Technology Collaboration Programme
by iea

August 2025

IEA Wind TCP Task 49

Failure Risk Evaluation of Floating Offshore Wind Turbines with Farm-Level Implications

iea wind

Prepared for the

IEA Wind TCP

August 2025

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IEA Wind TCP functions within a framework created by the International Energy Agency (IEA). Views, findings, and publications of IEA Wind do not necessarily represent the views or policies of the IEA Secretariat or of all its individual member countries. IEA Wind is part of IEA's Technology Collaboration Programme (TCP).

Acknowledgments

This report is an output of the International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) Task 49 on Integrated Design of Floating Wind Arrays. Considering the collective approach of IEA Tasks, this report stems from the discussion and ideas of many individuals within an international environment. We sincerely appreciate the involvement of all participants in Task 49 Work Package 3, as well as the additional feedback from other contributors to Task 49 and experts who contributed to our database. In addition, we gratefully acknowledge the contributions and discussions from Nikolay Dimitrov, Zahra Mojirinejad, and Marie-Antoinette Schwarzkopf; the contribution of Greg Bohan from Gavin & Doherty Geosolutions (GDG) for his participation in the initial FMEA meetings and the FMEA survey; and the input during final review from Monica Maher, Frank Lemmer, and Matthew Hall.

The contribution from Emmanuel Persent was supported by ADEME, the French Agency for Ecological Transition.

The Sustainable Energy Authority of Ireland provided financial support for Mitra Kamidelivand's contribution and Greg Bohan's inputs through the SEAI Research, Development & Demonstration Funding Programme 2022, Grant number 22/RDD/804.

The contribution from Rune Schlanbusch received funding from the Norwegian Research Council, ImpactWind SouthWest, project number 332034.

List of Acronyms

AC	Alternating Current
CPS	Cable Protection System
D	Detection
DC	Dynamic Cable
DPS	Dynamic Positioning System
FF	Floater Failure
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FOWA	Floating Offshore Wind Array
FOWT	Floating Offshore Wind Turbine
GW	Giga Watts
IDeA	Integrated Design of Floating Wind Arrays
IEA Wind TCP	International Energy Agency Wind Technology Collaboration Programme
IM	Importance Measure
IQR	Inter Quartile Range
MRR&I	Mooring Reliability, Redundancy and Integrity
MW	Mega Watts
O	Occurrence
OTEC	Ocean Thermal Energy Conversion
O&M	Operations & Maintenance
OPEX	Operational Expenditure
OWF	Offshore Wind Farm
RBI	Risk Based Inspection
RPN	Risk Priority Number
S	Severity
SOV	Service Operation Vessel
SKS	Station Keeping System
TLP	Tension-leg Platform
WFO	World Forum Offshore Wind
WP	Work Package

Executive Summary

This report has been prepared within Work Package (WP) 3 of the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 49 on Integrated Design of Floating Wind Arrays (IDeA). Task 49 is an international collaboration that offers open-access resources for research and development with the goal of facilitating the development of large-scale floating wind farms. Task 49's work includes examining array-level issues pertaining to the co-location of multiple floating wind turbines, such as their cabling, mooring, and layout systems; failure risks; logistical issues; the need of marine spatial planning; and potential avenues for future research. Task 49 is a four-year initiative that started in December 2021 and involves representatives from 12 nations' research institutes, universities, consultancies, technology providers, project developers, and regulatory bodies. The goals of its four WPs are as follows:

- WP1: Curate a set of site conditions representative of the global floating wind pipeline
- WP2: Develop reference array designs for typical site conditions and technology types
- WP3: Catalogue array-level failure risks, consequences, and mitigation strategies
- WP4: Identify critical innovation opportunities and marine spatial planning requirements.

The array-level component failure risk analysis presented in this report is the first major output of WP3. It provides a detailed description of the structural and substructural component failure modes with potential farm-level effects using the Failure Modes, and Effects Analysis (FMEA) approach. The identified potential farm-level failure modes require attention for effective failure mitigation to enhance reliability and reduce the operation and maintenance (O&M) costs of floating wind arrays. The FMEA survey incorporated data from an extensive literature review of all potential failure modes. These were discussed among WP3 participants during two workshops. In the first workshop, the FMEA survey, data, and methods were introduced. Participants engaged in discussions to clarify the failure modes, their scoring criteria, and whether the failure modes had farm-level implications. This enabled them to complete the FMEA survey for the initial preliminary FMEA results. The preliminary FMEA results were presented to WP3 participants in the second workshop, where participants finalized the FMEA survey. This concluded the FMEA survey for this report.

In addition, a literature-based review of annual failure rate data for floating offshore wind components has been carried out to support the operation expenditure (OPEX) modelling in WP2. As no commercial-scale floating projects are yet available for long-term failure rate analysis, the findings are derived from a small number of published reports and peer-reviewed studies that rely primarily on expert judgment and extrapolations from fixed-bottom offshore wind systems. While the sample size is limited, these estimates offer useful insights into expected reliability challenges in floating wind development.

Array-level failure mode risk analysis

The study focuses on identifying failure modes in floating offshore wind turbine arrays (FOWA) using a semi-quantitative FMEA approach. The objective is to assess the potential farm-level consequences of these failures and propose mitigation options. FMEA incorporates tools like Risk Priority Numbers (RPN) to quantify and prioritize failure modes based on their likelihood, severity, and detectability. This prioritization provides actionable insights for addressing the most

critical failure modes that might lead to cascading effects within the array. The results can serve as a framework for probabilistic risk analysis. While mitigation recommendations are not included in this phase of the study, they will be addressed in subsequent stages of WP3 work.

The FMEA includes five subsystems essential for the installation, operation, and maintenance of the wind farm: the floater (the floating structure that supports the wind turbine), the tower (the structure that holds the turbine above the floater), the transition piece (which connects the tower to the floater), station keeping (the mooring systems that keep the floater in place), and dynamic cables (the cables that transmit power from the turbines to the shore or offshore substations). These structural and substructural components are chosen as they form the critical infrastructure that ensures the stability, connection, and functionality of the entire wind farm. They are highly impactful subsystems specific to floating offshore wind farms and are more likely to create cascading failures across multiple turbines. A mooring line breakage, for example, might destabilize the floater, potentially affecting adjacent turbines, whereas a failure in the rotor or blade of a single turbine is generally limited to that turbine.

Since the detailed subsea architecture reference designs from WP2 (reference floating wind farm design) were unavailable at the start of WP3, the team defined a base case to guide the review of failure modes at the component level. The base case includes the IEA Wind turbine 15-MW reference floating wind turbine, a VolturnUS semi-submersible, catenary mooring design, a uniform water depth of 200 m, a generic seabed with no specific soil conditions, an aligned array layout in two main directions, a lazy wave cable configuration, and the site conditions of the Havbredey floating site in Scotland.

The RPN of each failure mode at the component level, as well as the RPN of failure modes with farm-level implications for each of the subsystems, are calculated by multiplying their scores of Severity (S), Occurrence (O) and Detection (D). However, the report focuses largely on the failure modes with potential farm-level ramifications. Their selections are based on the qualitative opinions of seven participants about component failures that may have an impact on the farm. If so, the rankings determined the risks.

There are 120 failure modes identified at the component level for the five subsystems (tower, floater, transition piece, station keeping, and dynamic cable) and the associated failure causes (environmental factors, design, operation, maintenance, installation, and manufacturing issues). From these failure modes, 20 are specified with farm-level implications:

- Tower Subsystem (RPN 126): Out of 23 failure modes, only 3 (13%) can impact the farm. The main failure mode (over 70% of RPNs) is tower cracks, caused by high waves, wind, or blade interactions, followed by plastic deformation failure due to design errors.

- Transition Piece Subsystem (RPN 153): Among 21 failure modes, 5 (24%) can affect the farm. The primary issue is cracking or breaking, with causes including climate change (40%), design errors (42%), and poor maintenance (18%).

- Floater Subsystem (RPN 355): Out of 30 failure modes, 12 (40%) can impact the farm. Design errors cause 35% of failures (capsize 18%, break 9%, sinking 8%). Operational failures account for 33% (fatigue 12%, cable connector damage 9%, extreme temperatures

6%, collisions 6%). Environmental factors cause 23% (typhoons, severe wind/waves, climate change). Poor maintenance quality causes 10%, leading to structural fractures and welding damage. Key failure modes include cracks, capsize, breakage, and sinking.

- Station Keeping (Mooring) Subsystem (RPN 299): Of 22 failure modes, 10 (46%) can affect the farm. Mooring line (ML) breakage and damage, due to wear, fatigue, friction, tension, corrosion, and poor materials, account for around 68% of the subsystem farm-level RPN. Mooring line winch failure, fairlead, and anchor failure during operation are responsible for the remaining 32% of RPN.

- Dynamic Cable Subsystem (RPN 448): Half of the 32 failure modes can impact the farm. Key issues include Cable Protection System (CPS) movement, cable fatigue, watertightness failures, conductor failures, hang-off damage, j-tube termination failures, reduced sediment, and debris disturbance. Design errors account for 43% of the dynamic cable RPN, followed by operational failures (31%), improper installation (10%), poor quality of insulating fluids during manufacturing (12%), and 10% environmental factors (floating debris and marine activities).

Use of farm-level failure mode analysis

FMEA data identifies critical failure modes with farm-level effects, such as the movement of the CPS due to incorrect installation, which can make the cable vulnerable to scour and require repair or replacement. FMEA data can also be used to provide failure mitigation recommendations, such as improved installation procedures, regular inspections and maintenance, additional protection measures, and monitoring techniques (e.g., fiber optic sensors) for the CPS movement failure mode. To model probabilistic risk analyses, a proposed Bayesian network probability analysis is conducted using an example of a 10-turbine wind farm. When the reference floating wind farm design and configurations are available from WP2, the proposed probabilistic risk analyses will be explored for all farm-level failure modes obtained from FMEA.

This failure risk analysis contributes to building confidence among stakeholders, investors, and insurers by demonstrating an understanding and management of potential risks. It also informs decisions on design modifications, operational strategies and maintenance planning, while identifying areas for further research to enhance system reliability and safety strategies.

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1. Introduction

International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 49 on the Integrated Design of Floating Wind Arrays is an international collaboration aiming to advance the development of large-scale floating wind farms by providing resources to the research and development and planning communities. As floating wind technology expands to larger scales and a wider range of site conditions, the industry faces a set of unique challenges to scale from existing demonstration projects to commercial-scale floating arrays. These challenges are not constrained to individual turbine systems, but instead encompass multidisciplinary considerations, including the mooring, anchor, and cabling design; array layout optimization; installation and operational logistics; environmental and marine spatial planning impact; and failure modes and analysis for utility-scale floating wind projects. Considering holistic design principles from the earliest stages of the industry will streamline the growth of cost-effective, globally deployed floating wind projects.

Task 49 is a 4-year effort that began in December 2021. The task aims to facilitate solutions to some of the challenges mentioned above by developing open-access reference information and designs. The task will provide baseline tools and data for the research community, including reference site conditions, reference array designs and toolsets, an array-level risk assessment framework, and a register of major research and planning questions faced by the industry. Combining these resources into a unified repository will help provide a standardized foundation for future innovation, development, and industrialization of floating wind projects worldwide. Task participants include representatives from project developers, technology providers, universities, consultants, regulatory agencies, and research institutions from 12 countries, which enable a global perspective on the questions facing the industry.

Task 49's four work packages (WPs) focus on specific areas of need, with the following objectives:

- WP1: Curate a set of site conditions representative of the global floating wind pipeline
- WP2: Develop reference array designs for typical site conditions and technology types
- WP3: Catalogue array-level failure risks, consequences, and mitigation strategies
- WP4: Identify critical innovation opportunities and marine spatial planning requirements.

The wind industry is entering new stages as the floating offshore wind technology advances into its commercial phase. With this transition comes the need to scrutinize the unique failure risks present in the floating wind arrays. Floating arrays will encounter a new range of failure modes previously unexperienced by other technologies, encompassing not only the turbines themselves but also the floating platform and its moorings, anchors, and dynamic power cables. Furthermore, the scale of floating wind arrays, unprecedented in other offshore industries, magnifies the likelihood of failures and amplifies the potential for array-wide impacts. Against these conditions, a comprehensive understanding of failure risks becomes crucial for the successful commercial deployment of floating wind technology.

As no large-scale floating wind projects currently have been commissioned (as of July 2025) the largest one is Hywind Tampen, Norway, rated 88MW and Green Volt, Scotland, the largest

consented targeting 560MW) establishing baseline design parameters and understanding the occurring failure risks to share with the industry will contribute to the acceleration of commercial-scale deployment of floating wind arrays

Compared to bottom-fixed offshore wind and traditional offshore oil and gas sectors, floating wind technology remains at an earlier stage of development. The floating wind industry will benefit from better design tools, data sets, benchmarks, and methodologies. An array-level design approach, involving coordinated consideration of platform spacing, cable layout, and mooring strategies, could help enable more efficient and cost-effective projects. However, failure modes and mitigation strategies are not well known. Thus, technological innovations are required to achieve cost-effective projects. This initiative focuses on international collaboration and data sharing to improve marine spatial planning [1]. Floating wind turbine technology is a crucial element in the sustainable transition. This technology is developed to harness higher and more consistent wind resources found in deeper waters, providing a viable solution for the increasing energy demand [2]. At the end of 2024, the total global offshore wind capacity has reached 83.2 GW [3], which does significantly contribute to the energy mix, especially for coastal/island communities [4].

Floating Offshore Wind Turbine (FOWT) technology has reached a prototype stage where the costs are decreasing. It faces challenges due to the complex and harsh marine environments and structural complexities. Therefore, innovative solutions and a thorough understanding and mitigation of related risks are essential. To investigate these risks, potential failures, and their effects on the system, a Failure Mode and Effects Analysis (FMEA) provides a useful tool [5], [6], [7]. This is crucial for the state-of-the-art design, installation, and operation of Floating Offshore Wind Turbines (FOWTs), accelerating the green transition.

As FOWTs are parts of Floating Offshore Wind Arrays (FOWA), it is not sufficient to only consider component-level risks. In addition to single turbine-level risks and mitigation strategies, farm-level uncertainties, risks, and mitigation strategies should also be addressed. WP3, which focuses on array-level failure risks and mitigation, attempts to address this topic by identifying failure modes, consequences, and effects on a floating wind turbine array. Adopting a FMEA approach, this initiative seeks to build the framework for a qualitative analysis and risk assessments at the floating wind farm array level. This has been achieved through a series of dedicated workshops, expert collaborations, and innovative processing methods.

This report includes several objectives:

- **Failure Mode Analysis of a Generic FOWT:** The first objective involves conducting a failure mode analysis of a generic floating offshore wind turbine using the FMEA method. This analysis identifies and prioritizes failure modes based on their likelihood, severity, and detectability. It is supported by an extensive literature review, discussions with the WP3 team, and expert input from industry and academics from two workshops, assuring a comprehensive identification of critical failure modes.

- **Identification of Farm-Level Implications:** The second objective extends the FMEA method to identify and categorize failure modes that could affect multiple turbines with a FOWA. For this purpose, farm-level implications are defined as the potential for a failure

in one component or turbine to disrupt the performance, stability or reliability of other turbines across the array. Survey participants were asked whether each identified failure mode could amplify to farm-level effects. If so, participants prioritized these failure modes using FMEA criteria, providing valuable insights into their importance.

- **Adaptation to Farm-Level Risks Using Probabilistic Modeling:** The third objective adapts the findings to examine farm-level implications within an anticipated floating offshore wind array, including potential cascading effects across turbines and addressing system-level uncertainties.

While the first two objectives have been fully achieved and their results are presented in this report, the lack of a specified FOWA configuration from WP2 at the start of WP3 necessitated a focus on demonstrating probabilistic modeling. Using Bayesian networks, an exemplary 10-turbine floating wind turbine array is analyzed to quantify and evaluate farm-level risks. This will be further explored in the next phase of WP3.

1.1. Overview of WP3 Activities

1.1.1. WP3 Development Plan

WP3 is a three-year task, running from 2023 to 2025. The first year of WP3 focused on identifying the failure modes at the component level. In 2024, WP3 assessed the failure effects at the array level in greater detail, and 2025 will be dedicated to developing failure mitigation strategies. The updated schedule is presented in **Figure *1***.

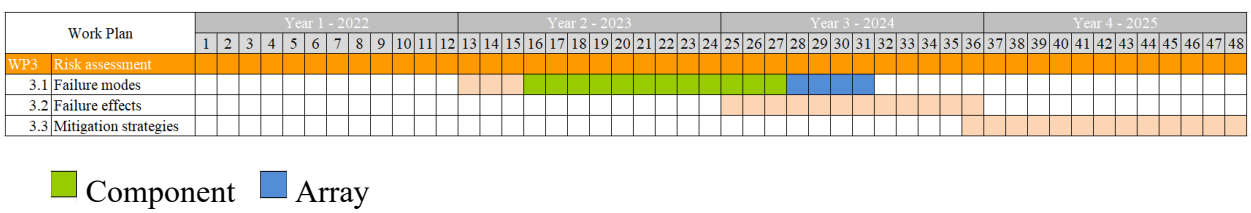

Figure 1: Work Package 3 planned schedule

WP3 aims at identifying failure modes related to FOWA and assessing the potential consequences and couplings of those modes in the context of an offshore wind farm. This WP is organized into three stages, with the following objectives:

- Develop a high-level list of failure modes and mechanisms at the farm level.
- Evaluate the likely consequences and couplings between the failure modes and mechanisms.
- Investigate various failure mitigation strategies.

WP3 was kicked off in March 2023 and is planned to be concluded in December 2025. A core WP3 team was formed, with specialists in FMEA, monitoring systems, insurance, class society, project development, research & development, and technical advisory.

1.1.2. Definition & Scope of Work

In its first year, WP3 conducted an FMEA survey at the FOWT unit level, incorporating expert input, regular discussion among the WP3 team, and two workshops. WP3 organized two FMEA workshops alongside broader whole-task meetings (held annually or biannually alongside conferences):

- An in-person workshop in Copenhagen in October 2023.
- An online workshop in March 2024.

