On Modeling the Operation and Maintenance of a Floating Offshore Wind Farm with Multiline Anchors

Implementing multiline mooring modeling in NREL WOMBAT tool

European Wind Energy Master

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by

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Cover: Principle Power (Modified) [1]

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Preface

The development of floating offshore wind farms represents a significant step forward in harnessing renewable energy from the ocean. This thesis, ”On Modeling the Operation and Maintenance of a Floating Offshore Wind Farm with Multiline Anchors,” aims to explore multiline anchors to enhance the efficiency and cost-effectiveness of these systems.

My interest in renewable energy and sustainable engineering solutions motivated this research. Growing up near the coast, I have always been fascinated by the power of the ocean and its potential to provide clean energy. This personal connection, combined with my academic background in engineering, inspired me to focus my thesis on floating offshore wind farms.

I would like to express my deepest gratitude to my supervisors, Dr. M. Zaayer, Dr. A. Nejad, and Dr. S. Arwade, for their invaluable guidance and support throughout this project. Their expertise and encouragement have been instrumental in the completion of this thesis. I am also grateful to my colleagues and friends at Delft University of Technology, the Norwegian University of Science and Technology, and the University of Massachusetts for their collaboration and support. A special thank you to Rob Hammond, whose support was instrumental in the software adaptions.

Additionally, I would like to thank my family for their unwavering support and encouragement. Their belief in my abilities has been a constant source of motivation. A special thank you goes to my close friends, who have patiently listened to my endless talk about anchors and wind farms, providing me with moral support and much-needed breaks throughout this journey.

This thesis investigates the potential of multiline anchoring systems in floating offshore wind farms, with a specific focus on the simulation and cost-benefit analysis using the WOMBAT software. The research includes case studies on Morro Bay and the Gulf of Maine, providing a comprehensive evaluation of different operational scenarios.

Conducting this research has been challenging and rewarding. It has provided me with valuable insights into the complexities of offshore wind farm operations and the importance of innovative engineering solutions in addressing global energy challenges.

I hope this thesis contributes to the advancement of renewable energy technologies and inspires future research in this vital field.

Marlou Dinkla
Delft, August 2024

Summary

The development of floating offshore wind farms (FOWF) represents a significant advancement in the renewable energy sector, offering a scalable solution to harness wind energy in deep-water locations. This thesis investigates the effectiveness of multiline anchor systems in improving the cost-efficiency, operation, and maintainability of FOWFs. Utilizing the modified Windfarm Operation and Cost-benefit Analysis Tool (WOMBAT), this research comprehensively analyzes multiple case studies, focusing on critical factors such as cost, profit, operational performance, and maintenance occurrences.

Case Study 3 compares the performance of multiline anchor systems against traditional single-line configurations in the Morro Bay scenario. The results indicate that multiline systems significantly enhance availability, reduce operational expenditure, and improve overall profit. Case Study 4 extends this analysis to the Gulf of Maine, confirming that multiline systems maintain their advantages under varied environmental conditions and extended operational lifespans. This study underscores the robustness and adaptability of multiline anchors in diverse offshore environments.

Case Study 5 provides a sensitivity analysis to evaluate the reliability of the simulation inputs. It demonstrates that the fundamental benefits of multiline systems remain consistent despite variations in mooring line failure rates. However, it also underscored the importance and need for available data and how the model and its outputs are only as credible as the inputted values.

The findings contribute to the offshore wind industry by providing actionable insights into the deployment of multiline mooring systems and offering recommendations for enhancing the cost-effectiveness and reliability of FOWFs. The research also highlights opportunities for further development of the WOMBAT tool, particularly in incorporating proactive maintenance strategies and environmental factors such as wind and wave directions.

This thesis supports the broader adoption of multiline anchor systems in floating offshore wind farms. With a demonstrated lower cost in operation and maintenance, it advocates for their strategic deployment in various environmental conditions to drive the transition to a sustainable energy future.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
FOWF	Floating offshore wind farm
FOW	Floating offshore wind
NREL	National Renewable Energy Laboratory
LCOE	Levelized Cost of Energy
OWE	Offshore wind energy
WOMBAT	Windfarm operations and maintenance cost-benefit analysis tool
FEED	Front end engineering design
O&M	Operation and Maintenance
BOEM	Bureao of Ocean Energy Management
TLP	Tension Leg Platform
O&G	Oil and Gas
MTBF	Mean Time Between Failures
NPV	Net Present Value
OpEx	Operational Expenditure
CV	Coefficient of Variation
SEM	Standard Error of Mean
CI	Confidence Interval
GW	Gigawatt
MW	Megawatt
MWh	Megawatt hour
CDF	Cumulative distribution function
GoMe	Gulf of Maine
HLV	Heavy lift vessel
CTV	Crew transfer vessel
AHV	Anchor handling vessel
VSG	Vessel support group - AHV for multiline anchors

1 Introduction

1.1. Background and Development of Offshore Wind Energy

The global energy landscape is transforming significantly as countries intensify efforts to shift towards sustainable and renewable energy sources. Offshore wind energy has emerged as a critical component in this transition, providing a scalable and technically efficient solution to the dual challenges of increasing energy demand and climate change mitigation. By 2023, cumulative global offshore wind capacity had reached 67.4 GW, a testament to the continuous expansion in key markets, particularly across Asia and Europe [2].

As the technology matures, emerging markets such as Australia, India, and the United States are poised for significant growth. In particular, the United States plans to add an additional 16.8 GW of lease capacity in the near future [2]. The U.S. offshore wind sector is anticipated to play a pivotal role in the global energy transition, with significant developments expected in floating wind sites along the western coastline [2].

The development of offshore wind energy in the United States began with the first grid-connected floating wind turbine demonstrator in 2013 [3], followed by the Block Island Wind Farm in 2016, which has a capacity of 30 MW [4]. To support the expansion of offshore wind energy, a comprehensive resource assessment was conducted, identifying potential areas for deployment. Figure 1.1 shows areas where fixed and floating offshore wind energy can be deployed; the bottom fixed area is yellow, and the floating area is blue. Not considered are potential siting constraints. The maximum water depth is constrained to 1,300 meters. It highlights that the west coast is suitable only for floating offshore wind due to deeper waters, while the east coast can support both fixed and floating installations.

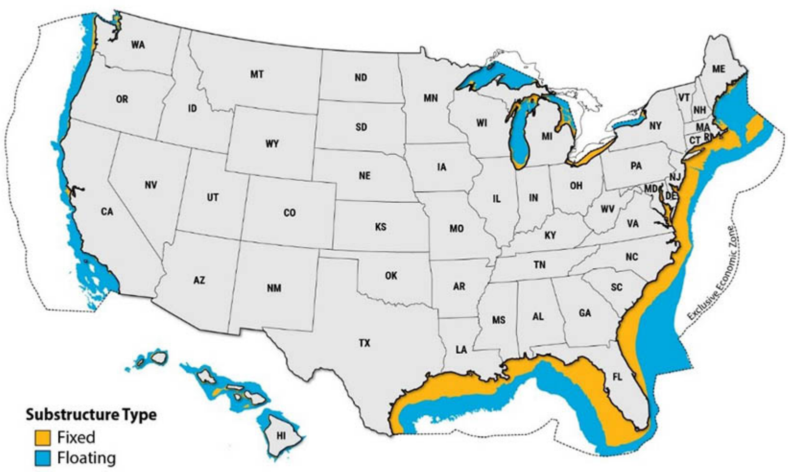


Figure 1.1: Locations of wind resources off the coast of the United States. Graphic by Philipp Beiter, NREL [5].

