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RESEARCH ARTICLE

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SPOWTT: Improving the safety and productivity of offshore wind technician transit

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Abstract

This paper describes the SPOWTT project. The intention of this project was to understand how sailing by crew transfer vessel (CTVs) to offshore wind farms affects the mental and physical wellbeing of individuals on board. The focus was on quantifying this impact, understanding the key drivers, with an aim to ensuring personnel can arrive to the wind turbines in a fit state to work safely and effectively. Impacts looked at subjective state beyond simply vomiting. Key results include the ability now to predict vessel motions from given Metocean conditions and vessel designs. We also discovered that the impact of vessel motions on seasickness is different for different symptoms and is driven not only by vertical *z*-axis accelerations but also by certain frequencies of motion in the *y*-axis. Frequencies other than 0.16 Hz were found to be impactful, and *x*-axis movements appeared to have a longer-lasting effect on the day's work. Through the formulation of a new, evidence-based understanding of seasickness, we have created an operational planning tool, designed to have a direct benefit on the safety and productivity of offshore wind farm operations.

KEYWORDS

human factors, offshore wind farm, operations and maintenance, sea-sickness

1 | INTRODUCTION

1.1 | Offshore wind farm operations and maintenance

Operations and maintenance (O&M) costs approximately £75,000/MW/year for offshore wind farms, of which £33,000/MW/year is for service and maintenance of the turbines (values for a specific turbine capacity).[1] The objective of the operational phase is to maximise wind farm income by balancing operational costs with income from energy sales and any ancillary revenue streams. This is achieved through a complex supply chain which ultimately delivers value to the wind farm owners, but which is usually established and managed in the first 3–5 years of the wind farm's life by the turbine supplier.

Maintenance is separated into proactive maintenance (e.g. regular service and upgrades to turbine components), and reactive maintenance (e.g. response to alarms and failures). For near-shore wind farms (typically less than 30 nm from an operations port), a small number of crew transfer vessels (CTVs) and technicians are kept on contract to handle minor reactive maintenance activities, which historically have accounted for 75% of malfunctions in an offshore wind farm.[2] The local service organisation also has equipment and spare parts; marine coordinators, to manage offshore operations and safety; and planners, to work with technician team-leaders to arrange each day's tasks.

Maintenance management planning involves a hierarchy of decision making, from long-term to short-term.[3] Simulation tools have been used historically to determine strategic plans for offshore wind farms, looking at the effects of climate and average turbine reliability.[4]

More recently, however, simulation engines have become capable of modelling daily maintenance in sufficient detail to provide decision support. Meeting the performance objectives of a wind farm currently requires site planners to solve a complex optimisation problem,[5] balancing, so far as practicable:

- Ensuring the safety of operations;
- Completing all work within a reasonable time period;
- Maximising energy production of the wind farm;
- Minimising costs of performing the maintenance:
  - Short-term, for example, from fuel consumption; and
  - Long-term, for example, deciding which vessel and how many technicians to hire.

All of these elements are strongly dependent on weather and sea conditions, which interact with:

- the vessel, determining the ability of technicians to transit and work; and
- the wind turbines, determining the power production at any given moment in time.

Planning has historically depended on rules-of-thumb for working limits on vessels. Decisions are taken on whether to sail, based on a threshold for wave height and the local experience of the marine coordinators. If sailing occurs, then the willingness of the vessel Master and technicians to transfer depends on their experience during the transit and while at site, and relevant H&S legislation. While this approach provides a well-defined process for coping with the realities and pressures of operational decision making, and offers some robustness against weather forecast uncertainty, it has significant opportunity cost. Some days, operations are not attempted which could have been conducted; other day operations are attempted when they cannot be safely conducted, particularly due to sea-sickness. This decision is also influenced by the strategy of the operating company, with some attempting more marginal transfers than others.

Recently, CTV performance has been studied in more detail, considering more Metocean parameters than just significant wave-height.[6,7] However, while tools such as P-plot[8] are accepted for displaying a vessel's historical performance, they are not in regular use for daily planning. Developments are also underway to provide more accurate, longer forecasts, with more spatial resolution and quantified uncertainty.[9] Application of our findings to larger vessels is also of significant importance. Service operation vessels (SOVs) are increasingly used for service activities at large sites further from shore, and some findings from CTV analysis should be applicable.

1.2 | Effect of vessel motions on technician physiology and psychology

Rules-of-thumb are used because trusted models to predict sea-sickness are not available, for reasons discussed in this section. Such models would need to assess the result of a given vessel sailing a certain route, in specific Metocean conditions, taking into account the characteristics of typical offshore wind farm technicians. Data availability is now because reporting of seasickness incidents is a complex organisational challenge and records tend to be difficult to extract. We now establish the current state-of-the-art in the human motion-response literature.

The basic physiological framework for understanding sea-sickness starts with Reason's[10] neural mismatch theory, giving an understanding of the causes and coping strategies of sea-sickness.

To consider effects of motion on sea-sickness, following Reason, the literature commonly focuses on vertical (*z*) acceleration and frequency. O'Hanlon et al.[11] show sea-sickness increasing with vertical acceleration but depending non-linearly on frequency, with the greatest effect around 0.2 Hz (see also Matsangas[12]). The total effect of a trip is summarised in the ISO/British standard methodology by integrating acceleration squared over the dose period,[13] weighting dose by frequency with a non-linear curve maximised around 0.16 Hz. This value of 0.16 Hz, or rounding to 0.2 Hz, occurs frequently. However, there is a stream of work extending to other axes than the vertical, from Bles et al.[14] (emphasising 0.2 Hz), Wertheim et al.[15] the NATO standard[16] through Bos[17] and Pisula et al.[18] The variable considered in much of this work is the probability of a passenger vomiting, termed Motion Sickness Incidence index (MSI).

One problem with much of this work is that it looks at different contexts to Offshore Wind CTVs, in particular large warships or ferries, whose movement is quite different from that of small CTVs—particularly where passengers generally remain seated; vibration dose value (VDV) (ISO 2631-1) is more applicable but does not help understand the state of the technician. Longer journeys also allow adaptation to the motion. Another is that this work largely considers sea-sickness only as vomiting; since SPOWTT is interested in the state of the technician on arrival, we need to consider a much wider range of symptoms.

Sea-sickness symptomology is well-documented within the literature and agreement can be found upon a set of symptoms,19–21 grouped into four sub-categories:

- cognitive (including dizziness or light-headedness);
- temperature (including feeling clammy or sweating);
- sopite (including fatigue and irritability); and
- gastrointestinal (including nausea and vomiting).

While vomiting can be measured, much of these data are subjective.

The literature also provides insight into measurement tools. No published scale met the data collection protocol requirements, having either too many items to be feasibly completed quickly, or questions framed to capture data retrospectively rather than current state. The Motion Sickness Assessment Questionnaire (MSAQ)[20] was chosen to be adapted for SPOWTT, providing a statistical basis on which four items could be selected to cover the four categories of seasickness symptoms based on the psychometric principles of factor loadings.

1.3 | The SPOWTT project

An opportunity exists to improve safety and productivity by better predicting the physiological and psychological effects on technicians of CTV transport. This challenge led to the formation of the multi-disciplinary multi-national project 'improving the Safety and Productivity of Offshore Wind Technician Transit' ('SPOWTT'). The main objective was to improve the health and safety of technicians by developing an evidence-based, open access model to provide more effective advice for the 'sail/no sail' decision.

Achieving this, and then building on the potential of such a model, required the following tasks:

- identifying the hazards and physiological and psychological impacts of technician transit;
- gaining a deeper understanding, through on-site measurements, of the role of different aspects of a technician's daily experience on their productivity, health and wellbeing;
- understanding sources and sizes of uncertainty when predicting the wellbeing and productivity of technicians offshore;
- developing an open access model and process for predicting technician wellbeing after transit;
- defining safe environmental limits for a vessel and proposing operational control measures to minimise in-vessel impacts;
- understanding the planning process on offshore wind farms and how information may be combined with weather forecasting sources (from satellites to wave buoys/radar) and best used to affect planning decisions;
- applying the improved wellbeing model inside a daily maintenance-planning decision-support tool and validating it in offshore wind farms;
- supporting development of commercially available tools to demonstrate how this model can be used for short-term and long-term decision support, including selection of appropriate vessels.

Figure 1 gives an overview of information flow, tasks and products in the project. (1) Vessel data analysis (BMO); (2) sea-sickness model (University of Hull); (3) vessel motion prediction (MARIN); (4) daily maintenance planning decision support (TNO and SMC). These tasks can be viewed as two parallel activities: building a data-driven model; then validating and applying it in a wider decision support framework.

