A simulation-based ship design methodology for evaluating susceptibility to weather-induced delays during marine operations

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ABSTRACT

In this paper, we present and test a discrete-event simulation approach for evaluating the inherent susceptibility to weather-induced delays during marine operations as a consequence of limitations in vessel response characteristics. The simulation routine replicates the execution of operations in a long-term perspective by applying weather data time series and vessel response-based operational criteria. Weather windows are taken as the basis for the operation start-up criterion. A case study is presented where we examine the capabilities of the simulation methodology towards reflecting the inherent weather challenges in operational scenarios and the ability to distinguish between alternative design concepts. Comparison is performed towards the percentage operability method and integrated operability factor to uncover advantages of the presented approach. Application of the simulation methodology is found to yield further knowledge of the inherent operational persistence and weather delay susceptibility of proposed vessel designs in the early phases of ship design.

KEYWORDS

Operational performance; simulation-based design; discrete-event simulation; ship design; weather windows; offshore construction vessels; marine operations; operability

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1. Introduction

Virtual testing has become an essential step in development and design of systems and technologies for a wide range of applications. For the maritime industry, the ability to test ship designs and concepts in an operational context, exposed to realistic weather conditions, represents a leap forward in terms of predicting and understanding design performance. The methodology presented in this paper aims to enhance knowledge of vessel design susceptibility for weather-induced delays during marine operations in the early design phases. It is based on a discrete-event simulation (DES) model that allows rapid testing of design concepts towards large sets of weather data. Operability is commonly assessed during design by estimating the limiting sea state curve for a chosen operational criteria, and calculating the percentage of operable sea states based on a scatter diagram generated using historical weather data from the area of interest. A virtual, simulation-based testing approach aims to replicate the long-term sequence of operations by introducing dynamics and models that govern vessel state transitions and behaviour. For ship designers, this provide freedom towards modelling more complex operational scenarios that better capture the associated operational challenges.

Vessels specialized for marine operations, such as offshore construction vessels (OCV), are often unique one-off designs custom made to perform specific sets of operation. These operations follow strict regulations and standards set by national directorates and class societies to ensure safety for personnel and economical assets. A challenging aspect of assessing the operability of such vessels is the requirement of weather windows. Traditional operability assessment is limited to analysis of single sea states, which implies operations with duration no longer than the sea state duration. Methods for assessing weather windows based on historical data exists, for instance the Weibull Persistence Method, and are often used for operational planning. However, according to the authors knowledge, these methods are rarely used in ship design and research.

An operability analysis is based on a criteria providing an operational limit. In a design context, such criteria are often set in accordance with ship owners and operators to reflect limitations of typical operations. For marine operations, most hydrodynamic limiting criteria falls under the category *motion response criteria*, according to the North Atlantic Treaty Organisation Military Agency for Standardization (2000). Such criteria are formulated directly from the vessel response characteristics, which are linked to limiting phenomena such as crane motions or structural loads. Clauss and Riekert (1990) and Berg et al. (2014) provide criteria for offshore operations. Another well documented type of criteria is the *derived response criteria*. This category contains limitations such as human comfort, motion induced interruptions, propeller emergence, slamming etc. Human comfort is a critical factor in design of passenger ferries, investigated in Tezdogan et al. (2014) using the percentage operability approach (%OP). An important note to designers is not to compromise on other aspects such as stability to maximize operability. After a series of small fishing vessels capsized off the coast of Spain, Mata-Álvarez-Santullano and Souto-Iglesias (2014) investigated whether designing for operability compromised safety aspects. An alternative operability assessment approach using Markov theory is presented in Anastasiou and Tsekos (1996), analytically establishing the distribution for the duration of operational activities based on the statistical properties of the return time of non-operable states.

If operational limits are exceeded, vessels are often kept standby at the site until a weather window allow operation. This disruptive event is referred to as waiting on weather (WOW), and is a major concern to operators due to the vessel cost structure based on day rates. Walker et al. (2013) assesses weather windows using Weibull Persistence Method for marine energy device installation off Britain's south-east coast to reduce installation costs, specifying vessels capable of operating in more severe weather conditions as one of the key factors for reducing downtime. Operational windows in the North Sea, Norwegian Sea and Barents Sea are studied in Kvamme et al. (2016) for an assumed operational limit of 3 m H_s. Guachamin Acero et al. (2016) presents a general methodology for establishing operational limits and assessing operability during the operation planning phase with emphasis on installation of offshore wind turbines.

Regulations for operation start-up is specified in Det Norske Veritas (2011a). The required weather window duration is defined as the planned duration plus contingency time to allow unforeseen events. Since the required weather window is evaluated towards the weather forecast, the limiting sea state is reduced to account for forecast uncertainty, see Natskår et al. (2015). This is done by applying α-factors depending on the type of operation, duration, and the significant wave height limit. Det Norske Veritas (2011b) provides recommendations for hydrodynamic and structural analysis of marine operations, providing recommendations for the Weibull Persistence Method, applied in Walker et al. (2013), and simulation-based approaches for assessing availability is presented in section 8.5. ISO 19901-1 European Committee for Standardization (2015) specifies the environmental considerations for assessment during marine operation design and planning. ISO 19901-6 European Committee for Standardization (2009) lists limiting phenomena to be avoided during operations as well as methods for analysing critical aspects of operations.

Research projects focusing on simulation-based methods for the maritime industry have been launched to provide the required tools and knowledge. For short-term simulations of marine operations, ViProMa (Virtual Prototyping of Marine Operations) applies distributed co-simulation and re-usable component and subsystem models for virtual prototyping (Skjong et al. 2017). Rokseth et al. (2017) presents a framework for modelling the interconnected dynamics of vessel and equipment during crane operations using bond graph. VISTA (Virtual Sea Trial) presents a simulation framework for complex marine operations, combining long-term and short-term assessment using DES and time domain simulations respectively in Erikstad et al. (2015). Erikstad et al. (2015); Skjong et al. (2017); Rokseth et al. (2017) applies the Functional Mockup Interface (FMI) standard for model exchange and co-simulation (Blochwitz et al. 2012). DES has also been applied to assess the long-term performance of maritime systems at vessel and fleet level. The IDEAS project presents an integrated decision support approach that allow comparison of ship designs based on simulation of vessels during sea passage (Fathi et al. 2013). For fleet assessment in the offshore industry, an optimised scheduling methodology for offshore construction projects containing a detailed operational description and a simulation model to account for weather uncertainty is presented in Kerkhove and Vanhoucke (2017). Maisiuk and Gribkovskaia (2014) addresses the fleet sizing problem of offshore supply vessels (OSV) using stochastic sailing times, service times and spot vessel rates. For movement of offshore mobile units, Shyshou et al. (2010) proposes a simulation model to assess the fleet sizing problem for anchor handling tug supply vessels (AHTS). Optimization and simulation is combined to assess the supply chain of OSVs in the Russian Arctic in Milaković et al. (2015). Bergström et al. (2016) presents a simulation-based probabilistic design method for assessing Arctic transportation systems, with focus on the additional information obtained by applying simulation and advantages of system thinking. The influence of uncertainty and model fidelity level for this approach is further addressed in Bergström et al. (2017).

The presented simulation-based methodology represents an alternative to the percentage operability and integrated operability factor (IOF) (see Gutsch et al. (2016, 2017)), which are established methods for assessing vessel susceptibility for weather delays and seakeeping performance during marine operations. To address this, we state the following research questions:

(1) What is the impact of considering weather windows as an operational criterion in terms of ship design performance evaluation?
(2) How does the proposed simulation-based methodology compare to the %OP and IOF methods in terms of evaluating the susceptibility to weather delays and distinguishing between alternative ship designs?

Application of DES in maritime research has been done to assess fleet size and mix problems for offshore support vessels, see for instance Shyshou et al. (2010); Maisiuk and Gribkovskaia (2014); Milaković et al. (2015). Bergström et al. (2016) addresses design and composition of LNG vessels in the Arctic at the fleet and ship level, focussing on transportation system performance. The novelty of this paper is a simulation-based approach which targets the effect of vessel design parameters on the susceptibility to weather induced delays, evaluated using motion response criteria. A new performance measure, which generalizes the percentage operability method by extending the operational scenario formulation, is presented and used to quantify the DES vessel performance estimates. Our problem description is on the ship level, presenting a methodology which provides information that exceeds existing methods for operability estimation. The resulting knowledge obtained from this methodology may however also provide information regarding the performance of vessels in fleet sizing and scheduling problems, which require estimates of possible delay situations. A case study is presented where the susceptibility to weather induced delays for OCVs are assessed for execution of light lift operations in the Norwegian Sea. Hindcast sea state time series from the Norwegian Meteorological Institute is used in the simulations.

