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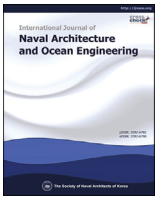

Exploring market uncertainty in early ship design

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A R T I C L E I N F O

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A B S T R A C T

To decrease Europe's harmful emissions, the European Union aims to substantially increase its offshore wind energy capacity. To further develop offshore wind energy, investment in ever-larger construction vessels is necessary. However, this market is characterised by seemingly unpredictable growth of market demand, turbine capacity and distance from shore. Currently it is difficult to deal with such market uncertainty within the ship design process. This research aims to develop a method that is able to deal with market uncertainty in early ship design by increasing knowledge when design freedom is still high. The method uses uncertainty modelling prior to the requirement definition stage by performing global research into the market, and during the concept design stage by iteratively co-evolving the vessel design and business case in parallel. The method consists of three parts; simulating an expected market from data, modelling multiple vessel designs, and an uncertainty model that evaluates the performance of the vessels in the market. The case study into offshore wind foundation installation vessels showed that the method can provide valuable insight into the effect of ship parameters like main dimensions, crane size and ship speed on the performance in an uncertain market. These results were used to create a value robust design, which is capable of handling uncertainty without changes to the vessel. The developed method thus provides a way to deal with market uncertainty in the early ship design process.

1. Introduction

To make sure health and environmental impact of energy-related emissions are limited, the amount of renewable energy needs to be increased substantially. One of the most promising renewable energy sources to do this is offshore wind energy, even though its current share in the global electricity supply is just 0.3% (IEA, 2019) (Garrad et al., 1993). Therefore, the European Union (EU) wants to decrease its harmful emissions by increasing its offshore wind energy capacity substantially. To meet its offshore wind energy targets of 150 GW by 2030 and 450 GW by 250, Europe has to install 20 GW each year by 2030 (Allen et al., 2019)(Vieira et al., 2019). To increase power production, wind-turbines are becoming larger in size and construction occurs further from shore. Because of this development, the levelized cost of energy (LCOE) of offshore wind has been gradually decreasing towards the LCOE of onshore wind and is projected to eventually get to a point where its LCOE can be compared to fossil fuels (Dedecca et al., 2016). However, in the Offshore Wind Outlook report published in 2019 (IEA, 2019), one of the crucial challenges for offshore wind energy is named to be the necessary development of efficient supply chains. The report explains that further decrease in LCOE is primarily dependent on the investment in ever-larger construction and support vessels, which is especially difficult in the face of uncertainty. This uncertainty comes from the seemingly unpredictable growth of market demand, turbine size and distance from shore within the offshore wind energy market. This makes it difficult for ship designers to design a construction vessel that has the right size and capabilities for use over multiple decades. Market uncertainty is not fully addressed in current literature concerning ship design, as highlighted by some authors in complex design (Brett et al., 2018), decision making (Garcia, 2020), uncertainty modelling (Erikstad and Rehn, 2015), and current practice in ship design (Pruyn, 2017). This research therefore expands on information from ship design practice and literature to determine how market uncertainty in the offshore wind market could be dealt with during the early ship design stages.

Ship design has been described by researchers as a complex design problem (Andrews, 1998) or a dancing landscape (Shields

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and Singer, 2017). Both describe the difficulties that arise in ship design due to increasingly complex mission statements and conflicting and changing requirements, which are commonly a consequence of persistent market uncertainty. Ship design can be categorized to have two objectives (McKenney, 2013); (i) the interpretation objective, determining the customer's requirements or vessel purpose and (ii) the prediction objective, predicting what design will fulfil the functional capabilities determined. To deal with complexity and create a design that best fits the determined function, design firms and researchers have developed design methods that help guide the process. The set-up of a design process therefore differs between firms, each created in a way that works best in their company culture and vessel segment. However, it can still occur that a design fulfils its function (what it was designed for), but not its purpose (need of the user), thus risking expensive refits, cancellation or overruns in cost and time. An example being the US navy's littoral combat ship project where; “decisions were made about attributes of the design without full understanding of their effect on both solving the problem or their effect on vessel costs” (Kana et al., 2016). Requirement definition is thus very important, but difficult, because each design process starts with different information and customer expectations (Simon, 1977), while the effect of conflicting and changing requirements on the vessel performance is unknown. Methods like requirements elucidation by Andrews, 2003 and others therefore create ways to provide insight in these effects during the early design stage. These are useful for examining the effect of decisions on the behaviour of vessel capability, but they don't always consider market uncertainty. To deal with uncertainty during the interpretation objective however, a comparable method should enable the designer to model the effect of design decisions on the financial performance of the vessel in a changing market.

Decision making in ship design under uncertainty has been researched by Garcia (2020), describing uncertainty as being a ’State reflecting the lack, inaccuracy or deficiency of information. Any situation outside pure certainty, independently of the degree of uncertainty.’(Garcia, 2020) (page xvii). As this paper deals with uncertainty due to a changing market, the necessary capabilities and economic situation of a ship are not fixed in future markets (Pruyn, 2017). The designer has to deal with uncertainty when making decisions, while being responsible for converging all inputs from stakeholders and integrating everything into a functional design (Pettersen et al., 2018) (McNamee and Celona, 1990). Decisions made during the early design stage have a large impact on the direction of the design process and the eventual performance of the design, since the freedom to make changes will rapidly decrease as is pictured in Fig. 1. As is shown by the slow increase of problem knowledge over time, a complex design is often only understood after the vessel has been built (Andrews, 1998), while this article argues that the question whether its functionality was sufficient in the market can only be answered after its lifetime. The lack of problem knowledge is therefore associated with design uncertainty, which decreases substantially when the design is built, and market uncertainty, which persists during the lifetime. This article focusses on the first two design process stages; requirement definition and concept design, where a designer is first interpreting and then refining requirements by reviewing alternative designs during the conceptual design stage. By visualizing the effect of decisions on performance in an uncertain market, the method aims to decrease market uncertainty by providing more knowledge of the problem when design freedom is still high. The goal being to improve the designers ability to determine the necessary requirements for the vessel to function well over its lifetime. Four strategies to deal with uncertainty are categorized by Thissen & Agusdinata (Thissen and Agusdinata, 2008); Ignore, Delay, Accept and Reduce, with the most appropriate strategy depending on the extent to which uncertainty influences the process (Garcia, 2020). The article researches which strategy and corresponding methods could be implemented in the design process to deal with market uncertainty.

In current practice, most design processes are arranged around experience, often creating a design from a reference ship (evolution). When a designer has no frame of reference for the whole or certain parts of the ship, because of unique requirements or uncertainty, designers might have to invent elements themselves (revolution) (Andrews, 1998). In any design process, both revolution and evolution occur, but the distribution of use depends on the knowledge of stakeholders (frame of reference) and the market segment. The description of the design process used in this article is based on the concept to knowledge theory (CK-theory) (Hatchuel and Weil, 2009) for ship design (van Bruinessen, 2016) and is visualised in Fig. 2. The ship design process goes from a concept space, with many undecided possibilities, to a knowledge space, where decisions have been made. Shifting between concept to knowledge can happen on four hierarchical levels in ship design; business case, ship, system and component (van Bruinessen, 2016). Designers can choose to evolve or innovate each level, but innovation should ideally be limited to only two levels in parallel. As a design can otherwise quickly become unmanageable, leading to large design iterations, requiring more time and effort.

The parallel exploration of business case and ship, as shown in Fig. 3, is selected as starting point for the method in this paper. The method aims to provide a designer the ability to explore the market uncertainty by researching the performance of a wide range of ship designs in the market at the start of the design process (requirement definition, improving project preparation) and co-evolving the business case and the ship design levels in parallel during the process (concept design, ensuring the design fulfils its purpose). Various existing methods were explored which came from two separate research fields looking into dealing with complexity (complex design methodologies) and uncertainty (designing for uncertainty) respectively (Andrews et al., 2018). Epoch Era Analysis (EEA) (Gaspar et al., 2012) and Markov Decision Processes (MDP) (Niese et al., 2015) where deemed most suitable, because these

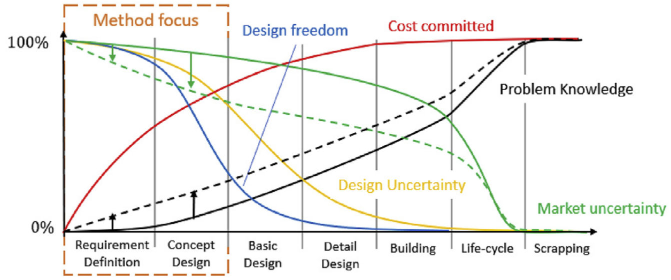


Fig. 1. Design freedom over the design process, adapted from Nam and Mavris (2008).

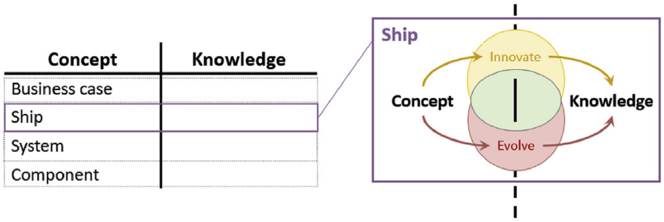


Fig. 2. Visualisation of ship design using CK-theory.

