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Use of response forecasting in decision making for weather sensitive offshore construction work

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ABSTRACT

Response forecasting is an emerging technology for supporting decision-making during offshore construction work. The method aims to improve the reliability and efficiency of weather-sensitive operations. This article identifies the motivations, advantages, and challenges of implementing a response forecasting decision-support service in an offshore organization from the perspective of an installation contractor. In addition, a case study based on a recent pipelay operation exemplifies the method and its impact on decision-making.

1. Introduction

Offshore installation work—for example, lifting large structures at sea (including offshore wind turbines), laying rigid or flexible pipelines, installing cables and umbilicals, installing mooring systems, and working close to platforms or subsea infrastructure—is often very sensitive to weather, especially to wave conditions. During an offshore construction campaign, decisions to commit to an operation ahead of time or to wait for more favorable weather are made regularly. These decisions have high economic impact and involve several stakeholders. The installation contractor (who performs the work) is subject to cost pressures stemming from the terms of the contract toward the client (who requisitions the work), where the costs related to weather-induced downtime can be the responsibility of the client, the contractor, or split between them. Transferring these costs, either fully or partially, to the installation contractor creates economic incentives for the installation contractor to reduce weather-related downtime, but it also causes additional pressure to operate under harsher weather conditions.

Limitations on weather conditions that ensure the integrity of installation equipment and product being installed are determined during the installation planning phase of an offshore construction project, often by simulating operations in a varied set of environmental conditions. Detailed information about the actual weather conditions that will be experienced during the execution phase is, however, missing from these calculations. Particularly, the simplification of a two-dimensional wave spectrum into a generic representation, such as JONSWAP (Joint North Sea Wave Project), is a necessary assumption representing an added uncertainty when calculations are completed months ahead of execution.

For application to the planning and scheduling of marine operations, response forecasting implies the prediction of a specific system response hours or days into the future, which can be calculated based on forecasted two-dimensional wave spectra. The predicted response should be directly relevant to the decision to commit to an installation window or wait for better weather conditions, and it should be continuously updated as more recent wave forecasts become available. For example, for an offshore construction project, a response forecast may predict stresses in the pipeline during laying, maximum loads on the crane during the splash zone crossing of a subsea structure, or the minimum distance between the vessel and a fixed platform during a riser pull-in operation. These forecasts are useful for the planning and scheduling of offshore operations. For much shorter reference periods—typically around 1 min into the future—responses can be predicted purely based on the measured response signals (Nielsen et al., 2018); however, this time scale is not suitable for the decision problems considered within the current article.

By avoiding a generic representation of the wave spectrum, response forecasting can provide decision makers with information based on more detailed input than the wave parameter forecast. There are, however, some differences between response forecasting and decision-

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making based on the forecasted wave parameters that make the comparison more complicated. Unlike forecasted two-dimensional wave spectra, which are used to produce response forecasts, spectral parameters are typically manually compiled by a forecaster prior to distribution to consumers based on all available sources of information, including the observations of current wave conditions. Additionally, time domain simulations are often too slow to provide response calculations within the limited time available to produce a useful forecast for ongoing operations, meaning that shortcuts must be made that sacrifice some of the accuracy of the calculations compared with the conventional analysis methodology.

It is also necessary to discuss the impact of a response forecasting tool on safety in the decision-making process and in the organization. For example, decision makers could experience undue pressure from stakeholders based on misinterpretations or misguided confidence in the results.

The present paper is organized as follows: A literature review is presented in section two. Section three provides a brief discussion on the interests of the different organizations involved in an offshore construction project. Section four provides a broad view of practical decision-making onboard a construction vessel, with an emphasis on the involvement of different parts of the organization and the wider aspects that need to be considered. Section five presents the role of installation analyses, showing how response forecasting differs from “upfront” installation analysis, motivating the use of response forecasting and listing the main challenges related to implementation. Section six discusses the role of response forecasting in the decision-making process while providing practical and experience-based guidance for the implementation of a response forecasting service. The decision-making process with and without response forecasting is further investigated in section seven through an application to a case study example. Finally, the main conclusions are summarized and discussed in section eight.

2. Response forecasting background

A report by the Health and Safety Executive (HSE) (Standing, 2005) documents the use of response forecasting from the early 1980s, indicating its availability and potential usefulness in a number of different operations while providing some advice for the development and layout of such a tool. The focus of the report is on health and safety implications. Although the HSE report opens for a broader definition of responses that include loads in risers or mooring lines, the cases and methods presented in the report are limited to the forecasting of floating structures’ motions that can be calculated in the frequency domain. Pipelay and subsea lifting operations are explicitly mentioned as operations where response forecasting might be useful but where the method has not, to date, been applied. Standing (2005) reports that the method is well established for deepwater drilling operations and heavy lifting operations. Response forecasting is judged to need further development for responses in monohull vessels due to discrepancies between measured and forecasted responses. Differences in vessel loading conditions and heading are thought to be the main reason for these discrepancies.

While the HSE report (Standing, 2005) indicates that the application of response forecasting is well-established for certain frequency domain cases, it does not specify a particular methodology for applying the forecasted responses in decision-making. Guachamin-Acero et al. (2016) introduce a method for offshore heavy lifting that relies on wave parameter limits, calculated vessel responses from forecasted two-dimensional wave spectra, and monitored vessel motions. This method suggests that a motion limit on the vessel can serve as a proxy for the actual operational limit, such as loads in the lifting wires. These vessel motion-based limits offer a simplified approach for applying existing methodologies to more complex analysis models and also extend to other scenarios. Legras (2008) demonstrates a suitable relationship to vessel motion for the bottom section of a flexible pipe in deep water. However, the scope of vessel motion-based criteria is limited and not suitable to predict, for example, loads in the splash zone.

Passano et al. (2008) introduce an onboard system designed for running simulations with updated weather and model parameters for pipelines and umbilicals. The study details the technical implementation of both the onshore preparation and the offshore application of this system, including an efficient method for time-domain simulations. The methodology is applied to a realistic umbilical installation case, but the study does not compare the operability against conventional methods.

The current study focuses on the commercial benefit of response forecasting for construction work such as pipelay operations and subsea lifting, where non-linear time-domain calculations are needed to assess workability in a specific weather condition. The case studies included in the HSE report typically compare forecasted and measured vessel/platform responses. In this study, response forecasting is contrasted against conventional methods for assessing weather windows. Since model uncertainties, such as those identified by Standing (2005) for monohull vessels, are present in both methodologies, this approach ensures that such uncertainties are fairly considered in the comparison. Earlier work does not comprehensively review the impact of response forecasting on the decision-making process during offshore construction work. This study compares the response forecasting method with conventional ways of assessing workability using a realistic procedure, considering different tasks on human decision makers and differences in the analysis process. Multiple sources of forecast data are collected from an actual offshore operation, including forecasted 2-dimensional wave spectra and meteorologist-intervened forecasted wave parameters, such that the effect of meteorologist intervention is included in the comparison.

3. Organizations involved in the decision-making process

Work performed offshore normally involves at least three stakeholders: the client who requisitions the work and, in many cases, operates and/or has a major ownership share in the offshore installation; the contractor who performs the work; and the marine warranty surveyor (MWS), who represents the insurance companies. Other stakeholders may also be involved, such as the shipowner in the case of the contractor using a chartered vessel or additional partners in the offshore installation. For simplicity, the stakeholders considered in the present article are limited to the client, the contractor, and the MWS, with the client being assumed to represent the operator and any other stakeholders in the offshore installation.

Delays during project execution can lead to economic consequences for both the client and contractor. The direct economic loss mainly relates to the cost of the installation vessel performing the work, which needs to be under hire for an extended number of days. The day rates for a large construction vessel are typically significant. Additionally, delayed completion of a project has ripple effects, such as a subsequent delay in the start of production, which can lead to the client experiencing a significant loss of income. Delays also cause knock-on effects for contractors, who often have highly utilized construction vessels, leading to impacts on subsequent projects and the contractors’ other commitments. Delays are particularly unfortunate for offshore campaigns with planned completion late in the season, as they can push operations into harsher and more unpredictable weather conditions; in such cases, delays may force the project to abort operations temporarily until a new season starts.

The liability for additional costs resulting from delays, including delays because of adverse weather conditions, depends on the cause of the delay and the contract terms agreed upon between the client and contractor. A clear advantage of putting the risk of weather delays on the contractor is to motivate the contractor to find solutions that minimize downtime because of weather, which would give the contractor a competitive advantage during bidding. This situation could be viewed as a win-win for both parties, with the gain coming from increased utilization of the work fleet. The client would benefit from both the reduced cost of the work and potentially earlier start-up of production. Whereas these conditions give a clear economic advantage, they also exert pressure on the contractor to deliver on the schedule and terms agreed upon during bidding. If the contractor seeks to win contracts by increased operability without developing innovative solutions that will truly achieve this goal, the pressure can manifest itself as increased risk to the products being installed, to installation equipment, and to personnel who could be faced with unexpected situations in rough weather conditions.

