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Dimensioning of port waterways for vessels handling offshore wind farms using the navigational risk analysis

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Abstract

This article indicates the development trends in the construction of offshore wind turbines worldwide, and the characteristics of existing and planned ships for wind turbine installation and maintenance; it presents an approach to design ports with their future operations in mind. Problem: The safety of navigation in port waterways is the basic restrictions for the construction of harbors (terminals) to handle ships used for the construction of OWT and for increasing their size. Navigational risk is a criterion of navigational safety assessment that allows its accurate estimation in port waterways. Method: The article presents the method for dimensioning port waterways for ships serving offshore sea wind turbine transport and construction. Furthermore, a method for determining the navigational risk of jack-up vessels navigating in port waterway areas is presented. Results: The authors have determined conditions for safe operation of these ships in restricted areas and defined the basic condition of navigational safety. The presented method of navigational risk analysis refers to the departure of a loaded ship carrying offshore wind turbine components in the presently designed port terminal in Świnoujście for handling offshore wind farm projects. Conclusion: These are universal methods that can be applied to the design of ports serving vessels that install offshore wind turbines in various types of waters.

Introduction

An analysis of global trends indicates that the power of both designed and installed offshore wind turbines is on the rise. At present, the maximum wind turbine installed at sea has a power of 9.5 MW (Renewable Energy World, 2021), while a larger 15 MW power turbine is to be installed by 2030 (The Maritime Executive, 2021). Even more powerful turbines are expected to exceed 20 MW in the years to come. The Polish economic zone of the Baltic Sea is to be a site of more than 400 14 MW wind turbines (Gucma & Gralak, 2021).

The construction of 14 MW, or larger turbines, will require specialized four-generation vessels. Their parameters differ significantly from those of comparable size cargo or passenger vessels. The basic differences of these offshore vessels in relation to other transport ships can be defined as follows:

- significantly greater hull width,
- maximum width of the ship with deck cargo greatly exceeding the hull width,
- air draft is much higher,
- excellent maneuvering characteristics (azimuth thrusters).

These differences impose specific conditions of the operation of offshore wind turbine (OWT) construction ships on port waterways. This particularly applies to the design and construction of terminals for handling these ships in the existing seaports.

The dimensioning of port waterways for ships intended for OWT construction require:

- determination of the conditions that will provide safe operation of OWT vessels on port waterways,
- determination of the basic condition of navigational safety of OWT vessels in restricted areas,
- analysis of the navigational risk of loaded OWT vessels leaving the port.

This paper presents a developed method of dimensioning port waterways intended for handling (jack-up) vessels that install offshore wind turbines. Furthermore, a method for determining the navigational risk of jack-up vessels navigating in port waterway areas is presented.

Literature review

At present, the largest offshore wind turbine in continuous use is the MHI Vestas V164-9.5MW, with the rotor diameter of 164 m (Engel, 2021). A 10-MW turbine installation is expected to be completed in the first half of 2022. It is the 3. generation turbine that requires 3. generation vessels for offshore installation. The prototype of 15MW OWT Vestas V236-15 MW will be installed in Østerild by mid-2022 (Vestas, 2021), where currently the largest one installed on land is a 12 MW prototype called Haliade-X from General Electric. It was installed for tests using land-based equipment in the port of Rotterdam in 2019. The first such wind turbine is to be installed at the Dogger Bank Teeside A and B Wind Farm in early 2022, while its modified version (with power increased to 13 MW) is to be located at the Sofia Farm (General Electric, 2020). The highest model of the Haliade-X turbine with 14 MW power output is to be built on the Dogger Bank Teeside C Farm in 2025 (Sonal, 2020).

The analysis of global trends in the size of the installed offshore wind turbines (which results from the increased power that is generated by them) clearly indicates that turbines used on offshore wind farms are those with an output of over 10 MW power, which are referred to as 4. generation turbines (Figure 1).

At the end of 2021, the world fleet included 137 ships suited to handle offshore wind turbine installation (GWEC, 2020). These include 12 vessels for installing offshore wind turbines with power output over 10 MW (NEEC, 2021), of which only four are capable of installing a 12 MW turbine (Tufts University, 2021). According to the terminology used in the offshore wind farms sector, three types of ships are used in the construction chain (Uraz, 2011; Anju, 2017; Douglas-Westwood, 2013):