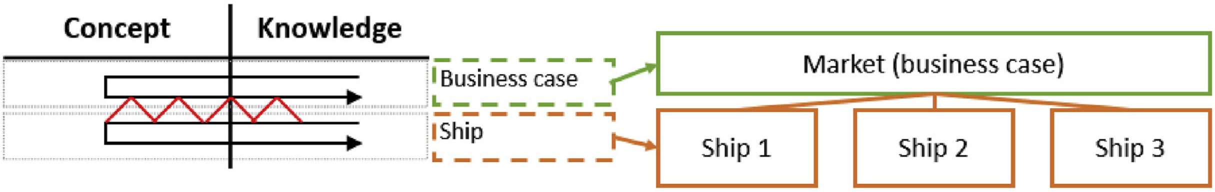


Fig. 3. General model description.

provide the right capability for use in parallel exploration and to deal with uncertainty. The method uses these uncertainty modelling methods to simulate changes in the market (EEA) and evaluate the financial performance (MDP) of different vessel designs.

To develop a general method, a case study is done for offshore wind foundation installation vessels. Market research into this segment found demand side (wind farms) and supply side (installation vessels) characteristics that can be used to model the market. Information from the 4COffshore wind farm database (4COffshore, 2019) is used to visualize demand, and design knowledge from the commissioning party; Ulstein Design & Solutions (UDSBV) is used to describe vessels in the case study. To decrease the LCOE of offshore wind, the increasingly large foundations have to be installed as quickly and cheaply as possible. To do this, capabilities like stability, speed, crane size and cargo capacity have to be optimized while the vessel stays competitive in market. Because of this, installation companies have switched focus toward heavy lift cargo vessels (HLCV's). The case-study therefore focusses on optimizing the capabilities of an existing HLCV monohull Ulstein design. However, no existing model or function is found that calculates how cargo, stability, speed and crane size are related for larger crane vessels. To estimate the effect of design decisions during early design, the capability of multiple HLCV designs for carrying and installing different foundation sizes over different distances is approximated. Behaviour of each design to changing market demand parameters, like foundation size and distance to shore over time, is researched using uncertainty modelling as shown in Fig. 4. This effectively creates three parts to the method; a market simulation, a ship model creating ship configurations, and an uncertainty model that evaluates the financial performance and capability of configurations in the market. These models are used in two early design stages; requirement definition (to gain more knowledge) and concept design (to co-evolve ship and market). The objective of the research is to model the effects of changing business case requirements due to market uncertainty during the early ship design phase, in such a way that the designer can explore the design space at the start and during the design process.

2. Methods

The case study is used to prove that the method is able to provide valuable insights about what the effect of certain design choices is on the performance of the vessel and overall business case. The case study is limited to scenarios with monopile type foundations, but can be expanded to other foundation types and scenarios as part of further research. In this chapter, the method set-up is explained in more detail, looking at the market simulation, modelling of ship configurations and the set-up of uncertainty modelling. The method is built using the programming language Python. The symbols list in the appendix A includes relevant input for the method.

2.1. Market model

The market simulation provides an overview of the current offshore wind market and visualizes expected trends in foundation size over the economic lifetime of a vessel by using data from the 4COffshore wind-farm database (4COffshore, 2019) and checking this against market forecasts from DNV-GL and IEA while also allowing the user to explore other scenarios. Existing methods, such as machine learning and simulation models for estimating or simulating data trends, were found to be difficult to use for this purpose. So the model therefore proposes another method that has components of both, combining their capability. The market trend simulation is loosely based on a geometric Brownian motion (GBM) (Erikstad and Rehn, 2015), where the drift and volatility are approximated from data. As is visualised in Fig. 5, the designer then gets the opportunity to shift the slope and range or add bounds to

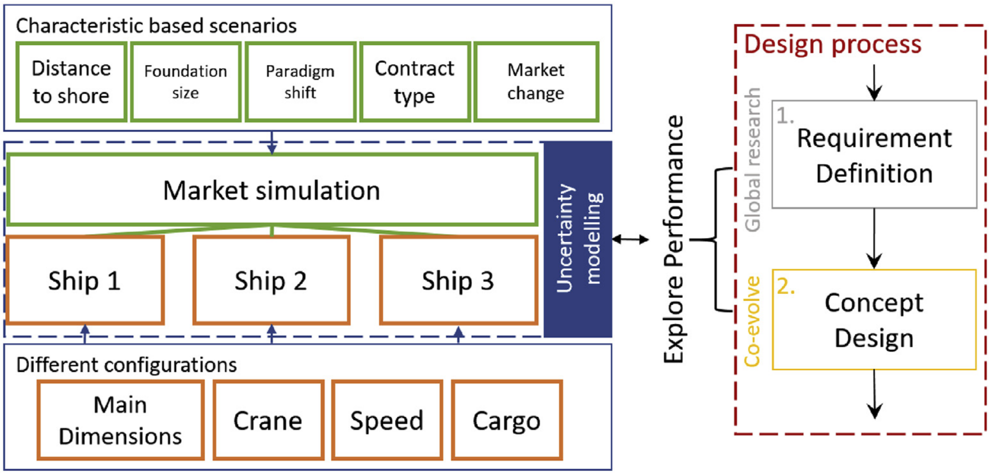


Fig. 4. Visualisation of the method as part of the ship design process.

create a market scenario they want to research. . Another part of the scenario creation is the effect of the trend on other foundation values like length and weight, which are calculated using correlation. The correlation is based on a linear regression model as used in machine learning, where the next data point is estimated using other values. This expands on previous offshore wind foundation regression research (Negro et al., 2017), but estimates monopile main dimension growth by analysing the spearman correlation value (Gautheir, 2001) of existing and planned wind-farms, while incorporating foundation design theory (Burton et al., 2011) to assess relationships found. Besides the foundation parameters, other scenarios regarding parameters such as distance from shore and contract type are varied using range values.

The spearman correlation coefficient for turbine, foundation and environmental parameters is shown in Table 1. Foundation length is assumed to depend primarily on water depth and is constrained to $50m$, which is the maximum depth for monopiles (Zhang et al., 2016) and a recurring maximum depth in the European market (Knijn et al., 1993), which is the target market for the case study. The turbine parameters, which dictate important loads that are used to design foundation geometry, mainly correlate with foundation diameter. Foundation weight is physically calculated using Eq. (1), which assumes the foundation as a hollow steel cylinder with a straight part W_{Fo_s} and a tapered end W_{Fo_t} with diameter D_{Fo} and length L_{Fo}. Wall thickness wt_{Fo} is determined using Eq. (2) from (API, 2000) with an adapted slenderness ratio. The depth-constrained length regression and the physical estimation for weight and regular data fits are compared in Fig. 6.

$$W_{Fo} = W_{Fo_s} + W_{Fo_t}$$
$$W_{Fo_s} = \pi \cdot L_{Fo_s} \cdot \rho_{Fo} \left(\left(\frac{D_{Fo}}{2} \right)^2 - \left(\frac{D_{Fo}}{2} - wt_{Fo} \right)^2 \right) \tag{1}$$

$$wt_{Fo} = 6.35 \cdot 10^{-3} + \frac{D_{Fo}}{120} \tag{2}$$

The diameter is found to also correlate well with time ($r_s = 0.86$), and because other values can be approximated well from diameter, it is used to forecast foundation size growth. A lower and upper bound per time step δT is determined to account for outliers and represent the market uncertainty, effectively creating a range in which contracts might occur each year. These are created by normalizing all points versus the mean trend-line and using the negative and positive points respectively to interpolate the bounds. To use the forecast, a probability density function $p_i(D)$ is created using the mean, upper and lower bounds for each year. To create asymmetric distributions while controlling the location of the mean, a custom probability distribution function was built and is visualised in Fig. 7. Five points at different percentiles are created by using a discrete probability mass function. The points are then interpolated, creating a probability density function $p_i(D)$ out of the mean and bound values for each year, where D represents the diameter of the foundation. The cumulative probability function $F_{year}(D)$ in Eq. (3) is created by integrating the probability density function and dividing by the area under the curve. The function can determine the probability of occurrence between two diameters and is used to create probability matrix T_{config}. This matrix stores the cumulative probability data for a range of diameters $[d_0 \ldots d_n]$ for multiple years $[y_1 \ldots y_n]$. This way, the foundation size development over time in a market is simulated using a stochastic description. A rough example of such a matrix for multiple years is shown in Table 2. In the final model, the diameter range step size is chosen to be 0.01m.

$$F_{year}(D_{Fo}) = \frac{1}{A_{p_i(D_{Fo})}} \int_{d_0}^{d_n} p_i(D_{Fo}) dD_{Fo}$$
$$T_{config} = \overset{p_{d,y}=F_y(D_{Fo})}{\begin{bmatrix} p_{d_1,y_1} & \cdots & p_{d_n,y_1} \\ \cdots & \cdots & \cdots \\ p_{d_1,y_n} & \cdots & p_{d_n,y_n} \end{bmatrix}} \tag{3}$$

2.2. Ship model

The goal of the ship model is to create multiple different vessel designs and calculate their financial performance and capability. The UDSBV vessel designs are used as reference for the modelling. Main design parameters that dictate the general capability of a vessel: Length, Beam, Depth, Speed, and Crane Capacity, are used as input for scaling. The ship model is divided into five modules: scaling, weight estimate, power and propulsion, mission, and cost and income. Each module can be verified and validated separately and might be changed to fit a new case or improve estimation.

