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Wind Turbine Installation Vessel Mission Reliability Modelling Using Petri Nets

Rundong Yan

Resilience Engineering Research Group, University of Nottingham, Nottingham, U.K
E-mail: Rundong.yan@nottingham.ac.uk

Sarah Dunnett

Department of Aeronautical and Automotive Engineering, Loughborough University, UK.
E-mail: s.j.dunnett@lboro.ac.uk

Lisa Jackson

Department of Aeronautical and Automotive Engineering, Loughborough University, UK.
E-mail: r.yan@lboro.ac.uk
E-mail: l.m.jackson@lboro.ac.uk

Offshore wind power is one of the main technologies helping to meet the global low carbon challenge. However, the significant expansion of the offshore wind industry and the rapid increase in the size and weight of turbine components will certainly amplify the risk issues during installation and transport of large Offshore wind turbines (OWTs). Currently, there are less than 20 vessels globally that can support the installation of these large turbines. These vessels are multi-functional, comprising highly integrated specific-designed systems and components. If any of these components fail it could cause significant project delays or even lead to catastrophic damage to the vessel and turbine, posing a risk to human life. In this context, this paper aims to develop a mathematical model using Petri nets to assess the risk and reliability of the mission of a wind turbine installation vessel (WTIV). The mission of the WTIV is segmented into consecutive phases, each of which serves a specified task. Critical phases can be identified, and their failure probability can be obtained using the model developed. The Petri net model outlined in this paper is deemed useful in aiding decision-making regarding installation for future offshore wind farm projects.

Keywords: Offshore wind, Logistics, Petri nets, Simulation, Offshore installations, Reliability.

1. Introduction

Global offshore wind power installation is growing rapidly every year, and the total offshore capacity in 2021 reached 57 GW (Global wind energy council 2022). Due to stronger and more consistent wind speeds, less noise and visual pollution, fewer turbine size restrictions, and greater flexibility in choosing site locations, the wind industry is increasingly directing its attention towards the offshore sector. This has further accelerated competition for larger turbines to maximize power generation and reduce levelized cost, with many projects now set to install 10MW+ offshore wind turbines (OWTs), such as Dogger Bank Wind Farm in the UK and Vineyard Wind 1 in the US (Global wind energy council 2022). Also, operation and maintenance costs are significantly lower when there are fewer turbines in an offshore wind farm (OWF) due to fewer installation vessel trips and less overall maintenance. However, the significant expansion of the offshore wind industry and the rapid increase in the size and weight of turbine components will certainly amplify the risk issues during the installation and transport of large OWTs. Due to the complex and harsh offshore environment, offshore installation is more difficult and demanding. Moreover, as the available offshore operation window period is limited, installation costs can be significantly higher.

Currently, there are less than 20 wind turbine installation vessels (WTIVs) globally that can support the installation of 10MW+ OWTs (Offshore Construction Associates 2022). In order to meet the surging demand for new advanced large OWT installations, more WTIV companies have announced plans for constructing and upgrading their vessels in the upcoming years (Gucma et al. 2022). However, the market for vessels capable of installing large offshore wind components is quickly being outpaced by growing demand from the global development pipeline. According to the report published prepared by H-BLIX, the demand of WTIVs will peak in 2024 and 2025, and the biggest demand for WTIVs will be between 2028 and 2030 (H-BLIX 2022). These vessels are specifically designed for the installation of large OWTs and consist of many critical subsystems. The failure of any of these subsystems could cause catastrophic damage to the vessel and turbine, even life-threatening. Furthermore, in OWF installation projects, if such a vessel needs to be repaired due to a failure, it is almost impossible to find another vessel on the market as a replacement within a short period of time. This may result in critical delays or even indefinite pauses of the project.

To minimize the likelihood of such events, this paper aims to develop a mathematical model using Petri nets (PNs) to assess the risk and reliability of the mission of a WTIV for installing large OWTs. The mission of the WTIV is segmented into consecutive phases, each of which accomplishes a specified task. With the aid of the PN model developed, critical phases can be identified and their failure probability can be calculated.