- wind turbine installation vessel – WTIV,

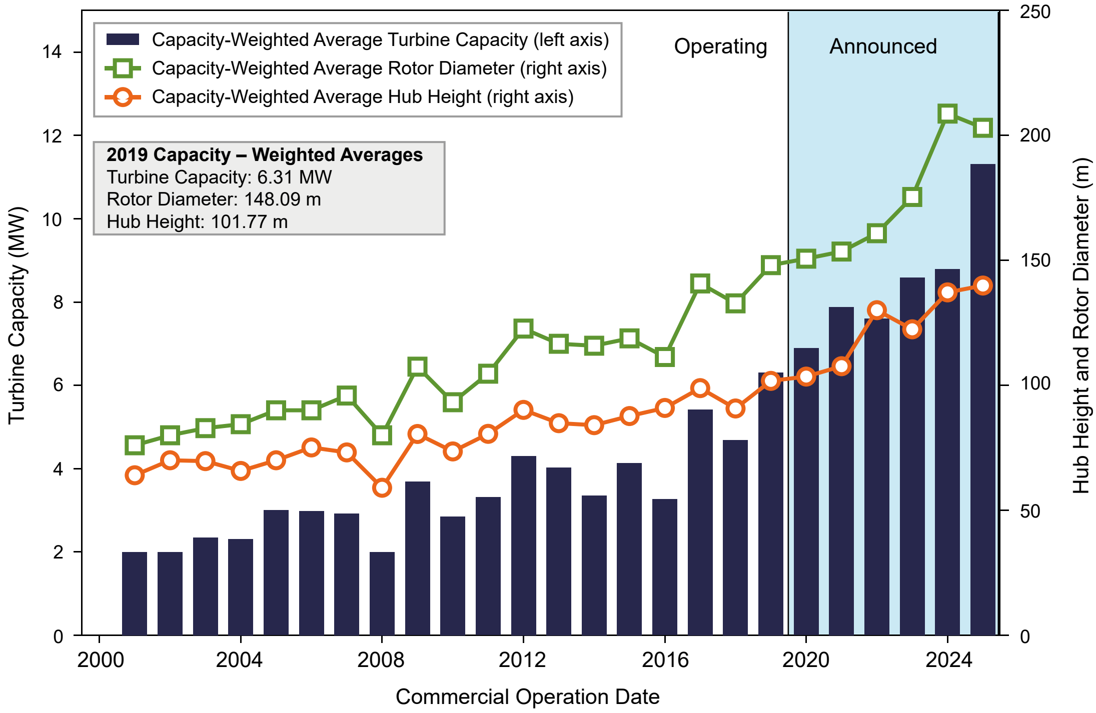


Figure 1. Projected trend of the increase in capacity and size of offshore wind turbines (Musial et al., 2020)

Figure 2. Ulstein Windlifter - the installation system of complete OWT (Douglas-Westwood, 2013)

- wind turbine transport vessel – WTTV,
- foundation transport and installation vessel – FTIV.

From the technical point of view, the type and parameters of the ship used in each of the above links for the offshore wind turbine construction chain are determined by two main factors (DNV GL, 2017; Letcher, 2017; K&L Gates, 2019;):

1. the size of the sea wind turbine,
2. the method of turbine installation in the area of the offshore wind farm.

It follows, from the analysis of the literature, that 4. Generation WTIV vessels will be used for the construction of 10 MW (and greater) turbines, including:

- jack-up, universal, and dedicated WTIV vessels,
- jack-up, self-propelled, and towed barges,
- heavy lift vessels,
- derrick barges,
- dedicated turbine installation vessels (TIV), e.g. Huisman or Ulstein Windlifter (Figure 2).

According to reports on wind energy operators, jack-up WTIV vessels will constitute the vast majority of ships used for OWT construction (Figure 3). They are significantly improved for ship stabilization and the outreach of installation equipment compared to conventional heavy-lift vessels (Rystad Energy, 2020).

Increased weight and size: towers, nacelles, and rotor blades of the offshore wind turbines require a larger sized ship, as well as increased tonnage, deck area and deck load capacity, crane/hoist lifting capacity, and crane lifting height. Jack-up offshore WTIV vessels are being fitted with increasingly longer legs, which translates into a capability of erecting wind turbines in deeper areas (Naschert, 2019; Ulstein, 2019). Based on the latest publications, an analysis is made that compares selected parameters, including for 3. and 4. generation ships; this is shown in Table 1.

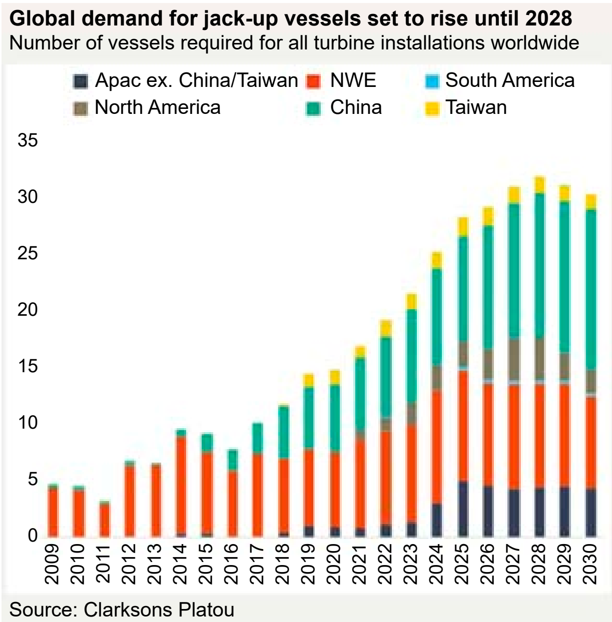


Figure 3. Estimated increase in the number of jack-up offshore WTIV vessels (Naschert, 2019)

