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Sustainable Marine Structures for Offshore Wind Energy: Failure Modes and Risk Assessment of Turbine Blade Failures-A Case Study of the Dogger Bank Wind Farm

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ABSTRACT

Offshore wind energy plays a critical role in global decarbonization efforts, with large-scale projects being increasingly installed in deep-water and high-wind environments. However, the commissioning phase

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of offshore wind turbines presents unique operational vulnerabilities that remain relatively underexplored in existing risk assessment studies. This research applies Failure Mode and Effects Analysis (FMEA) to investigate the August 2024 failure of an offshore wind farm (North Sea, UK, at the Dogger Bank), one of the first documented commissioning-phase structural failures in a commercial-scale offshore wind project. Six failure modes were identified, evaluated, and ranked using Risk Priority Numbers (RPN) derived from Severity (S), Occurrence (O), and Detection (D) ratings on a 1–10 scale, as defined by established offshore FMEA practice. Blade structural fracture at the root section received the highest RPN of 378 ($S = 9, O = 6, D = 7$), reflecting catastrophic consequences, and the absence of real-time load monitoring during non-operational phases. Pitch system locking ranked second ($RPN = 320, S = 8, O = 5, D = 8$). Root cause analysis identifies the convergence of three primary factors: operational analysis protocols, active load regulation checks, control system limitations during commissioning, and the absence of real-time structural monitoring. A three-layer mitigation framework is proposed: (1) immediate weather-adaptive commissioning controls with threshold limits; (2) redundant pitch control with independent emergency power; and (3) AI-enhanced structural health monitoring during all transitional phases. The findings highlight the importance of phase-specific risk assessment for commissioning, maintenance, and decommissioning stages to reduce operational risk. The proposed FMEA-based approach provides a transferable methodology for risk identification and mitigation in large-scale offshore wind turbine systems.

Keywords: Offshore Wind Energy; Wind Turbine Blade Failure; FMEA; Commissioning Phase Safety; Risk Priority Number; Dogger Bank

1. Introduction

Offshore wind energy has emerged as a foundation stone of the global renewable energy transition, offering high-capacity generation, consistent wind resources, and reduced land-use conflicts compared to onshore installations^[1]. Global offshore wind capacity reached record installations in 2024, with projects expanding into deeper waters and more challenging marine environments to meet decarbonisation targets^[2,3]. While extensive research has examined turbine reliability during normal operational phases, the commissioning phase remains comparatively underexplored, despite presenting unique structural and operational weaknesses^[4]. During commissioning, turbines may be immobilised, partially activated, and undergoing system validation tests, which can expose structural components to unregulated environmental loads such as extreme wind gusts and wave-induced vibrations^[5]. These transitional conditions create loading scenarios that are not fully addressed in conventional operational risk frameworks, highlighting the need for phase-specific

risk assessment approaches for offshore wind infrastructure^[6,7]. Despite major advances in turbine design and construction, the transitional phases of a turbine's lifecycle, particularly commissioning, contain structural vulnerabilities that remain insufficiently characterised in the risk and reliability literature. Among turbine components, rotor blades, pitch systems, drivetrain assemblies, and control systems are particularly in danger, as they are continuously exposed to cyclic low-energy loads and extreme weather events. Blade failures can result in catastrophic damage, prolonged downtime, high repair costs, and serious safety risks to personnel and surrounding marine infrastructure^[8,9]. Despite advances in turbine design and monitoring technologies, recent offshore wind incidents demonstrate that failures continue to occur across different phases of a turbine's lifecycle, including installation, commissioning, operation, and maintenance^[10]. While most existing studies focus on manufacturing defects or failures during normal operation, comparatively limited attention has been given to failures occurring during transitional phases, such as commissioning. During

these phases, turbines may remain powerless for extended periods, limiting their ability to actively regulate aerodynamic loads through pitch and yaw control. Exposure to extreme weather under such conditions can significantly increase structural stress, particularly on

rotor blades. **Figure 1** shows that offshore wind farm performance is influenced by multiple risk categories, including technical, environmental, economic, regulatory, and safety factors, all of which must be carefully considered during design, commissioning, and operation.

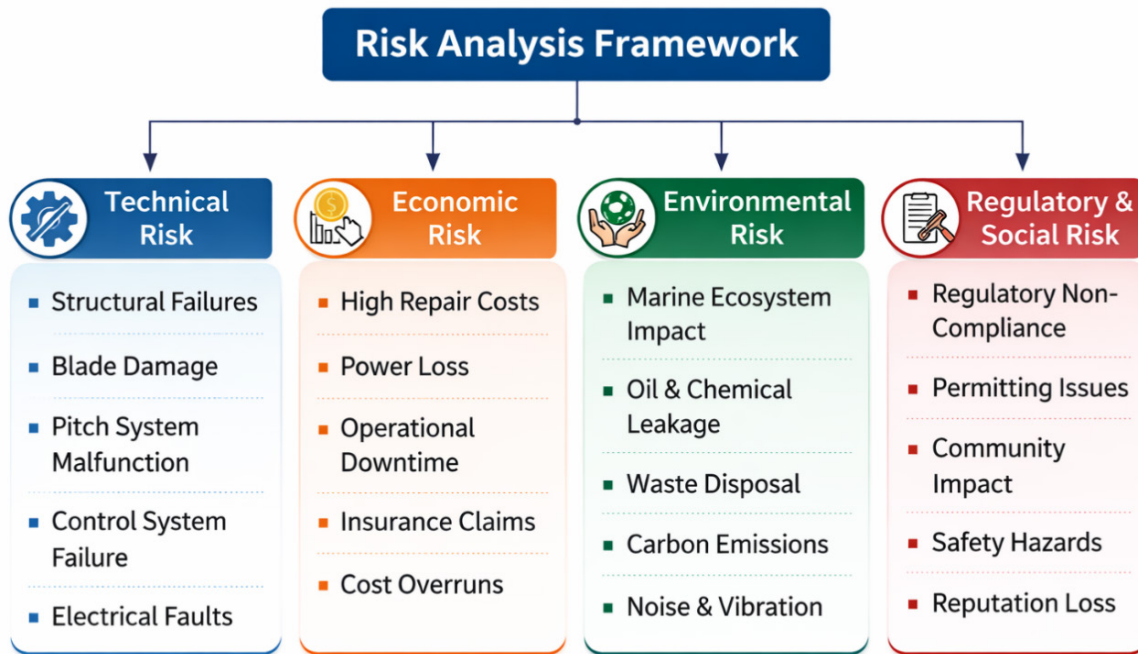


Figure 1. Major operational risk categories for offshore wind farms which influence overall system performance.