In September 2022, the U.S. Departments of Energy, Interior, Commerce, and Transportation launched initiatives to deploy 15 MW of floating offshore wind capacity and to reduce costs by 70% by 2035 [6]. This push is driven by the scarcity of operational commercial floating offshore wind farms, with only four currently in operation worldwide. The largest floating wind farm, Hywind Tampen, has 11 turbines with a total capacity of 88 MW [7]. This contrasts with bottom-fixed wind farms like that of Hollandse Kust Zuid in the Netherlands, which has 139 turbines and a capacity of 1390 MW [8]. An increase of 1164% in the number of turbines and 1480% in the capacity. Adding in that, the first U.S. commercial wind farm, a bottom-fixed one called Vineyard Wind, has 62 turbines and a capacity of 806 MW [9], highlighting the scale difference between bottom-fixed vs. floating installations and European wind farms vs. the US.

To achieve market competitiveness and provide tangible benefits to local communities, floating wind technology must leverage economies of scale. This approach has been successful for bottom-fixed offshore wind energy, which reduced its cost and levelized the cost of energy (LCOE) through economies of scale. The primary driver for this significant push in the United States, as opposed to Europe, is the difference in available development areas: Europe can utilize the North Sea shelf, while the entire west coast of the USA requires floating foundations for wind energy due to its deeper waters (Figure 1.1).

Europe's leadership in offshore wind energy comes from countries offering financial government incentives, well-developed permitting and regulatory environments, and by playing a role in the shaping of the country's public attitudes towards renewable energy. The U.S. government is replicating this through the formation of action plans, internal government agreements, and federal laws [10] [11] [12].

The USA has adopted an ambitious approach to floating wind energy, akin to its historical commitment to space exploration. As John F. Kennedy famously stated, 'We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard...' [13]. This mindset drives the U.S. federal government's initiative, the Floating Offshore Wind Shot, aiming to develop floating offshore wind technologies [14]. The initiative has the following goals in mind:

- Develop cost-effective technologies for deeper waters
- Bring power onshore to areas of high demand
- Create jobs in operations, construction, and manufacturing
- Expand supply chains, including tailoring port infrastructure to support development
- Deploy large amounts of reliable, clean power
- Help revitalize port and manufacturing communities
- Ensure environmental sustainability and ocean co-use

Commercial floating offshore wind is still relatively new, having been around for less than a decade. The first floating offshore wind farm (FOWF) was Hywind Scotland, which came online in 2017 [15], and the latest is Hywind Tampen, which came online in 2023 [7]. In that time, only an additional two windfarms have been built. One reason for this slow growth is the high LCOE for floating wind. According to the National Renewable Energy Laboratory (NREL) Cost of Wind Energy report in 2020, for a 12 MW Offshore wind turbine, the total LCOE of a fixed bottom wind plant is $95/MWh, while for floating wind it is $145/MWh [16]. This difference of $50/MWh (41.67%) highlights the cost challenge for floating wind.

Figure 1.2 shows the LCOE breakdown by component for a 25-year operating floating offshore wind project. The substructure and foundation account for 27.1%, and the operation and maintenance (O&M) constitute another 27.5%. B.D. Diaz (2016) proposed a cost-reduction strategy for floating wind energy by connecting multiple turbines to a single anchor, a concept known as multiline anchors or shared anchors [17]. It reduces the cost by having fewer anchors, thereby reducing the number of geotechnical site investigations and the number of installations. Figure 1.3 gives a visual representation of what a multiline anchor system looks like, with a single anchor that connects to three individual floating wind turbines through their own mooring line.

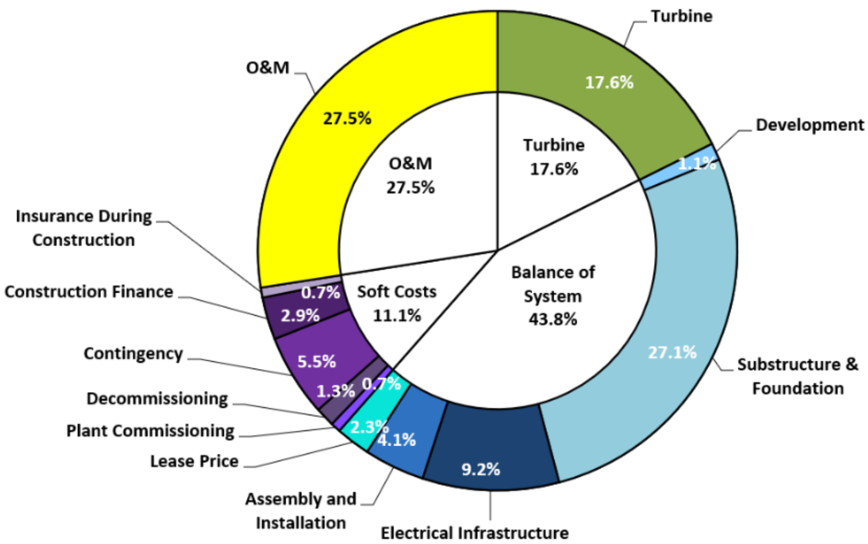


Figure 1.2: LCOE breakdown by component for a 25-year operating floating offshore wind project. [18]

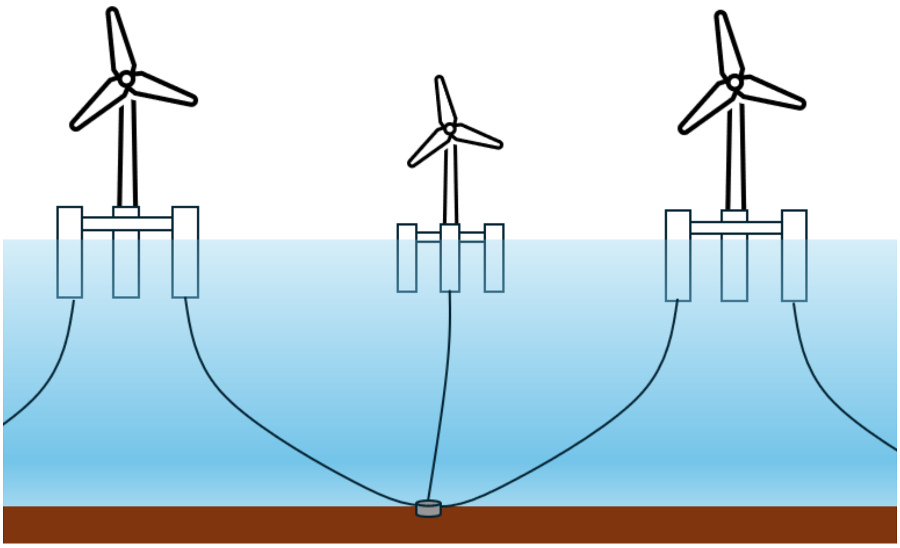


Figure 1.3: Illustration of a multiline anchor layout for mooring configuration of a floating offshore wind farm.

Implementing multiline anchors, as shown in figure 1.2, could reduce the 27.1% cost associated with substructure and foundation. Research by Casey Fontana indicates that 'the multiline concept may result in cost reductions of 8-16% for a 100-turbine wind farm, with mooring systems configurations featuring smaller depth-to-spacing ratios achieving greater reductions in combined line and anchor costs. [19]. However, if there is no cost reduction in the operation and maintenance of multiline anchors or the cost increases, the cost reduction purpose could be defeated. This research aims to investigate the effect of multiline anchors on the cost-benefit of operation and maintenance of FOWF.

1.2. Challenges of Floating Offshore Wind Farms O&M

J. McMorland clearly outlines the challenges of FOWF operation and maintenance [20]:

- weather sensitivity
- maintainability
- anchor cost and complexity
- mooring line cost and complexity
- turbine motion
- lack of available data due to infancy industry

1.2.0.1 Environmental and Weather Conditions

The harsh and variable environmental conditions in offshore locations critically affect the maintainability and reliability of FOWFs. High wind speeds, wave heights, and sea conditions can restrict access to turbines, leading to increased downtime and reduced operational efficiency. According to the FOW-CoE Implications report, weather windows - periods when the sea state is calm enough for maintenance activities - are crucial for planning O&M operations. Sensitivity analysis has shown that broader weather window limits can reduce operational costs and system downtime [21]. Additionally, increased distance from shore, typical of FOWFs, exacerbates these challenges due to longer travel times and harsher conditions [20].