The FMEA tables provide high-level insights and assign an RPN for each failure mode at the component level. Based on quantified RPNs in the FMEA tables, WP3 identified the most prominent failure modes for the following components: floater, tower, transition piece, station-keeping system, and dynamic cables. These tables also identify failure modes with potential farm-level implications, based on expert evaluations during the workshops. Using the quantified RPNs, WP3 identified the most prominent failure modes with farm-level effects in the following components: floater, transition piece, station-keeping system, and dynamic cables. The wind turbine generator, export cables, and offshore sub-stations are outside the scope of this task. For this FMEA analysis, the work group focused on the generic steel semisubmersible while assuming a FOWA at the Havbredey floating site in Scotland (see Section 4.1).

2. Review of Risk Analysis Standards

Using a risk-based approach that aligns with the FOWA at every stage is imperative, as it can pinpoint the subsystems and components that have the biggest effects on safety, the environment, and project assets, as well as the critical failure consequences of the system, as a whole. From there, mitigation strategies can be recommended. A set of standards for risk assessments is given in **Table *1***; some of these standards can be applied to FOWA, depending on the scope of the risk assessment and data availability.

Among the different risk analysis and management techniques in **Table *1*,** FTA and FMEA have been applied to floating offshore wind turbines [5], [7], [8], [9]. However, because the FMEA risk priority number technique can incorporate qualitative information through channels like expert elicitation, it may be helpful for FOWT, where quantitative failure data is either absent or insufficient.

Table 1: List of risk analysis and management standards

Risk Analysis & Management	Year	Standard
American Petroleum Institute	2017	API RP 17N Recommended Practice on Subsea Production System Reliability, Technical Risk, and Integrity Management
British Standard	2014	BS 5760, Part 5, Guide to failure modes, effects and criticality analysis
Bureau Veritas	2020	NI 525 Risk based qualification of new technology - Methodological guidelines
Det Norske Veritas	2021	DNVGL-RP-N101 Risk management in marine and subsea operations
Det Norske Veritas	2017	DNV-OSS-300 Risk Based Verification
Det Norske Veritas	2012	DNV-RP-D102 Failure Mode and Effect Analysis (FMEA) of Redundant Systems
International Electrotechnical Commission	2018	IEC 60812 Failure modes and effects analysis (FMEA and FMECA)
International Electrotechnical Commission	2006	IEC 61025 Fault Tree Analysis (FTA)
International Electrotechnical Commission	2016	IEC 61882 Hazard and operability studies (HAZOP studies)
International Electrotechnical Commission	2010	IEC 62502 Analysis techniques for dependability – Event tree analysis (ETA)
International Electrotechnical Commission	2019	IEC/ISO 31010 Risk Management - Risk Assessment techniques
International Electrotechnical Commission	1995	IEC-60300-9, Part 3: Application guide - Section 9: Risk analysis of technological systems
International Maritime Organization	2002	IMO MSC/Circ.1023−MEPC/Circ.392 Guidelines for Formal Safety Assessment
International Organization for Standardization	2016	ISO 17776 Petroleum and natural gas industries — Offshore production installations — Major accident hazard management during the design of new installations

FMEA, which is explained in the following section, is a structural approach for identifying potential failure modes within a system, evaluating the impact of those failures, and ranking them according to criticality. By systematically evaluating risk, FMEA supports the implementation of preventative measures to enhance system reliability. Several guidelines and standards outline the implications of FMEA, especially for renewable energy systems. Among them are:

- IEC 60812: This standard provides guidelines for the application of FMEA and FMECA [10].
- ISO 31010: This standard focuses on risk management and includes methodologies like FMEA and FMECA.
- DNVGL-ST-0437: It provides guidelines for the certification of floating offshore wind turbines and includes FMEA and FMECA as a tool for assessing the reliability and safety of these systems.
- MIL-STD-1629A: Although originally developed for military applications, this standard is also used in the renewable energy sector to perform FMEA and FMECA. It provides a structured approach to identify and prioritize potential failure modes [11].

3. Methodology

3.1. Choice of Methodology

This report adapts the FMEA method to assess and mitigate risks at the FOWT level, with a focus on identifying failure modes that could have farm-level effects. FMEA is particularly suited to the technological development process, enabling early identification of risks, estimation of their consequences and raking based on severity and likelihood [12]. The process steps are illustrated in ***Figure 2***. The section that follows (Section 3.2) provides details on the FMEA processing. The FOWT component-level risk assessment will serve as the starting point for identifying the array-level risks.

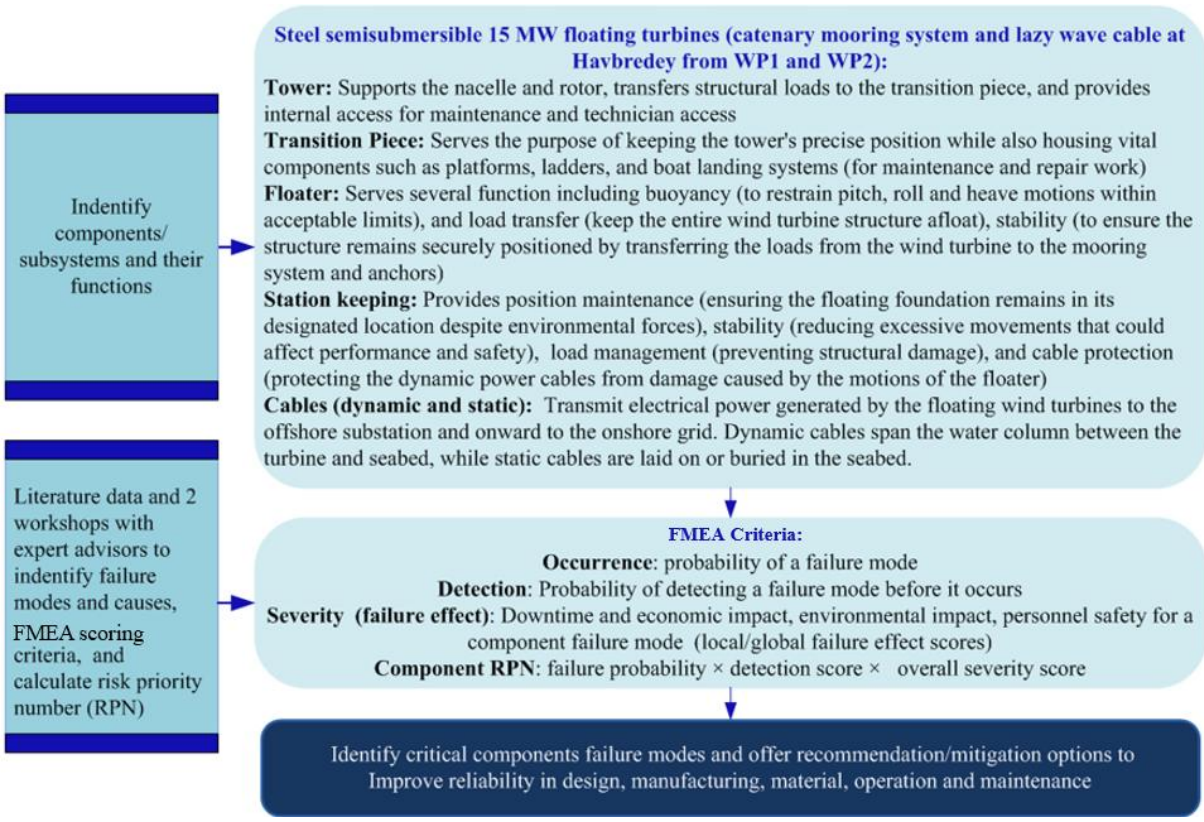

Figure 2: FMEA steps

As shown in ***Figure 2***, FMEA considers the structural and sub-structural components of the floating turbine, including floater, tower, transition piece, station keeping system, and dynamic cable. Wind turbine generator and substation components are not under investigation. Detailed mitigation recommendations will be addressed in the upcoming WP3 report; thus, they are outside the scope of this work.

3.2. Processing

The FMEA methodology consists of six main steps: system selection, system itemization, identifying the potential failure modes, expert selection, failure information calculation, calculation of RPN, and finally, the risk mitigation strategies. Initially, the system is defined for

the analysis. For this work, a generic steel semisubmersible with catenary mooring lines has been selected. The next step of this process is creating a system breakdown for the selected technology as components and subcomponents. In this work, it is defined as floater, station keeping system, dynamic cable, tower, and transition piece. Related failure modes for each component are defined and investigated to estimate their effects on the system's safety and functionality. For a wind turbine, this could also include considering the causes of failures and their end effects, such as damage to the structural parts, power loss, and/or safety risks [13]. The severity, likelihood, and detection are defined for the failure modes, and a guideline is prepared for the information-gathering process from the experts. The detailed guidelines for severity, occurrence, and detection can be seen in Tables 2, 3, and 4. Here, severity is considered in four classes: personnel safety, environmental impact, asset integrity, and operation, while asset integrity is considered for the whole project as a generic value depending on the cost of damage for a project located in Europe. The impact of a failure mode from minor to catastrophic events is referred to as the severity of the failure mode. The occurrence probability of the failure mode is evaluated by its likelihood. Detection is defined from very low to very high. Using the three factors discussed above, the criticality of the failure mode is assessed by computing the risk priority number (RPN) as in Equation 1. With this criticality assessment, the failure modes are prioritized to define the ones that require immediate action and arrange the mitigation strategies. By prioritizing limited resources, the most critical issues on the system performance and safety are mitigated effectively. Computation of RPNs is possible by gathering information from the experts in the field, and it is conducted by organizing two workshops. The details of this are given in the next chapters.

$$RPN = S(Severity) \times O(Occurrence) \times D(Detection)$$

Equation 1 Computation of risk priority number

Table 1: Severity matrix used for the FOWT. Modified from *[14]*

Severity class	Personnel Safety	Environmental Impact	Asset Integrity	Operation	Ranking
Catastrophic	1 or more fatalities	Significant environmental impact	Damage > 30 M €, total loss	Total Operational Loss, replacement	5
Critical	Multiple Major Injuries	Critical damage/pollution, minimal effect of control measures	Major Damage [10-30 M€]	Major repair needed (operational loss from 1 day to 1 week	4
Major	Multiple Minor Injuries, Major Injury	Major damage/pollution, low effect of control measures	Localized Damage [1-10 M€]	Minor replacement needed (operational loss < 1 day)	3
Marginal	Minor Injury (First Aid)	Minor damage/spillage, good effect of control measures	Minor Damage [0.1-1 M€]	Short Operational Loss (few hours)	2
Minor	No Injury	No damage/contamination	Negligible damage < 100 K€	Minimal Operational Loss	1

Table 2: Occurrence matrix used for the component level FMEA. Modified from [14]

Probability	Probability of failure	Possible annual failure rates	Ranking
Very frequent	Almost inevitable failures	>= 1 in 8	5
Probable	Repeated failures	From 1 in 8 to 1 to 80	4
Occasional	Occasional failures	From 1 in 80 to 1 in 400	3
Remote	Relatively few failures	From 1 in 400 to 1 in 150,000	2
Highly Unlikely	Highly unlikely failures	=< 1 in 150,000	1

Table 3: A detection matrix is to be used for the component level FMEA. Modified from [14]

Detection	Criteria: Likelihood of detection by design control	Ranking
Very Low	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control	5
Low	Low chance: the design control will detect a potential cause/mechanism and subsequent failure mode	4
Moderate	Moderate chance: the design control will detect a potential cause/mechanism and subsequent failure mode	3
High	High chance: the design control will detect a potential cause/mechanism and subsequent failure mode	2
Very High	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode	1

4. System Definition

4.1. Key Inputs from WP1 and WP2

WP1 (reference sites) completed its development of reference site conditions for floating wind arrays and has prepared a comprehensive report [15]. Following a metocean analysis of 49 sites that represent the global floating wind pipeline, the WP1 team assembled detailed metocean data for 11 selected reference sites along with generic characterizations of representative soil characteristics, infrastructure requirements, and other site-specific parameters. The site condition datasets have been published as an open-access resource.

WP2 (reference array designs) has completed the design basis report [1], which provides guidance and generic assumptions to guide reference floating wind array design. WP2 defined the scope of the reference array designs to focus on designing the array layout, mooring systems, and array cabling systems while using existing floating wind turbine designs. The scope ends at the substation's location to maintain focus on the array-level issues.

WP2 is working on developing three reference array designs, each for a different set of site conditions provided by WP1. Among the many proposed design options (**Table 4**), WP2 selected 3 reference designs based on the VolturnUS-S semisubmersible and IEA Wind 15-MW reference floating wind turbine for water depths of 60 m, 300 m, and 800 m. Additional design variants are proposed as future efforts to provide a greater variety of site conditions, support structure types, and design challenges.

Table 4: Outline of the reference array design options

Scenario	**Shallow (60 m)**	**Intermediate (300 m)**	**Deep (800 m)**
Key features	Shallow-water challenges and solutions	Seabed, anchoring, and layout challenges and solutions	Deep water challenges and solutions
Design variants (sequential)	V1: uniform *Optional variants*: V2: depth gradient V3: alternate mooring option	V1: uniform *Optional variants*: V2: irregular seabed+layout V3: typhoon conditions V4: shared anchor option	V1: uniform *Optional variants*: V2: shared mooring lines V3: TLP option
Array layout	Rectangular	Rectangular, then optimized	Rectangular, then alternate
Platform type	Semi	Semi or Spar	Semi, then TLP
Mooring type	Semi-taut, taut	Catenary, shared anchor	Taut, shared mooring, TLP
Dynamic cables	Lazy wave	Lazy wave	Catenary, fully suspended

The teams have designed mooring systems and addressed key array-level questions, including load case selection, fatigue analysis methods, and inclusion of wake effects in the loads analyses. WP2 is now designing dynamic power cables and array layout.

As the reference designs from WP2, in particular the detailed subsea architecture (mooring layout, dynamic and static cable layout) was not available at the start of WP3, the team decided to define a base case to guide the review on failure modes at the component level. The properties of the base case are as follows:

- IEA Wind turbine 15-MW reference floating wind turbine
- VolturnUS semi-sub (steel one), see **Figure 3**.

- Catenary mooring design
- Water depth: 200 m (uniform)
- Seabed: generic, no specific soil conditions
- Array layout: aligned, two main directions
- Cable configuration: lazy wave
- Site conditions: Havbredey floating site in Scotland.

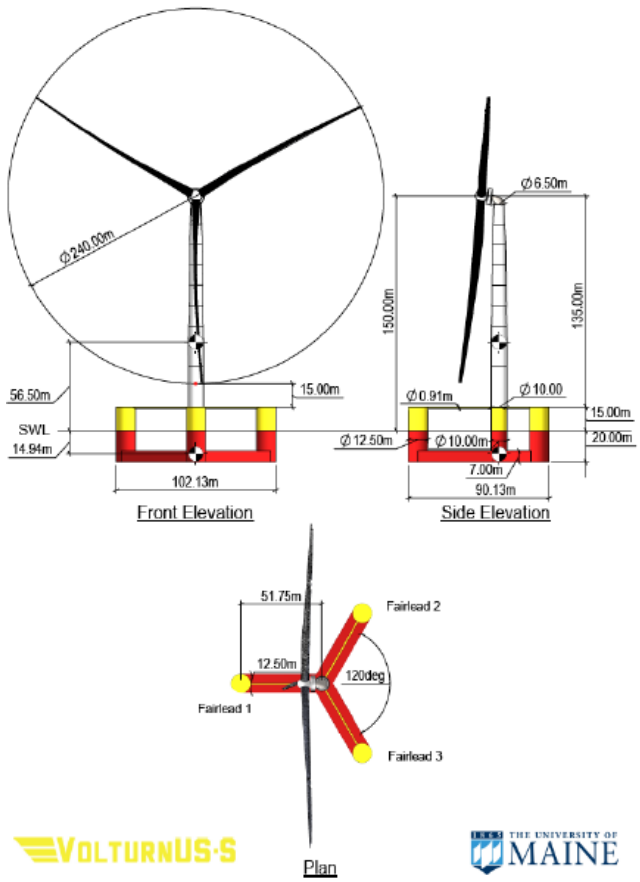

Figure 3: The UMaine VolturnUS-S reference platform designed for the IEA Wind 15 MW Turbine [16]

4.1.1. System Itemization Structure

The FOWT system consists of:

- Tower:
  - Structure (sections)
  - Flanges and bolts
  - Access systems (ladders, platforms)
  - Lighting and safety system
- Transition Piece:
  - Connection between tower and floater
- Floating Structure (floater):

    - Platform types (semi-submersible, spar, tension-leg platform)
    - Ballast system
- Station keeping system:
    - Mooring and Anchoring System including mooring lines (chains, synthetic ropes, tendons) and anchors (drag embedment, suction, gravity)
    - Winches
    - Fairleads
- Dynamic Electrical Systems:
    - Dynamic cables (intra-array, export cables)
    - CPS
- Control Systems:
    - Monitoring and control hardware/software
    - Sensors and actuators
- Auxiliary Systems:
    - Power supply and storage (batteries, diesel generators)
    - Safety and emergency equipment
- Wind Turbine Generator:
    - Rotor (blades, hub)
    - Nacelle (generator, gearbox, yaw system)

Each of these components plays a critical role in the efficient and safe operation of a FOWT. However, as previously stated, the FMEA report in WP3 focuses on the following key components: Floater, Tower, Transition Piece, Station Keeping (including Mooring System), and Dynamic Cable. They are discussed in greater detail in the following subsections. The selection of these components is justified based on their critical roles in the overall functionality and reliability of the FOWA. This targeted analysis helps in identifying potential failure modes, assessing their impacts, and developing effective mitigation strategies, ultimately enhancing the reliability and sustainability of FOWA operations.