The paper is structured in six sections. In Section 2, the simulation-based methodology for vessel design assessment is presented. Then, the case study for comparing the methodology towards existing methods is presented in Section 3. Thereafter, the results from the case study are given in Section 4. A discussion of fidelity level, sources of uncertainty, case study results and applicability of the presented methodology is given in Section 5. Finally, a conclusion with answers to the stated research questions is given in Section 6.

2. Methodology

In this section, a general description of the proposed simulation-based methodology for assessing susceptibility for weather-induced delays is given. First, we give a general problem description to emphasize the need and application for the methodology and motivate the case study. Next, we introduce the relative rate of operation (RRO), which is developed as a quantitative measure for evaluation of ship designs using simulation.

2.1. Problem description

In the early stages of design, the ability to conduct rapid testing of concepts is advantageous as it facilitates efficient exploration of a larger design space. However, the application of faster methods and routines should not compromise estimate accuracy and relevance, i.e. cause further abstraction of the problem. Our intention is therefore to present a methodology that captures the inherent challenge of the design task at hand, and provides additional valuable information for the designer. As mentioned in Section 1, our proposed methodology targets the assessment of susceptibility towards weather interruptions for vessels specially designed for marine operations. The scope of this paper is limited to single vessels performing operations which are restricted by criteria linked to the vessel motion response.

2.2. Method

Figure 1 shows the components and flow of information in the proposed simulation-based methodology. The method combines three independent components; the vessel, its intended operation, and specific scenario.

The vessel model contains information required to estimate the hydrodynamical responses critical for operation. If local criteria is to be applied, for instance crane tip motions, stern/bow heave motion, moonpool location assessments etc., the location of these points are included to allow derivation of local motion characteristics. The operation component consists of criteria which limit operation execution. For assessment of susceptibility to weather delays, we only consider criteria which are linked to the vessel response and environmental state. Combining vessel response characteristics and operational criteria allows derivation of the environmental limits of operation, which is given as input to the simulation procedure. The scenario component contains parameters for the system in which the vessel will operate, i.e. the site of operation and port, vessel transit speed, and other operational constraints. In addition, it contains information about the long-term behaviour of operation limiting factors, i.e. metocean variables.

In the DES environment, the vessel, operation and scenario components are combined to produce a long-term sequence of operation executions. This sequence describes the vessel's capabilities towards performing the operation in the given scenario and the susceptibility for weather delays, which can be quantified using a new performance measure, see Section 2.3 .

[Figure 1 about here.]

2.3. Relative rate of operation

Figure 2 shows four examples of long-term sequences of operation executions. The example cases vary in terms of weather window requirement and vessel length. Green segments indicate operation events, with vertical lines marking operation completion. Red segments indicate delays occurring for waiting on weather events. Even though all cases are simulated using the same time period and weather data, the number of completed operations is different due to varying operational duration and weather delays. The vessel operational performance is assessed using the *relative rate of operation* (RRO) measure in the simulation-based approach. RRO quantifies the operation's susceptibility to weather delays as a consequence of limitations in vessel design response characteristics.

[Figure 2 about here.]

For a specified time period, assuming deterministic transit, port and operation durations, a vessel is able to perform a certain number of operations provided it is not influenced by delays due to weather during operation. Exposing the vessel to weather will limit the number of operations that can be performed according to the operational limit and weather window criterion.

[Figure 3 about here.]

Figure 3 illustrates the RRO measure. The dashed line represents the planned operations, scheduled to take place at a specific, in this case constant rate, determined by the transit distance and operational duration. The dotted line describes the feasible number of operations, limited by the occurrence of non-operable weather events. Delay is taken as the difference between the planned and performed operations, indicated in red.

$$RRO = \frac{OP_{performed}}{OP_{feasible}} \tag{1}$$

The relative rate of operation, RRO, is taken as the ratio between the number of performed operations, $OP_{performed}$, and feasible number operations ,$OP_{feasible}$, see Equation 1. RRO generalizes the percentage operability measure by extending the scenario to include transit, port, and weather window requirements, set in the system component in Figure 1. The number of planned operations is calculated as the maximum number of operations feasible within the set simulation time, including the time spent in transit, port and operation.

3. Case study

This section presents the case study conducted to answer the research questions stated in Section 1. First, the particulars of the case study is presented in terms of the operational task, location and vessel type. Next, we give a detailed description of the assumptions and modelling of the simulation-based method, %OP and IOF.

3.1. Operation

The case study is set to the performance of subsea light-lift operations using OCVs. Lifting operations are classified as highly complex operations, involving large amounts of personnel and specialized equipment. Keeping the lifted object under control through all stages of lifting is critical and requires detailed planning for safe execution. Waves excite vessel hull motions, resulting in horizontal and vertical motions of the lifted object as a consequence of crane tip motions. Influence on response characteristics is low if the object mass is lower than 2 % of vessel displacement according to Det Norske Veritas (2011b). This is referred to as light-lift operations.

[Figure 4 about here.]

It is standard procedure to set the vessel heading such that the bow faces the weather in order to minimize vessel motions. This is possible provided that no operational constraint exists, such as close proximity to other structures or vessels. The operators may choose to have an angle β towards the weather to create a sheltered side of the vessel, as illustrated in Figure 4. A heading β of 15 degrees is chosen, which is a typical value since it provides some initial sheltering effects without having too strong roll excitations.

3.1.1. Site

The site of the operation is Haltenbanken in the Norwegian Sea, an area known for harsh weather conditions. It is assumed that the sailing distance between the site and port is 220 nautical miles. All vessel configurations are assumed to maintain a constant transit speed of 12 knots, implying a transit time of 18.3 hours.

3.2. Vessels

For assessment and comparison of operability measures and its impact of hull design variations, a hull geometry of a modern offshore construction vessel (OCV) design was selected as basecase vessel. The vessel hull is a design of a currently operating vessel in the offshore industry, developed for similar missions to that of this case study. Table 1 lists particulars for the basecase vessel.

[Table 1 about here.]

The hull geometry of the basecase vessel was homogeneously scaled creating a virtual fleet of comparable vessels with the varying main particulars: hull length (L_{oa}), beam (B), draft (D) and metacentric height (GM_t), see Table 2. Note that the beam is varied also for the length variation. This is done to maintain a reasonable L_{oa}/B ratio, which was determined based on a study of five OCV designs with L_{oa} on the range 80-160 m. The L_{oa}/B ratio was found to increase with length, from about 4.4 to 5.3 for 80 m and 160 m vessel respectively. A curve was fitted to the data and used to define L_{oa}-B combinations for variation of hull length as presented in Table 2. Since GM_t is defined by the waterline geometry, the vertical position of the center of gravity (COG) was adjusted in order to achieve the desired GM_t value.

[Table 2 about here.]

3.3. Simulation model

The system is modelled using the DES toolbox SimEvents (toolbox for discrete-event simulation in MATLAB). DES is a simulation class characterized by the assumption that the system state changes at discrete intervals triggered by the occurrence of events. An event is any occurrence which cause a change in the system state, triggered by a change in the system factors. A single vessel, generated as an entity at simulation initiation, starts the operation cycle in port as presented in Figure 5. Since our simulation routine considers single vessels, and we disregard the possibility of delays in operation caused by unavailable objects to be installed in port, we have not modelled the objects to be installed as entities. Hence, in this case study, the completion of operations is exclusively dependent on the occurring weather-induced delays caused by non-operable sea states at the site of operation.

[Figure 5 about here.]

Figure 5 shows the simulation procedure which consists of three main stages; port, transit and operation. This type of model is referred to as a roundtrip-model due to its loop formulation. The following states are defined to cover relevant vessel activities:

(1) **Port**

Location for crew exchange, mobilization of equipment and replenishment of food, water and fuel.

(2) **Waiting for weather in port**

If the current weather forecast show low or zero probability for operational success at the time of arrival, the vessel is kept in port until forecasts improve.

(3) **Transit port-site**

Transport leg required to reach the site of operation.

(4) **Operation**

In accordance with the specified operational description. Limited by the occurrence of non-operable sea states.

(5) **Waiting on weather at site**

Due to uncertainty in the weather forecasts issued while the vessel is in port, the operation may be postponed if the weather at site is non-operable at the time of arrival. In such cases the vessel is standby at site monitoring forecasts, proceeding to operation once the operational criteria are met.

(6) **Transit site-port**

Return to port - start new operation cycle.

An operational feasibility threshold is applied to avoid unrealistic WOW durations at site. A 72 hour deterministic weather forecast data is scanned when the vessel is in the WOW state. If H_s exceeds 5 m continuously for more than 12 hours, the vessel will return to port without performing the operation. If an operable weather window occur within the same horizon, the vessel will remain at site and perform the operation.

