O&M strategies for offshore renewable energy projects in Chile: a comparative analysis

Gonzalo Tampier, Natalia Aziares, Cristian Cifuentes, and Katherine Álvarez

Abstract—**Operation and maintenance (O&M) are fundamental aspects to study in offshore renewable energy (ORE) projects, due to high economic costs, operational difficulties involved and the immaturity of its development in emerging markets. In this study, a geo-referenced, time-domain discrete event simulation tool is presented, designed to evaluate the life cycle of ORE projects, evaluating different sites, technologies and O&M strategies at an early stage, to support decision-making of project developers and government entities. Using environmental (behind cast) and operational parameters (e.g. port closure criteria), the performance of devices at a site is evaluated, generating information about the energy production and downtime of devices and their effect on total energy production. Considering that maintenance is subject to environmental and operational limits for operations such as cargo handling or crew transfer, the current tool integrates the operational characteristics of both the device and the involved vessels, which are obtained from numerical simulations or model scale experiments. As an application example, a comparison of the effect of selecting monohull- or SWATH-type SOVs (service operations vessels) on a floating wind energy pilot project located in central Chile are presented.**

Keywords—**Discrete event-simulation, Offshore operations, Operational limits, Operations and Maintenance, Site accessibility**

I. Introduction

Operation and maintenance (O&M) represents a critical area of focus in offshore renewable energy (ORE) projects due to substantial economic implications and the inherent challenges posed by harsh marine environments, which can hinder maintenance activities. According to reference [1], O&M costs constitute more than 20% of the total costs in offshore wind projects, and as indicated by [2], this figure may rise to 31% for floating wind farms.

Chile is recognized as one of the countries with immense potential for offshore renewable energy (ORE) development, particularly in wave energy, tidal energy, and offshore floating wind power. These three types of energy generation exhibit distinct characteristics and varying levels of technological maturity, requiring concerted efforts in industrial innovation, research, and development to address scientific and technological challenges.

An important challenge to be solved in Chile is related to the accessibility to the farms, conditioned by operational wave conditions which are significantly higher than those found in the sites where offshore wind activity has already been developed, such as the North Sea [4]. An example of this is shown in Fig. 1, in which the occurrence of significant wave heights under certain limits is shown for locations off the coast of southern-central Chile (36.6°S, 73.4°W) and the North Sea (56.0°N, 3.0°E). As can be seen, the operational conditions are very different. For example, the probability of significant heights below 1.5 m does not exceed 18% in the selected Chilean location, while in the North Sea this probability can be as high as 78% in the month of July. This aspect is especially challenging for maintenance, increasing waiting times to access and therefore increasing downtimes, lowering energy generation, and reducing profits.

Part of a special issue for ICOE 2024. Manuscript submitted 17 March 2025; Accepted 2 May 2025. Published 9 September 2025.

This work was supported in part by MERIC (Chile) under CORFO grant 14CEI2-28228, ANID grant EQM170065 and Blue Economy CRC Project 2.20.003.

G. Tampier (gonzalo.tampier@uach.cl) and C. Cifuentes (cristiancifuentes@uach.cl) are with Institute of Naval Architecture and Ocean Engineering at Universidad Austral de Chile, Campus Miraflores, Valdivia, Chile.

N. Aziares (natalia.aziares@meric.cl) is with Marine Energy Research and Innovation Center (MERIC). J. Escriva de Balaguer 13105, Santiago, Chile.

K. Alvarez (k.v.alvarez@tudelft.nl) is with Dept. of Maritime and Transport Technology at TU Delft, Leeghwaterstraat 17, 2628 Delft, Netherlands.

