RealCoE

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Deliverable 4.3
Corrective maintenance manual

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Version	Description	Contributions
1.1.	General outline of Deliverable 4.3.	Vinit Dighe (TNO), Chen Yung (TNO), Vadim Uritsky (TNO), Iana Bakhmet (TNO), Sjoerd Drenkelford (TNO), Maggy De Man (JDN),Tiago Ribeiro (Principle Power), Clara de Moura Santos (Principle Power).
1.2.	General outline of Deliverable 4.3. with the proceeded reviewers' comments and feedback.	Vinit Dighe (TNO), Chen Yung (TNO), Vadim Uritsky (TNO), Iana Bakhmet (TNO), Sjoerd Drenkelford (TNO), Maggy De Man (JDN),Tiago Ribeiro (Principle Power), Clara de Moura Santos (Principle Power).

Reviewer

Name	Organisation
Flemming Rasmussen	DTU
Peter Bagger Hjuler	DTU
Alexandra Hof	GE
Mario Bachmann	GE
Anna Diedrichkeit	GE

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List of Abbreviations

CTV	Crew Transfer Vessel
IJV	Installation Jack-Up Vessel
JUV	Jack-Up Vessel
LCoE	Levelized Cost of Energy
MW	Mega Watt
SOV	Service Operation Vessel
TBD	To be defined
WP	Work package
WROV	Working Class Remotely Operated Vehicle
WEC	Wind Energy Convertor
WTG	Wind Turbine Generator

Summary

The REALCOE WP4 is carried out with partners: TNO, PRINCIPLE POWER, GE, JAN DE NUL NV, 8.2, BIBA and EnBW. WP4 is coordinated by Principle Power, where TNO is in the lead of Task 4.3. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 791875.

This report is a deliverable within the scope of WP4 "Optimisation of operation, service & maintenance concepts". In Task 4.3, innovative O&M interventions and accessibility strategies were identified for a reference 15MW bottom-fixed and a floating wind turbine generator and compared to baseline methodologies.

1. Introduction

1.1. Project identity

Project Name	Offshore Windfarm Project ReaLCoE
Employer:	H2020 EU Commission
WTG Reference:	15MW WTG
Wind Farm Reference:	As per Reference Wind Farm

1.2. Report background

The trend of offshore wind farms moving further offshore and the ascent of floating wind turbines are remarkable advancements in renewable energy. However, this expansion is not without its challenges, particularly in terms of offshore accessibility. Building and maintaining infrastructure in deeper waters demands substantial investments and innovative solutions. The development of specialized vessels, advanced logistics and skilled offshore personnel is crucial to ensure the success of these ambitious projects. As we continue to harness the immense potential of offshore wind energy, addressing accessibility challenges becomes paramount in sustaining our commitment to cleaner and more sustainable power generation.

Offshore accessibility is crucial for ongoing operation and maintenance (O&M) activities of offshore wind farms. Accessibility is defined as the fraction of time in which safe access to a wind turbine is achieved [1]. The O&M activities involve the mobilisation of access vessels, equipment and technicians to the offshore wind farm, and must be executed safely in variable and unpredictable weather. Bad accessibility will significantly delay the O&M activities and increase the downtime and energy losses of the offshore wind turbines [1]. Investments in advanced access vessels improve access to offshore wind farms. However, this might potentially greatly increase the cost of the O&M phase. According to Dalgic et al. [2], transportation costs can account for up to 73% of O&M costs. With O&M costs representing 15-30% of the entire lifetime cost of an offshore wind energy project [3], accessibility costs will have a direct impact on the investment rewards of an offshore wind farm. To address this issue, this research aims to optimize offshore accessibility under weather uncertainty by using probabilistic output O&M simulations.

1.3. Report objective

"How can we improve accessibility to offshore wind farms, while considering weather uncertainty, by implementing innovative Operations and Maintenance (O&M) solutions?

ReaLCOE Task 4.3. aims to identify accessibility and maintenance intervention strategies while considering a reference 15MW wind turbine (WTG), both for bottom-fixed and floating foundations. Method statements must be defined for preventive and corrective maintenance to ensure safe and efficient interventions on this WTG. The 15MW WTG will have a higher hub height and heavier components, potentially exacerbating the challenges of performing large component exchanges up-tower (e.g., blade), where the current approach requires the mobilisation of specialised crane vessels to perform the exchange in situ for bottom-fixed, and tow-to-port operation for floating turbines.

Innovative access and intervention strategies are explored together with the beneficiaries that contribute to Task 4.3.:

- Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO, task leader)
- Jan de Nul (JDN)
- Principle Power (PP, work package leader)
- General Electric Renewables (GE)

TNO compiles a database of available options suitable for personnel access considering both proven vessels and the next generation innovative concepts under development by industry. JDN, GE and PP develop the strategies for 15MW WTG large component exchanges on both fixed and floating foundations. TNO assesses vessel performance, considering different operational criteria, access systems for personnel and materials for various operations. TNO, GE and PP outline conceptual wind farm strategies to be evaluated in the UWISE O&M Planner according to the combinations of distance-to-shore and metocean conditions (e.g. harbour-based, service operations vessel). Promising strategies were selected by all project partners for the UWiSE O&M Planner analysis, which seeks to optimise the maintenance approach and assess the LCoE impact of various innovations and strategies assessed in WP4 Task 4.4.

1.4. Report structure

The following report is structured into five distinct chapters: In Chapter 2, we establish the foundational understanding of different maintenance strategies commonly employed in the offshore wind energy sector. Chapter 3 briefly introduces UWiSE O&M Planner: a discrete event-based logistic simulation tool developed by TNO. Different access strategies for bottom fixed and floating wind turbines are investigated in Chapters 4 and 5, respectively. Lastly, conclusions are presented in Chapter 6.

2. Maintenance strategies

Maintenance strategies for offshore wind, both for bottom-fixed and floating foundations, can be subdivided into corrective maintenance and preventive maintenance. Each comes with their respective subdivisions as shown in Figure 1.

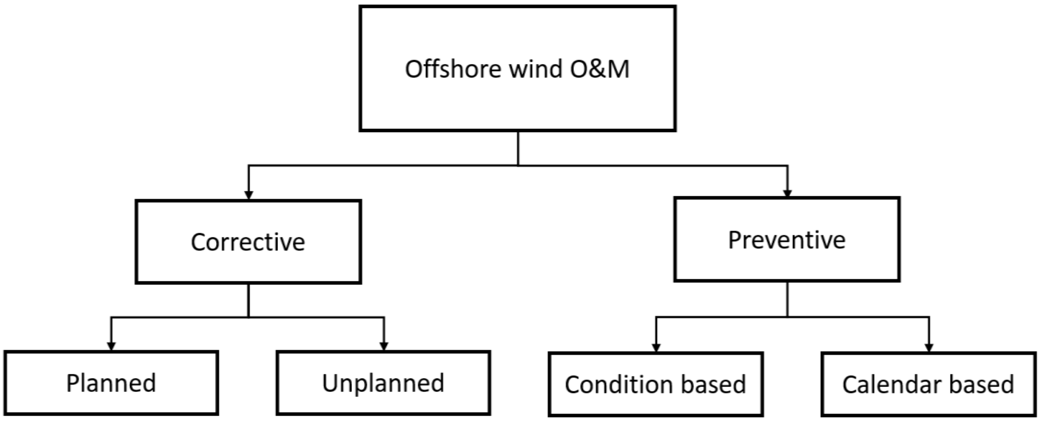

Figure 1. Subdivisions of maintenance strategies

Corrective maintenance: Corrective maintenance for offshore wind refers to the process of addressing and rectifying unexpected failures, breakdowns, or malfunctions in wind turbines or associated components after they have occurred. It involves identifying the problem, diagnosing the root cause, and taking the necessary actions to restore the equipment to proper functioning.

- Planned corrective maintenance: Planned corrective maintenance refers to maintenance activities that are scheduled and performed in response to identified issues, anomalies, or deteriorations in WTG component performance. This type of maintenance is carried out to address potential problems before they lead to unexpected failures.
- Unplanned corrective maintenance: Unplanned corrective maintenance involves addressing unexpected failures or malfunctions in WTG components that were not anticipated. It is reactive in nature and aims to restore equipment to proper functioning as quickly as possible.

Preventive maintenance: Preventive maintenance in the context of offshore wind energy refers to a proactive approach to maintenance that aims to prevent equipment failures, malfunctions, or performance deterioration by conducting regular inspections, servicing, and repairs/improvements. The goal of preventive maintenance is to identify and address potential issues before they escalate into more significant problems, ensuring the reliable and efficient operation of offshore wind turbines and associated equipment.

- Condition-based preventive maintenance: It refers to a maintenance strategy that involves monitoring the actual condition and performance of equipment and systems to determine the optimal timing for maintenance activities, leading to as low as possible downtime of the asset. This approach relies on real-time data, sensors, and predictive analytics to make informed decisions about when to conduct maintenance tasks, ensuring that they are performed in time, only when necessary based on the equipment's actual state.