3.4. Weather data

Weather data from the site, i.e. the long-term variability of H_s and T_p, is provided by the Norwegian Meteorological Institute. The dataset contains time series from 1957 to 2014. Fixed-length simulation is applied, utilizing the entire dataset. The weather data is sorted according to season producing four 123.456 h time series.

3.5. Port actions

The vessel will stay in port until a suitable weather forecast arrives. A simple deterministic criterion for leaving port is applied, where the limiting sea state curve is increased 20% and assessed towards the historical weather data and weather window criterion for the time the vessel will arrive at site. Hence, the criterion does not affect the RRO estimates, as the vessels will not miss any operable states due to conservative forecasts in port.

3.6. Operational criteria and limits

The core of any operability study is the knowledge of limiting phenomena and their governing factors. Hazards that can lead to limiting phenomena are identified using a hazard identification study (HAZID). After limiting phenomena are identified (cable tension, object collision hazards, slamming loads etc.), associated limiting criteria are determined. The criteria discussed here are limited to those that can be described and assessed by means of dynamic analyses. Motion response criteria are frequently applied to assess operability of marine operations. These may be divided into two groups; global and local motion criteria. Global criteria limits the global motion components of the vessel in the six degrees of freedom describing vessel motion, local criteria limits the combined surge, sway or heave motion of a specific part of the vessel. The choice of criteria depends on the purpose of the study and the amount of available information. In early ship design, or a research context, global criteria are often preferred due to their more generic form. For detailed engineering applications and operational planning, local criteria might be preferred to incorporate the necessary level of detail (for instance location of the crane tip, moonpool etc.).

For weather restricted marine operations, the applied limiting factors are usually metocean conditions describing the environment in which the vessel will operate, like waves, wind and current. In order to establish operational limits for upper weather thresholds, frequency domain analysis of response and short-term statistics are often used. This is outlined in Figure 6.

[Figure 6 about here.]

The first step of frequency domain analysis is to determine vessel response characteristics in six degrees of freedom, defined by the response amplitude operators (RAO) $|H_{\eta_i\eta_i}(\omega)|$ and phase shifts ϵ_i. Assuming a linear response process, we may express the response η_i of degree of freedom i exposed to a harmonic wave with amplitude ζ_a and frequency ω as

$$\eta_i(t) = \zeta_a \cdot |H_{\eta_i\eta_i}(\omega)| \sin(\omega t - \epsilon_i) \tag{2}$$

Further, by assuming rigid-body motion, the response vector $\mathbf{S}$ is expressed using all six degrees of freedom as

$$\mathbf{S} = \eta_1\mathbf{i} + \eta_2\mathbf{j} + \eta_3\mathbf{k} + \Omega \times \mathbf{r} \tag{3}$$

where the first three terms express translation in surge, sway and heave respectively, and $\Omega \times \mathbf{r}$ express the motion contribution locally in point $\mathbf{r}$ due to rotation in roll, pitch and yaw from rotation vector $\mathbf{\Omega}$. $\mathbf{S}$ is deterministic, and allows computation of displacements, velocities and accelerations for all locations on the vessel.

To assess response in an irregular sea state a characteristic wave spectra is introduced. Wave spectra describe the distribution of sea state energy among wave frequency components. Fourier analysis is used to create individual regular wave components with amplitude determined by the wave spectrum. The phase difference between the components is unknown, and assumed to be uniformly distributed on the interval $[0, 2\pi]$. This stochastic component gives rise to what is referred to as short-term variability. The implication of short-term variability is that we are not able to predict exact irregular response. Instead, irregular response is characterized using stochastic values. The response spectrum, $S_{\eta\eta}(\omega)$, is expressed using the response amplitude operator and wave spectrum $S_{\zeta\zeta}(\omega)$ as

$$S_{\eta\eta}(\omega) = |H_{\eta\eta}(\omega)|^2 S_{\zeta\zeta}(\omega) \tag{4}$$

The linear response assumption and harmonic loading implies a Gaussian distribution for the instantaneous response with expected value zero and standard deviation expressed as

$$\sigma = \sqrt{\int_0^\infty S_{\eta\eta}(\omega) d\omega} \tag{5}$$

The distribution of instantaneous response can be used to derive estimates for characteristic response values. If we assume a narrow-banded sea state, σ can be applied in a Rayleigh distribution describing individual amplitudes between zero-crossings. If we further assume that the individual amplitudes occur independently, we can derive the distribution for the largest observed amplitude within the sea state, as the Rayleigh distribution to the power N, where N is the number of amplitudes in the sea state. By defining operational limits as stochastic values, the limiting sea state curve can be expressed using the short-term response process distributions. In the presented case study the root-mean-square (RMS) value is applied as an operational limit. The RMS value of response in a sea state is equal to σ for linear systems, expressed in Equation 5. The limiting sea state curve is found by establishing the maximum H_s value for each T_p for which σ does not exceed the chosen limit. Other statistical measures, for instance the expected maximum or significant value of response, can be applied to find the limiting sea state curve using the same procedure.

[Figure 7 about here.]

3.7. *Short-term motion response calculations*

Hull and loading condition variations are performed in ShipX developed by SINTEF Ocean (former MARINTEK) along with calculations of motion response characteristics, as outlined in Section 3.6. We assume that all vessels are performing the same operations using equipment of equal quality and limitations in order to have a basis for comparison. Pierson-Moskowitz (PM) standardized wave spectra are used to model the sea surface behaviour corresponding wave load excitations. The chosen operational criteria for assessment of vessel design variations is 1.0 deg RMS roll motion response.

3.8. *Weather windows*

The time necessary for the performance of an offshore work task is a key parameter within the operational planning process. Det Norske Veritas (2011a) defines the duration of marine operations using an operation reference period, T_R.

$$T_R = T_{POP} + T_C \tag{6}$$

T_{POP} is the planned operation period, based on a schedule of the operation and experience with similar operations. T_C, the contingency time, is an additional duration accounting for unexpected delay. The planned operation period starts at the issuance of the latest weather forecast. The required weather window is defined as the duration between the start of the operation and the end of the reference period.

[Figure 8 about here.]

Figure 8 shows the occurrence of weather windows on Haltenbanken for the first half of 2012. The operational limits, shown in Figure 8(b), is calculated to prevent RMS responses exceeding 0.5 degrees in roll and 0.6 degrees in pitch by interpolation on the limiting sea state curve, as seen in Figure 7, and hincast T_p in Figure 8(a). Roll and pitch criteria are very sensitive to the T_p value relative to the modal natural period. We therefore observe an increase in the limiting H_s from January-June due to lower T_p, reducing probability of resonant response. The weather windows and non-operable states shown in Figure 8(c) are found by checking whether H_s from the hindcast data in Figure 8(a) exceeds the limiting H_s in Figure 8(c).

3.9. *Integrated operability factor*

For quantification of response-based operability of offshore vessels, the integrated operability factor (IOF) was introduced as a parameter for seakeeping performance in parametric studies (Gutsch et al. (2016) and Gutsch et al. (2017)). This measure assesses the steepness of the operability-limit curve, as illustrated in Figure 9. The level of the IOF is strongly influenced by the initial steepness of the operability limit curve and the choice of the maximum operational limit OP_{lim}^{max}. The range for calculation of the IOF between zero and OP_{lim}^{max} is kept constant. The IOF is calculated as the ratio of the enclosed area A_1 and the total area $A_1 + A_2$, see Figure 9 and Equation 7. The operability-limit curve is constructed using a series of percentage operability calculations for discrete operational limits OP_{lim}.

[Figure 9 about here.]

$$IOF = \frac{\int_0^{OP_{lim}^{max}} \%OP(OP_{lim})dOP_{lim}}{100 \cdot OP_{lim}^{max}} = \frac{A_1}{A_1 + A_2} \tag{7}$$

4. Results

This section presents the case study results as outlined in the previous section. Emphasis is made towards the ability to distinguish between different design alternatives and reflect the challenges of operational scenarios. Associated percentage operability and integrated operability factor results are presented to provide a reference and basis for comparison.

4.1. *Impact of operational limits and weather window criteria*

Table 3 shows the simulation results for the basecase vessel (Table 1) exposed to weather for all seasons and weather window requirements. The operational limit is kept constant at 1.0 deg RMS roll response. The RRO, as fraction of completed operations and feasible operations, varies consistently with regards to season and weather window requirement, showing increased difficulties for seasons with harsh environmental conditions (fall and winter) and longer weather window requirements.

[Table 3 about here.]

[Table 4 about here.]