1.2.0.2 Turbine Motion and Safety

The dynamic motion of floating turbines presents significant challenges for maintenance activities. The motion affects the safety and comfort of maintenance personnel, especially during transfers from vessels to turbines. Research highlights that structural motion reduces weather windows for maintenance by up to 5%, impacting overall turbine availability and increasing financial losses due to extended downtime [20]. Moreover, floating-to-floating transfers are complex and currently underexplored, requiring further investigation to ensure safe and efficient operations [20].

1.2.0.3 Mooring System Complexity

The design and integrity of mooring systems are critical for the stability and safety of FOWFs. The complexity of mooring systems, including the number of components and their arrangement, influences the frequency of failures and the cost of repairs. Simplified mooring designs with fewer components can reduce failure rates, but a degree of redundancy is necessary to prevent severe consequences such as cable damage and prolonged downtime [21]. The FOW-CoE report underscores that mooring system failures can result in unacceptable levels of unavailability, necessitating higher reliability standards than those in the oil and gas (O&G) industry [21]. For each wind turbine, a floating foundation requires already at least threefold of substructure components compared to a bottom fixed foundation. Consequentially, the mooring line and anchor layout are complex affairs to organize, install, operate, and maintain.

1.2.0.4 Cost and Economic Impact

Vessel availability, chartering costs, and the efficiency of marine operations significantly influence operational and maintenance costs. Vessel charter costs, particularly for specialized vessels like anchor handling tugs and cable lay vessels, constitute a major portion of O&M expenses [21]. Increasing the reliability of components and streamlining marine operations can reduce these costs. The FOW-CoE report suggests that improving the site accessibility (including vessel availability) and the reliability of mooring components can lower the LCOE for FOWFs [21].

1.2.0.5 Lack of Data and Standardization

One of the major challenges in the floating offshore wind industry is the absence of publicly available, comprehensive, standardized data on mooring system performance and failures. The offshore O&G industry has a more established framework for collecting and sharing reliable data, which is not yet fully developed for FOWFs. The SPARTA project, managed by ORE Catapult, is a promising initiative to create a database for sharing offshore wind farm performance and maintenance data [21].

To tackle these challenges, using software to model wind farms and conduct simulations can offer valuable insights over their lifespan. NREL has developed software called WOMBAT (Windfarm Operation and Maintenance cost-Benefit Analysis Tool), which is a scenario-based simulation allowing for the analysis of a wind farm's lifetime. A more extensive explanation of the software will be given in chapter 3.

1.3. Role and Importance of Simulation in Wind Farm Operations

In the evolving landscape of floating offshore wind farms, simulation plays a critical role in the design and deployment phases and extensively in the operation and maintenance phase. The unique challenges posed by FOWFs, such as remote locations, deep waters, and harsh marine environments, necessitate robust O&M strategies to ensure longevity and efficiency. Simulation tools are pivotal in developing, testing, and refining these strategies, thereby minimizing downtime and operational costs.

Strategic application of simulation in O&M facilitates detailed analysis of various operational scenarios, impacting the lifespan and efficiency of wind farms. Tools like WOMBAT, developed by NREL, are integral in this process. They enable operators to forecast and simulate potential failures, maintenance schedules, logistic operations and costs over the wind farm's life cycle [16].

WOMBAT, for instance, allows for scenario-based simulations that incorporate a variety of data inputs, such as weather conditions, component wear and tear, and crew availability. This helps in planning maintenance activities efficiently and in a cost-effective manner. The ability to simulate different maintenance strategies and their impact on the overall efficiency and cost of wind farm operations is crucial for optimizing O&M activities and can lead to significant cost savings. Currently, WOMBAT can simulate onshore wind farms and bottom-fixed offshore wind farms. The software can only partially simulate a floating wind farm, in two manners. First, for maintenance and repair, it can simulate an in-place repair known as In-Situ, or it can model a Tow-to-Port scenario for major repair or replacement. Secondly, substructure data of a mooring configuration can be input; however, the model can not distinguish between individual anchors and mooring lines. It sees the substructure and mooring configuration as a whole. This limitation is significant when evaluating the impact of multiline anchors, as the original form of WOMBAT can not do this configuration.

In addition to WOMBAT, there are several other O&M simulation tools available in the market, such as Shoreline O&M Design, ForeCoast Marine, and DNVGL's O2M, TNO's UWiSE, among others [22]. These tools are designed to support long-term logistical planning, forecast asset availability, and estimate lifetime operational expenditure for offshore renewable energy projects. However, despite their advanced capabilities, most of these tools are primarily tailored for bottom-fixed offshore wind farms or other marine renewable energy projects. They lack the specialized functions required to model the unique challenges associated with FOWFs, particularly the simulation of multiline anchor systems. WOMBAT, on the other hand, while also initially designed for bottom-fixed offshore wind farms, already possesses a foundational ability to simulate floating structures. This inherent capability, albeit limited, makes WOMBAT the more suitable choice for this research, and with modifications would be able to simulate multiline anchors.

Studies, such as those by Musial et al. (2023), have highlighted how simulation tools can integrate various data streams to create a comprehensive model of wind farm operations that helps understand and mitigate risks associated with O&M activities. These models provide a framework for testing hypotheses about how changes in mooring configurations and operation procedures can improve efficiency or reduce costs [23].

In conclusion, the role of simulation in the operation and maintenance of FOWFs is indispensable. As floating wind technology evolves and farms are deployed in increasingly challenging environments, the reliance on sophisticated simulation tools like WOMBAT will continue to grow. These tools not only support current operational needs but also pave the way for future innovations in wind farm management, potentially redefining how O&M strategies are developed and implemented across the industry. This research aims to leverage these simulation capabilities to assess the cost-benefit impact of multiline anchors on the O&M of FOWF.

1.4. Objectives and Scope of the Thesis

While FOWFs offer a substantial step forward in harnessing wind energy, they face significant O&M challenges, notably in mooring systems. As explained in section 1.2.0.3, a floating substructure is more complex than a bottom fixed substructure. Traditional mooring solutions entail significant costs and environmental impacts. Multiline anchors suggest a cost-effective and more sustainable alternative. Research papers and reports have documented how multiline anchors reduce costs and have less environmental impact. Less explored is the impact of multiline anchors on operation and maintenance costs and their overall effectiveness in various locations and scenarios. There are fewer papers and reports on the operation and maintenance of such a mooring system. Furthermore, it was found that there was room for improvement in the existing software; improvements could allow for the modeling of the costs associated with the O&M of multiline anchors. This project aims to use the self-made modified simulation software for a detailed cost analysis of multiline anchors in the context of O&M and to evaluate their broader implications.

The project's objective is to establish multiline anchors' viability for O&M efficiency in FOWFs, focusing on:

1. Cost-Reduction Efficiency: Analyze the economic benefits of multiline anchors compared to conventional mooring systems through detailed cost and performance analysis.
2. Simulation Enhancement: A modeling tool is needed to achieve objective one. For that, the multiline mooring model is implemented in the WOMBAT tool from NREL.