Digital Object Identifier: https://doi.org/10.36688/imej.8.271-278

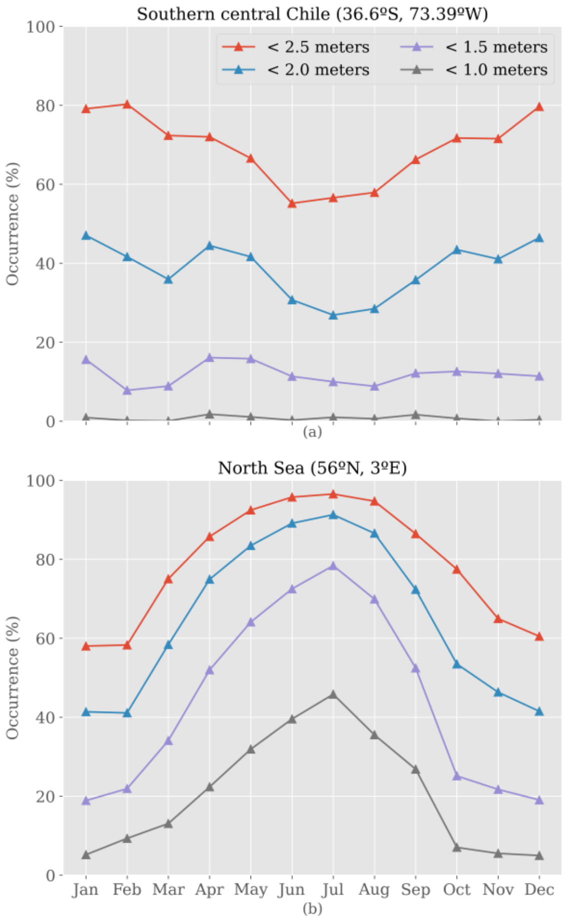

Fig. 1. a) Operational wave conditions in central Chile (36.6°S, 73.4°W) and b) North Sea (56.0°N, 3.0°E). Percentage of time with significant wave heights below 1.0 m (black), 1.5 m (violet), 2.0 m (blue) and 2.5 m (orange).

To accelerate the implementation of ORE in Chile, it is necessary to analyse different scenarios and local capabilities, proposing innovative technical solutions, identifying risks, and thus increasing economic competitiveness.

To support strategic decisions through the calculation of key performance indicators and life-cycle cost analysis of an ORE project, a discrete-event simulation (DES) model is being developed. This tool, called Adapt-ORE, allows us to compare different sites, technologies, vessels, and maintenance strategies, identifying risks and opportunities in our country and Latin America.

Several models related to O&M have been developed in recent years. For example, an extensive review of O&M models, mainly focused on fixed-bottom wind, are shown in [5]. However, the challenges involved in the maintenance of floating structures require adapted strategies and specific adjustments on O&M [6]. This issue has been addressed in earlier works such as [2], [7], [8] and [9].

The differentiating factor of Adapt-ORE is that it considers vessel response-based operational criteria. This means, to know the response of vessels (e.g., motion amplitudes and accelerations) at different sea states and to define thresholds that ensure the completion of tasks safely and reliably.

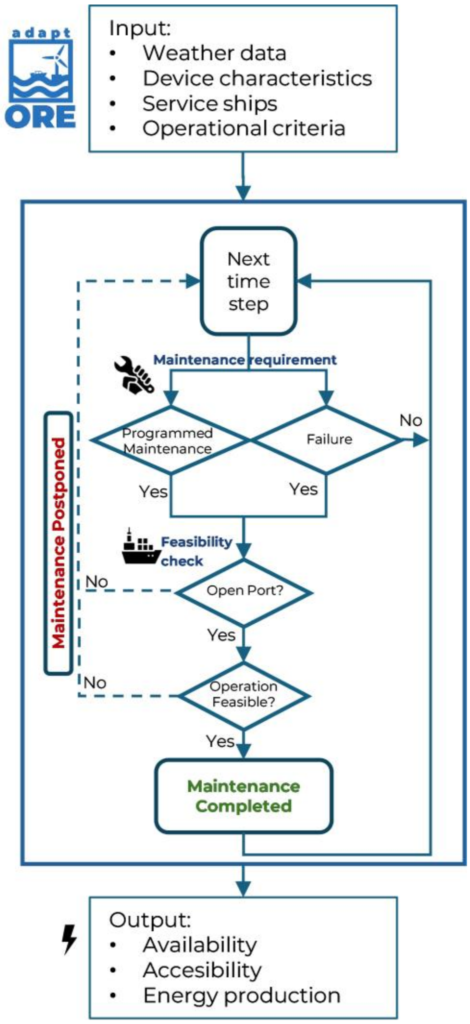

Fig. 2. Flowchart of discrete event simulations.