4. Decision-making during project execution

Offshore construction vessels operate under potentially harsh and varying conditions to execute nonroutine work. The work is typically performed according to a detailed schedule. Under normal operations, the overall decision is to follow the schedule or deviate from it. A deviation from the schedule is undesirable because of the economic consequences and implies that the risk associated with continued operations is potentially judged as being too high, either to personnel, vessel, installation equipment, or the products being installed. Unexpected situations can occur that may or may not be related to weather conditions. Some examples of unexpected events that were not planned for during offshore operations include resonances because of Mathieu instability during the lowering of equipment to the seafloor (Kang et al., 2017), bursts of internal waves (Osborne et al., 1977), or prolonged periods of swell waves in resonance with the equipment being used (Equinor, 2003). Under these circumstances, the organization still needs to make decisions that have consequences for the safety and reliability of the operations, on the one hand, and financial consequences, on the other hand, but with more uncertainty and often less time available to make a decision. These situations require competent and knowledgeable management. The theory of high-reliability organizations (HRO) stipulates that some organizations manage to perform reliably and without severe incidents even under such circumstances. HRO provides five principles that characterize such organizations: preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience, and deference to expertise (Roberts, 1989; Weick and Sutcliffe, 2015).

Step-by-step procedures are developed by the contractor's onshore organization during the detailed planning phase, including specific guidance on acceptable weather conditions for each task to be performed. Multiple design reviews are held among the client, MWS, offshore project crew, marine crew, and other stakeholders. Although design reviews between the client and MWS ensure compliance with the project goals, rules and regulations, best practices, and so forth; the involvement of the offshore organization is equally important to ensure that engineered solutions developed onshore consider the practical challenges faced by the offshore personnel who are meant to implement them.

Qualitative risk assessments, such as hazard and operability studies (HAZOP), are conducted during the installation planning phase. This involves a multidisciplinary team, including offshore organizations, who have the experience needed to identify and assess those risks related to the practical implementation of the plans. Reference can be made to Rausand and Haugen (2020) for details on the HAZOP approach. Recommendations from the HAZOP are followed up by, for example, introducing barriers, adapting procedures, or increasing the supporting knowledge to handle the risks identified. Quantitative approaches (Vinnem and Røed, 2020) could also be useful, but the required data are normally not available for specific marine operations.

Although the contractor's onshore organization supports the work during the execution phase, it is the offshore personnel who decide whether tasks can be executed safely. Offshore construction work is ongoing 24 h a day, including weekends and holidays, meaning that the onshore organization is normally less available during much of the working time. The highest authority in the project offshore crew is the offshore manager, who has the discretion to allow, deny, or require a change in any of the tasks developed during the installation planning phase and who signs task plans for execution. The captain is responsible for the safe operation of the vessel, its cargo, and personnel and has the highest authority onboard, also being above the offshore manager. If a crisis arises, the captain is responsible for coordinating a response. Additionally, the captain represents the vessel owner and is responsible for facilitating the execution of the project work.

5. Installation analyses and response forecasting

Computer simulations of operations that apply weather conditions as an input to a physics-based response model—namely installation analyses—are a common method for checking feasibility and determining the environmental limits for offshore installation work. In principle, response forecasting is a simple extension of this analysis process by rerunning models with more detailed weather conditions that can be obtained nearer to the point of execution.

Fig. 1 provides an overview of the three phases outlined in the production of the response forecasts. The process starts with an upfront installation analysis, which is normally performed for all projects, regardless of any intended use of response forecasting. This phase typically starts months before the operation, and the objectives are to determine the feasibility of the operations as they are initially planned, which may depend on the location and planned installation season. The analysis can be an iterative process in which the findings are used to optimize procedures. However, the scope of installation analyses is limited to assessing a few critical responses that indicate the risk of damage to a product or risk of an uncontrolled situation if a certain threshold has been exceeded. Examples of this include the stresses in a pipeline during laying or the tension in a rigging item during the lifting of a structure.

Unlike upfront installation analyses, response forecasting also requires continuous simulations during the execution phase as new weather forecasts are made available. For reliable execution, the process needs to be automated and monitored, and the models and simulation methods used for response forecasting need to be validated during the installation planning phase of the project. Successful implementation of response forecasting relies on several components working simultaneously: wave forecasts need to come through, computers calculating responses need to be operative, preprepared models need to be stable and suitable for running the new forecast conditions, and, if calculations are performed centrally, internet access is needed both where calculations are performed and at the site where results are used. It should also be noted that, even with on-site calculations and for decision-making based on forecasted wave parameters, an internet connection is needed to receive weather forecasts. Therefore, the requirement of an internet connection is not specific to the implementation of a response forecasting service.

The validation phase is used to select the best method for simulations during project execution; considering the required calculation time vs accuracy reduction and whether it will be feasible to implement the method using available computational power. Full time-domain simulations of a model may be too time-consuming for use in response forecasting; however, it is often feasible to reduce the simulation time but at some cost of accuracy. For example, some critical responses could be related to parameters that are computable in the frequency domain, such as vessel motions (Legras, 2008). For response models where this is not feasible, other methods may exist. A hybrid data-driven method for predicting time series loads in pipelines has been developed before (Chaves et al., 2015; Christiansen et al., 2013; Guarize et al., 2007; Srikonda et al., 2018). This method may also be applicable to other response models under stationary conditions. The method proposed by Passano et al. (2008) relies on rerunning short simulations around expected critical events in the time domain. Guachamin-Acero and Portilla

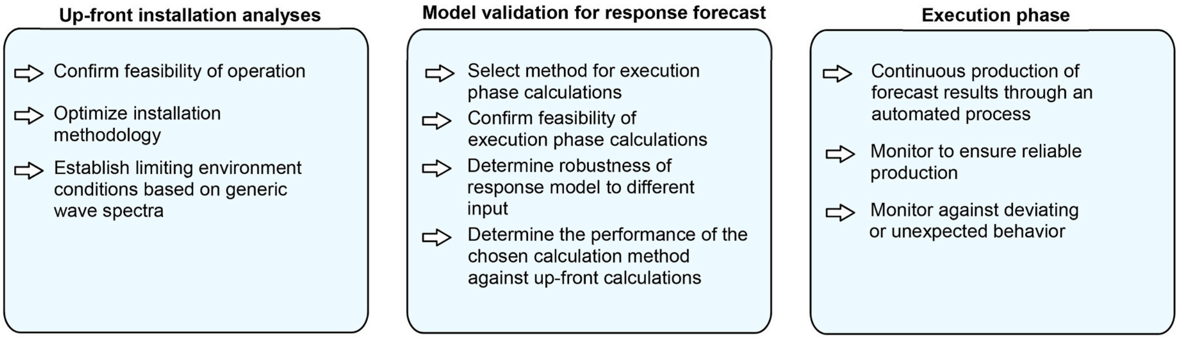

Fig. 1. Installation analysis objectives by phase.

(2022) have proposed a boosted regression tree model for the prediction of responses from wave spectral characteristics, which may have applications to lifting operations or other types of transient conditions. The performance of the selected method is validated in an independent data set containing a wide range of relevant wave conditions, such as selected historical records of two-dimensional wave conditions, against the results obtained using the original upfront analysis methodology. The validation data set may be selected based on Monte Carlo theory with the application of importance sampling (Melchers and Beck, 2018).

Within the limits of the underlying weather forecast and analysis models used to process it, response forecasts present decision makers with information that is directly relevant to their decisions. This can be displayed as a simple "yes" or "no" to performing a specific operation at a specified time but would typically also include the value predictions that are directly relevant to the decision. The alternative to a response forecast is to use the upfront installation analysis results directly and to perform a manual comparison between forecasted wave parameters and the calculated weather limits. Because these limits are often sensitive to the frequency and directionality of waves (Kragtwijk et al., 2002; Natskår et al., 2015), the comparison will usually imply a degree of interpretation. An example of this is the existence of two different wave systems with different characteristics of frequency and direction, often a combination of a wind-generated system and a swell system with long periodic waves. The planning phase work does not typically include such a complex but common sea state because of the immense number of possible combinations, meaning that decision makers must consider the combined effect subjectively at the site. Long swells that have frequencies in resonance with system frequencies may, for example, be overlooked in favor of a wind sea system that governs the total energy and peak of the spectrum. Response forecasts use the forecasted two-dimensional wave spectrum, which contains the most detailed information about the wave energy distribution available at the time of the decision.

6. Implementation of response forecasting in the decision-making process

Response forecasting intends to improve the performance of decision-making during offshore operations by integrating more detailed and representative weather data into the response models compared with conditions assumed during the upfront installation analyses, thereby improving the reliability of operations and reducing the cost of weather waiting. A response forecast also significantly simplifies information to offshore decision makers since the task of comparing forecasted wave parameters with limiting values is not well defined, particularly due to multimodal wave systems.