This research employs a comprehensive approach, including:

- Literature Review: Survey existing literature on FOWFs' mooring systems, focusing on multiline anchors. This review will provide a foundation for understanding the current state of research and identify gaps that this project aims to fill. In addition to what is in this thesis, previously, a separate literature review document was performed for a more expansive literature review.
- Model development and implementation in WOMBAT: Develop modifications to WOMBAT to simulate advanced mooring configurations accurately. These enhancements will enable more precise modeling of multiline anchors and other configurations and be able to analyze their impact on the O&M costs.
- Case studies for model validation and illustration of model capabilities: In total, five different scenario simulations are considered. They are as follows:
  1. Case 1: Convergence study of the modified simulation software - Determine the number of simulations needed for reliable results by running 50 simulations and checking for convergence by integers of 2 simulations (Chapter 5).
  2. Case 2: Model validation study - Compare the modified software version to its original using the Morro Bay scenario and data from the COREWIND project with a single-line anchor layout (Chapter 6).
  3. Case 3: Multiline layout study - Compare single-line anchor vs. multiline anchor layouts to determine which is more cost-effective, while keeping other inputs constant in the Morro Bay scenario (Chapter 7).
  4. Case 4: Gulf of Maine study - Evaluate the impact of different inputs such as metocean conditions, wind farm life cycle duration, and port distance, using the same wind farm and mooring layout as the previous case (Chapter 8).
  5. Case 5: Sensitivity study - Assess the impact of different failure rates of mooring lines in a multiline layout. In this analysis, no anchor failures and no mooring repairs are applied, in the Morro Bay scenario. (Chapter 9).

By addressing these objectives and using a structured approach, this project aims to provide a comprehensive understanding of the cost-benefit of multiline anchors in FOWFs.

1.5. Structure of the Report

This thesis is structured to provide a detailed analysis of the operation and financial implications of multiline mooring configurations in floating offshore wind farms, progressing logically from foundational concepts to in-depth case studies and analysis.

Chapter 2: Methodology and Design of Floating Offshore Wind Farms details the design considerations for floating wind turbine structures, the types, and benefits of the multiline anchoring system.

Chapter 3: Development of the Mooring Simulation Model provides detailed information on the WOMBAT tool and the development of the mooring simulation model, including the modifications made.

Chapter 4: Cases and Simulations Setup outlines the setup for the case studies and simulations. It describes the different wind farm scenarios and layouts and the operational and maintenance strategies employed.

Chapter 5: Case 1 - Convergence Study discusses the convergence study conducted to determine the number of simulation runs required to achieve stable and reliable average results. It focuses on the metrics Net Present Value and Operational Expenditure and provides insights into the statistical methods used to ensure convergence.

Chapter 6: Case 2 - Model Validation Study presents the model validation study comparing the modified WOMBAT software to its original version using data from the Morro Bay scenario. The accuracy and reliability of the software modifications are assessed in this section.

Chapter 7: Case 3 - Multiline Layout Study discusses the cost-effectiveness and operational performance of multiline anchor systems compared to single-line systems in the Morro Bay scenario.

Chapter 8: Case 4 - Gulf of Maine Study evaluates the impact of varying environmental conditions, operational lifetimes, and port distances on the performance of multiline and single-line configurations using the Gulf of Maine scenario. It compares the results to the previous case with the Morro Bay scenario.

Chapter 9: Case 5 - Sensitivity Study explores the impact of different failure rates of mooring lines in multiline configurations through sensitivity analysis. The study focuses on understanding how varying failure probabilities affect the overall performance and costs of wind farm operations.

Chapter 10: Discussion interprets the findings from the case studies, evaluating the advantages and limitations of the simulation models and the practical implications of the results for real-world FOWF projects.

Chapter 11: Conclusion summarizes the key findings of the thesis, discusses the implications for the offshore wind industry, and provides recommendations for future research.

2

Methodology and Design of Floating Offshore Wind Farm

2.1. Design Considerations for Floating Structures

The development of Floating Offshore Wind Turbines (FOWTs) has been propelled by the opportunity to exploit wind resources in deeper offshore locations. Adapted from offshore oil and gas technologies, these platforms must be tailored to meet the unique demands of wind energy, ensuring structural integrity, operational efficiency, and economic viability [24]. The offshore wind industry has found that the switch from bottom-fixed to floating substructures occurs between 60-100 meters (196-328 feet). This threshold is based on industry standards, engineering feasibility, and cost analyses. Additionally, each project is unique in what the location demands. Therefore, the following sections will explain the types and benefits of each floating substructure and multiline mooring.

FOWTs utilize various platform technologies such as semi-submersible, spar, barge, and tension leg platforms (TLPs), each chosen based on specific environmental conditions and stability requirements. These structures are designed to manage dynamic oceanic forces while supporting large wind turbines, balancing stability with efficient energy production [25]. The choice of substructure significantly influences the applicability of multiline anchors. Spars provide stability in deep waters but require a larger footprint in anchoring systems. Semi-submersibles offer flexibility in various water depths and are compatible with multiline anchors due to their distributed buoyancy. Tension-leg platforms, while providing excellent stability, may face challenges with multiline anchor integration due to their tethered nature and, therefore, small footprint. Figure. 2.1 gives an overview of the mentioned platforms from both a side and top view perspective. From the side view, it can be seen clearly how three of the four design concepts have a mooring configuration that aligns with the concept of multiline anchors, TLP does not.

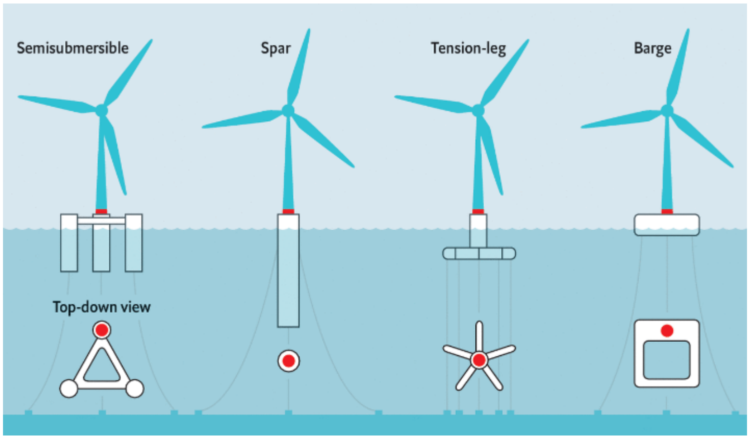


Figure 2.1: The different FOWT design concepts [25].

2.1.1. Key Design Considerations

2.1.1.1 Design Basis

A comprehensive design basis is crucial for the development of FOWTs, incorporating specific load cases, safety factors, and environmental conditions typical of offshore settings. Adherence to standards such as the IEC 61400 series and DNV-GL guidelines ensures that these structures can withstand challenging marine environments. Recent studies emphasize the need for an integrated design approach to optimize both turbine performance and platform stability, which directly influences the feasibility and effectiveness of multiline anchors [24].

2.1.1.2 Environmental Loading and Safety Levels

Floating platforms must be designed to withstand complex loads from waves, wind, and currents. The specific responses of the platforms to these forces dictate the choice of mooring systems and stability mechanisms [24]. With the help of Figure 2.2, the forces that need to be considered are:

- Wave Loads: Wave conditions require hindcasting and real-time data to predict structural responses and to displace buoyancy within a substructure. For multiline anchors, understanding wave loads is critical to ensure the stability and integrity of the anchor system.
- Wind Loads: Wind conditions influence the design of turbine nacelles and towers, which handle significant mechanical stress and transfer the structural loads to the substructure. This directly impacts the mooring systems and their compatibility with multiline anchors.
- Current Loads: Currents affect mooring systems and the stability of platforms, requiring robust anchor designs to maintain position and function effectively.