Table 4 compares the RRO, the percentage operability, and the IOF results during the winter season. This is shown using an exemplary range of global (heave, roll, pitch) and local (crane tip displacement) motion response criteria. As a local criterion, the crane tip displacement is assessed for a crane tip location over the splash-zone with the coordinates [0.3 L_{oa}, 1.0 B, 1.0 B]. Note, that the percentage operability takes all available operable three hour sea states into account, while the RRO only considers operable sea states occurring while the vessel is at site. We do however see that the RRO measure is higher than the percentage operability for all three hour weather window instances. This is due to the time spent in transit in the simulation procedure. The simulator attempts to complete as many operations as possible within the prescribed time, but is limited by non-operable weather and the return to port requirement. For low operational durations, the majority of the time is spent in transit, reducing the feasible number of operations. The effect of a minimum time between operations is not included in the percentage operability method, meaning that all occurrences of non-operable sea states directly affect the result.

4.2. Parametric design variation

Figure 10 shows the results of the RRO, %OP, and the IOF for all seasons, main dimensions, and combinations of loading condition. As expected, the winter and fall season results indicate more challenging conditions than summer and spring for all operational performance estimation methods. All methods are consistent in terms of determining whether the parameter has a positive or negative effect on susceptibility to weather delays, but the impact of the variation differ.

The RRO is distributed in distinct levels according to the input weather window requirement. These levels follow the same trend across all ranges of parameter variation in a consistent pattern, indicating a significant influence on the RRO. The impact of the weather window requirement is more prominent for cases with lower RRO. This is expected, since the time between feasible weather windows increase as a consequence of a reduction in operational sea state levels. From a design perspective the estimated added value, in terms of reduced susceptibility to weather-induced delays, increases when comparing alternative designs for longer weather window requirements. The influence of season and parameter variation on %OP is consistent with the RRO results. It is noted that the %OP curves coincide with the 24 h weather window requirement RRO curves. This is addressed in section 4.3.

The IOF stands out from the RRO and %OP results. For all scenarios in Figure 10, the IOF obtains a lower value, although with a similar curve shape. The IOF values are not directly comparable to the RRO and %OP values since the IOF is based on the inclination of the operability-limit curve and not a specific operational limit as for the two other methods. Hence, the IOF indicates the quality of the overall response-based performance of the vessel for the whole range of vessel motions up to the operational limit, rather than providing a value for the ability to perform a specific operation. The difference in IOF for varying parameters are therefore in some cases significantly larger than for the two other methods, especially for the summer season. This indicates that although the ability to perform a specific operation, given the operational limit used in the RRO and %OP calculations is high, the operability-limit curve is such that a reduction of operational limit will result in a more rapid decrease of the %OP. For example for the GM$_t$ variation in the spring season, the %OP and RRO results are close to symmetrical around a GM$_t$ of 3 m, while the IOF results indicate that reducing GM$_t$ might be a better option. IOF values are higher for lower GM$_t$, suggesting that reducing GM$_t$ is a better option in terms of weather-robustness. This information is discarded for the two other methods. GM$_t$ has a significant influence on the operational performance in all cases. The distinct curve shape is due to the relation between the operational limit and the roll natural period. For GM$_t$ in the range of 2.5-3.0 m, the vessel is likely to be subjected to sea states with T_p close to the natural period, increasing the probability of resonant motion. Either increasing or reducing GM$_t$ increases operability in this case by shifting the natural period away from the most commonly occurring T_p values.

[Figure 10 about here.]

4.3. Relation between relative rate of operations and percentage operability

The RRO curve for the 24 h weather window requirement coincides with the %OP curve in all cases presented in Figure 10. This indicate a tight relation between the RRO and %OP quantities. The RRO differs from the %OP by including transit and duration of operation as parameters. This implies that there is a minimum period of time between succeeding operations. To investigate the impact of this duration and the link between RRO and %OP, further simulation runs are conducted with varying transit leg distances between 0 and 1000 nautical miles. The results are shown in Figure 11 with the associated %OP value. When the transit distance is set to zero, the RRO and %OP results are equal for the 3 h weather window requirement. This is expected, as the operational scenario of the simulation matches the assumptions of the %OP method. For longer weather window requirements, the minimum time between operations resulting in equality increases proportionally to the weather window requirement length.

[Figure 11 about here.]

Table 5 lists the time periods between operations resulting in equal RRO and %OP levels. For the simulations in Figure 10, we assumed a constant transit distance between port and site of 220 nautical miles and a speed of 12 knots, implying a minimum duration of time between operations of 36.67 hours for transit to and from port. This agrees well with the 24 h weather window requirement values in Table 5.

[Table 5 about here.]

5. Discussion

5.1. Model fidelity and sources of uncertainty

The level of model abstraction must be carefully considered to ensure that all relevant behaviour of the vessel and the overall system is included. Bergström et al. (2017) demonstrates the importance and influence of model fidelity and uncertainties in design of Arctic maritime transportation systems. In view of this, a discussion regarding model fidelity impact and sources of uncertainty for the RRO estimates is given.

5.1.1. Response characteristics

In a ship design context, where the objective is to assess vessel design quality in the form of susceptibility to weather-induced delays, application of operational limits which describes the vessel's inherent attributes is vital. Hence, the fidelity level of the methods applied to obtain the limiting sea states are of great importance. In the presented case study in Section 3, linear strip theory in the frequency domain was used to estimate the vessel RAOs, see Figure 6. This method is common in the early design stage as it is both fast and known to give accurate results (ITTC 2011). Higher fidelity approaches for response calculations exist, for instance 3D potential theory methods (Söding and Bertram 2009) and computational fluid dynamics (CFD) (Kim 2011), where fourier transform of the response time series can be used to estimate vessel RAOs. In practice, these methods require extensive computational effort and skill to be performed successfully. In our opinion, panel methods and CFD are therefore not suited for testing of vessel design concepts in the early design stage.

5.1.2. Transit events

In the model used in the present case study, we assume that all vessel designs maintain the same deterministic transit speed of 12 knots. This is done under the assumption that the vessel will not encounter sea states which causes speed loss, voluntary or involuntary, and that no operational criteria for transit exists. However, transit can in some instances be an important operational stage, which can cause delays if sea states along the planned route exceeds predetermined thresholds. Towing operations, for instance of barges or self-floating objects, and transportation of sensitive cargo are some example cases where transit can be critical. In Bergström et al. (2016), where ship transportation in ice-infested waters is examined, accurate modelling of factors impacting transit time is essential for understanding maritime transport system capacity and behaviour. In our case, examining operation at a ship level, extending the model to include the influence of delays caused by rough weather in transit could yield further insight into the overall performance of the vessel. In the simulation procedure, the ship stands by in port if the forecast at site show low probability of operation success. It leaves port as soon as the forecast is improving, timing departure so that it arrives just as the conditions is sufficiently calm. This means that the vessel in many cases will sail in harsh weather in order to arrive in calm conditions, which can inflict exposure to transit delays. This suggests that including a transit model could further improve our understanding of the impact weather has on the ship's ability to support operation activities. The impact of such a model is likely to depend heavily on the transit distance between port and the operational site, which will affect the exposure time to weather along the route. It also suggests that we underestimate the susceptibility to weather delays in our case study since we neglect the possibility of delays in transit. For evaluation of vessel design, the transit model should have a fidelity level which facilitate estimation of transit duration based on the ship design parameters and operational limitations in question. Speed loss factors, such as wave added resistance and vessel motion criteria, should be considered for this purpose.

5.1.3. Weather data

Metocean parameters are inherently random and of aleatory uncertainty. For long-term description of metocean parameters, hindcast time series from the Norwegian Meteorological Institute was applied in the case study. Bitner-Gregersen et al. (2014) addresses uncertainties in wave description and their importance for engineering applications, and states that wave data from hindcast studies are the choice of data for development of design and operational criteria. Hindcasts data sets are affected by the assumptions adopted in the applied wave model. The quality of numerical wave models depend to a large extent on the accuracy of the upper boundary layer description, i.e. in particular the driving wind fields. Bitner-Gregersen and Guedes Soares (2007) and Campos and Guedes Soares (2016) shows that there are significant differences in commercial databases for hindcast wave data. The potential bias error and sampling uncertainty in RRO estimates due to uncertainty in the long-term wave environment description is difficult to estimate, as it would require a considerable analysis effort using wave data from several sources. Alternatively to hindcast data sets, stochastic long-term wave models can be developed to supply synthetic bivariate time series of metocean parameters. Guedes Soares et al. (1996) applies a linear autoregressive model to replicate univariate sequences of significant wave heights of the coast off Portugal. In Guedes Soares and Cunha (2000), bivariate autoregressive models for significant wave height and mean period is presented. A climate-based Monte Carlo approach is used for trivariate time series modelling of significant wave height, mean period and direction in Guanche et al. (2013), also allowing simulation at different locations. A survey of stochastic time series models for wind and sea states is presented in Monbet et al. (2007). Application of such model does however require extensive development and testing effort, which falls outside the scope of this paper.