4.1.2. Tower & Transition Piece

The tower and transition piece, which extends from the substructure to the nacelle connection, serve as crucial parts of the support structure. The tower supports the wind turbine's components, while the transition piece serves the purpose of keeping the tower's precise position. Their specifications and design are similar to those of the IEAWind 15-MW floating turbine, backed by reference designs for the UMaine VolturnUS-S [16] (Figure 3). The tower mass and height are 1,263t and 135m, respectively, while the transition piece height is 15m.

Because the tower and transition piece play critical roles in supporting the structural and wind turbine components, and they are directly exposed to severe sea conditions and numerous loads from the wind and waves, their reliability is extremely important. Any major malfunctions could have disastrous safety, environmental, and economic consequences.

The tower interiors give maintenance and service staff access, lighting, and safety, in addition to a way to transfer hand tools and parts to the nacelle. They support the electrical and control cables, switchgear housing, transformer housing, and other power take-off components. Equipment for survival is also stored inside the tower [30]. Components of the tower and transition piece include

pipe, pillars, lights, helicopter assistance as well as platforms for crew access and boat landings (for maintenance).

4.1.3. Floater

The floater serves as the primary buoyant structure that supports the entire wind turbine assembly, including the tower and nacelle, in deep water environment. Floater designs vary by platform types, with common configurations including semi-submersible, spar and tension-leg platforms. Each type offers distinct buoyancy and stability characteristics, which work in conjunction with the mooring system to maintain station-keeping and structural integrity [31]. The floater provides stability and buoyancy, allowing the wind turbine to harness wind resources efficiently. Any structural failure in the floater can lead to catastrophic consequences, including capsizing, sinking and significant economic losses. Components of the floater include:

- Ballast System: Used to maintain the floater's stability and position in the water. It includes adjustable ballast tanks that can be filled with water or air to adjust buoyancy.

- Structural Elements: Reinforced sections and joints designed to withstand extreme environmental conditions and dynamic loads.

Further details on the failure modes of offshore wind turbines can be found on numerical studies including but not limited to [32], [33]. The design and specifications of the semisubmersible floater assumed in this report, are similar to those of the IEA Wind 15-MW floating turbine, supported by reference designs for the UMaine VolturnUS-S [16].

4.1.4. Station Keeping System (Mooring Lines & Anchors)

The stability of the substructure and the turbine is dependent on the mooring system, which keeps the floating offshore wind turbines on station. Mooring systems will need to be tailored to the individual site conditions, the substructure used for each project and its economic considerations, and the overall design framework [26]. Depending on these factors, a mooring system may consist of multiple components, as illustrated in

Figure **4** [30], but not all these components are involved in an actual mooring system at the same time. Components of the station-keeping system can be given as [34]:

- Anchors: Mooring lines are connected to the seabed with anchors, and should stay connected during the lifetime of the project.

- Mooring lines: Mooring lines ensure the stability of the FWT system and transfer the loads from the floater to the anchors.

- Fairlead: A structural interface mounted on the floater that guides the mooring line from the platform to the water. It helps manage tension, reduce wear and maintain alignment of the mooring line under dynamic conditions.

- Jewellery: Jewellery is the broad range of items that can be attached to the mooring lines to improve the performance of station-keeping systems. Jewellery items can be given as

connectors, clump weights, in-line tensioners, load reduction devices, and mid-line buoyancy elements. For more information, please see the given reference.

- Topside connections: The Upper section of the mooring line is connected to the floater with the topside connection.

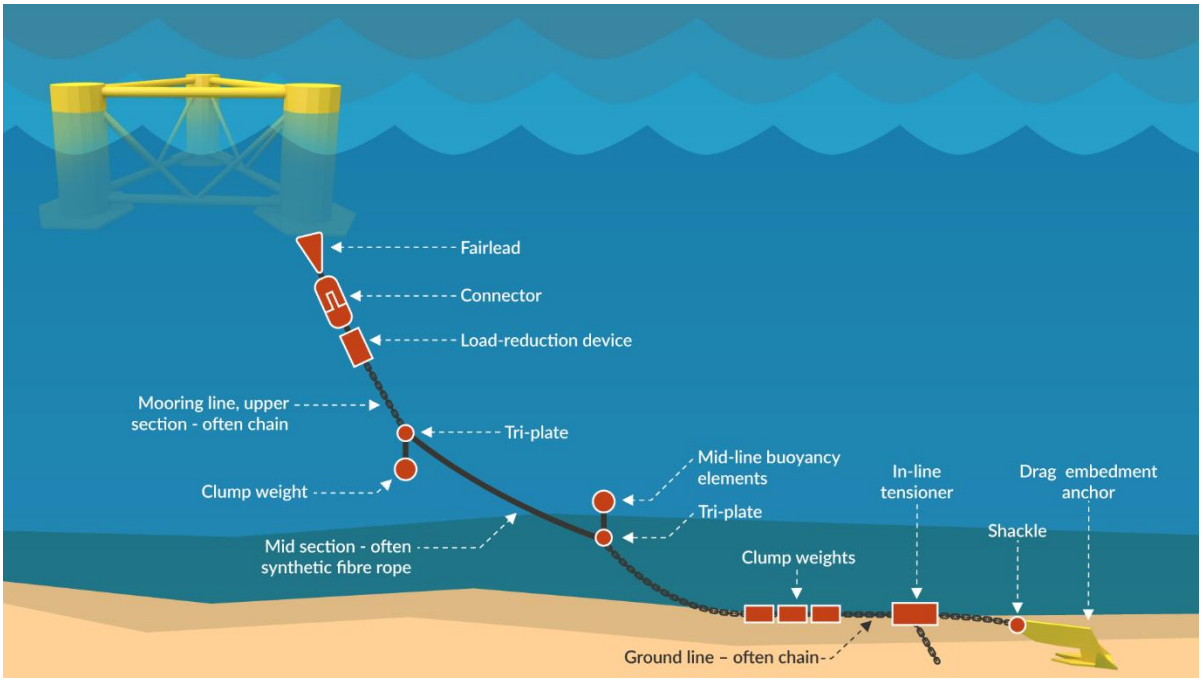

Figure 4*:* Components of a typical offshore wind turbine mooring system. An actual system would not employ them all at once [34] .

Mooring system for floating offshore wind turbines, are subject to various failures, including [26], [35], [36], [37], [38]:

- Extreme load failure caused by severe weather conditions (strong winds, currents and large waves). These extreme loads can exceed the design limits of the mooring lines, leading to breakage.

- Corrosion in the mooring lines and connectors due to the exposure to seawater, reducing their strength and raising the possibility of failure.

- Fatigue failure caused by cyclic loading and unloading of mooring lines, resulting in wear and unexpected failures and high failure consequence costs.

- Wear and abrasion due to contact with the seabed, floating debris, or other structures, leading to material degradation and reduced mooring system integrity.

- Anchor failure owing to inadequate holding capacity, abnormalities in the seabed, or incorrect installation, which result in the instability of the entire mooring system and allows the floating platform to drift.

- Accidental damage cause by, for example, ship collisions, dropped objects, fishing gear snag and vessel anchor drag which can result in severe damage to the mooring lines and anchors.

4.1.5. Dynamic Cable

Dynamic cables[1] in floating offshore wind projects require several auxiliary components to ensure reliable performance. A variety of auxiliary equipment are needed to control the dynamic cables' shape of motion and lessen localised bending at critical spots, and **Figure 5** shows an overview of this equipment. In a real system, the equipment required will vary depending on the type of dynamic cable, and it is unlikely that all of these parts would be used at the same time. Key auxiliary equipment of the dynamic cable includes [39], [40], [41]:

- Buoyancy Elements: These modules provide buoyancy to the cable, preventing it from sinking and maintaining proper tension.

- Connectors and Joints: These components allow seamless connections between cable segments, both within the intra-array network and at the export cable termination point. High-quality connectors are crucial for minimizing power losses and ensuring long-term reliability.

- Bend Stiffeners: Bend stiffeners protect the cable from excessive bending near connectors or other stress points. They maintain the minimum bend radius required for cable integrity.

- Clamps and Hang-offs: Clamps secure the cable to the floating structure, while hang-offs provide additional support. Proper installation and load distribution are critical for cable longevity.

- Tethers: Tethers help manage cable movement and prevent excessive sway. They play a vital role in maintaining cable integrity during dynamic conditions.

- Cable Protection Systems (CPS): CPS includes bend restrictors, abrasion sleeves and other protective elements designed to shield the cable from mechanical damage at vulnerable locations, such as the touchdown point on the seabed, entry/exit points on the floating substructure and exposed sections of the seabed. CPS components are critical for minimizing fatigue and wear during both installation and operation.

The specific design and configuration of these components can vary across different floating wind projects based on factors such as water depth, environmental conditions, and project-specific requirements. Developers, contractors, and manufacturers collaborate to optimize these auxiliary systems for each project.

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[1] Note: This section focuses on the dynamic portion of the electrical cable system. While static portions of intra-array cables (i.e., seabed-laid segments) are considered elsewhere in the report for failure mode analysis (see, Sections 6.2.2 and 6.3.3), they are not included in the scope of dynamic cable auxiliary equipment described here.

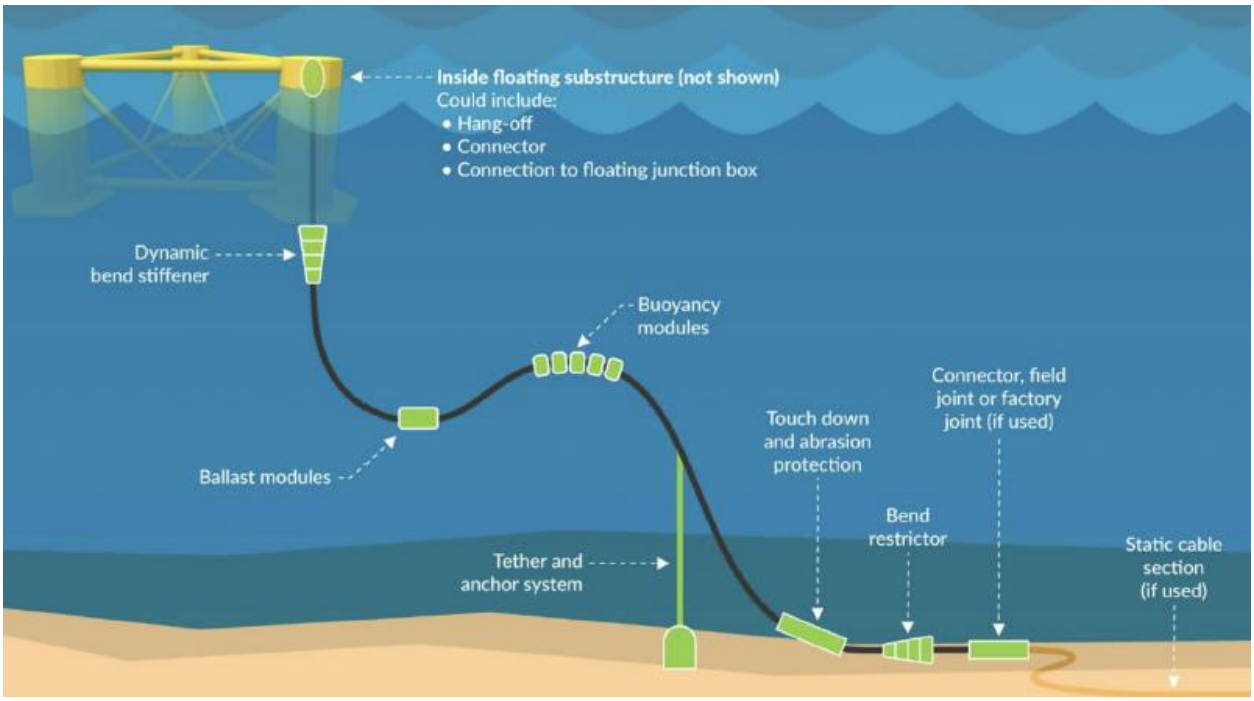


Figure 5*:* Dynamic cable auxiliary equipment. Figure from: BVG Associates/ORE Catapult [40]

In the case of floating turbines, cables extend through the water column from their substructure base down to the seabed. This exposes the cables to dynamic forces generated by marine currents and wave motion. Mechanical and electrical stresses can lead to cable failures. To withstand the increased stress, dynamic cables must be robust. Their motion and fatigue poses a higher risk of failure compared to conventional static cables [42].

4.2. Review of Failure Rates of FOWT Components

WP2 is developing a comprehensive cost and logistics model for reference array designs. This model will account for the influence of key parameters, including component costs, logistics expenses (such as vessel and port fees), and the impact of varying operational and maintenance (O&M) strategies for major repairs. A critical input for this analysis is the failure rate of wind turbine components, which is essential for estimating the operation expenditures (OPEX) in WP2. This section offers an overview of the potential failure rates for FOWT components.

The failure rates of floating offshore wind turbine components are not readily available, and existing data in the literature primarily originates from the oil and gas sector and bottom-fixed turbines (sometimes an altered failure rate approach or expert elicitation is used for adjusting the failure rates for FOWT components).
Due to variations in operational environments, design configurations, and the limited availability of reliability data specific to FOWT, these estimates should be interpreted with caution. As such, they should be considered approximate and indicative, serving as a foundational reference rather than definitive values. While these rates provide a useful starting point for analysis, they should ideally be supplemented with project-specific data and further expert support whenever possible.

This section offers reviews of failure rates for several components of FOWT from [17-41]. Whenever possible, sub-components and component failure modes/mechanisms are included.

4.2.1. Tower, Transition Piece and Floater

These components are grouped together because they share common failure causes and structural dependencies (e.g., cycling loading, which causes fatigue cracks and structural weakening, or errors in welding, material selection, and assembly can affect all three components similarly). Generic failure rate information for the structural component is presented in **Table 5** and is taken from the literature [22], [23] The failure caused by extreme environmental conditions (strong waves, typhoons, storms, collisions, and lightning strikes) or inadequate operation and maintenance is excluded. The failure effects of these situations, which are critical to address in the component failure risk analysis, are assessed using the FMEA method in the report.

Table 5: Failure rates of the tower, transition piece, and floater components (obtained from [22] based on [23]).

Structural components	Failure mode/mechanism	Failure/year
Tower, Transition Piece and Floater	Faulty welding/water tightness	0.061
	Material fatigue	0.096
	Pillar damage	0.044
	Pipe joint corrosion/fatigue*	0.140

* Failure rates due to pipe joint corrosion and fatigue refer to structural tubular elements commonly used in the tower, floater, and transition piece assemblies — particularly welded steel pipe segments that form part of the lattice, tubular, or semi-submersible support frames.

4.2.2. Mooring System

Understanding the primary threats to mooring systems and implementing effective failure mitigation strategies are critical to ensuring their reliability and performance. The significance of these risks becomes particularly apparent when considering the scale of floating offshore wind farms and their broader context, which includes cascading effects, economic costs, environmental safety concerns, and redundancy requirements. To gain a deeper understanding of the potential risks to mooring systems in FOWA, it is essential to consider the specific failure modes that contribute to overall system reliability. This aspect is addressed in the FMEA analysis (Section 6), which provides insights into the vulnerabilities of mooring systems in FOWA.

Data on the potential annual component failure rates serves as a critical input for cost modeling aimed at estimating O&M expenses and optimizing maintenance strategies. This information is particularly relevant for maintenance cost estimation, as the failure rates of mooring system components play a pivotal role in calculating the costs associated with both corrective and planned maintenance activities. Furthermore, failures may be compounded by long lead times for the availability of vessels, spare parts, and suitable weather windows, which can significantly impact repair schedules and associated costs, (see [19]). The oil and gas industry provides the only relevant failure rate data for the floating offshore wind mooring sector. The Catapult ORE report [24] offers a compelling case for why the FOWT cannot use failure data from the oil and gas

industry. Therefore, the majority of FOWT mooring system failure rate estimates are based on expert analysis.

The Mooring Reliability, Redundancy and Integrity (MRR&I) project by the Carbon Trust Floating Wind JIP presents six key findings [25]: (1) Many of the degradation threats of traditional oil & gas platforms are present for FOWA, (although rates may differ, as found by Catapult ORE). (2) Common-mode failures are critical, (3) fatigue loading is critical to the design of mooring systems, (4) Redundant systems can provide benefits through reduced start-of-life failures, (5) Availability depends on various FOWA-specific design parameters, (6) Risk-Based Inspection (RBI) strategies can bring clear benefits during the operational phase.

According to the WFO Mooring System Integrity Management White Paper [26] the annual failure rates for individual mooring lines are estimated to range from 0.1% to 2%, with an average of 1.05%. For a 1 GW FOWA using IEA 15 MW turbines and assuming a three-line mooring system per turbine, this failure rate translates to an 88% probability of at least one mooring line failure annually across 200 mooring lines (calculated as 1 - (1 - 0.0105)^200).
In [19], the annual failure rate for major repairs and replacements of the mooring line is 1.5% and 1.5%, and the subsea marine growth removal, which can form on mooring lines, anchors, floater hulls, and subsea structures, is also provided, as shown in **Table *6***.

Table 6: Failure rates of mooring systems [19]

Component	Failure/year/line (Minor repair)	Failure/year/line (Major repair)	Failure/year/line (Replacement)
Mooring line	-	0.015	0.0125
Anchor	-	0.015	0.0125
Marine growth removal	0.120	-	-

In [27], the annual failure rate of the hybrid synthetic mooring is given per km as 0.0017/km, while the drag-embedded anchor has a substantially lower annual failure rate (0.00012) for the assumed semisubmersible 15 MW turbine at 100 m water depth.

Some studies examine the failure rates for various failure modes within the mooring system, revealing substantially higher failure rates. **Table 7** compiles the generic failure data, drawn from the literature on three-line catenary mooring systems of the OC3 Spar-type FOWT, with significant contributions from [8] which builds upon the data in [22].