- Calendar-based preventive maintenance: It refers to a maintenance strategy that involves scheduling maintenance activities at specific time intervals based on a predetermined calendar schedule. This approach focuses on conducting maintenance tasks regularly and consistently, regardless of the actual operating condition of the equipment. The primary goal of calendar-based preventive maintenance is to ensure that maintenance tasks are performed at regular intervals to prevent potential failures and ensure the reliable operation of offshore wind turbines and associated equipment.

3. UWiSE O&M Planner

TNO Wind Energy Group is a market leader, developer, and owner of industry-standard O&M strategy modelling tools designed especially for offshore wind. These tools have been used for more than 15 years. TNO provides consultancy and software licenses and has a customer portfolio (O&M) of more than 30 leading companies in the offshore wind energy-related industry, including nearly all developers and wind turbine manufacturers currently active in the offshore wind sector.

UWiSE O&M Planner was developed based on TNO wind group's long-standing expertise in the Excel-based O&M cost simulation tool "ECN O&M Tool", which has been the standard in the wind energy industry since 2005. An upgrade was made in 2011 to a MATLAB-based simulation software "ECN O&M Calculator". As the wind energy industry continues to evolve, the simulation aims to model increasingly complex logistics in O&M planning for larger and upcoming offshore wind farms. As a result, TNO has been developing "UWiSE O&M Planner" and using the software for long-term O&M strategic planning since 2020.

UWiSE O&M Planner is built on a discrete event-based logistic simulation engine UWiSE (Unified Wind farm Simulation Environment), developed by TNO in 2017 onwards. The software enables users to perform multi-year simulations to calculate O&M costs, wind farm availability and energy production while taking into account uncertainties of weather and wind farm component reliability. Multi-year simulations that consider weather uncertainty by using the Monte Carlo sampling technique provide a valuable framework for decision-making in the planning, design, and operation of offshore wind farms. By running simulations for multiple weather years, the software calculates statistical estimates of the frequency and duration of favorable weather conditions for specific operations. This helps to identify patterns, seasonal variations, and the probability of encountering adverse weather. The software presents the impacts on O&M's key performance indicators of deploying different types and numbers of vessels each with their weather limits of operation. Figure 2 shows the user interface of UWiSE O&M Planner.

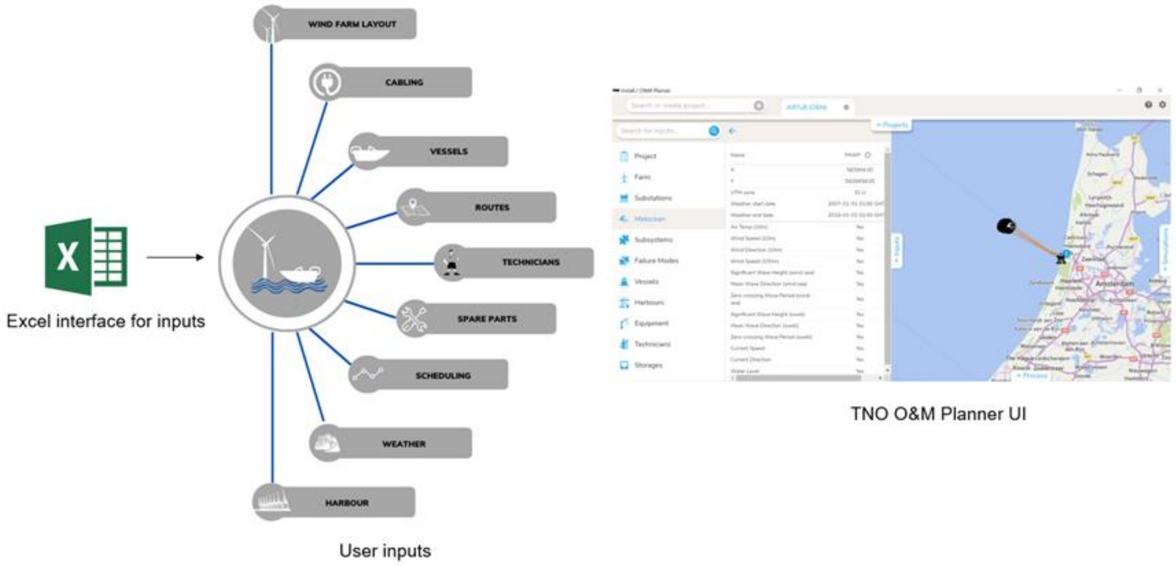

Figure 2. UWiSE O&M Planner graphical representation

The software aims to:

- Assist wind farm operators in optimizing O&M choices between various transportation types, equipment, personnel shift and spare part stock management options in terms of standard KPIs such as wind farm availability and repair costs.
- Conduct scenario analysis for an O&M project by varying the available resources.
- Provide an overview of preventive and corrective maintenance activities, the delays encountered (weather or resource) and associated costs.
- Provide insights into the wind farm downtime per component failure mode and per maintenance activities.
- Evaluate the O&M cost impacts of innovative concepts (e.g. large component replacement with self-erecting crane).

4. Bottom-fixed wind turbine maintenance

4.1. Site description

The expenses associated with the operations and maintenance of offshore wind farms constitute a significant portion of the levelized cost of energy. This report focuses on the investigation of available options suitable for personnel access considering both proven vessels and the next generation technologies. Conceptual wind farm strategies have been outlined for further evaluation in the TNO O&M Planner according to the combination of distance to shore and met ocean conditions.

For that purpose, a single bottom-fixed wind turbine with the capacity of 15 MW has been investigated. A hypothetical bottom-fixed wind turbine is located in the German North Sea, and relatively close to the shore, the distance from the coast to the wind turbine is around 80 km (Site A). The water depth is about 35-40 m, and the average wind speed at hub height is 10-10.5 m/s.

4.2. Maintenance activities

The following table will summarize the maintenance activities investigated for the bottom fixed wind turbine in the context of this research:

Table 1: Maintenance activities studied for the bottom fixed wind turbine

Action	Maintenance type
Major component replacement – Blade	Unplanned Corrective
Major component replacement – Blade bearing	Unplanned Corrective
Minor component repair – small	Unplanned Corrective
Minor component repair – medium	Unplanned Corrective
Minor component repair – large	Unplanned Corrective
Payload transfer	Preventive

4.3. Vessels and access systems

A general description for each vessel and access type is stated below. Assumptions are made to specifications such as mobilisation fee, daily charter rates, transit speed, towing speed, weather limits, personnel and lifting capacities etc. These specifications are ensured among the project partners to be in the right ballpark numbers and intentionally kept undisclosed if not specified below.

Table 2: Baseline access strategies (bottom fixed)

Vessel and equipment types	Main function	Main (assumed) characteristics
Large size Jack-up vessel (JUV)	• Perform major component replacement at the offshore site.	• 10 days of preparation for major components replacement. • Transit Hs ≤ 4.5m; and working offshore Hs ≤ 3.5m.
Medium Service Operation vessel (SOV)	• Serves as an offshore-based hub and warehouse. • Primarily used for scheduled maintenance but can be used for corrective maintenance when needed.	• Long-term chartered. • Port call twice per month. • Transit and transfer technicians or cargo at Hs ≤ 2.5m.

An array of innovation concepts, encompassing both conceptual and pilot stages, were explored and assessed for the maintenance of bottom-fixed offshore wind farms. These concepts were subjected to a ranking process based on criteria including feasibility, risk mitigation, cost benefits, and minimized downtime, leading to the selection of the most highly ranked innovations for subsequent modelling, the summaries of which are provided below:

Table 3: Innovative access strategies (bottom fixed)

Vessel and equipment types	Main function	Main (assumed) characteristics
Self-erecting crane system on a retrofitted floating vessel	• Perform replacement for blade and blade bearing at offshore site, without the use of a JUV	• Use of a retrofitted floating vessel • Pre-repair construction and post-repair deconstruction of a self-erecting crane scaffold
Motion compensated crane on retrofit JUV	• Perform replacement for blade and blade bearing at the offshore site using motion compensation system attached to the crane	• Increase in the allowed wind speed limit of a blade or blade bearing replacement
Extra lifting height crane	• Perform replacement for blade and blade bearing at offshore site, using a modified crane on a medium-sized JUV	• Use of a medium-sized JUV instead of a large-sized JUV
Advanced motion compensated gangway for SOV	• Transfer of technicians from the vessel to the turbine for minor corrective repairs	• Increase in the allowed wave height limit to Hs ≤ 3m for technician transfers • Additional day rate from the use of the advanced gangway.
Cargo drone	• Offshore drone delivery of required material and/or spare parts in anticipation of preventive maintenance	• Decrease in the duration of preventive maintenance due to eliminating the need to carry materials to the nacelle from the vessel • Additional OPEX cost of leasing a drone capable of transporting a payload of 30 kg.

4.4. Scenarios

The following section discusses scenarios related to offshore accessibility, with a focus on comparing baseline strategies to innovative strategies. For the strategies investigated, the results obtained show the differences in KPIs of the innovative strategy compared to the baseline strategy, for a number of maintenance actions covered in Table 1. The KPIs compared for corrective maintenance are total cost, as well as downtime. For each KPI comparison, one figure presented shows the spread of results in the form of box plots, wherein the centre line is the median value, and the bottom and top of the boxes are the 1st and 3rd quartile values, respectively. The end caps represent the lowest and highest values, with outliers excluded. Another figure is presented that describes the change in mean, as a percentage value, of that KPI for a given innovation, from the baseline value. All KPI comparisons are distributed in month.