5.1.4. Short-term response

Critical for the decision of operational start-up in the simulation model is the assessment of vessel short-term response. In the case study, we require that the RMS roll response does not exceed a prescribed threshold of 1.0 deg within a given window of operation. To assess whether this criterion is met, a limiting sea state curve is provided as input based on short-term response analysis in the frequency domain, see Figure 6. The common short-term analysis assumptions are that the sea surface elevation is a stationary, Gaussian process, for which the distribution of energy between frequency components can be described using a standardised spectrum.

Using a standardized wave spectrum, we are assessing an idealized representation of the sea surface behaviour. PM spectra are frequently applied for wind generated sea under the assumption that the sea state is fully developed. JONSWAP introduces the peakedness parameter as a model for developing sea states. Two-peak spectra, for instance Ochi-Hubble and Torsethaugen, considers the influence of swell. The Northwestern part of Europe, the region of the case study, includes partly enclosed as well as open sea areas. Strong winds occur throughout the region, inducing pure wind-driven and transitional sea states. In addition, swell components from the Atlantic Ocean can affect all but the most sheltered areas.

Our estimates of the sea state characteristic response value, i.e. the RMS response, is dependent on the assumption of Gaussian distribution of the sea surface and corresponding response process. Haver and Moan (1983) and Guedes Soares (1990) addresses uncertainties related to short-term modelling of waves and ship responses, respectively. Non-Gaussian surface behaviour is likely to occur when the ratio of wave amplitude and length, i.e. the wave steepness, is sufficiently large. On average, it is found that the validity of the Gaussian assumption decreases with increasing sea state intensity. Our concern is the borderline between operable and non-operable sea states, which in most cases will be in the calm to medium-severe sea state range. Hence, uncertainties related to the Gaussian response process assumption, is likely to have limited influence on RRO estimates.

Considering single, independent sea states leads to uncertainty regarding stationarity.

We do not know whether the spectral shape, described by spectral distribution parameters, is reasonably constant for the duration of the sea state. In the simulation procedure, we assess the occurrence of weather windows taken as a sequence of sea states below the limiting sea state curve. If one of the sea states in the sequence does not meet the operational criterion, the entire sea state sequence is deemed non-operable. In this regard, we do to some extent reduce this uncertainty since we consider succeeding values of H_s and T_p over the duration of the operation. The temporal development of the spectral shape parameters is therefore included at three hour intervals using the hindcast data in the case study. For cases where the operational margin is small however, a finer discretization might uncover cases where the operational limits have been exceeded due to volatile behaviour of spectral parameters. Such cases are however most likely rare due to the physical process and corresponding temporal characteristics of wind driven sea and swell influence.

Haver and Moan (1983) and Guedes Soares (1990) concludes that the dominating uncertainty related to short-term estimates of response is related to the choice of wave spectrum formulation. In particular, the influence of swell, which occurs more or less randomly, gives uncertainties in the low-frequency range of the spectrum. If data regarding the occurrence of swell is available, this uncertainty can be reduced by extending the wave spectrum description to include the effect of swell. Empirical methods for distinguishing wind and swell dominated sea states can be applied using the Torsethaugen spectrum formulation, see Det Norske Veritas (2010) Appendix A. In the case study, we applied the PM spectrum which assumes fully developed, wind-driven sea states. H_s and T_p were used as spectral shape parameters. The uncertainties associated with swell is equally present in RRO, IOF and %OP estimates. According to Det Norske Veritas (2010) and European Committee for Standardization (2015), the choice of wave spectrum for offshore activity studies depends on geographical area, the severity of the sea state and concerned activity. The choice of wave spectrum formulation is therefore case-specific, thus making it difficult to conclude on a preferred formulation.

5.2. Applicability and relevance

The core function of the presented methodology is to assess vessel design susceptibility to weather-induced delays during performance of marine operations in a long-term perspective. Discrete-event simulation, with its underlying assumptions regarding time discretization and state transitions, is applied for this purpose. Time between events is either assumed deterministic or governed by the occurrence of operable weather events according to hindcast weather data.

The ability to include influence of weather window requirements enables the construction of more realistic operational scenarios than the commonly applied percentage operability approach. As expected, Figure 10 shows that the RRO is strongly affected by the weather window length requirement. A more interesting trend, is that the difference in RRO between different design concepts is dependent upon the choice of weather window length. This suggests that with regards to decision making, our understanding and evaluation of operational performance should rely on methodologies that facilitate further description of operational scenarios than facilitated by the percentage operability method.

Three methods for assessing vessel operational performance were applied in this paper. %OP and IOF relies on static comparison of the limiting sea state curve and weather data. These measures indicate the operational performance using the operable - non-operable time ratio. The simulation-based approach is fundamentally different, as it is based around forming relevant operational scenarios and testing the capabilities of alternative designs in a long-term perspective. By including operational scenarios, determined by transit leg distance, weather window length, and port visit duration, we introduce cases which previously have been disregarded. We may for instance miss operable events if the vessel is in transit at the same time instant. Hence, a succession of operable weather windows does not necessarily facilitate a similar succession of operations, depending in our model on the maximum operational rate. We are in other words not only considering the availability of operable weather windows, but the relationship between such windows, operational constraints and vessel capabilities.

6. Conclusion

In this paper, a DES methodology is proposed for assessing the susceptibility for weather-induced delays due to limitations in vessel motion response characteristics during performance of marine operations. The tool is developed for rapid testing of alternative vessel designs in the early design stage. Further, the RRO is introduced as a quantitative performance measure which includes further description of the operational scenario than equivalent common measures.

The proposed methodology was benchmarked towards %OP and IOF for its ability to assess and distinguish alternative vessel designs in a case study. The outcome of the study allow us to answer the research questions presented in Section 1.

Our conclusion to the first question is that factoring in weather windows as an operational criterion has a significant impact on the estimated susceptibility to weather delays. For the basecase vessel with roll 1.0 deg RMS as an operational limit during winter season, the RRO results is distributed on the range 80.9% - 44.1% for weather window requirements between 3 - 60 hours, respectively. In contrast, the corresponding %OP result of 63.3% provides only limited information of the inherent limitations and capabilities of the design concept to perform the operation in the given scenario.

On the second research question, we conclude that the simulation approach is found to enhance knowledge towards the relationship between important vessel design parameters and susceptibility to weather delays during performance of marine operations. The common %OP assumptions, namely that operation can be performed within each occurring operable sea state, is a special case of the RRO formulation where we assume 3 hour operational duration and no port and transit activities. It is found that extending the underlying scenario to include relevant system activities affected the results, depending on the interactions between vessel activities and occurrence of operable weather windows. Such interactions are best captured using simulation, and DES, with its low computational cost and flexibility in terms of fidelity level, is considered a favourable technique for rapid long-term horizon testing of designs.

List of abbreviations

CFD	Computational fluid dynamics
COG	Center of gravity
DES	Discrete-event simulation
FMI	Functional mockup interface
HAZID	Hazard identification study
IOF	Integrated operability factor
OCV	Offshore construction vessel
OSV	Offshore supply vessel
PM	Pierson-Moskowitz
RAO	Response amplitude operator
RRO	Relative rate of operation
RMS	Root-mean-square
WOW	Waiting on weather

List of symbols

A_1	Area below operability-limit curve
A_2	Area above operability-limit curve
B	Vessel beam
D	Vessel draft
GM_t	Metacentric height above COG
H_s	Significant wave height
$H_{\eta_i\eta_i}$	Response amplitude operator of degree of freedom i
L_{oa}	Vessel length over all
$OP_{feasible}$	Feasible number of operations
OP_{lim}	Operational limit (variable)
OP_{lim}^{max}	Maximum operational limit
$OP_{performed}$	Number of performed operations
r_{44}	Roll radius of gyration
r_{55}	Pitch radius of gyration
$\mathbf{S}$	Response vector
$S_{\zeta\zeta}$	Wave spectrum
$S_{\eta\eta}$	Response spectrum
T_p	Wave spectral peak period
t	Time
T_C	Contingency time
T_{POP}	Planned operation period
T_R	Operation reference period
α	Alpha-factor
β	Vessel heading relative to incident wave propagation direction
ϵ_i	Response phase shift
ζ_a	Regular wave amplitude
η_i	Response of degree of freedom i
σ	Standard deviation of instantaneous response
ω	Wave frequency in radians
Ω	Rotation vector
%OP	Percentage operability

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Table 1. Basecase vessel particulars

Parameter	**L**$_{oa}$	**Beam**	**Draft**	**GM**$_t$	**r**$_{44}$	**r**$_{55}$
Value	120 m	24.3 m	7.0 m	2.0 m	35% B	25% L$_{pp}$

Table 2. Variations of main particulars

Variation of hull length

L_{oa}	80 m	100 m	120 m	140 m	160 m
Beam	18.3 m	21.4 m	24.3 m	27.3 m	30.4 m
Draft, GM_t, r_{44}, and r_{55} similar to basecase					

Variation of hull beam

Beam	21.3 m - 27.3 m, increment 1 m
L_{oa}, draft, GM_t, r_{44}, and r_{55} similar to basecase	

Variation of draft

Draft	5 m - 9 m, increment 0.5 m
L_{oa}, beam, GM_t, r_{44}, and r_{55} similar to basecase	

Variation of metacentric height

GM_t	1 m - 5 m, increment 0.5 m
L_{oa}, beam, draft, r_{44}, and r_{55} similar to basecase	

Table 3. Relative rate of operations assessed for the basecase vessel for varying weather window requirements and seasons. Constant operational limit 1.0 deg RMS roll.

