applied EEA in the maritime industry to design an anchor handling tug supply vessel (Gaspar et al., 2012).

EEA is selected as the scenario modelling method in this approach to capture the uncertain and the fast changing offshore wind market by generating various future possibilities each posing different vessel requirements. The main reasons for the application of EEA is the fact that EEA is capable of handling non-probabilistic input variables, which gives designers the opportunity to involve out of the box situations that can be helpful for future strategies and design choices. In comparison to other scenario modelling methods EEA is capable of handling dynamic uncertainty over time, which indicates that vessel requirements can be changed over time. It also provides the possibility of incorporating and assessing design flexibility, for example changing or upgrading vessel equipment onboard (Moallemi, et al., 2020).

By combining the scenario modelling approach given by Kosow and Gaβner (Kosow & Gaβner, 2008) and the EEA steps described by Curry and Ross (Curry & Ross, 2015) the following EEA steps are identified.

- **Defining epochs**: values are assigned to the identified key uncertainties in order to indicate the state of that uncertainty in a specific epoch, such as the power rating of an offshore wind turbine.
- **Generating eras**: various potential epoch combinations are analysed in order to define various eras. This analysis and construction of various eras can be conducted using statistical models or knowledge from experts (Curry, et al., 2017).
- **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. 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 2. 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. By combining the various epochs a set of eras can be generated, see eras 1, 2, and 3.

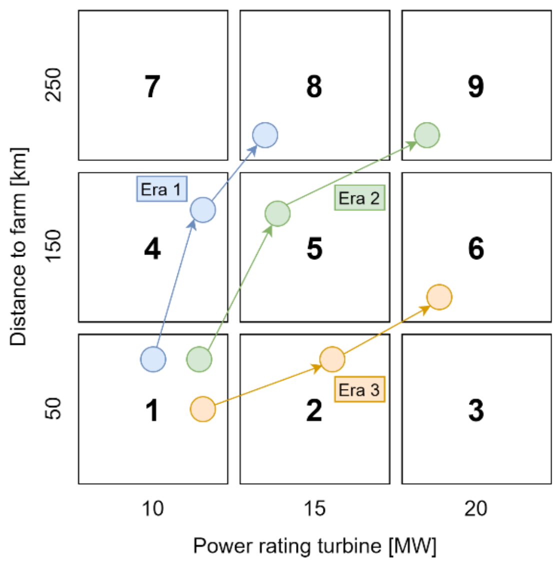

Figure 2. Epoch to eras – Based on figure by Gaspar et al (2015)

During the analysis the performance of the vessels are 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 are added together to determine the total costs of a vessel over a whole era (Gaspar, et al., 2012):

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

5. VESSEL GENERATION

5.1 STRUCTURE AND VARIABLES

With the parametric model a set of vessels is created in order to explore the vessel design space. The model transforms the main ship properties and the scenario situation towards vessel performance, for the main input and design variables used (see Figure 3).

Verification and validation has been conducted against existing vessels to ensure that each sub model and the model is implemented correctly and results are feasible.

Two stages can be identified. In the preparation stage the turbine power rating and the water depth are used to determine the cargo properties, which are of utmost importance as these define the objects that the offshore wind installation vessels should be able to handle. The exploration stage includes a set of input variables, a parametric model that translates the design variables towards vessel performance, and a module for analysing the vessel performance.