Recent studies have studied reliability, hydrodynamic performance, and structural strength in marine infrastructure systems ^[11]. For example, investigations into hydrodynamic behaviour and offshore structural performance have been reported in *Water and Journal of Water Process Engineering*, demonstrating the importance of numerical modelling and experimental validation for marine engineering systems ^[12]. Similarly, research published in *Applied Water Science and Water Resources Management* has examined fluid dynamics and infrastructure performance under complex environmental loading conditions ^[13]. Studies in *Ships and Offshore Structures* and *Innovative Infrastructure Solutions* further emphasise the significance of structural reliability and risk assessment methodologies in offshore engineering applications ^[14]. Despite these advances, most existing research primarily focuses on steady operational conditions or infrastructure design

performance, with limited attention given to transitional operational phases such as turbine commissioning or shutdown conditions ^[15]. Consequently, the structural and operational risks associated with these phases remain insufficiently characterised, particularly for next-generation large-rotor offshore wind turbines ^[16]. Addressing this gap requires systematic risk identification and prioritisation methods that capture phase-specific vulnerabilities, such as the Failure Mode and Effects Analysis (FMEA) approach adopted in this study. This gap is significant, as turbines during these phases face unique stress profiles, procedural complexities, and environmental exposures that differ markedly from normal operation. **Table 1** documents offshore wind failures from 2013–2024, confirming that commissioning-phase structural incidents constitute a recurring but underreported risk category that warrants dedicated analytical treatment.

Table 1. Documented offshore wind turbine system failures and related incidents (2013–2024).

Year	Location/ Project	Turbine Model	Failure Type	Failure Description	Suspected Root Cause	Ref.
2013	Alpha Ventus, Germany	Adwen M5000	Structural (Nacelle)	Rear nacelle casing detached and fell into the sea during operation.	Structural integrity deficiency in nacelle casing design; gearbox issues.	Buljan ^[17]
2015	Horns Rev 1, Denmark	Vestas V80-2.0 MW	Electrical	Internal transformer failures caused prolonged wind farm shutdown.	Electrical/thermal overload; ageing components; insufficient cooling.	GlobalData ^[18]
2016	Gwynt y Môr, UK	Siemens SWT- 3.6-120	Electrical Infrastructure	Repeated subsea export cable faults caused large-scale power outages.	Cable insulation hotspots and thermal degradation.	Power Technology ^[19]
2019	Blyth, UK	MHI Vestas V164-8.0 MW	Structural (Blade)	Blade structural cracking identified during inspection.	Fatigue crack at root-to-cover corner; cyclic loading and storm exposure.	Vestas ^[20]
2020	Fukushima, Japan	Hitachi 5.0 MW	Technical / Economic	Early decommissioning of floating wind demonstrator.	Low capacity factor (~32%); high O&M costs.	Kiyoki et al. ^[21]
2022	Greater Changhua, Taiwan	Siemens Gamesa SG 8.0-167	Fleet Reliability	Fleet-wide inspections due to component quality concerns.	Blade and bearing reliability issues across multiple projects.	Power Technology ^[22]
2023	Vineyard Wind, USA	General Electric (GE) Haliade-X 13 MW	Structural (Blade)	Blade fracture during testing phase.	Manufacturing defect; insufficient adhesive bonding; quality-control gaps.	Memija ^[23]
2024 ★	Dogger Bank A, North Sea, UK	GE Haliade-X 13 MW	Structural (Blade)—Commissioning Phase	Catastrophic blade fracture during commissioning under severe storm (winds >25 m/s, wave height > 6 m). Turbine pitch-locked and immobilised.	Immobilisation + pitch-lock prevented active load regulation during extreme winds. PRIMARY CASE STUDY.	Dogger Bank ^[24] , Lennon ^[25]

The objective of this study is to apply a structured FMEA framework to systematically analyse the Dogger Bank blade failure incident. Specifically, the research aims to:

- Identify root causes and contributing factors of the failure during the commissioning phase.
- Assess the severity, occurrence and detectability of identified failure modes using Risk Priority Number (RPN) ranking.
- Propose targeted risk mitigation strategies to prevent recurrence and enhance the resilience of offshore wind systems during transitional phases.

1.1. The Research Gap

The commissioning phase creates three conditions absent from conventional operational FMEA: (1) turbines are mechanically restrained and cannot perform active load regulation; (2) Supervisory Control and Data Acquisition (SCADA) systems operate in commissioning mode with reduced protective functionality;

and (3) structural health monitoring may not be fully operational. These conditions, combined with the very large rotor diameters of current-generation turbines, create a distinct and unaddressed structural loading scenario. This study presents the first structured FMEA targeting this scenario, grounded in the 2024 Dogger Bank incident.

1.2. Novelty and Key Contributions

Addressing the unique engineering and environmental challenges of pre-operational offshore wind projects, this paper presents a targeted risk assessment, delivering the following key contributions to both academic literature and industry practice

- FMEA specifically targeting a commissioning-phase blade failure at a commercial offshore wind project, extending the methodology beyond its traditional operational focus.
- RPN analysis with S, O, and D scores individually justified based on documented incident evidence,

historical failure data, and applicable design standards (IEC 61400-3, DNV-ST-0145).

- Identification of turbine immobilisation under storm loading as a critically underassessed risk mechanism in large-rotor offshore wind turbines.
- A three-layer prioritised mitigation framework with explicit acknowledgement of implementation barriers (cost, regulatory lag, data sharing, workforce readiness).