Weather window		**Winter**		**Spring**		**Summer**		**Fall**	
requirement	$\mathbf{OP}_{feasible}$	$\mathbf{OP}_{performed}$	**%RRO**	$\mathbf{OP}_{performed}$	**%RRO**	$\mathbf{OP}_{performed}$	**%RRO**	$\mathbf{OP}_{performed}$	**%RRO**
3 h	3011	2438	80.9	2809	93.2	3002	99.7	2738	90.9
12 h	2469	1776	71.9	2220	89.9	2452	99.3	2163	87.6
24 h	1991	1259	63.2	1725	86.6	1951	97.9	1633	82.0
36 h	1668	901	54.0	1375	82.4	1620	97.1	1287	77.1
48 h	1435	707	49.2	1154	80.4	1389	96.8	1053	73.3
60 h	1259	552	43.8	961	76.3	1204	95.6	866	68.8

Table 4. Comparison of relative rate of operation, percentage operability and integrated operability factor for varying operational limits and weather window requirements during winter season. The vertical crane tip displacement is calculated for a crane tip position during lowering-phase through the splash-zone, with characteristic coordinates [0.3 L_{oa}, 1.0 B, 1.0 B]

Operational limit RMS		**%OP**	**IOF**	**%RRO**					
				3 h	**12 h**	**24 h**	**36 h**	**48 h**	**60 h**
Heave [m]	**0.2**	24.0	7.2	44.5	31.4	21.9	16.1	12.1	9.0
	0.5	57.5	28.1	75.7	67.1	58.3	48.6	43.2	38.5
	1.0	89.7	53.8	95.9	93.7	90.8	87.9	83.4	80.3
Roll [deg]	**0.5**	35.2	19.8	59.3	44.9	32.7	24.4	19.1	14.2
	1.0	63.3	36.2	80.9	72.0	62.3	54.1	49.3	44.1
	1.5	82.4	49.3	92.0	88.0	82.6	78.6	74.4	70.1
	2.2	93.9	62.1	97.9	96.6	94.7	92.5	89.3	86.7
Pitch [deg]	**0.3**	4.35	2.2	13.8	5.7	2.9	1.2	0.8	0.0
	0.6	20.5	8.6	36.9	26.0	19.2	14.8	11.3	9.1
	1.0	51.2	21.7	67.6	59.9	52.7	44.7	39.2	34.8
	1.5	78.7	38.0	89.9	85.7	79.6	74.9	69.4	65.2
Vert. crane disp [m]	**0.3**	16.7	6.8	34.5	22.4	14.4	10.77	7.4	5.6
	0.6	48.7	18.8	67.4	58.1	48.8	41.4	35.2	30.6
	1.0	79.3	35.5	89.6	85.9	80.5	75.3	70.7	66.0

Table 5. Minimum duration between operations resulting in equal relative rate of operations and percentage operability.

Weather window requirement	**Winter**	**Spring**	**Summer**	**Fall**
3 h	0.0 h	0.0 h	0.0 h	0.0 h
12 h	13.4 h	13.3 h	13.2 h	12.1 h
24 h	35.8 h	32.0 h	34.0 h	31.7 h
36 h	82.4 h	66.8 h	71.2 h	65.1 h
48 h	147.3 h	117.0 h	131.8 h	127.6 h
60 h	191.5 h	182.8 h	175.0 h	184.6 h

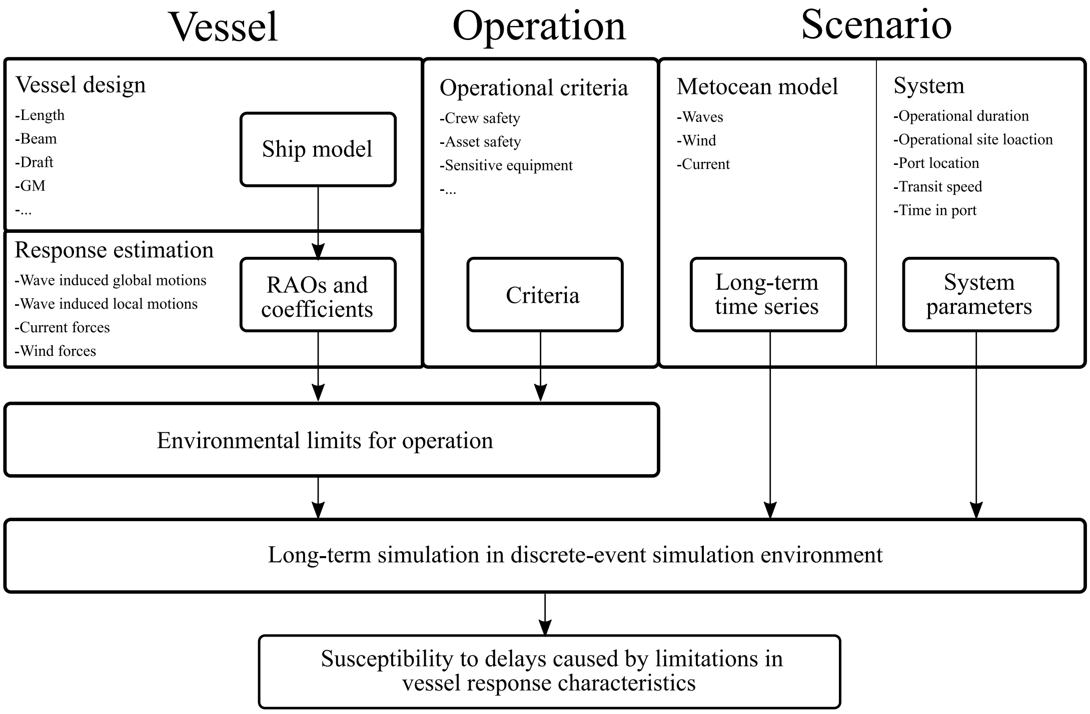

Figure 1. Process overview of simulation-based design assessment methodology

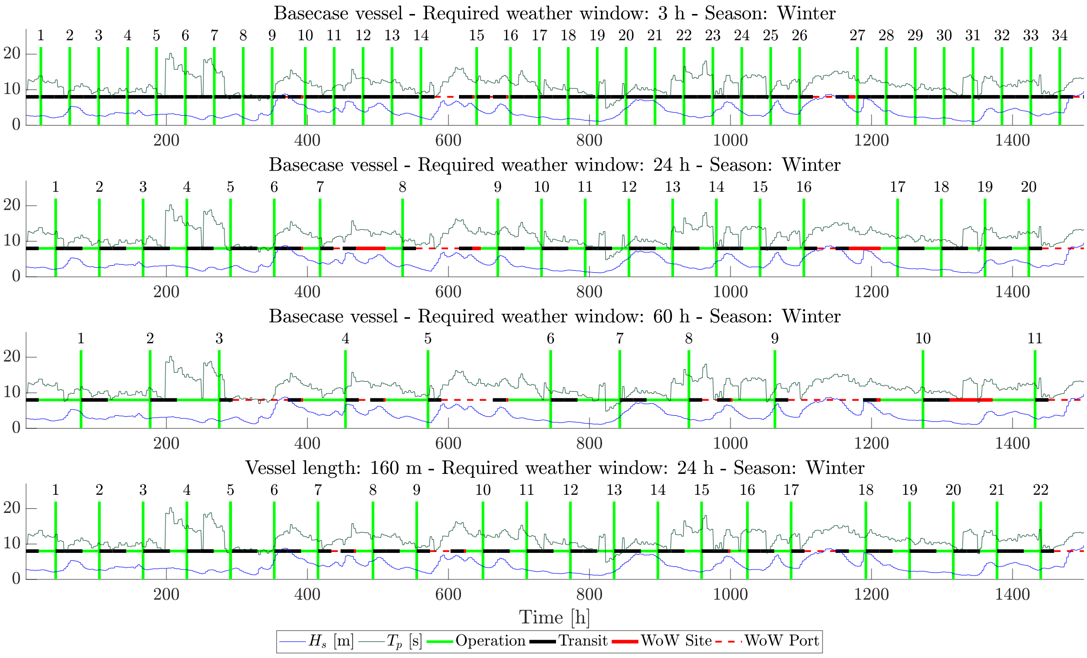

Figure 2. Simulated series of events for varying weather window requirement and vessel length.

