

FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

COM06: MAJOR COMPONENT REPLACEMENT

Public Summary Report



GENERIC REPORT

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In partnership with:



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EXECUTIVE SUMMARY

This report covers the modelling methods and findings of the second major component replacement (MCR) project done within the Offshore Renewable Energy Catapult's (OREC) Centre of Excellence (CoE). Large component failure poses a major risk to floating offshore wind (FOW). Fixed bottom wind relies heavily on jack-up vessels (JUVs) for MCR, a solution that cannot be utilised at most FOW sites due to increased water depths, relying instead on either tow-to-port (TTP) or in-situ MCR. This project provided a pathway to bridge the gap between design and offshore testing for in-situ MCR solutions through advanced simulation and modelling.

This project partnered with the National Decommissioning Centre (NDC) and SOLVE Wind. The NDC provided the offshore MCR modelling utilising their Marine Simulator, and SOLVE Wind provided details on their up-tower crane in-situ MCR solution.

The NDC modelled the up-tower crane positioning and gearbox replacement in three sea states. The modelled sea states had significant wave heights (H_s) from 1.5-2m, wave period (T_p) ranging from 6-10s, and wind speed at 8-10m/s. Motion was tracked from a universal point.

The results from NDC modelling found:

- An increase in crane and gearbox motion between sea state 1 (1.5m H_s , 6s T_p) and sea state 2 (1.5m H_s , 10s T_p);
 - This suggests a direct correlation between T_p and component motion during MCR.
- Sea state 3 (2m H_s , 10s T_p) regularly had the highest amplitude of component motion;
 - This points to a limitation in motion that will still directly rely on H_s .
- A variation in in-line tension and motion between hoisting and lowering operations; with hoisting operations having higher line tension, shorter acceleration amplitudes, and higher displacement amplitudes.
- Inconsistent patterns in sway and surge responses when comparing pre-defined line tension results; the sway responses at 2.5 tonnes/line are lower in sea states 1 and 3, but higher in sea state 1 compared to the lower tension.

The NDC's modelling and input from project partners formed the task setup and limitations for the weather downtime (WDT) and COMPASS modelling done by OREC. The WDT considered the variation in weather limits and task durations, while cost modelling focused on expected vessel usage and repair delays (not including in-situ technology chartering) for three varied in-situ exchanges compared to TTP operations. WDT and cost modelling found:

- All in-situ method variations had shorter WDT and overall time compared to the TTP method.
- At the 50th percentile, many in-situ MCR methods had no WDT from May to late August.
- In-situ methods with tasks that could be completed in different weather windows shortened overall WDT, especially in winter months.
- TTP methods require double to nearly quadruple the amount of offshore hours over the course of a full scale farm's lifetime.
- Minimising the in-situ MCR operational time can lower both offshore hours and wait on weather.

Benefits of modelling:

- Better understanding of how varied setups and sea conditions impact operations;
- Increased understanding of actual weather limitations to decrease unexpected weather delays.
- Comparison of different methods to understand cost impact

Benefits of in-situ MCR:

- **Shorter task duration:** While up-tower cranes require additional steps to be put into place, these operations are significantly shorter compared to the towing requirements of TTP, decreasing the turbine downtime and vessel usage.
- **Reduced vessel charter days:** Decreasing vessel usage, both in WDT and in use during maintenance, allow for an expected drop in costs, as fewer vessel days are required. This is also beneficial for potential large-scale maintenance campaigns, where vessel usage can quickly multiply.
- **Expanded working season:** The increase in weather limits for the in-situ MCR technology is expected to allow for work in the 'shoulder' seasons of late spring and early autumn. This in turn allows for a expedited repair schedule and increases the allowable repair window.

Limitations on in-situ MCR implementation:

- **Large component limitation:** Commercially available in-situ MCR technologies are not suitable for all components.
- **Lengthy initial mobilisation period:** In-situ MCR technologies often need to be custom fit for the specific turbine design. If this is not done during the design phase or early in the project, there will likely be a longer mobilisation period for the first operation while necessary customisation of the in-situ components are completed.
- **Limited readiness:** Only one company has carried out in-situ for FOW to date. The lack of widespread experience and duplication of work means that in-situ MCR has a higher perception of risk until more offshore exchanges can be done.

Despite these challenges, this project provides further understanding of in-situ MCR operations, and has equipped the NDC to test emerging technologies, identifying high motion points, expected weather limits, and visualisation of key MCR operations.

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NOMENCLATURE

AHTS	Anchor Handling Tug Supply (Vessel)
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CoE	Centre of Excellence
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COG	Centre of Gravity
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COMPASS	Combined Operations and Maintenance, People, Assets, and Systems Simulation
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DOF	Degree(s) of Freedom
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FOW	Floating Offshore Wind
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FOWF	Floating Offshore Wind Farm
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FOWT	Floating Offshore Wind Turbine
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H_s	Significant Wave Height
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JUV	Jack-up Vessel
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MCR/MCE	Major Component Replacement/Major Component Exchange
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NDC	National Decommissioning Centre
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ORE	Offshore Renewable Energy
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OREC	Offshore Renewable Energy Catapult
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RAO	Response Amplitude Operator
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T_p	Wave Period
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TRL	Technology Readiness Level
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TTP	Tow-to-Port
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WDT	Weather Downtime
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1 INTRODUCTION

Offshore wind is a thriving industry slowly expanding into large-scale floating offshore wind (FOW). The UK's net zero aims quote FOW to potentially reach 5GW by 2030 [1], emphasising support for the industry. But as offshore wind expands, there is an expected increase in demand for major component replacement (MCR) operations. Large component failure poses a major risk to FOW. Deep sea locations, expected for large scale FOW farms, are unable to utilise jack-up-vessels (JUVs) for MCR, which are used for fixed-bottom MCR.

MCR strategies for FOW rely heavily on tow-to-port (TTP) operations. For these, the turbine must be disconnected, towed to port for repair, before being towed back to site for reconnection. This puts strain on port space, vessel demand (especially for long tows), and risks further damage to mooring lines and cables. For some key components, in-situ MCR can be conducted as an alternative to TTP operations. However, in-situ MCR technologies, especially for FOW, are generally unproven and at lower technology readiness levels (TRL).

Working alongside project partners, this project directly supported the advancement of future in-situ MCR technologies through advanced modelling. The project addressed three key questions:

1. How can physics-visual simulation tools be used to model MCR operations on floating structures?
2. How do physics-visual simulation models contribute to derisking MCR?
3. What are the modelling limitations for derisking in-situ MCR?

1.1 Project Partners

This project was done in collaboration with the National Decommissioning Centre (NDC) and SOLVE Wind. A special thanks to both partners for their effort and time.

1.1.1 National Decommissioning Centre

The NDC supports offshore industries to improve the delivery of sustainable and environmentally-friendly offshore energy generation by supporting project development through advanced modelling. The NDC was a key partner for this project, as they provided simulations through the Marine Simulator. This 300-degree visual environment is equipped with four control stations, shown in Figure 1. It functions as a visual-physics simulation platform capable of evaluating, visualizing, and recording structure-environment dynamic interactions in real time across a range of sea states, weather conditions, and operational scenarios. This setup enables the assessment of rigid-body motion, including position, velocity, acceleration, and applied forces.



Figure 1: 300-degree Toroidal Dome Visualisation Suite in the NDC Marine Simulator

1.1.2 SOLVE Wind

Modelling in-situ MCR required collaboration with an existing or developing in-situ provider. This project worked with Liftra, who have designed a self-hoisting crane that mounts onto the nacelle to carry out MCR. Liftra are expanding into FOW, entering into a partnership with Esteyco to create SOLVE Wind. SOLVE Wind has developed a floating barge (called the ATOMS platform) that attaches to the base of the turbine to provide the laydown space for MCR.