2. Offshore Wind Technology

Offshore wind energy has become a foundation of large-scale renewable electricity generation due to its access to stronger, more consistent wind resources and its ability to support high-capacity installations^[26]. Compared to onshore wind farms, offshore projects enable the deployment of significantly larger turbines with higher hub heights and rotor diameters, resulting in improved capacity factor and energy yield^[2,27]. These advantages have driven the rapid expansion of offshore wind farms into deeper waters and more challenging marine environments. The transition from fixed-bottom foundations in shallow waters to floating substructures in deep-water sites represents one of the most significant technological advancements in the sector, enabling development further from shore in regions with superior wind resources but challenging seabed conditions^[28]. Offshore wind turbines are complex, integrated systems consisting of rotor blades, hub and pitch mechanisms, drivetrain and generator assemblies, tower and foundation structures, electrical and control systems, and auxiliary safety components. Each subsystem must operate reliably under continuous exposure to harsh environmental conditions, including high wind speeds, wave-induced dynamic loading, saltwater corrosion, and limited accessibility for inspection and maintenance. These conditions increase the probability of fatigue-related damage, accelerated material degradation, and unexpected failure modes compared to land-based turbines. Rotor blades represent one of the most critical and failure-prone components of offshore

wind turbines. Modern offshore blades exceed 100 m in length and are subjected to extreme aerodynamic loads, cyclic fatigue stresses, and stochastic wind and wave interactions. During normal operation, active pitch and yaw control systems regulate these loads by adjusting blade angles and rotor orientation. However, during non-operational phases such as installation and commissioning, turbines may remain inactive for extended periods, significantly reducing their ability to mitigate environmental loading.

Risk Implications for Fixed-Bottom and Floating Systems Support Structures

Foundation type significantly influences how an offshore turbine responds to environmental loading during standstill. The Dogger Bank A project employs monopile foundations in water depths of 18–63 m. Monopiles are the dominant foundation type for fixed-bottom offshore wind, offering simplicity and cost-effectiveness, but their first natural frequency must be carefully tuned to avoid resonance with wave energy and rotor excitation, a requirement governed by DNV-ST-0126 and IEC 61400-3-1^[29,30]. During commissioning standstill, without rotor-generated damping, the risk of tower-wave resonance is elevated. In contrast, floating foundations (spar-buoy, semi-submersible, Tension Leg Platform—TLP) introduce additional degrees of freedom and platform motion responses. While the Dogger Bank A failure involved a fixed-bottom monopile, the fundamental risk mechanism, pitch-locked blade overloading under storm conditions, applies equally to floating systems, where platform motion additionally amplifies blade root loads during standstill. Mitigation approaches differ between configurations: monopile systems require structural damping and scour protection; floating systems require mooring integrity and platform stability monitoring. **Table 2** summarises foundation types and their comparative risk implications. The failure modes identified in this study are most directly applicable to fixed-bottom configurations, but the FMEA framework is transferable to floating systems with appropriate adjustments to the Occurrence and Severity scores.

Table 2. Overview of offshore wind turbine foundation types and risk implications.

Type	Description	Depth (m)	Stability	Advantages	Disadvantages/Risk Notes	Cost	Ref.
Monopile	Single large-diameter steel tube driven into seabed.	0–30	High	Simple; cost-effective; widely proven.	Limited to shallow waters. Without rotor damping during standstill, wave resonance risk is elevated.	Low–Moderate	Lee et al., 2014 ^[31] , Vishnu and Suren-dran, 2019 ^[32]
Jacket	Steel lattice anchored with piles.	20–80	Very High	Deeper waters; oil & gas pedigree.	High cost. Suitable for commissioning in deeper sites; more stable than monopile under lateral loads.	High	GWEC, 2022 ^[33]
Tripod	Three-legged structure with central joint.	20–60	Stable	Broader base; simpler than jacket.	Limited depth; higher material use.	Moderate	GWEC, 2022 ^[33]
Spar-Buoy	Deep-draft floating cylindrical hull with mooring lines.	>60	Stable (deep)	Minimal seabed disturbance; deep-water capable.	Complex installation. During commissioning standstill, platform surge amplifies blade root bending moments.	Very High	Ibrahim et al., 2022 ^[34]
Semi-Submersible	Floating platform with multiple buoyant columns.	>60	Moderate	Flexible; suits variable depths.	Large anchoring footprint. Platform pitch motion during commissioning standstill increases blade fatigue loading.	Very High	Ibrahim et al., 2022 ^[34]
TLP	Floating hull tethered with vertical mooring lines.	>60	Extremely Stable	Minimal vertical motion; efficient load transfer.	Precise installation required. Most stable floating option during commissioning standstill.	Very High	Petracca et al., 2022 ^[35] , Bashetty and Ozelik, 2021 ^[36]
Tri-Floater (Barge)	Wide-base floating barge with catenary mooring.	>60	Moderate	Simple; cost-effective for deep water.	Less stable than spar or TLP in severe weather. Higher commissioning standstill risk than TLP.	Moderate–High	Kusuma et al., 2024 ^[37]

3. Methodology

The Failure Mode and Effects Analysis (FMEA) framework was used to investigate the 2024 Dogger Bank blade failure incident. FMEA is a proven, bottom-up risk assessment methodology that identifies potential failure modes, evaluates their effects, and prioritises cor-

rective actions based on severity, occurrence, and detectability. The methodology is particularly suited to analysing complex engineering systems, such as offshore wind turbines, where multiple interacting components and environmental factors contribute to overall system reliability. **Figure 2** illustrates the overall risk management methodology applied in this study.

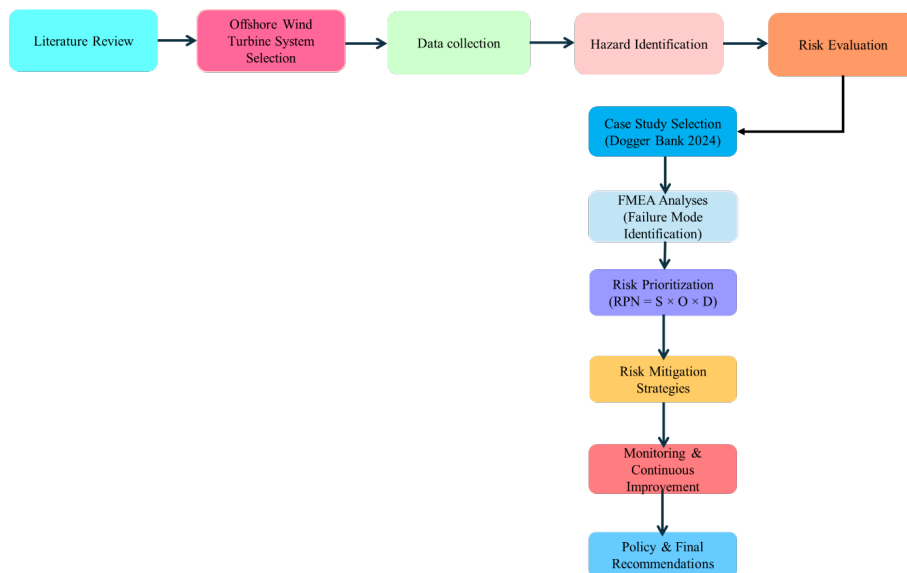


Figure 2. Methodological framework for FMEA-based risk evaluation of offshore wind turbine failures.