2.2.1. Ship scaling

The goal of the scaling module is to estimate geometrical coefficients out of the input values. The designer can either fix a parameter to a single value or research multiple configurations by selecting a lower and an upper value with a given step size as is shown in Fig. 8. No bulb area is assumed, Draught T is scaled using input vessel depth and, as no pitch is assumed, this is also taken to be the aft and forward draught. Two different types of draught are scaled; design draught (used for resistance and power estimations) and maximum draught (used for installation stability calculation).

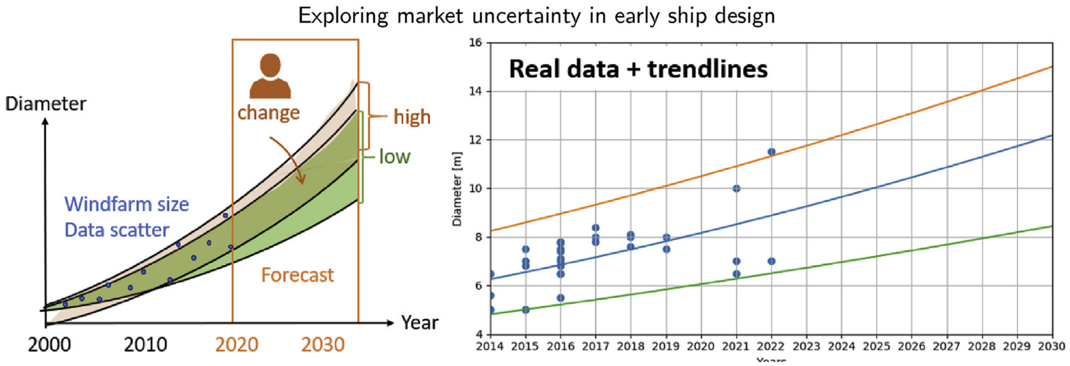


Fig. 5. Forecast of market trend using extrapolation from data scatter and example of principle with real data.

Table 1
Spearman correlation coefficient for monopile data from 4COffshore 05-03-2020.

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

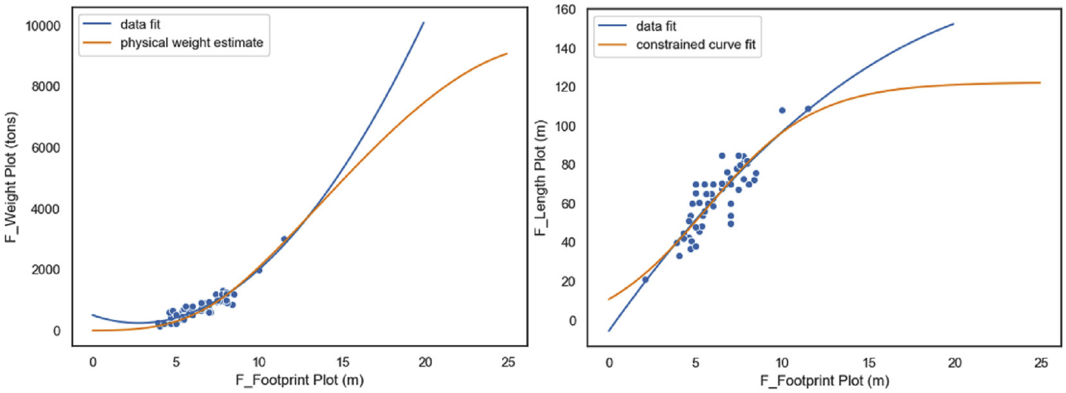


Fig. 6. Comparison between data fits and constrained length and physical weight estimate based on monopile design theory.

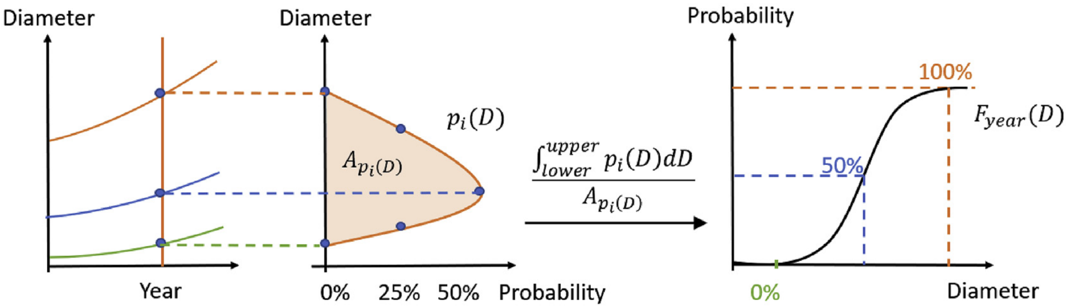


Fig. 7. Use of forecasted trendlines, transformation into probability density.

Table 2
Cummulative configuration matrix example.

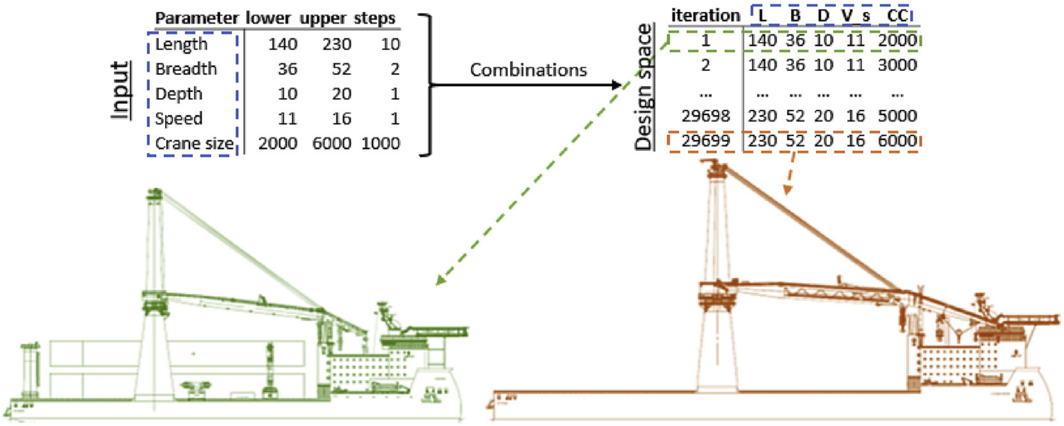
Year	Diameter [m]						
	6	7	8	9	10	11	12
2020	0.00	0.13	0.44	0.77	0.98	1.00	1.00
2021	0.00	0.07	0.34	0.66	0.92	1.00	1.00
2022	0.00	0.03	0.24	0.55	0.84	0.99	1.00
2023	0.00	0.01	0.17	0.44	0.74	0.95	1.00
2024	0.00	0.00	0.10	0.34	0.63	0.88	1.00

Design draught is taken as a percentage of the maximum draught, which is estimated from the minimum freeboard (IMO, 1988) and subtracting this value from the depth input. The longitudinal centre of buoyancy in percentage from the ships centre is determined using the Guldhammer & Harvald method as described by Kristensen and Lützen (2012). The midship coefficient C_M is estimated using a regression equation (Jensen, 1994), prismatic coefficient C_P and waterplane area coefficient C_{WP} are estimated from Papanikolaou (2014).

$$C_B = 0.8217 f_k \cdot L_{oa}^{0.42} \cdot B^{-0.3072} \cdot T^{0.1721} \cdot V_s^{-0.6135}$$

$$C_B = 0.8217 f_k \cdot L^{a_k} \cdot B^{b_k} \cdot T^{c_k} \cdot V_s^{d_k} \tag{4}$$

Block coefficient C_B is estimated using Eq. (4) for optimum block coefficient (Katsoulis, 1975) and was calibrated using reference vessels. Wetted surface S and other hull parameters are given by Holtrop and Mennen (1982)(Holtrop, 1984). The equations have been verified using empirical examples (Birk, 2019)(Holtrop, 1984) and are validated against reference vessels.



Parameter	lower	upper	steps
Length	140	230	10
Breadth	36	52	2
Depth	10	20	1
Speed	11	16	1
Crane size	2000	6000	1000

iteration	L	B	D	V_s	CC
1	140	36	10	11	2000
2	140	36	10	11	3000
...	...	...	...	...	...
29698	230	52	20	16	5000
29699	230	52	20	16	6000

Fig. 8. Visualisation of input data.