2 IN-SITU MAJOR COMPONENT REPLACEMENT

In-situ MCR is carried out on site, and refers to a wide variety of methods. This project focused on a self-hoisting up-tower crane used to replace a gearbox. Liftra's LT1800 self-hoisting crane was used as the model for hoisting and gearbox exchanges within the NDC modelling. The laydown area was provided by the ATOMS platform, shown in Figure 2, is a barge platform designed by SOLVE Wind that attaches to the turbine base.



Figure 2: The ATOMS Platform [2]

In-situ MCR tasks are outlined in the table below, as are the corresponding figures.

Table 1: In-situ MCR Task List

	Task	Figure
1	ATOMS Platform preparation and mobilisation	
2	ATOMS and vessel transit to site	Figure 3
3	ATOMS Platform positioning and connection	
4	Personnel transfer	
5	Crane interface installation	Figure 4a
6	Liftra Crane ascent and positioning	Figure 4b-e
7	Crane assembly	
8	Component Disconnection	
9	Component Lowering	Figure 5a-b
10	Replacement Raising	Figure 5c-d
11	Component reconnection	
12	Liftra crane disassembly	
13	Crane descent	
14	Crane interface removal	
15	Personnel transfer	
16	ATOMS Platform disconnection	
17	Return to port	
18	Demobilisation	



Figure 3: Approach of ATOMS Platform to the turbine

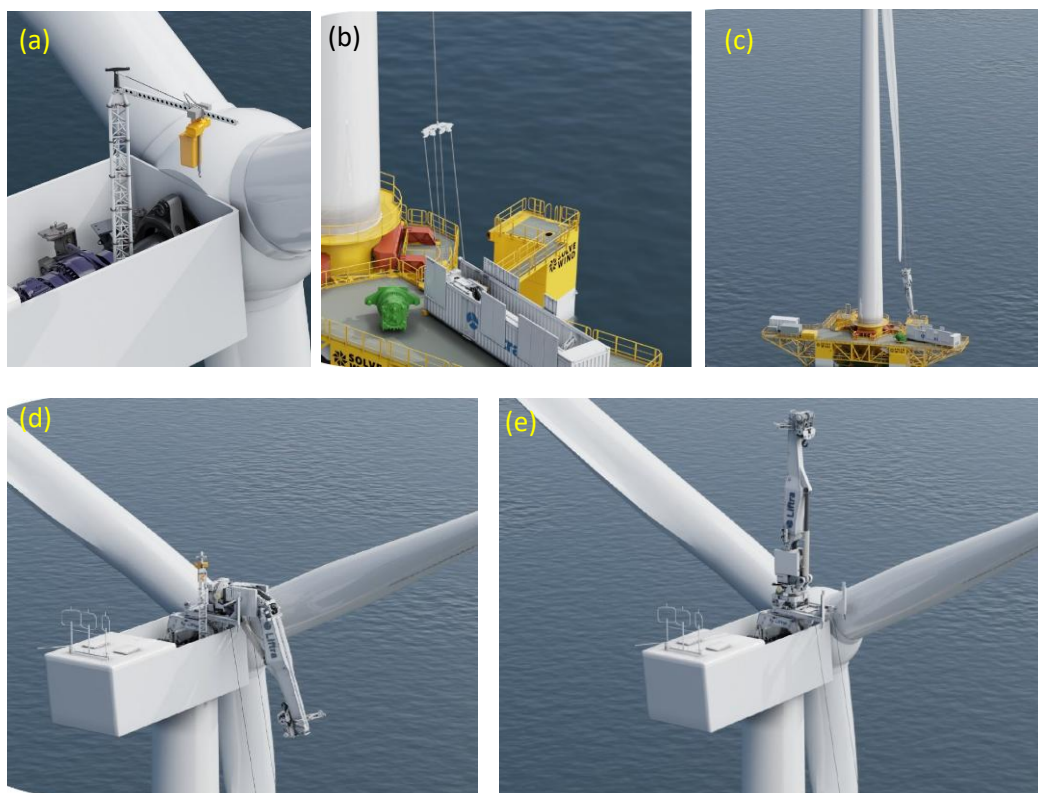


Figure 4: LT1800 Self Hoisting Crane Storyboard Visualisation, provided by SOLVE Wind

The crane utilises an internal climbing mechanism to rise to the top of the nacelle, where it is then secured onto a base pedestal. Once the crane is in position, the component exchange can begin.

The damaged component (e.g. the gearbox), is disconnected and removed. Following the guidewires, the gearbox is lowered onto the waiting platform. The crane is then hooked onto the new gearbox, which is then raised into position until secured, completing the MCR.