This methodology has been used in the maritime industry during the design stage of a vessel to evaluate its operability, and it is possible to find studies where it is applied in a DES (discrete-event simulation) model for marine operations [10] and fish farming [11].

This paper presents the first results to date, with focus on the operational stage of an ORE project in Chile using two different SOVs.

The aim of this work is to show the impact of accessibility on the overall energy generation. For this, a fictional case is created using two different maintenance vessel concepts for a floating wind farm located in central Chile. Specifically, two Special Operations Vessel (SOV) types will be compared, a SWATH and a monohull.

II. Methodology

A. *Adapt-ORE tool*

Adapt-ORE utilizes multiple input data to obtain performance indicators. These include site and port metocean data, device power performance, vessel operational thresholds, and schedules for corrective and preventive maintenance, alongside environmental criteria determining port closure and operability limits [12].

The feasibility of maintenance activities, specifically the occurrence of suitable weather windows, is assessed using the DES model to minimize downtime costs. Fig.2 illustrates the method's flowchart. When maintenance is required (either corrective or preventive), the operational cycle begins by evaluating the feasibility of vessel departures. This involves checking if environmental conditions at the port exceed permissible limits for departure. To prevent premature departures where operations might be hindered by adverse weather, forecasts of site-specific environmental conditions are also consulted.

If weather conditions surpass predefined thresholds, the vessel remains in port, and maintenance is postponed until favourable weather conditions return. Conversely, if conditions are suitable, the vessel departs and travels to the site to execute the necessary tasks.

Upon reaching the site, the feasibility of performing operations is further assessed (detailed in the subsequent section). If operational limits are exceeded, the vessel returns to port, and maintenance is rescheduled, initiating a new cycle. When conditions are favourable, the operation proceeds as planned.

B. *Feasibility of operation*

Maintenance can proceed if the wind speed remains below a user-defined threshold (typically 20 m/s) and the vessel's operational limits are not exceeded. These limits are specific to each vessel and its intended activities, influenced by hydrodynamic characteristics and environmental conditions.

To characterize each vessel´s seakeeping, Response Amplitude Operators (RAOs) are determined either numerically, using a BEM (boundary element method) panel code or experimentally on a wave tank, considering six degree of freedom responses. From the multiplication of the squared RAOs and a particular wave spectrum, the *motion response spectrum* of a vessel can be obtained, along with *derived responses* such as deck wetness, slamming probability, among others.

For specific operations like crew transfers (e.g. by walk-to-work, i.e. W2W platforms) or deck work, acceptable criteria for motions, accelerations or derived responses are crucial for safe and efficient operations. Despite the importance of this aspect, there is a lack of standardized seakeeping criteria for offshore operations [13]. Existing criteria such as NATO STANAG 4154 [14] or NORDFORSK [15] are widely used, but these only include ship- and crew-related aspects such as maximum accelerations, motion sickness incidence (MSI), motion-induced interruptions (MII), among others. For crew- or cargo-transfer operations between a crew transfer vessel (CTV) or service operation vessel (SOV) to an offshore wind platform, no established standard criteria exist [13]. For preliminary simulations within the development of

Fig. 3. Location of fictional installation site near Santa María Island and San Vicente reference port.