2. Offshore Wind Turbines and Vessels for Their Installation

2.1. *10MW+ offshore wind turbines*

To date, most of the newly announced offshore wind farm projects will have turbines that can produce between 8 and 15 MW of power. In 2021, the average offshore wind turbine capacity installed was 7.4 MW, more than double the 3.3 MW in 2011 (Musial et al. 2022). The increase in power comes with an increase in rotor diameter and tower height since winds generally increase as altitudes increase. Over the last decade, the average size of OWTs has increased by 138% and their rotor diameters have increased by nearly 50% to 163 meters in 2020 (Global wind energy council 2022). The power capacities of the latest announced OWT models have exceeded 10 MW, e.g. General Electric (GE) Haliade-X 12 MW, Siemens Gamesa 14 MW (SG 14-222 DD), Ming Yang MySE 16.0-242, Vestas 15MW, etc. (Jiang 2021). However, it should be noted that no OWT with a capacity greater than 10 MW has started commercial operation (as of December 2022). Currently UK Dogger bank is the world's largest offshore wind farm under construction. It will be the first OWF to commercially use GE Haliade-X 12MW turbines whose blade length is 107 meters (Dogger Bank Wind Farm Ltd 2022). All these facts show that the wind industry is trying to increase the size of OWTs at a rapid pace that exceeds expectations. The main reason behind this is that the capacity to generate more energy from a single turbine means that fewer turbines need to be built per wind farm. This means that capital expenditure can be reduced.

However, due to the dramatic increase in turbine size, new challenges have emerged for new wind farm projects. Firstly, large wind turbine components such as blades bring logistical issues. For example, moving such large components will certainly cause traffic disruption on roads. Hence, it is expected that the manufacturing of large components for these turbines should be as close to ports as possible. In addition, there is currently a shortage of ports and vessels to support the installation of these turbines. Furthermore, due to the higher tower and longer blade and the location of the turbines being further away from the land, the installation, maintenance and inspection take longer and become increasingly difficult. In the paper, the potential issues during the installation phase will be studied in detail.

2.2. *Installation process*

The installation cost of an OWF can be affected significantly by various factors such as the type of WTIVs used, the weather and sea conditions, the skill level of the installation teams, etc. (Hernandez C et al. 2021).

Using the installation of wind farms consisting of fixed-bottom OWTs as an example, the whole installation process can be divided into 6 steps (Hernandez C et al. 2021): (1) port logistics, (2) foundation installation, (3) transition piece installation, (4) turbine installation, (5) substation installation, and (6) cable-laying operations. In the paper, we will focus on the fourth step, turbine installation, which is the most important and complex step among the whole installation process to demonstrate how to assess the reliability of the OWT installation process.

A typical OWT has two tower segments, one nacelle, one rotor hub and three rotor blades. In practice, there are several different options for the assembly of these components (Guo, Wang, and Lian 2022). For example, they can be fully assembled offshore. Also, they can either be partially or entirely assembled onshore and then transported to the farm site. Onshore assembly can significantly reduce the complex offshore lifts and the requirements of vessel capacity. As a result, the processing time for the different assembly options also varies. Due to the huge size of 10MW+ OWTs, the full onshore pre-assembly strategy might not be feasible in practice. Therefore, this paper considers the single-blade assembly method, i.e. all the assembly operations are performed on the farm site. This is still the most widely used method as it requires a small load-bearing capacity. However, offshore assembly operations are difficult and inconvenient due to the strong wind and waves.

A turbine installation mission can be divided into six phases, namely (1) loading components onto the WTIV, (2) Sailing to the OWF site, (3) jacking up, (4) installing, (5) lowering down back to the floating level, and (6) Sailing back to the port. The mission can be regarded as successful only when the WTIV is able to operate successfully throughout all the phases without any break due to failures and maintenance. Such a period is known as a maintenance-free operational period (MFOP) (Chew, Dunnett, and Andrews 2008; Yan, Jackson, and Dunnett 2017; Wu and Wu 2015). The duration of each phase listed in Table 1 is either obtained from past literature or estimated based on the information and data about Dogger Bank Wind Farm (Kaiser and Snyder 2013; Rippel et al. 2021; Dogger Bank Wind Farm Ltd 2022).