3.1. Case Study Selection and Site Description

The Dogger Bank offshore wind farm was selected as the case study due to its scale, technological significance, and the availability of documented failure information. The project is situated in the North Sea, approximately 130–200 km off the Yorkshire coast, UK. The site spans waters 18–63 m deep with monopile foundations supporting GE Haliade-X 13 MW turbines. The North Sea environment is characterised by strong, consistent winds, as well as frequent storm systems that generate significant wave heights and wind loads. The blade-failure incident that occurred in 2024 during

commissioning provides a valuable opportunity to examine risk mechanisms associated with turbine standstill under extreme environmental conditions [38,39]. **Figure 3** shows the geographical location of the Dogger Bank Wind Farm.

3.2. Offshore Wind Turbine System and Data Collection

Several characteristics are carefully balanced in turbine design to maximise energy output, ensure structural integrity, and enable safe operation under variable and often harsh wind conditions. **Table 3** provides full technical specifications of the Dogger Bank project and the GE Haliade-X 13 MW turbine.

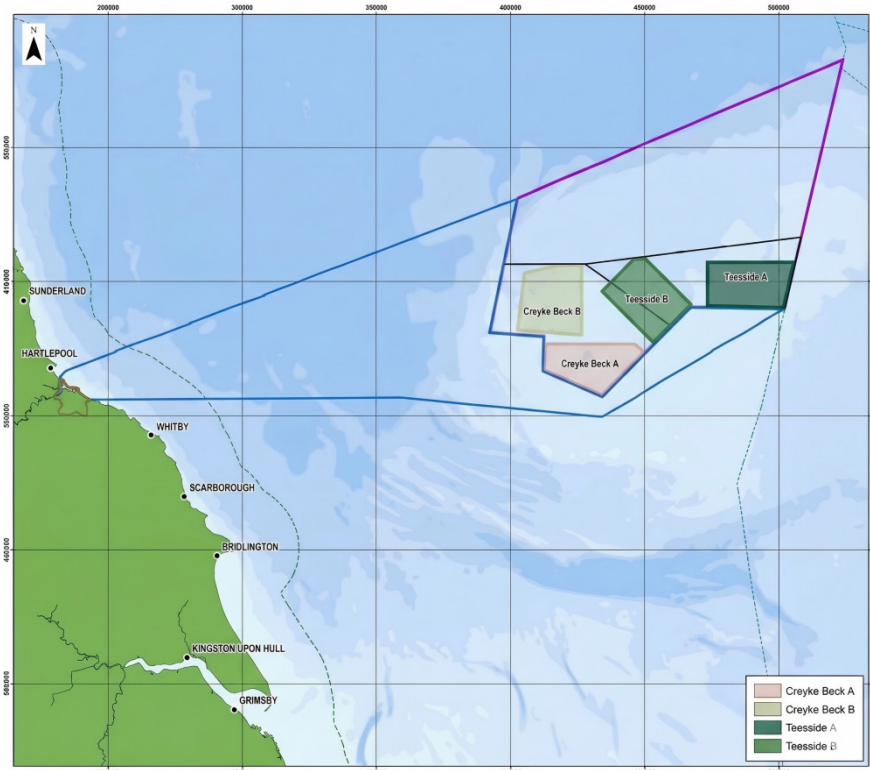


Figure 3. Geographical location of the Dogger Bank Wind Farm in the North Sea [40].

Table 3. Principal technical characteristics of the Dogger Bank wind farm [33,41].

Characteristic	Details
Location	✓North Sea, UK; approximately 130–200 km off the east coast of Yorkshire
Total Capacity	✓3.6 GW (three phases: Dogger Bank A, B, and C, each 1.2 GW)
Number of Turbines	✓277 turbines
Turbine Model	✓GE Haliade-X 13 MW (note: prior draft incorrectly listed as “Halide-X”—corrected here)
Turbine Rated Power	✓13 MW (Phase C variants up to 14 MW planned)
Hub Height	✓Approximately 260 m
Blade Length	✓107 m
Rotor Diameter	✓220 m

Table 3. Cont.

Characteristic	Details
Swept Area	✓~38,000 m ²
Annual Energy Production (per turbine)	✓Approximately 67 GWh
Capacity Factor	✓60%–64%
Water Depth	✓18–63 m
Rated Wind Speed	✓10.5 m/s (23.5 mph)
Foundation Type	✓Monopile with transition pieces (fixed-bottom)
Expected Operational Life	✓Up to 35 years
Project Completion	✓Expected full completion 2026
Power Transmission	✓AC converted to HVDC offshore; transmitted to onshore converter stations
Homes Powered (Estimated)	✓Up to 6 million UK homes annually

3.3. Hazard Identification

Hazard identification was conducted through a systematic review of documented failure evidence from the 2024 Dogger Bank incident^[24,25]. Offshore wind failure analysis and applicable design standards, including IEC 61400-3-1^[42] and DNV-ST-0145^[43]. The analysis focused on failure modes specifically associated with the commissioning phase, characterised by turbine immobilisation, restricted control system functionality, and incomplete structural health monitoring. Five primary hazard categories: (1) blade structural vulnerability under pitch-locked loading; (2) pitch and yaw control system limitations in commissioning mode; (3) SCADA and monitoring system gaps during non-operational periods; (4) tower-foundation dynamic response under storm wave loading during standstill; and (5) procedural and scheduling weaknesses that extend monitoring periods.