For **corrective maintenance** procedures, each simulation entails a single maintenance action performed on a single reference turbine. The investigated KPIs for these simulations are:

- **Total operational cost**: All the direct costs associated with this particular action – including vessel mobilisation costs, vessel operating costs, technician day rates, equipment costs, etc. - in addition to the indirect revenue losses that occur due to downtime. To specify, the capital investment to the innovations are not included.
- **Downtime**: the total time from the point of failure, until the moment the turbine is operating once more.

For **preventive maintenance** procedures, each simulation entails an entire preventive maintenance campaign, performed on all the turbines of the wind farm. In contrast to the corrective maintenance procedures, simulations were run for the months of May to September, inclusive, to reflect the fact that maintenance campaigns are typically held during the summer. The investigated KPIs for these simulations are:

- **Total operational cost**: all the direct costs associated with this particular action – including vessel mobilisation costs, vessel day rates, technician day rates, equipment costs, etc. - in addition to the indirect revenue losses that occur due to downtime.
- **Total campaign time**: The total time taken for the entire preventive maintenance campaign.

Table 4: Scenario 1 for bottom fixed turbine

Scenario 1	
Wind farm	Site A
Maintenance type	Unplanned corrective
Action	Blade replacement
Description	In this scenario, the blade replacement activity for the bottom fixed turbine is compared using four strategies. The baseline strategy consists of a large size jack-up vessel mobilized and positioned next to the bottom-fixed wind turbine, ensuring its stability and readiness for the blade replacement operation. A team of technicians and specialized equipment, such as cranes and rigging systems, are utilized to remove and seafasten the existing blade. Then, the replacement blade is lifted and positioned onto the wind turbine hub. Innovation 1 strategy employs a self-erecting crane on a retrofitted floating vessel, specially designed for offshore wind turbine maintenance. This compact crane is installed on the turbine's platform, reducing the need for additional vessels or large cranes. Innovation 2 utilizes a motion-compensated crane mounted on a retrofit JUV vessel to increase the weather limits for operation. Innovation 3 uses an extra lifting height crane mounted on a medium size jack-up vessel.
Baseline strategy	Large size JUV with a luffing boom crane
Innovative strategies	Innovation 1: Self-erecting crane on a retrofitted floating vessel Innovation 2: Motion compensated crane on a large size JUV Innovation 3: Extra lifting height crane on a medium size JUV

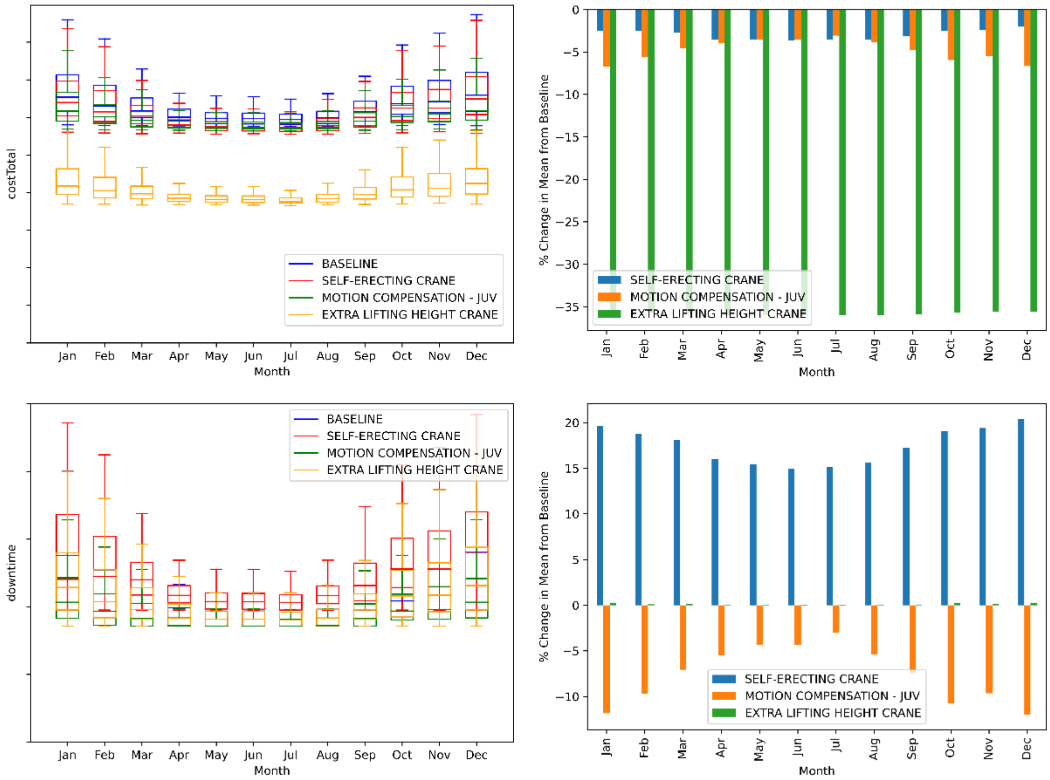

Figure 3: Comparison of total costs and downtime KPIs for scenario 1(bottom fixed)

The following overview can be obtained from the above results:

- Baseline: Higher total costs are shown in winter months, compared to summer months, due to higher variable costs (vessel operating costs, technician costs, revenue losses) from the increased time to repair. This pattern can be seen in the downtime distribution, which follows a similar distribution as the distribution for the *Extra Lifting Height Crane*
- Self-Erecting Crane: The total cost is consistently lower for all months of the year, compared to the baseline, although the differences in value are not significant, and are the least of the innovations. This is partly due to the fact that the costs of the replacement floating vessel are not significantly different from the costs of the large-sized JUV. The differences are slightly more pronounced in the summer months, due to differences in the execution of several weather-dependent procedures, such as the scaffold construction/deconstruction procedure needed for the self-erecting crane, instead of the jacking up/down procedure needed for the baseline. The downtime is significantly and consistently larger than for the baseline, largely due to the large amount of time required to perform the scaffold construction/deconstruction procedure.
- Motion-Compensation – JUV: The total cost is consistently lower than the baseline, as well as the *Self-Erecting Crane*. This effect, which stems largely from the increased wind speed at which the blade replacement operation can be performed, is more pronounced in the winter months, due to the associated higher wind speeds in these months and the subsequently lower variable costs. This reduction is still visible in the summer months, and the resulting cost is still always positive despite the additional equipment OPEX. This effect is also visible in the distribution of the downtime.
- Extra Lifting Height Crane: This innovation provides the largest cost benefit, by a large margin. This cost reduction, which is largely due to the use of the medium-sized JUV,

led to both lower variable (vessel operating costs) and fixed (vessel mobilization) costs, consistently for all months of the year. The downtime, however, is not significantly different, given that the weather conditions under which each step of the procedure is performed are mostly the same. Thus, the actual timeline of the procedure is mostly unchanged but is done at a lower cost.

Table 5: Scenario 2 for bottom fixed turbine

Scenario 2	
Wind farm	Site A
Maintenance type	Unplanned corrective
Action	Blade bearing replacement
Description	The blade bearing replacement process typically involves dismantling the turbine blade from the hub and removing the damaged bearing. Specialized lifting equipment and tools, such as cranes and rigging systems, are used to safely carry out the operation. A new bearing is then installed and properly aligned before reassembling the blade to the hub. In this scenario, four different strategies are compared.
Baseline strategy	Large size JUV with a luffing boom crane
Innovative strategy	Innovation 1: Self erecting crane on a retrofitted floating vessel Innovation 2: Motion compensated crane on a large size JUV Innovation 3: Extra lifting height crane on a medium size JUV