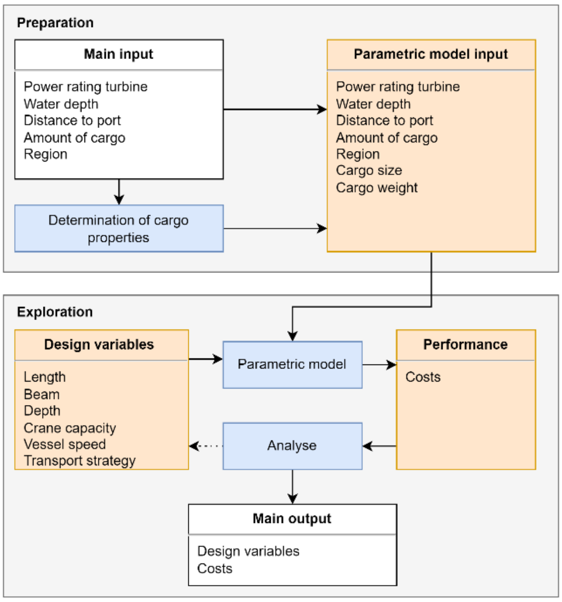

Figure 3. Overview model

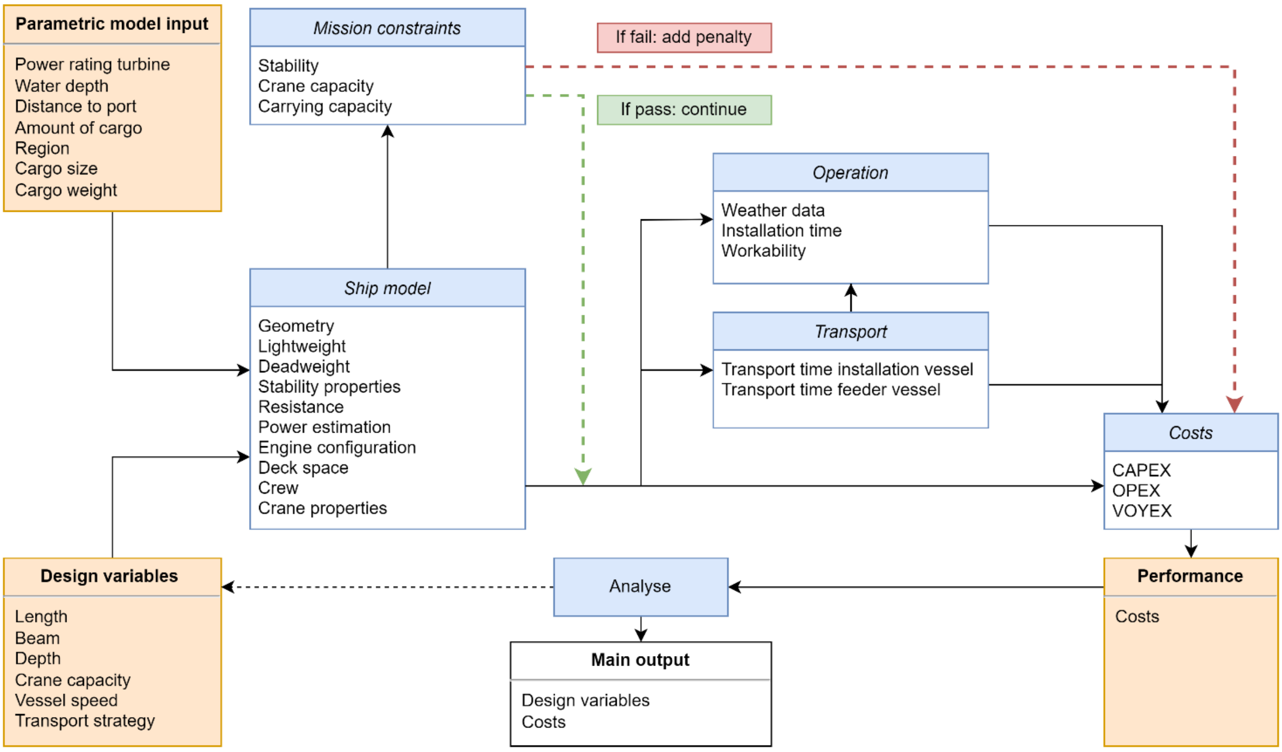

Figure 4. Overview parametric model

The vessel performance is 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 (Figure 4):

- **Ship model**: to specify the ship properties necessary for the other subcomponents.
- **Mission constraints**: assesses if the vessel can carry out the project.
- **Transport**: determines the necessary transport time of the vessels used in the project.
- **Operability**: defines the installation time and idle time of the vessels involved.
- **Cost calculation**: a module that determines the vessel costs based on the operational profile and vessel properties.
- **Analyse**: analyses the results from the parametric model in order to select the vessel having the lowest costs.