3.4. FMEA Rating Scales and Score Justification

Effective risk management is essential for wind installations, especially in offshore settings, where environmental and operational challenges differ significantly from those in land-based systems^[44,45]. Tropical weather patterns, marine corrosion, hydrodynamic stresses, and complex maintenance requirements create unique weaknesses that demand comprehensive risk analysis^[46,47]. This study employs a complementary assessment methodology, Failure Modes and Effects Analysis, for component-level risk prioritisation. S, O, and D ratings were assigned on a 1–10 scale consistent with established offshore engineering FMEA practice, as defined in **Table 4**. Scores were assigned by the re-

search team based on: (1) documented evidence from the 2024 Dogger Bank incident reports; (2) historical failure data from **Table 1**; (3) applicable design standards; and (4) engineering judgement informed by offshore wind FMEA literature. Explicit score justification is provided for each failure mode in **Table 4**^[48–50].

Table 4. FMEA rating scale definitions for S, O, and D (1–10 Scale).

Score	Severity (S)	Occurrence (O)	Detection (D)
1–2	Negligible; no operational impact.	Remote; failure unlikely in service life.	Detection virtually certain; automated alarms active.
3–4	Minor; slight performance degradation; easily recoverable.	Low; isolated occurrences historically.	High probability; detectable by routine inspection.
5–6	Moderate; significant performance loss or partial shutdown.	Occasional; failure occurs in some similar projects.	Moderate; requires dedicated monitoring system.
7–8	High; major system failure; extended downtime; significant repair cost.	Moderately high; documented recurrence in industry records.	Difficult; requires specialised sensor deployment.
9–10	Catastrophic; total component loss; personnel safety risk; multi-million € repair cost.	High; failure expected under defined conditions.	Very difficult or impossible without real-time continuous monitoring.

3.5. FMEA Process Steps

Failure Modes and Effects Analysis (FMEA) is an analytical methodology for identifying potential failure modes within a system, assessing their impact, and prioritising corrective actions based on their seriousness, incidence, and detectability in wind turbine power plants. FMEA is applied to evaluate various system components^[51].

The key steps of FMEA include:

- ✓ Identifying potential failure modes for each com-

ponent of the system.

- ✓ Definition of Risk Assessment Scales: S, O, and D scales were defined as in the Scaling table, consistent with established FMEA practice for offshore engineering.
- ✓ Identification of Failure Modes and Causes: Failure modes for each subsystem were identified based on incident evidence, applicable standards, and engineering analysis of commissioning-phase loading scenarios.
- ✓ RPN Calculation and Ranking: $RPN = S \times O \times D$ for each failure mode. Scores are explicitly justified.
- ✓ Critical Component Identification: Failure modes with $RPN \geq 300$ were classified Critical; $RPN 100\text{--}299$ as High Priority; $RPN < 100$ as Moderate.
- ✓ Mitigation Strategies Proposed: Targeted mitigation measures were developed for each failure mode and organised into a three-layer framework

FMEA provides a valuable tool for spotting weaknesses in wind turbine systems during design and operation. This method allows engineers to strengthen weak points before problems arise. Even minor issues that might seem unimportant at first can create major failures if ignored. FMEA systematically catches these potential failures early, when they're easier and cheaper to fix.

3.6. Risk Prioritisation in Wind Turbine Systems

Risk prioritisation in FMEA assigns comparative importance to identified failure modes based on their RPN scores, enabling targeted allocation of engineering and operational resources. This process ranks failure modes by probability and potential damage severity, allowing teams to focus on the most critical threats first. High-priority risks such as structural failures or electrical faults demand immediate attention, while lower-priority risks may be monitored or addressed later.

3.7. Risk Mitigation Framework

Mitigation strategies in offshore wind FMEA are systematically adapted responses designed to reduce the severity, occurrence, and detectability of prioritised failure modes. For this study, mitigation measures

were developed at three levels: (1) Design Modifications, changes to turbine hardware or control system architecture; (2) Operational Procedures, changes to commissioning protocols, weather management, and scheduling; and (3) Monitoring Enhancements, improvements to real-time sensing, data analysis, and alert systems.

3.8. Monitoring and Continuous Improvement

The final phase of risk management focuses on continuously monitoring and controlling risks while reviewing the system's performance over time. This approach ensures that risk mitigation strategies remain effective and the system operates smoothly under varying conditions. Real-time data monitoring plays a crucial role in this phase, using sensors and data collection systems to track the performance of solar panels and floating platforms, as well as environmental conditions. This includes monitoring structural integrity, energy production, and potential environmental impacts. Predictive maintenance leverages data analytics and machine learning algorithms to anticipate when maintenance is required, preventing unexpected failures. Regular inspections and audits, including physical checks and drone or underwater robot inspections, ensure that mitigation measures are implemented. Incident tracking records failures, near misses, and other incidents, which are analysed to enhance future operations and safety practices.

4. Results

The results are systematically organised to address the identified failure modes, their risk prioritisation, and the corresponding mitigation strategies derived from the analysis. During the commissioning of the Dogger Bank offshore wind farm, a GE Haliade-X 13 MW turbine experienced catastrophic blade failure under extreme storm conditions. The turbine was damaged during system testing and final adjustments when a North Sea storm system generated wind speeds exceeding 25 m/s and significant wave heights over 6 m. **Figure 4** documents the structural damage.

4.1. FMEA Results: Failure Modes, Scores, and Rankings

The FMEA identified six failure modes across the

turbine system. **Figure 5** illustrates the FMEA process flow. **Table 5** presents the complete FMEA, including explicit justification of S, O, and D scores, RPN values, and recommended corrective actions.



Figure 4. Photographic evidence of the Dogger Bank wind turbine blade damage ^[51].