2.2.2. Power and propulsion

The power and propulsion module estimates propulsion power and Dynamic Positioning (DP) power from resistance and environmental forces. Using the scaled hull shape, the resistance is estimated using Holtrop and Mennen's method as described by Birk (2019). The method is verified using example values from Birk and Holtrop & Mennen and was found to approximate reference vessel tank-test resistance data from Marin well. The resistance is used to determine the necessary propulsion power (Klein Woud and Stapersma, 2003). The thrust coefficient as required by the ship $K_{T,ship}$ for different advance ratio values J, is determined using values from Holtrop (1984). It is assumed two propellers describe the propulsive capacity for heavy lifting vessels accordingly. The propulsion power is calculated using effective power and efficiencies obtained from B-series polynomials (Oosterveld and van Oossanen, 1975) with the ship's thrust coefficient in an open water diagram.

DP power is estimated using a thruster power to force relationship (Bulten and Suijkerbuijk, 2013). The force is calculated using environmental wind, wave and current load equations (Karlsen et al., 2016) and environmental data corresponding to 90% occurrence from Table 5. Total installed power is calculated using Eq. (5), which assumes that all vessel configurations at least need DP2 or the maximum power balance scenario for the vessel, which is the sum of crane, accommodation, propulsion and DP power.

$$\begin{gathered}P_{inst} = \begin{cases} P_{inst_2}, & P_{inst_1} < P_{inst_2} \\ P_{inst_1} & otherwise \end{cases} \\ P_{inst_1} = 2 \cdot P_{DP} + PoB \cdot 7 + \frac{Crane_{capacity}}{4} \\ P_{inst_2} = P_{DP} + P_B + PoB \cdot 7 + \frac{Crane_{capacity}}{4}\end{gathered} \tag{5}$$

2.2.3. Weight estimate

The weight module makes an initial weight estimation in the early design phase by scaling several weight groups from reference vessels. The chosen weight groups are based on UDSBV internal protocol, so results can be validated easily. Scaling Vertical Centre of Gravity (VCG) of each weight group is done using input vessel depth D, as equal ship types show a relation between depth and VCG (Papanikolaou, 2014). Each weight group is scaled using values that are influential for that weight group:

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

2.2.4. Mission module

The mission module is the place where configuration and the market come together, for the case study the market is the transport and installation of foundations by the vessel. The amount of foundations with a certain weight, length and diameter that can be installed by a configuration are calculated for all foundation sizes that might occur in the market for the selected period. Deck area constrains the amount of cargo that fits on deck using Eq. (9) and the foundation length is constrained using Eq. (10). As the structural weight is scaled from reference, the deck strength is assumed to comply initially. It is assumed that between each foundation and transition piece, 10% of the foundation diameter is required for seafastening. Crane capacity constrains what weight can be installed. Stability is estimated using geometric metacentric height GM, rewritten to the height of the centre of gravity $KG = KM - GM$. The GM value is based on Eq. (6), which is a stability rule developed based on lifting experience (Harenberg, 2016). The KM value is determined using an equation from Papanikolaou (2014) and is validated using hydrostatic reports from reference vessels. The KG is calculated by solving a moment balance Eqs. 7 and 8 for N_{Fo}. The first part of the equation is the Vertical Centre of Gravity (VCG) and mass of the stored monopiles. The second value is the VCG and mass of the unloaded vessel. The ballast mass value is equal to $W_{bal} = DWT_{cargo} - N_{Fo} \cdot (W_{Fo} + W_{tp})$ and is multiplied by the location of ballast tanks represented by ratio x versus depth. The fourth value represents the weight and location of one foundation that is hoisted by the crane. The last value is the weight and height of transition pieces.

$$GM = 1 + 1.5\cdot\frac{W_{load}}{1800} \tag{6}$$

$$KM - GM = \frac{1}{\Delta}\left(\left(\left(\frac{N_{KG}}{N_{Fo}}\right)D_{Fo} + D\right)(N_{Fo}-1)W_{Fo} + LWT\cdot KG + x_{bal}W_{bal}D + h_{crane}W_{Fo} + N_{Fo}W_{TP}(D + VCG_{TP})\right) \tag{7}$$

$$\begin{gathered} N_{KG} = N_{Fo}(l_{Fo}-0.5) - N_{Fo,B}\left(\frac{(l_{Fo}-1)l_{Fo}}{2}\right) \\ l_{Fo} = floor\left(\frac{N_{Fo}+N_{Fo,B}-1}{N_{Fo,B}}\right) \\ N_{Fo,B} = floor\left(\frac{0.9B}{1.1D_{Fo}}\right) \end{gathered} \tag{8}$$

Carrying weight constrains the amount of foundations and transition pieces as well, the equation $DWT_{cargo} = N\cdot(W_{Fo} + W_{TP})$ calculates how many piles N with weight $(W_{Fo} + W_{TP})$ fit on board for the maximum cargo DWT. The amount of foundations on deck depends on the weight to DWT fraction, which should be a round number as shown in Fig. 9. Each criterion equation calculates the amount of piles on deck for a range of diameters and the minimum amount of piles is used as capability to calculate income and cost of installation.

$$\begin{aligned} N_{Fo,Deck} &= \frac{A_{Deck} - L_{Fo}B}{1.1D_{Fo}} \\ A_{Deck} &= L_{Deck}B - A_{crane} \end{aligned} \tag{9}$$

$$N_{Fo,L} = \begin{cases} 0 & L_{Fo} > L_{Deck} \\ \infty & otherwise \end{cases} \tag{10}$$

2.2.5. Cost and income

The cost and income module determines financial performance of the configuration by estimating the cost and income. Three cost categories; operational, capital and voyage expenses are calculated using Eqs. (11)–(13) (Stopford, 2009). Many of these values are calculated as percentage of the newbuild cost while aspects like port charges $Port_{charges}$ and fuel price $C_{fuel,tonne}$ are assumed fixed. The amount of trips is dictated by the amount of foundations that a ship can take and how many are installed each year. The amount that fit on board is given by the mission module. The amount installed each year is calculated using Eqs. (14)–(16) providing the amount of time for each part of the mission. The estimated times in hours are given in Table 3 and are based on internal research. The Newbuild Cost (NC) is estimated using Eq. (17), which uses a cost table provided by UDSBV that has been estimated from experience. There are five parameters dictating cost: steel weight, DP & propulsion power, ship length, crane capacity and amount of crew. The first two are calculated in their respective modules, while ship length and crane capacity are input values. The amount of crew is initially fixed but can be changed by the user.

$$CAPEX = Loan_{interest} + Loan_{repayment} + Equity_{return} \tag{11}$$

$$OPEX = C_{Crew} + C_{maintenance} + C_{s\&s} + C_{ins} + C_{management} \tag{12}$$

$$\begin{gathered} VOYEX = C_{Port} + C_{Fuel} \\ C_{Fuel} = trips_{yr}(P_{inst}\cdot t_{tot}\cdot sfc\cdot Perc_{use})C_{fuel,tonne} \end{gathered} \tag{13}$$

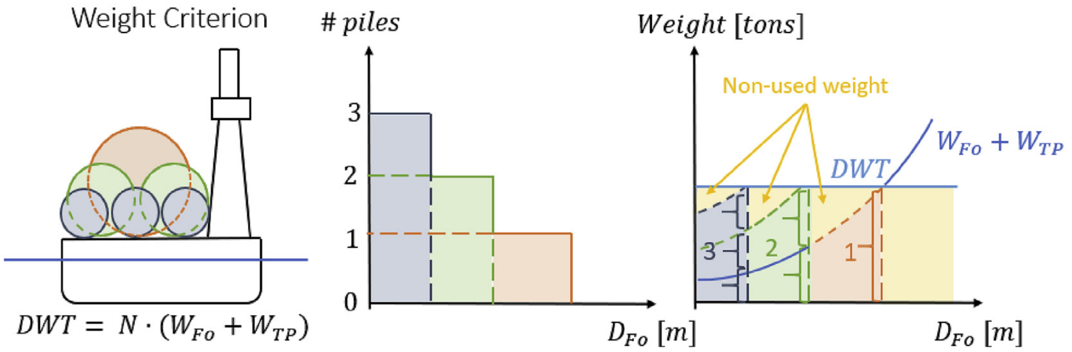


Fig. 9. Set-up and functioning of the Weight criterion.

Table 3
Monopile installation times from UDSBV internal research.