Table 1. Phase durations

Phase	1	2	3	4	5	6
Duration (hours)	5	8.7	2	72	2	8.7

2.3. *Wind turbine installation vessels*

In 2021, there were only 12 WTIVs capable of installing turbines with capacities greater than 10 MW. To meet the requirements and demands for installing thousands of these large OWTs around the world in the next decade, more shipowners have announced plans to build new WTIVs. Voltaire built by Jan De Nul is a typical example (Jan De Nul Group 2022). In December 2022, its construction was completed, and it left Nantong, China, where it was built. The lifting capacity of its main crane is 3,200 tons. Its four immense legs are 131.94 meters which make it capable of operating in sea depths of 80 meters. This vessel will play a critical role in the installation of 277 monopile GE Haliade-X 12MW turbines at Dogger Bank Wind Farm in the North Sea. The installation is expected to start in 2023.

In this study, the WTIV considered consists of five different subsystems, i.e. one crane system for loading and lifting the turbine components, eight engines as its power plant, four azimuth thrusters for the prolusion, one jack-up system for jacking up and jacking down the vessel, and one electrical system for control, navigation, and communication. Since the failure data of newly built WTIVs is limited, the failure data derived based on the global offshore wind power incident data in 2021 will be used in the study (G+ Global Offshore Wind Health & Safety Organisation 2022). The data is given in Table 2.

Table 2. WTIV subsystem failure rates

Subsystems	Failure rate (/year)
Crane	0.02524
Engine	0.00080
Azimuth thruster	0.00080
Jack-up system	0.02203
Electrical system	0.00275

3. Petri Net Modeling

A Petri net (PN) is a mathematical modelling language that is commonly used in computer science. It has been widely adopted to model a wide variety of complex systems, ranging from software and hardware systems to biological systems. To date, researchers have used it for tasks such as, simulating the behavior of a system, evaluating the reliability of a system, and optimizing the performance of a system.

PN's provide a direct bipartite graphical representation of a system, in which the system's behavior can be analyzed and simulated. It consists of two types of elements: places and transitions. Places are circular, and transitions, shown as squares, are illustrated in Fig. 1. Places represent the resources, materials, or conditions in a system. Transitions represent the actions or events that can change the state of the system. Arrows, known as arcs in PNs, link places and transitions together. Each arc can be given a weight to represent *n* single arcs with the same connections. In a PN diagram, this is indicated by adding a slash to the arc and a number, *n*, next to it. In addition, an arc that features a small circle at one end is known as an inhibitor arc. Such an arc has the ability to impede a transition from firing when it is enabled. Finally, small solid circles represent tokens that carry the information in the PNs.

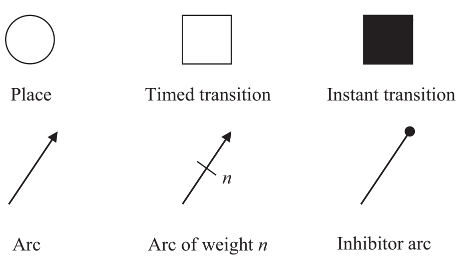

Fig. 1. PN symbols used in this work

A transition is enabled if the number of tokens in every input place is greater than or equal to the corresponding weights of the arcs to the transition. Once a transition is enabled it will fire after the time associated with it. The tokens will be removed from the input places and produced in the output places depending on the weights of the arcs connecting to the transition fired. The movement of the tokens between the places in the net gives the dynamic properties of PNs. The token marking in a PN at a given time shows the state of the system being modelled at that time.

PNs have been adopted to model phased missions of various complex systems (Chew, Dunnett, and Andrews 2008; Yan, Jackson, and Dunnett 2017; Yan, Dunnett, and Andrews 2023). In order to model a phased mission using PNs, three different levels of PNs need to be developed. The first level PN is the subsystem Petri net (SPN), which simulates the health states of each subsystem considered in the study. The second level PN is the phase Petri net (PPN), which simulates the subsystem failure mechanisms that correspond to the failure of a phase. Finally, the third level PN is the mission Petri net (MPN), which governs the change of phases through the mission. These three PNs are linked as illustrated in Fig. 2. The details of the nets are discussed in the following section.