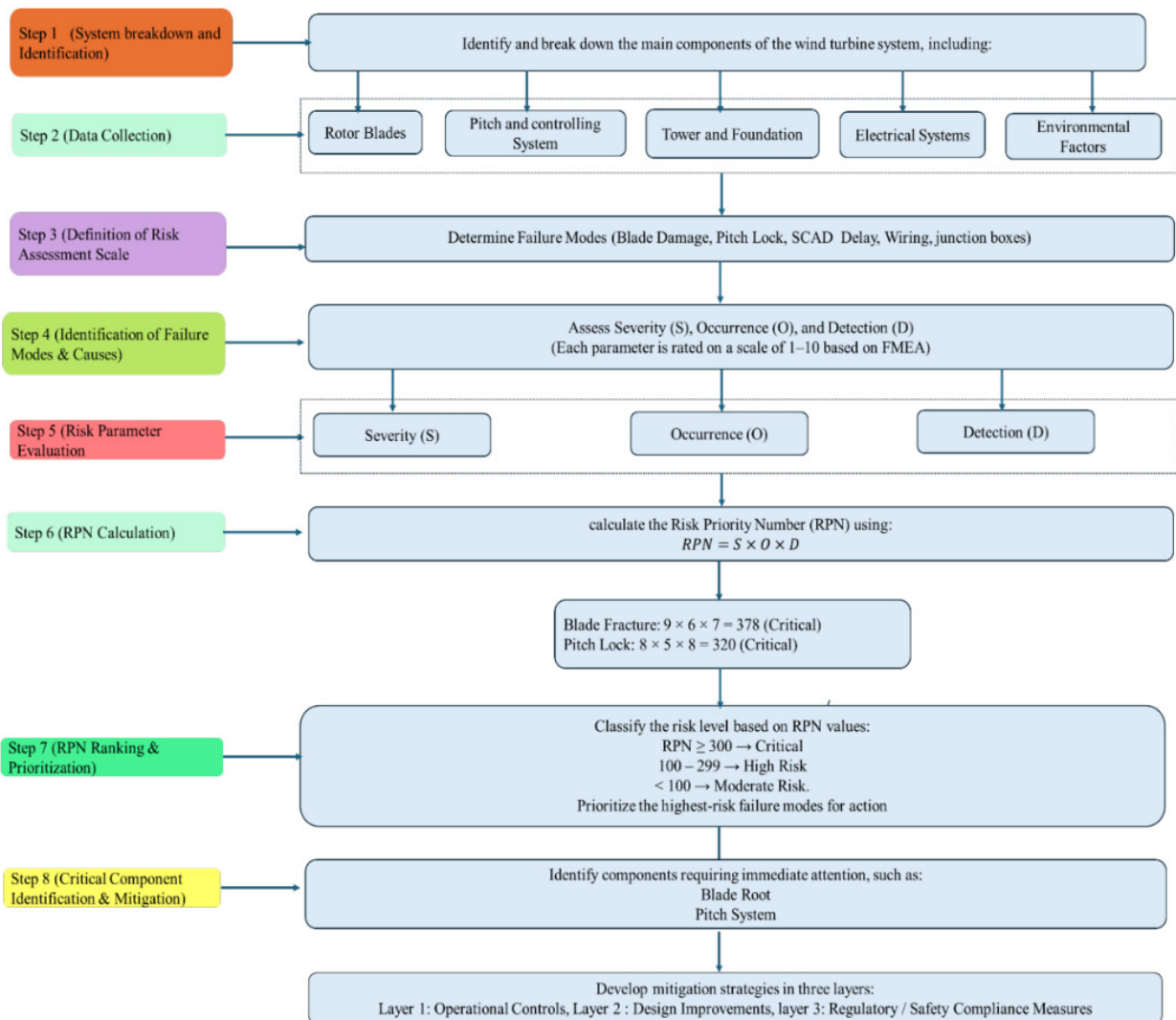


Figure 5. Failure Mode and Effects Analysis (FMEA) for offshore wind turbine failure.

Table 5. Commissioning-Phase Blade Failure (Dogger Bank 2024)—Full S/O/D Justification and RPN.

Components	Function	Failure Mode	Effects of Failure	Root Causes	Current Controls	S	O	D	RPN	Recommended Actions
Rotor Blades	Convert wind energy to rotational motion; withstand aerodynamic loads.	Structural fracture at root section during pitch-locked exposure to extreme wind loading.	Catastrophic blade separation; debris hazard; complete turbine shutdown; multi-million € repair cost.	(1) Turbine immobilised during commissioning; (2) Material fatigue or manufacturing defect; (3) Pitch system unable to feather blade.	Visual inspection; design safety margins; periodic Non-Destructive Testing (NDT) (unavailable during commissioning).	9 Catastrophic loss; personnel safety risk	6 Blade failures documented in commissioning storms (Table 1)	7 No real-time load monitoring during commissioning	378 CRITICAL	(1) Real-time strain monitoring during immobilisation; (2) Weather-based immobilisation time limits; (3) Enhanced root reinforcement per IEC 61400-3.
Pitch Control System	Adjust blade angle to regulate rotational speed and aerodynamic loads.	Lock/failure during commissioning mode; inability to feather blades under storm loads.	Loss of load regulation; overload transmitted to blade root structure; cascading mechanical failures.	(1) Commissioning software override; (2) Emergency power failure; (3) Hydraulic system malfunction.	Control system diagnostics; backup battery (limited duration).	8 Major structural consequence; extended downtime	5 Recurrent across GE Haliade-X platform [16,17]	8 No commissioning-mode pitch system diagnostics	320 CRITICAL	(1) Redundant pitch control logic; (2) Independent emergency power for pitch system; (3) Commissioning-mode load regulation algorithms.
Control & SCADA System	Monitor operational parameters; execute shutdown commands.	Delayed or failed storm-response algorithm during commissioning mode.	Extended exposure to peak loads; missed preventive shutdown window; structural stress accumulation.	(1) Commissioning mode limitations; (2) Weather data integration lag; (3) Algorithm threshold miscalibration.	Standard storm protocols (operational mode only); manual override capability.	7 High consequence; major structural stress	4 Occasional; software miscalibration documented in industry	6 Manual monitoring only; no automated commissioning alarms	168 HIGH	(1) Phase-specific control algorithms; (2) AI-enhanced weather prediction integration; (3) Automated escalation procedures.
Tower & Foundation	Support turbine structure; transfer loads to seabed.	Dynamic amplification/resonance under storm wave loading during standstill.	Accelerated fatigue damage; reduced structural lifespan; potential foundation settlement.	(1) Monopile natural frequency proximity to wave spectrum; (2) Soil-structure interaction; (3) Corrosion weakening.	Foundation design standards (DNV-ST-0126, IEC 61400-3); periodic underwater inspections.	6	3 Low; well-managed by design standards	7 Requires specialised sonar/inspection	126 HIGH	(1) Enhanced structural damping systems; (2) Real-time vibration monitoring; (3) Predictive corrosion management.
Commissioning Procedures	Safe transition from installation to operation.	Extended immobilisation without load mitigation due to weather delays or resource constraints.	Increased probability of storm encounter; prolonged vulnerability; cumulative fatigue damage.	(1) Weather delays in schedule; (2) Resource availability constraints; (3) Procedural conservatism extending immobilisation.	Weather window planning; project schedule buffers.	7	5 Recurrent commissioning delays documented in offshore projects	3 Weather forecasting provides advance notice; detectability is higher	105 MODERATE	(1) Dynamic commissioning scheduling; (2) Minimum-safe-configuration protocols; (3) Rapid-response team mobilisation.
Structural Health Monitoring (SHM)	Detect stress accumulation and early damage during all turbine phases.	Failure to identify critical load buildup during commissioning immobilisation.	Undetected failure progression; missed preventive action; false security from monitoring gaps.	(1) Sensor calibration drift; (2) Inadequate sensor coverage during commissioning; (3) Data interpretation delays.	Periodic validation; manual data review (post-event only).	6	4 Occasional; sensor gaps common during commissioning	4 Inspections possible but not continuous	96 MODERATE	(1) Automated anomaly detection; (2) Expanded sensor networks on blade roots and tower; (3) Real-time dashboards with alert thresholds active during commissioning.