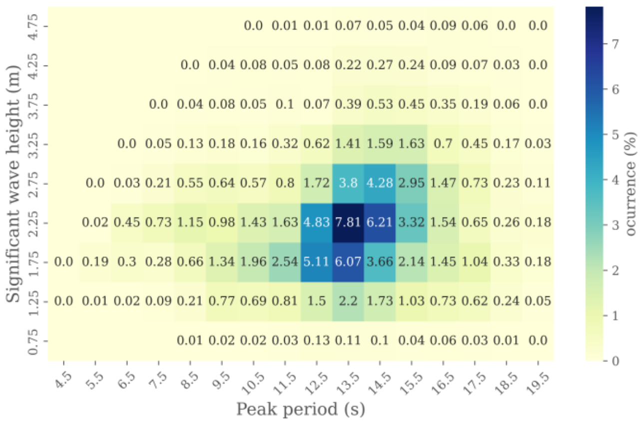

Fig. 4. Bi-variate wave scatter diagram at selected site.

our DES-tool, we used selected NORDFORSK criteria (i.e. light or heavy work). From these criteria, operational limit curves were obtained, to determine the maximum allowable wave height as a function of wave period [12][16]. In [17], a set of criteria were defined for the specific case of crew transfer using W2W systems, which include angles, relative distances and velocities, and will be used in the present study.

III. Case Study

C. *Site conditions*

A fictional floating wind project was defined at the westside of Santa María Island (37.05°S - 73.52°W) in central Chile (Fig. 3). This location is exposed to swell, with a typical wave period of 13 s and mean significant wave height of 2.2 m. A bi-variate wave scatter diagram of the site is shown in Fig. 4.

The study considers a pilot project with a single generic wind turbine with a hub height of 90 m and a rated power of 5 MW at a nominal wind speed of 10.4 m/s [18].

Wind data were extracted from ECMWF ERA5 reanalysis dataset [19] and wave data are from Waverys dataset by the Copernicus program [20]. A period of 5 years was analysed (2017-2021) with hourly resolution. The chosen port (San Vicente, 36.7°S, 73.1°W) is located ~50 km north from the site. Wind data at port location

TABLE I
MAIN DIMENSIONS OF SWATH AND MONOHULL SOVS

	SWATH	Monohull	Unit
Length (overall)	61	66	m
Breadth	26.5	15	m
Demi-hull breadth	8	-	m
Design Draught	7.5	5.3	m
Displacement	3660	4010	t

were extracted from a nearby weather station at Carriel Sur Airport [21].

A wind speed of 9 m/s was used as the environmental limit for departure, and it was determined by port closure statistics obtained from DIRECTEMAR [22].

The O&M in this study considers preventive and corrective maintenance. The quantity and duration were chosen according to the conclusions and considerations addressed in [23] and [24]. Because this study aims to compare routine maintenance, replacement of major components that require e.g. the use of crane vessels were left out of this study.

Thus, the evaluated scenario considers a total of 42 maintenances over the 5-year simulation: 1.4 annual preventive maintenances with a duration between 8 and 48 hours each, and 6.8 annual minor corrective maintenances with durations between 7 and 18 hours, as in [24].

Corrective maintenance is performed due to failures i.e., it implies downtimes from the moment the failure starts until the maintenance ends. On the contrary, preventive maintenance only implies downtimes during the duration of the maintenance.

D. SWATH vs. monohull SOV's

For this case study, two SOVs will be compared, a SWATH and a monohull, which have been described and analysed in [24]. The characteristics of these vessels are presented in Table 1, which shows that they are similar in length and displacement.

For this study, a W2W system has been considered which, depending on its characteristics and installation location, conditions the operational criteria shown in Table 2. This configuration has been used in a similar way in [25] and [26].

From these operational criteria and the motion response spectra, the operational limit curves shown in Fig. 5 are obtained. It can be observed that, for peak wave periods below 8s, the performance of the SWATH vessel is better than the monohull, whereas the contrary occurs for longer wave periods. Due to the preliminary nature of this study, only curves for head seas and a gangway angle of 90° were used, considering that it is expected, by design, that the platform access points will have an orientation that allows this configuration for the most prevailing wind and sea conditions (SSW).