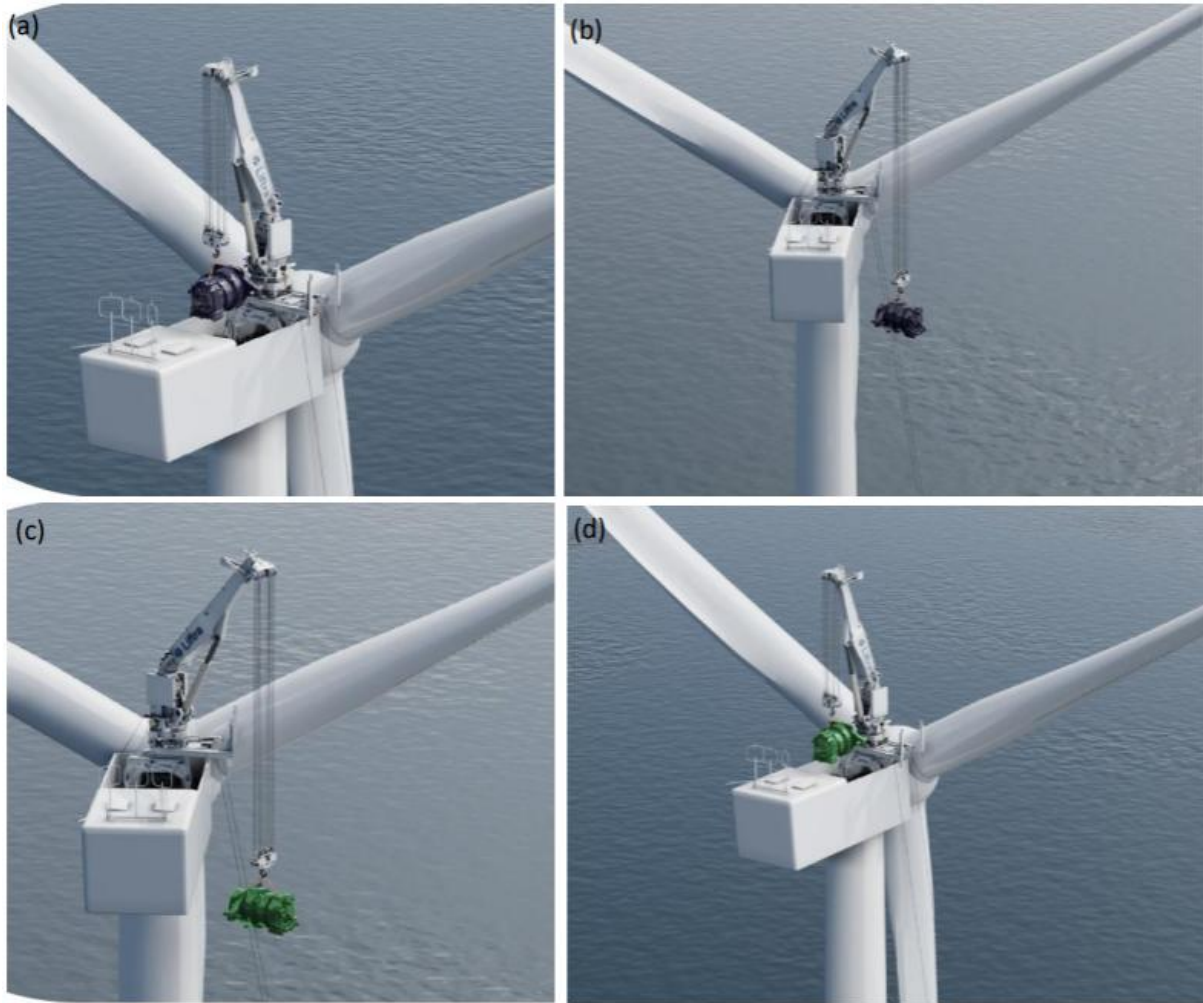


Figure 5: MCE Sequencing, provided by SOLVE Wind

Liftra's in-situ products are used widely in onshore operations. While this project focuses on a gearbox exchange, other products are able to handle blades and other large nacelle components, with some current limits on turbine size for suitability. They are fully equipped to handle MCR with an average duration of 4-6 days, including crane installation, component replacement, and crane disassembly [3].

3 NDC MODELLING

The NDC's Marine Simulator allows for low-cost testing of new and emerging offshore technologies. The collaboration between the NDC and ORE Catapult focused on:

- Understanding facility suitability for FOW technology modelling and evaluation
- Provide the setup of a FOW MCR test to allow for low-cost testing for emerging and low TRL in-situ technologies.

The modelling of an in-situ MCR operation evaluated:

- The feasibility of the self-hoisting crane for MCR operations in floating offshore conditions,
- The impact of varied environmental conditions on the MCR, and
- The sensitivity of MCR operation to varied input parameters, such as tagline tension.

These aims provided the focus for work in modelling the in-situ MCR campaign. This section will first detail the NDC Marine Simulator, then describe the model setup and calibration, results, and a discussion on findings.

3.1 NDC Marine Simulator

The NDC Marine Simulator is a physics-based modelling program that provided the numerical simulations of MCR for this project. The simulator combines Unity's advanced visualisation capabilities with Algorix's high-fidelity multi-physics computational engine, integrating both into a single, integrated simulation environment.

Algorix Dynamics divides imputed CAD models into triangular surface elements, allowing for calculating local elemental loads, including hydrodynamic and hydrostatic loads. These loads are integrated over the entire surface to obtain resultant forces and moments to all six degrees of freedom (DOFs) for every rigid body in the environment. For MCR modelling, this included the individual turbine, the ATOMS platform, and the connected FOWT-ATOMS coupled system.

The force calculations considered:

- Inertia terms with the added-mass contributions
- Linearised viscous-damping coefficients
- Stiffness matrix representing mechanical, hydrostatic, and mooring-related coupling between rigid bodies.

Each considered for the three linear and three rotational DOFs.

External loads (including buoyancy, drag, and lift) and environmental loads were calculated. Environmental force effects were done for current and wind, taking into consideration drag, viscous effect, pressure force effects, and the heading direction.

3.2 Setup and Model Calibration

The Marine Simulator utilises CAD files to measure motion and impacts from sea conditions. The modelling of an in-situ MCR technology required the installation and calibration of a reference turbine, the up-tower crane, the replacement gearbox, and the ATOMS platform.

This project focused on a gearbox exchange for a representative 20MW floating turbine, shown in Figure 6. The substructure is a centre-mounted semisubmersible, with a combined fixed and variable ballast system. The fixed ballast provides static stability and lowers the centre of gravity, while the variable ballast system enables adjustable weight distribution for optimising turbine position between turbine states (operational or at rest).

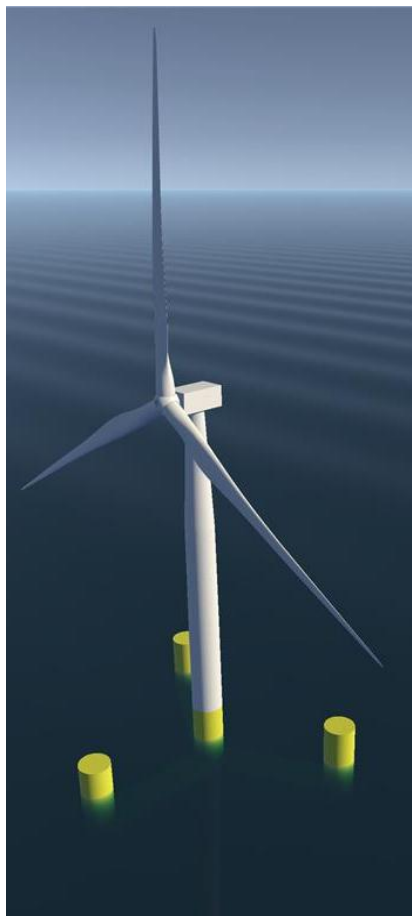


Figure 6: Centre-Mounted Semisubmersible Turbine used in NDC Modelling

A symmetrical three-line mooring system was used for modelling. Chain catenary moorings were used to provide responses under the varying external and environmental loads.

A model of the ATOMS Platform, represented in Figure 7, was modelled.

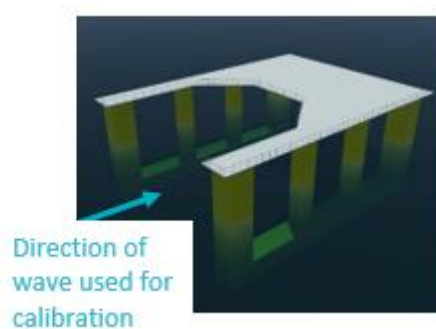


Figure 7: ATOMS2 Platform with Wave Heading Direction used for Calibration

Motion responses were calibrated for the 20 MW FOWT and ATOMS platform independently, and the two connected. The coupled turbine and ATOMS platform model closely follows the motion of the FOWT throughout most of the period range, especially for surge and pitch. The strong correlation highlights the influence of the FOWT on coupled motion.

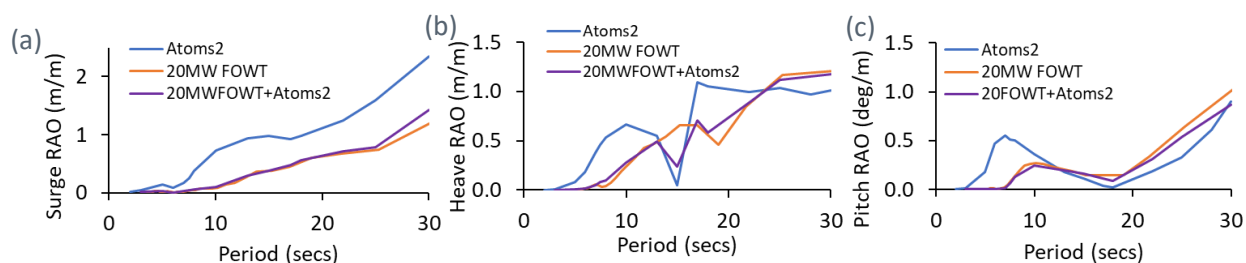


Figure 8: Displacement RAO Comparison between the FOWT and the ATOMS Platform individual and coupled for Surge (a), Heave (b), and Pitch (c)

The ATOMs platform has the highest impact in the heave direction, with a strong pull effect at 15s and 19s. At these points, the deviations reveal a nonlinear effect between the two bodies, highlighting the relationship as more complex than simple inference from individual responses.