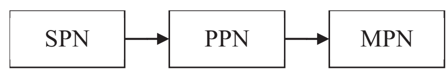

Fig. 2. The overall structure of the PN model

4. WTIV Reliability Model Generation

4.1. *Subsystem Petri net (SPN)*

In Fig. 3, the stochastic deterioration of each WTIV subsystem described in Section 2.3 is modelled using the SPN. Since the mission is regarded as an MFOP in the study, the maintenance process of these subsystems after their failure is considered. Hence, the SPN only shows two kinds of health state, i.e. 'Up' and 'Down', respectively. At the initial token marking of the net, each place indicating the "Up" state of a subsystem is allocated one token. Once a subsystem fails after a certain period of time, the token in the 'Up' place will be transferred to the 'Down' place. The times associated with these transitions can be computed using the random sampling and exponential distribution method based on the failure rate data given in Table 3. It is worth noting that this tier can have a preceding level representing component failures or failure modes if more information and data are available. Once a subsystem fails, the information about the failure will be fed into the PPN.

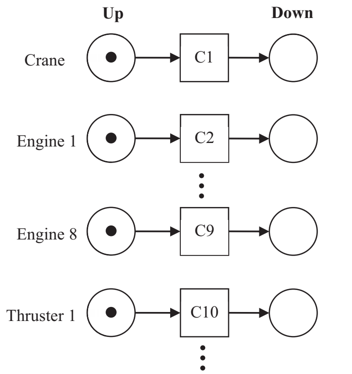

Fig. 3. Subsystem Petri net

4.2. *Phase Petri net (PPN)*

The logic for developing the PPN is the same as developing the fault trees for analyzing the failure of each phase due to subsystem failure. In the study, the PPN is developed for each phase defined in Section 2.2. To ease understanding, the PPN developed for Phase 1, loading components onto the WTIV, is illustrated in Fig. 4 as an example. In the Figure, it can be seen that the failure of Phase 1 may be caused by the failure of the electrical system or the crane. The crane failure will stop the loading of turbine components from the port to the WTIV. On the other hand, the failure of the electrical system will prevent the normal control or function of the crane. The transitions in the PN are instant as the failure of these subsystems will result in the phase failure immediately.

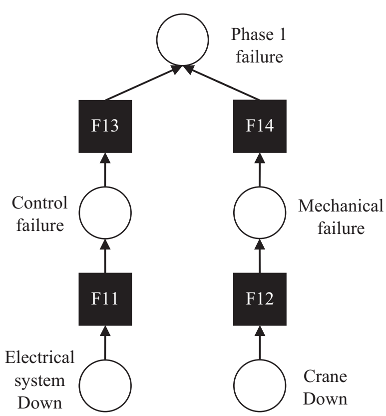

Fig. 4. Phase Petri net for Phase 1

4.3. *Mission Petri net (MPN)*

The MPN governs the change of phases from the beginning of the mission to the successful completion of the whole mission. The structure of the MPN is shown in Fig. 5. To activate the net, a token can be given to the place 'Mission start'. Then the token will flow through the places representing the phase in which the WTIV is operating. The time of each transition between two neighboring phase places is the length of the preceding phase. The system failure happening in each phase, i.e. the top event of the PPN for that phase, will directly result in the failure of the whole mission. Hence, if the WTIV is operating in phase *i* (shown as a token in place 'phase *i*') and the WTIV fails in that phase (shown as a token in place 'Phase *i* PN'), a token will be removed from the phase place and a new token will be given to the place 'Mission failure'. If the vessel completes all six phases without a failure, the mission will end and a new simulation iteration will start.