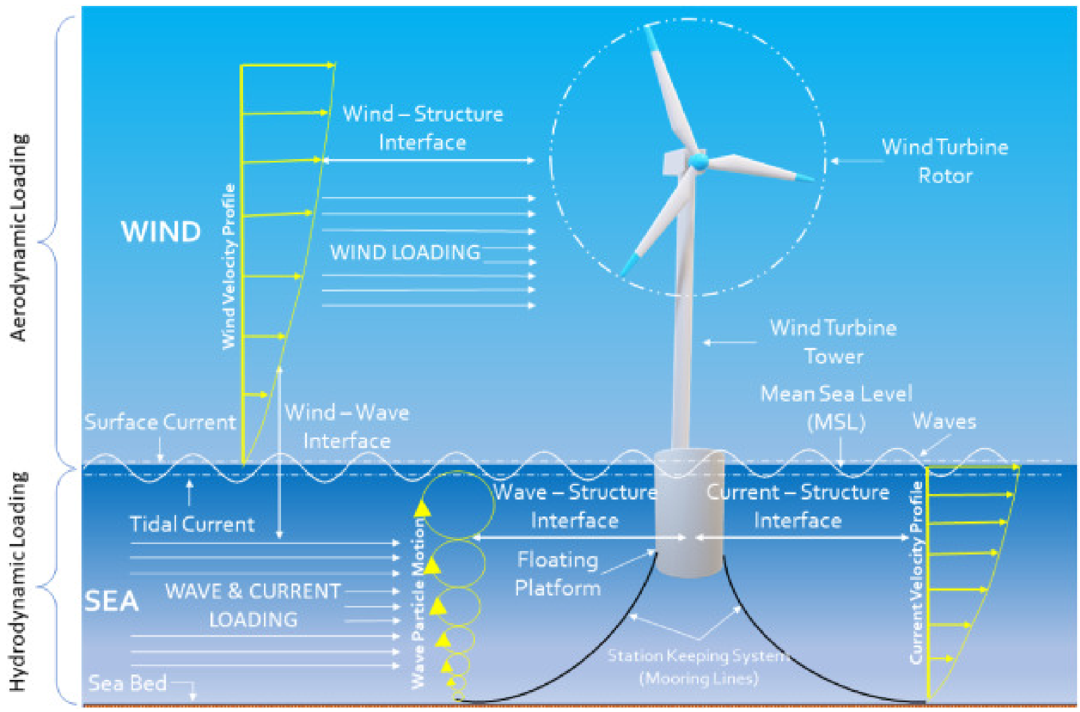


Figure 2.2: An illustration showing the fluid-structure interfaces and dynamic loads experienced by a FOWT [26].

2.1.2. Design of Platform Types

Depending on the conditions, there are a variety of designs to choose from. Figure 2.3 displays what stability is related to each type:

- *Spar-Type Platforms:* Preferred in deep waters due to their stability from significant draft and heavy ballast at the bottom. These platforms rely on gravity and hydrostatics for stabilization [25].

- *Semi-Submersible and Barge Platforms:* Semi-submersible platforms are flexible in water depth, supported by multiple buoyancy columns and comprehensive mooring systems to handle dynamic motions [25]. Barge platforms are also flexible in water depth, supported by a large waterplane for buoyancy and comprehensive mooring systems to handle dynamic motions. Semi-submersibles are more compatible with multiline anchors due to their distributed buoyancy and lower center of gravity, which allows for more stable anchoring.
- *Tension Leg Platforms:* Characterized by minimal motion due to taut moorings fixed to the seabed, ideal for environments with strict motion restrictions for turbine operation [25].

The types can be seen in commercial offshore wind farms seen in figure 2.4. The first is a barge design called BW Ideol Floatgen. The second is a semisubmersible in the WindFloat Atlantic wind farm, which was designed and constructed by Principle Power. The third is a spar, part of the Hywind Scotland wind farm from Equinor.

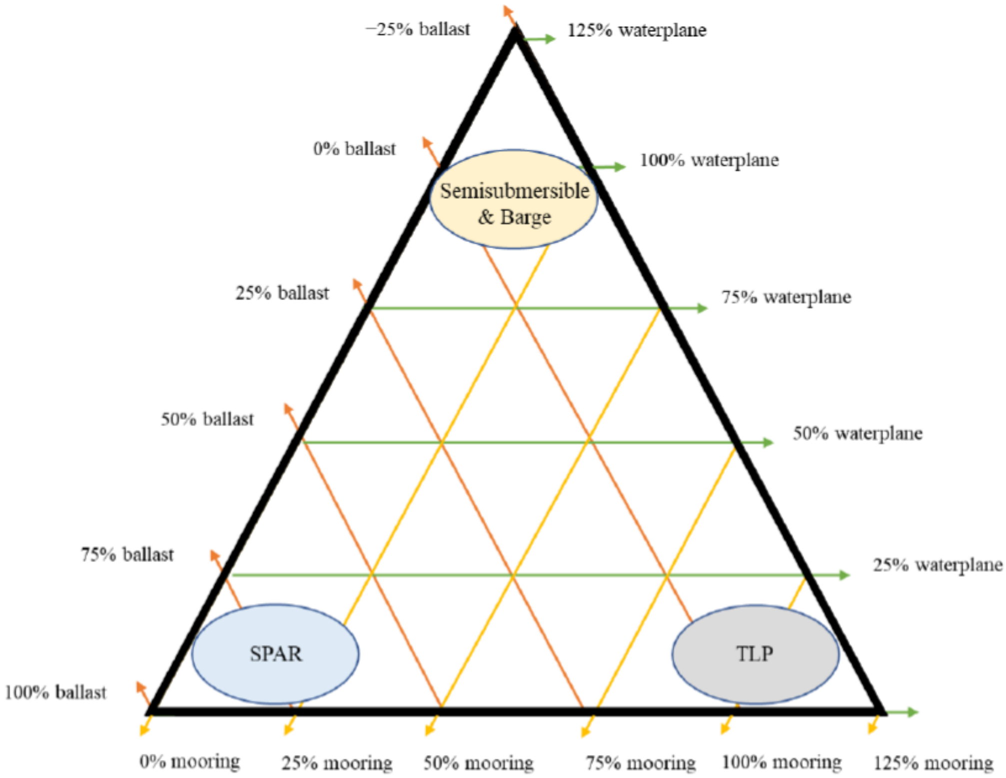
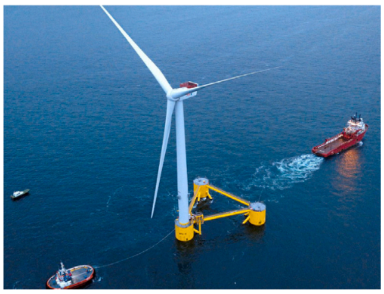


Figure 2.3: The floating foundations stability triangle [27].

(a) Barge by BW Ideol



(b) Semisubmersible by Principle Power

(c) Spar by Equinor

Figure 2.4: The barge, semi-submersible, and spar foundation-specific designs. Images: [28]

2.1.3. Mooring Systems and Anchor Types

The selection of mooring systems depends on various factors, including water depth, seabed conditions, and environmental loads. Computational models are essential for designing mooring configurations that endure these forces without failure, ensuring structural stability over the turbine's operational lifespan [29]. Different mooring configurations and anchor types depend on case-by-case situations. The depth of the ocean, bathymetry, and metocean conditions will be the leading factors in choosing the type of mooring configuration and anchor type. Figures 2.5 and 2.6show the common mooring configurations and the types of anchors used for floating structures.

Different mooring configurations, such as catenary, taut, and semi-taut, impact the feasibility and efficiency of multiline anchors. Catenary moorings, which use heavy chains and rely on their weight for stability, are effective in deeper waters but may not be compatible with multiline anchors due to their complexity in chain length and weight and, thereby, a higher cost. Taut moorings, which use high-tension lines, offer better stability and are more suitable for multiline anchors as they can distribute the load more evenly across multiple lines. Semi-taut moorings combine elements of both catenary and taut systems and can be adapted for multiline anchor setups to balance stability and flexibility. Tendon is not an option for multiline due to its small footprint and, thereby, not conducive to overlapping of anchoring location.