The task of comparing a forecasted response with its limiting value is very straightforward. Much of the uncertainty is managed through regulations, and the decision relies on a simple comparison between two numbers. Effectively, a response forecast can be seen as decision advice. Joslyn and Grounds (2015) have conducted experiments to study the differences in decision quality and conclude that adding specific advice is helpful, particularly in counteracting the human tendency to lower the threshold when the forecast is generally more severe. Even so, it must be noted that their experimental setup provides consistently reliable advice to the participants (the advice should always be followed to achieve the highest score). Advice from a response forecast should not be followed blindly because it is not always reliable. An assessment of the advice's quality is needed, which typically requires expert judgment.

Response forecasting introduces a level of automation in the decision process, such that some human judgment is replaced by machine judgment. This can be a positive development, especially in this context where the task is predominantly data integration (Endsley, 1995). Negative implications could include complacency due to a lack of understanding of how the automation system works (Wickens, 1995) and a shift towards more centralized decision making (Veitch and Alsos, 2022).

The digital distribution of response forecasts simplifies the process of providing access to personnel such as experts, who can contribute to decision-making independently of their physical location. The implementation of a decision-support tool should, however, not lead to more rigid and centralized decision-making, which would be a hindrance to reliability according to HRO (Weick and Sutcliffe, 2015); it should be acknowledged that the management onboard the vessel (e.g., the captain) has the responsibility for the crew and the vessel. Organizations should be wary of a wider distribution of response forecasts to stakeholders who do not have sufficient insights into the limits and functioning of the tool, including the management of the client and contractor, where misinterpretation of the forecast and a lack of situation awareness could lead to undue pressure on the offshore organization.

The response forecasting process can be interrupted, for example, because of breakdowns in the computers that run the required simulations or interruptions in the services used for distributing the results. This would lead to delayed or missing forecasts. Response forecasts could also provide faulty information because of errors in the analysis models, design criteria, weather input, or forecasting process itself. The analysis models and design criteria used in response forecasting are generally the same as the upfront installation analysis developed during the project planning phase. These should comply with standards and best practices applicable for the project, and although any error originating from the modeling or selection of design criteria is unfortunate, it is not specific to response forecasting. Response forecasting differs from upfront installation analysis in that simulations are executed automatically, and for some analysis problems, it requires more efficient calculation methods at the cost of accuracy. The automated simulation process includes simulations that combine weather input with response models, statistical processing, and the reporting of results to decision makers. Some response models may be suitable under certain weather conditions but become unstable under more severe conditions; similarly, simulation results may fit well with a selected probability distribution under certain weather conditions and poorly with others.

Situations that lead to missing or faulty information in the response forecast should primarily be avoided: by upfront validation, monitoring, redundancy in the system, and by ensuring the availability of competent personnel at short notice if a need arises. Plans should be made for a situation where response forecasts are missing; which implies falling back on a manual comparison of forecasted wave parameters with upfront installation analysis results. Additionally, the process and conditions for deviating from the normal procedure should be planned and accepted by the stakeholders involved, including the client and MWS.

Based on the discussion in this section, as well as practical experiences from applied response forecasting in offshore construction work, a list of principles is proposed for the implementation of a response forecasting service:

- The limitations of the response forecasts should be clearly communicated to personnel using the response forecast in decision-making and also to personnel who receive the forecast but are not directly involved in the decision-making.
- The response models and methods selected for analyses during the execution phase should be validated during the installation planning phase of the project by considering robustness, computational efficiency, and accuracy, and using a wide range of environmental conditions that fully represent the conditions that are relevant to the operation. Reduced reliability compared with the upfront installation analysis should be conservatively accounted for by uncertainty/safety factors.
- Engineers who are competent and familiar with the installation analysis for the operation should be available to the offshore manager for consultation and to continually monitor the results produced by the response forecasting service. Detailed results from the automated analysis needed to assess the correct functioning of the service should be made available.
- Competent personnel should be available on call to remedy any service interruption during the critical parts of the operation.
- Parameters from the wave forecasts used as an input to the response calculations should be continually compared against other sources, such as alternative forecasting services or monitored wave conditions, and the results from response forecasting should be deemed unreliable in the case of deviations being significant. An engineer should be available for this task.
- Service interruptions because of missing or invalid results should be expected, and a return to the use of manual comparison of the wave forecast against the upfront installation analysis results should be planned for.
- The captain of the vessel should, as always, be kept informed regarding the decision-making processes and risk evaluations because the captain is the highest authority on the vessel and has the right to abandon the operation at any time should there be safety concerns regarding the personnel or vessel. This includes any concerns about the reliability or applicability of the response forecasting service when relevant.
- Feedback from the offshore organization should be collected because it is crucial for designing a service that achieves the overall goal of more reliable and efficient operations.

7. Practical implementation of response forecasting

7.1. Introduction

The use of response forecasting as a decision-support tool has, up until now, been discussed in general terms. In this section, the implementation of a response forecasting approach for a specific operation is investigated in detail to highlight the practical differences in decision-making supported by a single value limit on the significant wave height (Hs) or a tabulated Hs limit.

The case study is based on experiences from a recent rigid pipelay project. The term “rigid pipelay” is used for laying steel pipes on the seabed, typically connecting two locations, for example, a production well and a processing unit, for the transportation of oil, gas, or water.

The section is organized as follows: Section 7.2 provides details on the case study operation, including the operational parameters required to identify suitable weather windows. Section 7.3 lists the data sources applied in the study, consisting of recorded, hindcast, and forecast wave data. A simple method for applying forecast uncertainty to two-dimensional wave spectra is discussed in section 7.4. Section 7.5 provides three different methods for applying a limiting wave criterion to the operation. Section 7.6 presents the forecast timeline from the calculation of the wave forecast that is initiated until decision support is available to the offshore crew. Finally, the different methods are compared in section 7.7.

7.2. Description of operation

The installation of an inline structure (ILS) can be a critical operation during a pipelay campaign. This is a structure that is welded into the pipe during the offshore campaign and deployed to the seabed together with the pipe. The process for installing it is described by the following steps (Fig. 2):

1. The pipe extending from the vessel to the seabed is clamped at the exit point from the vessel and cut to allow space for the structure.
2. The ILS is lifted onto the laying ramp, positioned, and prepared for welding.
3. The structure is welded to the pipe at both ends.
4. The clamp is released, and the ILS follows the pipe to the seabed as it is laid. Finally, the ILS lands on the seabed, and an additional pipe is laid until the structure is stable on the seabed.

The time to complete the full process is assumed to be two days (48 h). This duration significantly depends on the properties of the pipe, and the proposed 48 h could be representative of a complex cross-section and structure. The process can be aborted within a window of 24 h by cutting the structure from the pipe and welding a temporary cap onto the end extending from the seabed. The loose end can then be laid on the seabed and abandoned. Even though it is possible to abort the operation, it is undesirable because it places the whole operation back at the starting point and cutting the structure from the pipe reduces the material available for the next installation attempt. Therefore, the full duration of 48 h is used as the “safe to safe” operational duration.

Offshore installation work is performed in accordance with regulations, such as the DNV’s marine operations standard (DNV, 2021). This design code requires that a minimum contingency time of 50% be added to the planned duration, which means that a weather window of 72 h is required for a commitment to initiate. It also requires that the calculated limit for the significant wave height is adjusted to account for forecast uncertainty; typically, this requirement is satisfied by using a tabulated factor in the code labeled the α-factor (DNV, 2021).

7.3. Wave data

Three different sources of wave data are considered in the present case study: recorded wave parameters from a buoy, hindcast data from NORA3 WAM, which is a 3 km reanalysis provided by Meteorologisk institutt (The Norwegian Meteorological Institute, n.d.), and forecasted wave conditions. All data refer to the same field in the North Sea during the summer and fall seasons of 2021. Multiple sources of the forecasted wave conditions are also considered: data from two independent forecasters are obtained, and both forecasted wave parameters and a forecasted two-dimensional wave spectrum from each forecaster. It should be noted that the forecasted wave parameters are not a simple abstract of the two-dimensional wave spectrum. It is rather the forecasters’ best assessment of the weather situation based on multiple sources of data