5.2 CARGO PROPERTIES

The monopile dimensions and weight are based on the power rating and the water depth. For the length a linear trend line is based on a data set published by Negro et al. (Negro, et al., 2017):

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

The width of the monopile on deck is based on its diameter determined by a ratio of 1.25 between the power rating and the diameter (Ottolini, 2021a) and an additional width due to the sea fastening:

$$B_{monopile} = P_{turbine} / 1.25 + B_{add}$$

Based on the length, diameter, and wall thickness of 100 mm (Njomo Wandji, et al., 2015), the volume and weight of the monopile can be determined:

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

5.3 SHIP MODEL

5.3 (a) Geometry

The vessel geometry properties draught, freeboard, displacement, and hull shape coefficients are determined as these will be used as input for other components in this model.

The draught is set as a percentage of the depth of a vessel. The draught is assessed whether or not it provides enough freeboard to comply with the freeboard regulations according to the ICLL 1966 (IMO, 2016). If a certain draught does not provide enough freeboard, the draught is adapted in such a way that the vessel does comply with the freeboard constraint.

Empirical methods are used to determine the mid ship, waterplane area, and prismatic coefficient (Papanikolaou, 2014) (Schneekluth & Bertram, 1998) (Letcher, 2009) :

$$C_m = 1 / (1 + (1 - C_b)^{3.5})$$
$$C_{wp} = (1 + 2 \cdot C_b) / 3$$
$$C_p = / (L \cdot B \cdot T \cdot C_m)$$

The wetted area of the vessel design is calculated using the approach described by Holtrop and Mennen (Holtrop & Mennen, 1982).

5.3 (b) Lightweight and deadweight

A first insight in the vessel lightweight can be generated using the vessel length, beam, and depth. A more accurate result can be found by estimating the weight separately (Aalbers, 2000). 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 (Runge, 2021). Using the provided data the following weight components are identified and determined: hull, outfit, HVAC, accommodation, electrical systems, and machinery. All the components together form the lightweight of the vessel:

$$Lightweight = W_{Hull} + W_{outfit} + W_{HVAC} + W_{Accommodation} + W_{Electrical\ systems} + W_{Machinery}$$

Based on the lightweight and the vessel geometry the deadweight is determined:

$$Deadweight = \nabla \cdot \rho_{water} - Lightweight$$

5.3 (c) Stability

For the stability assessment the initial stability is assessed using the vessel GM, and the dynamic stability during loss of hook load is assessed using the vessel GZ curves. For the stability calculations the following steps are taken:

- **Hull generation**: a hull is generated based on the vessel dimensions and a basis hull shape. This provides the information for determining the KB and BM.
- **The center of gravity** of the vessel is determined based on the vessel weight, cargo, and a ballast plan to reduce the heel of the vessel and bring it to the required draught.
- **Hydrostatic properties**: using the software package DAVE (de Bruin, 2021) and the inputs from the previous stages the GM and GZ of the vessel are calculated.

5.3 (d) Resistance, propulsion, and installed power

The required installed power is defined as the maximum of the power necessary during transport and DP operation:

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

The necessary force from the DP system is calculated using the DP guidelines described in the DNV-GL standard (DNV-GL, 2018b) and multiplied by two to guarantee redundancy. 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 (IMCA, 2000).

The propulsion power is based on the resistance approximation using the empirical method published by Holtrop and Mennen (Holtrop & Mennen, 1982). The calculated resistance is transformed into required power generation by the main engines using the method described by Klein Woud and Stapersma (Klein Woud & Stapersma, 2012).

