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# Exploring Impact Of Condition Monitoring On Offshore Wind Farm Availability

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**Abstract**

This paper investigates the integral role of condition monitoring in shaping maintenance strategies for offshore wind farms (OWFs) with multiple offshore wind turbines (OWTs). Petri Net (PN) simulation models are developed to comprehensively assess how condition monitoring influences the operational dynamics of OWFs. The investigation addresses essential questions related to OWF availability and the number of different maintenance vessels required to charter within the design life of the OWTs. The research findings emphasise the nuanced interplay of condition monitoring and maintenance at the wind farm level. This paper provides practical insights into leveraging condition monitoring to enhance maintenance strategies in OWFs, offering valuable guidance for stakeholders in the field. The extended Petri Net simulation models present a robust framework for decision-making in wind farm management.

*Keywords*: offshore wind, Petri Net, simulation, wind farm, maintenance

## 1. Introduction

Wind power, recognised as a practical way to tackle climate change, is seeing a shift towards larger turbines located offshore. This move is driven by better wind resources and fewer concerns about visual impact, noise pollution, and land use in offshore areas. According to the Global Wind Report by GWEC, offshore wind farms (OWFs) have significantly expanded, with global capacity expected to reach 2 TW by the end of 2030 (GWEC, 2023). In the UK, as of mid-August 2022, there are 11,751 wind turbines with a total capacity exceeding 29.7 GW, and offshore wind contributes 14.7 GW (Wind Energy Statistics - RenewableUK 2023). In the first quarter of 2023, a noteworthy milestone was achieved as wind power contributed 32.4% of Britain's electricity, surpassing gas, which accounted for 31.7% (Drax, 2023). This marks the first instance in the history of the country's electricity grid where wind has claimed the highest share of power during any quarter. For the wind industry to attain sustainable and economically beneficial development, it is essential to optimise and maintain the operation and maintenance (O&M) costs linked with wind farms within an acceptable range. This strategic approach ensures not only efficient operations but also fortifies the long-term viability of the industry.

The cost associated with the maintenance of Offshore Wind Turbines (OWTs) in an OWF can be influenced by numerous factors, such as component reliability, farm accessibility, weather conditions, maintenance strategies, vessels, and so on. A lot of research has been conducted to find the optimal maintenance plan (Kou et al., 2022; de Boer and Xydis, 2023). For example, Yan and Dunnett adopted a Petri Net (PN) modelling method to effectively mitigate costs and minimise downtime, thereby enhancing the O&M strategies for a single OWT (Rundong Yan and Dunnett, 2021). Besnard et al. created an analytical model to assess the performance of different maintenance supports for OWFs with the consideration of various factors including location of maintenance accommodation, work shift organisation, technical support, and so on (Besnard, Fischer, and Tjernberg, 2013). Petros et al. developed a stochastic linear model to optimise the opportunistic maintenance scheduling for OWFs (Papadopoulos, Coit, and Aziz Ezzat, 2024). Different decision-making performance metrics such as cost and availability were considered in the research.

However, to the best of the authors' knowledge, no prior studies have investigated the influence of the accuracy and reliability of OWT condition-monitoring systems (CMSs) on the overall availability of turbines within an OWF. Therefore, this paper aims to fill this gap by developing a novel Petri net (PN)-based simulation model, explicitly considering it. The factor has historically been overlooked in research due to its computational complexity. The model is developed based on the authors' previous work focused on individual OWTs (Yan and Dunnett, 2021; Yan, Dunnett, and Jackson, 2023).

The remaining part of the paper is organised as follows. In Section 2, the wind farm considered in the study, the structure of the OWTs in the farm, the CMS considered, and the maintenance strategies that could be potentially adopted are defined; In Section 3, the PN modelling method is briefly reviewed; In Section 4, the overall modelling structure and associated PN models for simulating the maintenance activities in offshore wind farms are described in detail; In Section 5, the simulation results obtained using the PN simulation including the average number of repairs conducted in different scenarios and the corresponding OWF availability and downtime are discussed; In Section 6, the paper concludes with key research findings and potential future works.