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

$$t_{tot}=t_{sail}+t_{harbour}+t_{inst}=\frac{2dts}{V_s}+\left(t_{Fo,load}\cdot N_{Fo}+t_{dock}\right)+N_{Fo}\cdot t_{Fo,inst} \tag{14}$$

$$\begin{aligned} N_{Fo,yr} &= \frac{\eta_{days}}{t_{pfo,days}} \\ t_{pfo,days} &= \frac{1}{24}\left(\left(\frac{t_{tot}}{N_{Fo}}\right)\frac{1}{\eta_{work}}\right) \end{aligned} \tag{15}$$

$$trips_{yr} = ceil\left(\frac{N_{Fo,yr}}{N_{Fo}}\right) \tag{16}$$

$$\begin{aligned} NC \quad &= C_{class}(L_{oa}) + C_{steel}(W_{steel}) + C_{propulsion}(P_B, P_{DP}) + C_{generator}(P_B) + C_{electric-system}(P_B, P_{DP}) + C_{accomodation}(Crew) \\ &+ C_{systems}\left(Crane_{Capacity}\right) + C_{Crane}\left(Crane_{Capacity}\right) \end{aligned} \tag{17}$$

Two possibilities of revenue are defined and calculated using Eq. (18). One based on charter rate, where ships are rewarded a daily charter income $I_{charter}$ for all operational days times the percentage of contracts η_{contr} they are able to carry out. And another, based on installation capability, where ships are rewarded an income I_{MW} for the amount N_{Fo} and size MW of monopiles they install. The expected income q per foundation size is calculated for each amount that can be transported and installed as calculated by the mission module. This results in multiple vectors with cost and revenue values for different market states and are used to determine the expected cashflow for each scenario as part of the uncertainty modelling explained below.

$$\begin{aligned} R_{charter} &= \eta_{contr}\eta_{days}I_{charter} \\ R_{install} &= N_{MW,yr}I_{MW} \end{aligned} \tag{18}$$

2.3. Uncertainty model

The uncertainty model couples the market and ship configurations and is applied after the mission module to calculate the performance of each configuration in the market. As shown in Fig. 10, the "cut-off diameters" for a round number of piles on deck are linked to the cumulative probability density matrix from the market simulation. For each time step, the occurrence of contracts is calculated. In the example about 85% of contracts in 2030 will result in 3 piles on deck, which decreases toward only 40% of contracts in 2040 and 5% of the time no piles can be transported. For each configuration and market, the yearly amount of piles that can be transported and the occurrence of such a contract differs. The amount and size of piles and percentage of workable contracts is inserted into the cost and income module to calculate cost, revenue and profit of a vessel for a range of piles on deck $[N_{Fo}(D_1)\dots N_{Fo}(D_n)]$.

To quantify a vessel's financial performance over its lifetime, the expected value is used as a measure of merit. This value uses the probability of profit and calculates the mean profit of an investment, a decision can be substantiated by doing this for multiple investments. The expected value is calculated using a discounted Markov Chain with Rewards (MCR) with a finite horizon (Sheskin, 2016). The expected value at the start of a configuration's lifecycle $V(0)$ is calculated using Eq. (19) below. The salvage value V_T is the remaining value of a configuration at year T. The probability matrices $[P_1 \dots P_T]$ are created using Eq. (20) and represent the probability of occurrence of contracts that allow a vessel to transport a certain amount of piles for each year. The reward that a vessel will get for each amount of foundations on board is represented using vector $q([D_1 \dots D_n])$ and can be anything like cost, revenue or profit. The expected value of a vessel is given as a vector with expected value for each cut-off diameter or amount of piles on deck and is multiplied by the probability of occurrence in the very first year to get a total performance value. A profit vector and the calculation of the performance parameter; Return on Investment (ROI), are shown in Eq. (21). Several other values to check performance are also calculated, like the percentage of contracts that a vessel can perform and the amount of foundations that a vessel is able to complete over its lifetime, by multiplying the pile vector $[N_{Fo}(D_1)\dots N_{Fo}(D_n)]$ with each probability matrix. The expected cost of the vessel is also used to calculate the cost per pile and the target charter cost.

$$V(0) = q + \alpha P_1 \cdot q + \alpha^2 P_1 P_2 \cdot q + \dots + \alpha^T P_1 \cdot \dots \cdot P_T \cdot V_T \tag{19}$$

$$\begin{aligned} T_{config} &= \begin{bmatrix} p_{d_1,y_1} & \cdots & p_{d_n,y_1} \\ \cdots & \cdots & \cdots \\ p_{d_1,y_n} & \cdots & p_{d_n,y_n} \end{bmatrix} \\ P_1 = \begin{bmatrix} p_{d_1,y_1} & \cdots & p_{d_n,y_1} \\ \cdots & \cdots & \cdots \\ p_{d_1,y_1} & \cdots & p_{d_n,y_1} \end{bmatrix}&, \; P_T = \begin{bmatrix} p_{d_1,y_n} & \cdots & p_{d_n,y_n} \\ \cdots & \cdots & \cdots \\ p_{d_1,y_n} & \cdots & p_{d_n,y_n} \end{bmatrix} \end{aligned} \tag{20}$$

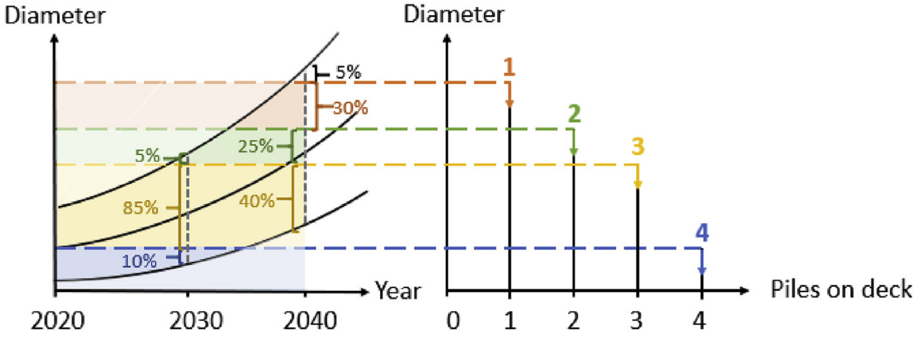


Fig. 10. Visualisation of market and ship model coupling, values are simplified.

$$q_{profit} = \begin{bmatrix} R(d_1) - C(d_1) \\ \dots \\ R(d_n) - C(d_n) \end{bmatrix}, \quad ROI = \frac{V(0) \cdot P_1}{NC} \tag{21}$$

2.4. Validation & verification

To check whether the models and their behaviour could be trusted, verification (checking internal consistency) and validation (justification of knowledge claims) studies were performed. This was done locally for each module and globally for the fully coupled model. The validation square methodology (Pedersen et al., 2000) was used for validation, which consists of empirical validation to test internal consistency (local) and external relevance (global) by using example problems. For verification, a sensitivity analysis was performed to verify the mathematical consistency and the behaviour of the model (Ye and Hill, 2017). As noted in the referenced papers, it is difficult to do a formal validation and verification for a model such as this. Nonetheless, the model has been checked to the best of the authors' capability and the check did give them confidence in the results for the case study. To ensure validity for other cases, modules should be calibrated again by using existing vessels and sensitivity analysis while also consulting expert knowledge.

Specifically, the case study was validated locally (for individual modules) and globally (for the coupled model) using reference vessels and test data. Local sensitivity of each module and the global sensitivity was analysed by varying single input values and assumptions and checking their effect on the module and total model output (Saltelli et al., 1999). The calculations in the Scaling and Power and Propulsion modules were verified using empirical examples (Birk, 2019) and validated by comparing open water characteristics and resistance and propulsion results from the model with basin tests from two existing HLCV vessels. The Weight module was verified by visualizing the effect of changing main dimensions and speed to test whether weight groups scaled logically and was validated by checking the weight of three existing HLCV vessels against the model output. The mission module was verified by visualizing each criterion equation and checking where each limited the amount of foundations for different input parameter combinations. It was validated by checking the stability and the amount of monopiles on deck against hydrostatic reports and data from two existing HLCV vessels. The cost and income module was verified and validated by disassembling the module into respective categories (costs regarding class, steel, propulsion and more) and checking each against the cost estimation of three existing HLCV vessels.

The global ship model results were then validated by checking how well it could approximate existing vessel capability and cost to transport and install different monopile sizes. The cost per foundation was recognized by UDSBV customers to be realistic. The model behaviour due to market uncertainty, as mentioned in the validation square, was validated using multiple example problems like the response to extreme markets (no contracts, only small or only large foundation sizes), market lock in (single foundation size) but also by applying the model to the historical offshore wind foundation market and evaluating the performance of currently operating vessels. The sensitivity of the model to uncertainty was researched by checking the effect of varying the uncertainty range and changing values like discount rate, income and salvage value. The V&V as described here was performed over multiple stages of development and did occasionally present errors in the code or assumptions, which were addressed accordingly. To increase confidence in the model, all assumptions and results were checked together with an experienced naval architect.

3. Results

Use of the method during the requirement definition stage in the design process consists of researching relevant scenarios and modelling their effect on vessel performance. Several scenarios relevant to the case study are modelled to research the effect of market uncertainty and demonstrate the capability of the method: effect of different possible markets, increasing distance to shore, different contract-types and development of monopiles without transition piece. All result graphs (Figs. 13–16) show the maximum financial performance (ROI in 100%) of a vessel design configuration against a reference parameter (length, breadth, depth, etc.). The shading shows the three next best configurations with that parameter. Whenever the shaded area is large, the difference with the closest values is high, which decreases confidence. It is also important to note that the return of investment and profit shown are merely measures of merit. The difference in return between simulated markets cannot be taken for granted as there are many factors, like success rate of the shipping company, which will effect the eventual size of return. The measure of merit does however show which decision variable value is more likely to be rewarded for each scenario.