3.2.1 Modelling Setup

Following calibration, modelling could be carried out for the crane positioning and removal, and gearbox lowering and hoisting operations. The simulations for installation and operations of the self-hoisting crane were formed from the storyboard detailed in Section 2.

Simulations were run across three different sea states, shown in Table 2. The JONSWAP spectrum was applied during simulations for more randomised behaviour.

Table 2: NDC Sea States Used for Modelling

Sea State	Significant Wave Height (m)	Wave Period (s)	Wind Speed (m/s)
1	1.5	6	10
2	1.5	10	8
3	2	10	10

Along with sea state variation, hoisting and lowering were done at each sea state with 1 tonne and 2.5 tonnes of tag line force, for a total of 12 simulated cases.

3.3 NDC Modelling Results and Discussion

3.3.1 Crane Hoisting and Lowering

The crane hoisting and lowering aspects were based on a standard 5 m/minute with the taglines and positioning already in place. With this, there was an average of 34.08 minutes for hoisting and lowering processes. Results focused on tracking crane motion during operations, allowing the amplitude of peak displacement and acceleration values.

The crane movement was tracked from a universal point to calculate motion during hoisting and lowering operations. This was done for each sea state, with hoisting and lowering trajectories shown adjacently below.

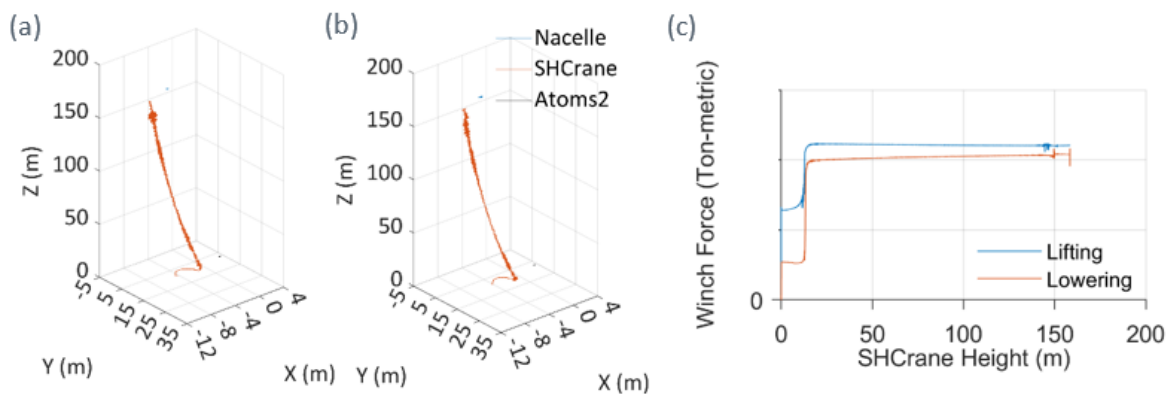


Figure 9: Crane Displacement Trajectories in sea state 1 for Hoisting (a) and Lowering (b) alongside Total Winch Forces (c)

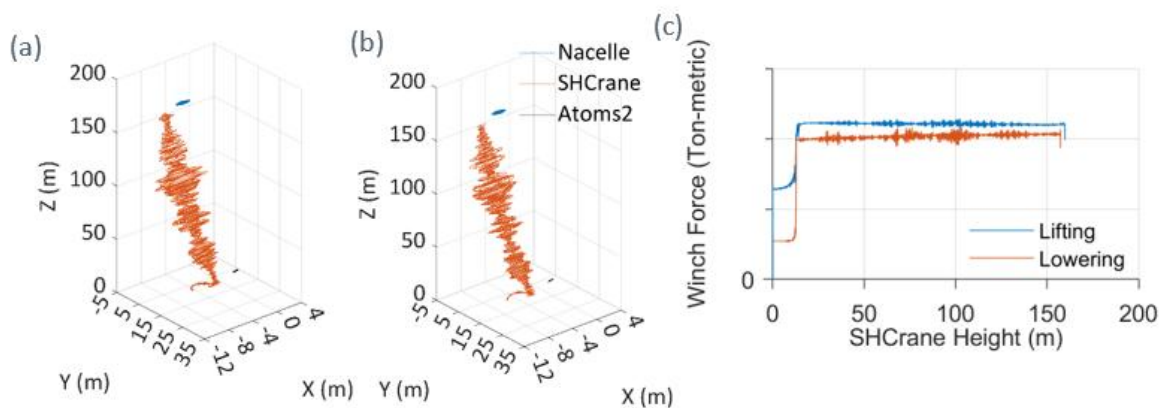


Figure 10: Crane Displacement Trajectories in Sea State 2 for Hoisting (a) and Lowering (b) alongside Total Winch Forces (c)

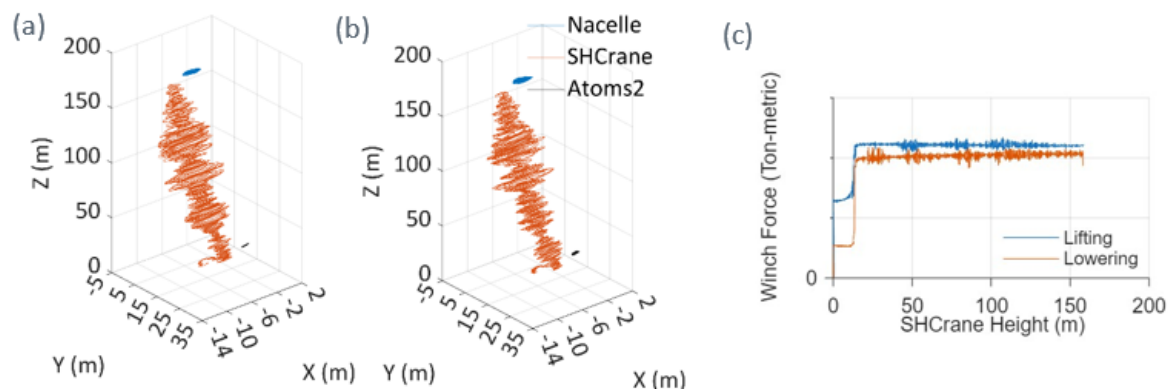


Figure 11: Crane Displacement Trajectories in Sea State 3 for Hoisting (a) and Lowering (b) alongside Total Winch Forces (c)

The total hoisting forces are consistently greater than the total lowering forces, demonstrated in all three sea states. This is due to additional friction losses when lifting against gravity. The drop in winch force from 0-13m is due to the crane maintaining contact with the ATOMS platform. The figure is simplified, as the crane rotates in two DOFs (rotation and translation).

From the tracked motion, the maximum amplitude of displacement and acceleration were calculated and illustrated in Figure 12. All motions were taken from a global point.

