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A Data-Driven Multi-Hazard Framework For Resilience Assessment Of Offshore Wind Turbine Decommissioning

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Offshore wind energy is considered as one of the fastest growing sustainable energy sources in the world. In addition to reducing greenhouse gas emissions, offshore wind can provide a reliable source of energy and contribute to energy security. Offshore wind turbines (OWTs) are the main technology used to harness offshore wind power and generate green electricity. OWT infrastructures are often designed for a lifespan of 25 to 30 years, with a possible extension of up to 5 years. Most of the OWT infrastructures that were built during the 1990s and early 2000s have reached, or are approaching, the end of their service lives and are likely to be shut down in the coming years. "Decommissioning" is the last but one of the most important phases of the life cycle of any offshore wind farm project. This phase consists of all activities carried out before, during, and after dismantling of OWTs and their supporting infrastructure and equipment, including foundation structures, transmission cables and electric units. The wind farm assets are disconnected from the grid, the components are dismantled, items left-in-place are buried or marked, and eventually the site is returned to, or as close as possible to, its original state.

Today, "resilience" is not explicitly considered in OWT decommissioning processes. However, with the ageing of OWTs, there is an essential need to safeguard coastal infrastructure and marine environment against any vulnerabilities that may be caused by decommissioning activities, with the aim of increasing the resilience and preparedness of critical entities. To ensure that OWT infrastructures are decommissioned safely and removed from the site with no harm to people, environment, port facilities, or the local ecosystem, a thorough understanding of vulnerabilities, as well as uncertainties, involved in offshore wind decommissioning projects is crucial. This will necessitate the community to define and agree on a set of industry-wide quantitative resilience metrics for future decommissioning projects and design appropriate controls to measure and mitigate the risks to infrastructure.

The OWT decommissioning is a complex and multi-disciplinary process that involves many technical, financial, operational, safety, legal, and environmental evaluations and requires appropriate involvement of "stakeholders" in the decision-making process. Currently, there is very limited data available from a few decommissioned OWTs regarding risks and safety of operations, and hence, the resilience assessment of OWT decommissioning projects is performed in a qualitative and descriptive manner. As the number of decommissioning projects being undertaken globally increases, more detailed data will be expected to become available, and future studies should consider the application of quantitative analysis (such as machine learning and predictive analytics) to resilience modelling of OWT decommissioning.

This paper is the first to undertake a methodical study and analysis of the disruptive events caused by or related to OWT decommissioning, aiming to acquire a profound comprehension of the essential factors influencing the resilience of OWT decommissioning projects and subsequently propose a unified set of metrics for assessing the resilience. We develop a data-driven, multi-hazard framework that integrates quantitative resilience measures, reliability analysis, computational simulations, and machine learning algorithms for the assessment of vulnerabilities and identification of areas at risk from a variety of threats. The analysis involves physical, technical, financial, operational, safety, regulatory, policy, and environmental risks occurring during the dismantling of OWT infrastructure, from the planning and consenting phase through to execution, site clean-up, disposal, and post-decommissioning monitoring stages (Table 1). Our approach relies on advanced risk assessment tools such as 'Fault Tree Analysis (FTA)', 'Bayesian Networks (BNs)' and 'Influence Diagrams', while utilizing the vast amounts of safety and incidents information gathered from multiple sources within the offshore wind energy sector to update/predict the overall resilience of infrastructure and operations (Figure 1).

Table 1. The baseline factors identified to influence the resilience of OWT decommissioning.

	Planning and regulatory compliance	**Execution**	**Disposal and waste management**	**Post-decommissioning**
Physical and Technical	- Inadequate pre-execution surveys	- Structural damage - Electrical damage - Transmission and distribution infrastructure - Dropped loads - Ship collision - Vessel flooding - Loss of towline, cutting, spill, crane damage	- collision - Vessel damage - Detached load (sea fastening)	- Risk from objects left in situ - Post-decommissioning monitoring systems
Regulatory and Operational	- Regulatory approval delays - Contact agreement delays	- Schedule delays - Limited experience of personnel	- Schedule delays - Port facility delays	- Contractual obligation for inspection - Change management
Financial	- Delayed contractual agreements - Regulatory fines - Inaccurate estimations	- Punitive damages - Task overruns - Dropped object - Retrieval cost	- Market fluctuation - Charter cost	- Higher clean-up risks - Future indemnity for items left in place
Policy and environmental	- Environmental approval delays - Policy change risks during approval process	- Environment loads - Natural hazards	- Environment impact	- Environment loads - Natural hazards - Policy change risks for items left in place
People	- Resource planning and workload allocation	- Human errors - Fatality, injury, electrical bums, asphyxiation	- Chemical exposure to human health - Toxic release	- Reassignment / redundancy risks
Objectives	Reliability/risk acceptance , Serviceability , Eco-friendly , Economic efficiency , Life cycle emissions			

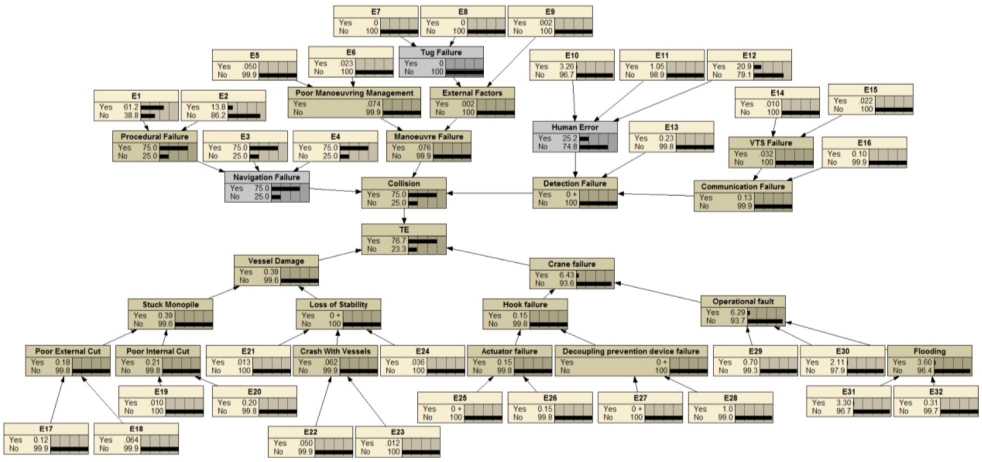

Fig. 1. The proposed BN model for assessing the resilience of OWT decommissioning operations.

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