Methodology for assessment of the operational limits and operability of marine operations

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Abstract

This paper deals with a general methodology for assessment of the operational limits and the operability of marine operations during the planning phase with emphasis on offshore wind turbine (OWT) installation activities. A systematic approach based on operational procedures and numerical analyses is used to identify critical events and corresponding response parameters. Identifying them is important for taking mitigation actions by modifying the equipment and procedures. In the proposed methodology, the operational limits are established in terms of allowable limits of sea states. In addition, the operational limits of a complete marine operation is determined by taking into account several activities, their duration, continuity, and sequential execution. This methodology is demonstrated in a case study dealing with installation of an offshore wind turbine monopile (MP) and a transition piece (TP). The developed methodology is generic and applicable to any marine operation for which operational limits need to be established and used on-board as a basis for decision-making towards safe execution of operations.

Keywords: *operational limits, marine operations, offshore installation, limiting parameters, allowable sea states, weather windows, operability*

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1 Introduction

Marine operations is "a generic term covering, but not limited to the following activities which are subjected to the hazards of the marine environment: Load-out / load-in, transportation / towage, lift / lowering, tow-out / tow-in, float-over / float-off, jacket launch / jacket upend, pipeline installation, construction afloat" (GL Noble Denton, 2015). This study deals with analysis of marine operations, and the required terms and definitions are provided in the appendix. These terms are shown in italics when introduced for the first time in this paper.

Marine operations are executed following a systematic *operational procedure*, which is normally developed in the planning phase based on information about the equipment, offshore site, etc. A marine operation consists of many activities or sub-operations. During planning of the offshore activities, risk management of *critical events* that can lead to failures is required (Det Norske Veritas, 2011). It involves the identification of hazardous events and the corresponding response parameters and critical activities as well as the quantification of associated risks, and suggestions for mitigation actions. Thus, as part of the risk management, it is necessary to avoid the occurrence of critical events by establishing limits to the response parameters below which the operations can be executed in a safe manner.

Consider the installation of a topside module using an offshore crane vessel. Based on an installation procedure, qualitative risk analysis can be conducted to identify hazardous events and critical operations. Figure 1 shows a critical offshore activity, for instance, the lift-off of a topside module from a cargo barge. A critical event is then the structural failure of a lifting wire. This event can be avoided if the total tension in the wire rope is kept below its minimum breaking load (including a safety factor that accounts for uncertainties). The tension in the wire rope can be assessed from numerical analyses. The sea states leading to a wire tension lower than the limit are the *allowable sea states* of the operation, which are the main focus of this paper.

The response parameter that describes the critical event and limits the execution of an activity, for instance the wire tension, is suitable to assess the magnitude of the loads when carrying out numerical analyses of the lift-off activity during the planning phase. This parameter (tension) can also be monitored "during" the execution of an operation, and thus, it is suitable for taking mitigation actions; however, it cannot be used as a criterion to make a decision on whether to start or not the lifting operation. This is because the decision needs to be made before the activities are executed, where there is no tension to be measured.

Thus, there is a loading condition (LC) that corresponds to the *monitoring phase prior to execution* of the operations, which is useful for making decisions on whether to start or not an operation. The decision is based on vessel responses, information from wave forecasts, and *operational limits* given in the operational procedure. The operational limits are compared with the sea state parameters or measurable vessel responses and the decision is made. In particular, Det Norske Veritas (2014a) states that operational criteria such as wind speed, wave conditions, and relative motions need to be provided for the monitoring phase, and should be included in the operation manual. Therefore, the operational limits should include both, *allowable limits* of sea states and allowable limits of responses of the vessels in monitoring phases prior to execution. Note that in general the environmental parameters that need to be considered will depend on the type of operation. For instance, wind speed is important for OWT blades installation, and wind and current speed are important for towing activities.

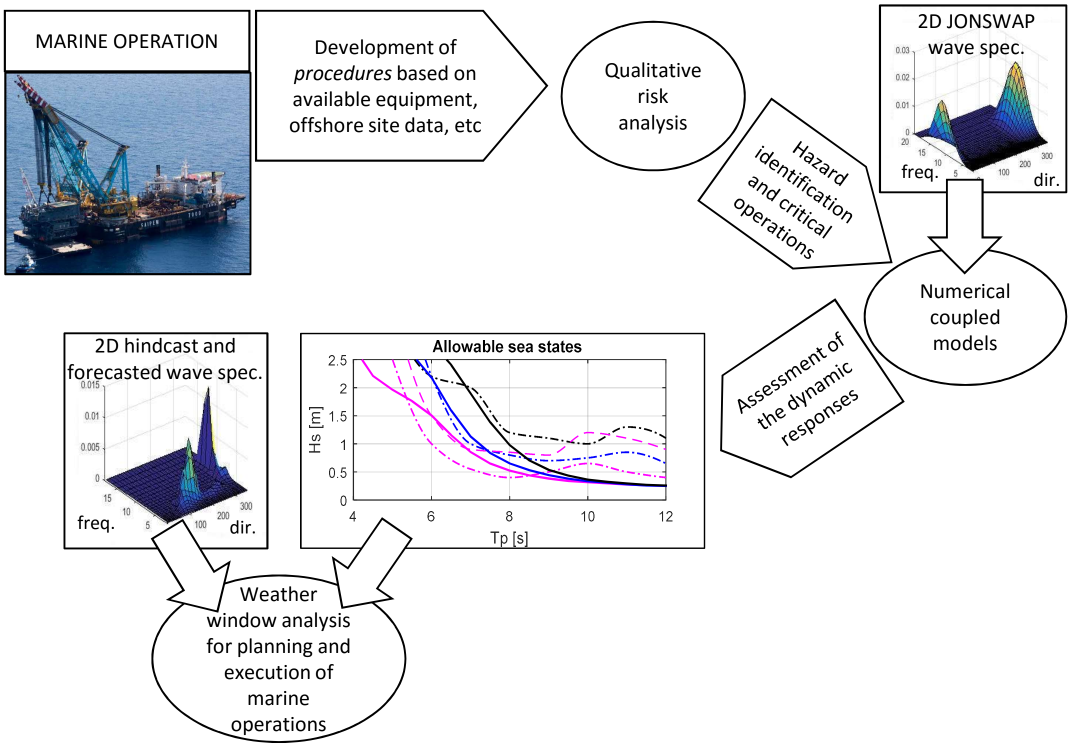


Figure 1: Overview of a general procedure for assessment of response-based operational limits and weather window analysis of marine operations

To date, limited work has been carried out to identify critical events and establish operational limits based on structural responses, and no systematic *methodology* seems to have been published. The current practice is to set these limits in terms of allowable sea states and *allowable responses* of the vessel in the monitoring phases prior to execution based on industry experience, so the origin of these limits is not clear. Moreover, only critical phases of marine operations are studied, e.g., by carrying out model tests under “specific” sea states. This paper aims at identifying critical events and establishing response-based operational limits (in terms of sea state parameters) for marine operations, see Fig. 1. Based on the operational limits, environmental data, and assessment of various sources of uncertainties, reliability analysis of marine operations can be conducted; however, this topic is out of the scope of this paper.

A literature review on operational limits of various marine operations is provided below. Det Norske Veritas (2011), International Organization for Standardization (2015) and GL Noble Denton (2015) provide recommendations on the operational criteria for planning and execution of marine operations. Parameters such as significant wave height (Hs), wind and current speed, and others that may affect the system responses are recommended to be included. For weather-restricted operations, i.e. with duration less than 72 hours, a design limit of the Hs parameter is normally considered. This parameter is reduced by alpha factors that account for uncertainties in the weather forecast methods and the reference period (duration) T_R of the activities. A study on derivation of alpha factors was carried out by Wilcken (2012). The alpha factor decreases with increasing T_R and increases with increasing Hs or when more reliable forecast methods are used. For instance, measurements using wave buoys or the presence of a meteorologist on site will increase the confidence of weather forecasting, so the alpha factors increase. As shown above, the design criteria for planning and execution of marine operations are mainly expressed in terms of Hs while the wave spectrum peak period (Tp) is not considered. Since floating units are highly sensitive to Tp, this parameter needs to be included. Moreover, the required terminology for analysis of marine operations is incomplete in the available literature.

Clauss and Riekert (1990a,b) presented a summary of operational limits in terms floating crane vessel motion responses. These limits were given based on experience from projects executed in the North Sea. Some of these vessel motion criteria were also expressed in terms of sea state parameters. Likewise, Smith et al. (1996) provided the operational limits in terms of allowable impact velocities for a jack-up vessel during the standard leg lowering procedure. The limits were derived from structural damage criteria based on structural analyses of leg members. Similarly, Clauss et al. (1998) proposed a methodology for assessment of the allowable sea states during offshore pipelaying based on maximum permissible stresses on the pipe. The methodology accounts for stresses from wave and vessel motions. In addition, Cozijn et al. (2008) assessed the operational limits for installing a module using a floating crane semi-submersible platform onto a floating vessel. The limits were derived based on numerical analysis, model tests, and offshore site measurements. Moreover, Graczyk and Sandvik (2012) established the allowable sea states for the lift-off and landing of an offshore wind turbine component on the deck of a ship. The dynamic response of the lifted object was estimated based on formulations given by Det Norske Veritas (2014b), and the allowable acceleration on the lifted object was simply assumed.

An approach to derive the operational limits in terms of Hs and Tp for a drilling jack-up unit during the deployment and retrieval of its legs was given by Matter et al. (2005). The allowable stresses in the spud cans, legs, and pinions were established based on structural analyses. These allowable stresses were expressed in terms of allowable vessel motions. By using the response amplitude operators (RAOs) in a free floating condition, these motions were expressed in terms of allowable sea states. Similarly, Ringsberg et al. (2015) presented the allowable sea states for a jack-up vessel during deployment of its legs. The sea states were identified by comparing the allowable forces on the spud can, which were derived from finite element modeling (FEM), with the characteristic values of the impact forces, which were computed from a coupled spud can and soil interaction model.

The literature cited above shows that the operational limits for marine operations have been assessed considering different approaches, which vary and are not clearly indicated. Moreover, the operational limits have to be assessed for potential critical activities where critical events can occur if the operational limits are exceeded.

In relation to identification of critical marine operation activities, failure events, and *limiting (response) parameters*, limited work has been done. Guachamin Acero et al. (2016) identified the critical events and limiting parameters for installation of an offshore wind turbine TP. This was done by conducting numerical simulations of the installation activities and assessing the magnitude of dynamic responses. Similarly, Li et al. (2016b) identified the limiting parameters for monopile hammering at shallow penetrations by assessing the dynamic responses in typical installation sea states. The approach adopted in these papers is systematic and suitable for analyzing any type of marine operation; however, the procedure was not explicitly given.

On the other hand, accurate or efficient *numerical methods* and numerical modeling methodologies are required for assessment of characteristic values of dynamic responses, which are necessary to establish allowable sea states. In offshore installation, sea states are treated as stationary processes, i.e. the wave spectrum parameters do not change in time. The wave forces acting into a dynamic installation system with time-variant properties can make a resulting process (from which the dynamic responses are assessed) to become non-stationary. This occurs because a change (e.g., winch speed) is imposed into the system, which makes the dynamic properties of the system, and therefore, the statistics of the responses to become time-dependent. Offshore activities need to be modeled as stationary or non-stationary processes and the problems can be linear or non-linear. Regarding non-stationary processes, Li et al. (2014b, 2015c) developed a method to account for shielding effects of installation crane vessels on monopile foundations and the radiation damping of the monopile during non-stationary lowering processes. A single lifting operation of an OWT tower and RNA using a floating crane vessel has been studied by Ku and Roh (2015) by applying the time domain (TD) method. Guachamin Acero et al. (2015) proposed a numerical method for quick assessment of dynamic responses and crossing rates of a docking pin out of a circular boundary. This method is suitable for mating operations. Based on the aforementioned studies, it is noticed that the available numerical methods are operation-dependent. Moreover, the state-of-the-art software developed by Century Dynamics-ANSYS Inc. (2011) and MARINTEK (2012), provide limited features for accurate modeling of marine operations. Thus, further development of methods and tools is needed.

The operational limits form the basis for assessment of the operability of a marine operation. The operability represents the available time for executing an operation in a given reference period and in a safe manner. It is normally assessed using the operational limits (in terms of sea state parameters) and scatter diagrams of the offshore site. Fonseca and Soares (2002) studied the operability of a container ship and a fishing vessel. Several criteria such as vessel roll and deck accelerations were considered, and a sensitivity study on the most relevant parameters was carried out. In addition, Tezdogan et al. (2014) assessed the operability of a high speed catamaran vessel based on passenger comfort criteria. A comparative study by applying various sea-keeping theories was conducted and the effect of seasonality was also investigated. Passenger comfort criteria have been studied by researchers and published in literature (Lawther and Griffin, 1987; Werenskiold et al., 1999). Furthermore, Wu (2014) assessed the operability for the docking operation between service vessels and offshore wind turbines. This was done for the current access method that relies on the friction force between the vessel and the foundation.