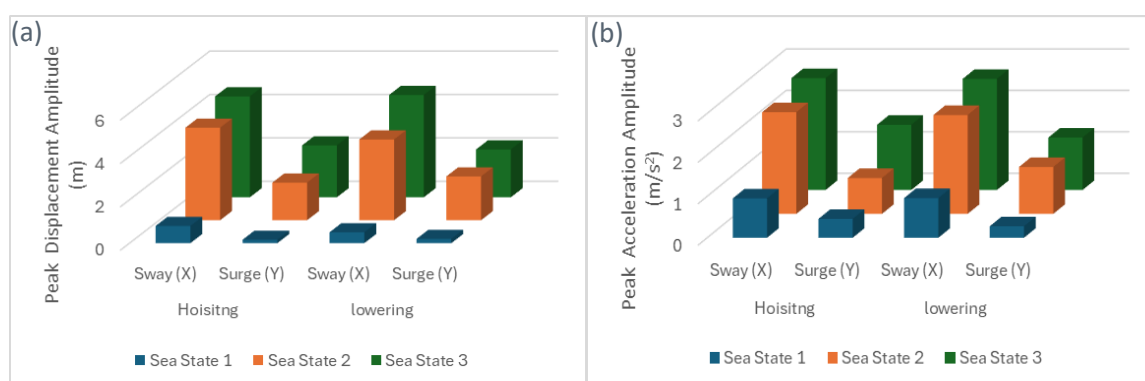


Figure 12: Crane Peak Response Amplitudes during Hoisting and Lowering Operations for Displacement (a) and Acceleration (b)

The responses of sea state 1 have the smallest peak amplitudes for displacement and lateral acceleration of all environmental states. The lower wave height compared to state 3, and the shorter wave period compared to state 2, are both likely contributors.

Sea state 2 shows the difference in motion based on a different wave period. The directional peak displacements are 5.1 and 2.6 times higher for sway and surge respectively at sea state 2 compared to sea state 1. The impact of the varied wave period is consistent with the surge displacement RAO of the combined FOWT and platform modelled at the same periods, demonstrating consistent responses. It also highlights in the impact of peak period on motion

The lateral displacement amplitude for sea state 3 is 1.1 times greater than sea state 2, a surprisingly small increase given the 0.5m increase in significant wave height.

3.3.2 Gearbox Hoisting and Lowering

The gearbox hoisting and lowering operations aimed to visualise and understand the motion and forces of the gearbox and taglines (respectively) during the MCR. The average hoisting and lowering

time was 30.8 minutes, starting from when the crane was slewed out of the nacelle, going nearly 167m down, ending on the ATOMs platform. The Marine Simulator modelled the hoisting and lowering operation in all three sea states for tag line configurations of 1 tonne/line and at 2.5 tonnes/line, tracking the displacement and tension.

The model track the movement of the gearbox, nacelle, and platform during operations from a universal point. This resulted in distance-time graphs, shown for each sea state in Figure 13.

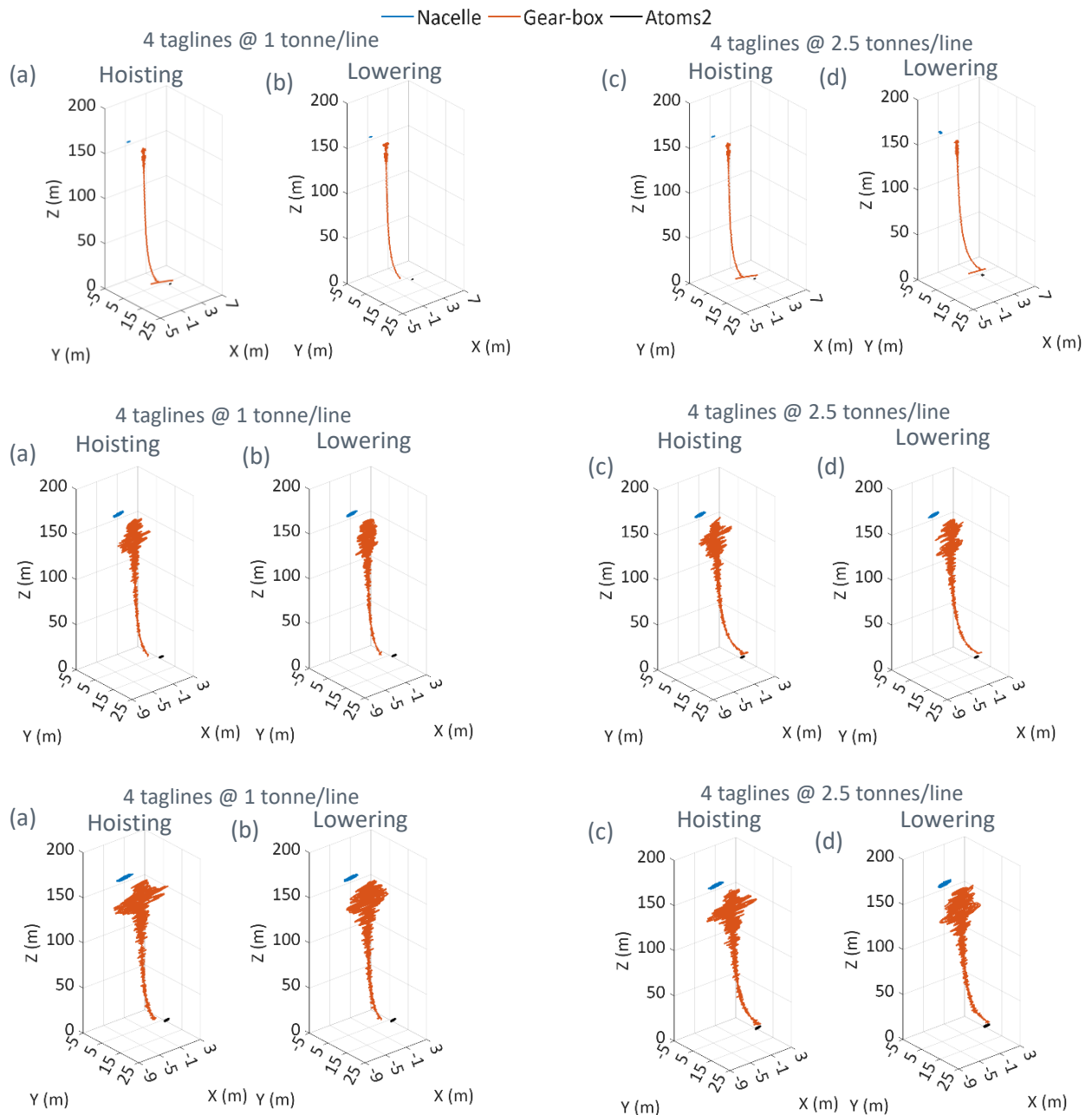


Figure 13: Displacement Graphs of Gearbox Hoisting and Lowering for Sea State 1 (top), Sea State 2 (middle), and Sea State 3 (bottom)

The peak amplitude responses for displacement and acceleration were measured from a global point, taken for each case. The peak displacement and acceleration occurred in sea state 3 at 1 tonne tension. Generally, the hoisting operation has shorter acceleration amplitudes, though higher displacement amplitudes. The difference is likely due to the constant winching speed of 12m/min. At

this speed, the hoisting operation experiences a faster system response, or a ‘shock’ effect at the highest elevation, increasing the response magnitude.

Figure 14 shows a graphical representation of peak responses across all case studies, comparing the influence varying sea states, operational direction, and line forces have on peak responses.