## 2. Offshore wind farm: turbine structure, maintenance, and monitoring

A postulated OWF, comprising 10 gear-driven OWTs, is used to demonstrate the methodology proposed in the research. As the wind power industry develops, new OWF projects are increasingly venturing farther from the coastline to capitalise on superior wind resources and address constraints arising from limited available space nearshore. Hence, positioned at an optimal offshore location, this wind farm ensures logistical efficiency and good wind resources, being approximately 240 kilometres from the nearest port. The selection aims to underscore real-world applicability and strengthen the credibility of the research findings.

### 2.1. Structure of the OWT

The gear-driven OWTs considered in the research have a capacity of up to 15 megawatts. These turbines consist of six critical subsystems: the rotor system, yaw and pitch (YP) system, braking system, drivetrain system, power system, and turbine structures, each contributing uniquely to their overall functionality. A brief description of each subsystem is given below, and the turbine schematic is shown in Fig. 1.

- The rotor system consists of three blades and the hub captures kinetic energy from winds. It initiates power generation by converting wind motion into rotational energy.
- The function of the yaw and pitch system manages the turbines' orientation and blade angles, maximising energy capture by aligning with the incoming wind flow.
- The braking system controls and regulates the speed of the OWT, ensuring safe and efficient operation by preventing overspeed in various offshore weather conditions (Dalgic et al., 2015; Abdollahzadeh, Atashgar, and Abbasi, 2016).
- The drivetrain system consists of the main shaft and a gearbox.
- The power system facilitates the transmission of rotational energy to the generator, enabling the conversion of mechanical energy into electrical power.
- The turbine structure includes a nacelle, tower, and foundation. It provides essential support and stability for the entire OWT, ensuring structural integrity and durability, and withstanding environmental forces and loads in offshore conditions.

In the study, the health status of these subsystems is categorised into four categories, i.e. normal, minor fault, critical fault, and failure (Le and Andrews, 2016). The wind turbine operates seamlessly when all subsystems are in a healthy state. In the event of a minor fault within a subsystem, it is assumed that the subsystem can still function, although generating abnormal conditions detectable by the Condition Monitoring System (CMS). Contrary to minor faults, critical faults exhibit higher detectability (i.e. the probability that a fault can be detected successfully) by the CMS owing to pronounced indicators such as excessive vibration. When a critical fault escalates into a failure, the wind turbine undergoes an immediate shutdown. The degradation of each subsystem is modelled to follow a Weibull distribution, with parameters derived from published wind turbine failure rate data (Leigh and Dunnett, 2016; Le and Andrews, 2016). In the paper, an estimation method was employed to determine the scale parameters ($\eta$) for subsystems existing in normal, degraded, and critical states, encompassing a specific percentage of the Mean Time to Failure (MTTF) as detailed in Table 1 (Rundong Yan, Dunnett, and Jackson, 2023b). The MTTF for each subsystem is calculated as the reciprocal of the failure rate, also provided in Table 1. Additionally, the shape parameters ($\beta$) of the distributions are assumed to be 1.2 to better model the increasing deterioration rates of mechanical components, as suggested by (Le and Andrews, 2016).

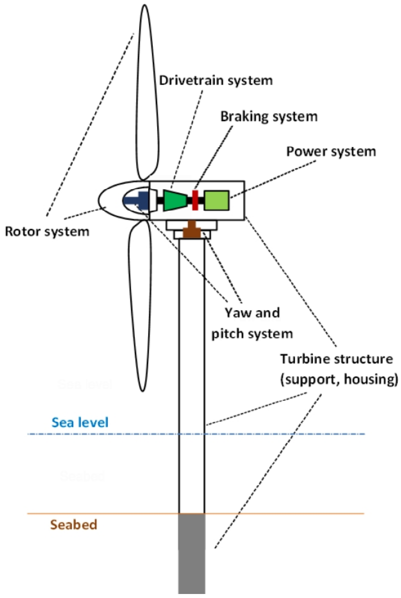


Fig. 1. Main subassemblies of the offshore wind turbines (Rundong Yan, Dunnett, and Jackson, 2023b).