Increasing the capabilities of 4. generation WTIV vessels allows the transshipment, transport, and installation of turbines up to 17 MW, and it significantly increases the transport capacity of previous generation turbines. Based on the interpolation and extrapolation of data from source materials, the maximum number of complete wind farms that can be loaded onto a vessel is determined as the function of the available cargo area (Figure 4).

By estimation of the load that affects the vessel's cargo deck, from the monopile foundation (12 MW turbine) that weighs up to 2600 tons, it is determined that WTIV ships with a load capacity greater than 25 tons/m^2, and a lifting capacity over 3000 tons, can also be used for their transport and installation. The transport and installation of 4. generation wind turbine elements, unlike the previous ones, assumes:

a. the tower is to be stowed vertically as a complete pre-installed component,

Table 1. Comparison of selected WTIV parameters, all generation vessels (Ulstein, 2019)

Generation:	1st	2nd	3rd	4th
Operational:	2005	2010	2015	2022
Description:	*First heavy lift jack-ups in offshore wind*	*New designs primarily for offshore wind*	*Scaled-up designs for larger turbines*	*Next generation for future 15 MW turbines*
Average crane capacity:	500 ton	900 ton	1400 ton	2500–3500 ton
Average variable load:	2000 ton	5000 ton	8500 ton	10 000–16 000 ton
Typical Wind Turbine:	3 MW	6 MW	9 MW	15 MW
Example:				

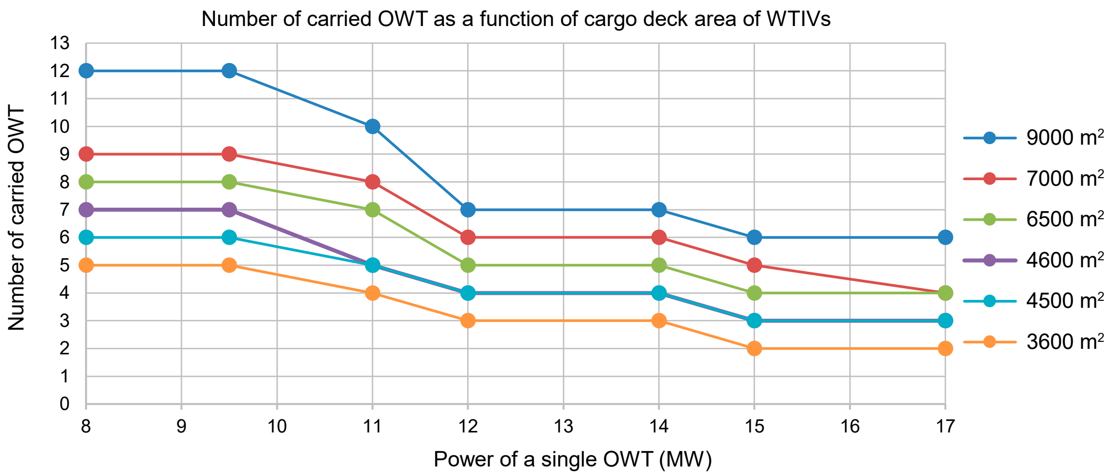


Figure 4. Maximum number of complete wind turbine assemblies loaded onto a ship

b. the blades are usually stowed athwartship, symmetrical, or asymmetrical to the vessel's center line.

1. to 3. generation wind turbine components are carried to the terminal by ro-ro, general cargo, or heavy lift ships, typical or slightly modified to manufacturer's needs, in one of these transport arrangements:
1. BE2T Bunny Ear – tower in two pieces and two rotor blades pre-installed to the nacelle,
2. BE1T Bunny Ear – complete tower and two rotor blades preinstalled to the nacelle,
3. R2T – rotor blades pre-installed to the nacelle and a tower in two parts,
4. SP5 – complete tower, nacelle, and rotor blades separately.

The most common transport arrangement of 3. generation OWT is BE2T Bunny Ear (Uraz, 2011).

In the case of OWT mounted onto a foundation, components are carried from the port to the installation vessel by towing self-propelled barges and, occasionally, heavy lift vessels. A frequent solution in the transport chain is that the WTIV is used for both transport and installation of the OWT in the offshore wind farm area. Floating OWTs are towed to the farm location by sea tugs. One of the most interesting solutions in this respect is WindFlip (Douglas-Westwood, 2013), in which a turbine is towed to the site, and positioned upright through ballasting (Figure 5).