5.3 (e) Deck space

The deck space layout is based on vessels that are currently active and built for the offshore wind installation market, such as the Orion, Alfa lift, and Les Alizés (DEME, 2021) (OHT, 2020) (JAN DE NUL, 2021). 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.

5.3 (f) Crew

Determining the maximum crew on board of the vessel provides insight in the accommodation size of the vessel (Runge, 2021). Therefore, current fleet data has been used to research possible relations between vessel dimensions, mission equipment, and crew on board. No significant correlations have been found between vessel dimensions and crew on board.

5.3 (g) Crane

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; a fixed crane (constant crane capacity over the vessel lifetime) and a changeable crane (crane upgrades will be carried out if necessary during a scenario).

5.4 MISSION CONSTRAINTS

To ensure the vessels are capable of carrying out the mission and comply with the requirements the following constraints are set.

5.4 (a) Stability

The assessment of the vessel stability is based on DNV-GL regulations (DNV-GL, 2015)(DNV-GL, 2019) (DNV-GL, 2021) and will be assessed using the following two criteria:

- GM during transit and lifting should be larger than 0.15 m.
- Dynamic stability in case of loss of load should comply the regulations, assessed based on the GZ-curve of the vessel.

5.4 (b) Carrying capacity

In case of a transport strategy in which 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 (In terms of length and width).
- The deadweight of the vessel should be sufficient.

5.4 (c) 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 that involves the static and an estimation of the dynamic loads (DNV-GL, 2014):

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

5.5 TRANSPORTATION

The transport module defines the time in which the vessel is in transit between the offshore wind field and shore:

$$T_{sailing} = (N_{trips} \cdot x_{offshore\ wind\ farm} \cdot 2) / V_s$$

Two transportation strategies can be applied and are analysed:

- Shuttle strategy: the installation vessel is responsible for both the transport and the installation of the components.
- Feeder strategy: additional feeder vessels are added in order to transport the components while the installation

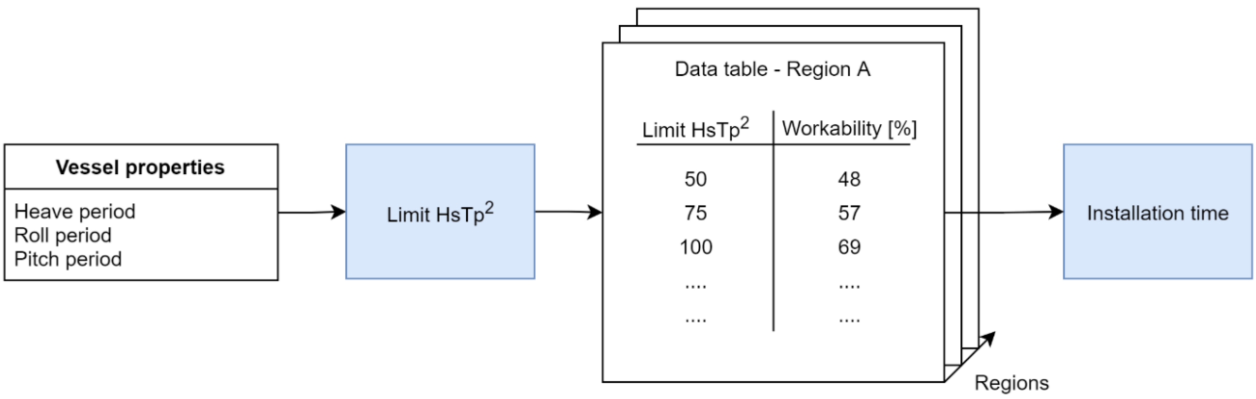

Figure 5. Installation time calculation

vessel stays at the installation site. A feeder vessel combination consists out of one barge and two tugs, and a minimum of two combinations is necessary.