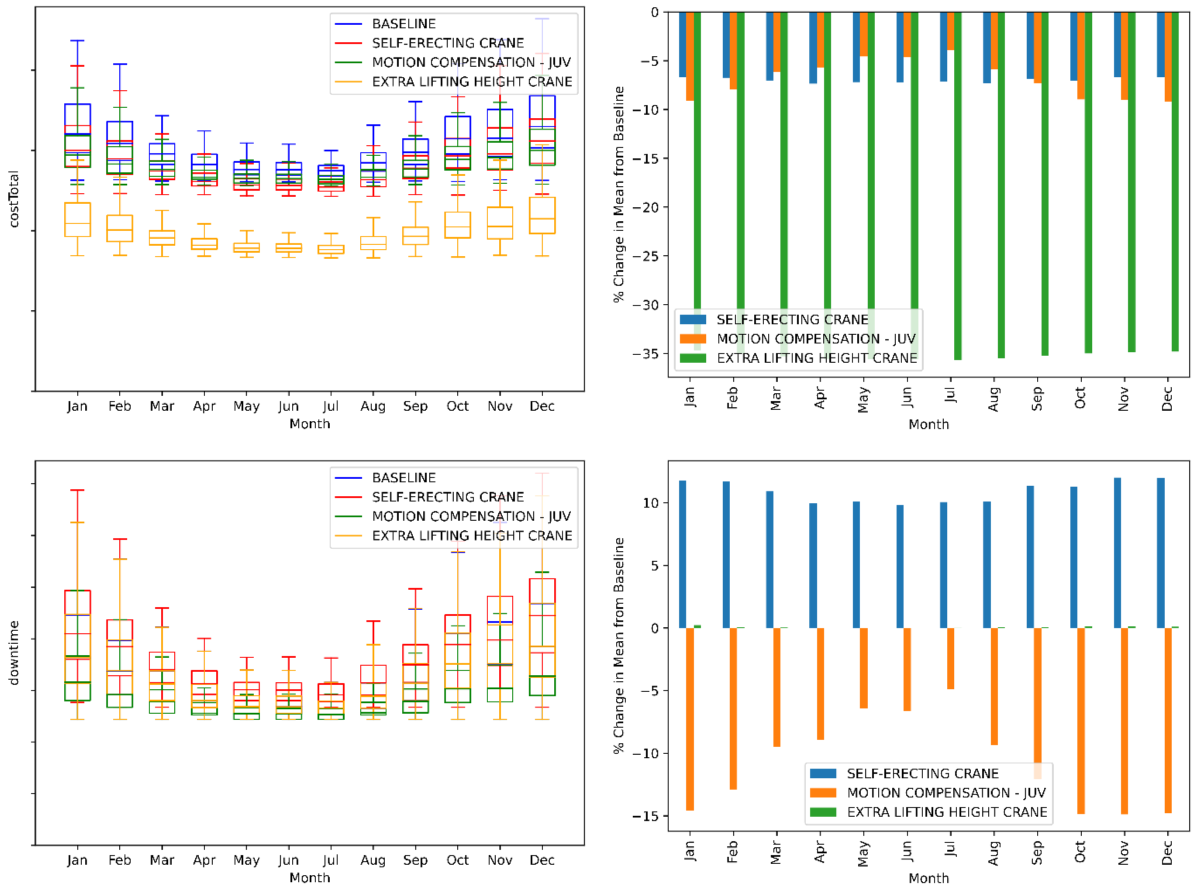

Figure 4: Comparison of total costs and downtime KPIs for scenario 2 (bottom fixed)

The following overview can be obtained from the above results:

- Baseline: Similar trends for the baseline values can be seen here, compared to the baseline values for the blade replacement.
- Self-Erecting Crane: Similar trends for the total cost and downtime can be seen here, with similar conclusions drawable as for the blade replacement. One notable difference is the comparatively higher reductions in mean total cost, as well as lower increases in mean downtime, implying this to be a more effective strategy for longer maintenance actions.
- Motion-Compensation – JUV: Similar to the *Self-Erecting Crane* innovation, higher reductions in mean total cost and mean downtime show higher effectiveness with longer procedures.
- Extra Lifting Height Crane: Both for total cost and downtime, the results of these simulations do not differ significantly from those of the blade replacement.

Table 6: Scenario 3 for bottom fixed turbine

Scenario 3	
Wind farm	Site A
Maintenance type	Unplanned corrective
Action	Minor component repair – small, medium and large maintenance
Description	In this scenario, a high-priority corrective operation is required for the reference wind turbine that has experienced a critical fault affecting its energy production. The operation must be completed swiftly to minimize downtime and maximize energy output. The operation target durations are “small”, “medium”, “large” maintenance hours and are compared using two different strategies.
Baseline strategy	SOV + default motion compensated gangway
Innovative strategy	SOV + advanced motion compensated gangway

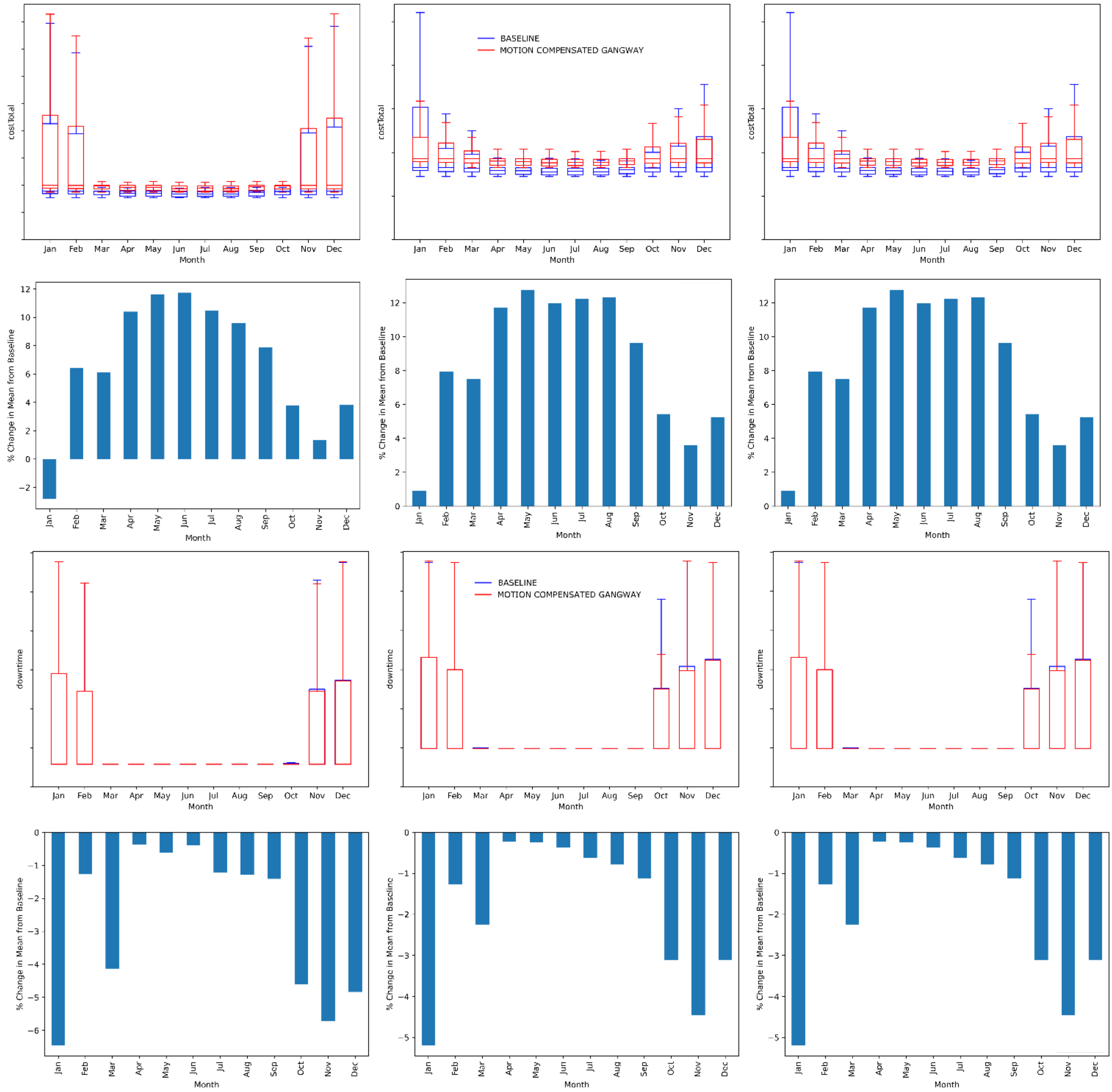

Figure 5: Comparison of total costs and downtime KPIs for Scenario 3; from left to right: "small", "medium" and "large" maintenance (bottom fixed)

The following overview can be obtained from the above results:

- "small" maintenance: It can be seen that the deployment of an advanced gangway on the SOV reduces the turbine downtime, especially a reduction by up to 6.5% in winter months. However, the total costs increase most of the months throughout the year, varying from 1% to 12%. Overall, it is not cost effective to deploy an advanced gangway that increases the workability slightly.
- "medium" maintenance: Similar to the "small" minor CM, the 8-hour minor CM using an advanced gangway does reduce the turbine downtime by up to 5%, but the costs

incurred increase throughout the year, varying from 1% - 13%. It again explains the default gangway that has an operational weather limit of Hs ≤ 2.5m is sufficient.

- “large” maintenance: Similar to previous results, the 12-hour minor CM using an advanced gangway reduces the turbine downtime by up to 3%, but the costs incurred increase throughout the year, varying from 1% - 12%. It implies the default gangway that has an operational weather limit of Hs ≤ 2.5m is sufficient.