Table 7: Failure rates of a 3-line catenary mooring system [8]

Component	Failure mode	Failure mechanism	Failure rate /year
Mooring system (Three-line-catenary)	Mooring line fatigue	-	0.1489
	Chain corrosion	-	0.0471
	Mooring line break	Abnormal stress	0.3565
		Friction chain wear	0.0607
		Transitional chain wear	0.0885
	Fairlead fatigue	-	0.1489
	Fairlead corrosion	-	0.0876
	Anchor failure	-	0.1577

4.2.3. Dynamic Cable

An important barrier to the effective installation and operation of floating offshore farms is knowledge of both static and dynamic power cable technologies and the lifespans that go along with them. The fatigue lifetime and anticipated failures of dynamic cable systems are currently poorly understood due to the technology's immaturity and brief industry experience [28].

The average failure rate of 0.0029 per km per year of alternating current (AC) transmission systems (static power cables) for offshore wind farms operating in Europe up to 2018 is compared to the average of 0.0007 failure/km/yr published by CIGRE in **Figure *6*** [29]. The figure is determined by dividing the total number of failures by the total cable length (km) each year operational. The work of [29] is also cited in [28] and [27] for the cable failure rate. Using failure rate from [29] and additional sourced data on age, cable length and expert opinions, [28] reports an annual range of 0.0019 to 0.0213 failure/km for cable. In [27], the annual failure rate of the static cable is 0.003/km, and because dynamic cables are subjected to a harsher environment, it is assumed that their failure rate is twice that of static cables.

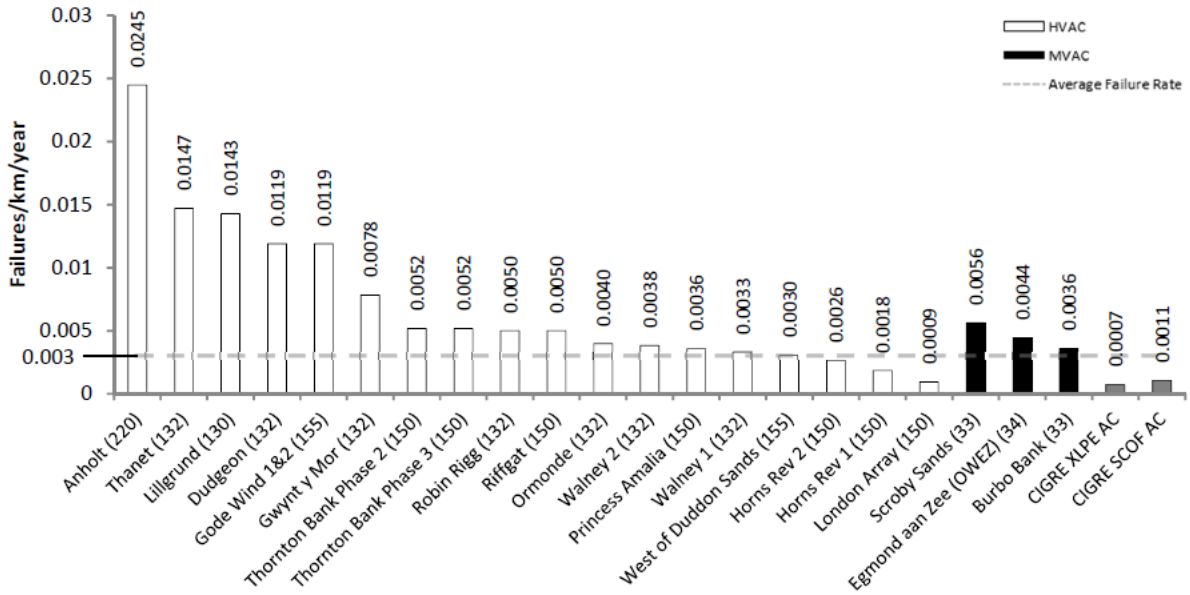


Figure 6: The failure rate of alternating current (AC) European offshore shore wind farm transmission connections until March 2018 *[29]*

In CoreWind [19], the failure rate of cable components is provided per farm (80×15 MW of Windcrete spar or ActiveFloat semi-submersible floating turbines) rather than the km of cable length, and these corrective failure rates are anticipated based on the components' 2-yearly scheduled inspection/repair cycle. **Table 8** displays the annual failure rates of dynamic cable, buoyancy modules, export cable, and offshore substations as provided in [19].

Table 8: Failure rates of dynamic cable and offshore substation [19]

Component	Failure/year (Minor repair)	Failure/year (Major repair)	Failure/year (Replacement)
Dynamic cable	-	0.025	0.016
Buoyancy modules	-	-	0.033
Export cable	-	0.020	-
Offshore substations (inspection after incidents)	0.200	0.010	-

4.2.4. Wind Turbine

The existing data on fixed-bottom wind turbines serves as a primary basis for estimating the failure rates of FOWT components. Literature typically classifies failure rates into three categories: minor, major, and replacement failures. The overall annual failure rate of wind turbine components can vary significantly depending on the turbine model, data sources, and study assumptions. For instance, [17] reports an annual failure rate per turbine of: 3.0 failures (minor),0.31 failures (major), and 0.08 failures (replacement). This is based on a simulation model of an 80-unit Vestas V90 3 MW wind farm. Similarly. Carrol et al [18] analysed annual failure rates per turbine from a database of approximately 350 offshore wind turbines (2-4 MW nominal capacity) operating in Europe and reported: 5.039 failures (minor), 0.856 failures (major), and 0.258 failures (replacement).

CoreWind [19] provides failure rates for three categories (minor, major, and replacement failures) across wind turbine components, substructures, and offshore substations in a commercial-scale floating wind farm with 80 IEA 15 MW turbines. These rates are derived from [20] (DTU 10 MW wind turbine's main shaft components), [18], [21] and expert interviews. **Table 9** [19] summarizes the failure rates of wind turbine components for floating offshore wind applications.

Table 9: Failure rates of wind turbines [18], [19], [20], [21]

Component-subcomponent	Failure/year (Minor repair)	Failure/year (Major repair)	Failure/year (Replacement)
Direct drive generator	0.546	0.030	0.009
Power converter	0.538	0.338	0.077
Main shaft-high speed side	0.025	0.005	-
Main shaft- connections	0.019	0.001	0.001
Main shaft se-bearings	0.147	0.005	0.008
Main shaft- break	0.040	0.015	-
Power electrical system	0.358	0.016	0.002
Yaw system	0.162	0.006	0.001
Pitch system	0.824	0.179	0.001
Blades	0.456	0.010	0.001
Total	**3.115**	**0.605**	**0.1**

5. Data Collection

5.1. Input Gathering for FMEA

This section describes the input-gathering process for the FMEA method, which was conducted through expert workshops and supported by a targeted literature review. The purpose was to combine insights from diverse professional backgrounds to identify and refine component-level failure modes and assess their potential farm-level implications.

An expert panel was assembled, comprising individuals with experience in offshore wind design, marine operations, risk assessment, maintenance and academic research. The selection of participants was based on their demonstrated expertise and practical contribution to floating offshore wind technology. A summary of participant profiles is provided in **Table *1***.

Before convening the workshop, a literature review was conducted to collect initial data about component-level failure modes, including causes and possible mitigation strategies. This review was structured in alignment with the system itemization defined earlier in this report.

During the workshop, participants were asked to evaluate the identified failure modes based on severity, occurrence, and detection, and to indicate whether any failures could plausibly lead to farm-level effects defined as consequences that extend beyond the affected component or turbine to influence the performance, stability, or reliability of other turbines in the array.

Two workshops were held to collect these expert evaluations. Participants were introduced to the findings from the literature review and engaged in structured discussions to refine failure definitions, contribute additional failure scenarios, and suggest mitigation measures. This process ensured that the FMEA incorporated both academic insights and operational experience.

Table 1: Participant background for the FMEA method

Sector	Years of Experience	Relevant Expertise
R&D	10 (incl. O&G)	10 projects related to condition and structural health monitoring offshore
Risk consultancy	15	Risk identification, and quantification for offshore wind, wave, tidal, and Ocean Thermal Energy Conversion (OTEC)
Insurance	36	Structuring risk finance solutions, optimizing risk finance solutions for companies with non-standard/ prototypical assets
Academia	15	Renewables with over 7 years offshore wind, tidal, and wave systems
Development	22 (incl. O&G)	Development of aerodynamics codes, realization of fully coupled simulations (servo-aero-hydro-elastic).
Industry	> 15	Offshore structural engineering, with the last 11 years dedicated to offshore wind

Research Institute	11.5	Development & Certification of tower structures, hub structure of a floating wind turbine Fatigue calculation and measurement analysis of a floating support structure & tower
Floating Development	2	Development stages of projects, both fixed and floating offshore wind farms, located in Spain, Italy, Philippines and Australia.

5.2. Array Level Upscaling

Section 4.3 presents the component-level risk assessment for a single FOWT. The critical failure modes and causes are identified, and to obtain farm-level risks, component-level risks are upscaled in this section and presented. Moving from turbine-level risk assessment to cover the entire FOWA requires a detailed, systematic approach that also investigates the mutual and interdependent risks within the farm. Understanding failure propagation is essential for assessing risk at the array level. Initially, the cumulative effects of an individual turbine within a FOWA should be analyzed to inform aggregate risk assessment. Turbines in a FOWA do not operate in isolation, particularly when shared mooring systems [43], [44]. Instead, they function as part of an interdependent system, where the failure of one unit can impose increased mechanical loads or dynamic forces on surrounding turbines. This interaction is critical to capture when evaluating farm-level risks [8]. Environmental conditions also have a significant impact in addition to the technical limitations. The regional weather patterns might also affect the operation of the farm and the failure of the turbines. To conduct a detailed wind farm risk assessment, the influence of the environmental condition should also be considered [45]. Some array-related risks, their causes, and mitigation strategies are given below in **Table *2***.

Table 2: Floating wind array specific risks

Risk	Cause	Effect	Mitigation Measures
Array Efficiency Reduction	Wake effect, turbine placement	Decreased overall energy production	Optimal turbine spacing, advanced layout design
Electrical System Failures	Grid integration issues, cable faults	Power loss, operational inefficiency	Redundant electrical systems, regular maintenance, and advanced grid integration techniques
Communication System Breakdown	Technical faults, software issues	Inefficient operation, delayed response to failures	Redundant communication systems, regular software updates and checks
Inter-turbine Collisions (Offshore)	Station keeping failure, or structural failure of one turbine	Damage to turbines, safety risks	Adequate spacing, monitoring systems and proper maintenance
Environmental Impact on Marine Environment	Noise, shadow flicker, oil leakage	Impact on wildlife, Community opposition, regulatory challenges, penalties, enforcement, prohibitions and suspensions	Environmental impact assessments, community engagement, careful site selection

Cumulative Mechanical Stress	Constant operation, environmental factors	Accelerated wear and tear, increased maintenance needs	Regular inspections, stress monitoring systems, robust design standards
Supply Chain Disruptions	Market fluctuations, logistical challenges, tariffs/trade wars	Delays in maintenance, increased operational costs	Diversified supply chains, strategic stockpiling of key components
Cybersecurity Attacks	Digital vulnerabilities, unauthorized access	Operational disruption, data theft	Robust cybersecurity protocols, regular security audits
Weather-Related Risks	Extreme weather events, climate change	Turbine damage, operational downtime	Weather-resistant designs, advanced forecasting, emergency response plans
Regulatory and Policy Changes	Political shifts, changes in energy policy	Financial risks, project delays	Active regulatory monitoring, flexible business strategies
Mooring Line Failures	Environmental stress, wear and tear	Drifting or misalignment of turbines, operational disruption	Robust mooring designs, regular inspections, and maintenance
External Vessel Collisions	Navigational errors, poor visibility, loss of vessel control, dynamic positioning system (DPS) failure, harsh sea state	Damage to turbines or service operation vessels (SOVs), safety hazards	Strict navigational protocols, vessel monitoring systems
Installation Challenges on Farm Location	Technical difficulties, unexpected soil conditions, weather conditions	Delays in project timelines, increased costs	Advanced planning, skilled installation teams
Operational Coordination Difficulties	Management complexity, communication issues	Inefficient operation, response delays	Integrated management systems, clear communication channels
Access Difficulties (Offshore)	Harsh weather, sea conditions	Maintenance challenges, increased downtime	Advanced access strategies, weather-adaptive planning
Underperformance of Turbines	Design flaws, unforeseen operational issues	Lower than expected energy output	Continuous performance monitoring, adaptive operational strategies
Seabed Erosion (Offshore)	Water currents, seismic events, anchor installation	Instability of anchors, structural risks, CPS movement and degradation	Seabed monitoring, erosion-resistant design
Accidents and Safety Incidents	Operational hazards, human error	Injuries to personnel, operational disruption	Safety protocols, training and emergency preparedness
Insurance and Liability Issues	Complex operational environment	Financial and legal liabilities	Comprehensive insurance coverage, risk management strategies
Social and Community Challenges	Noise, visual impact	Public opposition, legal challenges	Community engagement, visual impact assessments

6. Data Processing and Results

6.1. FMEA Results - Component Level

For the FMEA survey, 7 comprehensive tables of potential failure modes and their associated failure mechanisms, causes and end-effects of the tower, transition piece, floater, mooring systems, and dynamic cable components were used to obtain the FMEA scoring criteria (based on Table 3-5) at component level and potential failure modes with farm-level effects from workshop participants. This part presents the top ten important failure modes at component levels for each of the analyzed subsystems, followed by the results of FMEA for all failure modes with farm-level implications in the next section.

6.1.1. Tower Failure Modes

The analysis of failure modes for the tower component of a floating wind turbine identifies ten critical failure modes with the highest Risk Priority Numbers (RPNs). The prioritized failure modes mainly involve crack formation in the primary steelwork and welding of the tower, which pose significant risks, including potential tower collapse and loss of the turbine. The most critical failure mode is cracking in the primary steelwork due to stress and fatigue during installation (TO12). This can occur from environmental exposure to waves and wind, compounded by poor manufacturing and incorrect installation practices that lead to stress concentration points.

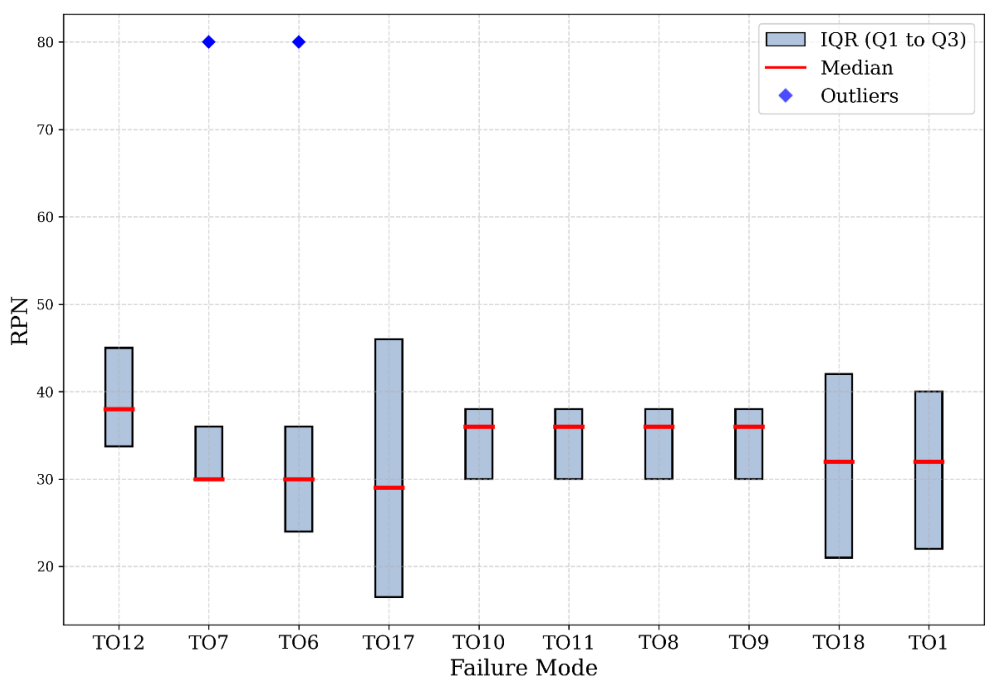


Figure 7: Critical failure modes for the tower

Figure *7* presents the box plot for the prioritized failure modes of the transition piece considering the interquartile range (IQR) which represents the spread of the data (range of the middle 50% of the data). Cyclic loading from wind and waves (TO7) is another prominent cause, leading to stress

concentration and material fatigue. These environmental factors, combined with overloading, result in cracks that compromise the integrity of the primary steelwork. Other significant failure modes involve material fatigue stemming from high-frequency loading conditions (TO6) and lightning strikes (TO17) that can cause cracks in the tower if lightning prevention systems are inadequate. Poor manufacturing quality (TO10) and poor manufacturing control (TO11) in welding can also lead to cracks due to insufficient control over materials and processes.

Welding failures further contribute to critical failure modes. Inadequate welding design procedures (TO9), and poor practices in harsh conditions (TO8) can lead to joint failures. These welding-related cracks, often resulting from environmental exposure or design errors, increase the risk of potential tower collapse. The possibility of resonance (TO1) occurring due to natural frequency matching with external forces also presents a risk of fatigue failure, which could lead to catastrophic outcomes, such as tower collapse or turbine loss.
The failure modes are ranked and prioritized based on the average RPN values. Discussing the results in **Figure** *7,* the means for the failure modes have similar values. When the outliers are considered, TO7 and TO6 have the highest RPN values. It means that cyclic loading from wind and waves (TO7) and material fatigue due to high-frequency loading conditions can be either experienced or defined as the most critical one by the expert, and it requires special attention. TO10, TO11, TO8, and TO9 have relatively lower variability compared to other failure modes. It can be said that there is more agreement in those failure modes. Especially for welding failure, its causes and end effects are less uncertain.
The critical failure modes for the tower component of floating wind turbines are predominantly associated with environmental exposure, poor manufacturing practices, overloading, and inadequate design considerations for welding and lightning protection.