5.6 OPERATION

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

5.6 (a) Installation time

The installation time is determined using an estimation of the workability that is 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 process to determine the installation time is visualized in Figure 5. The natural heave, roll, and pitch period are calculated as follows (Pinkster, 2006):

$$T_{heave} = 2\pi \cdot sqrt((m + a_{zz}) / C_{zz})$$

$$T_{roll} = 2\pi \cdot sqrt((I_{xx} + a_{\Phi\Phi}) / C_{\Phi\Phi})$$

$$T_{pitch} = 2\pi \cdot sqrt((I_{yy} + a_{\Theta\Theta}) / C_{\Theta\Theta})$$

The heave, roll, and pitch natural periods are used in combination with a reference $HsTp^2$ to determine the specific $HsTp^2$ limit of the vessels:

$$HsTp^2 = (HsTp^2_{reference} / (T_{avg.field} - T_{avg.reference})) \cdot (T_{avg.\ field} - T_{avg.\ vessel})$$

Based on the $HsTp^2$ limit it is possible to estimate the workability of the vessel. This workability can be used to estimate the necessary installation time:

$$T_{installation} = (T_{per\ turbine} \cdot N_{turbines}) / workability$$

5.6 (b) Idle time

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 other vessels to complete their tasks. The installation vessel will never experience idle time in this setup as an additional feeder vessel will then be added. The possible idle time of the feeder vessels is determined and used to calculate the costs.

5.7 COSTS

The costs are the key performance indicator that is being used to assess the performance of the vessel designs. As indicated by Stopford (Stopford, 2009) 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 are 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.

By combining the vessel costs on project basis the total costs of a vessel are determined:

$$C_{total} = C_{CAPEX} / 365 \cdot t_{project} + C_{OPEX} / 365 \cdot t_{project} + C_{VOYEX}$$

The various components that are used to determine the capital, operational, and voyage expenses are visible in Table 1.

Table 1. Costs sub components

CAPEX	Vessel build Upgradable crane
OPEX	Crew Repair and maintenance Stores and lubrication Insurance Administration
VOYEX	Fuel Port calls Additional vessel

6. CASE STUDY

6.1 DEFINING EPOCHS AND ERAS

For each of the key uncertainties in the offshore wind market (power rating of the turbine, water depth at the location, and distance between the location and the closest port) three states are defined based on available market reports (IRENA, 2016a) (IEA, 2019) and advice from a Heerema Marine Contractor (HMC) business analyst (Ottolini, 2021b), see Table 2. 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.

Table 2. Input variables 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

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. The four defined eras are:

- **Power rating turbine**: in this era the power rating of the turbines will increase over the years
- **Water depth**: only the water depth changes over time
- **Distance to farm**: investigates the impact of a changing distance
- **All variables**: in this era the impact of increasing all variables at each time step is investigated

6.2 CONCEPT VESSEL DESIGN SPACE

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 and is used to define the input variables in this research, see Table 3. The transport strategy has two different input variables. A shuttle strategy represents a situation in which the installation vessel transports the cargo. A feeder strategy corresponds to a situation in which a feeder vessel is being used to transport the cargo.

Table 3. Input variables parametric model

	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	-
Steps	9	7	5	6	6	-

Having these 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.

6.3 PERFORMANCE ANALYSIS

In the last stage of the case study the performance of the different vessel designs in the selected epochs and eras are assessed based on costs.

6.3 (a) General trends

During the analysis of the selected eras a set of general trends is visible:

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, which has been applied for this purpose before by Curry and Gaspar (Curry, et al., 2017) (Gaspar, et al., 2012). See Figure 6 for a visualization of the era in which the water depth increases over time.