An analysis of modern solutions for the transport of 4. generation OWT indicates that the transport of turbine elements will be performed using specially designed ships in the SP5 transport arrangement. Newbuilds dedicated to the transport of 4. generation OWT elements are called WTTV. Their general specification, and capabilities for the carriage of 14 MW turbine, is shown in Figure 6.

The relatively small size of the 1.–3. generation OWT foundation makes it possible to erect these turbines in offshore wind farms with depths of 40 m using WTIVs. The increasing dimensions

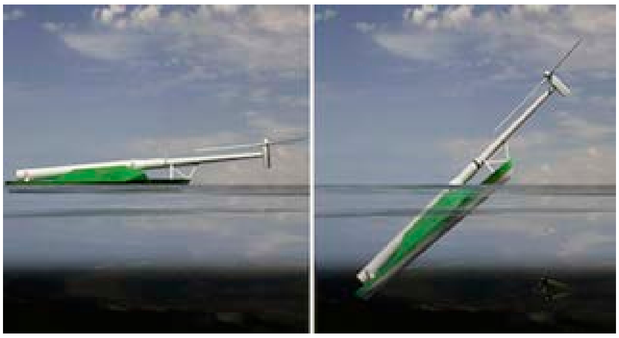
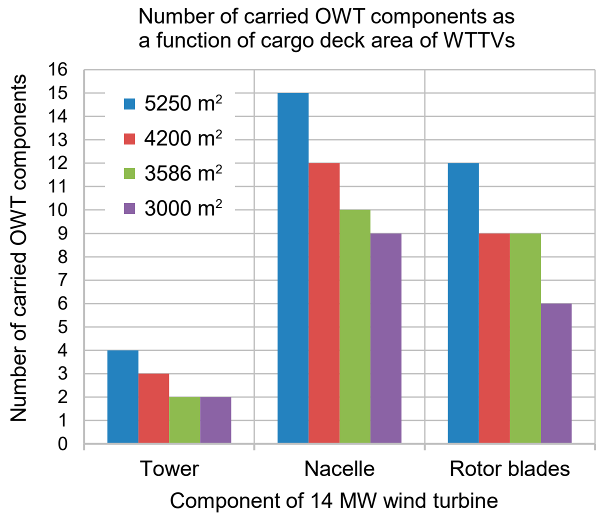


Figure 5. A depiction of windflip (Douglas-Westwood, 2013)



WTTV parameters	
Length Overall (m)	153
Breadth (m)	34
Draught (m)	8
Deadweight (t)	15 596
Deck area (m^2)	3496
Deck load capacity (t/m^2)	18

avg. values

Figure 6. General characteristics of WTTV vessels

and weight of the most frequently used XL monopile foundations for 4. generation turbines require dedicated FTIV vessels, while heavy lift vessels or derrick barges are less frequently employed (Rystad Energy, 2020). Based on the analysis of the literature, and technical documentation of vessels to be built, the authors have determined the characteristic parameters of 4. generation FTIV vessels (Table 2).

Carried by FTIV vessels, one-part XL monopiles are positioned horizontally, along or across the ship. The cargo piece is loaded and discharged using a powerful deck crane with large lifting and height capacity.

Considering the above, designing waterways in port areas to ensure safe operation of WTIV and WTTV vessels seems to be timely. The relatively small number of vessels (in global terms) navigating in port areas, in relation to the total number of vessels, and their dynamic development result in a significant increase in the size of vessels. The OWT elements transported by them make the dimensioning of port waterways, intended for handling these vessels, based on case studies instead of universal methods.

The authors observed that, from the point of view of conditions of safe operation, in port areas concerning fourth-generation WTIV and WTTV, in addition to the general guidelines for transporting OWT elements (DNV GL, 2017), general methods for formal risk assessment widely described by (Mehdi, Baldauf & Deeb, 2020) and case studies of installation ports (NYSERDA, 2017; Cao, 2020; COWI, 2020; Porter & Philips, 2020, and others), where PIANC and USACE methods are mainly used for dimensioning, there is a need to develop a universal method for dimensioning port waterways for these types of vessels.

Methodology

Conditions for the safe operation of WTIV and WTTV ships for OWT construction and maintenance in restricted areas differ from the conditions of safe operation of conventional ships. These differences can be described as follows:

- WTIV and VTTV ships can enter and depart from a port moving ahead or astern, this ability results from the characteristics of their propulsion and steering systems (azimuth propellers and thrusters),
- entry, departure, turning, and berthing of these ships can be executed without tugboat assistance due to their very good maneuverability,
- WTTVs are discharged and loaded by shoreside cranes or through a ramp (supersized cargo), with a possible increase in the ship's draft (T_{port}) so

Table 2. Comparison of various parameters of 4. generation WTTV vessels

Length Overall (m)	Breadth (m)	Draught (m)	Deadweight (t)	Deck area (m^2)	Deck load capacity (t/m^2)	Crane/hoist capacity (t)	Crane lifting height (m)
203	45	7.95	30 000	6502	28.7	3800	147.5

avg. values

that the deck and berth are at the same level. This requires appropriate water depth along the berth,
- WTIV vessels are loaded in the jack-up system by the crane of the ship that is supported by the system's legs. This requires the appropriate depth at berth and bottom construction.