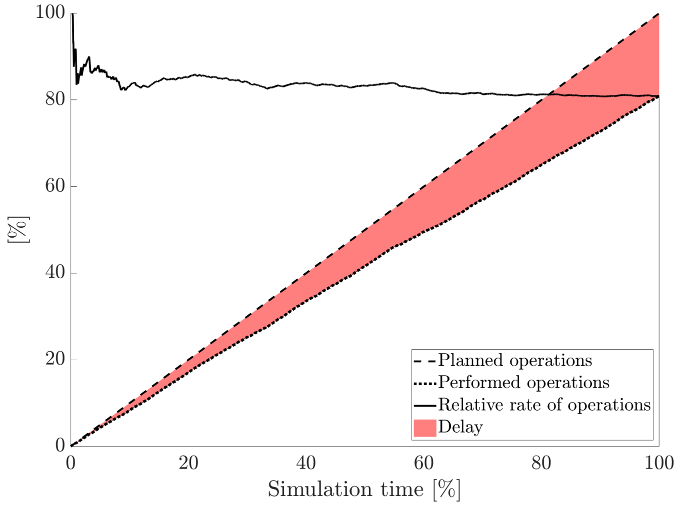

Figure 3. The relative rate of operation measure

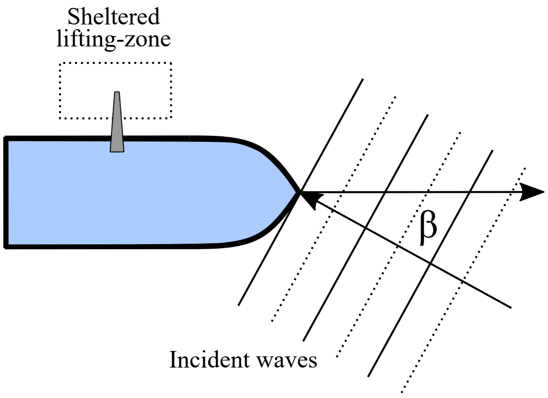

Figure 4. Vessel orientation towards incident waves during light-lift operation. A constant heading of $\beta = 15$ is assumed.

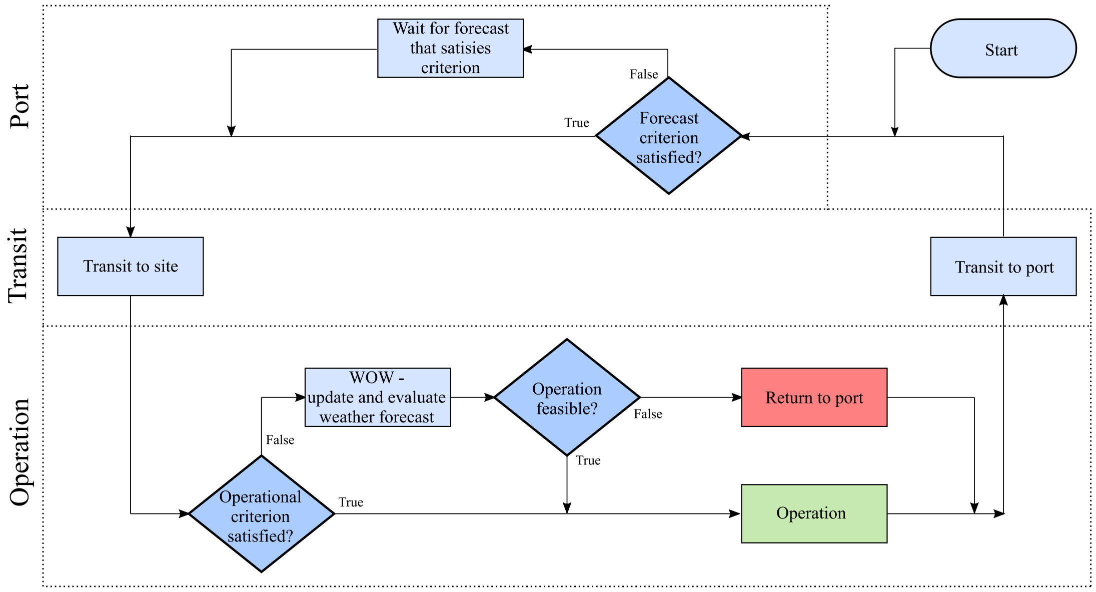

Figure 5. Discrete-event simulator flowchart

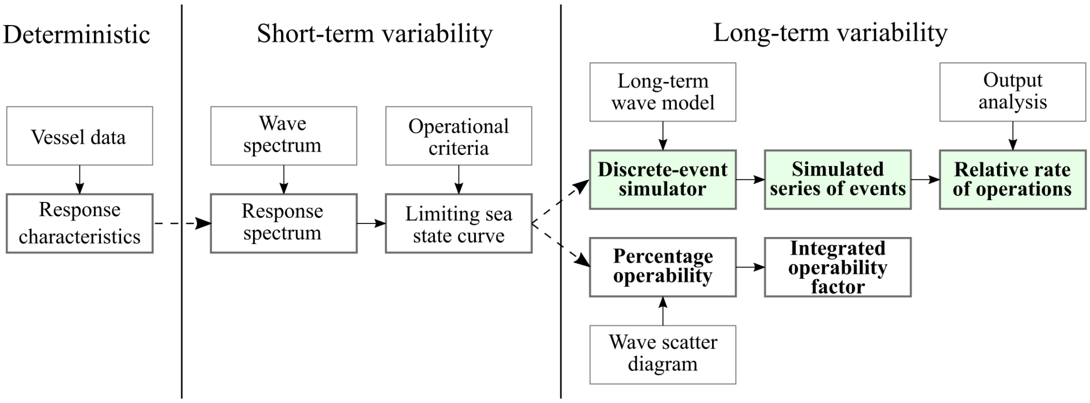

Figure 6. Outline for frequency domain approach

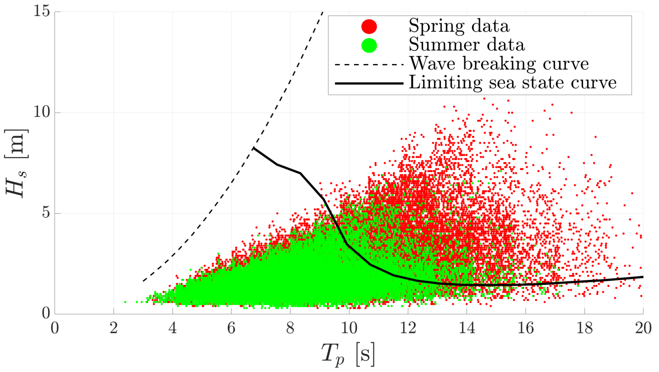

Figure 7. Limiting sea state curve for 2 degrees RMS roll angle, presented with historical data for H_s and T_p for spring and summer on Haltenbanken (1957-2014) as scatter distribution of 3 hours sea states

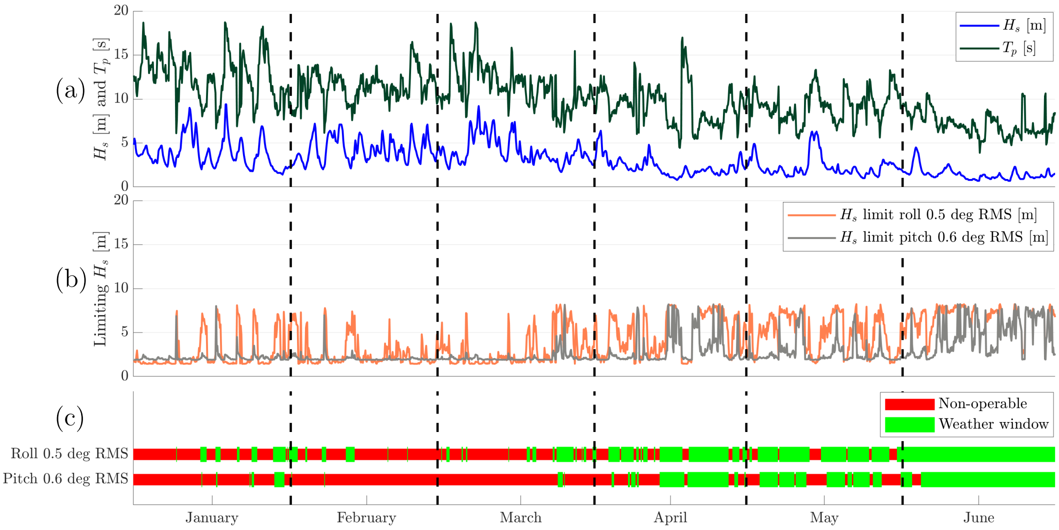

Figure 8. (a) :H_s and T_p time series covering January-June 2012 from Haltenbanken in the Norwegian Sea. (b): Operational limits calculated by interpolation of the limiting sea state curve using T_P from (a). (c): Weather windows and non-operable states determined considering occurring H_s in (a) and limiting H_s in (b).