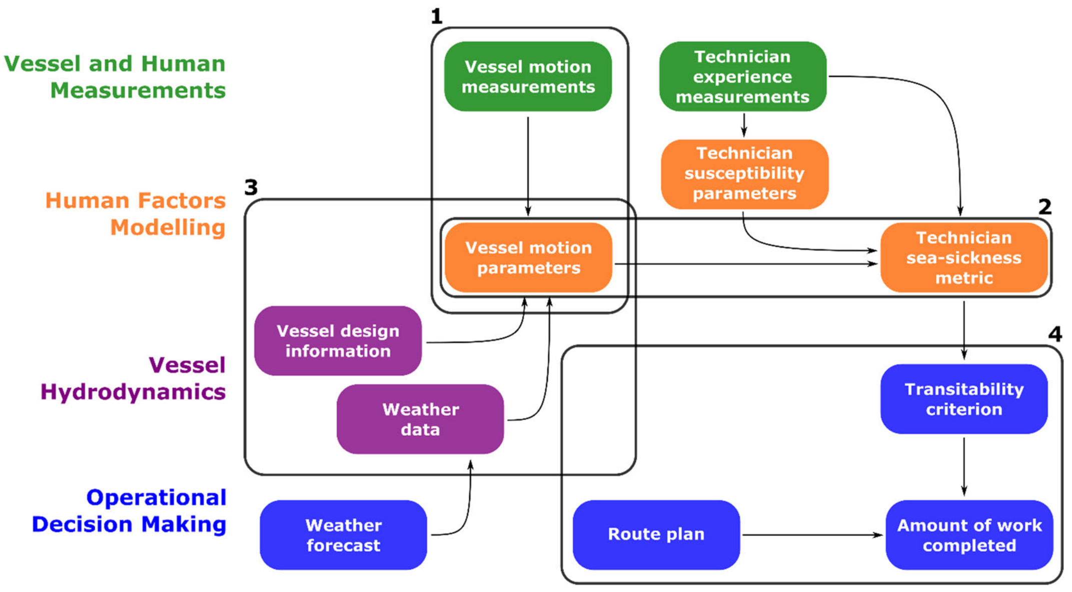

FIGURE 1 Project overview [Colour figure can be viewed at wileyonlinelibrary.com]

The paper is organised as follows. Section 2 reports data collection for vessel motions, followed by vessel motion simulations in Section 3. Section 4 details data collection of technician experience, followed by the construction of the sea-sickness prediction model in Section 5. Section 6 elaborates control measurements which can be used on-board a vessel. Section 7 describes how the sea-sickness model was applied and validated for daily maintenance planning, before considering commercialisation of long- and short-term marine coordination tools. Section 8 draws conclusions and provides guidance and open research topics for future projects.

2 | MEASURED VESSEL DATA

BMO used their vessel motion monitoring system (VMMS) to gather data on vessel motions, both to validate the hydrodynamic model (section 3) and to aid the development of the human factors model (Section 5). A measurement kit was developed and deployed on 14 different vessels, from 40 ton CTVs with relatively short hull length (15 m) to 80 tons 27 m-length vessels, from five distinct operators. The vessels were operated on five different wind farms, to ensure a large spread of sea climates and seasonal variety.

A pilot phase was followed by two measurement phases, then a phase supporting on-board decision tool testing, resulting in 2071 days of operation being monitored, representing around 2500 transit trips between port and wind farm.

Figure 2 shows a schematic of the kit. This monitored GPS location (longitude, latitude), absolute speed and heading of the vessel, all at 1 Hz; and the translational accelerations in 3D, angular accelerations around the 3D axes and attitude (pitch, roll, yaw) all at 40 Hz.

The data from three ships over 1 to 3 months were initially used to create a general overview of vessel and journey characteristics, weather conditions during transits, and sea-sickness indicators during the journeys. Based on accelerations, three sickness indicators were calculated: MSI, VDV, and a locally defined IR (illness rate) (similar to MSI but accounting for horizontal accelerations). These indicators are a first indication of the vessel behaviour and the possible effect on the well-being of the passengers.

Figure 3 shows an anonymised example from one of the vessels. The different colours within the individual plots represent the travel to and from the field and the time in the field. In the MSI, VDV and IR graphs the grey dots indicate transition periods (partly inside and partly outside the field). The figure shows a typical journey where the outward journey was rough (*z*-accelerations) which is reflected in the sickness indicators.

3 | VESSEL HYDRODYNAMIC MODELLING

To make vessel motion predictions as input for the sea-sickness model and thereby planning, the CTV's hydrodynamic performance must be calculated prior to journey. These are calculated for a specific hull form and must cover a very wide range of environmental conditions of currents, waves (wind sea and swell) and wind, to be applicable for all offshore wind farms. This section describes the simulation approach, and validation against on-board measurements and scale model tests.

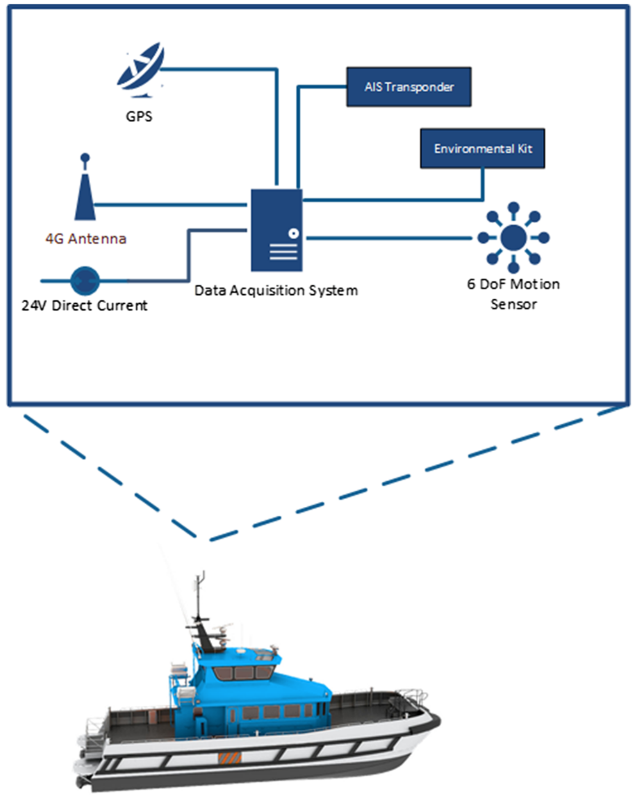

FIGURE 2 Schematic overview of the VMMS [Colour figure can be viewed at wileyonlinelibrary.com]