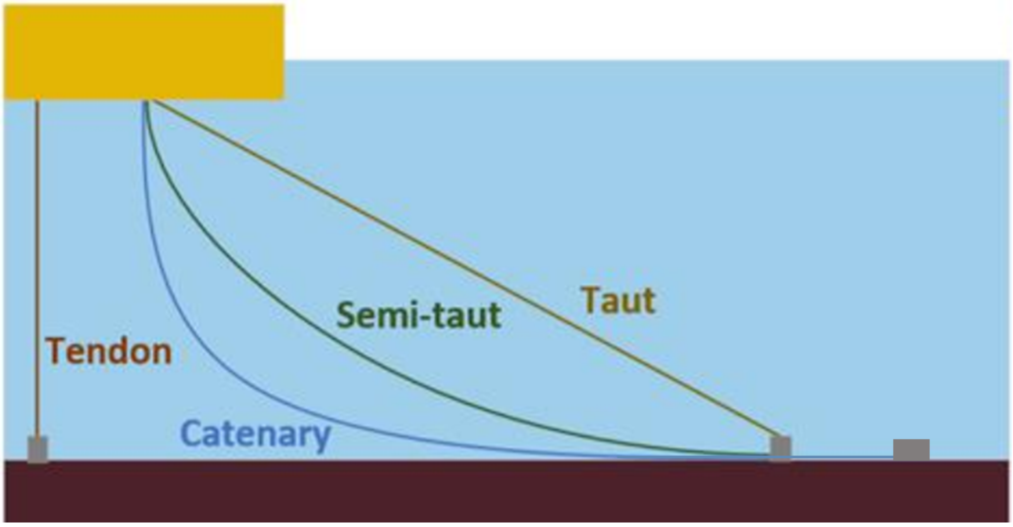


Figure 2.5: Illustration of mooring configurations. Original image: [30]

Anchor types also play a crucial role in the feasibility of multiline anchors. Drag anchors, which rely on horizontal resistance, may not provide sufficient stability for multiline configurations in soft seabeds. Pile anchors, which are driven deep into the seabed, offer higher stability and are more compatible with multiline systems due to their ability to support multiple lines. Suction anchors, which use differential pressure to stay in place, can be effective in various seabed conditions and are suitable for multiline anchors as they provide a strong and stable anchoring point.

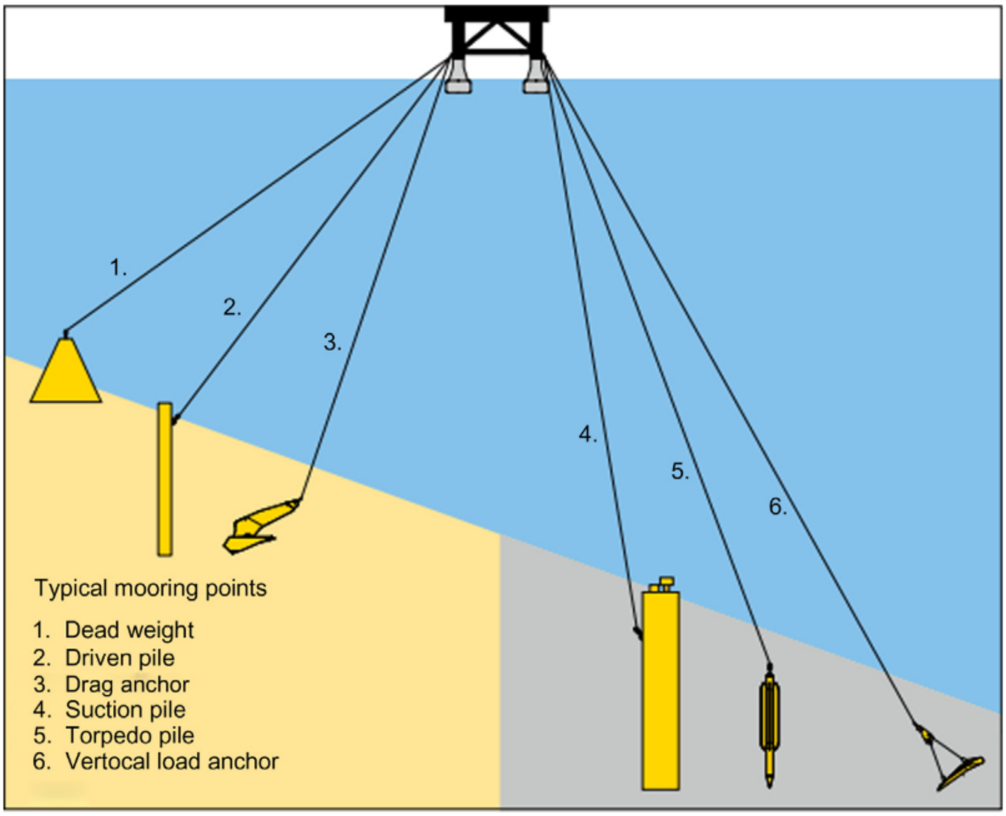


Figure 2.6: Different anchor types for shallow and deep water dependent on soil types [31].

2.1.4. Numerical Models and Simulation Approaches

Advanced simulation tools are crucial for designing and analyzing FOWTs. Integrating aerodynamic, hydrodynamic, and structural simulations helps predict performance under real-world conditions, identify potential issues, and facilitate design optimizations. Tools like OpenFAST, Orcaflex, AeroDyn, and HydroDyn are instrumental in understanding the interactions between wind turbines and floating platforms [29]. This understanding is critical in the design of floating offshore wind turbines and farms, also known as the front-end engineering design (FEED). However, none of this software focuses on or allows for the simulation of different operation and maintenance scenarios. These software don't deal with financial aspects or scenario-based events. A gap in research of FOWF has been found, especially in the O&M. Most of the industry is focusing on the FEED; focusing on an area less researched can fill a gap.

Created by the National Renewable Energy Laboratory, the Windfarm Operations and Maintenance cost-Benefit Analysis Tool is a scenario-based simulation tool. It allows for modeling trade-offs in decision-making regarding the operations and maintenance of wind farms over their life span. WOMBAT can be enhanced to evaluate multiline anchor systems specifically, addressing the current limitations in simulation tools regarding O&M scenarios.

Designing floating structures for offshore wind turbines involves addressing a range of engineering challenges, from understanding hydrodynamic behavior to ensuring economic feasibility. As technology advances, the integration of multidisciplinary design approaches will be key [29]. Continuous improvement in both the design methodologies and operations and maintenance strategies is needed for the success of FOWTs in delivering sustainable and reliable offshore wind energy.

2.2. Multiline Anchoring Systems: Types and Benefits

2.2.1. Introduction

The economic viability and structural reliability of FOWTs hinge significantly on their anchoring systems. Conventional single-line anchoring systems connect each turbine to a dedicated anchor, resulting in a high number of anchors and installation costs. In contrast, multiline anchoring systems aim to connect multiple turbines to a single anchor, thereby reducing the number of anchors required. This reduction in anchors leads to significant cost savings by minimizing material and installation costs and reducing environmental impacts due to fewer seabed disturbances [17].

Figure 2.7 displays different mooring configurations to avoid confusion. Only the first two are relevant to this study; shared moorings are not considered in either the software enhancement or the case studies. This study will compare conventional mooring to shared anchors to evaluate their performance and cost-effectiveness.