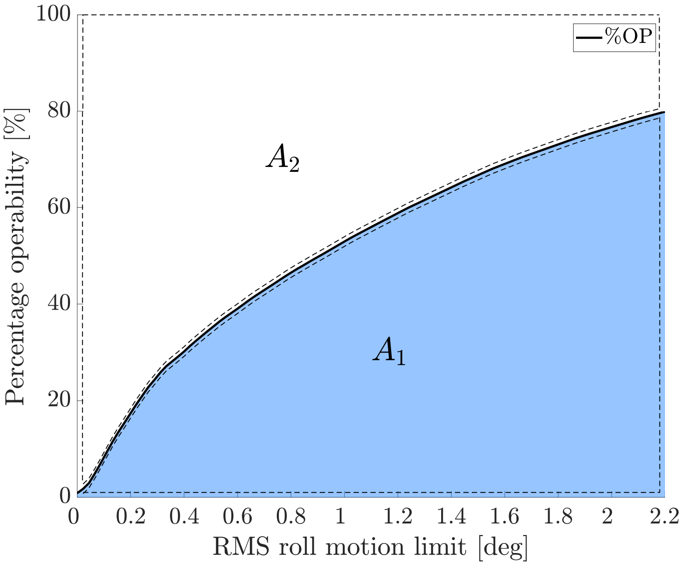

Figure 9. Integrated operability factor

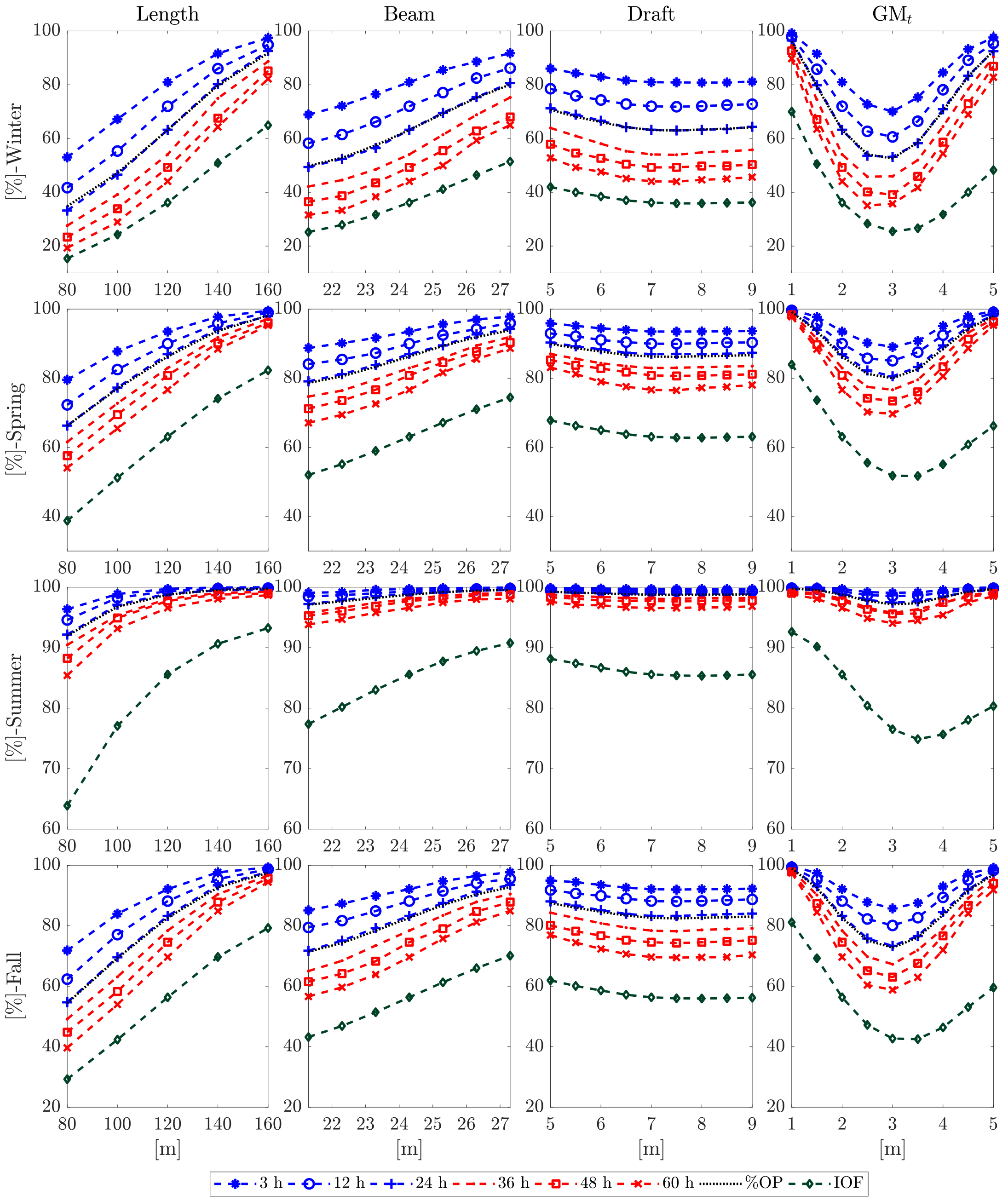

Figure 10. Relative rate of operations (red and blue) for varying weather window requirements, percentage operability (%OP) and integrated operability factor (IOF) for main dimension parameter variation (length, beam, draft, GM$_t$) and seasons.

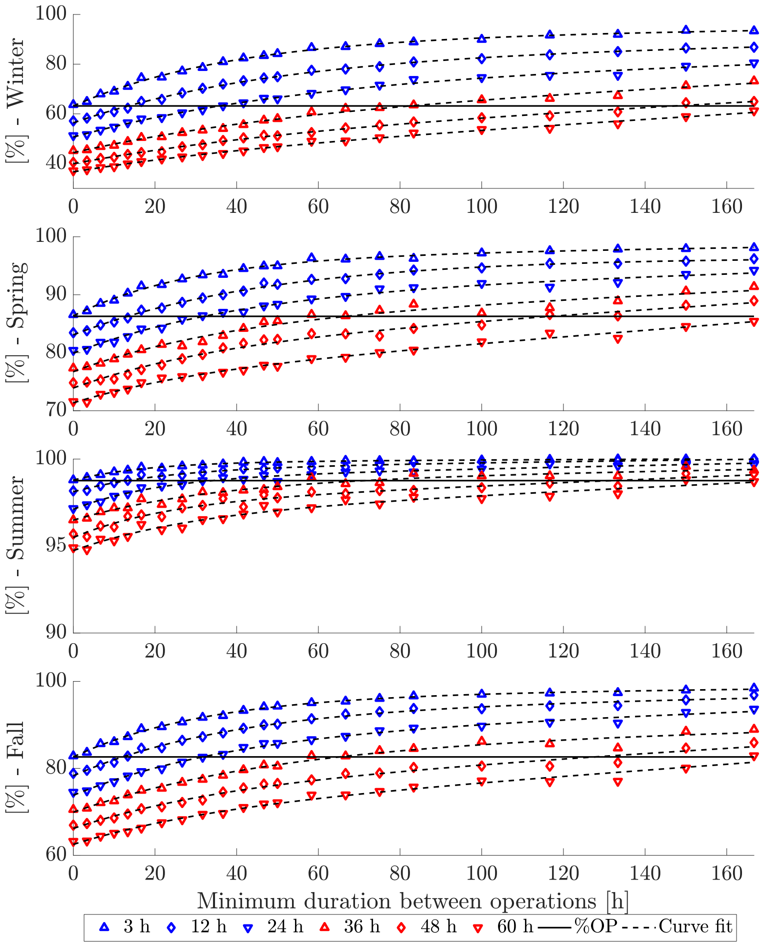

Figure 11. Varying minimum time between operations for the basecase vessel configuration limited by 1.0 deg RMS roll motion.