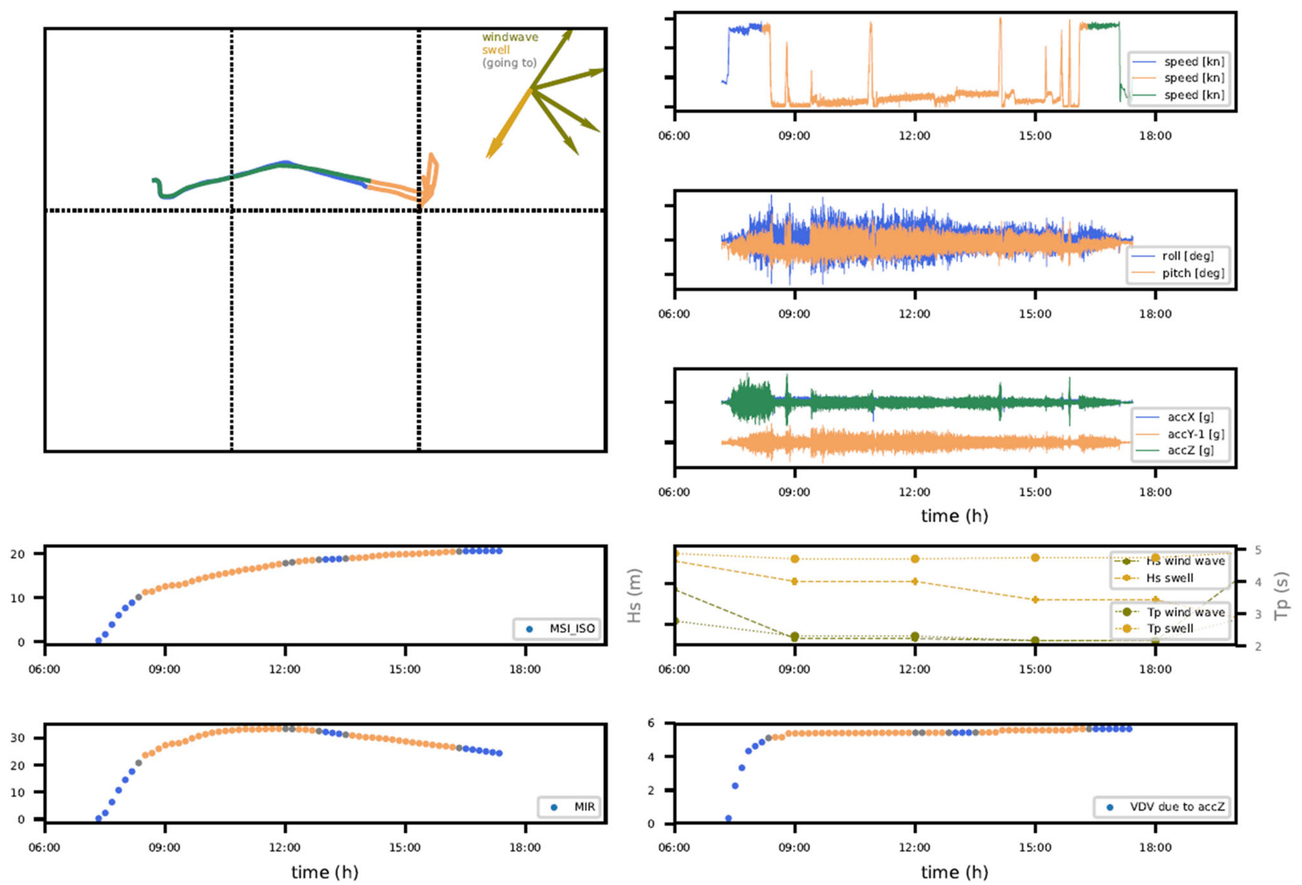

FIGURE 3 Example overview of one CTV travel day (anonymised). Left, top to bottom: Position plot; MSI over time; MIR over time. Right, top to bottom, time plots of: Speed; roll and pitch; accelerations; wave conditions (Copernicus); VDV [Colour figure can be viewed at wileyonlinelibrary.com]

3.1 | Numerical prediction approach

The hydrodynamic simulation approach is shown in Figure 4, summarised as follows:

- Simulations are performed with MARIN's existing non-linear hydrodynamic simulation code PANSHIP. Although this takes into account non-linear effects, such as lifting and slamming, to apply the results to a wide range of seastates the hydrodynamic simulations are linearised, considering every wave as a sinusoidal wave. The results are stored in 'RAO.db'.
- Vessel motion calculations are performed for the following variations:
  - Six realistic catamaran type CTVs ranging from 13 m through 25 m. Hull geometry (lines plan), main particulars (loading conditions and stability data) and appendages data (trim flap) are taken from public factsheets and on-board stability books.
  - Speeds. Typical CTV sailing speed of 25 knots, and also 15 and 20 knots to allow for the positive effects of voluntary speeds losses on motion behaviour, and thus sea-sickness.
  - More than 400,000 sea states consisting of oblique sea and swell waves, with variations in wave height (0.25–2.00 m), wave period (2–9 s) and wave directions. A JONSWAP wave spectrum and the cos-2 s wave spreading model was applied to represent realistic conditions.
- For each combination of CTV, speed and wave condition, root mean square (RMS) vessel motions and accelerations are calculated, and the sea-sickness as defined in Section 5.4 is calculated. Results are stored in a tabular format (labelled as 'Ship hydro transit db' and illustrated in Table 1) readable by O&M planning tools.

3.2 | Validation procedure for the vessel motion calculations

Trustworthy, validated calculation results are necessary to plan the daily operations based on the pre-calculated CTV motion response and associated sea-sickness. Initially, the results of the numerical simulations were validated based on the on-board measurements, as follows:

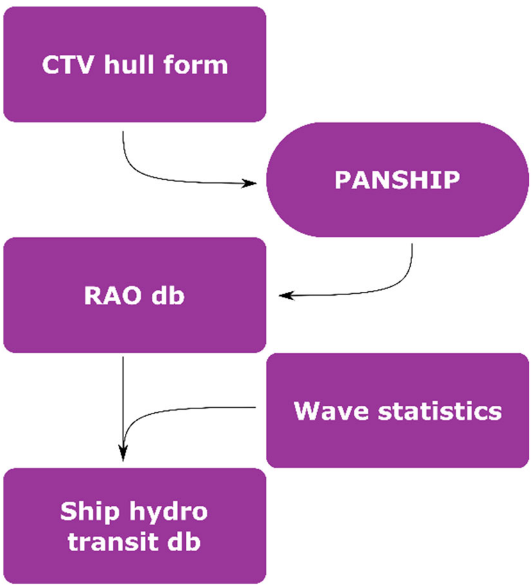

FIGURE 4 Information flow for hydrodynamic modelling [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Illustrative vessel hydrodynamic information

Input			Output				
Thrust (%)	Environmental conditions		Vessel speed (kn)	Vessel motions		Sea-sickness indicators	
	Significant Wave Height (m)	...		Heave acceleration (m/s^2)	...	Motion Sickness Incidence (%)	...
50	1.0	...	14.3	0.58	...	4.1	...
75	1.0	...	19.6	0.59	...	3.9	...
	...	...	...	...	...	...	...

i. Determine the actual environmental conditions at the location of the vessel. On-board measurements only provide vessel motions, while the wave conditions causing the vessel motions are not revealed. Environmental conditions are taken from a public hindcast model, Copernicus.[22] Copernicus provides three wave fields (wind-waves, secondary swell and primary swell) and the combined wave field. For each wave field, the mean wave direction and spectral parameters for wave height and wave period are given. Wave spectral definition and wave spreading are not given. The JONSWAP wave spectrum and the cos-2 s wave spreading model are assumed.
ii. Select voyages suitable for a one-to-one comparison. The numerical simulations are performed in the frequency domain and represent spectral parameters, while the on-board measurements represent time varying parameters. To allow comparison with the numerical results, the on-board measurements should not include time varying effects. A selection was made of about 100 voyages to a windfarm in relatively open sea without effects from the shore and with a relatively long travel distance and time, containing steady course, speed and environmental condition for a minimum of 10 min. These steady voyages allow derivation of good quality spectra of wave frequency motions and thereby comparison with the numerical spectra.
iii. Derive power spectra density functions (PSD) from the on-board measurements. These are compared to the calculated PSD. As an example Figure 5 shows the PSD of the motion response, both measured and calculated. This comparison shows a reasonable agreement, but other comparisons show less good agreements, originating from sources discussed in Section 3.3.

Results of both the simulations and the measurements were found to be sensitive to many uncertainties, related to the vessel data (hull geometry, loading condition); environmental conditions (wave spreading, effect of current) and numerical model (linearised approach). This results in a mismatch of full-scale measurements and simulations. Thereupon, additional laboratory CTV motion response model tests were performed to close the gap between on-board measurements and the numerical simulations, carried out with known vessel and environmental input parameters. These tests allow to confirm the validity of the calculated results, reveal the effect of wave directional spreading and confirm nonlinear effects. Moreover, model tests provide data for further improvement of the numerical model. The CTV motion response model tests will be described in another publication.