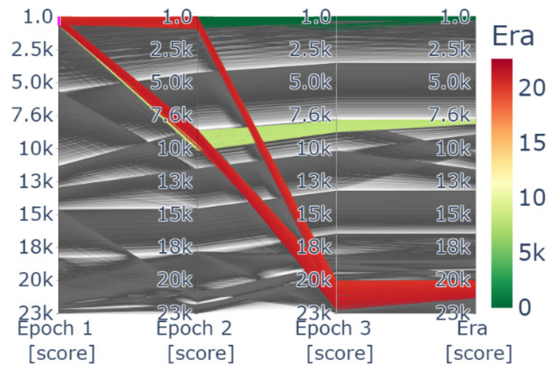

Figure 6. Performance changes over time (era – water depth)

Four axis are visible each indicating the performance of the created vessel designs in the selected epoch and corresponding era. 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 perform well 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. 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 (length, beam, depth)

The vessel length shows a positive correlation between the era costs and the vessel length, but it has a sudden drop around a vessel length of 200 meter, see Figure 7.

This decline of era costs can be related to the vessel deck space and cargo length (in this situation 71 meter). If the vessel length increases from 185 to 200 meter, the carrying capacity increases as it becomes possible to place two monopiles behind each other on the deck. This makes the vessel more efficient and therefore reduces costs. Further increasing the length will only increase the costs until a vessel length is reached at which an additional set of monopiles can be placed on the deck.

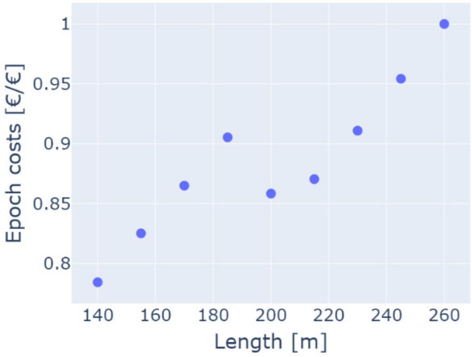

Figure 7. Impact of vessel length at costs

Increasing the beam has the same impact as increasing the length, as an increase in beam will improve the carrying capacity which improves the transport efficiency and reduces the costs. The vessels having a lower beam will face higher epoch costs, due to a penalty as they do not comply with the stability constraints. This indicates that there is a minimum beam necessary in order to carry out the tasks in the selected epochs and eras.

When investigating the results regarding the vessel depth, the lower depth of 12 meter is based on vessel stability and costs mostly the favourable depth in the selected eras. This is due to the impact of increasing the depth at both the build and fuel costs of the vessel.

Feeder vessel strategy

In the currently defined eras the feeder vessel concept is never the best strategy in terms of costs due to the increasing costs as result of the additional vessels involved.

Upgradable crane

An upgradable crane has been investigated as strategy to deal with the fast changing offshore wind market. By upgrading the crane later in the lifetime of the vessel the initial investment costs are lower which reduces investment risks. Figure 8 shows that the vessels having a crane that changes over time (indicated with a capacity of 1 mT in this figure) outperforms all vessels in the first scenario and then slowly starts to perform worse compared to the other vessels.

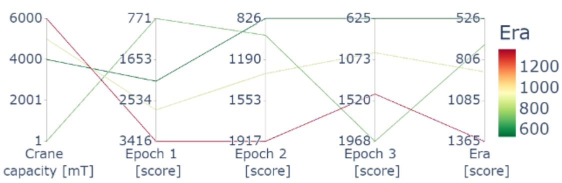

Figure 8. Performance of upgradable crane

This is expected, as the vessel will have a benefit in the beginning as the crane perfectly fits the necessary capacity. In later stages the vessels with a fixed and upgradable crane share the same specifications, while the costs of a fixed crane will be lower. The upgradable crane therefore is not the best option in this situation, but still outperforms the vessels with an over designed crane.

6.3 (b) Power rating turbine

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. 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. Vessels having a crane capacity of 2000, and 3000 mT will only be able to comply in the short term. 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.