Specific conditions of the operation of ships for the installation and maintenance of OWT leads to the formulation of the basic condition of the safety of navigation of these ships in restricted areas, which differs from that for conventional ships (Gucma, 2015; 2017). The basic condition of the navigation safety of ships for OWT construction can be written as follows:

$$\left.\begin{aligned} &\subset d_{ikz(1-\alpha)}\ D_i(t) \\ \boldsymbol{d}^{nad}_{ikz(1-\alpha)} &\subset \boldsymbol{D}^{nad}_i(t) \\ \bigwedge_{p(x,y)\in \mathbf{D}(t)} h_{x,y}(t) &\geq T_{x,y}(t) + \Delta_{x,y(1-\alpha)} \end{aligned}\right\} \tag{1}$$

while

$$\boldsymbol{d}^{nad}_{ikz(1-\alpha)} = f(\boldsymbol{d}_{ikz(1-\alpha)}) \tag{2}$$

where:

$\boldsymbol{D}_i(t)$ – navigable area in i-th section of the waterway (the condition of safe depth at instant t is satisfied),

$\boldsymbol{d}_{ikz(1-\alpha)}$ – safe maneuvering area of k-th ship performing a maneuver in i-th section of the waterway in z-th navigational conditions determined at the confidence level $(1-\alpha)$,

$\boldsymbol{D}_i^{nad}(t)$ – surface available navigable area in i-th section of the waterway (including shore infrastructure and moored ships),

$\boldsymbol{d}^{nad}_{ikz(1-\alpha)}$ – surface safe maneuvering area of k-th ship performing a maneuver in i-th section of the waterway in z-th navigational conditions determined at the confidence level $(1-\alpha)$,

$T_{x,y}(t)$ – ship draft at point (x, y) at instant t,

$\Delta_{x,y(1-\alpha)}$ – underkeel clearance at point (x, y) determined at the confidence level $1-\alpha$.

The parameters of the port waterway system (area and navigational subsystems) are a function of the conditions of safe operation of ships maneuvering therein (Gucma, 2015):

$$\begin{bmatrix} \boldsymbol{A}_i \\ \boldsymbol{N}_i \end{bmatrix} = F(\boldsymbol{W}_i) \tag{3}$$

where:

$\boldsymbol{A}_i$ – area subsystem (i-th section),

$\boldsymbol{N}_i$ – navigational subsystem (i-th section),

$\boldsymbol{W}_i$ – conditions of safe operation of ships (i-th section).

Port waterway systems, and conditions of safe operation of ships maneuvering, therein are defined depending on the type of waterway and performed maneuver (Gucma, 2017). For the above reasons, port areas serving ships for the OWT construction and maintenance will be divided into:
- approach channels (including port entrance),
- port basins (berth approaching with turning areas).

A set of conditions for the safe operation of the ships under consideration in port waterways can be written as follows:

$$\boldsymbol{W} = \begin{bmatrix} \mathrm{WTIV}, L_{c1}, B_1, B_1^{nad}, T_1, H_1^{st}, V_{i1}, \mathbf{H_i} \\ \mathrm{WTTV}, L_{c2}, B_2, T_2, T_2^{port}, H_2^{st}, V_{i2}, \mathbf{H_i} \end{bmatrix} \tag{4}$$

where:

L_c – overall length of the "maximum ship" (indices: 1 – WTIV, 2 – WTTV),

b – molded breadth of the "maximum ship",

B^{nad} – above surface width (including deck cargo),

T – draft of "maximum ship",

T^{port} – maximum draft of the ship at berth (as per the loading procedure),

H^{st} – maximum air draft with cargo (height from water surface),

V_i – allowable speed of "maximum ship" on i-th section of fairway,

$\mathbf{H_i}$ – set of hydrometeorological conditions acceptable for "maximum ships" in i-th waterway section.

$$\mathbf{H_i} = [d/n, s, \Delta h_i, V_{wi}, KR_{wi}, V_{pi}, KR_{pi}] \tag{5}$$

where:

d/n – allowable time of day (daylight or no restrictions),

s – visibility,

Δh_i – allowable drop of water level,

V_{wi} – allowable wind speed in i-th section,

KR_{wi} – wind direction restrictions (if any exist in i-th section),

V_{pi} – allowable current speed in i-th section,

KR_{pi} – restriction of current direction (if any).