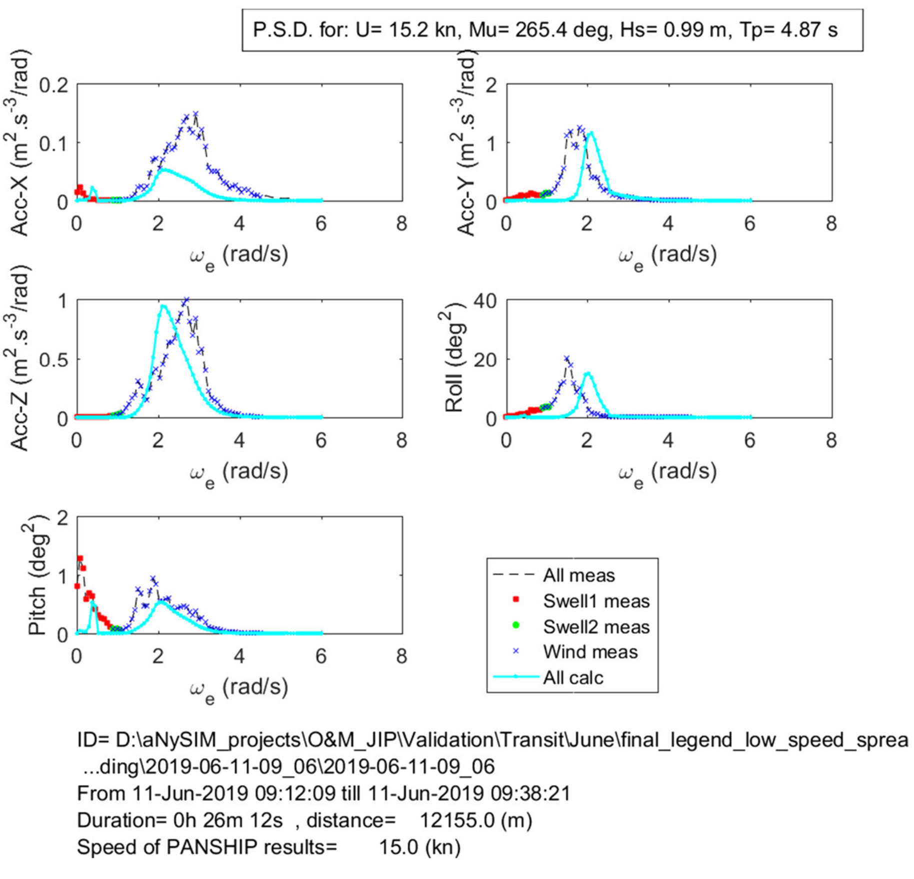

FIGURE 5 PSD of motion response, measured (dotted) and calculated (solid). Induced by: Primary swell (red), secondary swell (green), wind sea (blue). Ship-speed 15 kn, relative wave-direction 265 deg, significant wave-height 1.0 m peak wave-period 4.9 s [Colour figure can be viewed at wileyonlinelibrary.com]

It should be noted that operational constraints in deploying and retrieving wave buoy as measurement equipment for the wave conditions were such that, after initial assessment of hindcast models, the choice was made for the latter. Part of the uncertainty level can be lowered by measurement of the wave condition in a relevant body of water (i.e. the transit routes). A better option would be to 'scan' the waves from the vessel, so always obtaining actual in-situ data. Wave radars can be used for this, but are rather expensive. A new wave radar system is in development at MARIN, in cooperation with industrial partners, offering wave data of higher fidelity from a smaller, lighter and cheaper device. This will be applied in future research work.

3.3 | Validation results for the vessel motion calculations

The hydrodynamic assessment and evaluation by means of calculations, on-board measurements model tests is described in detail in Serraris et al.[23] The conclusions from the comparison between the hydrodynamic calculations, on-board measurements and model tests were:

- The results of the numerical calculations and on-board measurements show significant differences, originating from (1) uncertainties in the input parameters of the ship models, for example, actual hull geometry and weight distribution; (2) uncertainties in the actual environmental conditions: actual local seastates are not known in detail, only spectral forecast and hindcast predictions for large area are known. (3) Unidentified non-linear contributions: on-board measurements show low frequency and wave frequency response. The linearised calculations result in wave frequency response only. However, low frequency motions have marginal influence on sea-sickness. Furthermore, it is noted that the numerical spectral calculation represent steady voyage conditions, while actual voyages are often more irregular with variations in course, speed and local sea states.
- Vessel motion model tests are performed to isolate uncertainties from the vessel motion calculation model. The model test results show a good agreement with the numerical simulations.
- In order to improve the accuracy of the numerical ship motion and associated sea-sickness predictions, it is recommended to use more accurate vessel data and environmental predictions. Accurate environmental predictions could be obtained from in-field environmental measurements and/or on-board wave predictions.
- Nevertheless, during testing of the dispatch tool, see Section 7.3, the planners indicated CTV motion prediction and associated sea-sickness calculation do provide useful insight in the planning of daily operations.

4 | MEASURED TECHNICIAN DATA

Examination of the subjective experience of transit and the practicalities of collecting field study data started by interviewing 14 offshore-wind industry professionals. Findings covered the experience of sea-sickness, frequency, the effect of mental workload, symptoms, coping strategies, recovery time and environmental triggers. The effects of sea-sickness covered anxiety, fatigue and readiness to work. This phase also aimed to gather data on past transits, but despite considerable efforts from the Siemens Gamesa Renewable Energy (SGRE) team, it was not possible to find relevant, reliable, quality information from the in-house reporting tool. Access was provided to some sea-sickness incidence information; while the lack of detail meant this did not contribute to the study, it did suggest that understanding the implications of vessel motion for sea-sickness would have been useful in decisions whether to sail.

A number of subjective factors were then collected using a bespoke App, run on the technicians' iPads that are routinely used to manage work tasks. This allowed data collection with minimal intrusion into the technicians' normal working day. Data were collected at six time-points

- T1 – Prior to transit
- T2 – During transit to turbine (around halfway)
- T3 – On the turbine, prior to work
- T4 – On vessel, prior to transit to dock
- T5 – During transit to dock
- T6 – 'End of workday' prior to disembarking

In addition, if sea-sickness was felt to be acute, a 'T99' report could be filled in at any time.

In a Phase 1a pilot study, data were collected from six SGRE technicians on the Lynn & Inner Dowsing wind farm. Overall, the sample size available was much smaller than originally planned, due to various organisational factors including those caused by site ownership changes. Nevertheless, the exercise indicated that the chosen methods could provide important guidance for the main data-collection study.

Physiological data were also collected. This eventually did not form part of the final study, since insufficient evidence could be collected to show that movements of technicians' bodies were sufficiently different from the movements of the vessels and secondly because it inhibited technicians from collaborating with the study.

In addition to the VMMS vessel data collected above, an environmental kit was installed on a select number of vessels which recorded oxygen levels, temperature and sound pressure levels (noise) in the cabin to see whether these had any effects on the subjective states of the subjects.

This was followed by a Phase 1b data collection and a period of reflection on lessons learned. There were issues with the performance of the data-collection App, and this was revised for what was hoped to be a much bigger Phase 2 data-collection period. In the event, the subjective data comprised 360 person days (trips outbound and inbound together): 175 person-days for Phase 1 and 185 person-days for Phase 2. These data represent the output of extensive engagement with site staff, despite which it should be noted that the final data set is substantially smaller than anticipated, for a variety of reasons. (These reasons are discussed in the SPOWTT final report and some are sensitive, but they include: the demand on the participants, operational priorities, difficulties of having research team members in the field, hiatuses in operations, and some initial problems with the app).

Further data cleaning was then conducted, resulting in 82 days (164 outbound and inbound transits) for Phase 1 and a further 82 days (coincidentally) for Phase 2 where there was usable app data. BMO then provided the corresponding vessel measurement data (Section 2), specifically:

- duration;
- noise measures: an average figure, a figure increasing with duration (equivalent 1 hour), and an effective maximum;
- temperature measures (RMS, mean, median, min, max and range);
- RMS value of the acceleration of the sensor in each axis;
- Roll, pitch and yaw RMS;
- the power spectral density (‘power’ below) of the acceleration signal on each of the three axes at each of the 4 frequencies of interest above
- the energy spectral density (ESD) (i.e. power * duration) over the entire transit on each axis and at each frequency similarly.

There were a few trips in the final part of Phase 2 that were taken upon a vessel that was not fitted with BMO measurement equipment, but for most trips, there was extant data.

At project inception, consideration was given to investigation of the impact of individuals' fitness on their predisposition to sea sickness, but this could not be implemented for operational reasons. A variety of demographic data for individuals was available; this is not used here because (a) there were insufficient individual participants for findings to be robust, and (b) these variables are not under the control of the schedulers.

5 | HUMAN FACTORS ANALYSIS

5.1 | Subjective data

Sea-sickness was defined as comprising five related symptoms: nausea, dizziness, sweatiness (temperature disturbances), irritability and headaches. There were few reports of symptoms, with headaches being the most frequently reported. All symptoms (except sweatiness) were at their worst at T2. T3 is typically reported once safely located on the turbine, possibly explaining why this is not cumulatively worse than T2, as some recovery will have taken place. Mean differences were relatively small.

In addition to measuring current sea-sickness symptoms, experience of a developing state which can be stemmed, if actively controlled, was also examined. Both physical management strategies (e.g. lying down) and mental management strategies (exerting additional mental effort to maintain control) were reported at T2 & T5, although only infrequently. Management of sea-sickness was very highly correlated to symptoms.

Fatigue is an important area, having clear implications for safety. Relatively low levels of fatigue were reported. Fatigue was lower, on average, at the end of each journey than the start, suggesting that generally the transit experience was not inherently fatiguing for those journeys we measured, most of which were not problematic or borderline (this may be partly also due to time-of-day effects and technicians sleeping on the journey).