In comparison to the other eras larger beams are performing better, see Figure 9 that shows the distribution in this era of the top 5% vessels.

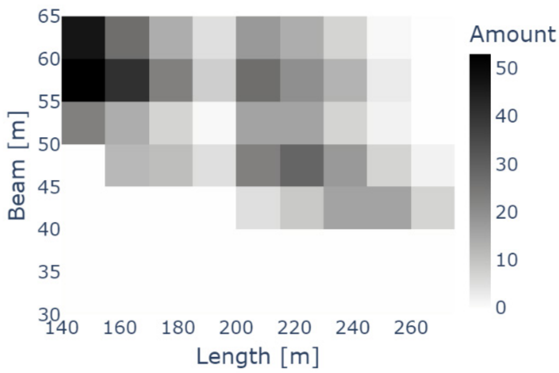

Figure 9. Era power rating impact at beam and length

The more darker a square is the more vessels are present in that specific beam length combination. 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.

6.3 (c) Water depth

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. Vessels having a length lower than 170 meters will be able to transport the cargo only in the short term, as their deck length is not sufficient for the longer monopiles in later stages. This limit posed in the third epoch is also visible as a light area on the left in the multi-dimensional histogram in Figure 10.

In addition to the length constraint Figure 10 also shows the beam constraint, by the light blocks at the bottom of the

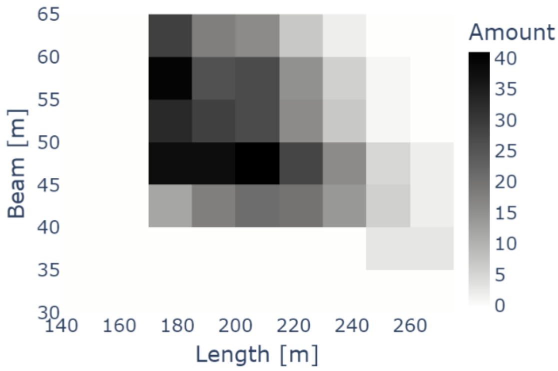

Figure 10. Era water depth impact at beam and length

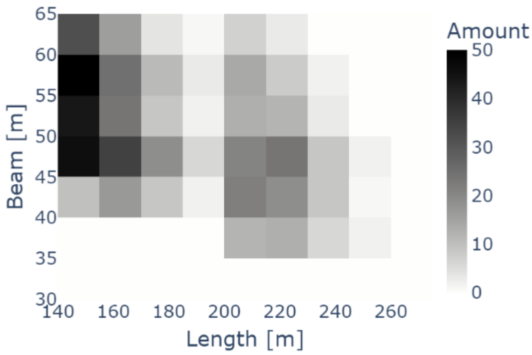

Figure 12. Era distance impact at beam and length

figure. This beam constraint is due to the lack of stability the vessel experiences withholding it from successfully carrying out its mission.

6.3 (d) 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. It does have an impact on the optimal vessel speed. In Figure 11 the lowest costs per speed and distance is visualized, while excluding the impact of the transport strategies 'shuttle' and 'feeder'.

The trend visible in this figure, is that when the distance to the offshore wind farm increases 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 increasing the fuel costs. A reduction in project time will result in a reduction of the OPEX and CAPEX costs.

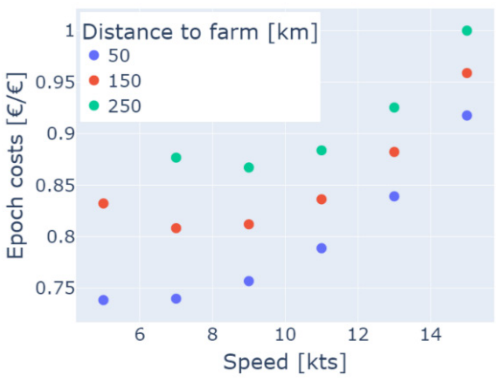

Figure 11. Vessel speed at different farm distances

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 12. As mentioned before, the beam/length preference does not change over time due to increasing distance.