6.1.2. Transition Piece

The transition piece, which connects the tower to the floating structure, is particularly susceptible to failures stemming from environmental exposure, poor welding practices, and structural fatigue. According to the results, the most prominent failure modes include fatigue in the primary structure and welding joints caused by unbalanced loads or wind-induced vibrations (TP6), and cyclic loading (TP4). These dynamic conditions can lead to fatigue crack initiation and propagation, ultimately causing the failure of the tower connection. Welding failures (TP19) are another critical concern, often resulting from poor welding practices or suboptimal heat treatment during maintenance or installation. Such failures can lead to joint failure and overall structural instability of the transition piece.

Corrosion and fatigue are also significant failure modes. Fatigue is mainly due to improper analysis or human error in the design process (TP1). In the transportation, and installation phase (TP8) fatigue is also critical when the transition piece is exposed to bending and twisting loads where corrosion is a contributing factor. These conditions can exacerbate material fatigue and lead to potential loss of load transfer and structural failure. Extreme environmental conditions, such as hurricanes or storm surges, can also cause cracking (TP21) of the primary structure and welding joints, pushing them beyond their design limits and causing structural instability.

Additionally, brittle fractures can occur in extreme environmental temperatures during operation (TP2), shifting the ductile-to-brittle transition temperature and resulting in loss of structural

integrity. Changes in wave spectrum and resonance (TP3) can further increase loads, causing structural plastic deformation in the transition piece and threatening load transfer efficiency. Lastly, large forces from waves, wind, and vessel motion during installation (TP15) can lead to combined cracking, and fatigue exacerbated by loss of material due to corrosion, undermining the stability and reliability of the transition piece.

The critical failure modes for the transition piece are predominantly driven by environmental exposure, overloading, poor design, and welding practices. To mitigate these risks, enhanced quality control for welding and robust/advanced material selection is required to ensure the reliability of FOWT systems.

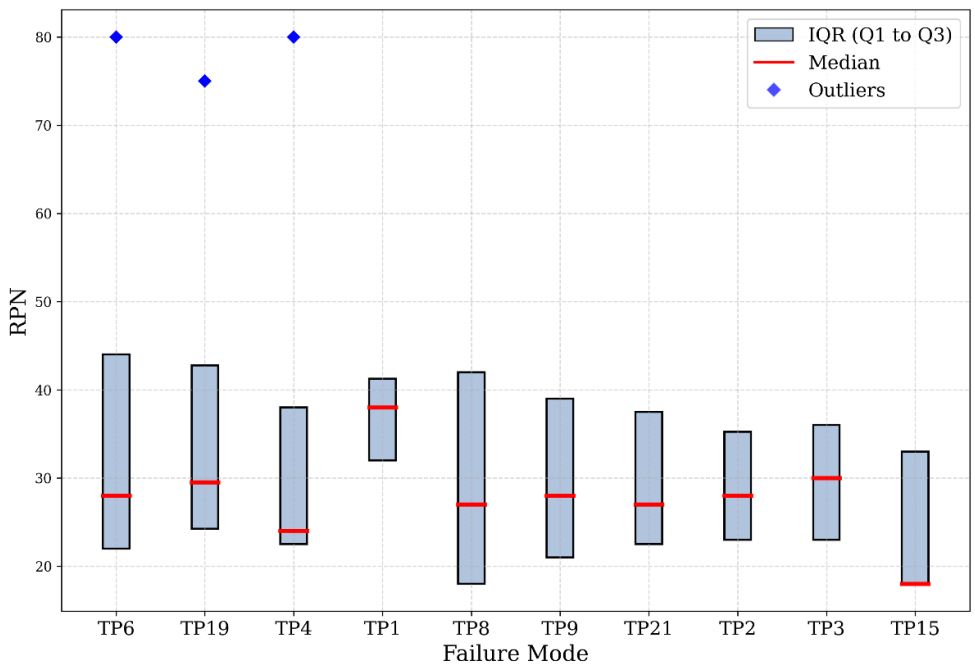


Figure *8*: Critical failure modes for the transition piece

The top three failure modes, Fatigue due to unbalanced loads (TP6), welding failure/cracks due to poor welding practices (TP19), and fatigue cracks due to cycling loading (TP4), have the maximum RPNs as outliers where the pattern follows the means.

6.1.3. Floating Support Structure Failure Modes

The most critical failure mode for the floater is identified as cracks in the primary structure and welding (Floater Failure (FF)9), which often result from fatigue due to continuous vibration and resonance. Environmental exposure and poor or inadequate maintenance strategies can worsen these conditions and lead to structural failure. Corrosion and fatigue in the primary structure (FF7) are also critical concerns, with fatigue being particularly significant due to excessive fatigue life consumption during installation or transportation.

Structural failure and capsize (FF1) is a critical failure mode for the floater, which is mainly caused by human error during the analysis/design process. The end effects of this failure mode are the watertight fault, loss of stability, and potential collapse of the system. Cracks (FF28) and welding defects (FF30) on the floater can develop due to poor quality control, manufacturing defects, and poor welding practices. Cracks and welding defects can result in loss of structural integrity and watertightness, increasing the risk of sinking. Secondary structure failures (FF6) are connection failure, cable damage due to dynamic umbilical connection under mechanical stress, and environmental exposure. The cracks and corrosion on the secondary structure components can result from poor maintenance practices, inefficient detection (FF13) and exposure to harsh environmental conditions, leading to degradation of the structural components (FF22), reduced system stability, and, finally, potential collapse.

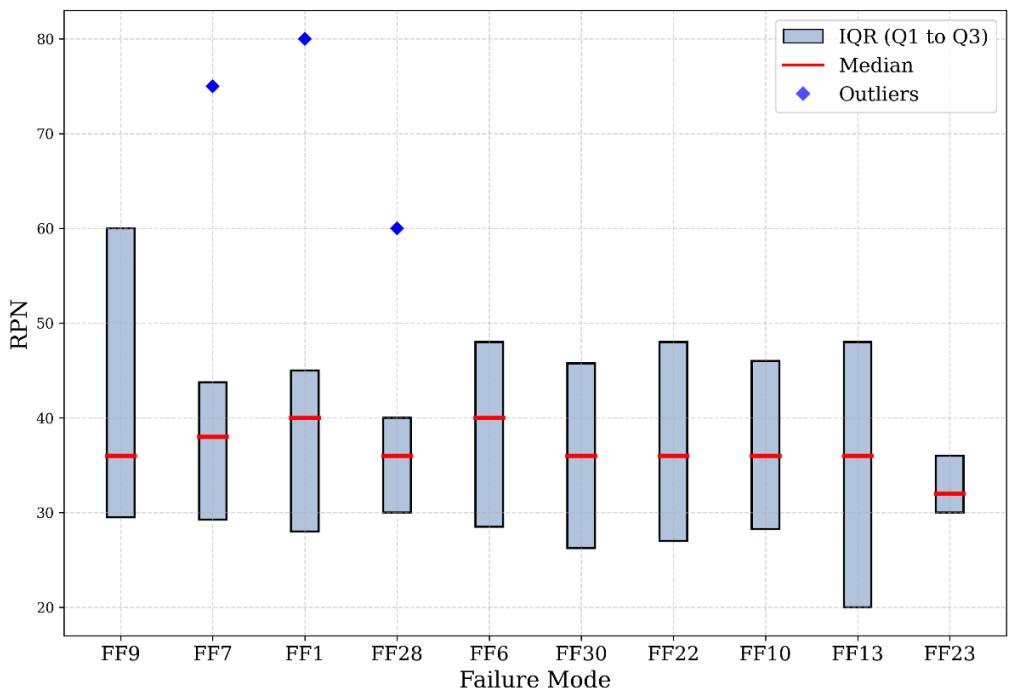


Figure *9*: Floating substructure critical failure modes (failure mode codes are explained in text)

Fatigue due to the underestimation of steel thickness (FF10), manufacturing defects (FF23) or environmental loads can result in corrosion and cracks in the floater, which creates high risks to system stability. Environmental exposure, poor manufacturing practices, and deficiencies threaten the structural integrity and stability of the FWT system.

The outliers in **Figure *9*** show that fatigue due to excessive fatigue loading during installation (FF7), structural failure and capsize due to human error in the analysis phase (FF1), and cracks due to undetected defects during quality control (FF28) also have critical RPNs according to inputs from the experts. Compared to other components, the floater has relatively shorter boxes, which means that the experts' general opinion about the failures is consistent.

6.1.4. Station Keeping System Failure Modes

One of the most critical failure modes involves mooring line wear, which can result from poor fabrication quality (SKS14), improper handling (SKS16), excessive tension, or line bending and twisting. These conditions can lead to platform instability and potential drift with the loss of integrity of mooring lines. Mooring line breakage (SKS20) is another significant failure mode caused by hysteretic heating or wet-dry cycling, which can cause degradation of the mooring lines over time.

Anchor failures are also among the critical failure modes that can affect system integrity. Anchor failures can result from abnormal working conditions (SKS1) due to poor installation or cyclic degradation (SKS2) under environmental exposure. Anchor failures can lead to anchor detachment, which would allow the platform to drift, creating significant operational hazards.

The buoyancy elements of the mooring lines are susceptible to failure (SKS3) due to material fatigue and environmental exposure, leading to loss of buoyancy and increased line stress. Similarly, clump weight detachment (SKS4), caused by material fatigue and harsh environmental conditions, increases line stress and potential platform instability.

Failures related to the fairlead components include fatigue (SKS5) and corrosion (SKS6) failure due to poor maintenance and environmental exposure. Poor maintenance and environmental exposure can cause mooring line damage and increased mooring wear and finally have an impact on the overall platform stability and station keeping. Mooring line fatigue can result from improper operational procedures (SKS13), such as excessive loading, bending, and twisting of the lines. This can lead to platform instability and potential drift, posing serious risks to the integrity and functionality of the floating wind turbine system.

Figure *10* presents the RPNs of critical failure modes as a box plot, where more information about the data can be seen as variability and maximum values. Mooring line breakage due to hysteretic heating or wet-dry cycling (SKS 20) has a high maximum RPN value of 50, which is higher than other critical failure modes. This failure mode is seen as critical and needs special attention for mitigation strategies. To mitigate the failure effects, quality control during manufacturing, robust design standards, detailed operational procedures, and effective maintenance strategies can ensure an asset management strategy for the component and reliability and safety of the structure.

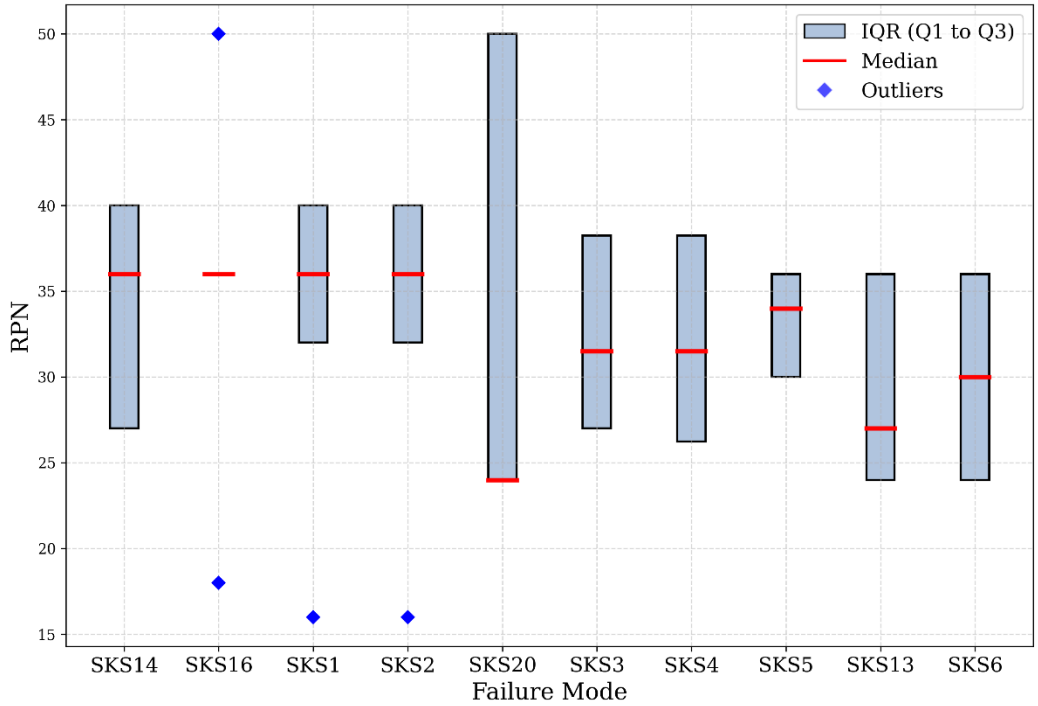


Figure 10: Critical failure modes for the station-keeping system

6.1.5. Dynamic Cable Failure Modes

The most critical set of failure modes for the entire FOWT system involves the CPS, which is vulnerable to abrasion (DC26, corrosion DC27, and fatigue, DC25). The main reasons for the failures in CPS are seabed mobility, scour, and marine growth that cause the CPS movement and degradation. Design inefficiency, incorrect installation, and lack of data on the deployment location accelerate those problems and can cause potential cable failure and power loss.

Conductor failure and insulation breakdown are critical failure modes for the cable system integrity. Critical failure modes such as conductor fatigue cracks (DC19), insulation breakdowns (DC3), accelerated mechanical fatigue (DC1) and failure of watertightness (DC16) arise from mechanical stress, repeated stress cycles, and manufacturing defects. Unexpected dynamic events, such as loss of a mooring line or electrical overloads, can trigger failures on the conductor or insulation breakdown, which can result in reduced power transmission efficiency, downtime, and loss of cable structural integrity.

Sheath damage (DC15) is also another significant failure mode for the cable system, which is caused by mechanical stress and environmental exposure. Sheath damage can lead to exposure of cable internal components and potential faults in the cable. Improper burial of the static or export cable (DC31) due to environmental exposure or improper installation practices can result in a reduced sediment cover lower than the design amount, which increases the risk of cable exposure and wear. In this report, the main focus is the dynamic cable and static cable is considered here only as a part of power cable system.

The data variation of the dynamic cable can be seen in **Figure 11**, where DC26 (abrasion) and DC25 (fatigue), which are failure modes related to CPS due to lack of data on the deployment and design inefficiency, have the highest outliers, which lie on the high-risk scale. Similar to the other components, the mean RPNs have slight variation, where DC19 and DC15 have higher variability in the data. For DC3 there is no variability in the data, and the expert input is the same. Risk mitigation strategies for dynamic cable critical failure modes include standardized design and installation practices, detailed environmental assessment, and quality control measures during manufacturing.

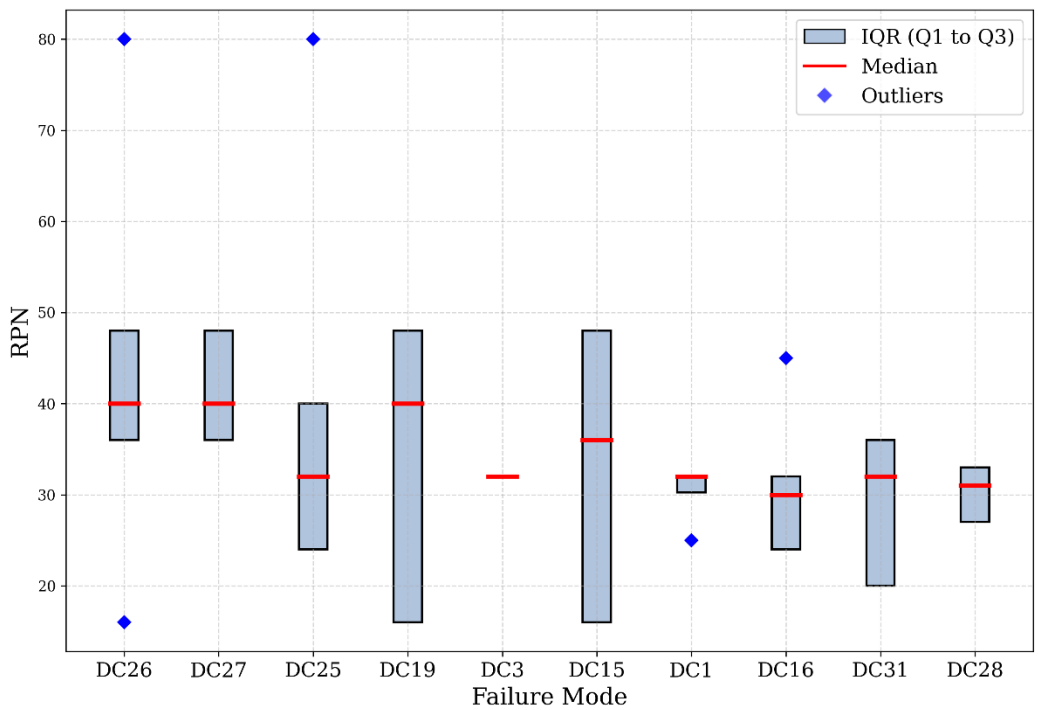


Figure 11: Critical failure modes for the dynamic cable

6.2. FMEA Results - Farm Level

A component failure in one turbine can lead to cascading effects within a floating offshore wind array, which can happen in different ways [46], for example:

- Structural integrity interactions: Although turbines in a FOWA are typically spaced far apart, certain interdependencies, such as shared electrical cables or control systems, can result in indirect effects. For example, the failure of a structural component (e.g., floater or tower) may disrupt array-wide dynamics or increase fatigue loads on nearby turbines due to changes in hydrodynamic behavior or control responses.
- Shared mooring system effects: In configurations where mooring lines or anchors are shared between turbines, the failure of a single mooring component can redistribute tension across the system. This may affect the positional stability and loading of adjacent turbines,

especially in cost-optimized layouts with limited redundancy. In contrast, failure of a mooring line that supports only one turbine is unlikely to directly impact neighboring units.