The subsystem of the approach area is described by a set of parameters:

$$\boldsymbol{A}_i = \begin{bmatrix} t_i \\ l_i \\ D_i \\ D_{ij}^{nad} \\ h_i \end{bmatrix} \tag{6}$$

where:

t_i – type of i-th section of fairway,

l_i – length of i-th fairway section,
D_i – width of available navigable area of i-th fairway section (width at bottom),
D_{ij}^{nad} – the shortest surface distance from i-th fairway axis to a danger in j-th direction (restricted by surface infrastructure and the parameters of ships moored near the fairway),
h_i – minimum depth of i-th section of fairway.

For WTIV and WTTV vessels the one-way and two-way fairways are distinguished, while WTIVs with a deck cargo having the breadth $B^{nad} > B$ may proceed only along a one-way traffic lane. Some sections of fairways may also require that these ships proceed forward stern first.

The navigation subsystem for the ship position determination is described by a set of parameters:

$$\mathbf{N_{in}} = \begin{bmatrix} p_{in} \\ m_{in} \\ n_{in} \\ w_{in} \end{bmatrix} \quad (7)$$

where:
p_{in} – accuracy of n-th navigational system in i-th section of the waterway (directional error perpendicular to the fairway center line at a specific level of confidence),
m_{in} – availability of n-th navigational system in i-th section of the waterway (dependent on the time of day and visibility),
n_{in} – reliability of n-th navigational system in i-th section of the waterway (technical reliability),
w_{in} – reliability of n-th navigational system in i-th section of the waterway.

Systems of WTIV and WTTV position determination are autonomous systems, not related to waterway infrastructure. Their operation is based on satellite RTK or DGPS systems.

The port basin area subsystem is described by a set of parameters (Gucma, 2017):

$$\mathbf{A}_i^p = \begin{bmatrix} l_i \\ D_i \\ h_i \end{bmatrix} \quad (8)$$

where:
l_i – length of approach channel to i-th berth (m),
D_i – width of available navigable area within the approach channel to i-th berth (m),
h_i – minimum depth of approach channel to i-th berth (m).

WTIV and WTTV vessels have very good maneuverability, therefore the berth approach area also functions as a turning basin, and the width of the available navigable area is adopted as $D = 1.5\ L_C$. The depth at berth is determined by accounting for the port draft T_{port} of the WTTVs and the height of the jack-up leg base in WTIVs.

Results

The safety of navigation in port waterways is a basic restriction for the construction of harbors (terminals) to handle ships used for the construction of OWT and for increasing their size. Navigational risk is a criterion of navigational safety assessment that allows its accurate estimation in port waterways. The navigational risk of OWT construction vessels maneuvering in specific operational conditions, in a given area (i-th section of the waterway), can be represented by the function:

$$R_i = f(\boldsymbol{W}_i, \boldsymbol{A}_i, \boldsymbol{N}_i, I, Z) \quad (9)$$

where:
$\boldsymbol{W}_i$ – a set of conditions of safe operation of OWT construction vessels maneuvering in a given area (i-th section of the waterway),
$\boldsymbol{A}_i$ – subsystem of the area (i-th section of waterway),
$\boldsymbol{N}_i$ – navigational subsystem of a specific waterway,
I – parameters of the vessel traffic intensity in a given waterway,
Z – parameters of the vessel traffic control system in a given waterway.

Navigational risk is defined as the possibility of loss in a specific time interval, and it is expressed as the product of accident probability during a specific maneuver and losses resulting from the accident. In addition, the definition of risk has been supplemented with the frequency of executing the specific maneuver (where risk of a specific accident exists). Assuming that an accident and its consequences are independent events, navigational risk can be represented as the product (Gucma & Ślączka, 2019):

$$R_i = \sum_{q=1}^{m} P_{Aiq} I_{Ri} S_{iq} \quad (\text{year}^{-1}) \quad (10)$$

where:
P_{Aiq} – probability of q-th type of navigational accident occurrence in i-th section of the waterway,
I_{Ri} – annual frequency of performing a given maneuver in i-th section of the waterway,
S_{iq} – consequences of q-th type of accident in i-th section of the waterway.

When analyzing risks and types of accidents that may occur during maneuvering of a specific ship in restricted areas (sea waterways), we should distinguish two general causes of occurrence (Gucma et al., 2021):

1. crossing the available navigable area due to prevailing navigational conditions, accounting for the navigator's qualifications,
2. crossing the available navigable area due to technical failure of ship equipment: rudder, main engine, generator sets, or assisting tugs.

It should be noted that in marine traffic engineering, human errors during maneuvering in restricted areas (sea waterways) are considered only in the group of maneuvering errors (maneuvering inaccuracy) that result from the navigator's qualifications and the methods of ship position determination. Qualifications of the navigator, and navigational methods used, are accounted for in model tests (simulation experiments) and empirical tests (MTEC method) that determine the probability of accidents, when navigational conditions deteriorate and technical equipment failure occurs.