Table 7: Scenario 4 for bottom fixed

Scenario 4	
Wind farm	Site A
Maintenance type	Preventive
Action	Payload transfer
Description	In this scenario, we will compare two distinct methods for transferring a critical payload to the wind turbine location. The first method involves utilizing a Service Operation Vessel (SOV) for the technician and payload transfer, while the second method utilizes the SOV only for technician transfer and an additional drone for the payload transfer from the shore to the turbine nacelle.
Baseline strategy	SOV
Innovative strategy	SOV + Drone

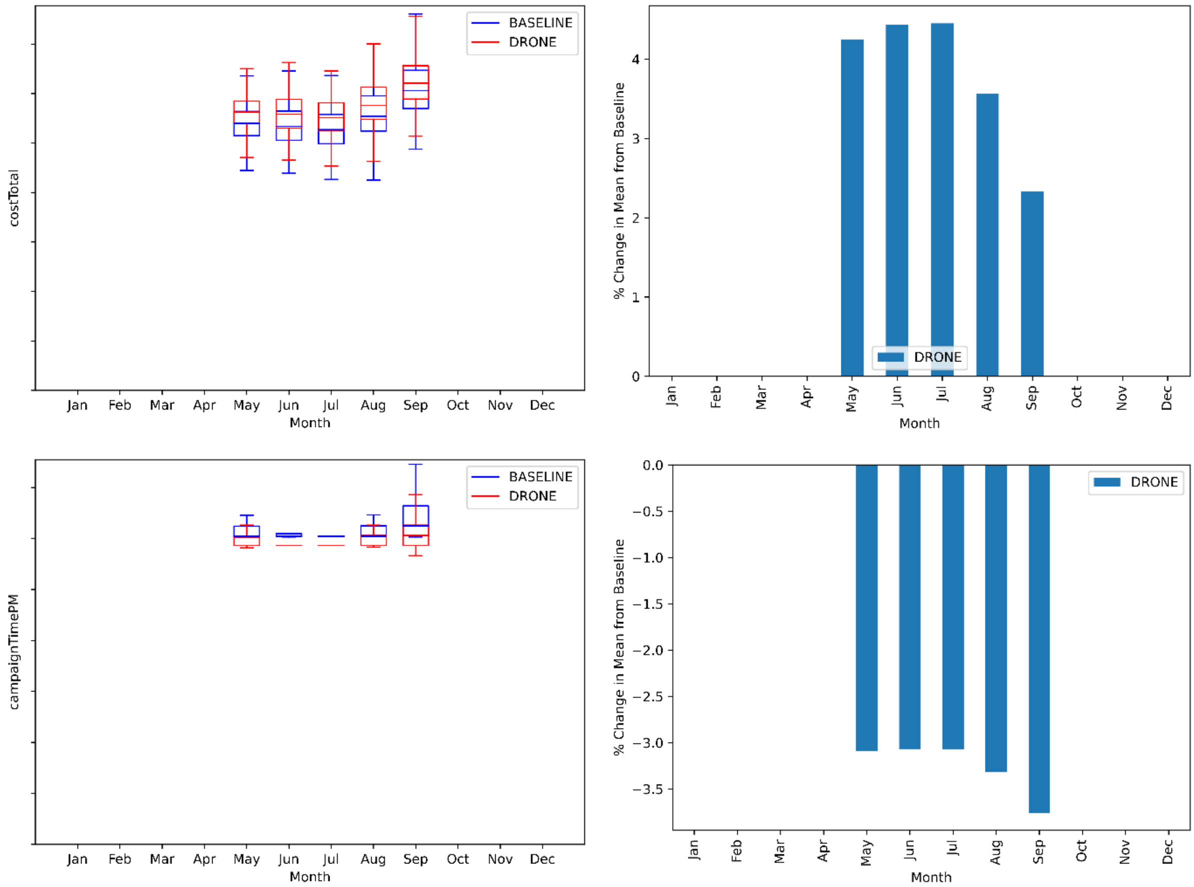

Figure 6: Comparison of total costs and total campaign time KPIs for scenario 4 (bottom fixed)

The following overview can be obtained from the results:

- Baseline: Relatively similar costs can be seen in all summer months, although increasing costs and campaign times in August and September are clearly seen, a result of less favorable weather conditions for these maintenance activities.
- Drone: Consistently higher costs for preventive maintenance campaigns can be seen, with these costs increases all between 2-5%. Conversely, total campaign durations are also consistently lower, by a value between 3-4%.

5. Floating wind turbine maintenance

5.1. Site description and access strategy

A hypothetical floating wind farm is set up in this study. As this report aims to investigate the improvement in accessibility, only one floating wind turbine is simulated. To support the 15MW turbine, PP's WindFloat technology is considered. The WindFloat is a semi-submersible column-stabilized offshore platform with water-entrapment plates, designed to host an offshore WTG in one of its three columns. The platform's station keeping system is composed of mooring lines and mooring anchors. The wind turbine is located 35 km (18 nm) offshore from the nearest O&M port in West Europe. The average water depth of the wind farm is 75 m.

Owing to its relatively near distance to shore, a CTV-based logistic strategy is selected as the main access means for preventive and corrective maintenance. The baseline model deploys a typical CTV, using bump and jump access to the platform, which is limited to the significant wave height of 1.5 m. The innovation concepts will investigate CTVs of different sizes and with different access systems that have higher seakeeping capabilities.

As for major corrective maintenance, the baseline scenario considers the tow-to-port strategy, while the innovative concepts investigate strategies to perform in-situ maintenance, such as deep water heavy lift vessels or self-erecting systems.

5.2. Maintenance actions

Table 8: Maintenance activities studied for floating wind turbine

Action	Maintenance type
WTG major component replacement – Blade	Unplanned corrective
WTG major component replacement – Blade Bearing	Unplanned corrective
WTG/Platform minor component repair – small maintenance	Unplanned corrective
WTG/Platform minor component repair – medium maintenance	Unplanned corrective
WTG/Platform minor component repair – large maintenance	Unplanned corrective
WTG – One-day preventive maintenance	Preventive
Access vessel sharing between WTG and floating substructure operators – One-day preventive maintenance	Preventive

5.3. Vessels and access systems

A general description for each vessel and access type is stated below. Assumptions are made to specifications such as (de)mobilisation fee, daily charter rates, transit speed, towing speed, weather limits, personnel and lifting capacities etc. These specifications are ensured among the project partners to be in the right ballpark numbers and intentionally kept undisclosed if not specified below.

Baseline technologies for floating wind farm maintenance:

Table 9: Baseline access strategies (floating)

Vessel and equipment types	Main function	Main (assumed) characteristics
CTV (small catamaran)	Access for technicians from O&M port to the wind turbines that are close to shore.	• Capacity for up to 12 technicians. • Total free deck space for spare parts up to 22 m^2 and the cargo weight up to 6 tons. • Daily port call. • Transit speed of 25 knots. • Bump-and-jump method of transfer with weather limit of 1.5m Hs.
Anchor-handling vessel	Disconnect and connect moorings and dynamic cables from and to the floating substructure.	• Fitted with a work-class ROV for subsea operations.
Offshore tug	Tow the disconnected substructure-turbine-assembly at the wind farm to and from the major component replacement port.	• Tow speed at 3 knots.
Assist tug	Assist offshore tug to manoeuvre the position of the substructure-turbine assembly during towing.	• Transit at the same speed of 3 knots as the offshore tug during towing.
Harbour tugs	Tow the disconnected substructure-turbine-assembly within the major component replacement port.	• Tow speed at 3 knots.
Onshore heavy lift crane	Lift major turbine components off and onto the floating substructure for replacement at the quayside of the major component replacement port.	• Lifting capacity of performing major components exchange at the hub height of the reference 15 MW turbine.

An array of innovation concepts, encompassing both conceptual and pilot stages, were explored and assessed for the maintenance of floating offshore wind farms. These concepts were subjected to a ranking process based on criteria including feasibility, risk mitigation, cost benefits, and minimized downtime, leading to the selection of the most highly ranked innovations for subsequent modelling, the summaries of which are provided below:

Table 10: Innovative access strategies (floating)

Vessel and equipment types	Main function	Main (assumed) characteristics
Self-erecting crane system on a retrofitted floating vessel	Perform replacement for blade and blade bearing on-site.	• Use of a retrofitted floating vessel • Pre-repair construction and post-repair deconstruction of a self-erecting crane scaffold
Compact Motion compensated gangway on large CTV (catamaran)	Increase the weather tolerance when transferring technicians from the vessel to the turbine for minor corrective repairs	• Increase in the wave height limit for technician transfers • Additional vessel cost from the use of the compact motion compensated gangway
Cargo drone	Offshore drone delivery of required material and/or spare parts in anticipation of preventive maintenance	• Decrease in the duration of preventive maintenance due to eliminating the need to carry materials to the nacelle from the vessel • Additional OPEX cost of leasing a drone capable of transporting a payload of 30 kg.
Resource sharing for WTG and Platform maintenance	Reducing vessel costs and revenue losses by performing preventive maintenance procedures for wind turbines and platforms jointly, rather than individually	• Creation of a new procedure wherein the actions of wind turbine and platform preventive maintenance are performed jointly

5.4. Scenarios

The following section discusses scenarios related to offshore accessibility, for the floating wind turbine, with a focus on comparing baseline strategies to innovative strategies. The KPIs compared for corrective maintenance are total cost, as well as downtime. For each KPI comparison, one figure is presented that shows the spread of results in the form of box plots, wherein the centre line is the median value, and the bottom and top of the boxes are the 1st and 3rd quartile values, respectively. The end caps represent the lowest and highest values, with outliers excluded. Another figure is presented that describes the change in mean, as a percentage value, of that KPI for a given innovation, from the baseline value. All KPI comparisons are organized by month.