It should be noted that this section only assesses whether a failure mode could have an impact at the farm level, as defined by the potential of single component failure affecting the performance, stability or reliability of another turbine in the array. This assessment is based solely on the expert opinions received from the FMEA survey and reflects perceived interdependencies between turbines. It does not take into account the number of turbines that could be impacted or the variations in possible deployment sites as it is beyond the conventional FMEA approach. A technique to calculate the farm-level effects is proposed in Section 6.3, assuming an array configuration for ten floating turbines.

Participants in the FMEA survey were asked if they believed a component failure mode would cause a farm-level failure. This binary 'yes' or 'no' response was further classified, and a high-level result of component failure modes and criticality numbers was generated. **Figure 12** depicts a summary of the procedure, and the results of the analysis are presented in this section.

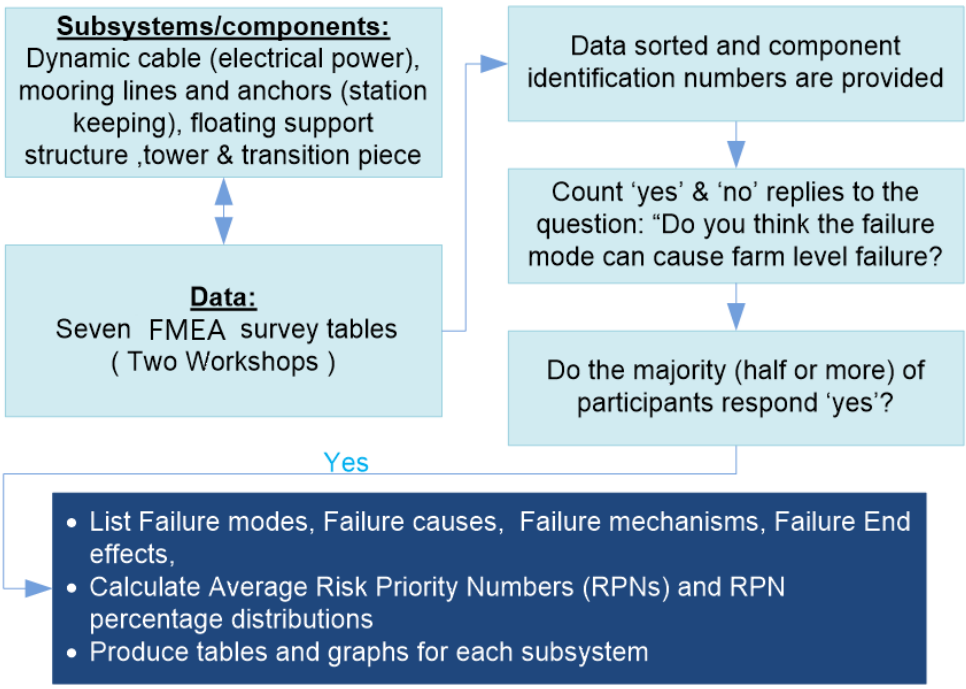


Figure 12: Farm-level failure mode analysis based on the FMEA survey

6.2.1. Tower and Transition Piece Failure Modes - Farm Level Effects

While the transition piece is typically regarded as a component of the substructure for fixed-bottom offshore wind turbines [50], it is the primary structure for floating offshore wind turbines [51]**Error! Bookmark not defined.** This subsection presents the failure modes of the tower and transition piece coupled with their impacts at the farm level. For the tower, the FMEA survey gathered 23 failure modes for the steelwork primary structure and welding components. Only 3 (13%) failure modes were identified in the survey as those with potential farm-level effects, as

described in **Table 3**. Figure 13 depicts an overview of the data from Table 3, as well as a breakdown of failure causes (root) for each of the farm-level failure modes of Tower components.

Table 3: A description of failure modes with potential farm-level failure effects for the tower

Component	Failure mode	Failure root	Failure mechanisms	End effect	RPN	± STD	%RPN
Primary steelwork	Cracks	Climate change/ environmental factors	Stress concentration and fatigue due to high waves/winds/high frequency of loads (above design assumptions)	Potential collapse and failure of whole facility	39	21	44.9%
Primary steelwork	Cracks		Blades and tower interactions (tower shadow) caused by the extreme motion of floater in high wind/wave		22	11	25.1%
Primary steelwork	Plastic deformation	Design	Insufficient yield strength and lack of detailed stress analysis and simulation		26	8	30.0%

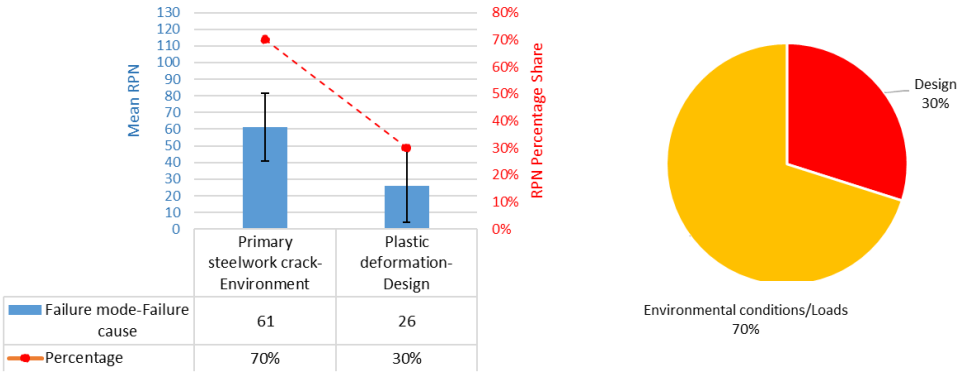


Figure 13: An illustration of component failure modes with potential farm-level effects for the tower (left) and failure cause distributions (right)

The predominant failure mode (over 70% of the obtained RPNs for the tower farm-level impact failure modes) in **Table *3*** was determined to be the tower crack failure mode; the other tower failure mode that may have farm-level consequences was plastic deformation (or irreversible changes in shape due to excessive stress). While design errors may be the cause of plastic deformation failure, environmental conditions such as high waves and wind that exceed design assumptions were responsible for tower cracks, either due to fatigue or interactions between blades and tower (tower shadow) caused by floater motion.

The FMEA survey for the transition piece covered 21 failure modes. The participants rated 5 (24%) of the failure modes as those that could have a farm-level impact, which are presented in **Table 4**. **Figure *13*** illustrates a summary of **Table *4*** data.

Table *4*: A description of failure modes with potential farm-level failure effects for the transition piece

Component	Failure mode	Failure root	Failure mechanisms	End effect	RPN	± STD	%RPN
Primary structure & welding	Cracks /break	Climate change/ Environmental factors	Large forces on transition piece beyond the design limits (caused by large storm surges and hurricane)	Tower unit collapse, buckling of the transition piece, floater unit damage	33	18	21.5%
Primary structure	Structural plastic deformation	Climate change	Changes in wave spectra/increased loads	Local stress accumulation	29	7	19.0%
Primary structure & welding	Break	Design	Analysis and calculation fault (human errors)	Tower collapse, floater unit damage	35	9	23.1%
Primary structure & welding	Break		Under-designed structure due to insufficient environmental data		29	13	18.8%
Primary structure & welding	Break	Maintenance	Improper quality control and undetected defects		27	7	17.7%

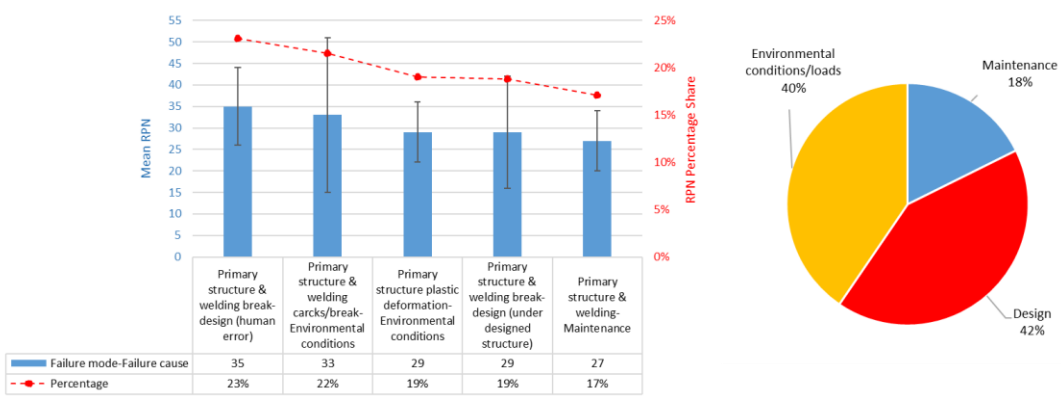


Figure 14: An illustration of component failure modes with potential farm-level effects for the transition piece (left) and failure cause distributions (right)

According to the FMEA analysis in Table 4, the only failure mode that can potentially have an impact at the farm level is the transition piece cracking or breaking. Climate change or harsh environmental circumstances that surpassed the design limits account for roughly 40% of the RPNs, design mistakes account for 42%, and inappropriate maintenance accounts for 18% of the total transition component RPNs.

6.2.2. Floating Support Structure Failure Modes - Farm Level Effects

A semi-submersible floating substructure, which is included in this study, typically consists of three or four buoyant columns or other floating elements at the periphery that are connected using pontoons and/or trusses. They are typically ballasted to provide additional stability [47]. The dimensions of a typical steel semi-submersible for a 15 MW turbine are around 80 × 90 × 35 m^3, with an unballasted mass of approximately 3,500 t [34]. In this report, a high-level component of the floating support structure is comprised of [34], [48], [49]:

- The primary structure, which consists of the main structural elements that sustain the base of the wind turbine tower, offers buoyancy and shields off loads from the mooring system. It is made of components such as the main hull, columns, and buoyancy chambers.
- The secondary structure, which supports various components including platforms, walkways, access ladders, and other non-primary load-bearing elements.
- Welding, which is essential for assembling steel and other components for the floating support structure. Structural integrity, load-bearing capability, and durability are guaranteed by proper welding.

In the FMEA survey, the floating support structure subsystem included 30 failure modes, and participants rated the occurrence, severity, and detectability of each failure mode. Table 5 lists the average RPNs of 12 failure modes (or 40% of all failure modes) that the majority of participants believed their failure would have possible repercussions at the farm level. **Figure *15*** illustrates a synopsis of the results retrieved from Table 5 as well as a breakdown of the failure cause (root) for the probable farm-level effects of the failure modes of the floating support structure.

The RPN averaging method is applied solely to aggregate expert judgments across the same failure modes, ensuring a standardized consensus while accounting for variability in expert assessments. While arranging failure modes by decreasing mean RPN provides a reasonable indication of relative importance, the high standard deviation values highlight significant differences in expert assessments. Given this range of opinions, it is prudent to consider these failure modes equally critical. This approach applies consistently across all tables in this subsection to maintain methodological consistency

Table 5: A description of failure modes with potential farm-level failure effects for the floating support structure components

Component	Failure mode	Failure Root	Failure mechanisms	End Effect	RPN	± STD	%RPN
Primary structure & Welding	Cracks	Operation	Fatigue due to continuous vibrations/resonance	Structural failure	43	17	12.0%
All structure	Capsize	Design	Analysis and Calculation fault due to human error	Watertight fault, Potential floater unit sinkage	40	20	11.3%
All structures & Welding	Structural break	Maintenance	Undetected defects due to poor quality control	Watertight fault, potential floater unit sinkage	35	13	9.7%
Secondary structure	Additional structure failures	Operation	Dynamic umbilical connection/cable fail	Potential failure	33	12	9.4%
All structures	Structural break	Design	Under designed structure/Component due to insufficient environmental data	Watertight fault, Potential Floater Unit sinkage	30	7	8.5%
Secondary structure	Floater unit sinkage	Design	Insufficient structural strength and cracks on the floater resulting in water ingress to the support structure	Potential Failure/Asset damage/ Energy production loss	29	11	8.1%
Primary structure & Welding	Capsize	Environmental condition	Extreme horizontal oscillatory force	Asset damage/ Energy production loss	27	7	7.5%
All structures	Hit by dropped objects	Environmental condition	Typhoon/strong wind/wave	Damage to the facility, vast economic loses	26	12	7.3%
Primary structure	Capsize	Design	Analysis and calculation fault due to human error	Project cancellation	26	15	7.2%
All structure	Structural break	Environmental condition	Design parameter superseded due to climate change	Structural reassessment	24	9	6.8%
Primary structure & Welding	Structural break	Operation	Structure brittle fracture due to extreme environmental temperature	Tower collapse	23	11	6.4%
All structure	Floater unit sinkage	Operation	Structures break/collapse due to collision with other FOWT	Potential failure/Asset damage, energy production loss	20	15	5.7%

*RPN can be as low as 1 or as high as 125 for each failure mode.
A smaller standard deviation (STD) indicates a greater degree of agreement among the experts' opinions, and conversely a larger STD indicates a wider range of opinions.

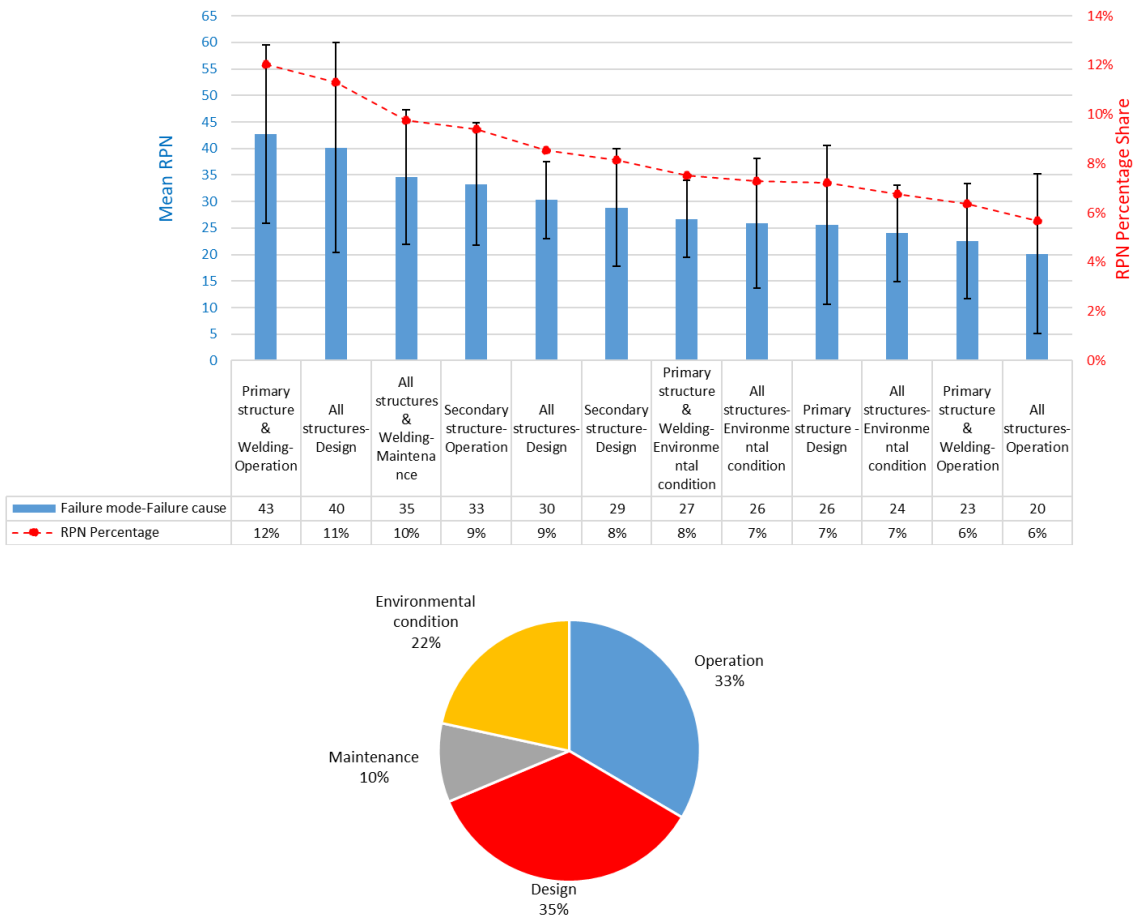


Figure 15: An illustration of component failure modes with potential farm-level effects for the floating support structure (FSS) (top) and failure cause distributions (bottom).

Results in Table 5 shows that:

- Common failure modes in the floating support structure subsystem that can have farm-level implications include cracks, capsize, break, floater sinking, and others.
- Errors in design are responsible for 35% of the failure causes of component failure modes, including capsize (18%), break (9%), and floater sinking (8%).
- Operation failure causes, which account for 33% of component failures, include fatigue (12%), damage to dynamic cable connectors (9%), extreme temperatures (6%), and collisions (6%).
- Environmental factors such as typhoons, severe wind and wave loads, and dramatic climate change can be responsible for 23% of failure mode RPNs.
- Insufficient quality control during maintenance is the cause of 10% of the RPNs linked to the farm-level failure consequences in this subsystem, increasing the possibility of structural fracture and welding damage.

The identification and classification of the RPNs facilitate the recommendation-making process for mitigating the failure modes in the subsequent risk analysis stage of WP3.

6.2.3. Mooring System Failure Modes - Farm Level Effects

The IEA Task 49 will investigate a semi-taut mooring system for shallow water depths of 60 m, a catenary for intermediate water depths of 300 m, and a taut synthetic for deep water depths of 800 m. These mooring system types include a mix of some of the components shown in

Figure 4. The FMEA report covers the following generic components for mooring systems [10], [24], [25], [26]:

- The mooring lines that connect the floating platform to the seabed provide the tension needed to keep it stable and in position. They absorb and disperse the forces exerted by wind, waves, and currents. They are typically made of steel chain, wire rope, or synthetic fibre rope. The choice of material depends on factors such as water depth, environmental conditions, and cost.

- The buoyancy elements provide the necessary lift to counteract the weight of the mooring lines, ensuring they remain suspended at specific depths rather than sinking to the seabed. They help to control the tension in the mooring lines and keep them from dragging on the seabed, which can cause wear and damage.