The operability should preferably be assessed from weather window analysis, where the *sequence*, duration, and *continuity* of each activity can be included. Nielsen (2007) provided a procedure to estimate the available time for execution of a marine operation. The procedure is based on the conditional distribution function of Hs on the duration of weather windows, so the time histories of hindcast wave data are employed. Bergøe (2015) provided the operability of jack-up and floating units. Although the allowable sea states were simply assumed, the sequence and duration of the activities were incorporated in the analyses. In addition, Velema and Bokhorst (2015) identified the weather windows for installation of a subsea storage module. The heading providing the best responses was selected based on directional wave spectra from updated weather forecasts and on-board numerical simulations. Moreover, Gintautas et al. (2016) proposed a methodology for identification of weather windows with the aim to support on-board decision-making during offshore wind turbine installation. This is done by on-board numerical simulation of the operations and probabilistic assessment of the dynamic responses, which are computed using updated forecast wave data. In the analyses, the sequence and duration of the activities were included; however, the operational limits were simply assumed.

The literature review given above has addressed operational limits and operability of marine operations related to ship maneuvering during normal operation and weather-restricted operations such as offshore transport and installation. It has been shown that no systematically derived operational limits have been linked to weather window analysis and the various approaches followed to identify *workable weather windows* vary and were not explicitly given. This paper provides a methodology for systematical derivation of response-based operational limits and assessment of the operability of weather-restricted marine operations. This information is the basis for planning and on-board decision-making towards safe execution of marine operations.

This paper consists of the following sections. First, a methodology for assessment of limiting parameters and operational limits of marine operations is proposed. The operational limits are established in terms of Hs and Tp wave parameters, and wind and current actions are not considered. Second, a procedure for weather window analysis for planning and execution of marine operations is provided. Third, the methodology is applied to a case study of OWT monopile and transition piece installation. Finally, the conclusions and recommendations of this work are given. In addition, a glossary of terms and definitions that are necessary for modeling and analysis of marine operations is provided in the

Appendix.

2 General procedure for planning and execution of marine operations

This section provides alternatives for assessment of workable weather windows (WOWW) during planning and execution of marine operations. The workable weather windows are useful to estimate the operability during the planning phase. For the execution phase, these weather windows are suitable to make decisions on starting or stopping times.

2.1 Marine operation execution phases and loading conditions

Figure 2 shows two phases during the execution of a marine operation. First, there is a monitoring phase prior to the (actual) execution of marine operations (DYNAMIC SYSTEM 1) in which the responses of the vessel e.g., motions, velocities, accelerations are monitored and compared with the operational limits given in the operational manual. This is done to make a decision on whether to start or not an operation. In this loading condition, the system is hydrodynamically weakly non-linear with time-invariant properties and the resulting processes are stationary. Thus, frequency domain (FD) methods can be applied. This is suitable for computations using on-board systems.

Second, there is an execution phase with loading conditions in which the critical events can occur (DYNAMIC SYSTEM 2). Thus, these loading conditions are necessary for numerical analysis and assessment of the allowable limits of sea states. Moreover, during the execution of the activities, some dynamic responses can be monitored, for instance the wire tension. This parameter can be used to take mitigation actions (if the tension reaches dangerous levels), but not to make decisions before executing an offshore activity.

2.2 Planning phase

During the planning phase, the operability of a marine operation is required. It provides essential information for feasibility, selection of vessels, equipment, season, and headings. It also helps in planning logistics, optimization of processes, etc.

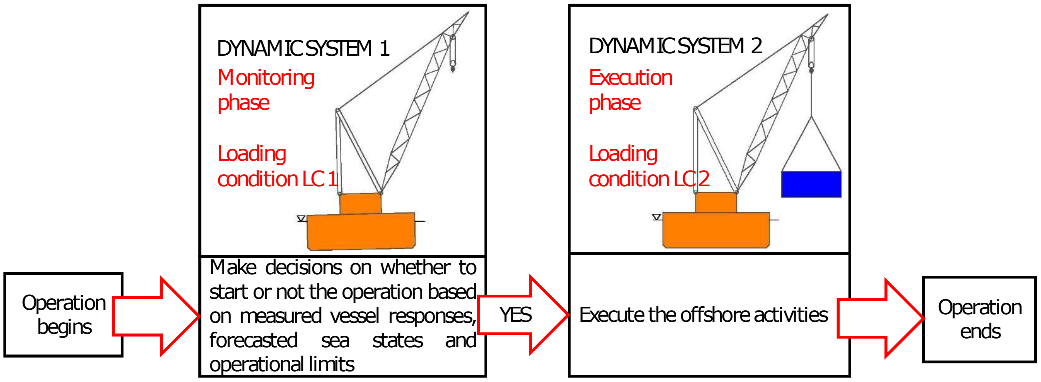


Figure 2: Phases and loading conditions for execution of a marine operation

Figure 3 shows two approaches for assessing the operability of a system during the planning phase. First, the allowable limits of sea states can be compared against the time histories of hindcast wave data of the offshore site, see Fig. 3 (a). The workable weather windows can be identified and used to establish the operability of a marine operation for any month, season and heading. The methodology for assessment of the allowable limits of sea states is addressed in Sec. 3. Second, the characteristic values of the limiting parameters for DYNAMIC SYSTEM 2 computed using hindcast wave spectra are directly compared with the allowable limits, see Fig. 3 (b). Notice that the second approach is practical only for linear or linearized systems where the resulting processes are stationary. This is because TD simulations of non-stationary processes and non-linear systems are computationally expensive for a large amount of hindcast wave data.

A detailed description of every step required for analysis of marine operations during the planning phase is provided in Sec. 3.

2.3 Execution phase

As it was mentioned above, there are two phases during the execution of marine operations. A monitoring phase prior to execution where decisions are made, and the actual execution phase. Figure 4 shows two alternatives for selection of weather windows for the execution phase.

Unlike using hindcast wave data for the planning phase, the execution phase requires updated weather forecast of the offshore site. The workable weather windows can be identified by directly comparing the weather forecast data with allowable limits of sea states, see Fig. 4 (a). In this case, the uncertainties in forecasted wave spectral parameters (Hs, Tp) need to be accounted for. This

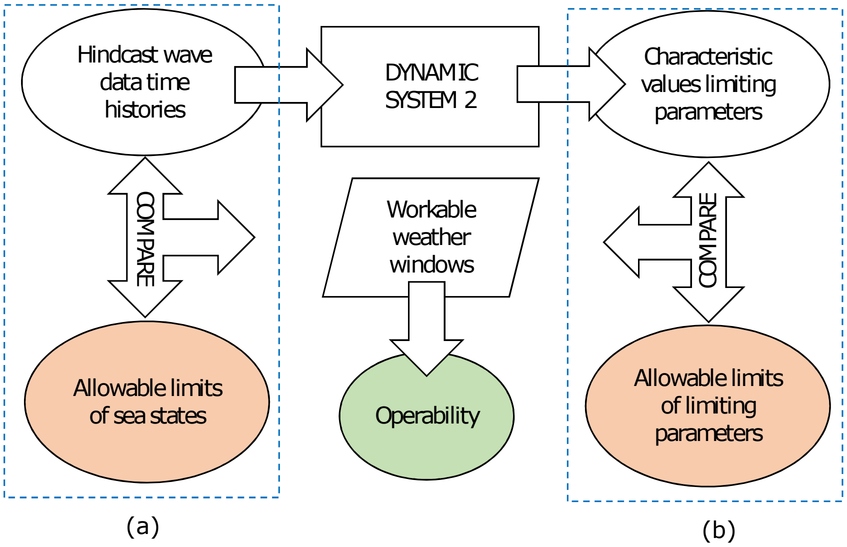


Figure 3: Methodologies for weather window analysis and their application on "planning" of marine operations. a) Weather window analysis using allowable limits of sea states; b) Weather window analysis using allowable limits of limiting parameters

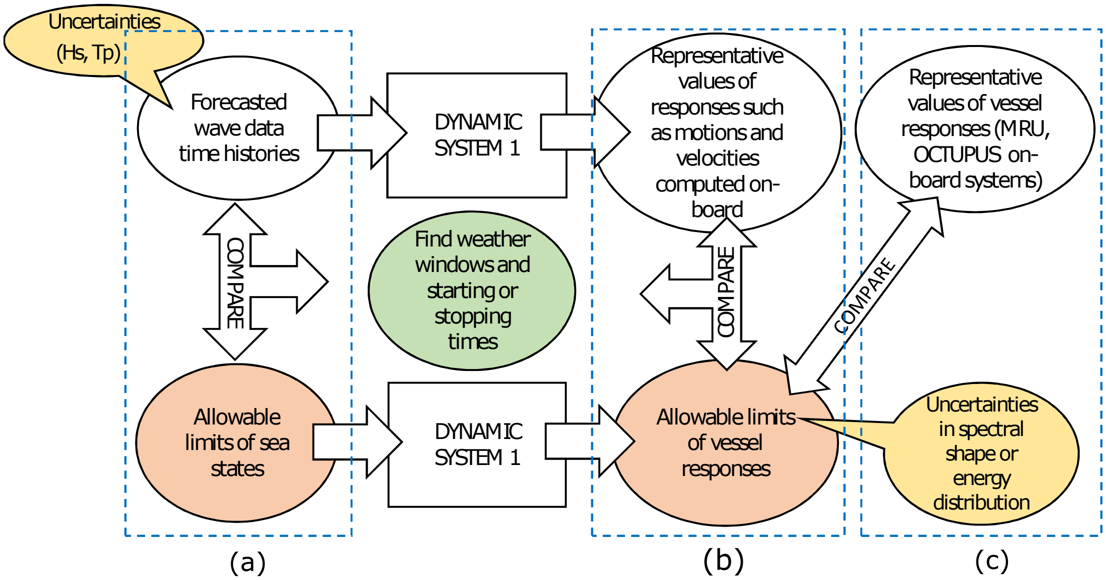


Figure 4: Methodologies for weather window analysis and their application on "execution" of marine operations. a) Weather windows analysis using allowable limits of sea states; b) Weather windows analysis using allowable limits of motions responses in monitoring phases prior to execution; c) On-board monitoring systems

can be done by applying reliability-based reduction factors to the allowable limits of sea states based on distribution functions of forecasted wave spectral parameters. Natskår et al. (2015) assessed the forecast model uncertainty by developing probability density functions (PDFs) of Hs as function of forecast lead times (time between issuing the forecast data and their predicted occurrence) for the Norwegian Sea. This was done by determining the difference and ratio between hindcast (which was assumed to be as accurate as measured buoy data) and forecasted Hs. The model uncertainty was provided for lead times up to 7 days and for various Hs intervals. Furthermore, these distributions are the basis for derivation and calibration of alpha factors dealt with in Det Norske Veritas (2011).

Note that the allowable limits of sea states are established using DYNAMIC SYSTEM 2, and thus, correspond to the real loading conditions for the execution. Based on engineering practice and recommendations given by Det Norske Veritas (2011), to make on-board decisions prior to execution, it is also required to have allowable limits of responses that can be monitored using the loading condition of DYNAMIC SYSTEM 1, see Fig. 4 (b). Converting allowable limits of sea states into allowable limits of responses is practical and necessary. As stated earlier, in this phase, FD methods can be applied efficiently, i.e., using the RAOs together with the wave spectra of the allowable limits of sea states. Meanwhile, the responses of the vessel in DYNAMIC SYSTEM 1 can be predicted using forecasted wave spectra based on the FD method. Therefore, the predicted responses can be compared with the allowable limits of responses to find workable weather windows, see Fig. 4 (b). In this case, the uncertainties in wave spectral shape (energy distribution) need to be included, because the vessel responses are derived from allowable limits of sea states using theoretical wave spectra such as JONSWAP and PM. The theoretical wave spectra normally differs from the forecasted directional (2D) wave spectra, see e.g. Fig. 5.

In addition, the allowable limits of the responses for monitoring phases prior to execution can be compared with measurements from on-board monitoring systems such as motion reference units (MRU) and OCTUPUS-Onboard, see Fig. 4 (c). This should be done whenever these systems are available to support on-board decision-making, especially when significant differences between the weather windows obtained by applying the methods shown in Figs. 4 (a & b) are observed. Using all this information, the weather windows for any heading can be identified, and the starting and stopping times can be selected.