Table 11: Scenario 1 for floating wind turbine

Scenario 1	
Wind farm	Site E
Maintenance type	Unplanned corrective
Action	Blade replacement
Description	In the scenario of replacing a blade for a floating wind turbine, two different approaches will be compared: the "tow to port" approach and the "self-erecting crane" approach. The tow to port operation involves detaching the damaged or malfunctioning blade from the floating wind turbine and towing the entire turbine to a designated onshore maintenance facility for the replacement procedure. The self-erecting crane approach involves using a specialized crane located on the floating wind turbine itself to hoist and replace the blade while the turbine remains offshore and connected to mooring lines and power cables.
Baseline strategy	Tow to port
Innovative strategy	Retrofit floating vessel + self-erecting crane

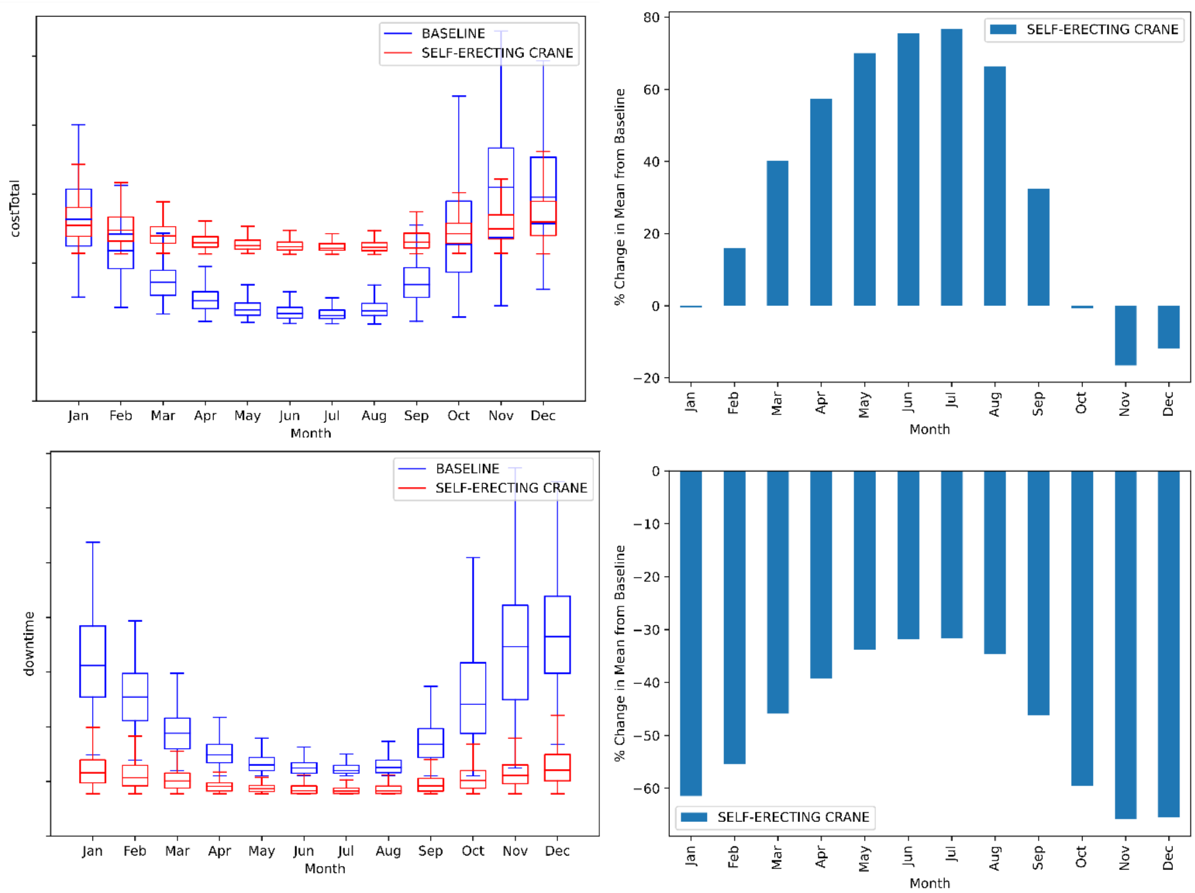

Figure 7: Comparison of total costs and downtime KPIs for Scenario 1 (floating)

The following overview can be obtained from the results:

- Baseline: Total costs for blade replacement vary widely by month, being significantly higher in the winter. In this scenario, the turbine is towed to port to perform major component replacements before being towed back to the site. The large time required for towing, in combination with the stringent weather restrictions under which towing can be done, leads to large delays in the winter when weather conditions are especially unfavorable for towing. This can be seen in the distribution of downtime as well, where values are significantly larger in the winter compared to the summer.
- Self-Erecting Crane: The effect of the self-erecting crane is that of a much smaller dependence on weather, resulting in a much flatter profile across the year compared to the baseline. This can be seen in the downtime distribution, where downtimes are consistently, and in the winter, significantly, lower than in the baseline. The total operational cost (see page 15 for definition) is also much higher, and cost savings are only seen in the winter months when baseline costs are excessively high. This is due to the overriding effect of the high vessel costs incurred, even when downtimes are lower.

Table 12: Scenario 2 for floating wind turbine

Scenario 2	
Wind farm	Site E
Maintenance type	Unplanned corrective
Action	Blade bearing replacement
Description	In the scenario of replacing a blade bearing for a floating wind turbine, two different methods will be compared: the "tow to port" operation and the "self-erecting crane" approach. In both these strategies, the successful removal and replacement of blade bearings constitute of intermediate steps, which are beyond the scope for the current discussion, but considered during the modelling.
Baseline strategy	Tow to port
Innovative strategy	Retrofit floating vessel + self-erecting crane

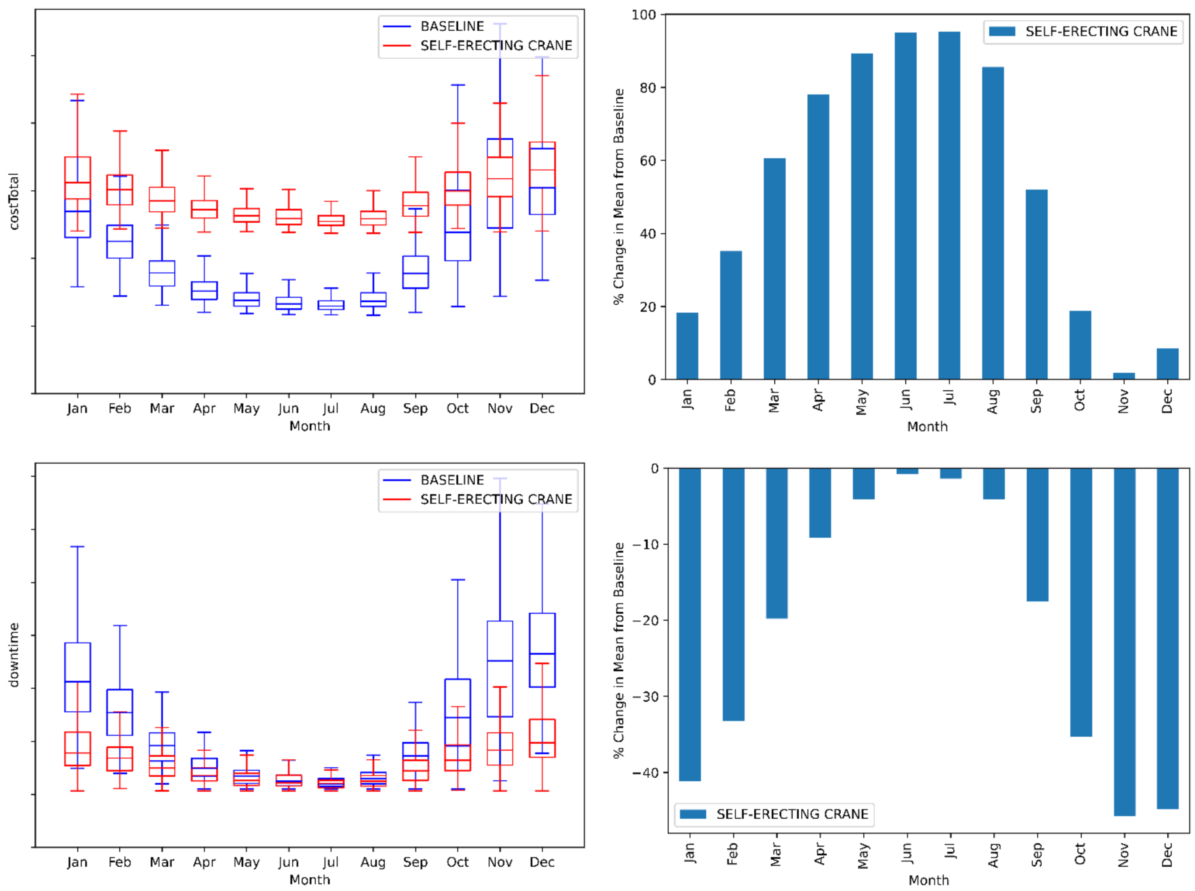

Figure 8: Comparison of total costs and downtime KPIs for Scenario 2 (floating)

The following overview can be obtained from the results:

- Baseline: A similar trend can be seen as compared to the blade replacement action, wherein both downtime and total cost is much larger in winter months.
- Self-Erecting Crane: Similar effects can be seen as compared to the blade replacement action, wherein an overall flatter profile is observed for both downtime and total cost with this innovation. However, in contrast to the blade replacement action, less cost improvements can be gained here from this innovation; costs are consistently higher throughout the year without any real improvements in the winter. This can again be attributed to the effect of high vessel costs (fixed and variable) compared to the baseline case. Similarly, the distribution for downtime is still consistently lower compared to the baseline, but reductions are lower, and are nearly insignificant in the summer months.