Technical characteristics of WTIVs (a number of simultaneously working generator sets) allow a neglect of the probability of technical failures that limit the maneuverability of these vessels during port maneuvers. Given the above, we should assume the following emergency scenarios for a jack-up vessel leaving the port without tugboat assistance.

1. striking a port structure:
   - crossing the available distance to the port structure by the deck cargo of the jack-up vessel in the approach channel.
2. striking a moored ship:
   - crossing the available distance to a berthed ship by the deck cargo of the jack-up ship during fairway passage.
3. collision with another vessel:
   - crossing the available distance to a fairway ship on the opposite course by deck cargo of the jack-up vessel.

An emergency scenario that includes collision with another ship on the fairway depends solely on the vessel traffic management system, which strictly limits two-way traffic on fairways for WTIVs carrying deck cargo. Therefore, the navigational risk of fairway passage of a loaded WTIV can be written as follows:

$$R_i = f(\boldsymbol{W}_i, \boldsymbol{A}_i, \boldsymbol{N}_i) \tag{11}$$

The largest navigational risk is created by a maximum jack-up ship leaving an offshore wind terminal. Such ships may carry on deck wind turbine blades up to 150 m in length (15 MW turbines), which are stowed athwartships, i.e. across the ship's center line. These blades may be regularly loaded on deck symmetrically or asymmetrically. In the former case, 110 m blades (for 14 MW turbines) will extend the ship's above water breadth to B_{nadw} = 110 m, where the blade ends will be x^{j}_{nadw} = 55 m from the ship's center line, on each side. In asymmetric stowage of blades, when B_{nadw} = 110 m, the distance of blade end to one side will be x^{j}_{nadw} as much as 80 m. It should be noted that the choice of side for the asymmetric stowage varies and depends on the phase of construction work at the offshore farm.

The probability of performing a smooth collision free maneuver by a given type and size of ship, in specific navigational and hydrometeorological conditions, managed by a navigator with specific qualifications, is:

$$P_{nj} = P\,(X_j \le D_{in}) \tag{12}$$

and expressed by the normal standardized distribution (Gucma, 2015):

$$P_{nj} = P\left(\frac{X_j - \bar{x}_j}{\delta_j} \le \frac{D_{nj} - \bar{x}_j}{\delta_j}\right) \tag{13}$$

where:

- X_j – maximum distance of ship's extreme point in j-th direction from the waterway center line (random variable),
- $\bar{x}_j, \delta_j$ – mean value and standard deviation of maximum distances of ship's extreme points in j-th direction from the fairway center line,
- D_{nj} – minimum distance from danger in j-th direction from the fairway center line.

The distribution parameters $\bar{x}_j, \delta_j$ are calculated from real-time simulations or empirical tests of a given maneuver, which are intended for the determination of the parameters for the safe maneuvering area.

The probability of accident occurrence in a year, caused by crossing the available navigable area by the "maximum ship" in i-th section of the port waterway, is determined by the following relationship (Gucma et al., 2021):

$$P_{wi} = P_{ai} \cdot I_r \cdot \Delta t_i / G_r \ \ (\text{year}^{-1}) \tag{14}$$

To calculate the accident probability, the maximum probability of moving outside the available navigable area is selected from a set of dangerous directions:

$$P_{ai} = \max_j P_{aij} \tag{15}$$

where:

- P_{wi} − probability of an accident in a year that is caused by moving outside the available navigable area by the tested ship in *i*-th waterway,
- P_{ai} − maximum probability that the safe maneuvering area of the tested ship travels beyond the available navigable area,
- I_r − mean annual intensity of tested ship's passages through *i*-th section of the fairway (year^{-1}),
- Δt_i − mean time of passage maneuver through *i*-th fairway section by the tested ship (h),
- G_r − hours per year (8760 h).

Navigational risk is often identified with the annual probability of occurrence of a given accident type for specific consequences (determinant of consequences) (Gucma, 2009).

In port waterways, accidents where fatal casualties may occur are only those where a ship passing through the fairway hits a moored ferry or another passenger ship. If any of the accident scenarios assumes loss of life, it should be considered separately before making an economic risk analysis that refers to the ship's passage through the examined waterway system. The risk of an accident where human life is at stake is determined through the following relationship:

$$R_s = P_A \cdot P_{sp} \tag{16}$$

where:

- R_s – risk of an accident resulting in loss of life,
- P_A – probability of an accident where human life is threatened,
- P_{sp} – probability of death as a result of a specific accident.

The condition of accepting an accident that results in loss of life fulfills the relationship:

$$R_s \leq R_{s\,akc} \tag{17}$$

where:

- $R_{s\,akc}$ – acceptable risk of a fatal accident.