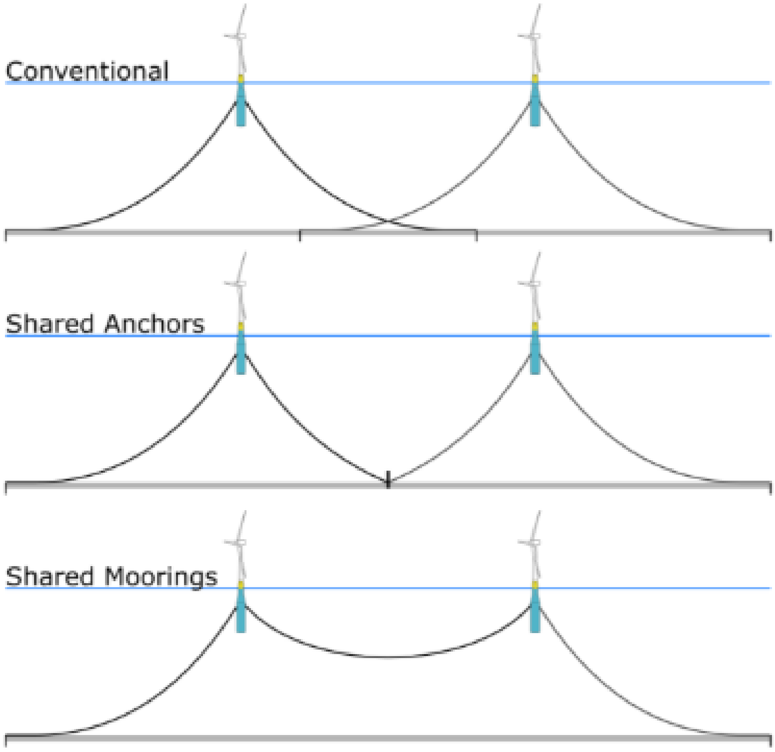


Figure 2.7: Individual moorings, shared anchors, and shared mooring lines. [32]

The interconnectedness of multiline anchors introduces complexity in load distribution and potential cascading failure modes across multiple turbines, as highlighted by Hallowell et al. (2018)[33]. Despite these challenges, multiline anchor systems offer significant benefits in terms of cost reduction, system redundancy, and reduced environmental impact.

2.2.2. Types of Multiline Anchoring System

Though there is more than one possible configuration in which multiline anchors can be applied, this research applies only to 3-line anchor systems. The 3-line system is eminently studied and referenced and has been successfully implemented in a commercial wind farm, providing a reliable benchmark for analysis.

2.2.2.1 3-Line Anchor System

The 3-line anchor system (seen in figure 2.8) is designed to connect three turbines to a single anchor, distributing the mooring forces among the connected turbines. Each anchor is typically loaded in multiple directions due to the connected lines, requiring robust design and careful placement.

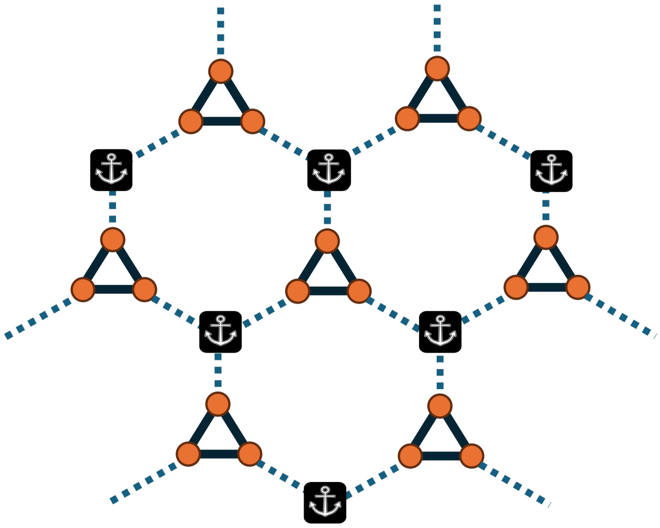


Figure 2.8: Bird eye view of a 3-line multiline anchor layout.

2.2.3. Benefits of Multiline Anchoring Systems

2.2.3.1 Cost Reduction

Multiline anchoring systems significantly reduce material and installation costs by minimizing the number of required anchors. According to Devin (2019), optimized shared mooring systems can lead to cost reductions of up to 25% compared to traditional single-line systems [34].

2.2.3.2 Reduced Environmental Impact

A reduction in the number of anchors directly translates to fewer seabed disturbances, making multiline anchoring systems particularly suitable for environmentally sensitive areas. This environmental benefit is helpful for gaining regulatory approvals and maintaining the ecological balance in offshore wind farm locations.

2.2.4. Case Studies

2.2.4.1 Optimized Shared Mooring and Anchoring Strength (Devin, 2019)

In Devin's (2019) thesis, a detailed simulation was performed to evaluate the reliability and cost-effectiveness of optimized shared mooring systems. The results demonstrated significant cost savings while maintaining acceptable reliability levels.

2.2.4.2 System Reliability Analysis of Multiline Anchors (Hallowell et al., 2018)

Hallowell et al. (2018) conducted a comprehensive Monte Carlo simulation to assess the reliability of multiline anchors. The study highlighted that while multiline anchors reduce costs, they also introduce the risk of cascading failures. Proper design considerations, such as anchor sizing and mooring line configuration, are essential to mitigate these risks.

2.2.4.3 COREWIND D4.2 Floating Wind Operation and Maintenance Strategies Assesment

The COREWIND D4.2 report provides a comprehensive assessment of operation and maintenance strategies specifically tailored for floating offshore wind farms. The study emphasizes the integration of advanced digital tools and predictive maintenance approaches to optimize the performance and reliability of floating wind installations. It also presents extensive failure and maintenance data, offering valuable insights into the most common issues faced by floating wind systems and the effectiveness of different maintenance strategies. Additionally, the report explores the economic implications of various maintenance strategies, highlighting the potential for significant cost savings through the adoption of condition-based maintenance and the use of autonomous inspection technologies.

2.2.4.4 Mooring Integrity Issues and Lessons Learned Database (DeepStar® Project 20401)

The DeepStar® Project 20401 provides an extensive database on mooring integrity issues and lessons learned from oil and gas applications. While these failure rates are specific to floating production storage and offloading units and other oil and gas platforms, they offer valuable insights into common failure modes and the importance of robust design and inspection practices. The project identified that the majority of failures are related to mooring lines, particularly at the splash zone, rather than anchors [35].

2.2.4.5 Improving Mooring Integrity through Standardized Inspection Practices (DeepStar® Project 14903)

The DeepStar® Project 19403 emphasizes the importance of standardized inspection practices to enhance mooring system integrity. This project underscores the necessity of robust design, quality manufacturing, and proper installation practices to prevent failures. It highlights that anchor failures are extremely rare in permanent mooring systems, contrasting with the higher incidence of mooring line failures [36].

2.2.5. Conclusion

Multiline anchoring systems present a promising solution to reduce costs and environmental impacts in floating offshore wind farms. While they introduce complexity in load distribution and reliability challenges, careful design and simulation can significantly improve their effectiveness. Future research should continue to focus on optimizing these systems through advanced modeling and empirical case studies. This step of furthering the technology has already started with the company SEMAR and its trademarked Honeymooring mooring technology [37]. Incorporating insights from oil and gas mooring systems can further enhance the reliability and efficiency of multiline anchors.

3

Development of the Mooring Simulation Model

3.1. WOMBAT Simulation, Operation and Maintenance Software

3.1.1. Introduction

This section delves into the critical role of operations and maintenance in wind energy, emphasizing the unique challenges faced by floating offshore wind farms. It introduces the WOMBAT software, a powerful tool developed by NREL to optimize O&M strategies through advanced simulation techniques. Other tools were discussed in section 1.3 and 2.1.4, but this chapter will not recap this. This chapter demonstrates the enhancements made to WOMBAT to address previously specific limitations in simulating multiline anchors.