Table 1. Failure rates of wind turbine subsystems (Le and Andrews, 2016; Rundong Yan, Dunnett, and Jackson, 2023b).

| Subsystem | Failure rate (/year) | Percentage share in MTTF | | |
|---|---|---|---|---|
| | | Normal | Minor fault | Critical fault |
| Rotor | 0.0868 | 70% | 20% | 10% |
| Drivetrain | 0.0600 | 70% | 25% | 5% |
| Power system | 0.1430 | 70% | 25% | 5% |
| YP system | 0.1534 | 70% | 20% | 10% |
| Braking system | 0.0799 | 70% | 20% | 10% |
| Structure | 0.0790 | 70% | 20% | 10% |

## 2.2. Maintenance strategy

The enhancement of wind turbine reliability and availability is a critical pursuit within the realm of wind energy infrastructure. To achieve this objective, diverse maintenance strategies could be adopted to maintain the reliability and availability of OWTs at consistently high levels of reliability and availability. In the offshore wind power industry, three primary maintenance approaches are commonly employed: periodic maintenance, corrective maintenance, and condition-based maintenance (Nakagawa, 2005; Le and Andrews, 2016; Seyr and Muskulus, 2019; Rundong Yan, Dunnett, and Jackson, 2023b).

In the domain of offshore wind energy, periodic maintenance currently plays a critical role in maintaining the reliability and availability of turbines deployed in the challenging marine environment (Elusakin et al., 2021). The saltwater exposure, high winds, and other environmental conditions necessitate systematic maintenance regimes. Hence, the regular inspections and maintenance of the critical subsystems of the OWTs via routine inspections are essential to ensure sustained operational efficiency of the OWTs in an OWF. During the periodic maintenance, several activities can be conducted. For example, the faulty subsystems can be repaired or replaced. Lubrication procedures are implemented to mitigate friction and wear in essential moving parts such as gearboxes and yaw systems. Cleaning protocols address the salt deposits and debris on turbine blades, maintaining their aerodynamic efficiency and preventing corrosion.

Corrective maintenance represents a reactive approach, initiated after a failure has occurred. In the study, it is assumed that following the completion of corrective maintenance, a comprehensive turbine inspection is systematically conducted. This proactive measure is deemed imperative due to the turbine’s temporary shutdown for repair, providing a strategic opportunity for a detailed inspection (Kang and Guedes Soares, 2020).

Condition-based maintenance, on the other hand, is conducted based on the successful detection of faults by the sensors and monitoring devices on key components in the system (Yang et al., 2014). Its efficiency and effectiveness are directly linked to the fault detection capabilities of the CMS integrated into the wind turbine. The CMS continuously collects real-time data on parameters like vibration, temperature, and fluid conditions. One of the main advantages of condition-based maintenance in offshore wind power is that it enables operators to predict when maintenance interventions are required, allowing for a proactive response to emerging issues before they escalate into costly failures. This predictive capability is particularly importance in the offshore environment, where accessing and servicing turbines can be logistically challenging and expensive.

### 2.3. Condition monitoring system

The Condition Monitoring System (CMS) for OWTs represents a complex assembly of various sensor types and monitoring methodologies designed to provide continuous, real-time surveillance of critical components (Tusar and Sarker, 2021). The fundamental objective of the CMS is to recognise early indicators of potential faults, thereby facilitating proactive maintenance measures and mitigating downtime. Different induction measures such as vibration, temperature, oil condition, etc., have been adopted in the CMS of OWTs (Yang et al., 2014). The CMS is further complemented by a remote monitoring and control system, allowing centralised supervising of OWFs for efficient decision-making and swift responses to maintenance requirements.

In this paper, it is assumed that all the OWTs in the postulated OWF have the same CMS. The subsystems that the CMS can monitor and their detection capabilities assumed based on expert knowledge and past literature are listed in Table 2 (Yang et al., 2014; Rundong Yan, Dunnett, and Jackson, 2023b). On the other hand, it is assumed that the sensor groups for monitoring different subsystems can appear in two possible health states, i.e. working properly, and failed. Once a sensor group fails, the health condition of the subsystem monitored by it will be unknown and it is assumed that the sensor group will be repaired during the next periodic maintenance. The assumption is made that the failure of each sensor group follows a Weibull distribution, wherein the parameters $\beta$ and $\eta$ are set to be 1.2 and 16.67 years, respectively.