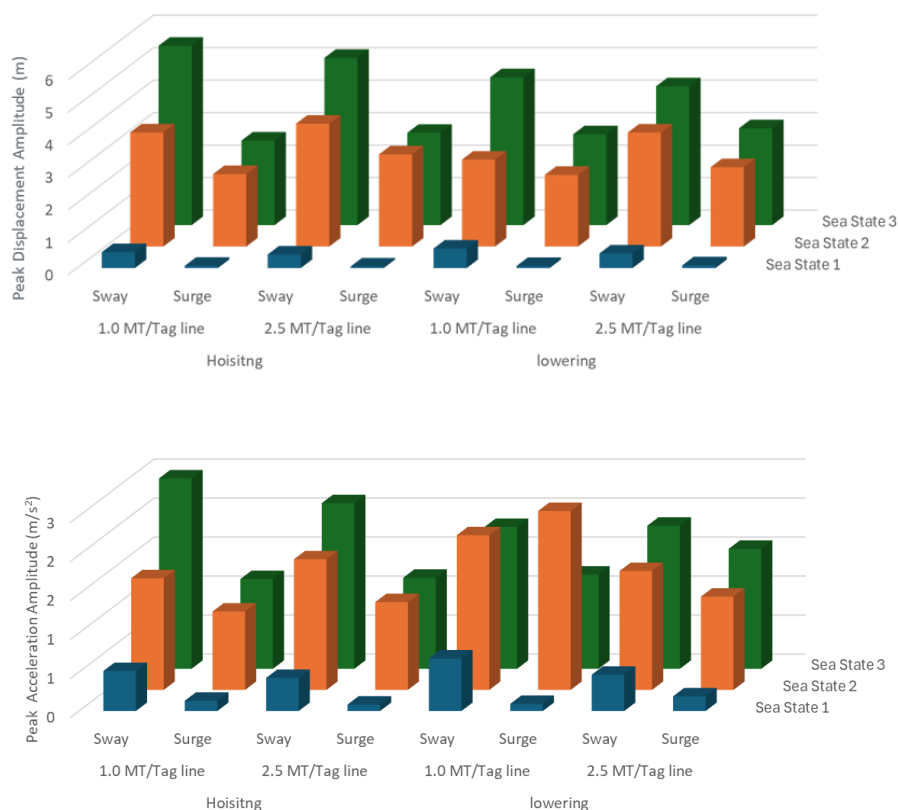


Figure 14: Peak Displacement (top) and Acceleration (bottom) Responses for Gearbox MCR

3.4 Key Findings

The NDC simulations provided a visual and numerical understanding of the in-situ MCR campaign. Key observations from the varied case study were made:

Impact of Wave Period:

Sea state comparison finds that peak wave period has the strongest impact on the system response, with the difference in peak responses between sea states 1 and 2 having a noticeable jump, despite identical significant wave heights. Sea state 3 still maintains the highest peak responses of all case studies, with the highest significant wave height, illustrating that higher significant wave height will result in higher peak responses. It is likely that with increasing wave heights, the peak displacement and acceleration would continue to rise.

Hoisting and Lowering Differences:

There is also a noticeable difference between hoisting and lowering operations, especially at harsher sea states. Sea state 3 has an approximately 1.3 times greater peak amplitude during hoisting compared to lowering operations. This suggests hoisting operations increase the degree of motion in

harsher sea states. This is not seen as dramatically in sea states 1 and 2, with only a 1.1 times greater response from hoisting compared to the lowering operation.

Estimated timings for operations:

Modelling provided an estimated timeframe for the MCR operation, including the installation of the crane technology. While human factors and delays cannot be simulated, the timeframe provides an estimation for planning maintenance strategies.

The average crane installation time is 34 mins 5 secs, for each the hoisting and lowering operations. At the winching speed, the maximum global lateral displacement (sway) amplitude during SH crane transits reached 4.65 m in the most severe simulated sea state, with peak relative surge accelerations with respect to the nacelle of up to 0.26 m/s^2 .

The gearbox average hoisting/lowering time is 30 mins 48 secs from slewed position of SHC. The global lateral (sway) peak displacements for the gearbox during transit reached 5.52 m, with global peak sway accelerations up to 2.44 m/s^2 , both recorded in sea state 3 and under the 1 MT/tagline tension. A minimum collision clearance of 0.9 m and a maximum relative acceleration of 1.30 m/s^2 was observed. These were observed in sea state 3 and under the 2.5 MT/tagline tension.

Impact of Tag Line Tension:

The impact of tag line tension on peak responses have inconsistent impacts on peak motion. While there is variation, the 2.5 tonnes peak responses are not higher nor lower across all sea states compared to the 1 tonne peak responses. This inconsistent trend shows that increasing tension can dampen or amplify sway depending on the environmental conditions.

4 WEATHER DOWNTIME MODELLING

The NDC modelling fed into work done within the ORE Catapult, focusing on WDT and vessel use of the in-situ method compared to TTP methods. The WDT Model is an internal tool focusing on a single operation starting at any given point throughout the year. It uses historic data to estimate the total length of a MCR campaign, including the expected wait on weather. This section details the setup, case studies, and results from the WDT model.

4.1 Setup

Weather data was taken from two sites, one in North Scotland and one in the Celtic Sea, shown in Figure 15. The points show the starting port and the offshore location.



Figure 15: Modelling Site Locations

Site details are found in Table 3.

Table 3: Site Location Details

Site	Site Coordinates	Transit coordinates	Port coordinates	Distance to port (km)	Site Name	Port Name
1	59, -5	58.25, -5.75	57.5, -5.75	210	N Scotland	Kishorn
2	51.5, -6.25	51.5, -5.25	51.5, -3.75	170	Celtic Sea	Port Talbot

Weather data was taken for each location from the Lautec records, using records from 1990 to 2019 [4].

The initial task list, detailed in Table 4, details the weather limits of each task, as well as identifies any tasks that must be completed within the same weather window, marked under the “grouped” column. The setup assumes that the ATOMS platform, vessel, and replacement component are available for tow-out in three days; this allows for the focus on the operation itself, and doesn’t take into account the time for procurement and planning.

Table 4: Base Task List for In-Situ WDT Model

	Task	Group	Duration (hours)
0	ATOMS Platform preparation and mobilisation		72
1	ATOMS and vessel transit to site		7
2	ATOMS Platform positioning and connection		2
3	Personnel transfer		1
4	Crane interface installation	A	10
5	Liftra Crane ascent and positioning	A	2
6	Crane assembly		6
7	Component Disconnection		6
8	Component Lowering	B	1
9	Replacement Raising	B	2
10	Component reconnection		6
11	Liftra crane disassembly	C	6
12	Crane descent	C	1
13	Crane interface removal	C	10
14	Personnel transfer		1
15	ATOMS Platform disconnection		1
16	Return to port		7
17	Demobilisation		24
	Total Duration		138 (5.75 days)

4.2 Case Studies

A series of case studies were conducted to compare between technology development, site variation, and task duration. Some variation in real-world application will come from port suitability, where TTP operations are much more limited in port usage compared to the in-situ method used.

The base case details are shown in Table 4. The base case was developed based on storyboarding provided by Liftra, and modelling done by the NDC. An overview of the different sensitivity studies is in Table 5.

Table 5: WDT Sensitivity studies

Sensitivity Study	Description
1	Increased the wave height limit to 3m for all tasks
2	Decreased the wave height limit to 2m for all tasks
3	Weather limits identical to base case. Shorter time for tasks 4 and 13
4	Removed the wind limit.

The wave height variations allowed for a comparison of cases where technology development allowed for operations in harsher weather, and on the opposite, where more caution was taken regarding weather limitations. The shorter duration aligns with experience in the learning curve resulting in shorter overall duration. The wind limit removal was to understand the impact of wind in the base case, and how it impacts planning and delays, even during calmer seas.

In addition to the sensitivity studies for in-situ MCR, a TTP operation was also simulated. This allowed for a comparison to the estimated duration of different MCR maintenance strategies. The TTP information was taken from previous ORE Catapult work.

4.3 Outputs and Discussion

The WDT model takes the given task list and weather data, and determines how long each group of tasks would take. This is determined by identifying when, based on weather limits, a task could occur. This information is collected for each year, and mapped out from the 5th to 95th percentile.