Table 13: Scenario 3 for floating wind turbine

Scenario 3	
Wind farm	Site E
Maintenance type	Unplanned corrective
Action	Minor component repair –small, medium and large maintenance
Description	In this scenario, a high-priority corrective operation is required for the reference wind turbine that has experienced a critical fault affecting its energy production. The operation must be completed swiftly to minimize downtime and maximize energy output. The operation target durations are “small”, “medium” and “large” maintenance and are compared using two different strategies. In the baseline strategy, CTV is used to transfer technician. For the innovative strategy, CTV is combined with the gangway system that has higher Hs limit for technician transfer.
Baseline strategy	CTV
Innovative strategy	CTV + compact motion compensated gangway

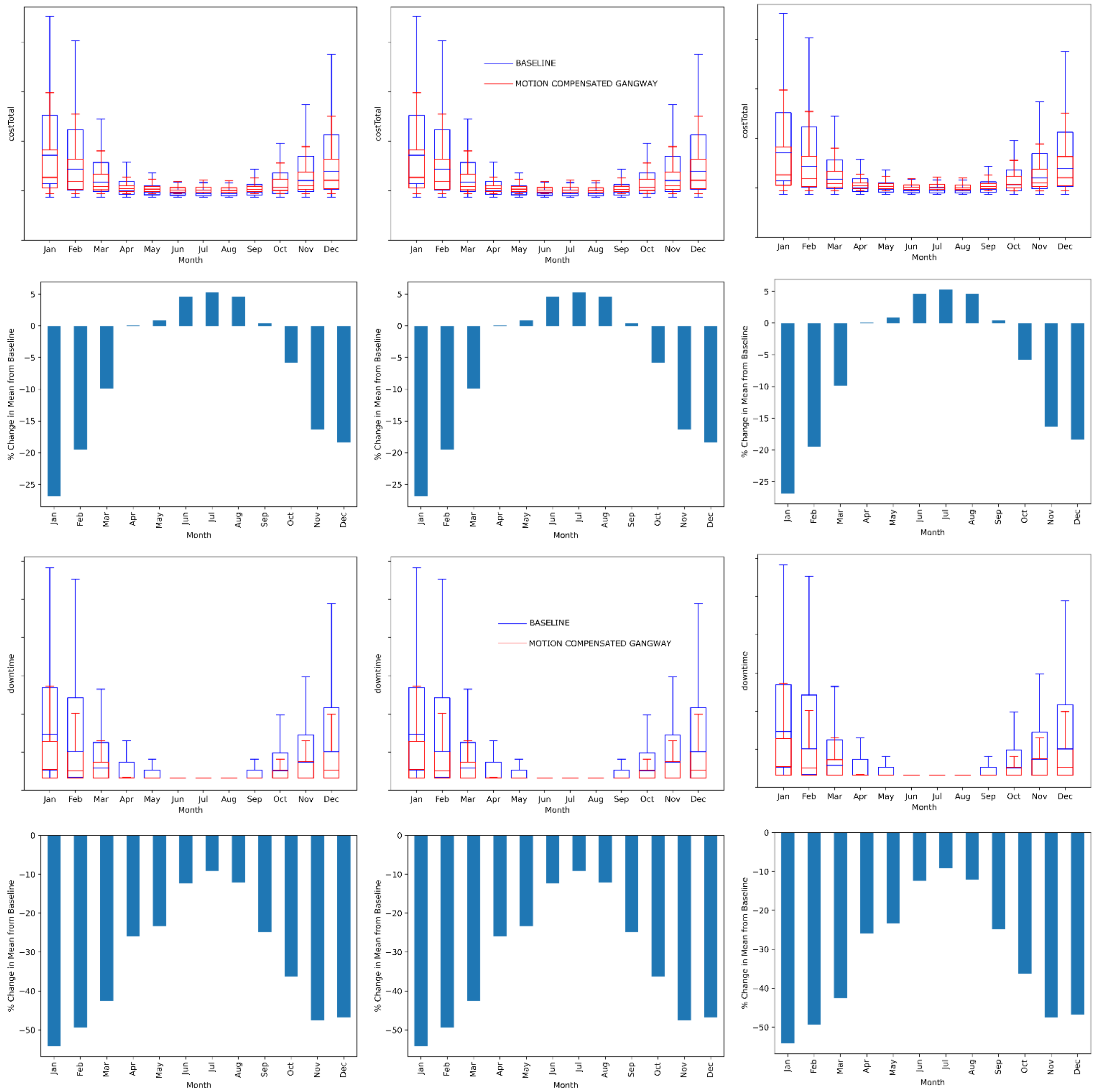

Figure 9: Comparison of total costs and downtime KPIs for Scenario 3; from left to right: “small”, “medium” and “large” maintenance (floating)

- Small maintenance: In the case of “small” minor corrective maintenance (CM), it can be observed that the deployment of gangway on the CTV brings more benefits in months from October to March, when more wind and waves are expected; the turbine downtime is reduced by 35%-53%, and total costs are reduced by 5%-26%. As for from April to September, the turbine downtime decreases by 9%-25%, but the total costs increase up to 5%, which is correlated to the additional costs of gangway. However, overall, the benefit accrued from the gangway in the winter months outweighs the costs incurred in the summer months. Another trend is that the boxplots of the baseline are mostly longer than the ones with gangway. This implies that with the use of gangway, the weather windows or accessibility are enlarged, there is less dependence on weather, and hence higher certainties to the resulting total costs and downtime.

- Medium maintenance: Similar trends can be seen in the results of “medium” minor CM compared to the results of “small” minor CM. However, when using gangway for “medium” CM, the overall benefits in both terms of cost and downtime are less than using it for “small” CM, which is only due to the longer hours taken for maintenance action. Overall, it is beneficial to deploy a gangway to improve the transfer of technicians. Further study is suggested to look into the option of deploying the CTV without a gangway during summer months and deploying the CTV with a gangway during winter months.
- Large maintenance: It can be observed that the results of “large” minor CM are almost identical to the results of “medium” minor CM. This implies an overall benefit, as the maintenance hour increases, but the changes in total costs remain. Overall, it is also beneficial to deploy a gangway to improve the transfer of technicians. Similarly, further study is suggested to look into the option of deploying the CTV without a gangway during summer months and deploying the CTV with a gangway during winter months.

Table 14: Scenario 4 for floating wind turbine

Scenario 4	
Wind farm	Site E
Maintenance type	Preventive
Action	Payload transfer
Description	In this scenario, we will compare two distinct methods for transferring a critical payload to the wind turbine location. The first method involves utilizing a Crew Transfer Vessel (CTV) for the technician payload transfer, while the second method utilizes the CTV for technician transfer and an additional drone for the payload transfer.
Baseline strategy	CTV
Innovative strategy	Drone

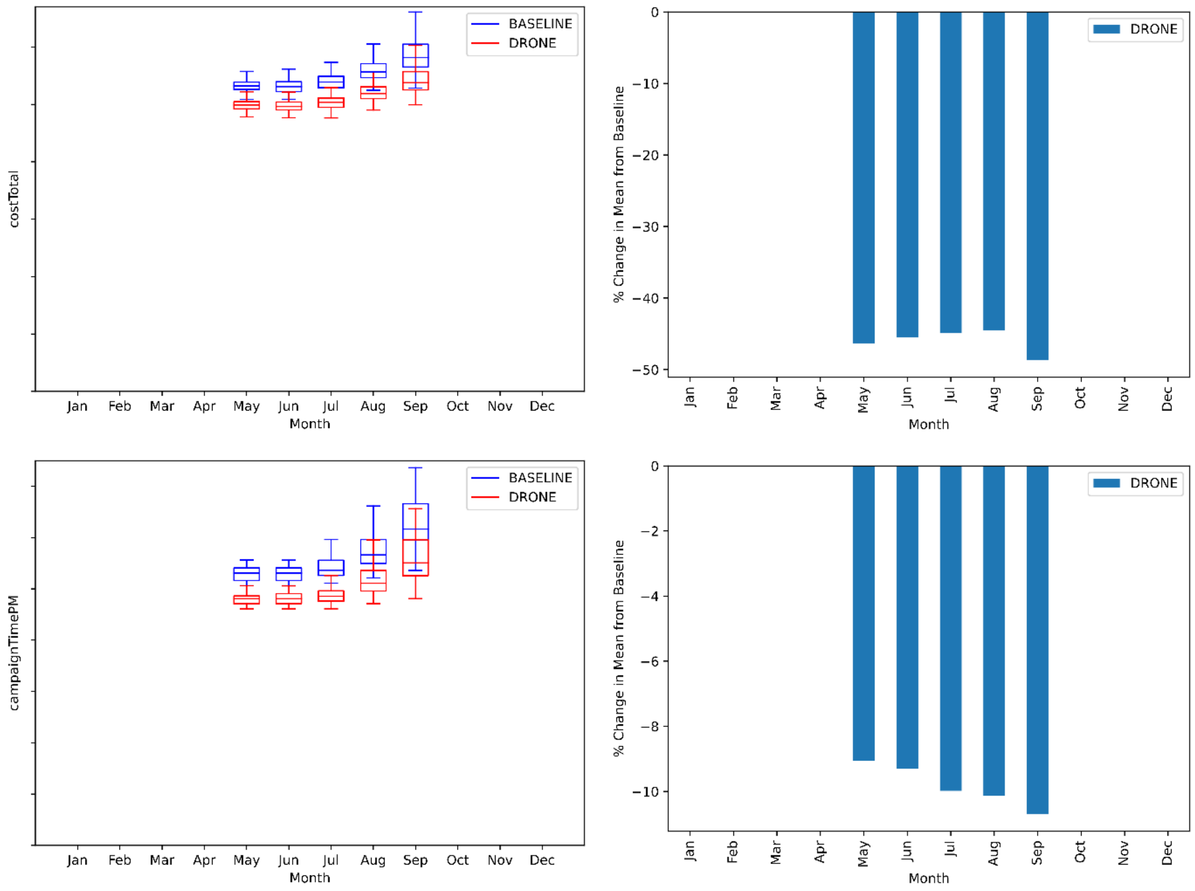

Figure 10: Comparison of total costs and campaign time KPIs for Scenario 4 (floating)