In addition to measures of subjective state, technician evaluations of readiness to work, planned tasks and required recovery were incorporated as proxies for objective measures of work. Within individuals these scores were significantly correlated, suggesting that recovery time taken was relatively consistent with evaluations of safety requirements. Some technicians reported a shorter amount of time for recovery than that needed to feel safe, which requires further investigation.

5.2 | Combined analysis

With acknowledged caveats about data quantity and quality, the relationship between vessel motion and person state is now examined. To utilise the limited amount of data, each trip was treated as a separate piece of data, ignoring that multiple trips were made by the same participant and multiple participants were on the same transit; it had been hoped to perform repeated-measures analyses but the number of participants was too small and unbalanced.

Sets of hierarchical multiple regressions were used to explore the factors predicting the range of sea-sickness symptoms. Results came from using the frequency-weighted data, and specifically the 'energy' (ESD) figures (since the effect of duration would be expected to be multiplicative). With a limited amount of environmental data, we found possible significance in the mean temperature (temperature had featured in T2 reports), so this data-item was maintained, but we did not use the remainder in the analysis. We found:

- At T2, initial impressions suggest that the condition of the technician before sailing is important, in particular the level of sleepiness they feel. Nausea and physical management of symptoms appeared to be most sensitive to vessel motion, followed by dizziness and active mental management of symptoms, with *x*, *y* and *z* accelerations all important.
- Time T3 is key for SPOWTT, when technicians are about to start work on the turbine. At this point, particular sea-sickness symptoms seem to be coming from vessel motion: nausea, dizziness and headaches, driven from all three axes at various frequencies but particularly the *y* direction (especially 0.16 Hz). Subjective readiness to work seems to depend more on the prior state of the technician: the previous night's sleep in particular. However, vessel motion also influences mental and physical fitness to work (*y* motion at 0.16 Hz). Feelings of fatigue at T3 seem to depend largely on condition prior to travelling.
- At T4, evaluation of work performance ('how engaged/effective/efficient were you?') showed the journey out to have quite an effect, particularly X movements: perhaps these have a longer-lasting effect. By T4, fatigue is due to the demands of the work as well as the initial state of the technician.
- At T5 there were few strong relationships, mostly coming from the state of the technician when leaving the turbine but also some still from T1, and anxiety about the sail home - notably different from the position at T2. For both T2 and T5, it should be noted that vessel-motion variables were for the whole journey, half of which was after T2/T5, so these results should be treated with some caution.
- Time T6 showed a complex set of effects, with symptoms caused by both the state of the technician on beginning the journey back, and vessel motions. All three dimensions (*x*, *y*, *z*) play a role. Irritability, mental fatigue and sleepiness are all affected: important as the technician is about to drive home.

All of these analyses highlight the complexity of the impact of transit on work and wellbeing. It is clear that a full understanding requires a multidimensional model of sea-sickness (and of fatigue). Also, a frequency weighted measure of motion parameters is important for understanding the relationship between motion and the range of dependent variables.

5.3 | A novel sea-sickness factor

SPOWTT needed to identify a single variable representing 'sea-sickness'. The data collected have a number of relevant variables at time T3: three fatigue variables and three variables about readiness to work—which according to the results above appeared to be more related to initial state of the technician than to the journey—plus five different symptoms of sea-sickness and overall evaluation of 'sea-sickness'. These latter six are highly inter-correlated and factor analysis shows one component in the data representing 65% of the variance:

$$\begin{aligned} SS_{comp1} = {} & 0.908 \cdot nauseous_3 + 0.918 \cdot dizzy_3 + \\ & 0.663 \cdot sweaty_3 + 0.623 \cdot irritable_3 + \\ & 0.793 \cdot headachy_3 + 0.884 \cdot SS_{overall3} \end{aligned} \tag{1}$$

This component had 241 valid responses, of which 47.7% had a value of 4.79 (when no sea-sickness was reported); the remainder ranged in value from 5.41 to 27.98, with a mean of 10.31. It should be noted that SPOWTT data is by definition self-selected on journeys that can be sailed; if weather is too bad, a full journey does not occur and no data is obtained. This variable proved to be a good predictor of (the three) variables which indicate how ready-to-work the technician is, or feelings at time T4 as to how their day went (three relevant variables): the correlations of the component variable with these six variables were all significant at the 0.1% level, although moderate correlation coefficient values (0.25–0.37) suggested that other factors also influence this state.

5.4 | A novel sea-sickness prediction model

Given the areas of divergence and agreement in the literature, special attention was paid to the frequency of the motion, and all dimensions of motion were considered. However, it was feasible only to calculate the cumulative vessel motion with given pre-chosen frequencies. It was decided that, since BS2631 and the literature identifies 0.16 Hz, this should be one frequency. Operational experience within the consortium suggested that 0.4 Hz was also important; thus, in order to cover a range, the analysis concentrated on four frequencies: $f_1 = 0.1$ Hz ($T_z = 10$ s), $f_2 = 0.16$ Hz ($T_z \approx 6.3$ s), $f_3 = 0.4$ Hz ($T_z = 2.5$ s), $f_4 = 0.6$ Hz ($T_z \approx 1.7$ s).

To compare this variable against vessel movements, we used a logistic function:

$$\text{logit}_{SS} = \ln\left(\frac{SS}{1-SS}\right) \tag{2}$$

where SS is normalised in the range [0,1] for convenience, as follows:

$$SS = \frac{(SS_{\text{comp1}} - 4)}{43.4} \tag{3}$$

such that the minimum component score (4.79) gives a very low level value of SS (arbitrarily, 0.02) and a maximum component score of 43.1 gives a high value of SS (arbitrarily, 0.9).

A regression was carried out between the logit function and the independent variables, including vessel motions, duration and drop-off order. Only the outbound journey was considered, since only this journey affects people's ability to work on the turbine; and psychological effects demonstrated on the outbound and inbound journeys are quite different. Vessel motions included power and energy variables, and also the square-root of the PSD- and ESD-values.[24] Various hierarchical regressions were investigated, but the clearest was as follows, giving sea-sickness as a function of only four significant variables, all the 'power' of vessel acceleration:

$$\begin{aligned} \widehat{\text{logit}}_{SS} = \; & -3.499 + 18.876 \cdot P\left\{acc_X^{f_3}\right\} + \\ & 37.552 \cdot P\left\{acc_Y^{f_2}\right\} + 11.369 \cdot P\left\{acc_Z^{f_3}\right\} + \\ & 281.337 \cdot P\left\{acc_Z^{f_2}\right\} \end{aligned} \tag{4}$$

where $P\{acc_A^f\}$ represents the 'power' of the acceleration signal on axis A at frequency of interest f.

Finally, we recover the prediction of seasickness by inverting Equation 2:

$$\widehat{SS} = 1 - \frac{1}{\exp^{\widehat{\text{logit}}_{SS}} + 1} \tag{5}$$

If this equation had been used to predict sea-sickness on the trips for which data were collected (remembering that these data are only for trips calm enough to sail) for 99.5% of the trips, it would give a prediction below 0.4. Uncertainty levels could also be calculated; these are not used for this analysis but should be in future development.

6 | CONTROL MEASURES FOR HUMAN FACTORS

The aim of SPOWTT was to understand how transit affects the mental and physical wellbeing of individuals, with an aim to ensuring personnel can arrive at the wind turbines in a fit state to work safely and effectively. The impact on a technician's health and safety is established through a reduction in their likelihood to develop sea sickness symptoms. Further, the SPOWTT report highlights that some technicians require significant 'recovery time' before they are fit to begin specific work upon arriving at the turbine, otherwise they are inherently at a higher degree of safety-risk.

SPOWTT further examined opportunities for control strategies and making recommendations around the causes and effects of sea-sickness, to reduce risks to safety and productivity.

- Anecdotal data shows that sea-sickness is under-reported. The complexity and early symptoms of sea-sickness should be communicated, and reporting mechanisms established. This can assist early mitigation strategies and the development of wellness programs.

- Strategies to account for recovery times, fatigue and sleepiness scales could be considered by sites and industry (e.g. Epworth Sleepiness Scale,[25] the UK HSE Fatigue and Risk Index Tool).
- Further consideration is needed into how to ensure technicians are given sufficient recovery time.
- Technicians experience concern over developing weather conditions, which further increases the state of un-readiness.
- Methods to reduce *x*-axis motions of vessels and/or the humans on them would be beneficial.