These timelines are taken for each week throughout the year and graphed to get an visualisation of how long the task will take based on when in the year it's started. The summer months (April-August) are highlighted in white, and generally correlate with the periods of shortest WDT.

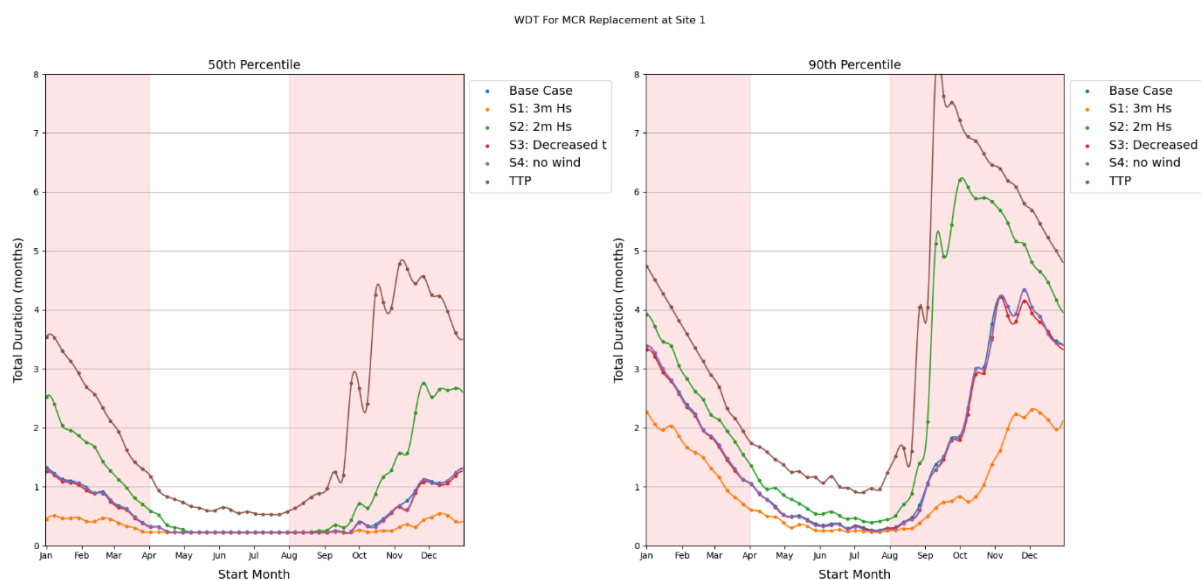


Figure 16: 50th and 90th Percentile Duration of all MCR Simulations based for Site 1

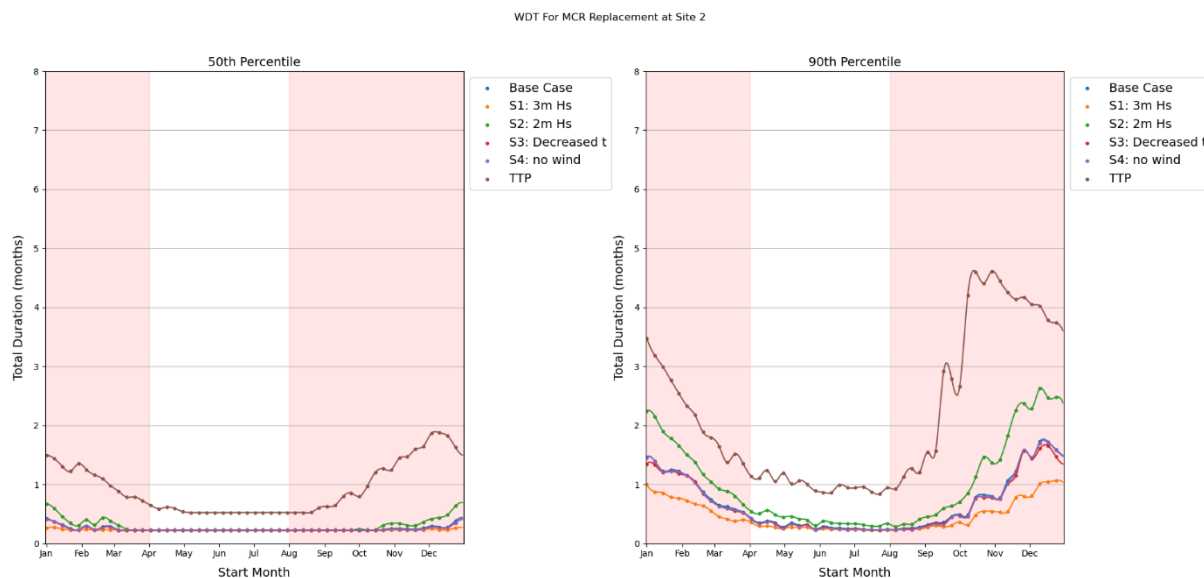


Figure 17: 50th and 90th Percentiles Duration of all MCR Simulations based for Site 2

Comparison of WDT allows for better understanding of multiple factors on MCR suitability and risks to delay.

Time of Year

The starting point of the operation will have a major factor in determining if MCR can occur. The areas in white on the graph are considered the 'summer' months, and are when planned maintenance is normally scheduled. This is because the winter months, usually starting in late September, see a quick rise in WDT due to the harsher sea conditions.

TTP operations follow the same annual pattern, with towing limitations preventing operations from being completed over the winter months at the 90th percentile, and having the highest WDT during the autumn and early winter months.

Location

Along with time of year, the location and regular sea conditions can impact when operations can occur. Site 2, located in the Celtic Sea, is more sheltered than Site 1, in the North of Scotland. This results in calmer conditions, lengthening when MCR can occur. For example, on June 1st for both sites, at the 50th percentile there is no WDT. At the 90th percentile, there is some WDT at Site 2, with 8 times the WDT at Site 1.

TTP Comparison

TTP is the expected MCR strategy for the first generation of FOW farms. While TTP will likely be necessary for some components, such as blades and direct drive generators, in-situ solutions are quickly advancing to provide on-site solutions.

Work conducted as part of the PR39 project showed similarly shorter time frames for in-situ MCR during the summer months, but had higher WDT compared to TTP operations between autumn and spring. The in-situ MCR modelling, with the North Sea site shown in Figure 18, had the lowest peak WDT well above 4 months in the 50th percentile [5]. This was largely due to the harsher weather restrictions on in-situ methodologies. However, by providing a laydown space through providing the

platform and increasing the workable weather limits, in-situ exchanges can have a shorter timeline compared to that of TTP. This change in expected WDT reflects the impact technological developments can have on the feasibility of in-situ MCR operations.