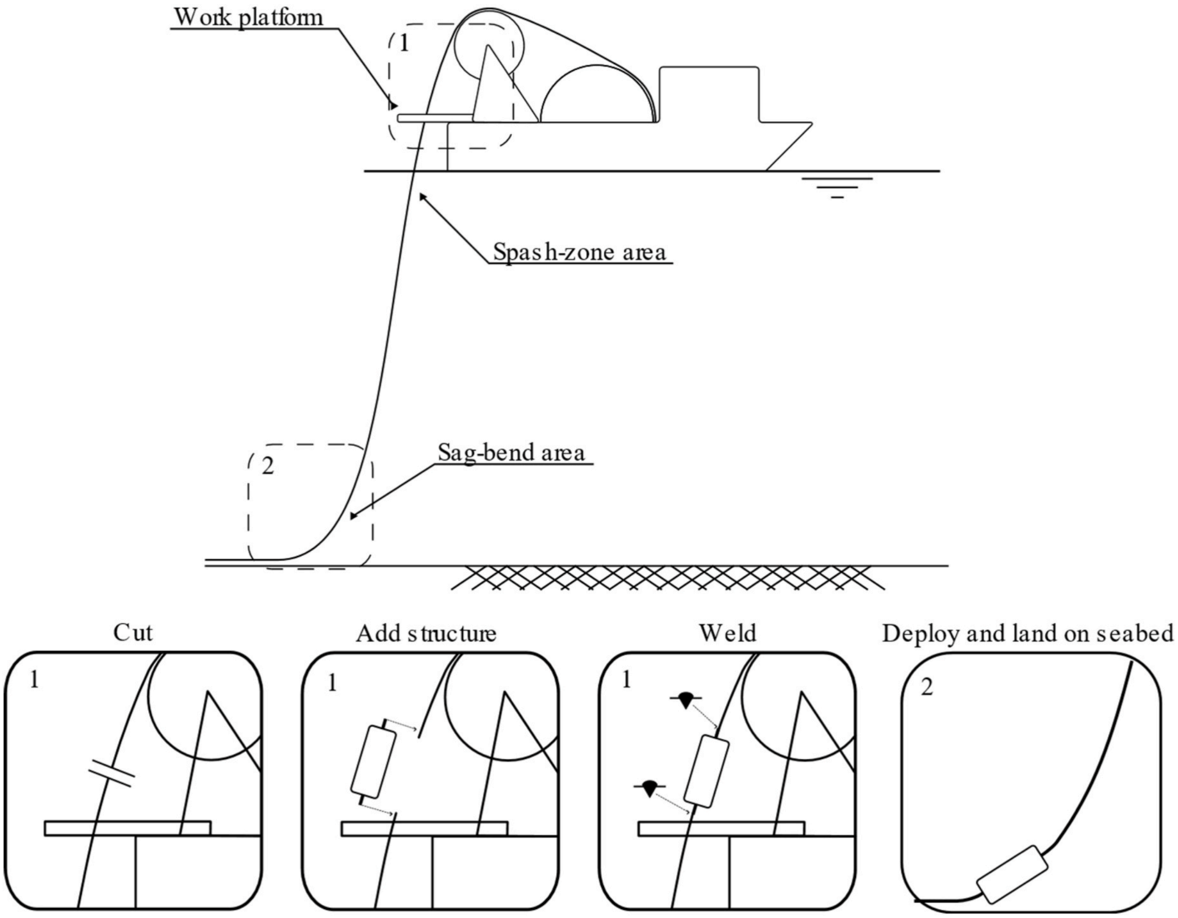

Fig. 2. Schematic view of a reel-lay vessel and installation of an inline structure (ILS).

that are integrated based on their trustworthiness and consistency. An interesting account is given by Daipha (2015) regarding how forecasters work with different data sources and deal with uncertainty. In total, six different wave data sources are considered, as shown in Table 1.

The performance of decision-making based on different forecast sources is compared through the number of correctly identified weather windows (efficiency), where the true response is lower than the limit and the number of incorrectly identified weather window (reliability/un-reliability), where the true response is higher than the limit. It is then necessary to assume a reference wave spectrum as the ground truth. Observed wave spectra of sufficient resolution are not available at the location, so for this purpose, the NORA3 WAM hindcast wave spectrum is applied. The accuracy of the hindcast data can be measured against the recorded data in terms of wave parameters to assess its suitability for the purpose of the present study. This has been generally considered in Breivik et al. (2022), where NORA3 is shown to have equal or better performance in estimating Hs compared with other hindcast data sets such as NORA10 (Bruserud and Haver, 2016; Reistad et al., 2007).

Specifically, for the present study, two campaign durations are considered in which full data sets are available: Campaign #1, from May 30 to August 20 covering 83 days, and Campaign #2, from September 10 to December 1 covering 82 days. Comparisons of the NORA3 WAM hindcast data against observed the data for the two campaigns are shown in Figs. 3 and 4, respectively, only including cases with monitored Hs between 1.5 m and 3.5 m, which are relevant sea states for the operation.

The trends in the comparisons are similar to those found in the literature (Breivik et al., 2022; Haakenstad et al., 2020; Reistad et al., 2007), with a small bias but a more significant standard deviation of the error. Although the hindcast wave spectrum is not a true representation of the actual sea state, it is generated using the same wave models that form the basis of wave forecasts produced ahead of time, hence applying a more accurate atmospheric input. As such, a comparison using the NORA3 WAM hindcast data as a reference is suitable to describe the uncertainty in responses caused by the simplification of the wave spectrum into a parametric representation and the uncertainty in the input to the WAM model at the issue time of the forecast. The effect of corrections to the forecasted wave parameters based on observations or adjustments based on known weaknesses in the wave models, that is, the effect of forecaster intervention, cannot be assessed in this comparison.

The significance of forecaster intervention is, instead, considered by comparing the prediction error of the significant wave height from the forecasted wave spectra, which is purely model based, and the forecasted wave parameters, which have undergone intervention, against

Table 1
Wave data sources applied in the case study.

Data label	Data source	Information
Recorded data	Wave buoy	Wave spectrum parameters
Hindcast	NORA3 WAM provided by Meteorologisk institutt (The Norwegian Meteorological Institute, n.d.)	Full two-dimensional wave spectrum
Forecaster #1: Parameter	First independent forecaster, wave parameters	Wave spectrum parameters
Forecaster #1: Spectrum	First independent forecaster, two-dimensional wave spectrum	Full two-dimensional wave spectrum
Forecaster #2: Parameter	Second independent forecaster, wave parameters	Wave spectrum parameters
Forecaster #2: Spectrum	Second independent forecaster, two-dimensional wave spectrum	Full two-dimensional wave spectrum

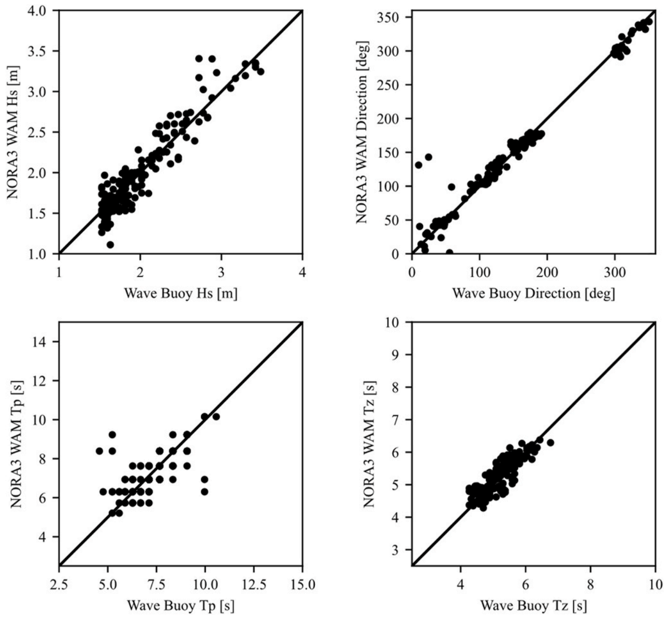

Fig. 3. Comparison of hindcast wave parameters against the measured parameters for Campaign #1.

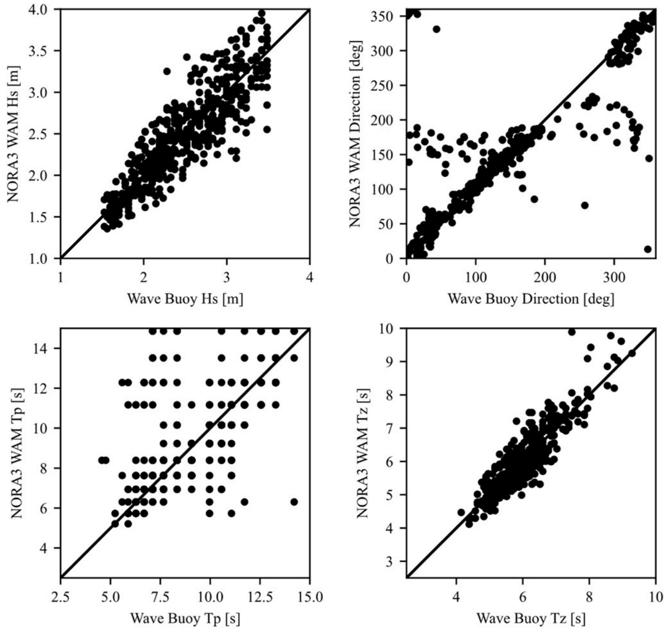

Fig. 4. Comparison of hindcast wave parameters against the measured parameters for Campaign #2.

Table 2
Root mean squared (RMS) error in hindcast and forecasted Hs compared with wave buoy measurements by forecast lead time for Hs between 1.5 m and 3.5 m during Campaign #1.