Mette et al.[26] mention several recommendations and coping strategies to deal with sea-sickness, the first four of which were reinforced by feedback received during the project:

- the stomach should not be too full or too empty;
- fatty or sweet food should not be eaten before/during the trip, rather foods rich in carbohydrates;
- fix on the horizon or lie on the back with head raised and eyes closed;
- using drugs against sea-sickness can lead to fatigue and limit working ability;
- chew a ginger root;
- avoid histamine-containing foods (salami, tuna).

It should be noted that SPOWTT was concerned with short-term rather than long-term health effects, although future should consider the long-term implications of exposure to such effects.

MARIN also designed an on-board tool to inform the captain/skipper, so (s)he can take sea sickness into account in operational choices. After leaving port, actual vessel motions can be measured and these used to calculate and inform the captain of sea-sickness. An additional step also forecasts sea-sickness at destination or, for example, an hour in advance. Figure 6 shows the user interface trialled.

The on-board sea-sickness tool using MSI as the sea-sickness indicator was installed on one vessel. It is expected that the captain will develop a feeling on what MSI typically limits the effectiveness of technicians, so their feedback is required. The tool therefore included an anonymous customer satisfaction survey box (Figure 7); in further research this will be used to define limiting conditions.

Based on the MSI value and forecast, the captain could take actions to reduce the MSI on arrival, either changing the route (sailing in a more protected area could be beneficial, or changing heading with respect to waves), or changing the vessel speed (which influences vessel motion behaviour and possible wave impacts). The system will show the effect of vessel speed and course on the MSI for a CTV.

As well as motion, there is a wide literature on other contributors to sea-sickness, particularly field-of-vision but also environmental factors such as noise, temperature and smell. Data were collected on some of these other factors within SPOWTT (see Section 4), but results were not sufficiently reproducible or significant to include in this paper.

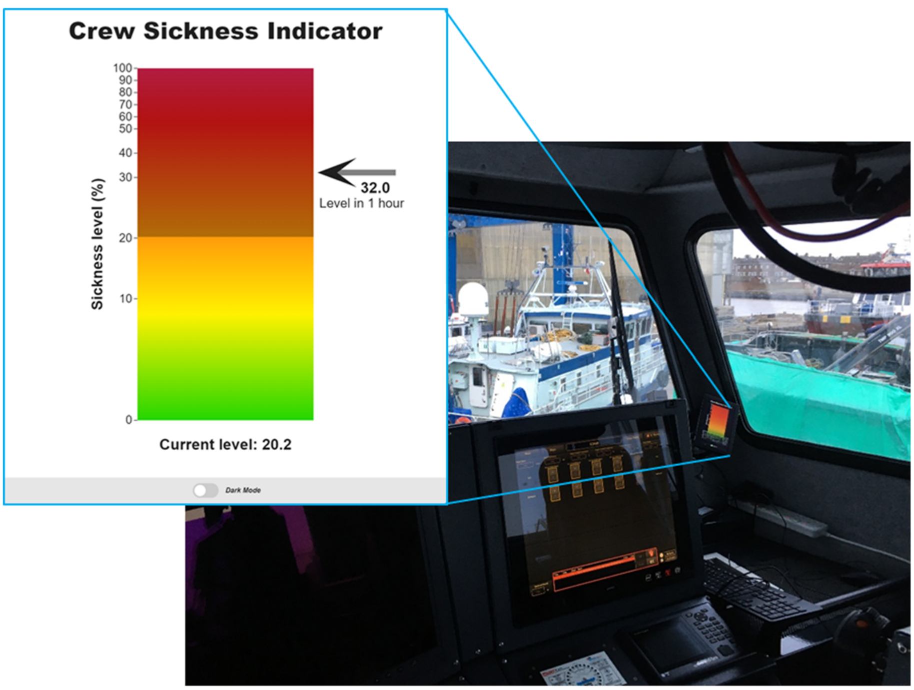

FIGURE 6 MSI indicator on-board CTV bridge [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 Satisfaction survey box [Colour figure can be viewed at wileyonlinelibrary.com]

7 | DECISION SUPPORT SYSTEMS

7.1 | Maintenance planning decisions

Section 6 described possible on-board mitigation measures, including slowing down or re-routing the vessel. These will in turn have an influence on the effectiveness of the day's work plan, and therefore wind farm profitability. It is preferable, where feasible, to predict and account for such issues at an earlier stage. Therefore, the SPOWTT project also investigated this approach, in particular with the aim of demonstrating how more accurate sea-sickness modelling can be used to enable a wind farm to benefit from moving beyond the rules of thumb described in Section 1.1.

Key decision steps available before the technicians go to sea (working backwards in time) are:

1. Checking the weather forecast on the morning of the voyage, determining whether the voyage should go ahead either: as planned; with adjustments; or not at all.
2. Transfer planning the previous day, including whether to sail and choices of routes and timings of turbine visits. Interviews during SPOWTT with staff at a UK offshore wind farm resulted in the flowchart in Figure 8, which is typical for an offshore wind farm. The dashed box highlights the decision process which the tool described in Section 7.2 supports.
3. Selection of the contracted vessel. This is discussed further in Section 7.4.

7.2 | Daily maintenance plan simulation

Decisions with longer-term resonances often have numerous possible options, with outcomes that can be complex to predict. In these cases, computer simulations often provide a faster and more accurate way of forecasting the future and sifting through options than human heuristics. An example of such a heuristic would be the concept of a 'weather day': if significant wave-height is forecast to be above a certain vessel-relevant height, trips are currently not planned, which can result in wasted trips, or lost opportunities.

TNO's 'Despatch' software aims to make the choice of plan for the next day faster, more effective, and more focused on business objectives. This software uses a discrete event simulator to evaluate the outcome of a plan in terms of key performance indicators (KPIs) such as number of work orders completed, time and cost of technicians, cost of vessels, or wind farm energy output. Site planners can use this information to try different plans quickly, discuss trade-offs with site management and team leaders, and make decisions. Several key improvements were made to the software in SPOWTT:

1. the process of daily maintenance planning was understood in detail by working on several wind farms side-by-side with the planners;
2. a new user interface was designed and built, to enable site planners to test the software during their daily job and feedback;
3. vessel motions and sea-sickness limitations were introduced, resulting in variable speed vessels and closer conformity of the simulation with human transit limitations.

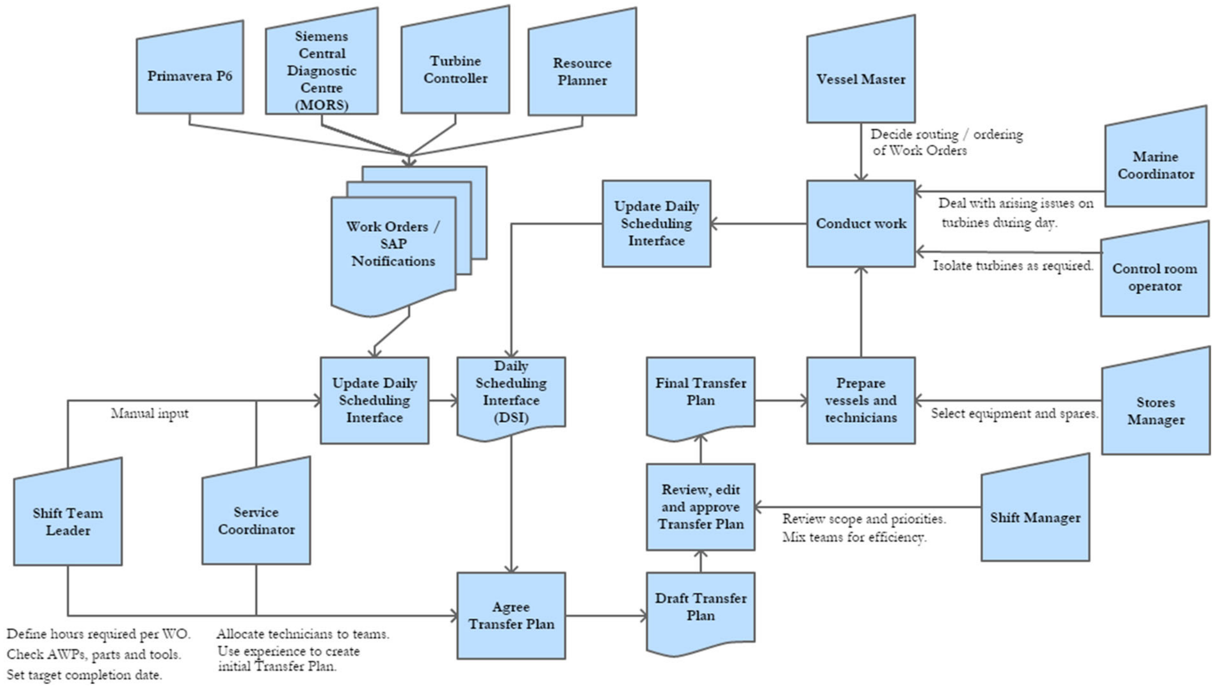

FIGURE 8 Daily maintenance planning process [Colour figure can be viewed at wileyonlinelibrary.com]