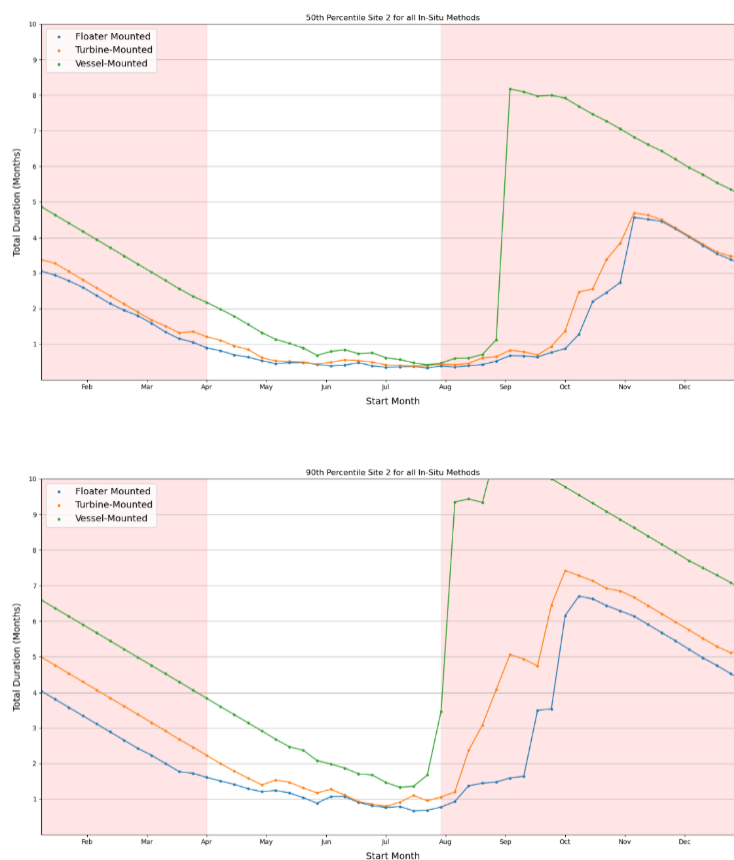


Figure 18: In-situ WDT Modelling Results from PR39 at the North Sea site [5]

Key Benefits of in-situ MCR

The WDT model highlighted key benefits of an in-situ MCR alternative. The three key aspects minimising WDT are:

- Short grouped tasks,
- High weather limits, and
- Shorter task duration.

Smaller grouped tasks allow for utilising short weather windows, even in winter months, when maintenance would often be limited because of long periods of harsher sea conditions. Similarly, increasing the workable weather limits extends the summer period of minimal WDT, and allows for more maintenance to occur in winter months.

Shorter task durations, while having a relatively small impact, still decreases offshore hours for workers, and potentially allows for utilisation of shorter weather windows.

Modelling Limitations

When considering real-world applications, there will always be variation to simulations. Because simulations are based on previous weather records, there is a certainty that allows even small weather windows to be used. This is likely not the case when considering practical applications, which require forecasted data to allow for a clear weather window for operations to occur.

There is also an assumed 3-day mobilisation time for all case studies. In practice, planning and equipment acquisition will take much longer. This modelling focused more on the weather downtime of the activities themselves, rather than overall task planning.

5 CONCLUSION

Large increases in FOW expected over the next decade will likely come with an increased demand for MCR operations. Existing plans rely on TTP operations, and in-situ MCR has been carried out only once on a FOW turbine. More in-situ technology providers are gradually entering the offshore wind market; however, most technologies are at low TRL, and lack pathways to further testing and development. This project furthered understanding of in-situ benefits and limitations, and developed a method with the NDC for testing in-situ exchange technologies.

The work addressed three key questions:

1. How can physics-visual simulation tools be used to model MCR operations on floating structures?

The NDC's Marine Simulator provides a unique visual aspect that allows potential issues such as collisions or complex points within the exchange to be modelled. While providing the visual aspect, it also tracks component location and motion, identifying peak movements and accelerations. This combination allows for a comparison of different variations of the same process, as either crane or technology variation or environmental variations to understand key factors and motion in different conditions. This allows developers to understand risk areas to their in-situ technology and method, and to better plan for offshore operations.

2. How does such a tool contribute to derisking MCR?

The tool is now equipped to act as a midway point for low TRL technologies to prove their technology before prototyping, increasing confidence and identifying necessary changes. It also allows for testing of variations of the technology, providing a better understanding of different operations.

3. What are its limitations in use?

The model should not be used as proof to a full level 9 TRL. As calibration is based on computer models, there is a limit to the degree of complexity in both objects and the environment that can be achieved. Regarding the objects, while there is easy integration of CAD models, there is not a variety of detailed turbines readily available, meaning that testing different turbines may require further input from turbine providers.

5.1.1 In-Situ MCR Benefits and Limitations

In-situ MCR offers an alternative to TTP operations at a lower vessel use and faster operation. Aspects that were especially beneficial from modelling allowed for faster MCR exchanges, decreasing vessel costs and shortening periods of turbine downtime. These included:

- Provided laydown area: The SOLVE Wind ATOMS platform directly benefited the MCR operations throughout modelling. It limited the floating-to-floating exchanges expected with FOW in-situ MCR, provided points for tag line connection, and replaced the time for building a laydown area with a shorter installation time of the ATOMS platform.
- Shorter grouped tasks: Shorter grouped tasks expand when MCR is highly suitable, and can help in decreasing WDT.

- Increase from expected weather limits: Working alongside an in-situ technology developer allowed better understanding of expected weather limits, allowing for faster response times and lowering expected WDT.

There are added benefits of MCR when compared to TTP operations that extend beyond specific technologies. The operation doesn't risk further damage to mooring lines or cables, as it removes the need for disconnection and reconnection. It is also often significantly shorter than TTP campaigns, which in turn may lower vessel usage and overall costs. It also decreases the demand on ports, as in-situ repairs do not require quayside space for turbine connection and repairs.

Despite wide reaching benefits, in-situ MCR does have fairly significant limitations regarding component suitability, technology readiness, and customisation requirements. In-situ methods are generally only suitable for nacelle components such as a gearbox, as was modelled here. Direct drive systems, blades, and even full nacelles currently rely on TTP with no commercial ready solutions for in-situ replacement.

There are some lower TRL technologies that are hoping to be suitable for carrying out these larger scale in-situ MCRs, but key issues with commercialisation include a high barrier to entry, limited opportunities for testing and demonstration, and limited communication between turbine OEMs and technology developers. These aspects have limited available in-situ MCR technologies, and make it challenging for technologies to develop into a usable and commercial scale solution.

For in-situ solutions, including the one modelled for this project, some customisation will likely be necessary based on turbine design. While this is best to be discussed and formed at the start of any large-scale FOW project, initial in-situ MCR development may have a longer mobilisation period to allow for customisation of components, mainly the base for the crane, that provides the support for the crane to carry out the exchange. Each site may also have variability in 'best case' for setups, when considering wave interactions on motion, nearest port for towing, and turbine substructure design.

5.1.2 Future Work

Development of future projects and research into in-situ MCR is vital to supporting the development and commercialisation of FOW. Key areas that would benefit from future research and development include:

- Furthering understanding of mobilisation requirements: The period of time between component failure and MCR beginning may require a lengthy process of acquiring vessels and a replacement component, agreements with various repair partners, as well as the base discussion of MCR method. Having a clear course of action between failure and MCR operations understood and analysed may assist in planning for MCR during future large-scale FOW projects.
- Utilising the Marine Simulator for testing future in-situ MCR solutions: Following the initial use of the Marine Simulator for testing in-situ MCR, the NDC is now well-equipped to act as a middle point for emerging in-situ technologies to test their technologies as a further proof of concept. It would also be able to support testing varied methods and analysing component motion during the operations, allowing for a better understanding of potential complications before offshore MCR is completed.
- Variation in in-situ evaluation for varied foundation design. Different designs will have different impacts from sea conditions and motion during MCR operations.

- Defining impact of motion from in-situ MCR in relation to workable conditions and component damage. There is a lack of publicly available information on how motions would impact workability or potential damage to the replacement component, that further work could quantify to better understand limitations and expectations.
- Further vessel analysis: the comparison of vessel use was limited in modelling due to the varied nature of TTP vessel requirements. Further analysis could delve deeper into the comparison of vessel demand for in-situ MCR compared to similar TTP operations, including vessel requirements, costs, and availability.

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