Lead	Hindcast	Forecaster #1		Forecaster #2	
	Spectrum	Spectrum	Parameter	Spectrum	Parameter
0	0.18	0.21	0.22	0.20	0.22
12	n/a	0.22	0.25	0.22	0.23
24	n/a	0.28	0.31	0.23	0.29
48	n/a	0.36	0.36	0.26	0.30
72	n/a	0.48	0.43	0.37	0.38

observed values from wave buoy measurements. This comparison is summarized in Tables 2 and 3 in terms of the root mean squared (RMS) error of the Hs against wave buoy measurements for different forecast lead times. The error of the hindcast wave spectrum is also included as a reference.

The comparison shows that there are only small differences in the RMS error between the parameter forecast and the spectrum forecast. An explanation may be found in Magnusson et al.'s (2001) observation, showing that a statistical improvement in forecasts from manual intervention is only visible for stormy conditions and that such conditions are not normally suitable for offshore installation work. Note that the mean error is expected to be low. Therefore, it has been omitted for clarity.

7.4. *Weather forecast uncertainty*

For projects following the DNV marine operations standard (DNV, 2021), uncertainty in the wave forecasts is normally accounted for by using an α-factor. This factor is applied to the limiting design Hs, which is established through the upfront installation analyses, resulting in a reduced allowable operational Hs to account for uncertainty in the forecast. The application of the α-factor to the design Hs is shown in Eq. (1).

$$H_{S,operational} = \alpha \cdot \mathrm{H}_{S,design} \tag{1}$$

A similar approach can be used for response forecasting by scaling the energy in the forecasted wave spectrum before it is applied to the response model, as shown in Eq. (2). Here, S denominates the values of the frequency and directionally dependent wave density spectrum, and this scaling is equivalent to scaling the Hs by the alpha factor.

$$S_{design} = S_{forecast} \cdot \left(\frac{1}{\alpha}\right)^2 \tag{2}$$

The alpha factor is not fixed; instead, it depends on the duration from the forecast issue to the end of the planned operation, the limiting significant wave height, and the level of available forecast services and monitoring aids. The age of a forecast, that is, the duration from the issue of the forecast until the time that the forecast applies, is a strong indicator of forecast uncertainty. For wave forecasts, a single alpha factor is normally used to scale the limiting Hs for the operation, providing a flat alpha factor for the whole operation duration while, for response forecasts, it is convenient to scale each forecast based on its age, accounting for increased uncertainty as the forecast progresses.

It is possible to use a higher alpha factor (reduced uncertainty) if specific mitigating measures are put in place, such as having two independent wave forecasts, the availability of a dedicated forecaster, or wave measurements at the site. These measures are often put in place for weather-sensitive operations, and as a result, an alpha factor is applied in the present study corresponding to Tables 2–7 in the DNV's marine operations standard that accounts for these measures. The factor varies between 1.0 and 0.61, depending on the significant wave height and operational duration. Specifically, for a 48 h operational duration and significant wave height between 2.0 m and 4.0 m, the alpha factor varies between 0.75 and 0.78.

Table 3
Root mean squared (RMS) error in hindcast and forecasted Hs compared with wave buoy measurements by forecast lead time for Hs between 1.5 m and 3.5 m during Campaign #2.

Lead	Hindcast	Forecaster #1		Forecaster #2	
	Spectrum	Spectrum	Parameter	Spectrum	Parameter
0	0.28	0.27	0.24	0.28	0.26
12	n/a	0.29	0.29	0.28	0.31
24	n/a	0.32	0.29	0.31	0.34
48	n/a	0.39	0.39	0.39	0.42
72	n/a	0.51	0.49	0.44	0.48

Alternative methods exist for including the forecast uncertainty that have not been considered. Wu and Gao (2021) propose a method for developing a response-based alpha factor that accounts for uncertainty in wave period and wave direction; however, this factor is specific to a response model and applies a generic representation of the wave spectrum. Guachamin-Acero and Li (2018) propose a method based on ensemble forecasting; however, this method assumes that limits are set on the weather forecast characteristics rather than responses, which stipulates that an additional uncertainty factor is needed if the forecasted ensemble cannot be assumed to cover the full range of possible weather conditions. The application of the ensemble method to response forecasting would also imply a vast increase in computational effort.

7.5. Limiting criteria for pipeline structural integrity

The main concern of the installation analyses is that the pipe could buckle, either close to the structure or at the clamped position on the vessel. Environmental conditions under which the pipe might fail depend on the pipe's cross-sectional properties, the structure's dimensions and weight, water depth, current conditions, and limitations on the installation equipment and vessel's motion characteristics. Critical parts of the operation normally include the exit of the structure from the vessel, the structure transition through the splash zone, and the structure landing on the seabed. In terms of Hs, limiting wave conditions could typically range from 1.5 m to 3.5 m.

To evaluate the local buckling criteria for a specific sea state, it is necessary to develop response models and run time-consuming simulations. During project planning and execution, this is normally done for a select set of environmental conditions during the upfront installation analysis and, potentially, for the forecasted wave conditions during the execution phase. The present case study requires a statistical comparison between different decision-making criteria, and the response model needs to be evaluated for a very large number of sea states. This leads to a considerable number of computationally demanding simulations.

Instead, the simulation time is reduced by the use of a surrogate model. Specifically, the full time-domain finite element simulations of the vessel and pipeline are replaced by a linear vessel-only model that can be evaluated in the frequency domain to identify the characteristic maximum vertical velocity at the hang-off location for a specified wave condition. As a result, the local buckling criteria on the pipeline are replaced by an approximately equivalent limit on this velocity. It is known that the vertical velocity at the position of the pipe exit from the vessel ("the vertical hang-off velocity") is an important parameter for describing tension and bending radius on pipes, flexibles, and cables close to the seabed during deep water installations (Legras, 2008). Unfortunately, the vertical hang-off velocity does not satisfactorily account for effects at the top of the pipe, such as direct wave loads on the pipe and structure or direct bending of the pipe at the hang-off location because of vessel roll and pitch, and it cannot satisfy the project's need for accuracy in load prediction for the ILS installation scenario. Even so, it is a good parameter for the purpose of a statistical study comparing different methods of forecasting and decision-making because much of the system's sensitivity to wave period and wave direction stems from the motion of the installation vessel.

Three different decision-making criteria are considered for comparison: (1) a single Hs limit that is checked against the wave parameter forecast, (2) a tabulated Hs criterion that is principally equivalent to a single JONSWAP spectrum modeled based on a wave parameter forecast, and (3) a response criterion based on the two-dimensional wave forecast without meteorologist intervention. The alternatives are detailed in Table 4.

Table 4
Alternative decision-making criteria compared in the case study.

#	Label	Note
1	Single Hs limit	A single, conservative, limit on the significant wave height that is checked against the wave parameter forecast
2	Tabulated Hs limit (JONSWAP approximation)	A tabulated limit on Hs for different combinations of wave period and wave direction (typically the spectral peak period and mean wave direction). The limit represents a two-parameter JONSWAP approximation of the wave spectrum from the governing wave direction, with an additional assumption on wave spreading.
3	Response limit	A limit applied directly to the relevant response. This limit must be compared against a characteristic value that is calculated from the forecasted two-dimensional wave spectrum

The first approach of considering a single limiting value of Hs does not take into consideration the frequency or directionality of the waves, and conservatively, the lowest possible limiting value for any combination of wave direction and frequency must be used in decision-making. This limit is approximately 2.5 m for the case study. The associated extreme 3 h hang-off velocity amplitude in this sea state is 1.6 m/s for the construction vessel under consideration. The approach is illustrated in Fig. 5, where forecast uncertainty is accounted for by dividing the forecasted Hs (prediction) by the DNV α-factor (DNV, 2021) (dashed line) to compare with the design limit.

No weather window is identified in Fig. 5 because the scaled Hs (dashed line) grows well above the operational limit around September 17, about 24 h too early to fit a 72 h weather window. The predicted escalation of the Hs at 48 h, that is, just at the end of the planned operational period, is a real concern because there is often uncertainty around the timing of a weather buildup. Therefore, starting an operation based on the Hs limit and forecasted data shown in Fig. 5 is against DNV's operations standard.

A lookup table of limiting Hs values for combinations of wave period and direction is normally developed during the installation planning phase so that conservatism can be reduced, where each value in the table is calculated under the assumption that a single JONSWAP spectrum—or a similar parameter-based wave spectrum model—can adequately represent the wave condition. This approach is illustrated in Fig. 6. It is principally equivalent to response-based criteria that are based on a JONSWAP approximation of the wave conditions, assuming that the lookup table is highly detailed.

The decision maker is required to match the characteristics of the wave condition specified in the forecast with the parameters available from the reported table, which is a subjective assessment. Because the case study operation is sensitive to higher wave periods, more weight should be placed on the swell component of the forecast. Even so, for the case study, it is necessary to approximate this decision process, and the peak values representing the total sea are used. Where not available, the peak values are estimated based on the available forecast parameters, here assuming a JONSWAP-shaped wave spectrum.