3.1. Effect of different possible markets

In Fig. 13, the results of three different future markets are shown, (i) one that assumes that foundation size growth is not limited (non-bound), (ii) one that assumes that there will be a tipping point at an average of 17 MW in the market, and (iii) a third that assumes that there will be no growth after the wind-farms that are currently planned at an average of 13 MW. The second market was deemed as the most likely market by UDSBV and is shown in Fig. 12, while the

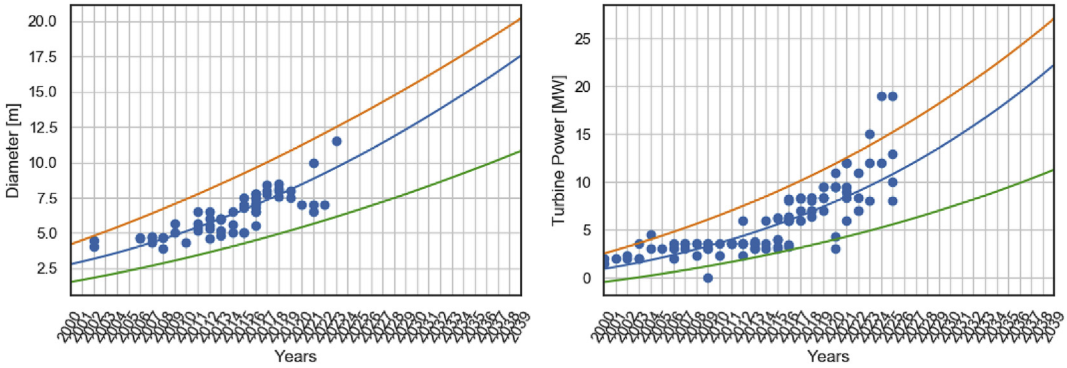


Fig. 11. Visualisation of non-bound future market.

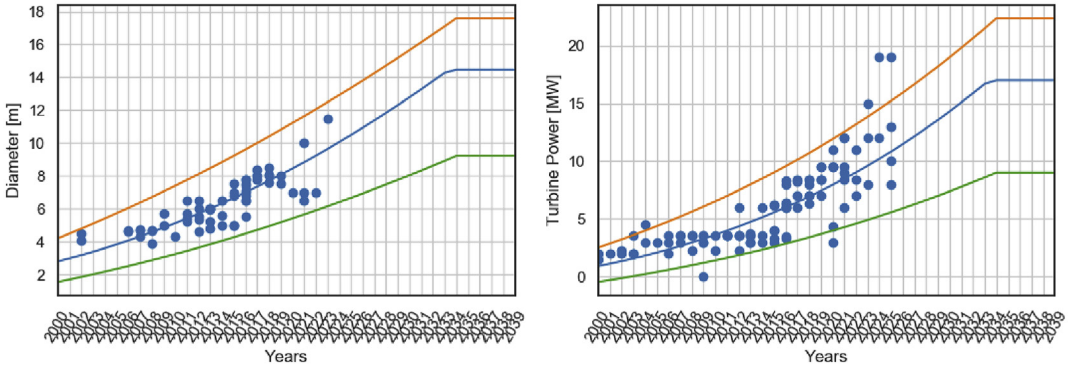


Fig. 12. Visualisation of future market, bound at mean turbine size of 17 MW.

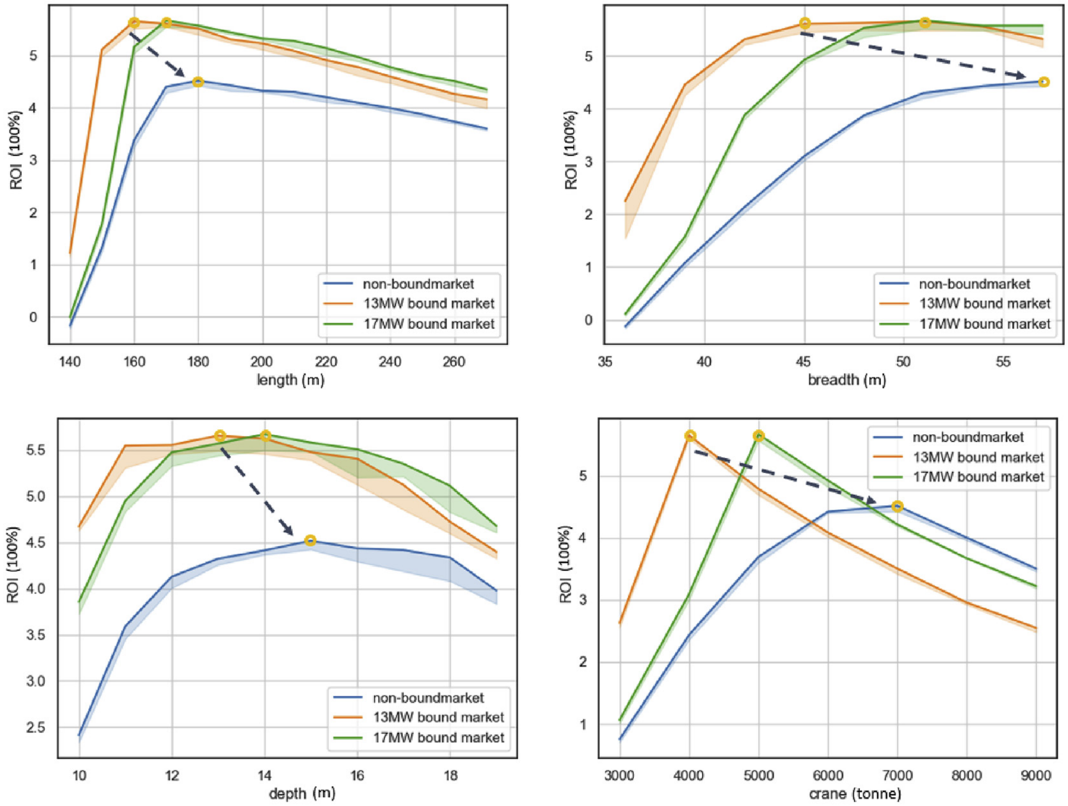


Fig. 13. Results of three different future market projections.

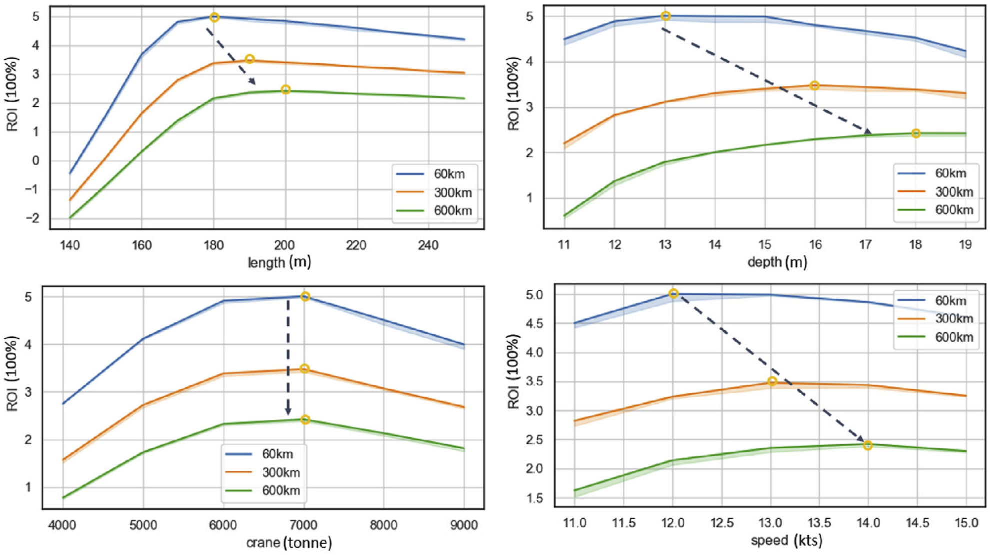


Fig. 14. Maximum profit for different distances to shore.