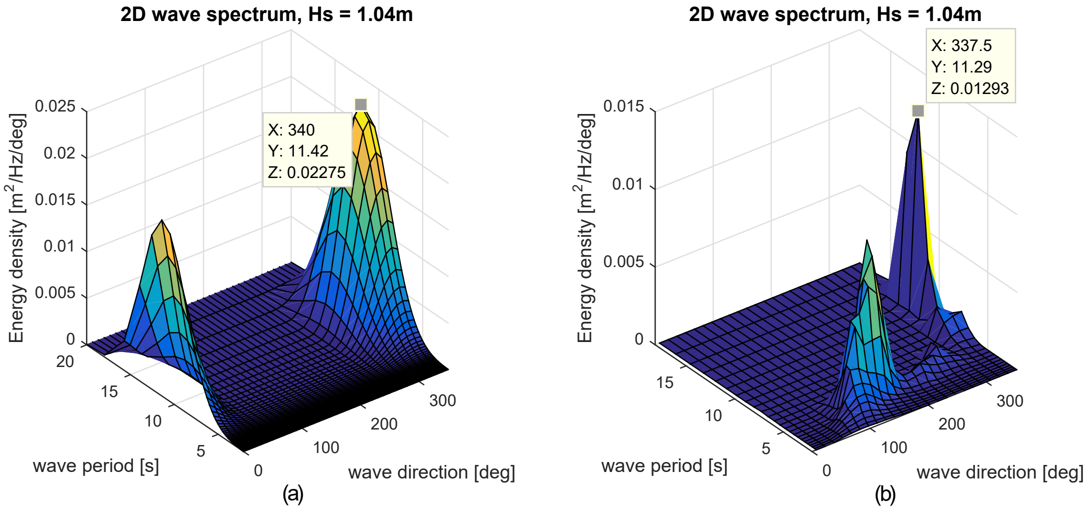


Figure 5: Example of directional wave spectra. a) Reconstructed using forecasted wave parameters and JONSWAP formulation; b) Forecasted wave spectrum

3 Methodology

The detailed procedure for establishing the operational limits of offshore activities, and their application on weather window analysis are given in this section.

3.1 Operational limits of individual offshore activities

In this subsection, a general methodology to identify critical events and corresponding parameters that limit the operations (limiting parameters), as well as to establish the operational limits of a marine operation is given. The procedure shown in Fig. 6 is described below.

Identification of potential critical offshore activities: Bertsche (2008) Ch. 3 provided a standard approach that is widely used in reliability engineering to identify potential flaws in the design of a mechanical system such as a gearbox. This approach can be modified and adapted to marine operations.

Based on a given operational procedure (step 1 in Fig. 6), a preliminary selection of activities that could lead to critical events is required, see step 2 in Fig. 6. The preliminary selection needs to be done by personnel experienced with related projects, technical discussions for reviewing similarities with past related projects or existing documentation, e.g., offshore standards, guidelines, reports, media. Convenient qualitative reliability methods to identify these events and corresponding limiting parameters are: root cause diagrams, fault tree analysis (FTA) diagrams, failure mode and effect

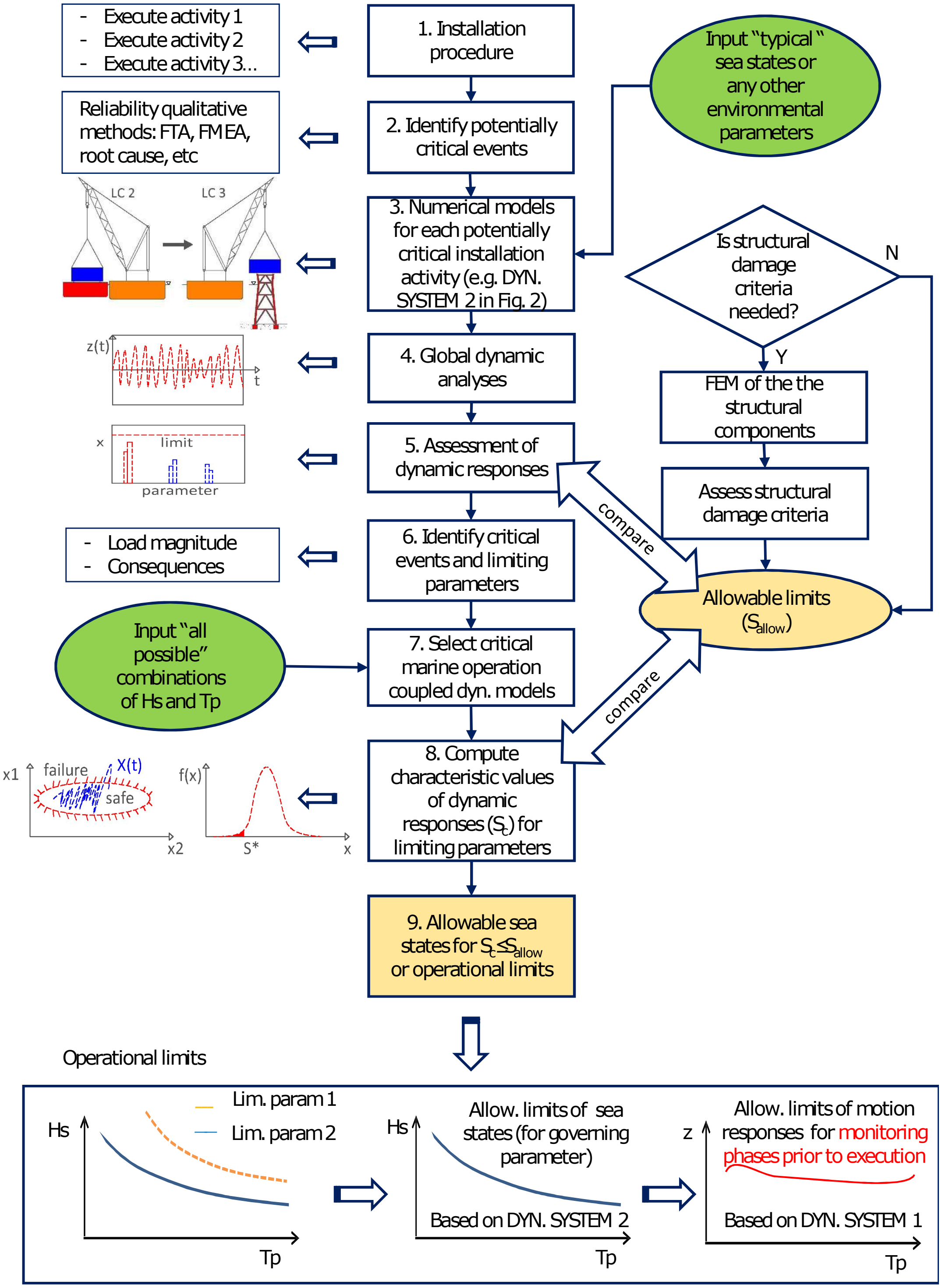


Figure 6: General methodology to establish the allowable limits of sea states

analysis (FMEA), etc.

Numerical modeling of potential critical activities: Coupled dynamic models of the system with the structures in the "real loading condition", e.g., DYNAMIC SYSTEM 2 in Fig. 2, are required for numerical analyses of these activities, see Fig. 6 step 3. A global dynamic analysis of the system under reasonable or "typical" environmental conditions (step 4) will show which parameters may reach dangerous levels when compared against their allowable limits (maximum values including safety factors that the limiting parameters can take before safety margins are exceeded) and therefore limit the operation (step 5). A typical example is occurrence of snap loads in the lifting wires during the initial phase of lift-off operations. Snap loads are of non-linear nature and can lead to a total tension larger than the allowable tension for which the rigging system has been designed. To assess the occurrence of these loads during a load transfer, the actual non-stationary lifting process (including the winch speed) has to be simulated using several seeds. If these loads occur and reach dangerous levels, the snap force or the corresponding snap velocity becomes a limiting parameter. In addition, the lift-off activity may include other limiting parameters, e.g., pendulum motions. Furthermore, non-stationary process TD simulations involving non-linear systems are normally required to model lifting operations.

Identification of critical events and limiting parameters: Following the quantitative assessment of the dynamic responses, the *governing limiting parameters* of each offshore activity and corresponding failure events are identified, see step 6 in Fig. 6. "The procedure given here is general, systematic and a reasonable way to properly identify the limiting parameters".

Assessing the characteristic values of limiting parameters: For the limiting parameters that were identified, the dynamic coupled models of the corresponding offshore activities are employed, see step 7 in Fig. 6. By applying "all" possible sea states (or any other environmental parameters) to the system, the characteristic values of the limiting parameters are calculated (step 8). The response statistics need to converge in order to reduce the statistical uncertainty, and thus, several random seeds need to be applied. The characteristic values correspond to target percentiles or exceedance probabilities from extreme value distributions. The exceedance probability depends on the type of operation and consequence of failure events. For instance, the probability of exceeding an allowable tension during a lift-off activity has to be small enough to guarantee safety, because if a failure event occurs, the operation cannot be reversed and the consequences are catastrophic. In contrast, a failed attempt of a mating operation can be tried again, because it is reversible, and thus, it can be designed for a larger probability of exceedance.

Setting allowable limits of limiting parameters: Allowable limits are readily available for elements such as slings and wire ropes, mating gaps for float-over operations and crane lifting capacity. However, for events related to mechanical impact damage criteria, the limits may not be available. Normally, FEM of the contact problem is required. Once the structural damage criteria are established, they can be expressed for instance in terms of allowable impact velocities. The allowable limits need to include safety factors due to the various sources of uncertainty.

Operational limits: By comparing the allowable limits and characteristic values of the limiting parameters, the allowable limits of sea states are established, see step 9 in Fig. 6. From the operational limits shown in Fig. 6, it is observed that the limiting parameter 2 "governs" the execution of the operation because its allowable limits of sea states are lower than the ones for parameter 1. The allowable limits of sea states computed using DYNAMIC SYSTEM 2 can be expressed in terms of allowable limits of responses that can be measured in monitoring phases (DYNAMIC SYSTEM 1) prior to execution. In this paper, both are known as "operational limits". The above given procedure can be conducted for any heading of offshore platforms.

Operational limits including uncertainties: It was stated above that the allowable limits of the limiting parameters should include a safety factor that accounts for the various sources of uncertainty. In marine operations, the uncertainties sources can be for instance, the human actions, the environment, the numerical models, and the equipment. The human decisions made based on visual observations and experience can lead to selection of higher or lower sea states than the ones provided in the operational manuals. In addition, the sea state parameters and energy distribution (see multimodal wave spectra in Fig. 9) given in forecast data are subjected to uncertainties in the mathematical models and duration of operations. As it was shown before, statistical models given by Natskår et al. (2015) or alpha factors provided by Det Norske Veritas (2011) can be used to account for uncertainties in forecasted Hs as function of forecast lead times. The alpha factors are reduction factors that can be applied on the design values of Hs (operational limits). In fact, Det Norske Veritas (2011) states that the alpha factors should be calibrated to ensure that the probability of exceeding the operational limits (in terms of Hs) with more than 50% is less than 10^{-4}. Based on this statement, it is demonstrated that these factors are considered to be independent of the type of operation and consequences of failure events. Moreover, Tp needs to be included because it is an important parameter for floating vessels. Thus, distribution functions that account for uncertainties in both Hs and Tp parameters are required.

Furthermore, the dynamic coupled models used to simulate the offshore activities are not an exact representation of the real systems, which are generally simplified. In addition, there is statistical uncertainty when computing characteristic values of limiting parameters. With respect to the allowable limit of an structural component, the uncertainties in the material capacity and geometric imperfections need to be included.

By considering the various sources of uncertainty, the probability that a dynamic response exceeds its allowable limit can be calculated. Then, reliability-based safety factors for target failure probabilities can be established, see e.g., (Melchers, 2002).

To establish the allowable limits of sea states, the allowable limit and characteristic value of a limiting (response) parameter corresponding to a target percentile or failure probability Pf or rate of crossing a safe boundary ν^+ are required. In equation (1) $S_c(Hs, Tp)$ and S_{allow} are the characteristic value and the allowable limit of the limiting parameter respectively, and γ_s is a reduction or safety factor that accounts for the various sources of uncertainties. As stated earlier, this safety factor will also depend of the type of operation and consequences of the failure events. For the cases where the equality holds, the sea states are the operational limits of the marine operation.

$$S_c(Hs, Tp) = \frac{1}{\gamma_s} S_{allow} \tag{1}$$

In this paper, the contributions of the various uncertainty sources are not addressed, but will be required for future reliability analysis of marine operations.