The design limit and prediction shown in Fig. 6 are plotted in terms of vessel response on the vertical axis. It should be noted that the solid red line is not in fact observed data but is calculated based on the vessel model and hindcast two-dimensional wave spectra. In addition, the forecast uncertainty is accounted for by scaling the response instead of the significant wave height. This is possible because the vessel response spectrum is calculated by a linear transformation of the wave spectrum; therefore, a scaling of the response is equivalent to scaling the Hs of the input spectrum. For responses that do not scale linearly with Hs, it would be necessary to establish an equivalent response-based alpha factor to scale the limiting value, which is not generally possible. Hence, a scaling of the forecasted wave spectrum is a more general approach. It is observed that a weather window (green dotted area) can be established because the weather buildup around September 18 is not as significant in terms of vessel response as would be expected based on Hs alone. The response calculation accounts for the vessel's sensitivity to wave periods and directions, and a wind-driven wave condition typically has shorter

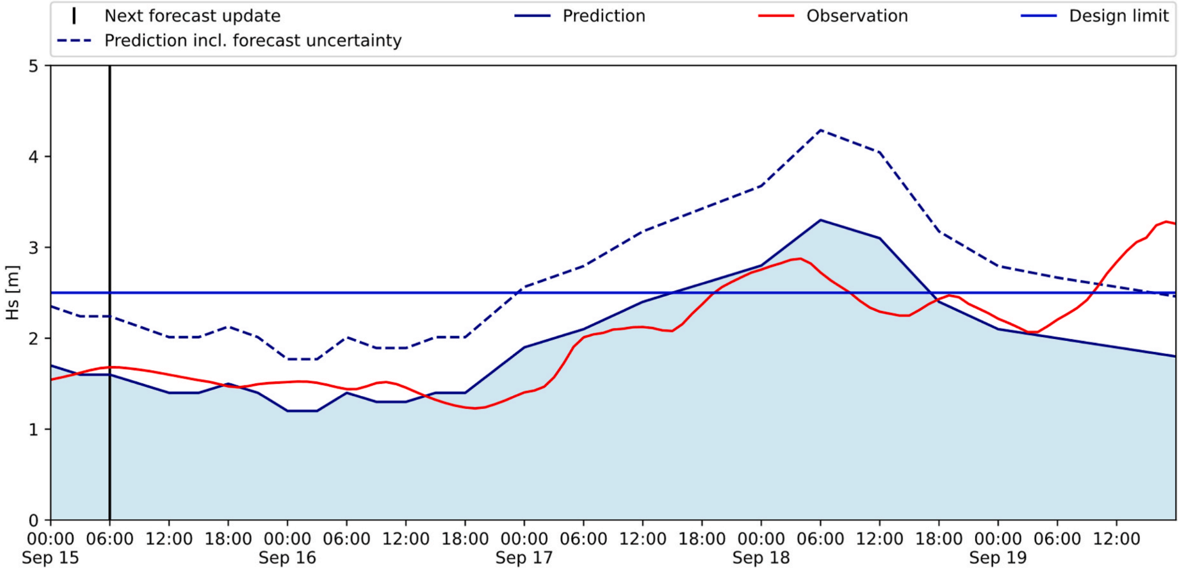

Fig. 5. Example of missed weather window, single Hs limit, and 72 h window with 2.5 m limit on Hs.

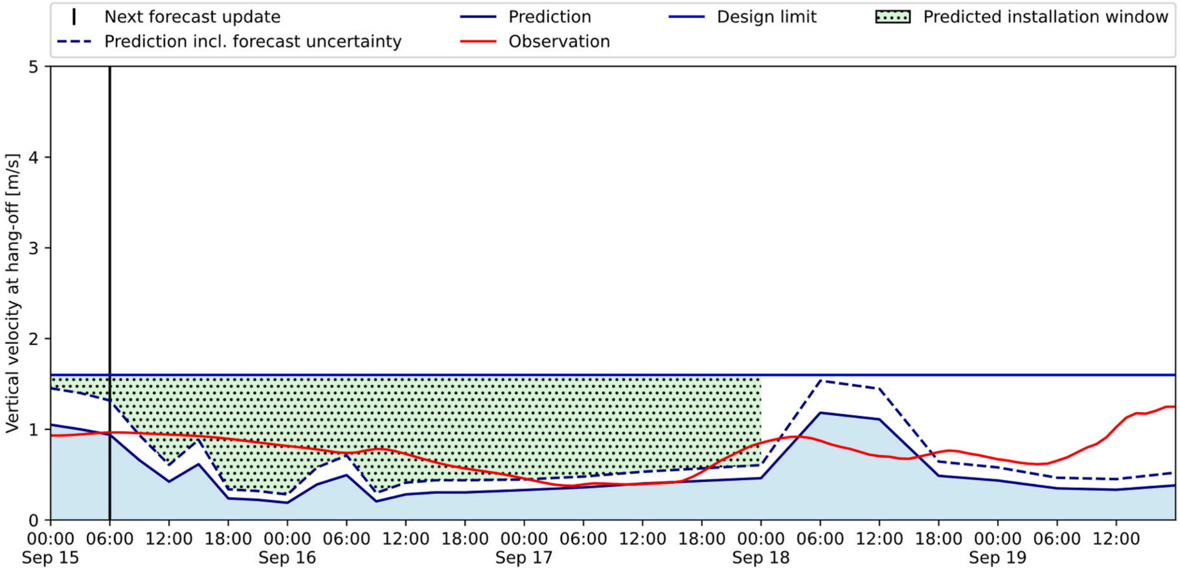

Fig. 6. Example weather window, tabulated Hs limit (JONSWAP approximation), 72 h window with 1.6 m/s limit hang-off velocity.

wave periods compared with swell waves originating from old storm conditions elsewhere, inducing less vessel motion.

The third approach, using a response-based limit, is shown in Fig. 7. Similar to Fig. 6, the predicted responses are shown (solid dark-blue line), as well as the design criteria (solid blue horizontal line). Instead of using a constant alpha factor based on the planned operation duration, a varying alpha factor is used based on the lead time of each forecasted spectrum such that the uncertainty increases as the forecast progresses. The prediction based on the scaled two-dimensional wave spectrum, that is, including the effect of forecast uncertainty, is shown as a dark-blue dashed line.

From Fig. 7, it is observed that the transition between a swell dominated system and a wind dominated system, around September 17, is smooth and fits well with the observation data, and the predicted installation window is well within the criteria. The duration of unavailability of the forecast to decision makers indicated in the figure as a hatched area stems from the stated issue time on the forecast. The issue time of the two-dimensional wave forecast is different from the meteorologist-intervened forecast because it has a different origin coming directly from the wave and atmospheric models. Although the two-dimensional wave forecast has a stated issue time at midnight between September 14 and 15, it is not distributed to consumers until several hours later, and further processing of the wave forecast is required before the calculated responses are available to decision makers at around September 15 at 12 a.m.

7.6. Comparison of the decision-making timeline for practical response forecasting and wave forecasting

The timely distribution of forecasts to decision makers is important. Therefore, it is interesting to consider the differences between decision-making based on a wave parameter limit by using the wave parameter forecast directly, and a method based on response limits, using calculated responses that are derived from the forecasted wave spectrum.

Fig. 8 shows the timeline for decision-making based on response forecasts, from the wave forecast issued until the operation is completed.

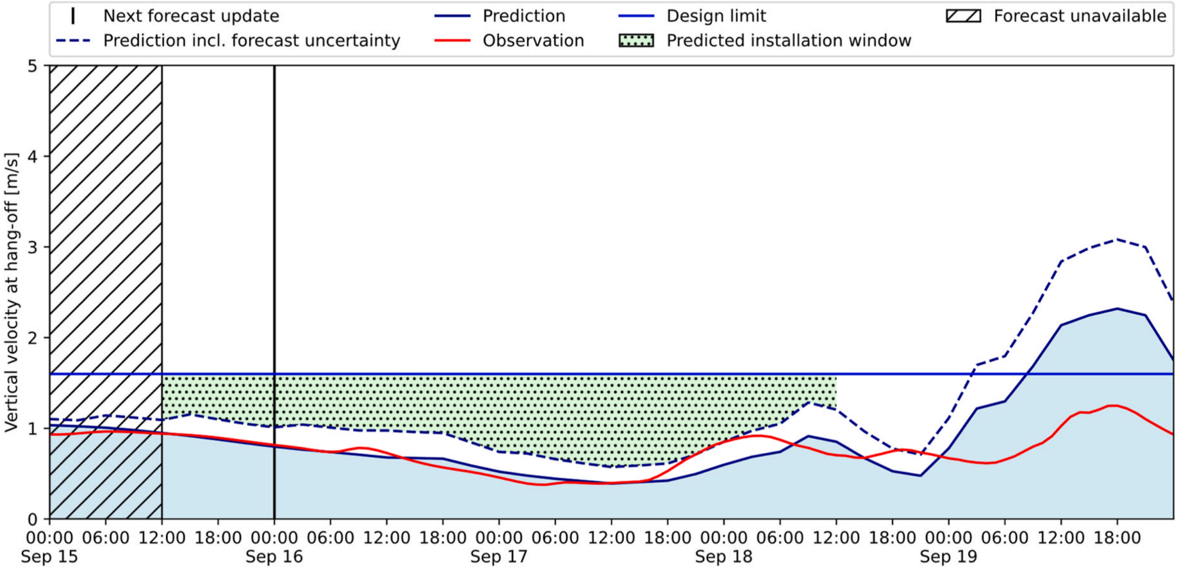

Fig. 7. Example weather window, response limit, 72 h window with 1.6 m/s limit on hang-off velocity.