Table 2. Fault detection capability for each subsystem of the OWT (Rundong Yan, Dunnett, and Jackson, 2023b).

| Subsystem | Detectability of CMS | |
|---|---|---|
| | Minor fault | Critical fault |
| Rotor | - | - |
| Drivetrain | 0.50 | 0.90 |
| Power system | 0.80 | 0.95 |
| YP system | 0.70 | 0.90 |
| Braking system | 0.70 | 0.95 |
| Structure | 0.50 | 0.90 |

## 3. Methodology

Petri net (PN) modelling method is adopted in the research. It serves as a mathematical modelling language widely adopted in the field of computer science. Its application extends to the modelling of various complex systems. Researchers have employed it for various tasks such as simulating system behaviour, assessing system reliability, and optimising system performance (Prescott and Andrews, 2013; Davies and Andrews, 2021; R. Yan, Dunnett, and Jackson, 2022; Lotovskyi, Teixeira, and Soares, 2020).

PNs provide a direct bipartite graphical representation of a system, enabling the analysis and simulation of system behaviour. They consist of two types of elements: places and transitions. As shown in Fig. 2, places, depicted as circles, indicate the resources, materials, or conditions in a system. Transitions, depicted as squares, represent the actions or events that can alter the system’s state. Arrows, known as arcs in Petri nets, connect places and transitions. Each arc can be assigned a weight, indicating the presence of *n* individual arcs with the same connections. This is denoted by adding a slash to the arc and a numerical value, *n*, next to it. Moreover, an arc featuring a small circle at one end is termed an inhibitor arc, with the ability to inhibit a transition from firing when it is enabled. Lastly, small solid circles denote tokens, serving as carriers of information within the PN structure.

A transition can be activated when the number of tokens within each input place surpasses or equals the respective weights assigned to the arcs inputting to the transition. After the activation, the transition is executed following the designated parameters associated with it. Tokens are subsequently removed from the input places and allocated to the output places. The number of tokens removed or produced in the places depends on the weights of the arcs connecting to the activated transition. The marking of tokens within a PN model represents the state of the system modelled.

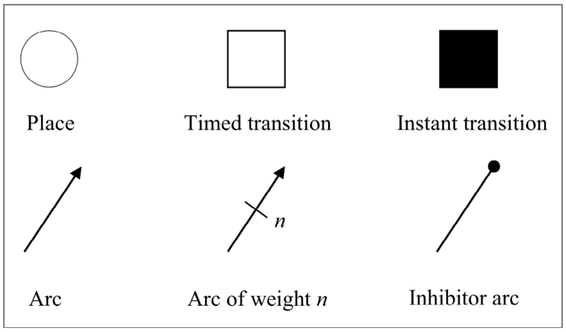


Fig. 2. PN symbols used in this work (Rundong Yan, Dunnett, and Jackson, 2023a).

## 4. Modelling the O&M of OWFs using PNs

In the paper, four types of PN models are developed to simulate the O&M within an OWF. The overall model structure is illustrated in Fig. 3.

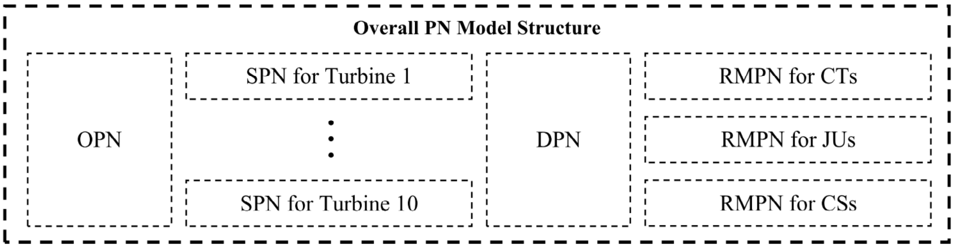


Fig. 3. Overall PN model structure.

The first PN model, Operation Petri net (OPN), specifically models the operation life of OWTs within the OWF, incorporating periodic maintenance activities. The assumed design life for the OWTs in this research is 20 years.