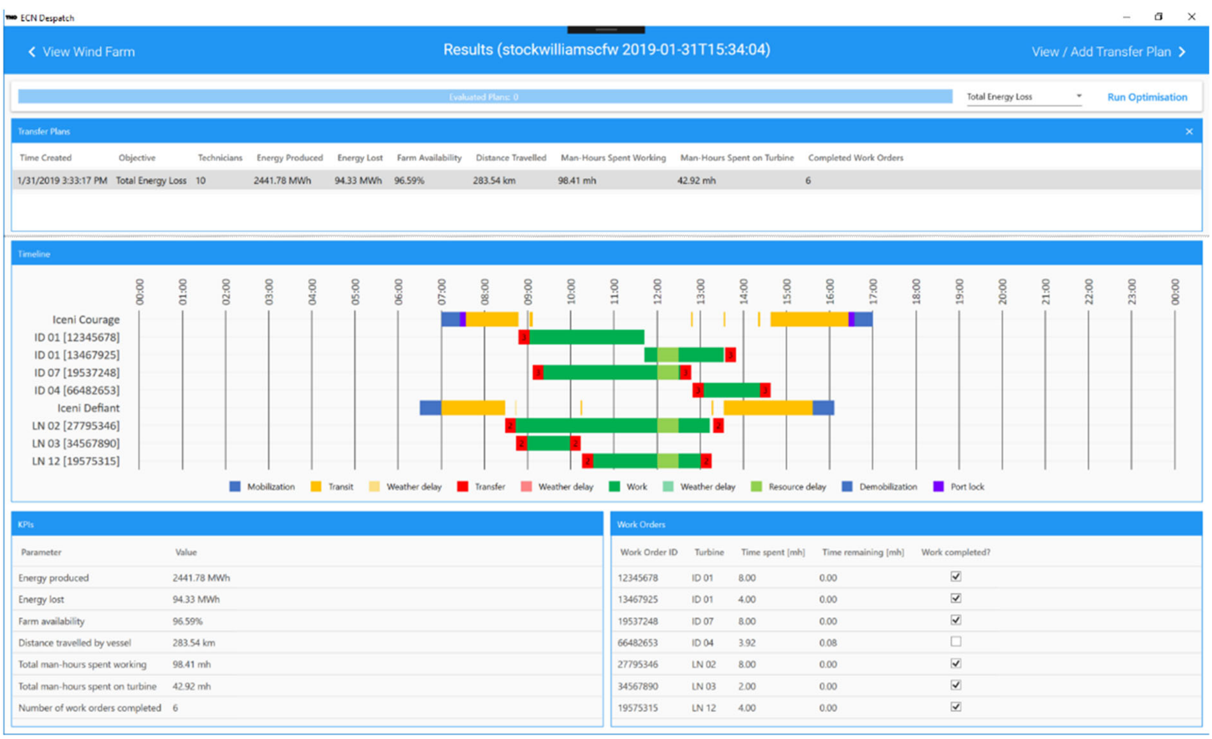

FIGURE 9 Simulation of a daily plan in Despatch [Colour figure can be viewed at wileyonlinelibrary.com]

The creation of a plan involves matching technicians into teams, placing them on vessels and assigning tasks. Various rule sets for business processes regarding acceptable combinations of technicians and work orders are built in. Finally, for each plan the simulation outcome is displayed, as illustrated in Figure 9. The screen is split into three sections from top to bottom: a list of all transfer plans tried (sortable by various KPIs), a Gantt chart of the selected transfer plan, and more detailed KPIs for the selected transfer plan.

During transit, the appropriate speed (or none) is looked up regularly during the voyage, depending on the vessel's current heading and the weather. This look-up file can be created directly by a user by specifying a text file with weather conditions and the resulting vessel speed, or generated from the more sophisticated vessel motions table provided by MARIN and shown in Table 1, using a pre-processing software tool (available free-of-charge as a SPOWTT product).

Despatch also has many other features not used in this project, in particular automatic transfer plan optimisation,[5] which can now also include sea-sickness modelling and variable vessel transit speed, if a suitable look-up table is available.

7.3 | Testing

Testing on-site with planners was undertaken during SPOWTT. A protocol was developed for the trials within daily operation. The methodology comprised a designated trial period; on-site training and familiarisation with the software; semi-structured workplace interviews and observations at the start and end of the trial and every 2–3 months throughout; a simple regular online survey for prompted feedback; and immediate user-driven feedback using either existing external tools or integrated within the DSS.

Only two sites were able to proceed with using the software for operational reasons, with only one engaged with the software beyond the installation period. Feedback from this site is summarised:

- the user interface is pleasant and easy to use;
- the tool helped planners foresee weather disruptions to total time on turbine;
- the Gantt chart was particularly useful to determine when the second team to be dropped off would arrive. The tool proved accurate in predicting this, even without vessel motions information;
- considering energy loss is now a regular part of the daily planning process, and energy price is also being considered. Despatch provides an easy way to calculate and understand the consequences of O&M on these KPIs;
- forecast confidence is an important factor when decisions are made; incorporating uncertainty in the plan could be useful in making planning decisions earlier.

While all feasible attempts were made to make the tool easy to use, it is unavoidable that some extra work is created, since the tool is not interfaced directly to the site's asset management system. Thus work orders and weather must first be imported manually into the tool (turbines, technicians and vessels are set up in a database running in the background), which proved a barrier to daily use.

7.4 | Commercialisation

During SPOWTT, SMC received the transfer plan simulation part of Despatch for integration into their ATLANTIS™ Marine Co-ordination software, to provide a holistic planning and implementation tool for Marine Coordinators and Planners. ATLANTIS™ considers predefined routes

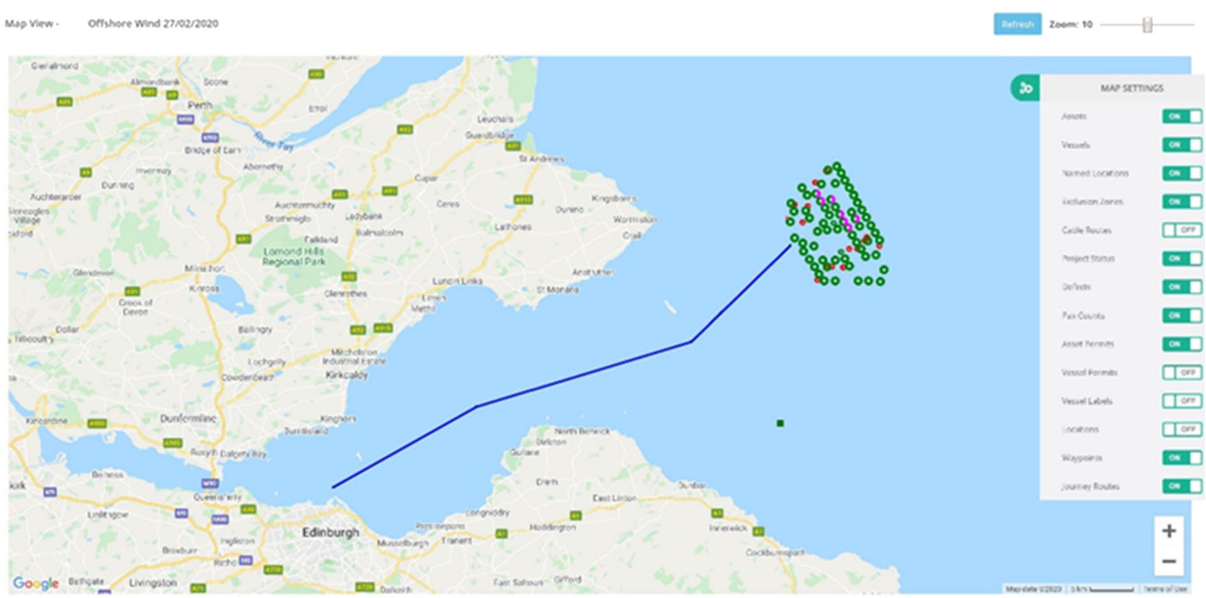

FIGURE 10 SMC Atlantis™ [Colour figure can be viewed at wileyonlinelibrary.com]