The following overview can be obtained from the results:

- Baseline: Relatively similar costs can be seen in all summer months, with increasing costs and campaign times in August and September as a result of less favorable weather conditions for these activities.
- Drones: Preventive maintenance campaigns were shown to have consistently lower costs by 6-8%. This can be attributed to the effect of consistently lower campaign durations, which were found to be lower by 9-11%. This implies that the cost improvement associated with reduced campaign durations outweighs the additional OPEX cost of the drone, thus providing an overall net benefit.

Table 15: Scenario 5 for floating wind turbine

Scenario 5	
Wind farm	Site E
Maintenance type	Preventive
Action	WTG and Floater maintenance
Description	In this scenario, two different strategies will be compared. The baseline strategy consists of different vessels utilized for carrying out the maintenance activities for the wind turbine and the floater, respectively. The innovative strategy would utilize the same vessel to transfer technicians and perform wind turbine and platform maintenance simultaneously instead of during individual campaigns. In these simulations, the baseline is defined as the running of three simultaneous campaigns, one for the WTG and two for the floater. These campaigns are run simultaneously, starting on the same date. The total cost is thus defined as the summation of the individual campaign costs, whereas the duration is defined as the duration of the longest individual campaign. In the combined case, a single campaign is run that entails all the work done of the three individual campaigns.
Baseline strategy	CTV (WTG Preventive Maintenance) + CTV (Floater Annual Campaign) + CTV (Floater Annual Inspection)
Innovative strategy	CTV (Combined Inspection)

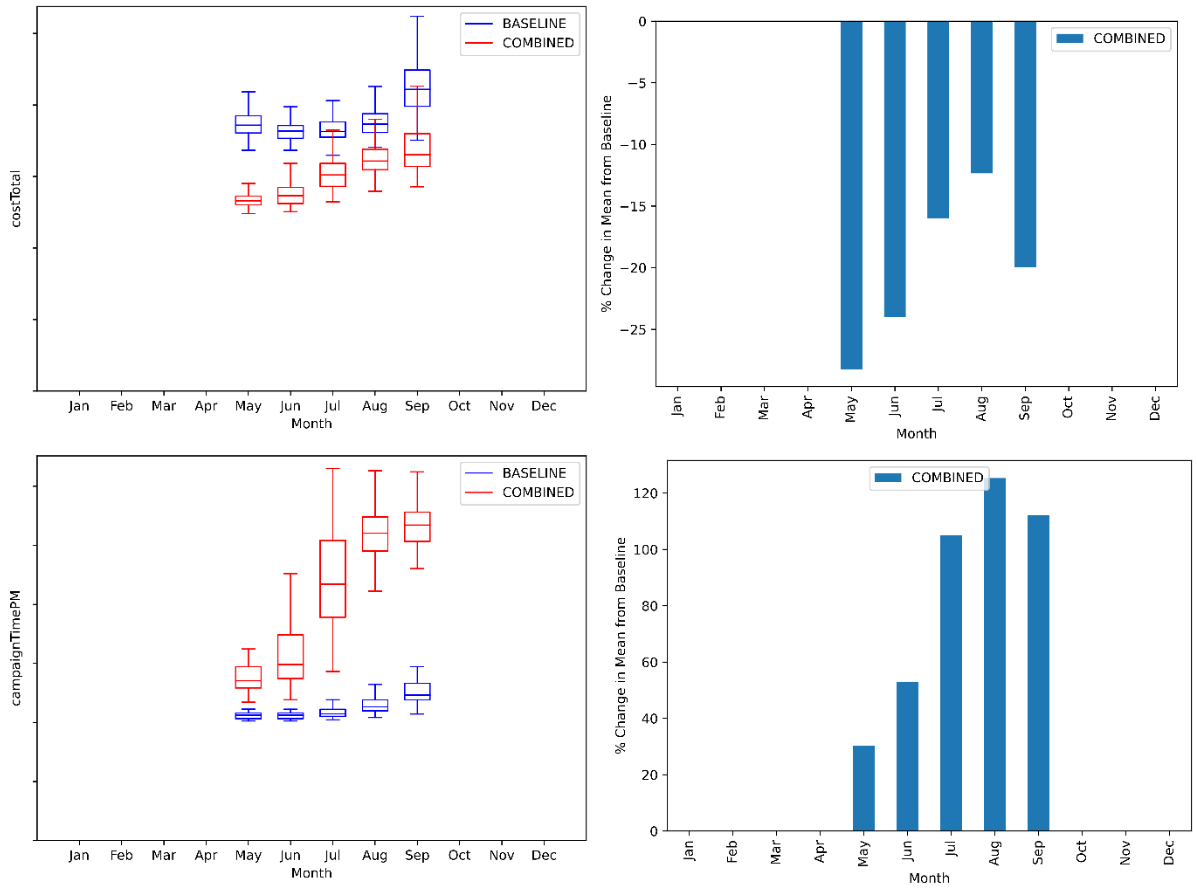

Figure 11: Comparison of total costs and total campaign time KPIs for scenario 5 (floating)

The following overview can be obtained from the results:

- Baseline: While total costs can be seen as relatively stable during the summer, September introduces larger costs due to more weather delays and higher associated variable costs. Total campaign durations also follow this trend, for the same reason.
- Combined: A large reduction in costs can be seen from combining campaign resources, despite significantly longer campaign durations, implying that running a single campaign for longer is more cost effective than running simultaneous operations, despite the choice of vessel being more expensive. The campaign duration trend for combined operation increases drastically towards the late summer, however, implying that with later start dates, the risk of running excessively long campaigns becomes significant. The large increase of campaign duration is due to the stricter weather limits of the combined campaign which, if started in the late summer, tended often to not finish until after the winter when the stricter weather limits are once again satisfied. Corresponding baseline individual campaigns with those same weather limits had lower maintenance times and thus finished before the winter.

6. Conclusions

The objective of this study was to explore innovative access strategies aimed at enhancing the accessibility of offshore wind farms, while accounting for the weather uncertainty. The research encompassed a comprehensive market analysis in collaboration with project partners and discussions with strategy (concept) developers. Subsequently, a method statement was defined to integrate these innovative strategies and assess them in comparison to established baseline strategies, applicable to both bottom-fixed and floating wind turbines using reference wind farm sites.

The comparative analysis was facilitated through the utilization of the discrete event-based logistic simulation tool, UWiSE O&M Planner, developed by TNO. This tool effectively addressed the inherent challenges of weather uncertainty by employing the Monte Carlo sampling technique, thus providing valuable statistical estimates for various key performance indicators (KPIs). These KPIs encompassed both time-based and yield-based metrics, offering a holistic evaluation of the proposed access strategies.

For major component replacements on the bottom-fixed wind farm, a higher-capacity crane allowed for the use of a smaller JUV, significantly reducing operating costs, while a crane-retrofit innovation that reduced the weather limitations led to lower downtimes at similar operating costs. Minor correctives action KPIs were not significantly improved by use of a motion-compensated gangway, as the weather restrictions for technician transfer from an SOV were not a limiting factor to begin with. Preventive maintenance campaigns benefited slightly from use of a drone to reduce total campaign time, but at slightly higher costs.

For major component replacements on the floating wind farm, the self-erecting crane was found to have higher costs in the summer, due mostly to the relatively high vessel operating costs, although downtime was significantly reduced as there was no longer a need to tow the turbines to a port for maintenance. Minor corrective action KPIs were improved by use of a motion-compensated gangway, as the weather restrictions for technician transfer from a CTV are lower compared to those from an SOV. Preventive maintenance campaigns benefited by use of a drone both through duration, as well as lower costs. Combining WTG and platform preventive maintenance campaigns resulted in far lower costs, albeit with much higher campaign durations due to the combination of strict weather limits and comparatively higher maintenance times.

It is important to emphasize that this study serves as a guiding framework for diverse stakeholders involved in offshore wind farm operations and maintenance, offering insights and recommendations to optimize their access strategies.

References

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