The System Petri net (SPN), as the second model, is developed to replicate the stochastic degradation processes and diverse health states characterising turbine subsystems. The faults that can be detected by the CMS are highlighted in a light green textbox as illustrated in Fig. 4. The health state degradations in the turbine are represented by Transitions "W1" to "W17". In this investigation, it is assumed that the durations for these follow Weibull distributions defined by the parameters outlined in Table 1. Given the presence of ten OWTs within the OWF, the SPN is iteratively incorporated into the model 10 times, aligning with the number of turbines.

The third model, Detection Petri net (DPN), is tailored to model fault detection mechanisms facilitated by the CMS. It will be activated once a fault occurs.

The fourth and final model, Recovery and Maintenance Petri net (RMPN), is designed to simulate the vessel chartering, process to prepare and conduct the maintenance. This study accounts for three distinct vessel types – Crew Transfer Vessel (CT), Jack-up Vessel (JU), and Crane Vessel (CS) – each contributing to specific repair or replacement activities (Rundong Yan, Dunnett, and Jackson, 2023b). Consequently, the RMPN is imported 3 times to the model, each one corresponding to a unique vessel type.

It is important to underscore that vessel capacities are subject to limitations. In the event of a fault, if a vessel capable of conducting the required task has already been chartered, it will undertake the assigned maintenance task without necessitating the chartering of an additional vessel. However, in cases where the remaining capacity of the vessel is insufficient, chartering of an alternative vessel becomes necessary.

For a detailed structure of the PN models, readers are directed to the work conducted by the authors (Rundong Yan, Dunnett, and Jackson, 2023b). Notably, these models were developed to address the details of a singular Offshore Wind Turbine (OWT).

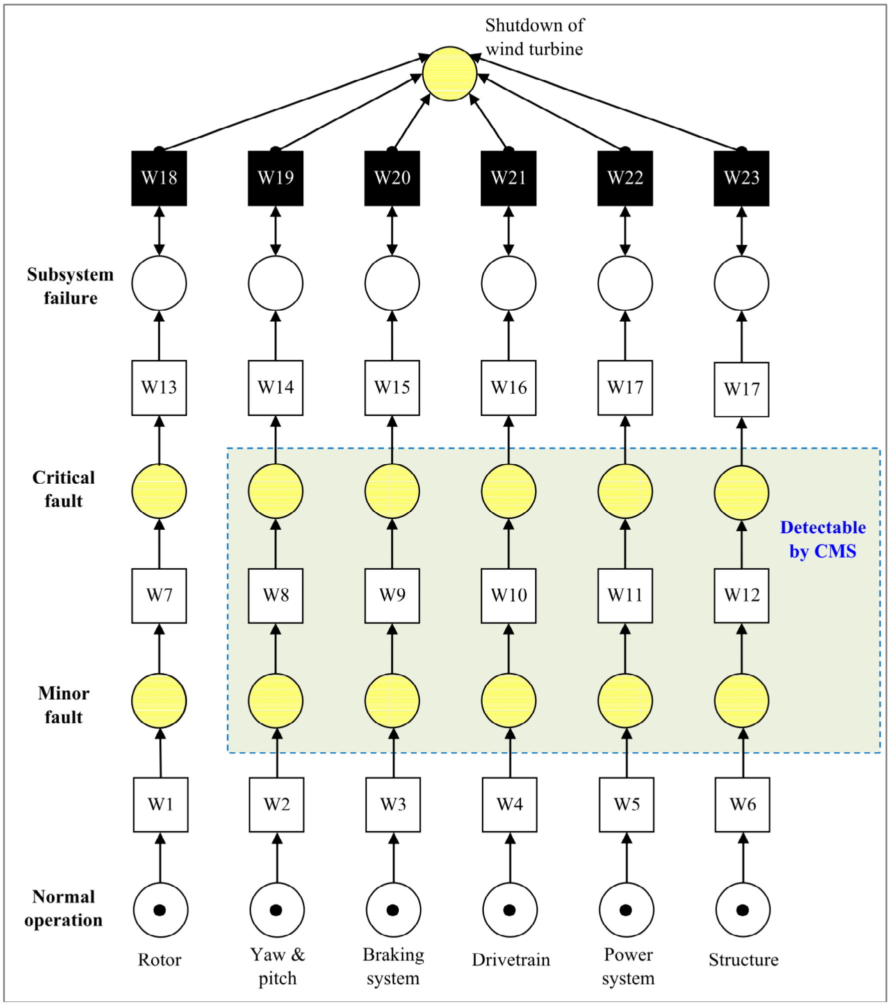


Fig. 4. System Petri net (SPN).