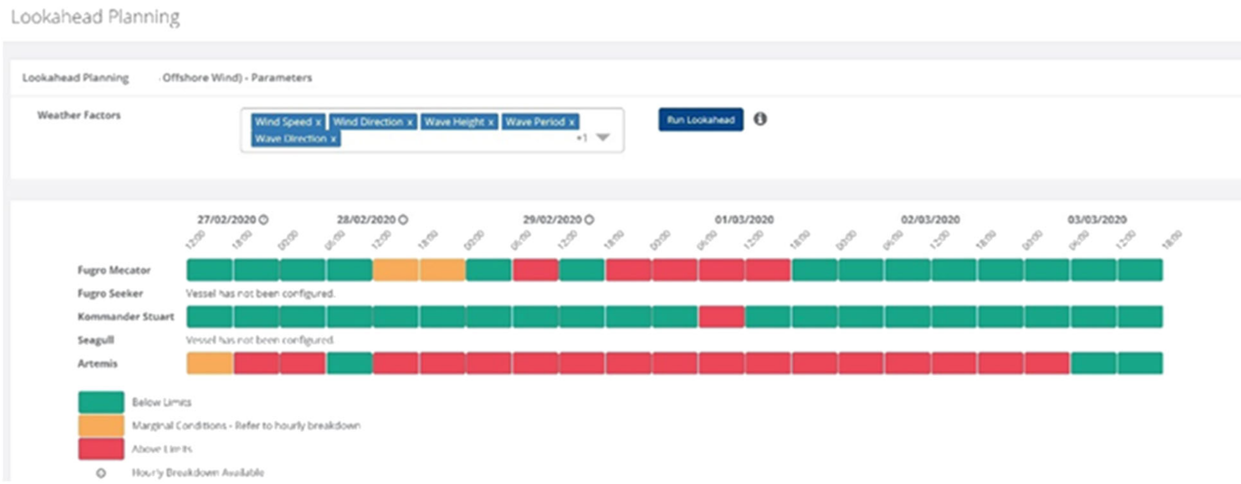

FIGURE 11 Lookahead planning section of SMC Atlantis [Colour figure can be viewed at wileyonlinelibrary.com]

between mobilisation port and site (and vice versa), as well as weather forecast data to determine potential impacts of transit on vessels and personnel, as shown in Figure 10.

ATLANTIS™ allows transit routes with multiple waypoints. Users are thus able to replicate transit passages to and from site, navigating both geographical and human defined boundaries (e.g. shipping lanes). Key vessel data can be input, setting performance parameters against individual vessels which influence the outputs of journey simulations. Integrating a StormGeo weather forecasting API and including the work on the impacts of weather on vessel motion above, simulations can be run for multiple vessel types across multiple journeys simultaneously.

ATLANTIS™'s Lookahead Planning feature gives users a picture of the implications of forecasted weather against vessel capabilities, which can be utilised during, for example, planning meetings (see Figure 11), 3-day look ahead marine coordination meetings, and daily project meetings. ATLANTIS™ gives higher confidence in short-term decisions by accounting for forecasted environmental conditions and their effects on vessel motions and sea-sickness.

SMC will continue to develop ATLANTIS™. SMC will initially look to implement a vessel selection support tool, using historical vessel performance data held by ATLANTIS™ to assess performance and reliability. The tool will be available across all existing and planned marine coordination projects in 2020; this currently totals 11 offshore projects globally but is expected to rise in the coming months.

8 | CONCLUSIONS AND FURTHER WORK

Enabled by SGRE and its suppliers and customers, SPOWTT has performed measurement campaigns of offshore wind farm technicians (University of Hull and ORE Catapult) and their transit CTVs (BMO). Analysis of these data by University of Hull and BMO has provided insight into the different symptoms of sea-sickness, its correlations with motion and the initial state of the technician. Two novel developments are: a single parameter representing sea-sickness which appears to be a good predictor of readiness-to-work; and a model for sea-sickness with an equation which fits the current dataset well. Such tools aim to integrate the numerous sources of information required for operational decision-making, both onshore and at sea, reducing the complexity of modern wind farm operations. Through their use, the financial impact of each decision can be made more transparent, and the value of improved data and information can be quantified, so that sound investment decisions can be made.

This sea-sickness model has been used by MARIN, along with their time-domain hydrodynamics simulations, to calculate extensive data-tables for several typical ship hull forms, applicable to any offshore wind farm. Further, a trial has been conducted of the use of this information on-board a ship, to inform the captain of current and near-future sea-sickness.

Two commercial end-products have been further developed, to influence daily and long-term planning on offshore wind farms. TNO's *Despatch* software provides simulations of daily plans with CTVs, which now incorporate variable transit speeds and sea-sickness. SMC's *ATLANTIS™* software is available as commercial product for marine coordination, building in part on the transfer plan functionality of *Despatch*.

SPOWTT has also identified actionable recommendations for industry, including the use of control measures, sea-sickness management techniques, operating procedures, use of decision support tools in practice. These all combine to reduce and mitigate potential health and safety impacts associated with offshore wind farm operations, improving site productivity and reducing operating costs.

Reports, source code and software delivered from the SPOWTT project are available on the SPOWTT website (https://ore.catapult.org.uk/stories/spowtt/), which acts as a repository of all detailed public information.

This prompts further research about the nature of sea-sickness and different symptoms. This would cover study of technician states before boarding; objective measures of cognitive performance; characterising vessel-motions and work on uncertainty in the predictions. MARIN is using the validation findings to improve further its prediction methods on ship motions and sea state definition, as well as refining the on-board control-measures system. University of Hull is using the understanding gained to build on their established psychology work. BMO is using the MARIN hydrodynamic database for further vessel-motion studies and more validation data, and using the sea-sickness model for further prediction modelling/validation. TNO is continuing to extend and apply Despatch with wind farm operators, and to address larger, further- offshore wind farms which use Service Operation Vessels (SOVs). SGRE is continuing to focus on improving technician health and safety, including development of an industry recognised occupational stress risk assessment and training programme.

This was a large project, with a complex set of stakeholders and long timeframe. It included various technological developments, delivered by multiple, geographically diverse partners. We learned a number of lessons from the project, including the following:

- The importance of an inter-disciplinary approach, particularly incorporating the lived experience of the technicians. Due to distances involved, shift times, substantial work volumes during summer months, and the requirement to respond on short notice to operational changes (inherent to offshore-wind), access to the technician workforce was sometimes problematic.
- Lessons about planning access to technicians carefully at the proposal/consortium stage; the need for support of the organisation/management in performing trials, and the usefulness of participants being allocated work time in which to participate during the trial period.
- The value of on-site presence during development and testing of the decision-support systems proved invaluable: it enabled researchers to gain a richer understanding of the decisions-making, it enabled SPOWTT tools to be adapted to the needs of each site, and developed understanding of how to integrate with current systems and tools.

As with any research project, several challenges emerged during delivery:

- Engagement/motivation of technicians was a major concern, and there were problems with proposed incentivisation schemes; this should be considered at the very beginning. Having an effective 'champion' at each site office was useful.
- Since the final data set is substantially smaller than anticipated, results are much more tentative, and the proper planned 'repeated measures' statistical analysis would not be reliable or appropriate. Further, only journeys which actually occurred are measured, so there is no data in extreme conditions.
- App development and implementation support proved problematic. The contracted supplier consisted of a single individual, causing availability problems at critical moments. Challenges emerged regarding compatibility with different iPad configurations used at sites; different operating system builds and corporate security restrictions presented issues with connectivity and functionality.
- Buy-in from site owners was essential to participation of sites, and a significant proportion of owner/operators declined to get involved in SPOWTT.
- It was originally conceived that a 'fitness for work' assessment could be undertaken from technicians performing tasks when they were ready to start work. However, it soon emerged that this could not be asked as it would interfere too much with the maintenance work.
- There were some differences in the definition of the wave spectrum used by BMO and MARIN, resulting in miscommunication and increased time pressure. There was also insufficient time to subject Equation 4 to rigorous testing for robustness.

Nevertheless, SPOWTT has delivered a significant advance in understanding one of the offshore-wind industry's key challenges, which will only become more relevant as increasing numbers of wind farms are built across the world. Ultimately, only eliminating the need to go offshore can remove the possibility of sea-sickness.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

Specific sea-sickness data: authors elect to not share data due to personal and commercial confidentiality. Data are openly available in a public repository that does not issue DOIs. The data that support the findings of this study are openly available in https://ore.catapult.org.uk/stories/spowtt/: SPOWTT project report, TNO Programme for Pre-Processing Database, Source Code of Onboard 'Control Measures' system, MARIN Representative Hull, Description of the MARIN hydrodynamic databases.

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