3.2 Operational limits of a complete marine operation with continuous activities

An offshore activity may or not be continuous with respect to the preceding one. Some sequential activities cannot be split or interrupted if the weather condition deteriorates. Figure 7 (a) shows that for a group of continuous activities (1-3), the limiting parameter(s) that result in the lowest allowable limits of sea states will govern the execution of these group of activities. This limiting parameter reflects the *governing activity* of its group, see activities 2 and 3 of group 1 (G1). The lower envelope of the allowable limits of sea state are the operational limits of this group of activities, see envelope 1 in

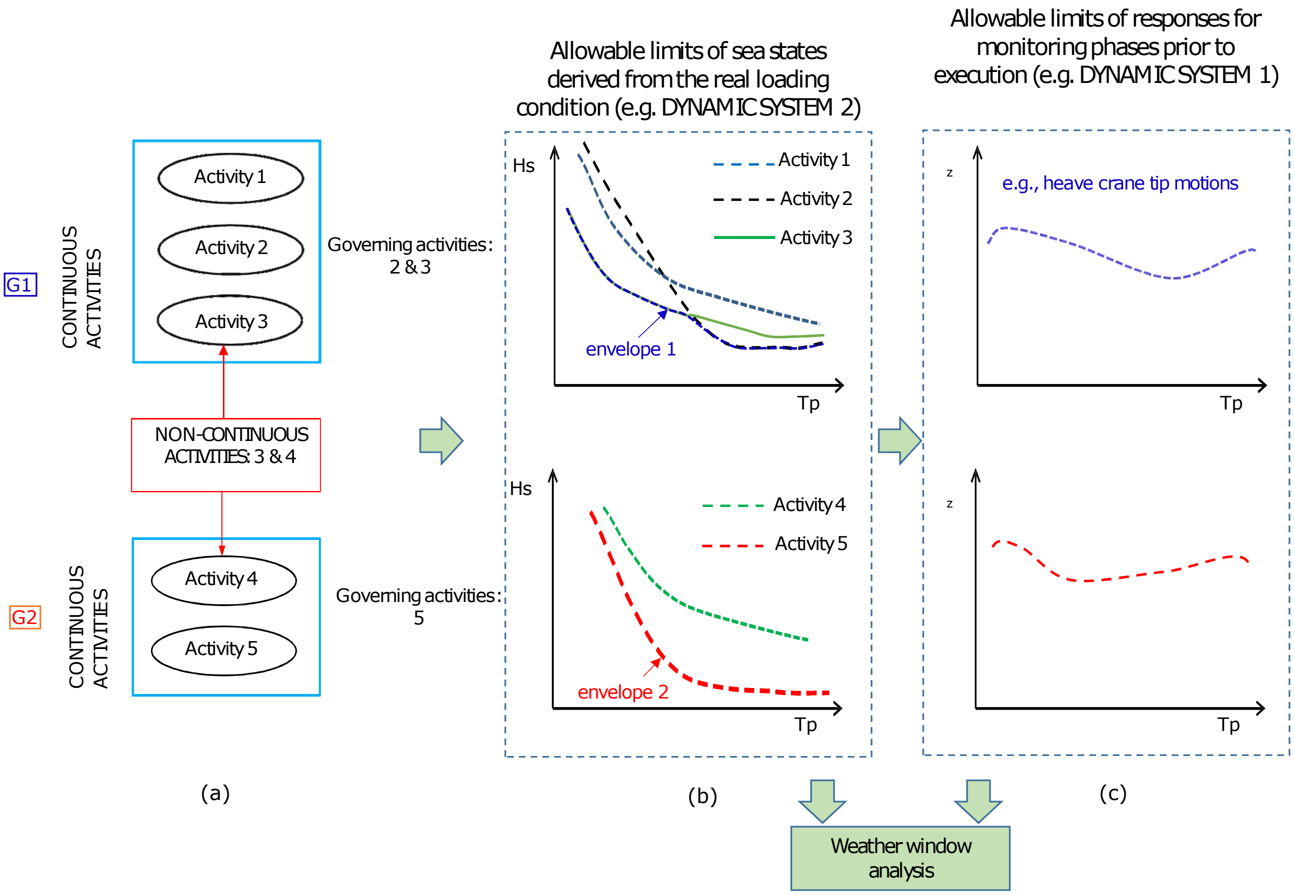


Figure 7: Operational limits for groups of continuous activities for weather window analysis. a)Groups of continuous offshore activities; b)Allowable limits of sea states for the planning and execution phases; c)Allowable limits of motion responses for monitoring phases prior to execution

Fig. 7 (b). Note that by increasing the allowable limits of limiting parameters for the activities 2 and 3, e.g., by compensating the motion responses of the system, the operational limits can be increased. For the group of continuous activities 4 and 5 from group 2 (G2) shown in Fig. 7 (b), only the activity 5 will govern this part of the operation.

The allowable limits of sea states for groups of continuous activities G1 and G2 given in Fig. 7 (b) should be provided separately when carrying out weather window analysis. These operational limits should not be combined, because they are not continuous and can be restrictive for some activity groups, and thus, result in unnecessary downtime.

The operational limits for groups of continuous activities in Fig. 7 (b) were derived for the real execution loading conditions, where the processes can be non-stationary and the systems can be non-linear. Thus, these allowable limits of sea states derived during the planning phase correspond to the actual limiting parameters and real loading conditions of the system; therefore they are physically correct. This fact makes this methodology strong and suitable for any offshore operation.

3.3 Operability analysis for the planning phase

During planning of marine operations, information about the operability is required. This can be assessed based on weather window analysis using seasonal environmental data of the offshore site together with the operational limits derived in the previous subsection.

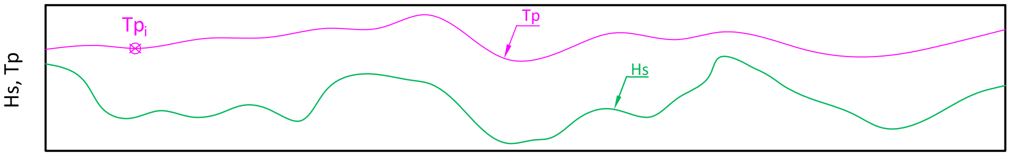
The weather windows can be identified in a straightforward manner. The Hs and Tp parameters (and any other environmental action parameter) time histories of hindcast (for operability analysis) wave data are required, see Fig. 8 (a). For every time step, the corresponding Tp_i is used to identify the allowable Hs_i for every group of activities, see Fig. 8 (b). By comparing the time histories of hindcast Hs and their allowable limits (for corresponding Tp), the workable weather windows of each group of activities can be identified, see Fig. 8 (c).

Then, the required weather windows of each activity group is put in sequence, including their respective duration. An example for two groups is shown in Fig. 8 (e), where t_{R1} and t_{R2} are their reference periods or duration (Det Norske Veritas, 2011). A starting time for activity group G1 is first identified. After G1 is finished, G2 starts. Since G1 and G2 are not continuous, they can be split. Following this procedure, the workable weather windows of the complete operation can be identified. The ratio between the available and maximum possible number of WOWWs for the total period of analysis corresponds to the operability of a complete marine operation.

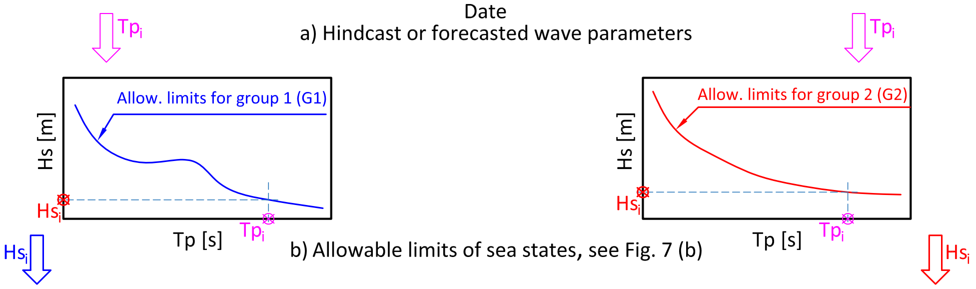
3.4 Weather window analysis for execution of marine operations

The weather windows for the execution phase are identified following the same procedure proposed in the previous subsection; however, the forecasted wave data need to be used, see Fig. 8 (a). The methodology suggested in this paper for weather window analysis requires the inclusion of forecast uncertainty in the Hs and Tp parameters, see Fig. 4 (a). The uncertainty can be assessed and included as reduction factors in the allowable limits of sea states. This can be done for instance, by applying the statistical models developed by Natskår et al. (2015).

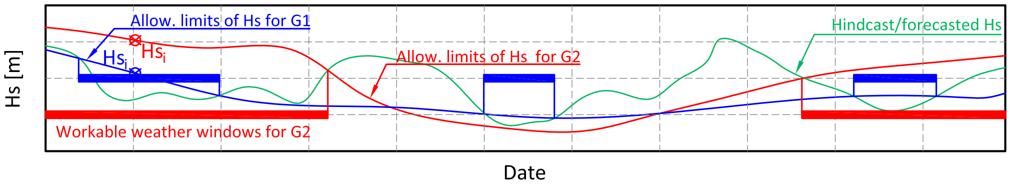
It is well-known that floating vessels are sensitive to the wave peak period and direction. In addition, mixed seas or multimodal spectra are commonly encountered at sea. These effects can only



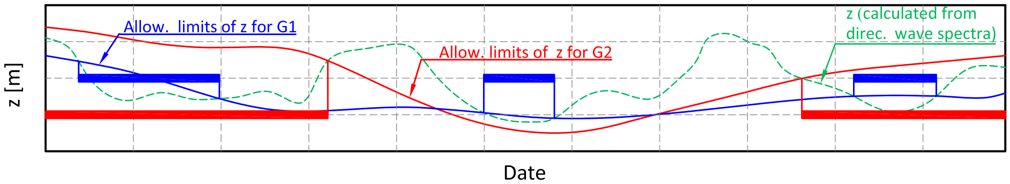
a) Hindcast or forecasted wave parameters



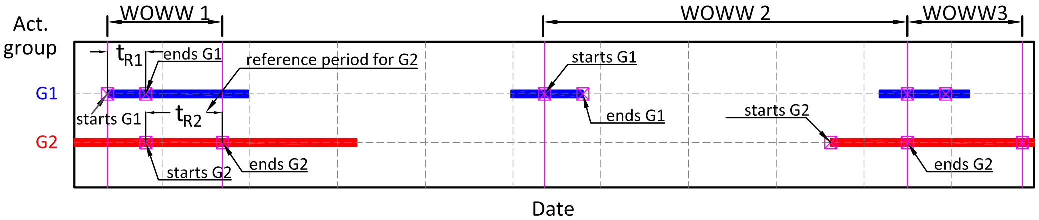
b) Allowable limits of sea states, see Fig. 7 (b)



c) Hindcast or forecasted Hs and allowable limits of Hs



d) Calculated and allowable limits of responses for the "monitoring phase"



e) Workable weather windows for the entire operation

Figure 8: Weather windows analysis including continuity and duration of offshore activities. a) Hindcast or forecasted Hs and Tp; c) Allowable limits of Hs for corresponding Tp; c) Hindcast or forecasted and allowable limits of Hs; d) Dynamic responses based on forecasted wave data and allowable limits of responses for the monitoring phase prior to execution; e) Workable weather windows

be captured by the dynamic responses of the floating vessels. This is because the allowable limits of sea states are normally derived in the planning phase using theoretical spectral formulations such as JONSWAP and PM. The allowable motion responses for the monitoring phases prior to execution are therefore required, and need to be predicted as accurately as possible. These motion responses can be calculated by applying the forecasted directional wave spectra. By doing this, the uncertainties in wave direction and energy distribution are reduced. By comparing these responses with their allowable values (including spectral shape uncertainties), the weather windows can be identified, see e.g., Fig. 8 (d).

The weather windows are obtained after combining the results using both criteria: allowable limits of Hs and responses, see e.g., Fig. 4 (a,b). These criteria together with the on-board monitoring systems need to be used for selecting the starting and stopping times of the operations.

During the execution phase, there is another source of uncertainty. This is related to the human decision on starting and stopping times of the operations which normally differ from the ones computed using on-board systems. In summary, there are various sources of uncertainty, which need to be considered for probabilistic assessment of the weather windows during the execution phase. However, this topic is not addressed in this paper.

4 Case study on monopile and transition piece installation

In this section, the methodology is applied to the installation of the monopile (MP) and transition piece (TP) of an offshore wind turbine using a floating crane vessel; this case study only focuses on the planning phase. The allowable limits of sea states for individual and groups of continuous activities are assessed. These limits do not include uncertainties in the various modeling parameters and are used for weather window analysis. The weather windows are used to assess the operability of the entire operation. Sensitivity studies on several operability cases for different operational limits of the activities are conducted.

4.1 Installation procedure

A general procedure applied for the installation of MP and TP structures using a heavy lift vessel (HLV) is shown in Table 1.