6.4 (e) 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 with an assigned dynamic amplification factor of 1.1, a crane capacity of 6000 mT is required. A combined impact of the previous eras is visible when looking at the preferred beam length combinations. In Figure 13, the darker areas at the top indicate that the model prefers a wider beam. The lighter area at the left side of Figure 13 show the length constraint the vessel has due to the length of the monopiles.

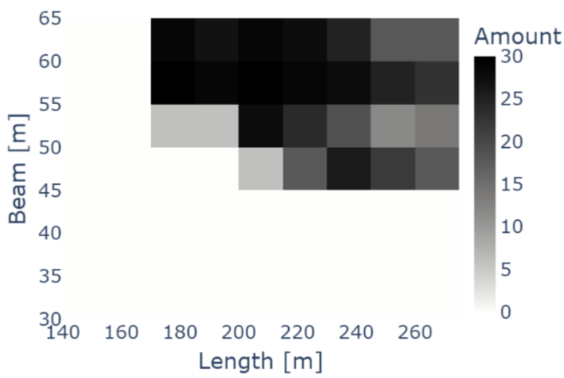

Figure 13. Era all increasing impact at beam and length

6.4 (f) Future offshore wind installation vessel

When providing advice 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:

$$S_{eras} = (S_1 \cdot SW_1 + S_2 \cdot SW_2 + S_3 \cdot SW_3 + S_4 \cdot SW_4) / (SW_1 + SW_2 + SW_3 + SW_4)$$

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 14.

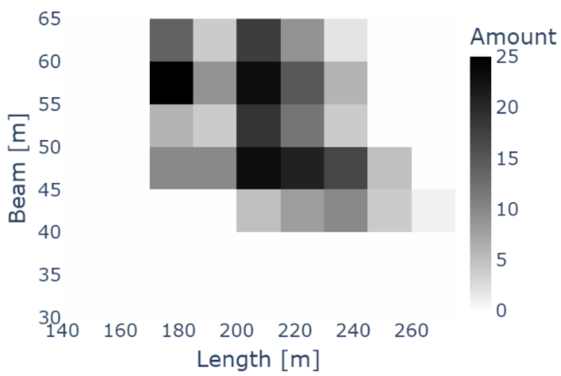

Figure 14. All eras impact at beam and length

There are three preferred combinations, a vessel length of 170 meters and a beam of 55 meters or 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 4.

Table 4. Newbuilds offshore wind installation market (Deme, 2021) (Jan De Nul,2021) (Jumbo Maritime, 2021)

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 maritime	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 monopiles, while the vessels currently being built show applications in which they install jackets and transport transition pieces as well. Another reason of this can be due to the behaviour visible in Figure 15.

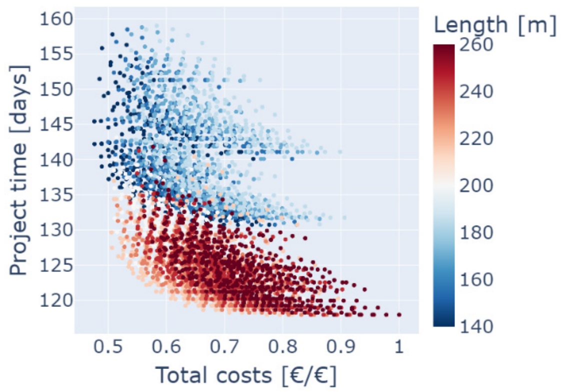

Figure 15. Project time versus project costs

If a vessel has the lowest costs it does not necessary mean 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 on 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 should outperform the vessels having a higher crane capacity in the current market.

7. CONCLUSION

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. This method 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 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 by applying different weighing factors to the various epochs. 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.

8. FUTURE WORK

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 method it is advised to investigate data analysis techniques for multi-dimensional data.

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