## 5. Simulation results and discussions

In order to evaluate the impact of condition monitoring and maintenance vessel capacity on the OWF availability, the PN models proposed in the previous section are embedded into a Monte Carlo simulation. The following are the simulation assumptions:

- Natural disasters are not considered.
- The health state of the subsystems after maintenance is regarded as good as new.
- The false alarms generated by the CMS are not considered in the study.
- The periodic maintenance is assumed to be conducted once per year.
- During the periodic maintenance or comprehensive turbine inspections following turbine shutdowns, the OWTs need to be temporarily shut down for a duration of 5 days.

The data given in Tables 1 and 2 are imported into the simulation calculation. he simulation is programmed in Python. The relevant calculations are carried out on a personal computer with a Windows 10 operating system. The specification of the computer is Intel(R) Core(TM) i7-7500U CPU @ 2.70 GHz, 16 GB RAM. The It is found that the simulation results converge to stable values after about 10,000 simulations.

The average number of failures and faults detected by the CMS and the average number of faults and failures recovered within the lifetime of the 10 OWTs in the OWF are obtained via the simulation. The calculation results are listed in Table 3.

Table 3. The average number of failures and faults detected and recovered.

| Subsystem | Minor faults detected by CMS | Critical faults detected by CMS | Minor faults repaired | Critical faults repaired | Failures recovered |
|---|---|---|---|---|---|
| Rotor | 0 | 0 | 18.76 | 2.92 | 0.89 |
| Drivetrain | 8.09 | 0.76 | 15.90 | 0.87 | 0.03 |
| Power system | 32.69 | 2.33 | 40.38 | 2.51 | 0.20 |
| YP system | 30.49 | 3.60 | 42.32 | 3.96 | 0.39 |
| Braking system | 15.66 | 0.96 | 22.21 | 1.05 | 0.04 |
| Structure | 10.85 | 1.54 | 21.14 | 1.66 | 0.12 |
| Sum | 97.78 | 9.19 | 160.72 | 12.96 | 1.68 |

In the analysis presented in Table 3, it is found that over the 20-year lifespan of the OWTs within the OWF, the average numbers of the repaired minor and critical faults in the OWT subsystems amount to 160.72 and 12.96, respectively. The CMS detects 60.84% of minor faults and 70.92% of critical faults overall. Notably, the subsystem most frequently requiring repairs is the YP system. Nevertheless, it is the rotor failure that results in the most OWT shutdowns due to failure. This can be attributed to the limitation of the CMS, as it lacks the capability to monitor the health status of the rotor. This underscores the indispensable role that the CMS plays in strengthening the operational and maintenance (O&M) effectiveness of the OWF.

Moreover, the successful completion of these maintenance activities involves chartering CTs, JUs, and CSs an average of 43.44, 48.58, and 2.82 times, respectively. Through the adoption of the maintenance strategy defined in this study, coupled with the implementation of the specified CMS, the OWF consisting of 10 OWTs can achieve an overall availability of 98.57%.

## Conclusion

The present study adopts the Petri Net (PN) method to systematically investigate the impact of condition monitoring and maintenance vessel capacity on the availability of OWFs. The simulation demonstrates the flexibility and adaptability of the developed PN models, establishing them as a robust approach for simulating maintenance activities within OWFs and evaluating the overall availability of the farm. Moreover, the simulation facilitates the successful derivation of the number of diverse maintenance activities required and the corresponding chartering of maintenance vessels throughout the operational lifespan of the OWTs in the OWFs. As a trajectory for future research, there exists an opportunity to explore the effectiveness of different CMSs in ensuring the availability of OWFs. Additionally, an investigation can be conducted to analyse the impact of the number of OWTs on maintenance costs across entire OWF projects.

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