- Fairleads, which serve as mooring line guides and are crucial for maintaining correct alignment and preventing damage.

- Winches, which are used to adjust the tension and length of the mooring lines, play a crucial role during installation and maintenance.

- Anchors secure the mooring lines to the seabed. Anchors ensure that mooring lines remain fixed to the seabed, providing a stable base for the floating platform. The type of anchor used depends on the seabed conditions and the specific requirements of the wind farm.

As per the FMEA survey respondents, out of the 22 failure modes of the mooring system components, 10 (46%) have the potential to affect the farm. The descriptions of the failures are provided in **Table *6*** and **Figure *16*** presents a breakdown of failure causes with probable farm-level effects.

Table 6: A description of failure modes with potential farm-level failure effects for the mooring system components

Component failure mode	Failure root	Failure mechanisms	End effect	RPN	± STD	%RPN
Fairlead failure	Operation	Fairlead fatigue	The anchor cannot be dropped and lift	35	9	12%
Anchor failure	Operation	Abnormal working conditions	Anchor failure	35	11	12%
Mooring lines broken	Operation	Mooring line wear due to hysteretic heating or wet-dry cycling	Asset not in correct location or position	35	17	12%
Mooring Line Fatigue	Operation	Mooring line fatigue due to Improper operational procedures, such as excessive loading, bending or twisting.	Mooring line strength decrease or broken	31	10	10%

Mooring lines broken	Operation	Friction chain wear due to significant movement and tension due to the forces of wind, waves	Asset not in correct location or position	29	12	10%
Mooring lines broken	Operation	Transitional chain wear due to repeated loading and unloading cycles over time	Asset not in correct location or position	28	11	9%
Mooring line breakage	Manufacturing	Poor splice quality/ workmanship/qualification	Mooring line strength decrease or broken	28	8	9%
Mooring Line Corrosion	Maintenance	Mooring lines corrosion due to improper maintenance of the corroded components	Mooring line strength decrease or broken	27	8	9%
Mooring winch failure	Maintenance	Mooring winch failure due to undetected hazard during operation	Asset not in correct location or position	26	9	9%
Mooring line wear	Design	Mooring lines wear due to underestimation of seismic events during design or due to rope compression not considered	Mooring line strength decrease or broken	26	9	9%

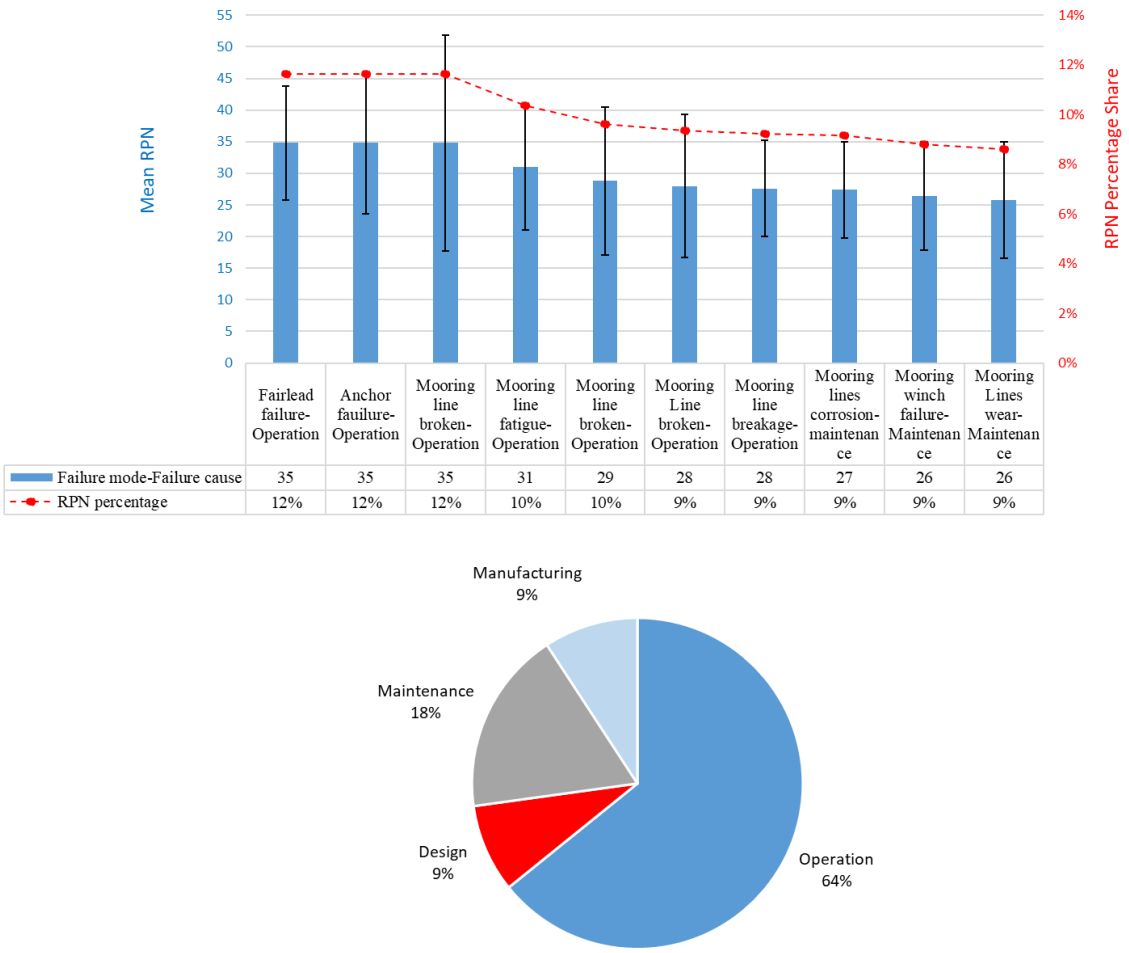


Figure 16: An illustration of component failure modes with potential farm-level effects for the mooring systems (top) and failure cause distributions (bottom)

Results in **Table 6** indicate that:

- Mooring line breakage accounts for around 50% of farm-level RPNs due to wear, fatigue, friction, and tension during operation as well as due to inferior manufacturing materials.
- Other mooring line failure modes, each accounting for around 9% of RPNs, include mooring line wear due to design flaws (for example, underestimation of seismic occurrences), corrosion, and winch failure due to poor maintenance.
- Fairlead fatigue and anchor failure during operation are each responsible for 12% of RPNs.
- These failure modes are mostly caused by operation errors (64%), maintenance faults (18%), and manufacturing/design concerns (9% each).

It should be noted that all of the FMEA scorings for the failure modes with farm-level effects are based on the subjective opinions of the experts who participated in the FMEA survey. Although this falls within the scope of this report, which attempts to provide a common failure risk analysis, the complexity of failure propagation necessitates the use of alternative probabilistic models to further investigate the effect of a component failure in a turbine, with the potential for propagation to farm-level impacts, such as causing failures or shutdown in adjacent rubines within an array. One such approach is Bayesian network analysis, which is illustrated in the next section using a 10-turbine FOWA example.

6.2.4. Dynamic Cable Failure Modes - Farm Level Effects

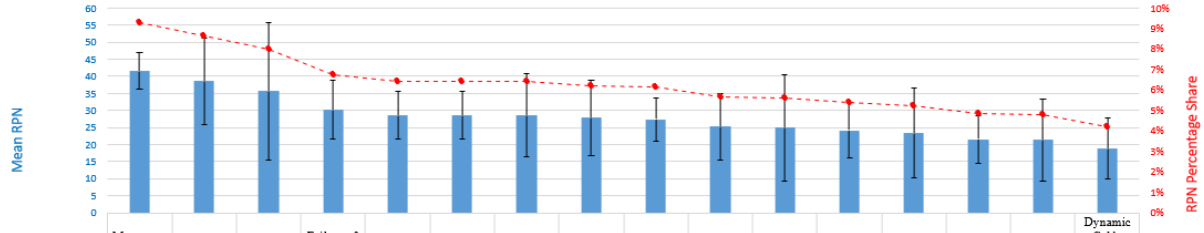
The Task 49 reference design specifies the types and property assumptions for dynamic cables. The lazy-wave dynamic cables are considered for shallow-water designs (60 m water depth) and intermediate-water designs (300 m water depth). Fully suspended power cables are proposed for deep-water design (water depth of 800 m). The FMEA survey, in this report, however, evaluates a high-level failure mode of the dynamic cable's auxiliary components listed below [41].

- Buoyancy modules, which lift the lazy wave type cable segment at midwater and guide the suspended type of cable throughout, keeping it off the seabed.
- Hang-offs, which secure the cable to the top of the floater platform.
- The cable protection system (CPS), which helps shield cables from wear and tear, abrasion, fatigue, and harmful movement like overbending in vulnerable spots. It is typically made up of bend stiffener, bend restrictor, i-tube and j-tube, joint and connections.
- Static cable/export cable.

In the FMEA survey, participants identified 50% of the 32 dynamic cable failure modes as failure modes with potential farm-level effects. **Table *7*** describes the various failure modes and their average RPNs. **Figure *17*** demonstrates an overview of the results obtained from **Table *7***, as well as a breakdown of failure causes (root) for the most likely farm-level effects failure types of dynamic cable components.

Table 7: A description of failure modes with potential farm-level failure effects for the dynamic cable components

Component	Failure mode	Failure root	Failure mechanisms	End effect	RPN	± STD	%RPN
Cable Protection System (CPS)	Movement of CPS due to scour/seabed mobility	Installation	incorrect installation	Cable being vulnerable to scour and need for repair or replacement	42	5	9.3%
CPS	Movement of CPS due to scour/seabed mobility	Design	lack of data of the deployment location	Cable being vulnerable to scour and need for repair or replacement	39	13	8.6%
Dynamic Cable	Fatigue Cracks	Operation	Repeated stress cycles - bending motions	Crack may evolve in a fault of the cable - Cable weakening	36	20	8.0%
Dynamic Cable	Failure of watertightness	Manufacturing	Errors or defects during manufacturing	Reduced or interrupted electricity flow	30	9	6.8%
Static cable/Export Cable	Reduced sediment cover lower than designed value for protection	Design	Insufficient information for the deployment location	need for re-burial, change of cable protection requirement or even replacement of cable	29	7	6.4%
Touchdown point	Reduced sediment cover lower than designed value for protection	Design	Insufficient information for the deployment location	need for re-burial, change of cable protection requirement or even replacement of cable	29	7	6.4%
Dynamic Cable	Small bending radius	Operation	Mechanical stress - excessive bending	Cable damage - insulation degradation	29	12	6.4%
Dynamic Cable	Failure of watertightness	Operation	Damage on the cable due to extreme environmental events	Reduced or interrupted electricity flow	28	11	6.2%
Dynamic Cable	Material degradation due to accelerated mechanical fatigue	Design	Underestimation of dynamic conditions - Unexpected contingency scenario (e.g., loss of mooring lines)	Structural damage - cable composition weakening	27	6	6.1%
Insulation	Failure of insulations	Design	Improper design; need quality insulation materials and protection	Fault in the cable - power disruption	25	10	5.6%
Conductor	failures of conductors	Operation	Internal damage: Problem in insulation material - Electrical overload	Electrical faults - loss of production	25	16	5.6%
Joints and terminations	Failure of end termination	Manufacturing	Poor quality of insulating fluids	breakdown of insulation	24	8	5.4%
J-tube	Corrosion	Design	Seawater exposure, environmental conditions due to insufficient coating	J-tube degradation affecting cable integrity	23	13	5.2%
Hang-off	Damage/ corrosion of mechanical parts	Design	Wrong design/execution of the isolation material	High risk/ total loss of the line / production loss on the string	22	7	4.8%
Dynamic Cable	Detachment	Operation	Connector failure/ mechanical stress	Cable disconnection, water penetration, power loss	21	12	4.8%
Dynamic Cable	Debris disturbance	Environmental conditions	Floating debris/ marine activities	Cable damage, operational disruption	19	9	4.2%



	Movement of Cable Protection System (CPS)-Installation	Movement of CPS-Design	Fatigue cracks of Dynamic Cable-Operation	Failure of watertightness of Dynamic Cable-Manufacturing	Static/Expoert cable damage-Design	Touchdown point damage-Design	Small bending radius of Dynamic Cable-Operation	Failure of watertightness of Dynamic Cable-Operation	Material degradation of Dynamic Cable-Design	Insulation failure-Design	Conductor failure-Operation	Joints & terminations failure-Manufacturing	J-tube corrosion-Design	Hang-off damage-Design	Dynamic Cable detachment-Operation	Dynamic Cable debris disturbance-Environmental conditions
Failure mode-Failure cause	42	39	36	30	29	29	29	28	27	25	25	24	23	22	21	19
Percentage	9.3%	8.6%	8.0%	6.8%	6.4%	6.4%	6.4%	6.2%	6.1%	5.6%	5.6%	5.4%	5.2%	4.8%	4.8%	4.2%

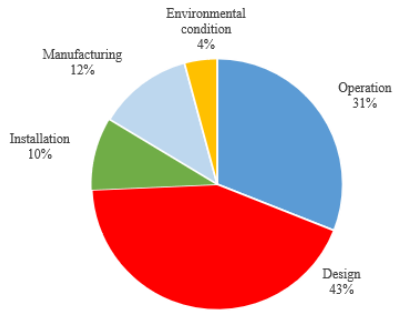


Figure 17: An illustration of component failure modes with potential farm-level effects for the dynamic cable (top) and failure cause distributions (bottom)

Results in **Table 7** indicate that:

- Common dynamic cable failure modes that could affect farms include CPS movement due to installation or design errors; cable fatigue due to repeated stress, cable watertightness and failure of conductors, or detached cables during operation; damage to hang-offs due to incorrect design; failure of j-tube end terminations due to manufacturing errors; reduced sediment in the export cable or touchdown due to design errors; and debris disturbance from environmental factors.
- Design errors account for 43% of the dynamic cable RPNs, including CPS movement (9%), reduced stability of static cable and touchdown points (6% each), material degradation and insulation failures (6% each), and j-tube corrosion and hang-off damage (5% each).
- Operational failure causes, which account for 31% of all dynamic cable RPNs, include fatigue cracks (8%), small bending radius, watertightness and conductor failures (each 6%), and detachment (5%).
- Improper installation can also result in the CPS movement, which can be vulnerable to scouring (around 10%). Defects and poor quality of insulating fluids can lead to the loss of watertightness (7%) and damage and corrosion of mechanical elements of hang-offs components (5%). Finally, environmental factors, such as floating debris and marine activities, can be responsible for 4% of dynamic cable failure modes.

6.3. Bayesian Network Probabilistic Analysis

Bayesian networks are tools used in failure analysis. They combine graphical structures (i.e., mathematical representations of relationships between failures) with failure probabilities. Many studies use Bayesian networks to assess critical failures of mechanical systems. Studies have used Bayesian network analyses to study floating offshore wind turbine failures [22], [55], [56].

In the Bayesian network, each node of the graph represents a failure, and the edges connecting nodes show the causal relationships between failures. Calculations across Bayesian networks, called Bayesian inference, explain the probability of a failure A given a failure B already occurred. To build and use a Bayesian network, it is necessary to construct a network structure and estimate initial failure probabilities.

6.3.1. Network Design

There are two designs for the structure of the network. The first structure (referred to as the 'linear' design) pulls data exclusively from the failure modes and failure effects sections of the FMEA table, including all the components. Comparatively, the second structure (referred to as the 'circular' design) uses information about the causes of failure, modes, effects, systems, and turbine to create the nodes automatically without manual interference.

In the linear design, to obtain the nodes of the graph, all the failure modes and failure effects from the FMEA table are converted into nodes. The edges from failure effects to failure modes are added based on descriptions in the FMEA table and our previous knowledge on failure modes connections. This creates a foundation for the network. However, Bayesian networks must be acyclic graphs (i.e., have no loops). Hence, we manipulate the constructed graph into an acyclic graph G using a modified breadth-first search. First, an arbitrary starting failure is chosen and added to G. Next, all the direct effects (or 'children') of the starting failure are found and added to G, and connected to the starting failure. Then, each of the children of the starting failure is added to G, making sure to exclude failures already in G. This exclusion ensures that G remains acyclic. This process is repeated for the grandchildren, great-grandchildren, etc., of the starting failure until no failures are missing from G. An example of the linear design of a broken mooring line can be seen in **Figure *18***.

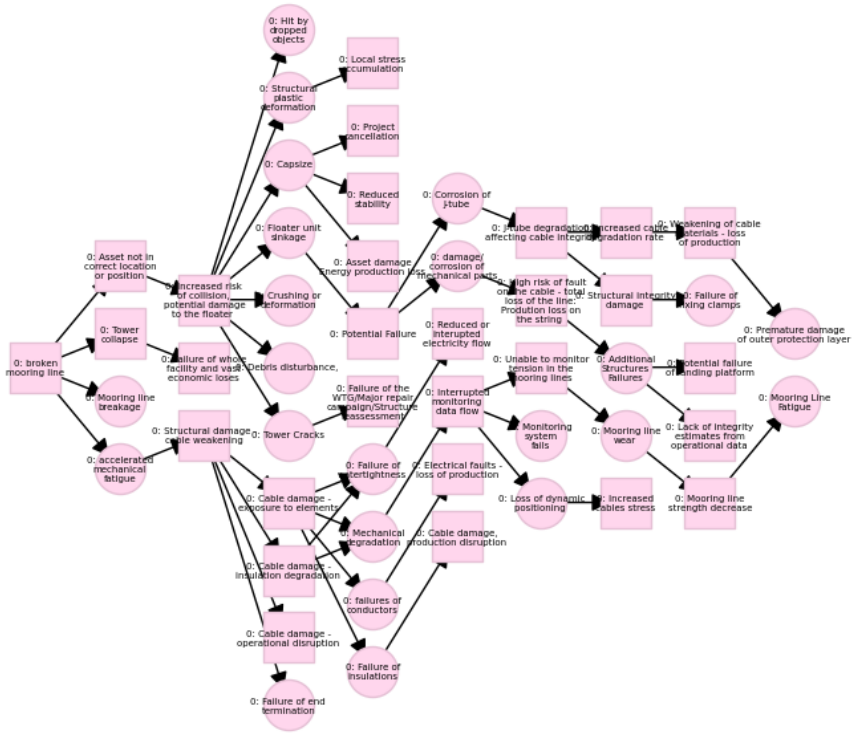


Figure 18: Graphical structure for a Bayesian network using the linear design for one turbine and starting at the 'broken mooring line' failure mode

Yet, since the failure matrix is confined to the components and phenomena in a single turbine, an additional step is required to extend the method to the array level. When finding the children of failure i in turbine j, if the majority of experts listed that the failure could affect the array, then we add both the children of failure i in turbine j and the children of failure i in turbines close to the turbine j. The array layout used for the implementation is presented in **Figure *19***.