4.2. Root Cause Analysis of the 2024 Dogger Bank Blade Failure

The 2024 Dogger Bank blade failure resulted from the convergence of three primary and mutually reinforcing root causes. First, operational immobilisation protocols required the turbine to remain in a pitch-locked, parked configuration during commissioning, preventing any active aerodynamic load regulation. Under North Sea storm conditions generating sustained winds exceeding 25 m/s, the 107 m blades experienced root bending moments that significantly exceeded the

design fatigue envelope. Second, control system limitations during commissioning mode prevented the execution of standard storm-response algorithms. The SCADA system in commissioning configuration lacked access to the full operational protective shutdown logic [52]. Third, the absence of real-time structural load monitoring during commissioning meant that progressive stress accumulation in the blade root went undetected until catastrophic fracture. These three factors are not independent: absent monitoring prevented detection; control system limitations prevented automated response; and immobilisation protocols ensured contin-

uous exposure throughout the storm. Their interaction represents a systemic vulnerability not captured in conventional operational FMEA.

It is important to note that this incident directly involves the GE Haliade-X platform, which experienced a related blade failure at Vineyard Wind, USA in 2023^[53,54]. The Vineyard Wind failure was attributed to a manufacturing defect, while the Dogger Bank failure was due to a commissioning-phase protocol issue. These distinct root cause paths on the same turbine platform suggest both a design-level review requirement for the GE Haliade-X blade configuration and the importance of site- and phase-specific risk assessment.

4.3. Integrated Mitigation Framework

Based on the FMEA results, an integrated mitigation framework is proposed comprising three layers, prioritised by urgency and implementation complexity:

Layer 1: Immediate Operational Measures (0–6 months)

- Weather-based analysis and time limits: Establish maximum continuous monitoring periods (72 h) with mandatory safe-configuration protocols if forecast wind speeds exceed defined thresholds (recommended: 15 m/s sustained). This directly addresses the root cause of extended pitch-locked storm exposure.
- Any turbine in commissioning mode must be placed in minimum-load configuration with enhanced monitoring when national meteorological storm warnings are active for the project site.
- Real-time data from site-specific weather buoys must feed into commissioning scheduling decisions, with a daily meteorological review by a qualified offshore meteorologist during all active commissioning periods.

Layer 2: Short-Term Design and Engineering Modifications (6–24 months)

- A battery-backed emergency pitch actuation system capable of full blade feathering, independent of grid power and main hydraulics, must remain operational in commissioning mode. Compliance

with IEC 61400-1 safety system requirements is mandatory.

- Reprogram SCADA commissioning mode to include storm-response algorithms equivalent to those in operational mode, including automated feathering commands and manual override capability available to onshore operators at all times.
- For next-generation turbines, review root section composite lay-up and adhesive bonding specifications under pitch-locked storm loading as a distinct design load case per IEC 61400-3 Ultimate Load requirements^[55,56].

Layer 3: Long-Term Regulatory and Industry Actions (2–5 years)

- Mandatory phase-specific FMEA: Require commissioning-, maintenance-, and decommissioning-phase FMEA as part of project certification, with weather management plans as a specific required deliverable.
- Require continuous blade root strain and tower vibration monitoring during commissioning, with data transmitted to onshore monitoring centres and automated alert thresholds active regardless of turbine operational status.
- Industry-wide incident reporting database: Establish a mandatory anonymised database for offshore wind commissioning incidents, analogous to the aviation ASRS system, to enable cross-project learning and prevent recurrence. This is especially critical given the second similar incident at the same turbine platform within two years.

4.4. RPN Summary and Priority Classification

Following the detailed assessment of individual risk factors, the calculated Risk Priority Numbers (RPN) establish a quantitative hierarchy of critical vulnerabilities for the commissioning phase. As shown in **Table 6**, the RPN-based ranking enables clear prioritisation of failure modes and aligns corresponding mitigation measures with their required implementation timelines.

Table 6. RPN ranking summary, priority classification, and mitigation implementation timeline.

Failure Mode	S	O	D	RPN	Class	Primary Mitigation	Implementation Layer
Blade Structural Fracture	9	6	7	378	CRITICAL	Weather immobilisation limits; real-time SHM deployment	Layer 1 (immediate) + Layer 2
Pitch System Lock	8	5	8	320	CRITICAL	Independent emergency pitch power; commissioning-mode control logic	Layer 2 (6–24 months)
SCADA System Delay	7	4	6	168	HIGH	Phase-specific algorithms; AI weather prediction	Layer 2
Tower/Foundation Resonance	6	3	7	126	HIGH	Structural dampers; vibration monitoring	Layer 2
Commissioning Procedures	7	5	3	105	MODERATE	Dynamic scheduling; minimum-safe-configuration	Layer 1 (immediate)
SHM Gaps	6	4	4	96	MODERATE	Automated anomaly detection; expanded sensors	Layer 2–3

4.5. Limitations and Future Research Directions

- The analysis is based on a single incident, which, while representative of a broader failure class, limits statistical generalisation. RPN Occurrence values are subject to revision as more commissioning-phase incident data become available through the proposed industry database.
- Some root cause allocations are based on press reporting and publicly available incident documentation rather than direct access to turbine SCADA data or forensic engineering reports, which were not publicly available at the time of writing.
- Despite explicit justification for each score, FMEA inherently contains subjective elements. Future research should apply fuzzy-FMEA or Bayesian RPN approaches to quantify scoring uncertainty. Expand FMEA applications to decommissioning and major maintenance phases. Develop quantitative probabilistic risk assessment models for transitional phases
- The Dogger Bank A configuration is a monopile-founded fixed-bottom turbine. Floating offshore wind systems present additional failure modes not fully captured in this analysis.
- Investigate advanced monitoring technologies (e.g., fibre optics, acoustic emission) for real-time structural health assessment
- Explore regulatory frameworks for mandatory phase-specific risk assessments in offshore wind projects.