The developed navigational risk analysis method for OWT vessels was used in the design of a Świnoujście-based terminal, which is intended for handling offshore wind farm ships (Figure 7) (Gucma & Gralak, 2021). The referred work includes the determination of the navigational risk of a loaded "maximum jack-up ship" passage with 110 m wind turbines, along the Szczecin–Świnoujście fairway, from the turning area Obrotnica Mielińska to the port exit. The highest navigational risk of this maneuver occurs while passing the Świnoujście Ferry Terminal, where the minimum distance from the fairway center line to a moored ferry, L_C = 230 m, at the modernized berth No. 2 is D_n = 100 m (Figure 7).

The planned number of departures of a loaded jack-up vessel from Świnoujście is I_r = 21 (Gucma,

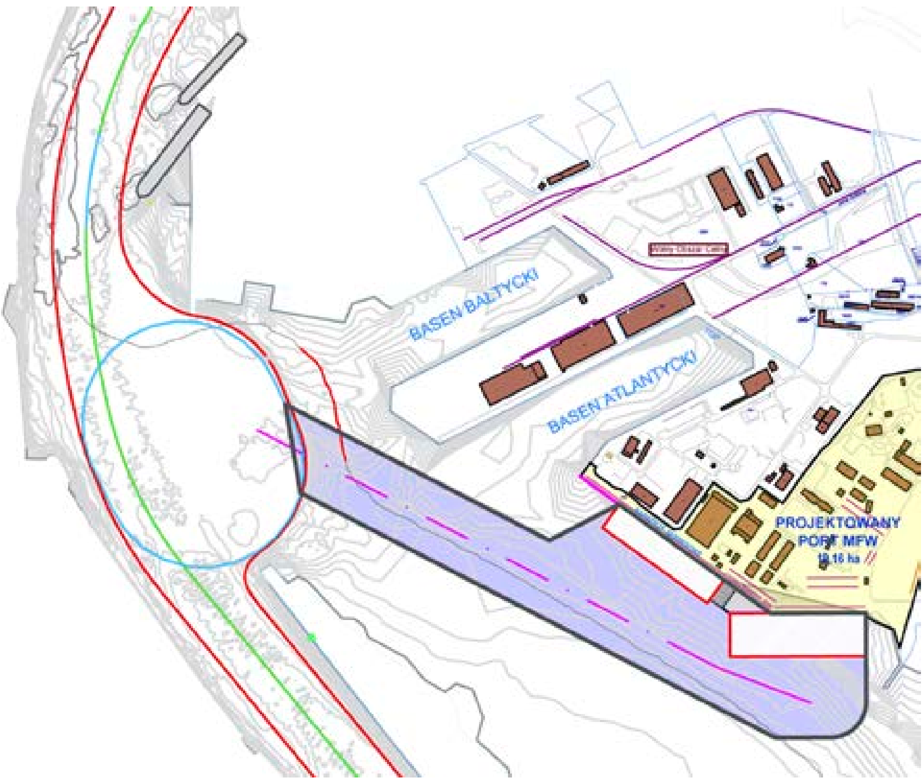


Figure 7. Designed offshore wind farms handling terminal in Świnoujście

2021). Accounting for the occupancy rate of berth No. 2, which concerns ferries, the annual probability of impact by an outgoing jack-up ship on a ferry, $L_C = 230$ m, is:

$$P_a = 6.7 \cdot 10^{-7} \text{ (year}^{-1}\text{)}$$

Considering the consequences of such an accident and accounting for the time of passenger embarkation, the risk of passenger death is (Gucma, 2021):

$$R_{sp} = 3.3 \cdot 10^{-7} \text{ (year}^{-1}\text{)}$$

This risk is lower than the risk of acceptable deaths of a group of passengers, $R_{akc} = 1 \cdot 10^{-6}$ year^{-1} (Gucma, 2009). Thus, the condition of navigational safety is fulfilled, i.e.:

$$R_{sp} < R_{akc}$$

Discussion

The developed methods were verified by its application on the example of the newly designed OWT installation port in Świnoujście. Obtained results were considered reliable by experts, maritime pilots, and port authorities, which provides a basis for its practical use in designing further waterways of this type in maritime areas of ports in our country. The presented methods require verification, e.g. with non-autonomous simulation methods. For this purpose, it is planned to conduct research with the participation of captains of jack-up vessels on the navigational-maneuvering FMBS.

Conclusions

This article indicates the development of trends in the construction of offshore wind turbines worldwide, and the characteristics of existing and planned ships for wind turbine installation and maintenance. A method has been developed for dimensioning port waterways for ships that serve offshore sea wind turbine transport and construction. The authors have determined the conditions for the safe operation of these ships in restricted areas and defined the basic condition of navigational safety. The presented method of navigational risk analysis refers to the departure of a loaded ship that carries offshore wind turbine components in the presently designed port terminal in Świnoujście, which handles offshore wind farm projects. These are universal methods that can be applied to the design of ports serving vessels that install offshore wind turbines in various types of waters.

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