TABLE II
OPERATIONAL CRITERIA AND LIMITS FOR W2W OPERATION [15]

Item	Limiting value	Unit
Roll angle	±10.0	°
x-displacement	±3.2	m
y-displacement	±3.2	m
z-displacement	±4.0	m
x-velocity	±2.0	m/s
y-velocity	±1.2	m/s
z-velocity	±3.2	m/s

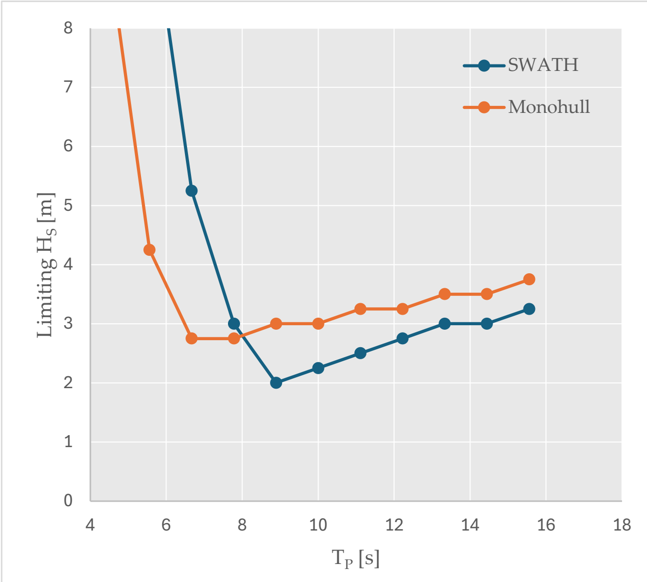

Fig. 5. Operational curves of SWATH and Monohull (from [22]).

IV. RESULTS

Table III presents the mean time between weather windows of various durations (rows) during which the significant wave height remains below a specified limit (columns). These values indicate how frequently such favourable conditions occur, emphasizing the importance of selecting optimal maintenance strategies to account for weather-related constraints.

In Table IV, the results of the performance of the generic turbine are shown when using the SWATH or monohull vessel for maintenance. It can be observed that the average annual energy production using a SWATH for maintenance is 21.33 GWh, whereas an average of 21.51 GWh can be generated when using a monohull.

As for the lost energy, that is, the energy that was not generated due to downtimes, an average of 0.54 GWh per year is obtained for the SWATH case, and 0.37 GWh per year for the monohull.

Reviewing the performance of the vessels to carry out the scheduled maintenance, it can be observed that the SWATH had a port waiting time of 602 hours per year, which is equivalent to an average of 73.4 hours of waiting for each maintenance. On the other hand, the monohull totalled only 215 hours per year, which is equivalent to an average of 26.2 waiting hours per maintenance. These waiting times caused the turbine to be out of operation for 202 hours per year when using the SWATH, and 136 hours when using the monohull.

TABLE III
MEAN TIME BETWEEN WEATHER WINDOWS

Window length	Limiting significant wave height 1.0 m	1.5 m	2.0 m	2.5 m
6h	2298 h	233 h	77.3 h	41.5 h
12 h	3647 h	308 h	98.1 h	51.4 h
24 h	21909 h	562 h	147.8 h	73.3 h
48 h	43822 h	1669 h	320.1 h	133.6 h

TABLE IV
SIMULATION RESULTS FOR GENERIC WIND TURBINE USING SWATH OR MONOHULL CTV FOR MAINTENANCE

	SWATH	Monohull	Unit
Mean produced power	2.43	2.45	MW
Annual energy production	21.33	21.51	GWh
Annual energy loss	0.54	0.37	GWh
Plant factor	48.68	49.08	%
Downtime	202	139	h/year
Port waiting time	602	215	h/year

Fig. 6. Visualisation example of discrete event simulations results, for a selected period (Sept. to Dec. 2017).

Fig. 6 shows the obtained results for a selected period within the total series. In panel a) the wind speed is depicted, which regularly exceeds the nominal speed of the turbine (10.4 m/s), which is consistent with panel d), which shows the power generated by the turbine. The significant wave height and peak period at the site are shown in panels b) and c), respectively. Along with the significant wave height in panel b), limiting wave heights for each vessel given by their operational curves are shown. The limiting wave height for the monohull is consistently higher than the limiting wave height of the SWATH, which is also reflected in the operational curves for longer wave periods, shown in Fig. 5. Panels e) and f) are related to the performed maintenance, showing in the upper panel (e) the operation and downtime, related to maintenance. In panel f), the waiting time and actual maintenance time associated with these downtimes are shown.