5. Discussion

The blade failure observed during the Dogger Bank commissioning phase can be explained through the interaction between environmental loading and operational constraints imposed during turbine immobilisation. During commissioning, turbines are often placed in a locked or partially active state while system verification procedures are conducted. Under such conditions, the pitch system may be unable to actively regulate aerodynamic loads. Consequently, extreme wind gusts can generate significant bending moments and cyclic stresses at the blade root region, which is already a critical structural junction between the rotor blade and hub assembly. When turbines remain immobilised during high-wind conditions, aerodynamic loads cannot be redistributed through normal pitch adjustments, resulting in localised stress accumulation and increased structural fatigue risk. In addition, turbulent atmospheric conditions in offshore environments can induce rapid load fluctuations and asymmetric aerodynamic forces across the rotor plane, further amplifying stress concentrations at structural interfaces. Similar cause-and-effect relationships between environmental forcing and infrastructure performance have been reported in recent hydrodynamic and marine engineering studies, where complex environmental interactions significantly influence structural response and system reliability. These findings demonstrate that failure mechanisms in offshore wind systems are not solely component-based but are often driven by the combined effects of environmental loading, operational constraints, and control system limitations, emphasising the need for integrated risk assessment during tran-

sitional operational phases. Island nations have taken several practical steps to support and promote offshore wind energy projects, particularly in areas with significant potential for large-scale offshore wind farms. For example, the UK government has implemented supportive policy frameworks, including the Contracts for Difference (CfD) scheme ^[57], which provides long-term price stability for renewable electricity generation and encourages private investment in offshore wind projects such as the Dogger Bank wind farm. In addition, regulatory bodies have established streamlined marine spatial planning and environmental permitting processes to facilitate project approval while ensuring environmental protection. The International Renewable Energy Agency (IRENA) plays an important role in global policy coordination for offshore wind, publishing guidance on cost reduction, safety improvements, and regulatory harmonisation. IRENA's "Offshore Renewables: An Action Agenda for Deployment" (2021) ^[43,58], identifies risk management during installation and commissioning as a key area requiring enhanced international cooperation. The Global Wind Energy Council (GWEC) "Global Wind Report 2024" ^[3]. Similarly, it identifies commissioning delays and weather-related installation risks as increasing concerns as turbine sizes grow. Furthermore, government-supported infrastructure development, including grid expansion, port upgrades, and transmission network improvements, has played a critical role in enabling the integration of large offshore wind capacities into national energy systems. Public funding and research initiatives have also been directed toward improving offshore wind technologies, operational safety, and risk management strategies ^[59]. These governmental initiatives not only accelerate the deployment of offshore renewable energy but also strengthen energy security, reduce carbon emissions, and support the long-term sustainability of island and coastal energy systems.

6. Conclusion

This research presents a structured Failure Mode and Effects Analysis (FMEA) of the 2024 blade failure at the Dogger Bank A offshore wind farm. Serving as the

first FMEA to explicitly target a commissioning-phase structural failure at a commercial offshore wind project, this analysis yields the following four key conclusions:

- First, the commissioning phase creates a distinct and systematically unaddressed structural loading scenario. Pitch-locked turbines with 107 m blades exposed to North Sea storm conditions experience root bending moments that can exceed design load envelopes without the protective load regulation available during normal operation. This mechanism is absent from conventional FMEA frameworks and from current design load case standards, and must be explicitly incorporated into project risk assessment requirements.
- Second, the 2024 blade failure resulted from the interaction of three systemic weakness immobilisation protocols, commissioning-mode control limitations, and absent real-time SHM — rather than any isolated component defect. Addressing these factors individually will be insufficient; only an integrated, phase-specific risk management approach can adequately address the combined exposure.
- Third, quantitative RPN analysis identifies blade structural fracture (RPN = 378) and pitch system locking (RPN = 320) as critical failure modes requiring immediate action, with an average Detection score of 5.8 across all failure modes, indicating a systemic monitoring gap during commissioning. Reducing this monitoring gap by mandating real-time monitoring across all transitional phases is the industry's highest-leverage single action.
- Fourth, the three-layer mitigation framework proposed immediate operational measures, short-term design modifications, and long-term regulatory actions, providing a prioritised and feasible implementation pathway for turbine operators, manufacturers, and regulators. Implementation barriers, including cost, regulatory lag, data-sharing constraints, and workforce readiness, are explicitly acknowledged and must be addressed through coordinated industry and regulatory action.

- The FMEA framework developed here is directly transferable to other large-rotor offshore wind platforms and project configurations.
- As rotor diameters continue to increase and offshore projects expand into more extreme environments, phase-specific risk assessment during commissioning, maintenance, and decommissioning will become not merely best practice but a prerequisite for safe offshore wind operations at scale.
- Regulatory authorities should require phase-specific risk assessments as part of project approval processes, moving beyond current requirements that primarily address operational safety.
- Demonstrates the effective application of FMEA to commissioning-phase failures in offshore wind systems, extending the methodology beyond its traditional applications in operational reliability.

Author Contributions

Conceptualisation, K.S.; validation, C.E.; investigation, C.E. and S.S.P.; writing—original draft preparation, N.K.; writing—review and editing, M.R.M. and K.S.; visualization, C.E.; supervision, M.R.M. and K.S.; project administration, S.S.P.; funding acquisition, M.R.M. and S.S.P. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest regarding this publication.

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The authors utilise generative AI tools, such as Scopus AI, to identify relevant references, and Grammarly, Claude, and Microsoft Copilot, to enhance sentence clarity, grammar checking, sentence structure refinement, and improve the readability of the English text in this manuscript. After using the tools, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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