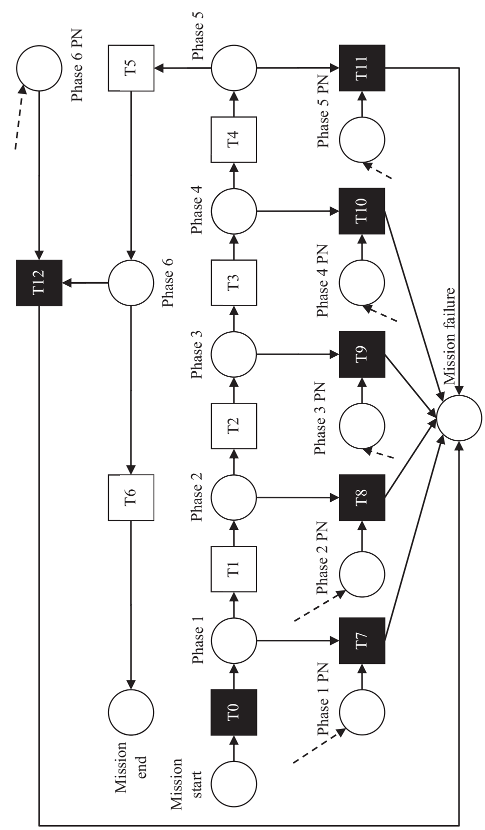

Fig. 5. Mission Petri net

5. Simulation

In order to evaluate the reliability of the WTIV for installing 10MW+ OWTs, the PN models proposed in the previous section can be used for simulation. The model is solved using Monte Carlo simulation and tracking the critical token movements in the nets. The mission phase durations in Table 1 and the failure data in Table 2 are used as inputs for the simulation. As preliminary research, this paper does not consider certain factors that have a substantial influence on the reliability of the WTIV. These factors, such as human errors, various weather conditions, loading capacity of the WTIV, different installation strategies, etc., will be studied in the future by further extending the PN models developed in the paper.

Embedding the PN into a simulation, the phase unreliability and mission reliability can be calculated. Firstly, to demonstrate the methodology, the required number of turbine installations is set to be 1. After running a series of simulations, it was observed that the simulation results converged to stable values after the number of iterations exceeded 40,000. In order to ensure a good convergence of the computing result, 1,000,000 simulations have been performed in the process of this calculation. The results obtained are listed in Table 3. From the results presented in Table 5, it is found that phase 4 'installing' is the most unreliable phase. This means that the WTIV is more likely to fail when it is undertaking installation tasks in the OWF. In addition, it is found that the overall mission reliability is 0.9993619 considering the successful completion of all six phases. This indicates that the WTIV is very reliable for installing a single turbine.

However, the WTIV is often required to install multiple OWTs in an OWF. Currently, the largest fully operational OWF is Hornsea 2 which consists of 165 wind turbines (Ørsted A/S 2022). If the WTIV fails during the installation phase of an OWF project and the vessel cannot be easily repaired, it will result in a significant delay to the project's progress and lead to considerable economic losses. Therefore, to enable the simulation of the WTIV performing multiple OWT installation tasks, modifications have been made to the MPN model. After running the simulation for installing 20 OWTs without maintenance, it is found that the reliability of the WTIV for completing the MFOP is decreased to 0.9871300. This suggests that the method proposed in this paper can help determine the number of OWTs that can be installed in an MFOP before the reliability of a WTIV drops to an unacceptable level, and the optimal inspection and maintenance interval to maintain its high reliability.

Table 3. PN simulation results

Phase	Phase unreliability	Mission reliability at phase end
1	0.0000110	0.9999890
2	0.0000190	0.9999700
3	0.0000430	0.9999270
4	0.0002790	0.9996480
5	0.0001981	0.9994499
6	0.0000880	0.9993619

6. Conclusion

This paper employs the PN method to systematically assess the reliability of WTIVs for the installation of 10MW+ OWTs. The simulation results indicate that the PN method proposed in this paper is a reliable and efficient approach to evaluating the mission reliability of WTIVs, and it can successfully identify the critical phase of the operation. For future work, more detailed subsystems and components, along with their dependencies, will be taken into account in the PN models. For instance, if a WTIV can operate even after the failure of a single engine, the PPN structure must be adjusted accordingly. Additionally, the PN models should incorporate human errors, which can have a significant impact on the failure of OWT installations. Furthermore, the PN models should also consider the impact of complex weather conditions on the safety of turbine installations.

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