If the maintenance was corrective, i.e. associated with a failure, the turbine was not operating from the time of the turbine failure until the maintenance is completed. On the contrary, in a preventive maintenance, the downtime hours correspond only to maintenance hours. As shown in the figure, the downtime is higher when using the SWATH, since waiting times for maintenance increased when compared to the monohull vessel.

Although the obtained results show that the differences between both vessels are small, the results for a larger farm could be significant. For example, for a farm with 100 turbines, the farm would generate 18 GWh more per year, just by the decision of using monohulls instead of SWATH vessels.

V. Conclusions and Future Work

The developed tool allows the analysis of different aspects including vessel types, different operational criteria, site/ port locations, or the interdependence between any of these aspects for offshore renewable energy projects, including wave, tidal and floating wind.

In this case, the effect of the usage of two different SOVs showed that, although with a small difference, the use of a conventional monohull may be a better strategy than using a SWATH in the selected site, which is characterised by long wave periods. This is contrary to the conclusions of other studies (e.g. [22]), which analyse sites with shorter wave periods. In our specific case, the use of a monohull may have additional advantages such as a lower acquisition price and operational costs.

Currently, our staff is conducting tank tests with scaled models of a SWATH and a monohull, evaluating their interaction with a generic floating wind turbine, which will allow us to analyse other relevant strategies and criteria, in particular for smaller CTVs using simpler transfer strategies without W2W technologies, which may be suitable for our local conditions and can find added applicability for smaller devices such as wave energy converters or multi-use structures (e.g. for the integration of energy and aquaculture production).

REFERENCES

[1] C. J. Crabtree, D. Zappalá, and S. I. Hogg, “Wind energy: UK experiences and offshore operational challenges,” *Proc. Inst. Mech. Eng. Part J. Power Energy*, vol. 229, no. 7, pp. 727–746, 2015, DOI: 10.1177/0957650915597560, [Online].

[2] L. Castro-Santos and V. Diaz-Casas, “Life-cycle cost analysis of floating offshore wind farms,” *Renew. Energy*, vol. 66, pp. 41–48, 2014, DOI: 10.1016/j.renene.2013.12.002, [Online].

[3] M. Shadman et al., “A Review of Offshore Renewable Energy in South America: Current Status and Future Perspectives”, *Sustainability*, vol. 15, 2023, DOI:10.3390/su15021740 [Online].

[4] G. Tampier, C. Cifuentes, N. Aziares, R. Cárdenas and K. Álvarez, “Offshore Wind Technologies for Chile: Perspectives and Challenges” MERIC Technical Report, 2024. Available: https://meric.cl/repositorio/

[5] M. I. H. Tusar and B. R. Sarker, “Maintenance cost minimization models for offshore wind farms: A systematic and critical review,” *Int. J. Energy Res.*, vol. 46, no. 4, pp. 3739–3765, 2022, DOI: 10.1002/er.7425, [Online].

[6] K. Saeed, J. McMorland, M. Collu, A. Coraddu, J. Carroll, and D. McMillan, “Adaptations of offshore wind operation and maintenance models for floating wind,” *J. Phys. Conf. Ser.*, vol. 2362, no. 1, p. 012036, 2022, DOI: 10.1088/1742-6596/2362/1/012036, [Online].

[7] G. Rinaldi, P. R. Thies, and L. Johanning, “Improvements in the O&M modelling of floating offshore wind farms,” in *Developments in Renewable Energies Offshore*, 1st ed., CRC Press, 2020, pp. 481–487. DOI: 10.1201/9781003134572-54, [Online].

[8] N. Avanessova, A. Gray, I. Lazakis, R. C. Thomson, and G. Rinaldi, “Analysing the effectiveness of different offshore maintenance base options for floating wind farms,” *Wind Energy Sci.*, vol. 7, no. 2, pp. 887–901, 2022, DOI: 10.5194/wes-7-887-2022, [Online].