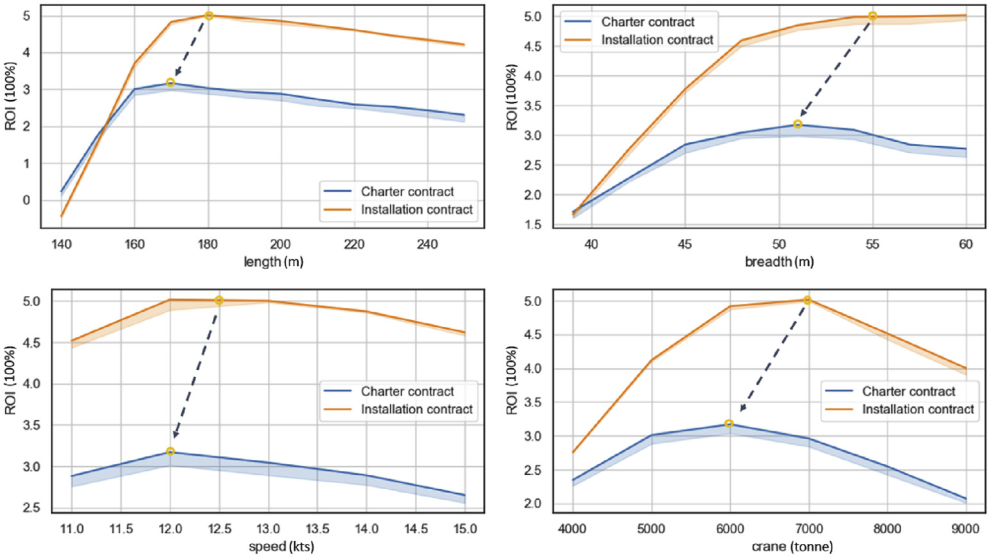


Fig. 15. Effect of different contract types on design parameters.

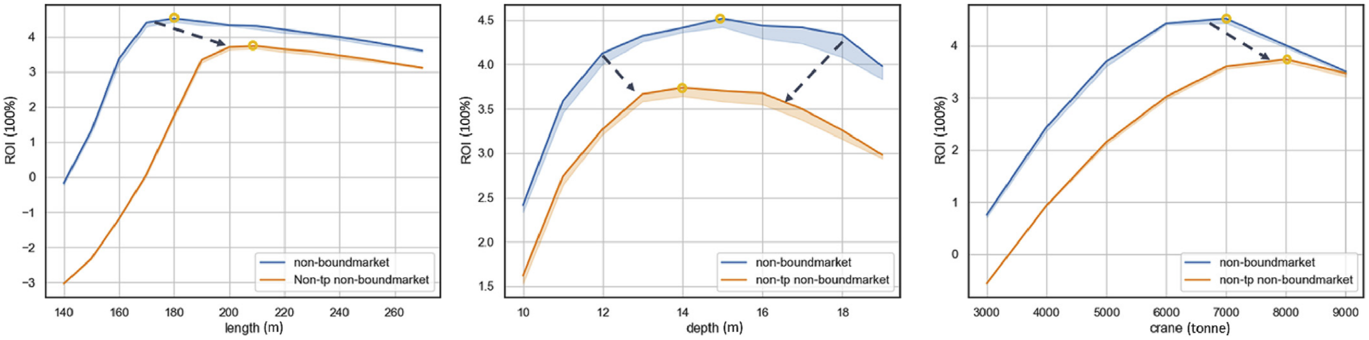


Fig. 16. Effect of development of monopiles without transition piece.

non-bound market is shown in Fig. 11. The outliers of 19 MW are found to be unrealistic, as a maximum turbine size of 14–15 MW has only recently been presented for 2024. Four design parameters are shown and the point where the maximum return on investment occurs is shown using a yellow circle, while the dashed blue arrows show the general development. The bound market shows that smaller values are preferred, as lowest vessel cost results in a larger return. From this optimal point onward the curves are rather flat. The non bound market results are much broader, rewarding a certain range of parameter values. Optimal vessel depth increases for larger foundations sizes, as it mainly determines the available cargo weight. The stability decreases for larger depth and the optimal point is located between the weight and cargo criteria.

3.2. Effect of increased distance to shore

In Fig. 14, the average distance from shore is increased to see whether it favours different configurations. An installation contract is used for income, which rewards increased placement. The average distance to shore for the last two years is 60*km* as calculated from 4COffshore. As is expected, an increase in distance does decrease the overall return on investment as the fuel use increases and the income decreases due to longer transit times. The larger the distance to shore, the better a larger depth, speed, and vessel size becomes, while the curve also seems to flatten for these values. This can be explained by an increase in cargo capacity as available cargo weight increases because of larger depth. The vessel breadth also increases to account for stability, which decreases with larger depth. The increase in length increases the cargo capacity without affecting stability, while minimally increasing the resistance (as frictional resistance and wave resistance increase only slightly for increased depth). The figure thus shows that an increase in distance results in a reward for vessels with larger cargo capacity.

3.3. Effect of different contract-types

Using the non-bound market, the effect of different contracts rewarding either vessel capability (charter) or amount installed (installation) is researched. Charter contract typically rewards smaller vessels which cost less. Installation type contracts reward based on decreasing placement cost by improving placement efficiency. This is evident in the speed and crane capacity figures. The optimal speed is fairly broad for the installation contract, while a peak is clearly visible at 12*kts* for the charter contract. The crane capacity figure shows how 6000 and 7000 ton cranes perform well with an installation contract, while the peak is broader and shifted to the left toward 5000 till 7000 ton cranes for the charter contract.

3.4. Paradigm shift toward monopiles without transition piece

Technical developments might also change the state of the art in the coming years. One such development, is the monopile without transition piece, which results in an extension of the foundation with about 20 m (SIF-group, 2019). Thus requiring a larger crane boom height and it results in an increase in foundation weight. Again using the non-bound market provides the results shown in Fig. 16. As expected, the optimal vessel and crane size increase for the increased foundation length and weight. The vessel depth peak also becomes narrower, because the vessel needs more installation stability (right side) and cargo weight (left side). From an installation perspective, because the foundation size increase affects stability and carrying capability, the development seems like a bad idea but it could be taken into account.

4. Discussion

During the requirement definition stage, the model can be used to explore relevant parameter ranges and scenarios. Besides using graphs to visualize relations between performance parameters and decision variables, a database with decision variables and corresponding performance for each design alternative is also included. The model intentionally does not output a single optimal design, but a design range, to show the design space boundaries and get the user to explore the effects of a decision and changes in the market. For each scenario, the designer should examine the change between possible design ranges and establish the trade-offs to decide on. Besides performance parameters, the relation between decision variables also have to be examined carefully, because combined, chosen values could be infeasible or suboptimal for other scenarios and performance parameters. The insights can then be used to decide which decision variables would make for a value robust design, which is able to perform well within the expected future market.

In Table 4, the design ranges of each scenario for the case study are summarised. The scenarios researched were selected because of their diversity and relevance to the offshore wind foundation installation vessel market and show the potential use of the model. However, it should be noted that there are many other important scenarios to research. Scenarios regarding different foundation types, installation techniques, vessel types and others would also be interesting to research in a design process or as part of future research. To examine these, the model can easily be adapted due to its modular setup. Of the scenarios researched, the different probable markets provide insight into which size and capability would be necessary for different expected markets. The research into the effect of increased distance from shore demonstrated that larger average transit distance affects vessel design parameters. By using more detailed geographical data, the vessel could be made to fit the expected average travel distance. The different contract types, which target capability and placement efficiency respectively, show how the method can take the effect of company strategy on vessel design into account. With the development of TP-less monopiles, the installation vessel would need to increase in size and crane capacity.

What categories have priority and what aspects to research should be discussed and explored in more detail together with a customer during the requirement definition stage. The knowledge gained can then be used to research trade-offs and establish

Table 4
Optimal design ranges and initial design proposal.

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

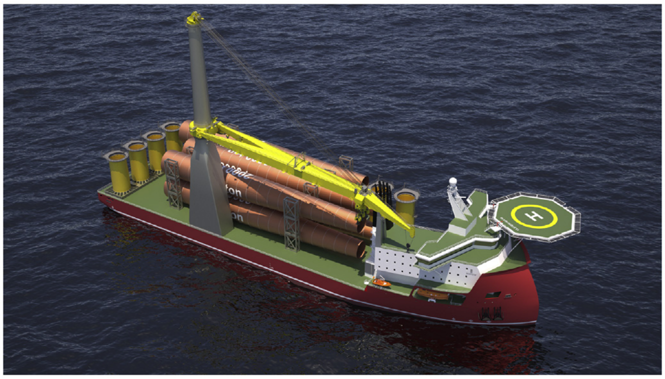


Fig. 17. Initial design visualisation.

requirements to proceed with in the conceptual design stage. For the case study, a design was assumed to have to function well for both contract types, to sail 300 km distance to a project on average, be big enough to comply with the larger cargo requirement for increased distance and TP-less piles and have the ability to lift the piles as described in the 17 MW expected market. The resulting initial design parameters are included in Table 4. During the following conceptual stage, whenever decision variables are fixed, the market is refined or other scenarios need to be researched, the model can be used in parallel to examine whether the chosen parameters still comply. A visual representation of a conceptual design stage result is shown in Fig. 17.