Table 1: General procedure for MP and TP installation

Activity No.	*Description*	*Required sub-activities*	*Duration [hrs]*	*Critical events*	*Limiting parameters*	*Continuous*
1	Mooring the HLV	Anchor handling	8	Capsizing of the AHV		n
2	Monitor motion responses	Monitor Hs, Tp, measurable motions, decide whether to start or not the operation	0.5	N.A.		n
3	Relocate the MP	cut MP sea-fastening	3	N.A.		
		Connect rigging	0.5	Human injury	Crane tip, lifting block, spreader motions	n
		Lift-off the MP	~ 1 *min*	Wire rope breakage	Dynamic tension or snap loads	n
		Position MP onto upending frame	0.1	Not possible to position the MP	pendulum motions	y
4	Upend the MP	Connect the internal lifting tool	0.5	N.A		n
		Lift-off the MP	0.1	Structural damage of the upending frame	Impact forces	n
5	**Lower the MP to the seabed**	Open the gripper, position the MP	0.1	N.A.		y
		Lower the MP	0.2	Failure of gripper components	Impact loads	y
6	Place the hammer on the MP	Hook on, lift-off and place hammer on the MP	0.5	N.A.		y
7	**Hammer the MP**	Hammer and correct MP inclination	0.5	Failure of the gripper system	Contact forces	y
		Drive MP to final penetration	0.3	N.A.		y
8	Remove hammer	Remove hammer, MP soil plug	0.5	N.A.		y
9	Reposition HLV	Adjust catenary mooring length	0.5	N.A.		n
10	-Cut TP sea-fastening	Unbolt flanged connections	0.5	N.A.		n
11	Connect TP's rigging		0.5	Human injury	Horizontal motions	n
12	Lift-off the TP		~ 1 min	Wire rope breakage	Snap loads	y
13	Lower the TP	Align TP with MP and lower	0.2	N.A.		y
14	**Monitor TP motions**	Align TP and MP end tips	0.1	Mating is not possible	Horizontal motions	y
15	**Mating with MP**	Lowering	0.1	Structural damage	Impact loads	y
				Sling breakage	snap loads	
16	Leveling and grouting		3	N.A.		n
17	Disconnect rigging		0.5	N.A.		n

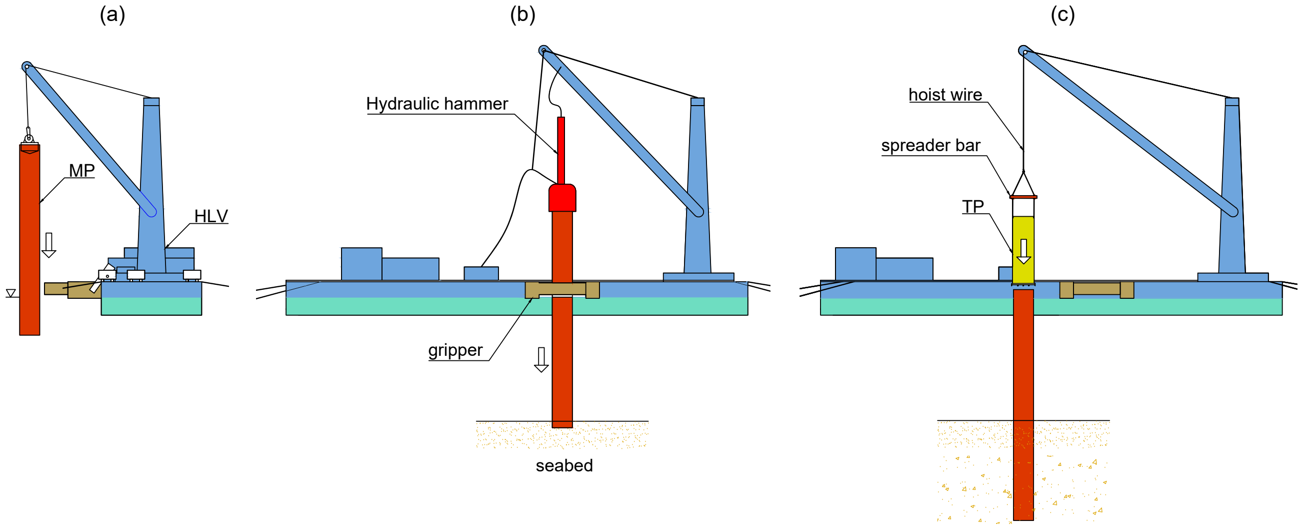


Figure 9: Schematic view of OWT installation activities considered for numerical analysis. a) MP lowering; b) MP initial hammering process; c) TP mating

A preliminary selection of potential critical installation activities is required for establishing the operational limits. Note that some activities can be carried out in parallel (e.g., cut sea-fastening while monitoring motion responses prior to an operation) and only the ones considered critical need to be modeled. Table 2 shows the activities considered in this study. An illustration of activities (2-4) is shown in Fig. 9. It follows that only activities (2-3) should be modeled as continuous, and the lower envelope of their operational limits needs to be considered.

Table 2: Installation activity groups for weather window analysis

Activity No.	*Group*	*Activity*	*Duration [hours]*	*Continuous*	*Allowable limits of sea states*
1	1	Mooring the HLV	8	n	$H_s = 2.5$ m (assumed)
2	2	MP lift-off and lowering	2	n	Fig. 11 (a)
3	2	MP hammering	1	y	Fig. 11 (b)
4	3	TP installation	1	n	Fig. 11 (d)

4.2 Identification of potential critical events and limiting parameters

The installation procedure given in Table 1 applies for a HLV that transports the MP and TP structures on its own deck. Lift-off and relocation of structures within the own deck of the vessel are normally not crucial because the relative motions between the crane tip and the structure are small. The potential critical events and limiting parameters could be identified from a root cause diagram, see Fig. 10. In this figure, the critical events are shown in red boxes, while the possible causes are shown in blue boxes and correspond to limiting parameters. The green color represents possible contingency actions. The possible causes that could lead to undesired events in these activities are summarized below.

Potential critical installation activities are: MP lowering, positioning and securing the MP in the gripper device, holding the MP during the initial hammering process, mating the TP and landing the TP on the MP. The critical events are: wire rope breakage, uncontrolled MP pendulum motions, structural damage of the gripper device, unacceptable MP inclination, TP mating is not possible and TP brackets structural failure.

The limiting parameters are: wire rope tension, MP horizontal motions, gripper contact force, MP inclination, TP bottom tip motions and TP landing velocity.

4.3 Numerical modeling of offshore installation activities

Based on the preliminary selection of critical installation activities, numerical coupled models are built. These models are required to assess the dynamic responses and identify limiting parameters, see Table 4.

4.3.1 Floating installation vessel, MP and TP

The installation of the MP and TP is carried out by a monohull HLV. The positioning system is based on catennary mooring lines, that allow the operations in shallow water and in close proximity to other structures. The water depth for the MP and TP installation is 25 m. The crane is capable of performing lifts of up to 5000 tonnes at an outreach of 32 m. The main particulars of the vessel, MP and TP are shown in Table 3.

4.3.2 Numerical model of the MP lowering operation

During lowering of structures through the wave zone and towards the sea bed, the dynamic features of the system change continuously. The non-stationary process must be analyzed differently from a stationary case (Sandvik, 2012). For MP lowering using a floating vessel, the hydrodynamic interactions between the HLV and the MP should be also included in the numerical simulations. Thus, the methodology developed by Li et al. (2014b, 2015a), that allows including the shielding effects from

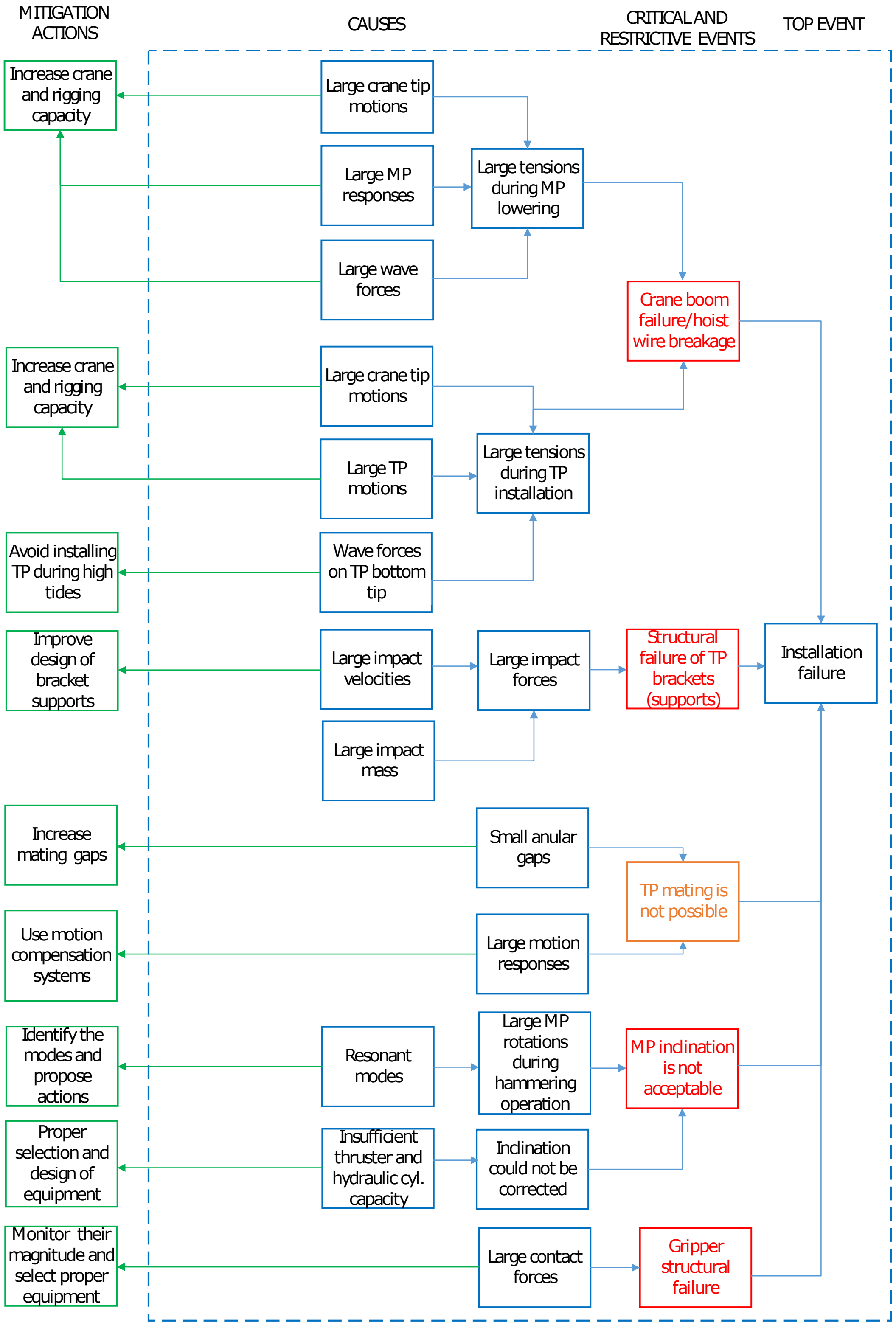


Figure 10: Root cause diagram for MP and TP installation failure event

Table 3: Main particulars of the structures (Li et al., 2016b)

Parameter	*Notation*	*Value*	*Units*
- *HLV*			
Displacement	$\bigtriangledown$	5.12×10^4	tonnes
Length	L	183	m
Breadth	B	47	m
Draught	T	10.2	m
Metacentric height	GM	5.24	m
Vertical position of COG above keel	VCG	17.45	m
- *Monopile*			
Mass	M_{MP}	500	tonnes
Diameter	D_{MP}	5.7	m
Length	L_{MP}	60	m
- *Hammer*			
Mass	M_{Hammer}	300	tonnes
- *Transition Piece*			
Mass	M_{TP}	300	tonnes
Diameter	D_{TP}	6.0	m
Length	L_{TP}	23	m

the HLV and the radiation damping of the MP during the entire lowering process, was applied. The influences of those factors, e.g., non-stationarity, shielding effects, radiation damping on the operability of the MP lowering operation were studied by Li et al. (2016a).

The numerical model was established using the MARINTEK SIMO program (MARINTEK, 2012). The coupling between the HLV and the MP includes the lifting wire and the gripper device. Time-domain simulations were performed for the entire lowering operation in short-crested seas with varying sea state parameters and wave directions. The numerical model is shown in Table 4.

4.3.3 Numerical model for the initial hammering operation

The coupled dynamic model for the MP initial hammering process is composed of a HLV, MP foundation, hammer and the gripper device. After being lowered down to the sea bed, the MP is supported vertically by the soil and laterally by the gripper device. Then, the main lift wire is released. The gripper consists of several hydraulic cylinders. By varying the stroke length of the cylinders, the gripper is able to correct the mean inclination of the MP during the initial hammering process. The gripper device was modeled as a four fender system with chosen stiffness and damping coefficients. Soil-MP interactions were modeled using distributed non-linear springs as well as proper hysteretic soil damping.

Because the MP penetration increases step by step with the hammer blows, steady-state time-domain simulations were performed for incremental MP penetration depths and the dynamic responses of the system were evaluated. For detailed description of the modeling approach and parameters as well as discussions on the time-domain simulation results, refer to Li et al. (2016b).

4.3.4 Numerical model for the TP mating

The dynamic coupled model was built in the ANSYS-AQWA (Century Dynamics-ANSYS Inc., 2011) software. The model is composed of a HLV, a TP structure, a spreader bar, a main block (hook) and wires connecting the rigging system, see Table 4. Time domain simulations were used to find the horizontal surge and sway displacements of the TP's bottom tip prior to the mating phase (TP's bottom about 2 m above the MP's tip). For detailed information on the main particulars of the rigging system and other modeling parameters, refer to Guachamin Acero et al. (2016).