[9] A. Dewan, and M. Asgarpour, “Reference O&M concepts for near and far offshore wind farms” ECN E-16-055 Report, 2016. Available: https://projecten.topsectorenergie.nl/storage/app/uploads/public/5d3/ff0/cc1/5d3ff0cc19673456604507.pdf

[10] E. Sandvik, M. Gutsch, and B. E. Asbjørnslett, “A simulation-based ship design methodology for evaluating susceptibility to weather-induced delays during marine operations,” *Ship Technol. Res.*, vol. 65, no. 3, pp. 137–152, 2018, DOI: 10.1080/09377255.2018.1473236, , [Online].

[11] E. L. Nørgaard, “Defining and evaluating long-term operability of service vessels in exposed aquaculture,” M.Sc. thesis, Dept. Marine Technology, NTNU, Trondheim, NOR, 2019, [Online].

[12] N. Aziares, G. Tampier, R. Cárdenas, N. Jara, J.M. Ahumada and C. Cifuentes, “Adapt-ORE: A Simulation Tool for Adaptive Operation and Maintenance of Offshore Renewable Energy Farms”, in *3rd Pan-American Marine Energy Conference*, Barranquilla, Colombia, 2024.

[13] M. Zu, K. Garme, A. Rosén, “Seakeeping criteria revisited”, *Ocean Engineering*, vol. 297, 2024, DOI: 10.1016/j.oceaneng.2024.116785, [Online].

[14] NATO, STANAG 4154 Edition 3, 2000

[15] NORDFORSK, Assessment of ship performance in a seaway. Copenhage, Denmark, 1987.

[16] N. Jara, “Numerical derivation of operational limits using open source BEM-solver NEMOH”, “Obtención numérica de límites operacionales mediante uso del open source BEM-solver NEMOH,” Dipl. thesis, Inst. of Naval Arch. And Oc. Engineering, UACh, Valdivia, Chile, 2023.

[17] M. Wu, “Numerical analysis of docking operation between service vessels and offshore wind turbines”, *Ocean Engineering,* vol. 91, pp. 379-388, 2014. DOI: 10.1016/j.oceaneng.2014.09.027 [Online].

[18] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. 2009. Definition of a 5-MW Reference Wind Turbine for Offshore System Development. NREL/TP-500-38060. Available: https://www.nrel.gov/docs/fy09osti/38060.pdf.

[19] Hersbach, H. et al., “Complete ERA5 from 1940: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service (C3S) Data Store (CDS)”, 2017. DOI (product): 10.24381/cds.143582cf

[20] COPERNICUS Global Ocean Waves Reanalysis, 2024. [Online]. DOI (product): 10.48670/moi-00022

[21] Dirección Meteorológica de Chile, 2023. [Online]. Available: https://www.meteochile.gob.cl/PortalDMC-web/

[22] Sistema de Visualización de Instalaciones Portuarias - DIRECTEMAR website, 2023. [Online]. Available: https://svip.directemar.cl/

[23] A. Myhr, C. Bjerkseter, A. Ågotnes and T. A. Nygaard, “Levelised cost of energy for offshore floating wind turbines in a life cycle perspective”, *Renewable Energy*, vol. 66, pp. 714-728, 2014

[24] J. Carroll, A. McDonald, and D. McMillan, “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines”. Wind Energ., vol. 19, pp. 1107–1119, 2016. DOI: 10.1002/we.1887 [Online].

[25] B. Li, D. Qiao, W. Zhao, Z. Hu and S. Li, “Operability analysis of SWATH as a service vessel for offshore wind turbine in the southeastern coast of China”, *Ocean Engineering,* vol. 251, 2022. DOI: 10.1016/j.oceaneng.2022.111017. [Online]

[26] R. Guanche, M. Martini, A. Jurado and I. J. Losada, "Walk-to-work accessibility assessment for floating offshore wind turbines", *Ocean Engineering*, vol. 116, 2016. DOI: 10.1016/j.oceaneng.2016.03.013 [Online]