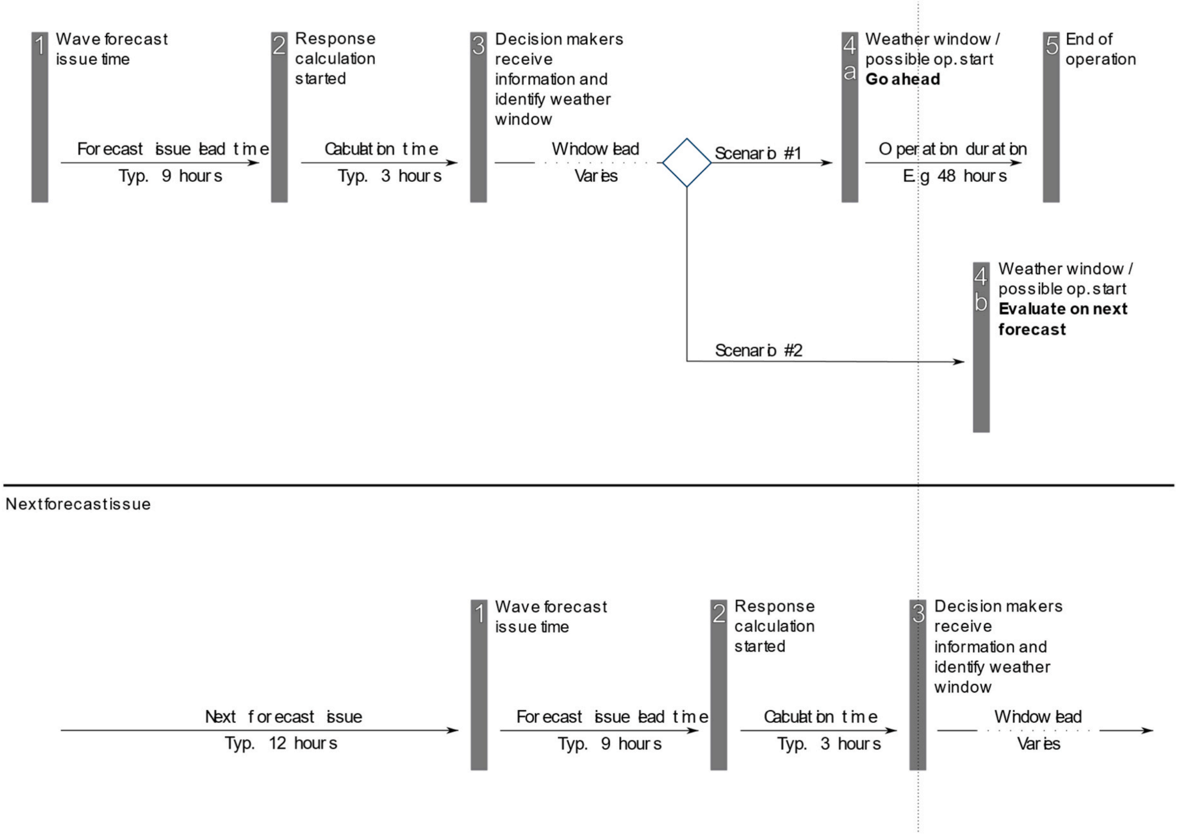

Fig. 8. Forecast-based decision-making schedule, response forecasting.

For the case study data, the stated forecast issue time is 8 to 9 h prior to distribution to consumers. This is labeled "step 1" in the figure. Response calculations are started immediately after the wave forecast is received in step 2 by combining each forecasted wave spectrum with one or several response models for each forecasted point in time. The duration it takes to calculate responses depends on the complexity of the response model, the available computational power, and calculation methods; however, a duration of 3 h has been applied in this case study, a duration in which the results from the forecast are still considered to be useful.

On completion of the response calculations, decision makers can identify potential weather windows in step 3. A weather window may be identified close in time, or it may be identified later in the forecasted duration, if at all. The duration from the forecast is reviewed by decision makers until the operation is started in step 4a, labeled "window lead," hence varying. If the window lead is relatively short, then the operation can be executed within the identified weather window, and step 5 indicates the end of the operation. If, on the other hand, the window lead is longer than the time between forecast issues (typically 12 h), it means that the forecast is already outdated and succeeded by a more recent forecast by the time the operation is due to start. This scenario is indicated by step 4 b. In this scenario, the next forecast is used for decision-making.

Fig. 9 shows the decision-making timeline based on the wave forecasts. The steps in the decision-making process are quite similar, but they do not include response calculations. It should also be noted that the forecast issue lead time, the time from step 1 to step 2, is typically zero because forecasts are manually updated with the most current knowledge about the wave and weather conditions just before forecast distribution and that the time between forecast issues is typically 6 or 12 h. In practical terms, this means that forecasts are perceived as being fresher at the time that they reach the decision makers, which also has an impact on the selection of the α-factor. Because the wave parameter forecasts provide spectral parameters rather than full wave spectra, it is possible for a meteorologist to manually adjust the values in the forecast, such as Hs (significant wave height) and Tp (spectral peak period) based on, for example, the latest observations. The difference in the definition of "issue time" between the wave parameter forecast and wave spectrum forecast may also explain why the forecasted wave spectrum often has slightly lower RMS errors at the same lead time in the case study data, as observed in Tables 2 and 3 in section 7.3.

7.7. Comparison of forecasting methods

The intent of the response forecasting method is to improve the performance of decision-making, leading to improved reliability and reduced cost of weather waiting. If an operation is performed in wave conditions that are too severe because the operation's sensitivity to the wave period and wave direction is not sufficiently accounted for by a generic wave spectrum, there is an increased probability of damage to the pipeline being installed. Conversely, if the operation is postponed because a possible weather window is not correctly identified, the contractor and/or client suffers an economic loss because of the increased construction time. A comparison between the three different methods, as described in section 7.5 (see Table 4), should therefore be based on the number of correctly identified weather windows (a higher number implies reduced cost) and the number of incorrectly identified weather windows (a higher number implies reduced reliability).

To make a realistic comparison between the use of forecasted wave parameters and forecasted wave spectra, it is not sufficient to compare responses calculated from a forecasted two-dimensional wave spectrum and corresponding generic JONSWAP wave spectrum. It is necessary to consider the different sources of the data, as described in section 7.3, the difference in application of the weather forecast uncertainty factor, as described in section 7.4, the information available to the offshore crew, as discussed in section 7.5, and the difference in the forecasting timeline, as described in section 7.6.

Based on this, the decision-making process is simulated through recorded data, and the number of nonoverlapping weather windows is counted. The counted weather windows are benchmarked against hindcast data, meaning that the reference response in hindcast data is calculated for each of the identified weather windows from the forecast and compared against the design limit (i.e., the limiting vessel downward velocity at the pipe hang-off position).

By applying the same method to the hindcast data, 27 windows are identified for Campaign #1 and 9 windows are identified for Campaign #2. These windows are, by definition, correctly identified because the hindcast defines the ground truth in the present study. The results from the forecast are presented in Tables 5–8 using data from different forecasters and different campaigns. Weather windows where the reference response is within the design criteria are deemed to be correctly predicted and counted in the first row. Any weather windows where the reference response exceeds the design criteria are counted in the second