4.4 Identification of critical events and limiting parameters

From the numerical models, several dynamic responses are assessed quantitatively under representative installation sea states. The aim is to find those ones whose values may reach dangerous levels and could lead to undesired events. A summary of the critical events and limiting parameters considered in this study is shown in Table 4 and are explained in more detail below.

4.4.1 MP lowering operation

From the numerical analyses, the critical event during the MP lowering operation was identified. This is the failure of the hydraulic system in the gripper device due to large relative motions followed by impact loads between the MP and the HLV at the gripper connection (Li et al., 2016a).

This event will not only stop the operation but also may pollute the environment if leakage of the hydraulic fluid occurs. The limiting parameter is the relative horizontal displacement between the MP and the HLV-gripper system at the gripper elevation. The allowable limit is the allowable gap between the MP and the hydraulic piston rods when they are retracted. Impact forces during the lowering operation must be avoided.

4.4.2 MP initial hammering operation

The critical event for the initial hammering process was identified to be the structural failure of the hydraulic cylinders in the gripper, while a *restrictive event* was found to be the unacceptable MP inclination at the end of the operation. The limiting parameters are the cylinder contact force and the inclination of the MP.

The total cylinder contact force includes the dynamic forces due to the waves, the ones induced by the HLV and MP relative motions, and the mean correction force for the MP inclination using the hydraulic cylinders. Li et al. (2016b) provided detailed discussions on the critical events and the limiting parameters of this process.

4.4.3 TP mating operation

The critical events for the TP installation were found to be the structural failure of the TP's bracket support during the landing phase, and a restrictive event was found to be the failed mating attempt between the TP's bottom tip and the MP's tip. The limiting parameters are the TP's landing impact velocity and horizontal displacements and velocities of the TP's bottom tip respectively. For details about the systematic identification of these parameters, refer to Guachamin Acero et al. (2016).

In this paper, the TP heave impact velocity is not considered because the allowable limit for impact velocity requires structural damage criteria based on FEM, which are not available.

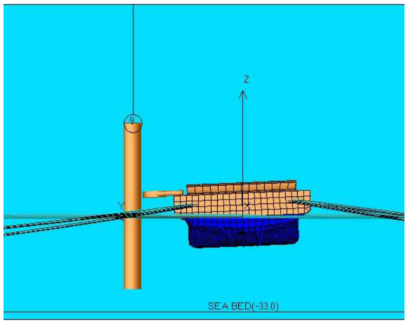
4.5 Allowable limits of sea states and governing activities

The allowable limits of sea states are obtained after comparing the characteristic values with the allowable limits (of the limiting parameters). Figure 4 shows typical dynamic responses and allowable limits for the installation activities considered in this case study. Based on equation (1), examples of the allowable limits of sea states for the groups of continuous activities are shown in Table 4, and they are further analyzed below.

4.5.1 Allowable limits of sea states for the MP lowering operation

The allowable limit for the hydraulic cylinder contact force could be exceeded if an impact between the MP and hydraulic piston rods occurs. An allowable gap of 1.0 m (condition in which the pistons

Table 4: Case study on MP and TP installation

<table>
<tr><th></th><th>(a) MP lowering (Group 2)</th><th>(b) MP hammering (Group 2)</th><th>(c) TP mating (Group 3)</th></tr>
<tr><td>Numerical models</td>
<td>
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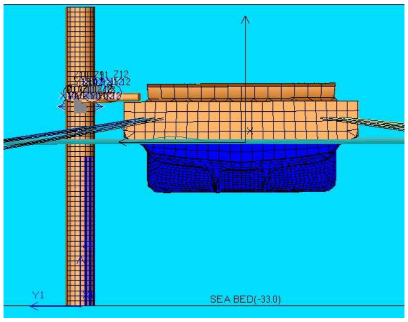
<td>
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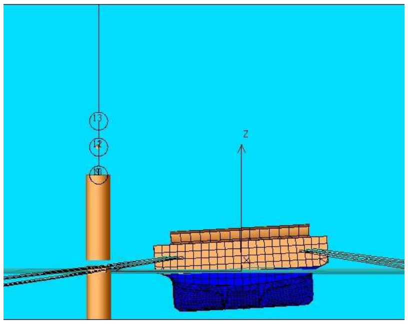
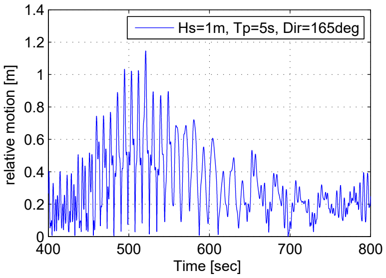
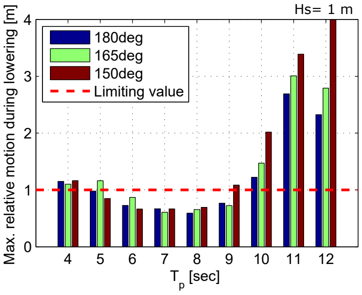
<td>
</td></tr>
<tr><td>Lim. param.</td>
<td>Crit. event: Structural failure of hydraulic system caused by MP impact loads

Lim. parameter: Horizontal motions of the MP at gripper connection</td>
<td>Crit. event: Structural failure of the hydraulic system caused by contact forces and MP inclination out of tolerance
Lim. parameter: Total contact force on the hydraulic cylinders and MP inclination</td>
<td>Crit. event: Mating operation is not possible due to large TP motions

Lim. parameter: Horizontal motions of the TP's bottom tip</td></tr>
<tr><td>Characteristic response examples</td>
<td>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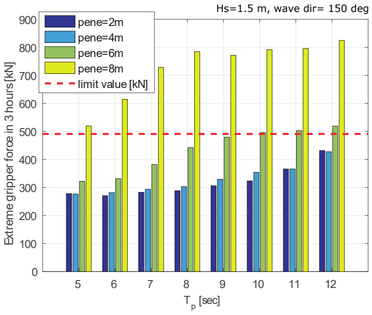
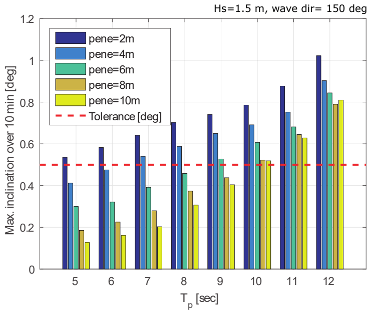
<td>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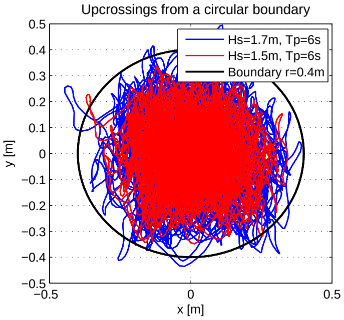
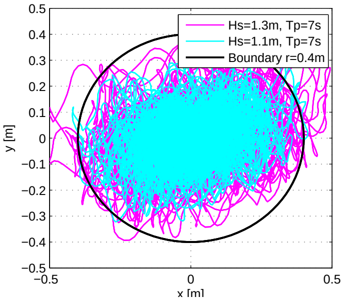
<td>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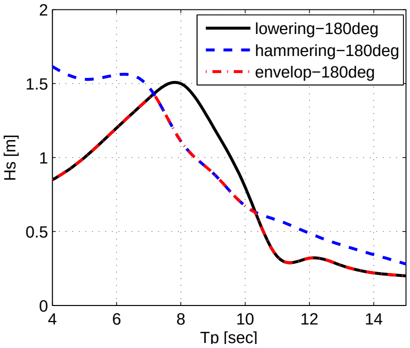
<tr><td>Allow. limits of sea state</td>
<td colspan="2">
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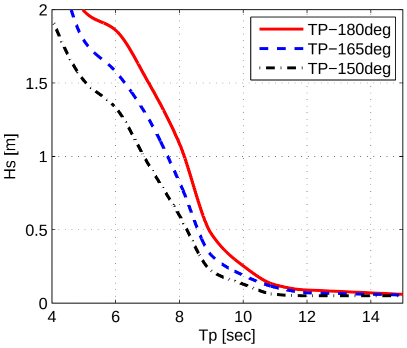
<td>
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are fully retracted) was considered, see Table 4. By studying the entire lowering process, the sea states that result in MP motions (at the gripper elevation) larger than the allowable limit were considered unacceptable, and thus, the allowable limits of sea states were established. These limits are shown in Fig. 11 (a) for various vessel headings. The results for the best heading are also presented, since the best responses do not always correspond to a specific heading.

4.5.2 Allowable limits of sea states for MP hammering operation

The allowable limits of sea states for the MP initial hammering process were obtained by applying the methodology developed by Li et al. (2016b). Both the hydraulic cylinder contact force and the MP inclination were evaluated and compared with the allowable limits (491 kN for the contact force and 0.5 deg for the MP inclination). The contact forces were assessed for incremental penetration depths. The maximum penetration depth corresponds to the condition when the MP can stand on its own. The final MP inclination was also checked with the allowable limit. The allowable limits of sea states for the initial hammering operation for various headings are shown in Fig. 11 (b).

4.5.3 Allowable limits of sea states for MP installation

Because the lowering and MP hammering operations are continuous activities, the lower envelope of the allowable limits of sea states are the operational limits of this group (group 2 in Table 2) of activities, see Fig. 11 (c). It is found that for short waves with peak periods shorter than 7 s, the first-order motions of the MP due to wave actions (for the lowering phase) govern the installation. Similarly, the HLV crane tip induced motions limit the installation for peak periods longer than 10 s.

4.5.4 Allowable limits of sea states for TP mating

The allowable limits of sea states were derived using the methodology proposed by Guachamin Acero et al. (2015) which is based on the allowable rate of crossing that the TP's bottom tip can perform out of a circular safe boundary (equivalent to the annular gap between the MP's outer wall and the TP's finger guides). For this case study, the annular gaps with $r = 0.3$ and 0.4 m and a crossing rate of 1 time per minute (0.0167 Hz) were considered. These are reasonable operational criteria for this activity. The allowable limits of sea states for various headings and $r = 0.3$ m are shown in Fig. 11 (d), where it is shown that the best heading corresponds to head seas. For sea states with peak periods

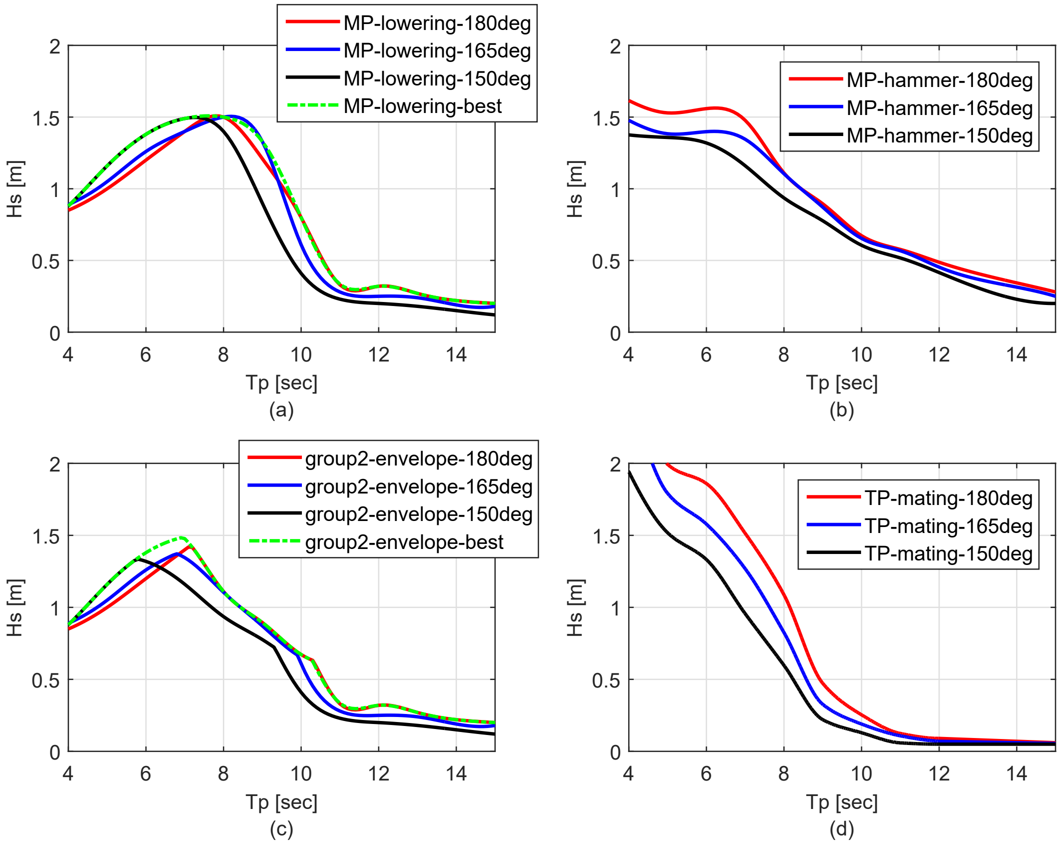


Figure 11: Allowable limits of sea states for single activities and activity groups (Ref. to Table 2) for various headings. a) Allowable limits of sea states for the MP lowering operation; b) Allowable limits of sea states for the MP initial hammering process; c) Allowable limits of sea states for group G2; d) Allowable limits of sea states for group G3

longer than 8 s the installation would not be practical since the first-order motions of the HLV greatly excite the pendulum motions of the TP.