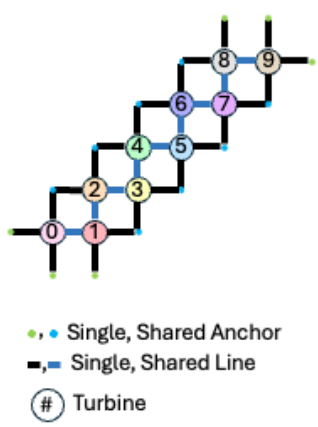


Figure 19: Floating array design used for the array-level linear network design

The benefit of the linear network design is that it accounts for failure effects, causing additional failure modes to occur. In other words, the failure modes and failure effects interact with each other in this design. However, the addition of edges based on our prior knowledge leaves room for error and adds increased uncertainty to our results.

Alternatively, the circular design creates nodes from the failure causes, failure modes, failure effects, component systems, the floating turbine, and the farm. This method was originally proposed by Li, Guades Soares, and Huang in their paper about floating offshore wind turbine failure analysis [55]. The main difference between their work and ours is that they base their structure on a fault tree while we base our network on our FMEA table. Additionally, we add failure causes to our Bayesian network, while Li, Guedes Soares, and Huang focus only on failure modes, effects, systems, and turbines [55]. For this network design, we construct edges from failure causes to failure modes, from modes to effects, from effects to systems, from systems to the floating turbine, and from the floating turbine to the farm, given the relationships outlined in the FMEA table. With this construction, our graph is already acyclic. There is no need for any more steps to complete our network.

Although the farm failure node is redundant in the single turbine array, it becomes critical when multiple turbines exist in the array, as the farm failure node connects all the turbines together, allowing a farm-level failure analysis. See **Figure *20*** for an example of the circular network design with multiple turbines.

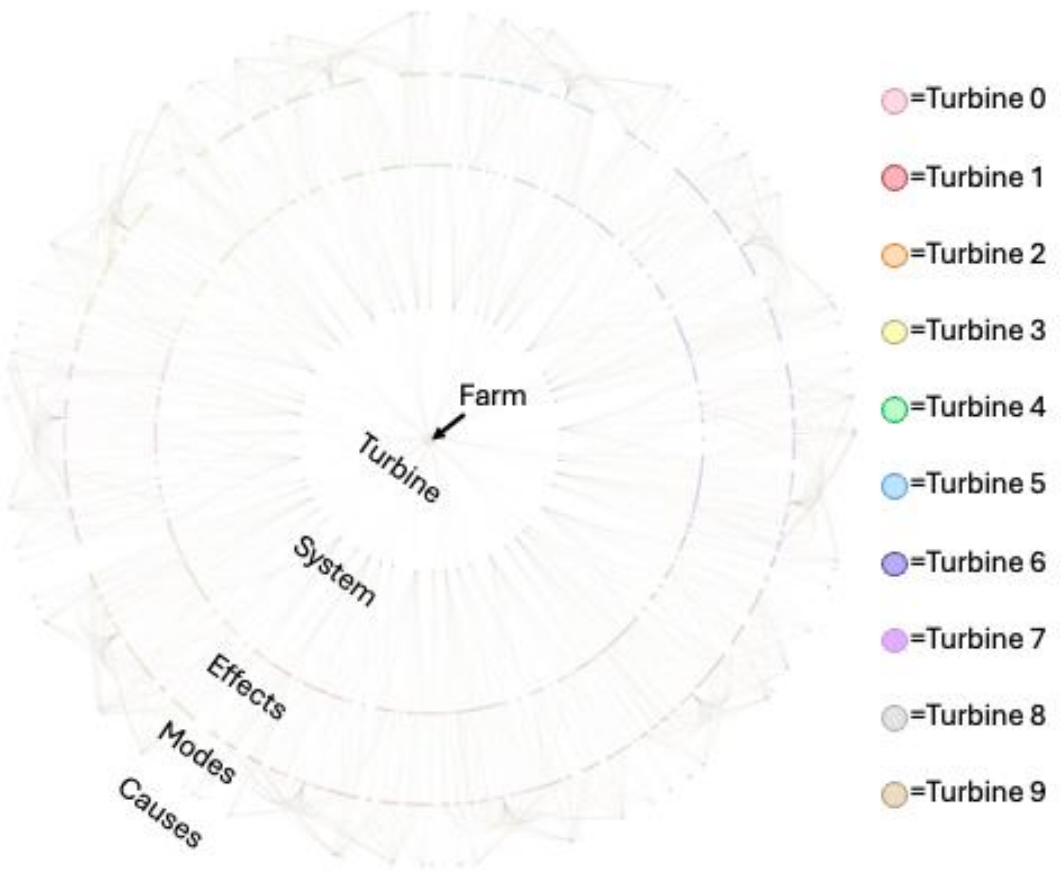


Figure 20: Circular design network for 10-turbine array (using the same array layout as described in the linear 10-turbine network example)

6.3.2. Estimate of Initial Probability

Now that we have the network structure of our Bayesian network, we need the initial probabilities of every node in the graph. We consider two ways to do this: using the risk priority numbers (RPNs) or the occurrence values from the FMEA table.

In the FMEA table, each row contains a failure cause, failure mode, failure effect, component system, RPN, and occurrence level. When using the RPNs as our initial probability, we want to consider all relevant RPNs in the FMEA table. So, for a specific failure node x_i we average the list of RPNs from the rows in which the failure node x_i lies. Since the RPNs range from 0-125, our average RPN also exists within this range. Dividing our average RPN by 125 gives us a value between 0-1 and thus can be used as a probability. Thus, the equation for our conversion between RPN and probability is as follows:

$$\Pr(X) = \text{Avg}(\text{RPN}(x_i))/125$$

where $\text{Avg}\big(\text{RPN}(x_i)\big)$ is the average RPN of failure x_i. The benefits of converting RPNs to probabilities are that the process is relatively simple (low computational costs) and because the RPN values are directly from experts. Yet, since RPNs are based on occurrence, severity, and

detection, converting RPNs to probabilities includes irrelevant information. The probability of failure x_i does not depend on the severity and detection of failure x_i, yet these properties are accounted for in the computed probabilities when we use RPNs.

An alternative to using RPNs for initial probabilities is to compute probabilities based on the occurrence values in the FMEA table. Kirchhof et al. present a probability interval table in their article that they used to convert occurrence rates in a FMEA table to initial probabilities in a Bayesian network [57]. This information is reproduced in **Table 8**.

Table 8: Table linking FMEA occurrence rates to probability intervals, from [57]

FMEA Occurrence Rate	Probability Interval
1	$[0, \quad 1 \cdot 10^{-6}]$
2	$(1 \cdot 10^{-6}, \quad 50 \cdot 10^{-6}]$
3	$(50 \cdot 10^{-6}, \quad 100 \cdot 10^{-6}]$
4	$(100 \cdot 10^{-6}, \quad 1 \cdot 10^{-3}]$
5	$(1 \cdot 10^{-3}, \quad 2 \cdot 10^{-3}]$
6	$(2 \cdot 10^{-3}, \quad 5 \cdot 10^{-3}]$
7	$(5 \cdot 10^{-3}, \quad 10 \cdot 10^{-3}]$
8	$(10 \cdot 10^{-3}, \quad 20 \cdot 10^{-3}]$
9	$(20 \cdot 10^{-3}, \quad 50 \cdot 10^{-3}]$
10	$(50 \cdot 10^{-3}, \quad 1]$

While their occurrence rates range from 0-10, the occurrence rates in our FMEA table range from 0-5. To account for this difference, we first average the occurrence rates for each failure (in the same way that we averaged RPNs in the method above), then multiply the average by 2, and finally round the product to the nearest whole number. The equation for this process is as follows:

$$\mathrm{Rate}(x_i) = \mathrm{Round}\big(\mathrm{Avg}\big(\mathrm{Occur}(x_i)\big) \times 2\big)$$

where $\mathrm{Avg}\big(\mathrm{Occur}(x_i)\big)$ is the average occurrence level of failure x_i and $\mathrm{Round}(x)$ is the function that rounds x to the nearest integer. From our computed occurrence rate of failure x_i, we set the initial probability of failure x_i equal to a random value within the associated probability interval. While this methodology of calculating initial probabilities removes the excess information included in the probabilities from RPNs, we introduce a random element into our calculation. This reduces our confidence in value, as it is no longer solely based on the information from experts.

6.3.3. Calculation of Bayesian Inference

Bayesian inference calculates the conditional probabilities based on the graphical structure and initial probabilities of the Bayesian network. We use the following equation to conduct Bayesian inference (i.e. calculate the probability of failure b given failure a):

$$\Pr(b|a) = \alpha \sum_{\forall y \in Y} \Pr(b, a, Y)$$

where $\Pr(b, a, Y)$ is the probability of events b, a, and Y occurring, where Y is the joint probability distribution of all other failures in our acyclic graph, and $\alpha = (\Pr(b|a) + \Pr(\neg b|a))^{-1}$ for $\Pr(\neg b|a)$ the probability of b not failing given a has failed. When using the linear network design, we calculate $\Pr(b|a)$ for every pair of failures a, b in our Bayesian network. But when we use the circular network design, we calculate $\Pr(b|\text{Farm})$ for every failure b in our Bayesian network and 'Farm' the farm-failure node.

6.3.4. Conditional Probabilities and Importance Measures

For conducting the Bayesian inference across the linear network design, we selected an initial failure point and used the failure data from the FMEA table to compute the probability of each possible failure given the starting failure. This process is repeated for different failure starting points.

After conducting Bayesian inference across the linear network design, we get an $n \times n$ matrix where n is the number of failure nodes in the Bayesian network of conditional probabilities. Averaging across the rows of our matrix gives us the average of probabilities $\Pr(b|a)$ for all failures b (i.e. a is fixed). We interpret this value as the "impact" of failure a. Conversely, averaging across the columns of our matrix gives us the average of probabilities $\Pr(b|a)$ for all failures a (i.e. b is fixed). We interpret this value as the "susceptibility" of failure b. To determine critical failures in our Bayesian network with linear network design, we consider failures with the maximum impact and those with the maximum susceptibility. **Table 9** shows the most critical failures for four Bayesian networks constructed from the FMEA table. The full table is not included in this report. The results presented in **Table *9*** depends on the selected array layout, and since we use the exact information from the FMEA tables, this method focuses on the local failure interactions. It gives more information about which failure modes and effects will cause additional failure modes and effects to occur.

Table 9: Critical failures for the constructed Bayesian networks using the FMEA table

Probability Type	Number of Turbines	Critical Failures (Impact)	Max Impact Probability	Critical Failures (Susceptibility)	Max Susceptibility Probability
RPN	1	Tower abnormal vibration	19.91%	Failure of watertightness	23.72%
RPN	10	Tower plastic deformation (for turbine 5)	26.33%	Failure of watertightness (for turbines 4 & 5)	28.09%
Occurrence	1	Tower abnormal vibration	1.19%	Mooring line fatigue	1.51%
Occurrence	10	Material degradation (for turbines 0 & 9)	1.68%	Accelerated mechanical fatigue (for turbines 0 & 9)	2.54%

The main difference between the linear and circular network designs is the introduction of three new types of nodes, which are component failures (see Section 4.1.1), turbine failures, and farm failure. Here, the component failures are connected to the failure effects; turbine failures are connected to component failures and turbine failures are connected to the farm failure. Once we complete Bayesian inference across the circular network design, we get probabilities for each node

in the Bayesian network. We determine the critical nodes of each layer in our circular network (cause, mode, effect, and system) by finding the failure nodes with the maximum conditional probability in their layer. These conditional probabilities are normalized by dividing them by the sum of conditional probabilities in their layer. Normalization does not change which failure node is critical, but it converts the conditional probabilities into importance measures (IMs). For these purposes, we are defining IMs as the probability of failure a led to a farm failure, given that we know that a farm failure has occurred. **Table *10*** shows the critical failures and measures of importance for four Bayesian networks constructed from the FMEA table. Here, only the failure modes that are most likely to be the cause of a farm-level or turbine-level failure are presented for each method using circular network design.

Table 10: Critical failures and importance measures for the constructed Bayesian networks

Probability type	Number of turbines	Critical Cause	Cause IM	Critical Mode	Mode IM	Critical Effect	Effect IM	Critical System	System IM
RPN	1	Operation	97.61%	Fatigue cracks	3.28%	Structural failure	3.26%	Floating support structure	20.82%
RPN	10	Operation	~100%	Fatigue cracks (turbines 0-9)	0.33%	Structural failure (turbines 0-9)	0.33%	Floating support structure (turbines 0-9)	2.08%
Occurrence	1	Operation	~100%	Loss of dynamic positioning	9.89%	Operational disruption	9.09%	Dynamic cable	32.27%
Occurrence	10	Operation	~100%	Loss of dynamic positioning (turbine 7)	1.21%	Exposure to elements (turbine 9)	0.95%	Mooring lines (turbine 7)	3.87%

It is not possible to directly compare two methods. While linear network captures the local failure interaction, the circular network design presents which failure causes, modes, effects, and components have the highest impact on farm-wide failure, considering the global relationship of the turbines and their components. Another point here is that the same data is used for both methods, but the critical modes and effects are not the same. Therefore, instead of selecting one critical failure mode from each method, other failures with a high ranking should be considered.

6.4. Next Step in Failure Risk Analysis

The next step in WP3 is to provide failure mitigation measures for all farm-level failure modes for the structural and substructural components (tower, floater, transition piece, station keeping, and dynamic cable) analyzed in this report. Thus, the entire FMEA database can be readied for publishing in an open-access repository. Based on the failure modes and causes discussed in this report (Section 7.2), and given the scarcity of FOWA failure data, the following pathway will be used to acquire effective failure mitigation measures:

- Review relevant industry standards and guidelines, such as those from the IEC, ABS, and DNV GL. Analyse the requirements and recommendations specified in these standards to build applicable mitigation measures.

- Conduct direct consultations with a small group of experts (e.g., those who participated in the first stage of the FMEA survey) to gather insights into potential failure mitigation solutions and obstacles in applying them in FOWAs. Structured interviews or questionnaires will be used to ensure consistency and comprehensiveness in their responses.

The interactions between turbines are investigated in the current work for a 10-turbine FOWA using the Bayesian network (Section 7.3); however, additional expert input is required to better understand these interactions and their likelihood. This will be addressed in the next report by:

- Investigate methods to compute initial failure risk probabilities for the Bayesian network analysis. As data from floating offshore wind turbines becomes accessible, failure rates can be used as a basis for these probabilities.
- Implement a Bayesian network of a floating wind farm array design to conduct array-level risk assessment. To investigate the interactions of the farm-level failures, this method should be applied to a real-sized farm. (An array design from WP2 can be used for this purpose.)

7. Conclusion

WP3 of IEA Wind Task 49 gathered data on the failure rates of floating wind turbine components from existing literature. It carried out a thorough Failure Mode, and Effects Analysis (FMEA) to estimate the Risk Priority Number (RPN) of 120 potential failure modes for structural and substructural subsystems such as the tower, transition Piece, floater, station keeping, and dynamic cable. These subsystems are chosen based on their importance to the overall functionality, reliability, and safety of Floating Offshore Wind Arrays (FOWA).

A base case is established to guide the review of failure modes at the component level. This includes the IEA Wind turbine 15-MW reference floating wind turbine, a VolturnUS semi-submersible, catenary mooring design, a uniform water depth of 200 m, a generic seabed, an aligned array layout, a lazy wave cable configuration, and the site conditions of the Havbredey floating site in Scotland.

The failure modes, mechanisms, and causes data are the result of an intensive literature review and two workshop discussions with experts from a variety of sectors, including R&D (focusing on condition monitoring and structural health monitoring), risk consultancy, risk and insurance, academia, development, and industry. Five comprehensive FMEA tables are produced.

The RPN of failure modes with potential farm-level implications is identified, together with their scores in terms of the likelihood of failure occurrence, effects (financial, safety and environmental), and detectability for the five subsystems. Focusing on the farm-level failure modes of the selected subsystems allows for a thorough investigation of the most influential failure modes, ensuring that appropriate mitigation measures may be created to enhance FOWA performance and safety.

For each of the five subsystems, farm-level impacts are categorized based on the RPN obtained from experts. Common failure mechanisms (e.g., fatigue due to continuous vibrations or resonance of the floater, friction and tension of the mooring line during operation, J-tube/hang-off corrosion of dynamic cable, etc.) are described for each of the failure modes.

The distribution of failure causes linked to the farm-level failure consequences in each of the subsystems is discussed, including design errors, manufacturing defects, improper installation, operational failure causes, environmental factors (typhoons, dramatic climate change), and insufficient quality control during maintenance. This comprehensive analysis ensures that all potential sources of failure are considered, providing a complete picture of the risks involved, which is essential for developing effective mitigation recommendations in the next step of WP3.

A Bayesian network analysis is proposed, in which some information from the FMEA farm-level analysis, such as failure occurrence, is used as the initial probabilities to calculate the Bayesian interface (conditional probability of probability of second event occurring given the first event has already occurred), and to analyse the probability of farm-level effects of a failure mode using a 10 turbine example. This establishes a baseline that can be used in the following phase of WP3.

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