5. Conclusions

The proposed method provides an improvement when compared to the traditional way of dealing with market uncertainty in ship design. Current practice effectively ignores changes in the market (Pruyn, 2017), resulting in some design decisions being made without fully understanding their effect on solving the problem or their effect on vessel costs (Kana et al., 2016). To research this effect early in the design process, the new method uses uncertainty modelling, this methodology has been proven to be able to provide valuable insights by several researchers (Niese et al., 2015) (Gaspar et al., 2012). The method decreases the perceived market uncertainty by increasing knowledge of its consequences when design freedom is still high (Nam and Mavris, 2008). In this way, the vessel can be designed with the right purpose in mind, in such a way that good performance in the expected market is more likely. This was shown to be especially important in offshore wind, where uncertainty comes from the seemingly unpredictable growth of market demand, turbine size and distance from shore (IEA, 2019). By using the proposed method, a value robust design was created together with UDSBV that is more likely to perform well on average in the expected market. The next step is to use this method during a real design process, iteratively improving assumptions and co-evolving design solutions and market scenarios. This decreases the customer's perception of market uncertainty and increases their confidence in the design solution. In this way, despite uncertainty, the investment by ship owners in the ever-larger construction vessels needed for further offshore wind energy development could be ensured (IEA, 2019).

This article set out to create a method that could be used to deal with market uncertainty during early ship design. By performing a case study into offshore wind foundation installation vessels, the method has been proven to be able to model the uncertain market and vessel designs. Moreover, the method can be used to research the performance of different designs in a market. Using it, a designer is therefore able to explore the effects of an uncertain market in early ship design. The article differentiates from previous research in three avenues. Firstly, it focuses on the growing and highly unpredictable offshore wind market. Secondly, it incorporates forecasting models based on offshore wind foundation diameter. And lastly, it proposes an uncertainty modelling method for use as part of the ship design process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

A. Symbols list

Decision variables (input)					
Configuration range			C_{fuel}	[mln eur]	total fuel cost
B	[m]	Vessel breadth	C_{gen}	[mln eur]	cost of power generators
$Crane_{capacity}$	[tonne]	Crane Capacity	C_{ins}	[mln eur]	insurance cost
D	[m]	Vessel depth	$C_{maintenance}$	[mln eur]	cost of maintenance
L_{oa}	[m]	Vessel length over all	$C_{management}$	[mln eur]	management overhead cost
V_s	[kts]	Vessel Speed	C_{prop}	[mln eur]	cost of propulsion thrusters
Scenario variables			C_{Port}	[mln eur]	cost of port charges
η_{days}	[#]	amount of days operating each year	$C_{s\&s}$	[mln eur]	stores and supply cost
$Contract$	[0,1]	charter 0 or installation contract 1	C_{steel}	[mln eur]	cost of steel structure
dts	[km]	distance to shore	$C_{systems}$	[mln eur]	cost of systems
$I_{charter}$	[eur]	income for operational day	$Equity_{return}$	[%]	expected return on equity
I_{MW}	[eur]	income for amount and size (MW)	$Loan_{interest}$	[%]	interest rate for loan
f_{max}	[-]	foundation size upper bound function	$Loan_{repay}$	[%]	repayment rate for loan

(*continued*)

f_{mean}	[-]	foundation size mean function	NC	[mln eur]	newbuild cost of the vessel
f_{min}	[-]	foundation size lower bound function	N_{crew}	[#]	number of crew accomodations
			$N_{Fo,yr}$	[#]	amount of foundations placed in a year
Performance parameters (output)			$N_{MW,yr}$	[#]	amount of megawatts placed in a year
ROI	[-]	expected return on investment	$OPEX$	[mln eur]	yearly operational expenses
$profit$	[eur]	expected profit	$R_{charter}$	[mln eur]	yearly charter revenue
$cost$	[eur]	expected cost	$R_{install}$	[mln eur]	yearly installation revenue
$revenue$	[eur]	expected revenue	sfc	$[g/kwh]$	specific fuel consumption
$cargo$	$[m^2]$	cargo space	$t_{Fo,inst}$	[h]	installation time per foundation
$chartercost$	[eur]	minimum cost of charter	$t_{Fo,load}$	[h]	in port loading time per foundation
$pilecost$	[eur]	minimum cost per foundation	t_{inst}	[h]	time spent installing
$lifepile$	[#]	amount of piles placed over lifetime	$t_{pfo,days}$	[days]	total installation days per foundation
$Mwpile$	[#]	amount of MW placed over lifetime	t_{port}	[h]	time spent in port
			t_{sail}	[h]	time spent sailing to installation site
Market model			t_{tot}	[h]	total time spent on mission
ρ_{Fo}	$[kg/m^3]$	Density of foundation material	t_{dock}	[h]	time spent docking and loading supplies in port
A_{p_i}	[-]	Area under probability density curve	$trips_{yr}$	[#]	amount of trips per year
$[d_1 \ldots d_n]$	[m]	foundation diameter range	$VOYEX$	[mln eur]	yearly voyage expenses
D_{Fo}	[m]	foundation diameter	mission		
$F_{year}(D_{Fo})$	[-]	Cumulative probability function	Δ	[tonne]	Displacement
L_{Fo_s}	[m]	Foundation length	A_{Deck}	$[m^2]$	deck area available for cargo
p_i	[-]	Probability density function	A_{crane}	$[m^2]$	deck area taken by crane
p_{d_n,y_n}	[-]	diameter n occurrence for year n	GM	[m]	geometric metacentric height
T_{config}	[-]	Diameter occurrence probability matrix (transition matrix)	h_{crane}	[m]	height of cranetip
wt_{Fo}	[m]	Foundation wall thickness	KG	[m]	centre of gravity height from keel
W_{Fo_s}	[tonne]	Foundation weight of straight part	KM	[m]	metacentric height from keel
W_{Fo_t}	[tonne]	Foundation weight of tapered part	l_{Fo}	[#]	amount of foundation layers
W_{Fo}	[tonne]	foundation weight	L_{Deck}	[m]	deck length or vessel length without accomodation
$[y_1 \ldots y_n]$	[#]	range of years	$N_{Fo,L}$	[#]	deck length constraint
			$N_{Fo,B}$	[#]	amount of foundations placed in width
Ship model			$N_{Fo,Deck}$	[#]	amount of foundations on deck
ship scaling and weight			N_{Fo}	[#]	amount of foundations fit on board
a_k	[-]	katsoulis length exponent	N_{KG}	[m]	centre of gravity of stack of foundations
b_k	[-]	katsoulis breadth exponent	VCG_{TP}	[m]	vertical centre of gravity of transition pieces
C_B	[-]	block coefficient	W_{bal}	[tonne]	ballast weight
c_k	[-]	katsoulis draught exponent	W_{load}	[tonne]	Installation load weight for one foundation
d_k	[-]	katsoulis speed exponent	W_{TP}	[tonne]	transition piece weight
DWT_{cargo}	[tonne]	available weight for cargo	x_{bal}	[-]	ratio vertical centre of gravity of ballast weight versus depth
f_k	[-]	katsoulis scaling factor	propulsion and power		
T	[m]	Vessel draught	H_s	[m]	significant wave height
T_{des}	[m]	Vessel design draught	P	[-]	Table 3 wind and wave probability of occurrence
T_{max}	[m]	Maximum vessel draught	P_{DP}	[MW]	Dynamic positioning power
W_{steel}	[tonne]	Vessel steelweight	P_{inst}	[MW]	installed power
cost and income			P_B	[MW]	Propulsion power
η_{contr}	[%]	amount of available contracts	T_p	[s]	wave period
$\eta_{eng_{use}}$	[%]	percentage of installed power used	V_c	$[m/s]$	current speed
η_{work}	[%]	workability of the vessel (fixed)	V_w	$[m/s]$	wind speed
$CAPEX$	[mln eur]	yearly capital expenses			
C_{crew}	[mln eur]	crew wage	**Uncertainty model**		
$C_{accomodation}$	[mln eur]	cost of accomodation	α	[%]	discount rate
C_{class}	[mln eur]	class certification costs	$[P_1 \ldots P_T]$	[-]	probability matrices of contract occurrence per year
C_{crane}	[mln eur]	cost of the crane	q_{profit}	[mln eur]	reward vector
$C_{electric-system}$	[mln eur]	cost of electric system	$V(y_n)$	[mln eur]	expected discounted value in year y_n
$C_{fuel,tonne}$	[eur/tonne]	fuel cost per tonne	V_T	[mln eur]	salvage value

B. Wind and wave statistics table

Table 5
Wind and wave statistics.

P	H_s	V_w	V_c	$1 - P$	T_p
2.5	0.66	1.4	0.75	97.5	3.46
5	0.79	2.19	0.75	95	3.89
10	1	3.3	0.75	90	4.47
20	1.35	4.95	0.75	80	5.26
30	1.7	6.21	0.75	70	5.81
40	1.9	7.48	0.75	60	6.33
50	2.3	8.74	0.75	50	6.80
60	2.6	10.01	0.75	40	7.24
70	3	11.39	0.75	30	7.68
80	3.5	13.11	0.75	20	8.18
90	4.2	15.53	0.75	10	8.80
95	4.9	17.6	0.75	5	9.26
97.5	5.3	19.32	0.75	2.5	9.60
98	5.6	19.9	0.75	2	9.71
98.5	5.8	20.59	0.75	1.5	9.84
99	6.1	21.51	0.75	1	9.99

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