4.5.5 Allowable responses for the monitoring phase prior to execution

The allowable limits of sea states for each group of continuous activities can be expressed in terms of allowable limits of motion responses for the monitoring phase prior to installation (see e.g., DYNAMIC SYSTEM 1 in Fig. 2). Figure 12 (b) shows the allowable limits in terms of significant values ($2 \times rms$) of the Z crane tip motions of the HLV. It is observed that for short wave periods, the allowable limits of heave crane tip motions have small amplitudes and are very similar for all groups of activities. Thus, this parameter may not be adequate for decision-making. The limiting parameter for the MP lowering operation was found to be MP horizontal motions at the gripper elevation due to direct wave action on the MP (Li et al., 2016a). Since this parameter is not directly related to the HLV responses, it is not relevant to monitor the crane tip motion. Instead, the Hs parameter is more appropriate for the MP lowering operation. Similarly, for the TP mating phase, the horizontal motions of the crane tip could be more relevant. However, it is observed that for larger wave peak periods, the heave crane tip motions can be used as an operational criterion, because the responses are larger and can be compared with measurements from on-board systems.

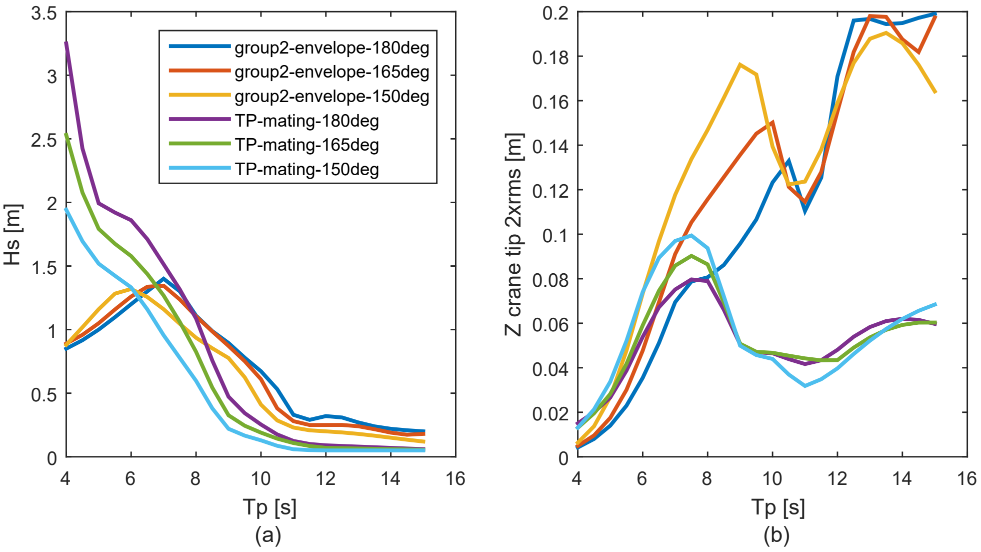


Figure 12: a) Allowable limits of sea states for MP and TP installation derived from the real execution phases; b) Allowable limits of heave crane tip motions for the monitoring phase prior to installation

Thus, it is necessary to properly select and specify the parameters to be monitored in the operation manuals. In this case study, the crane tip heave motion was used as an illustrative example. Furthermore, the allowable limits of motion responses for monitoring phases prior to execution are required, but are not addressed in this case study.

4.6 Operability analysis for the planning phase

Based on the procedure given in Sec. 3.3, and for the activity groups and duration defined in Table 2, an assessment of the operability can be provided. Hindcast wave data of the selected offshore site and operational limits of the groups of installation activities provided in the previous subsection are applied.

4.6.1 Site condition

The wave data from the Central North Sea, site 15 studied by Li et al. (2015b) was chosen for the weather window analysis of the MP and TP installation. This site is suitable for MP foundations with an average water depth of 29 m, and the location is close to the Dogger bank wind farm. The hourly sampled hindcast 2D wave spectra from the period 2001-2007 were used for weather window analysis.

4.6.2 Operability study cases

Relevant case studies are considered to compare the operability when changing the allowable limits of limiting parameters and neglecting some of them. The cases are summarized in Table 5.

Table 5: Cases for operability analysis

Case	Allow. limits of lim. parameters	Allowable limits of sea states
1	refer to subsection 4.5	refer to Fig. 11 (c) for MP installation (group 2), Fig. 11 (d) for TP mating (group 3)
2	increase TP mating gap to r= 0.4 m	refer to Fig. 11 (c) for MP installation (group 2), Fig. 13 for TP mating (group 3)
3	MP lowering is not considered critical	refer to Fig. 11 (b) (group 2), Fig. 11 (d) for TP mating (group 3)
4	the same as case l	refer to the envelope in Fig. 14 for the complete operation

Case 1. This is a base case where the allowable limits of sea states are evaluated in accordance to subsection 4.5. Figure 11 (c,d) provides these operational limits. The operability is obtained by assessing the workable weather windows using these operational limits and reference period of analysis.

Case 2. The allowable mating gap for TP installation is increased from 0.3 m in case 1 to 0.4 m in case 2. The purpose is to increase the operational limits for TP mating and quantify its influence on the operability. Figure 13 shows that the allowable limits of sea states for the mating gap with r= 0.4 m are higher than those in Fig. 11 (d) with r= 0.3 m.

Case 3. This case is defined to increase the operational limits for MP installation (group 2). Because MP lowering governs the installation in short waves, it is possible to avoid the critical

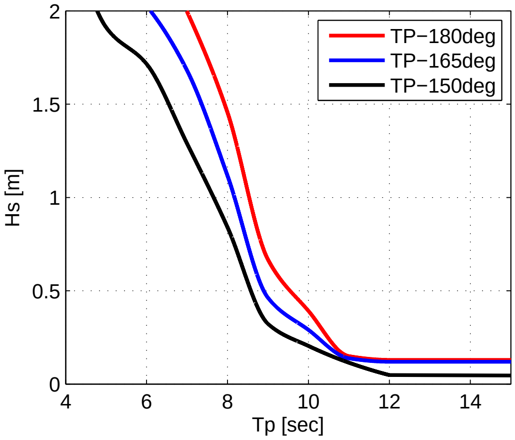


Figure 13: Allowable limits of sea states for various headings for TP mating (group 3) with allowable mating gap of r=0.4 m (case 2)

event (failure of the hydraulic cylinders) by using bumpers inside the gripper. Thus, the MP lowering operation is no longer critical and the operational limits for group 2 are the same as the ones for the MP hammering operation, e.g., Fig. 11 (b) instead of the envelope in Fig. 11 (c).

Case 4. The allowable limits for the limiting parameters are the same as case 1. However, the approach used to derive the operability for case 4 is simplified. The combined lower envelope of the operational limits from all installation activity groups is used, see Fig. 14. This is equivalent to the commonly simplified engineering approach using a scatter diagram, in which the duration of the activities is excluded.

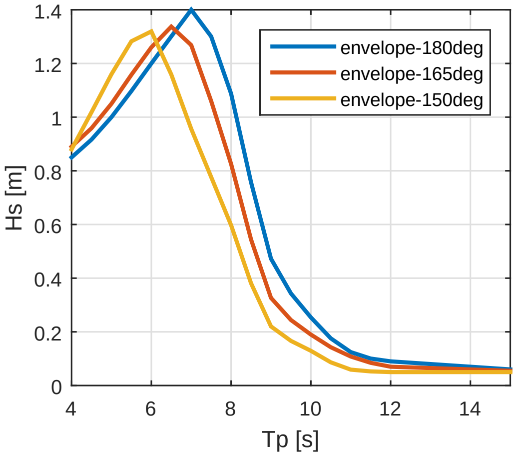
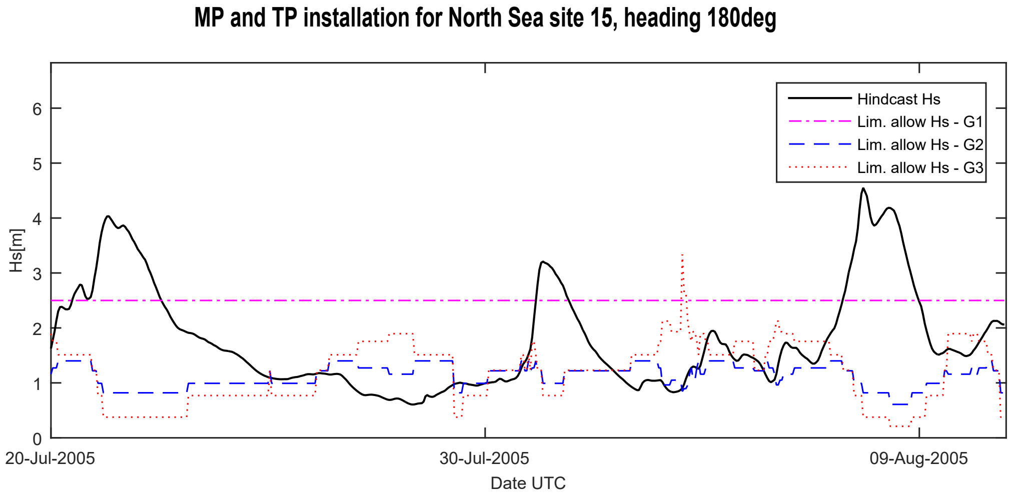
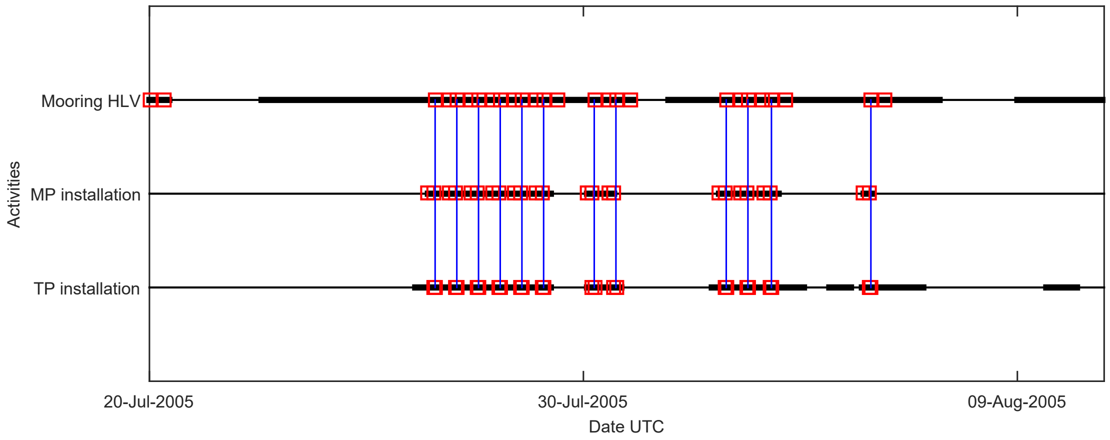


Figure 14: Allowable limits of sea states for case 4. Lower envelope from all activity groups



a) Significant wave height[m]



b) workable weather windows

Figure 15: Typical weather window analysis based on hindcast wave data at universal time coordinate (UTC), and heading into the waves. a) Hindcast and allowable limits of Hs (for corresponding Tp); b) Workable weather windows

4.6.3 Weather window analysis using hindcast wave data

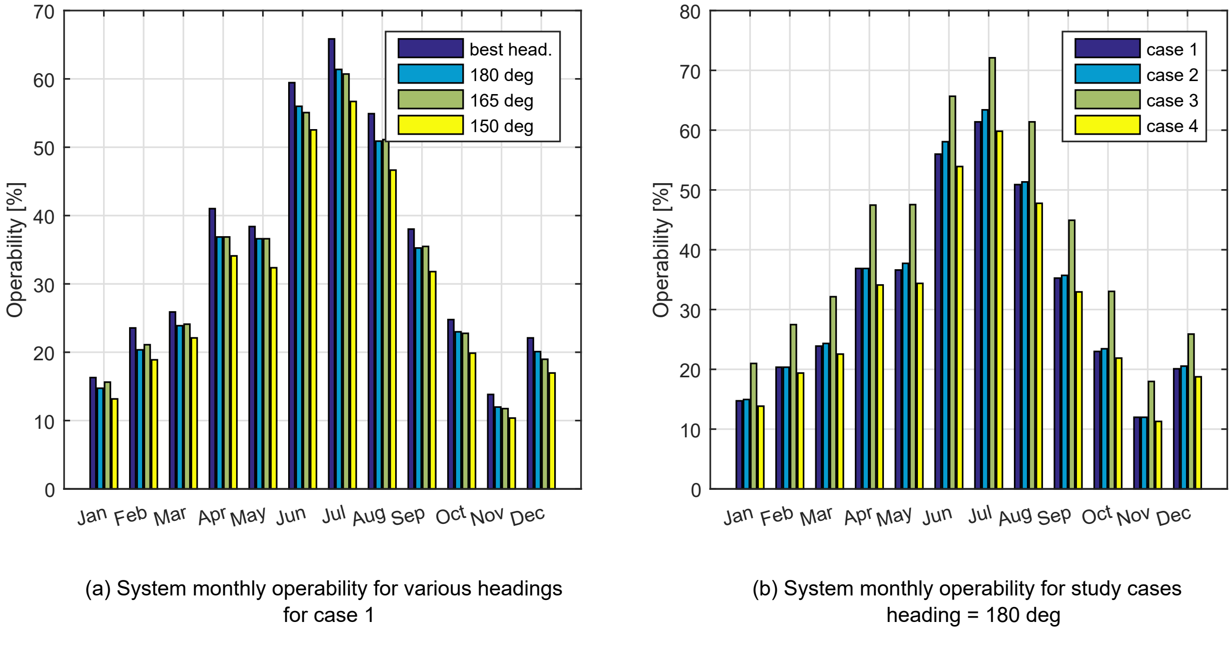
The allowable limits of sea states are used to identify the workable weather windows. For the planning phase this is done using hindcast data, see Fig. 15 (a). The workable windows are shown in Fig. 15 (b). This analysis can be done for all headings of the vessel. Then, the results can be sorted by month and the best headings and seasons easily identified.