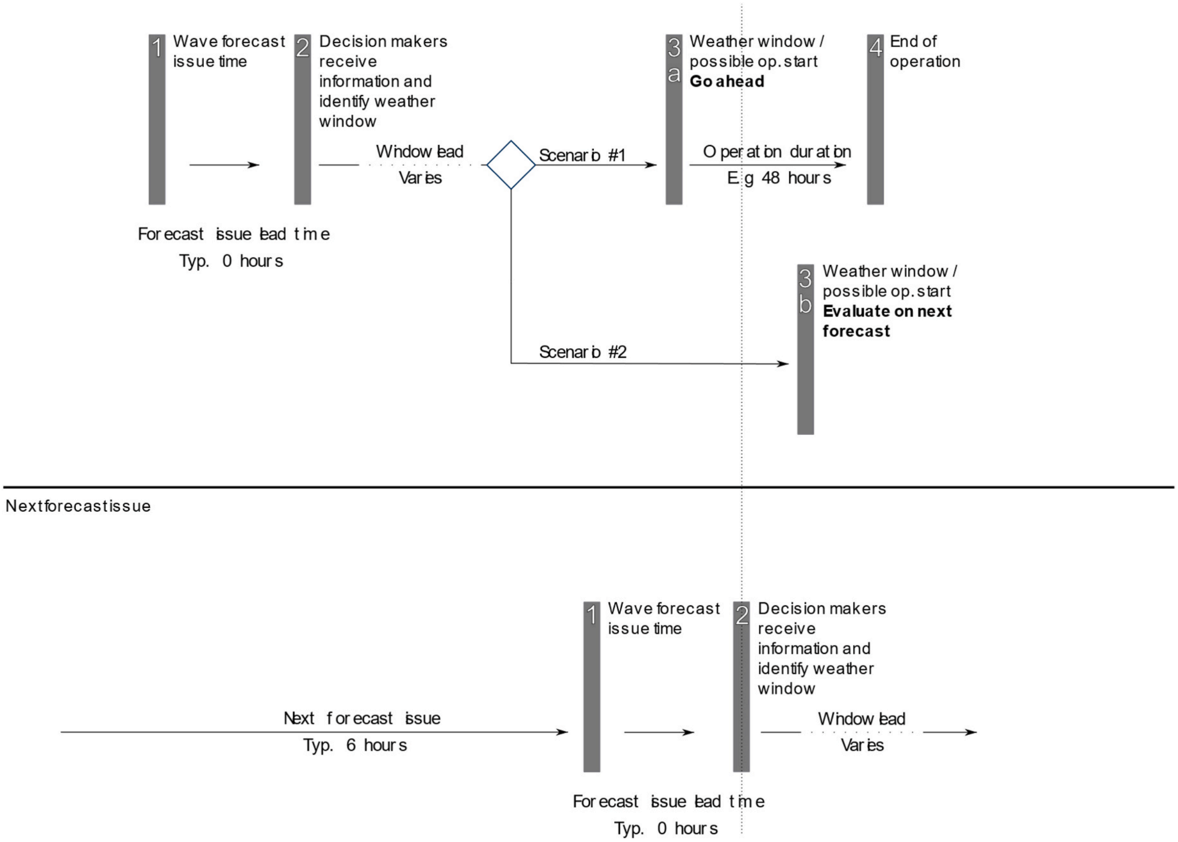

Fig. 9. Forecast-based decision-making schedule, wave forecasting.

Table 5
Weather window count for Forecaster #1 during Campaign #1 with different decision-making criteria.

	Response limit	Tabulated Hs limit	Single value Hs limit
Correctly predicted	23	25	18
Exceeds criteria <0.25 m/s	0	1	0
Exceeds criteria <0.5 m/s	0	0	0

Table 6
Weather window count for Forecaster #2 during Campaign #1 with different decision-making criteria.

	Response limit	Tabulated Hs limit	Single value Hs limit
Correctly predicted	26	24	20
Exceeds criteria <0.25 m/s	0	0	0
Exceeds criteria <0.5 m/s	0	0	0

Table 7
Weather window count for Forecaster #1 during Campaign #2 with different decision-making criteria.

	Response limit	Tabulated Hs limit	Single value Hs limit
Correctly predicted	4	7	1
Exceeds criteria <0.25 m/s	0	1	0
Exceeds criteria <0.5 m/s	0	1	0

Table 8
Weather window count for Forecaster #2 during Campaign #2 with different decision-making criteria.

	Response limit	Tabulated Hs limit	Single value Hs limit
Correctly predicted	6	4	1
Exceeds criteria <0.25 m/s	0	0	0
Exceeds criteria <0.5 m/s	0	0	0

or third row, depending on the level of exceedance.

The first column of Tables 5–8, ‘Response limit’, represents decision-making steps shown in Fig. 8, using calculated responses from the 2-dimensional forecasted wave spectrum, where forecast uncertainty is applied by scaling the wave spectrum with an alpha factor, as discussed in section 7.4. The identification of weather windows from a forecast according to this approach is exemplified in Fig. 7.

The second column, ‘Tabulated Hs limit’, represents decision-making steps shown in Fig. 9, comparing a tabulated limiting Hs from up-front analysis against values in a wave parameter forecast, effectively assuming a JONSWAP-shaped wave spectrum. Forecast uncertainty is applied by scaling Hs with an alpha factor, as discussed in section 7.4. The identification of weather windows is exemplified in Fig. 6.

The third column, ‘Single value Hs limit’, is derived from a similar process to the second column but uses a conservative limit on the Hs parameter for all wave directions and all wave periods. The identification of weather windows according to this approach is exemplified in Fig. 5.

Although the results based on forecasted wave parameters and forecasted wave spectra look very similar for Campaign #1, taking place during the summer, the comparison indicates that forecasted wave spectra are more accurate compared with forecasted wave parameters during Campaign #2, which take place during the fall. Even so, the number of weather windows is small, which means that this result cannot be expressed with confidence. Although Forecaster #1 predicts a higher number of correct weather windows for Campaign #2 using the forecasted wave parameters, this forecaster also predicts two installation windows where the design criterion is in fact exceeded. A common method that allows reduced weather uncertainty factors according to the DNV operations standard is to base the decision on the worst of two independent forecasts. In this scenario, both methods seemingly identify four windows as the minimum between the two forecasters for Campaign #2.

8. Summary

In this article, we have outlined how the method of response forecasting impacts decision-making during the execution of offshore installation projects. The method is an emerging technology for many types of installation work that require complex time-domain simulation models for the accurate prediction of responses. Guidance is provided for the implementation of the method in an organization that places emphasis on mitigating tendencies for oversimplification and overconfidence in results. Training and awareness among decision makers on the limits of the method, as well as the availability of expertise in the decision-making process, are important aspects for this.

Data collected from a recent project, executed during summer and fall 2021, are used in a qualitative study to compare the use of response forecasting against the traditional use of forecasted wave parameters in practical decision-making. The performance advantage of a response forecast stems from the use of two-dimensional wave spectra. Still, even though a two-dimensional wave spectrum contains much more information compared with spectral parameters, the origin is somewhat different. Forecasted parameters undergo a manual review by a meteorologist prior to the issue to adjust for known model weaknesses and incorporate other sources of data such as wave measurements. Currently, forecasted two-dimensional wave spectra are commonly provided directly from an atmospheric model without intervention. During Campaign #2 in the fall season, which is the most critical period for installation work, the response forecasting method seemed to be the most accurate because it correctly identified a larger number of weather windows with the second forecaster, while decision-making relying on forecasted wave parameters incorrectly identified two windows with the first forecaster, thereby increasing the risk of a pipe buckle. It should be noted that the total number of windows was very small for this case study. Hence, it is not the intent of the present study to conclude on the performance of the different forecasting methods. Rather, it has been shown that both sources of information are useful during the decision process. The response forecast incorporates multimodal wave conditions in a much better way compared with a single JONSWAP approximation, while meteorologist-intervened wave parameter forecasts provide a fresher view of the wave conditions that may reveal discrepancies between the forecasting model’s prediction and the meteorologist’s assessment at an early point. Decision makers may utilize both sources of information.

In conclusion, the present study has identified both the advantages and caveats for the introduction of response forecasting: (1) The ill-defined task of decision makers to manually interpret forecasted wave conditions into the generic conditions assumed during upfront installation analyses is avoided. (2) Decisions are based on more detailed information about the wave conditions because full two-dimensional forecasted wave spectra may be applied to the response models. (3) Timely distribution of response forecasts to decision makers is, however, a challenge because the response models may be computationally expensive. (4) Unlike forecasted wave parameters that are intervened by meteorologists, commercially available two-dimensional forecasted wave conditions currently do not integrate additional sources of information, such as measured wave conditions.

The present paper has only briefly described the challenge of computing time for running complex simulation models during project execution, so it is necessary to develop more efficient methods for running such simulations in the future. Furthermore, the selected method of using the DNV α-factor directly on the two-dimensional wave spectra is only stated and not thoroughly examined in the current paper; further work is needed to compare the chosen method against the traditional use of the α-factor and other methods to incorporate forecast uncertainty.

CRediT authorship contribution statement

Øystein Døskeland: Conceptualization, Methodology, Software, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Ove T. Gudmestad:** Conceptualization, Investigation, Writing – review & editing, Supervision. **Petter Moen:** Conceptualization, Data curation, Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

Øystein Døskeland reports financial support was provided by Subsea 7 Norway AS. Petter Moen reports financial support was provided by Subsea 7 Norway AS. Øystein Døskeland reports financial support was provided by Research Council of Norway. Øystein Døskeland reports a relationship with Subsea 7 Norway AS that includes: employment. Petter Moen reports a relationship with Subsea 7 Norway AS that includes: employment.

Data availability

The data that has been used is confidential.

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Abbreviations

HAZOP	Hazard and operability study
HRO	High-reliability organizations
Hs	Significant wave height
ILS	Inline structure
JONSWAP	Joint North Sea Wave Project
MWS	Marine warranty surveyor
NORA3	The 3 km Norwegian Reanalysis
RMS	Root mean squared
Tp:	Spectral peak period
WAM	Wave modeling

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