4.6.4 Operability results

The operability for the MP and TP installation is calculated from the weather window analysis by taking the ratio between the counted number of WOWs and the maximum possible number of windows for complete operations in the reference time period (2001-2007). Figure 16 (a) shows the operability of case 1 for various headings and months.

Based on the operability numbers shown in Fig. 16 (a), it is possible to select the season for the installation campaign. For this case study, and by considering that the number of OWT installations are large, the period June-August will provide good workability and little downtime. Thus, operational limits derived systematically are very important for a realistic assessment of the performance of offshore installation vessels.

Figure 16 (a) shows that when optimizing the heading for each individual installation activity (best heading), the operability is increased (about 4.5%) for the month of July when compared with head seas (180 deg). This can be achieved if a DP vessel and updated weather forecast are available.



(a) System monthly operability for various headings for case 1

(b) System monthly operability for study cases heading = 180 deg

Figure 16: a) Operability for case 1 for various headings; b) Operability for cases 1-4 in head seas

The operability for cases (1-4) are compared in Fig. 16 (b), where only the results for head seas of each activity group are shown. For the month of July, it is seen that by increasing the allowable gap for the TP mating operation (case 2) the operability increases by only 2%. In contrast, for case 3 which assumes that the operational limits for MP lowering are increased and the activity is not critical, the operability of the whole operation increases by 11%. Therefore, it is important to reduce the severity of governing activities and optimize the installation headings in order to increase the total operability. The operability for case 4 using a simplified approach is compared with case 1. An underestimation of the operability by approximately 1.6% can be observed. This is because the combined envelope does not consider the discontinuity between groups, which can be restrictive for some activity groups.

5 Conclusions and recommendations

This paper deals with a systematic methodology for assessment of the operational limits and operability of weather-restricted marine operations with emphasis on offshore wind turbine installation activities.

A general and systematic approach for establishing response-based operational limits of marine operations was developed. The approach is based on numerical simulations of potential critical marine operations. By carrying out a quantitative assessment of the system dynamic responses, the critical events and corresponding limiting (response) parameters are identified. For a limiting parameter, a characteristic value needs to be assessed based on extreme value distributions for a target exceedance probability. This probability depends on the type of operation and consequences of failure events. The characteristic value is compared with the allowable limit of the limiting parameter, so that the corresponding environmental conditions can be identified. The limits of these environmental parameters represent the operational limits of the marine operation.

In this paper, the operational limits were derived based on numerical analyses of real execution phases, i.e. loading conditions of the the various critical activities. These operational limits were expressed in terms of sea state parameters such as Hs and Tp, and motion responses such as crane tip motions of monitoring phases prior to execution. In these phases, the dynamic system is weakly non-linear with time-invariant dynamic properties, and the system dynamic responses are a result of a stationary process; therefore, frequency domain methods can be efficiently implemented to on-board systems.

Furthermore, the sequence and continuity of marine operations were considered to establish the operational limits of groups of continuous activities. This was done by selecting the lower envelope of the allowable limits of sea states and assuming that a sea state is stationary i.e., the wave spectrum parameters do not change during the execution of each group of activities.

It has been shown that the allowable limits of sea states and vessel responses in monitoring phases are useful for weather window analysis. Identification of workable weather windows is necessary for assessment of the operability of a marine operation during the planning phase and to support on-board decision-making on whether to start or not an operation during the execution phase. In fact, it is recommended that allowable limits of responses in monitoring phases are computed using directional wave spectra (2D) from updated forecasts, because these spectra will provide more accurate results and reduce uncertainties in wave parameters and energy distribution.

An approach for assessing the operability of marine operations was developed. It is based on weather window analyses, where the allowable limits of sea states of each group of continuous activities and the hindcast wave data time histories are compared. The sequence, duration and continuity of groups of activities are shown to be important for assessment of the operability.

The methodology provided in this paper was shown in a case study for monopile (MP) and transition piece (TP) installation using a floating heavy lift vessel (HLV). The allowable limits of sea states for various installation activities were illustrated. It was shown that different activities govern the entire installation depending on the sea states and headings. The operability was assessed using different operational limits, which were derived by varying the allowable limits of limiting parameters. The results show that an increase in the TP and MP mating gap does not significantly improve the operability. In contrast, heading optimization based on wave forecast (heading the HLV to achieve the highest operational limits) provides better operability. For an offshore site in the Central North Sea, the best installation period is between June and August. Since the parameters limiting the operations were identified, system upgrade and mitigation actions are possible to improve the operability.

The proposed methodology is systematic, practical and relevant for marine operations executed with floating vessels. In addition, a more complete and useful list of terms and definitions required for standardizing the analysis of marine operations has been suggested.

This work has been limited to establish the allowable limits of sea states based on characteristic values and semi-probabilistic assessment (assuming safety factors) of allowable limits of limiting (response) parameters. In the future, the various sources of uncertainties such as human decisions, weather forecast, structural component mechanical properties, and numerical models need to addressed. Thus, the operational limits can include safety margins, which are needed for making decisions on-board vessels. Reliability analysis of marine operations are needed as a basis for deciding mitigation actions to keep the risk within acceptable levels. The proposed methodology needs to be customized for other marine operations such as towage, anchor handling, etc.

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6 Appendix - Glossary of terms and definitions used in this paper

The definitions of the terms discussed in this paper are provided in alphabetical order.

Activity sequence and continuity

Offshore activities are generally sequential, see e.g., Nielsen (2007). This means that some activities cannot start if any one of the preceding activities is not finished. For example, the landing phase of a TP onto a MP foundation cannot occur if the mating phase is not completed. Moreover, some activities are continuous and cannot be interrupted if bad weather approaches or motion responses are beyond acceptable limits. This is because in this loading condition and under more severe environmental conditions, the system structural integrity may be compromised. Moreover, the operation can be irreversible. An example is the lift-off activity of an OWT substation. It needs to be followed by the lowering, mating and landing activities.

Allowable limits

In marine operations, the allowable limits are the maximum values that response parameters limiting the operations may reach to remain within acceptable safety margins. For a mating operation, the allowable limit can be given in terms of acceptable crossing rates of a mating pin out of a given annular gap. For the hoist wire tension, the allowable limit may be given in terms of minimum breaking loads (MBLs) including safety factors.

For the sea state parameters, the allowable limits are known as “allowable limits of sea states”, which are the main focus of this paper. Similarly, for the vessel responses that can be measured on-board prior to execution, for instance, motions, velocities and accelerations, the allowable limits are known as allowable limits of responses. The allowable limits of the sea states and responses need to be provided in the operational manuals to support on-board decision-making.

Allowable responses (for the monitoring phases prior to execution)

This term refers to all responses of a vessel in a monitoring loading condition prior to execution which are equal or less than the allowable limits of the responses.

Allowable sea states

These are all Hs (for corresponding Tp) with values less than or equal to the allowable limits of sea states. By comparing the allowable limits S_{allow} and characteristic values $S_c(Hs, Tp)$ of the limiting parameters, the operational limits or "allowable limits" of sea states can be established in terms of Hs and Tp parameters. For a group of sequential and continuous activities, the combined lower envelope will provide the allowable limits of the sea states.

Det Norske Veritas (2011) addresses Hs as part of the "limiting operational environmental criteria". However, the Tp parameter is not considered.

Characteristic value of a limiting parameter

According to design codes, see e.g., Det Norske Veritas (2013), the load effects can be represented by a characteristic value as far as possible derived from statistical data for a specified target percentile. The percentile is selected based on the duration of the operation and the risks associated with failure events. The characteristic values of dynamic responses (of limiting parameters) can be calculated based on a "target" non-exceedance probability P_f or corresponding rate of crossing a boundary ν^+. Moreover, this characteristic value is different from the extreme value used to select the equipment, which is calculated by considering its service life time.

Critical events and restrictive events

A critical event is an occurrence that could cause human fatalities or injuries, pollution or economic losses. A critical event such as the structural failure of a crane is normally irreversible. On the other hand, a restrictive event does not lead to catastrophic consequences and could be reversible. For example, a failed attempt of a mating operation can be tried again and is reversible. In contrast, an unsuccessful installation due to out-of tolerance inclination of a monopile foundation after its final penetration is irreversible.

Governing limiting parameters

This term refers to one or more parameters limiting the entire operation, i.e. resulting in the lowest allowable limits of sea states. Identification of these parameters is important for taking mitigation actions and upgrading the system capabilities.

Governing offshore activities

From a sequence of continuous activities, the governing offshore activities have the lowest allowable limits of the sea states or allowable limits of responses.

Limiting (response) parameters

These are parameters that allow the quantification of a critical event and limit the operations. If the characteristic value of a limiting parameter exceeds its allowable limit, the safety margins are reduced and failure may occur. A limiting parameter for hoist wire rope breakage (critical event) is the dynamic tension or the snap velocity (relative velocity between the lifting points). The limiting parameters can also refer to the environmental parameters such as Hs, Tp and wind speed because sometimes the specification of the equipment is given in terms of these parameters.

Other limiting parameters such as impact forces and corresponding velocities that can lead to structural failure, need to be derived from structural damage criteria based on FEM or mechanical tests of existing designs, see e.g., (Li et al., 2014a).

Marine operations

According to Det Norske Veritas (2011), marine operations are non-routine operations of limited duration to handle objects and vessels in the marine environment during temporary phases.

A marine operation is a process involving interaction among the dynamic systems, operational procedures, environmental actions and human intervention.

Methodology

In this paper, methodology refers to a sequential set of steps that are required for identification of limiting parameters and derivation of operational limits.

Monitoring phase prior to execution of marine operations

This phase refers to a loading condition “prior” to execution of an offshore activity, in which the motions of the vessels can be monitored (Det Norske Veritas, 2014a). This phase is used for monitoring parameters that can be measured using on-board systems and are representative for the marine operation activity. The purpose is to support on-board decision-making. Notice that monitoring motion responses in this phase is different from monitoring limiting parameters (e.g., monitoring wire tensions) "during" the execution phase. This is because the monitoring of limiting parameters is only useful for taking mitigation actions, but not to decide whether or not to start an operation.

Numerical methods

These are methods that are used to find approximate numerical solutions for equations of motion of dynamic coupled models. This can be done using frequency or time domain techniques. For stationary processes and weakly non-linear systems, the solutions can be found using frequency domain methods. For non-stationary processes resulting from systems with time variant properties or non-linear systems, the responses normally need to be computed using time domain methods.

Operability of marine operations

Operability refers to the available time for safe execution of a marine operation during a reference period that normally is given in terms of months or seasons.

Operational limits

Det Norske Veritas (2011) refers to this term as operational limitations. In this paper, operational limits are allowable limits of sea states and motion responses in a monitoring loading condition prior to execution. Any sea state or motion response with values below the operational limits are acceptable. Whenever the operational limits are used in the monitoring phase prior to execution (for decision-making), the assumption of "stationarity" of the environmental condition is implicit through the entire operation.

The allowable limits of other limiting parameters such as wire rope tension and impact velocities cannot be used as operational limits because they are not practical for decision-making or cannot be monitored prior to the execution phases.

Operational procedures

The operational procedures or manuals are sets of systematic actions that provide information on the activities, sequence, duration and required sub-operations. Table 1 shows a typical simplified procedure for installation of an offshore wind turbine MP and TP using a floating heavy lift vessel. Operational procedures are required to identify potential critical activities and carry out numerical simulations.

Workable weather windows (WOWW)

These are sets of continuous allowable sea states with a duration longer than the minimum required to complete a marine operation.

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