3.1.1.1 Role of O&M in Wind Energy

Operations and maintenance are vital for the sustainability and efficiency of wind farms. Effective O&M strategies minimize downtime and optimize performance, ensuring the longevity of the wind farm. Floating offshore wind farms face specific challenges such as harsher weather conditions, accessibility issues, and the dynamic behavior of floating structures, which necessitate more complex and robust O&M strategies [38] [39].

3.1.1.2 Economic Impact of O&M

O&M costs significantly impact the levelized cost of energy, a critical metric for the economic viability of wind projects. Effective maintenance strategies that reduce O&M costs can substantially lower LCOE, making wind energy more competitive. For floating wind farms, approximately 36% of the total project costs are incurred during installation, operation, and dismantling activities [40]. Therefore, optimizing O&M strategies is essential for enhancing the financial performance of wind farms.

3.1.1.3 Advantages of Simulation in O&M

Simulation tools are invaluable for planning and risk management in wind farm operations. These tools enable operators to model various maintenance scenarios, predict failures, and plan interventions, thereby improving operational efficiency and reducing costs. By simulating different mooring layouts, designers and operators can identify the most cost-effective approaches and enhance the overall reliability of the wind farm.

3.1.2. Overview of WOMBAT Software

3.1.2.1 Introduction to WOMBAT

WOMBAT was developed to address the complexities of O&M in wind farms. The tool helps designers and operators compare the cost impacts of different layouts, various O&M strategies, and technologies, facilitating better decision-making and cost optimization [41].

3.1.2.2 Features of WOMBAT

WOMBAT is characterized by its modular design and flexibility, allowing it to simulate both land-based and offshore bottom fixed wind farms. Its prescriptive modeling approach via discrete event simulation enables the tool to account for weather and site-specific variability, allowing the user to understand the cost and energy impacts a certain failure rate and O&M strategy has [42] [41].

3.1.2.3 Utility and Adaptability

WOMBAT's customization features allow users to integrate new technologies and maintenance strategies easily. It supports scenario-based planning, enabling users to evaluate the impacts of different layouts, mooring configurations, and failure rates on O&M cost. This adaptability makes WOMBAT a valuable tool for both current operations and future planning [41]. This adaptability is what allowed for the modification made, which will be described in section 3.2.

3.1.3. Software Architecture and Functionality

3.1.3.1 Core Components of WOMBAT

The layout of WOMBAT is extensive and intricate, with interlocking components. Figure 3.1 breaks it into three sections: the core, the wind farm, and the utilities (the yellow-colored boxes). The dark blue boxes represent the main individual scripts that handle the software's operations, while the light blue boxes provide a detailed breakdown of the wind farm's components. The red-outlined light blue box highlights the added mooring component, which enhances the software's ability to model mooring configurations with higher fidelity. This addition allows for the analysis of the floating offshore wind farms with the same level of detail as bottom-fixed offshore wind farms.

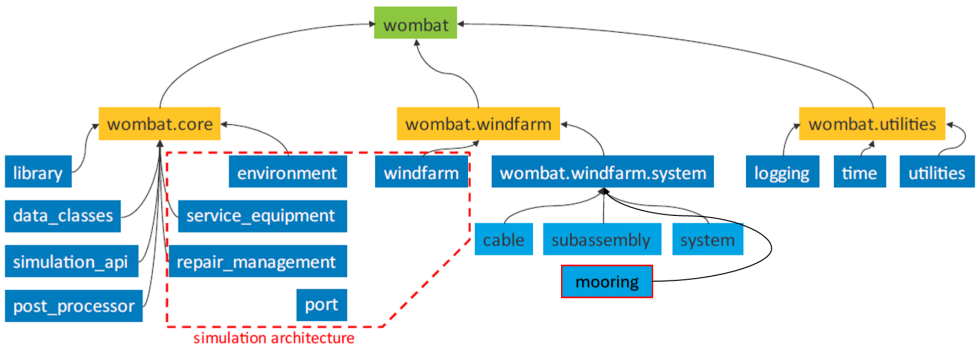


Figure 3.1: Diagram of the WOMBAT software architecture. Original image: [43].

The central components are highlighted in a dashed red line. These are the environment model, wind farm model, repair manager, port, and servicing equipment. Each component plays a specific role in the simulation process [43]:

- Environment model: Handles weather data and timing, crucial for scheduling maintenance.
- Wind farm model: Stores information about turbines, substations, cables, and other infrastructure.
- Repair manager: Schedules and manages repair tasks based on equipment status and availability.
- Servicing equipment: Tracks the capabilities and costs of various maintenance vessels and equipment.
- Port: Tracks the operations done in the port.

3.1.3.2 Simulation Process in WOMBAT

WOMBAT uses discrete event simulation to model a series of events sequentially, focusing on the timing and impact of maintenance activities. Variables such as weather data, equipment status, and failure rates influence the scheduling and execution of maintenance tasks [43]. Following along on the timeline of figure 3.2 the simulation process includes:

- *Starting the simulation with initial conditions and configurations:* At the start of a simulation, all the defined systems and subassemblies, weather profiles, and service equipment are created from the user inputs and are placed in a ready-to-run state.
- *Monitoring subassembly failures or maintenance intervals:* Each subassembly has user-defined repair and maintenance tasks with their own timing, which triggers events once a specified time has elapsed. Failures randomly sample the time to the next failure using a Weibull distribution. The exact working of the Weibull distribution are explained in next section.
- *Assigning repair tasks to available servicing equipment:* The repair manager passes the failure or maintenance request to an appropriate piece of service equipment. Once the service equipment is assigned to the task, it will travel to the turbine and perform the repair. The service equipment accumulates downtime when weather conditions are outside of safe operating conditions and during non-work hours.
- *Conducting maintenance and tracking O&M costs and downtime:* After the repair is complete, the time and costs are logged, and the simulation resets the subassembly with a new time to failure.

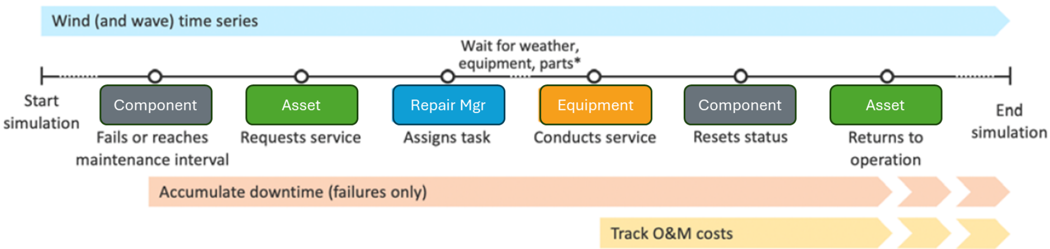


Figure 3.2: Conceptual overview of a single event within the simulation architecture. [43]

3.1.3.3 Time to failure model in WOMBAT

In the WOMBAT system, predicting the time to failure of components is essential for effective maintenance and operational efficiency. Central to this process is the Cumulative Distribution Function (CDF), a fundamental tool in probability theory and statistics.

The CDF describes the probability that a random variable will take on a value less than or equal to a specific threshold—in this case, the time t by which a component will fail. Mathematically, the CDF provides the probability, $F(t)$, that a component will have failed by a certain time:

$$F(t) = P(T \leq t) \tag{3.1}$$

In reliability engineering, the CDF is crucial because it allows us to quantify the likelihood of failure over time, providing a clear understanding of how risk accumulates as components age.

The Weibull distribution, expressed through its CDF, is given by the following equation:

$$F(t) = 1 - \exp\left(-\left(\frac{t}{\lambda}\right)^{\beta}\right) \tag{3.2}$$

Each variable in this equation plays a critical role:

- $F(t)$ represents the probability that the component will fail by time t.
- t is the specific time at which the failure probability is evaluated.
- λ (scale) and β (shape) parameters define the behavior of the distribution, ensuring that the model accurately reflects the operational realities of different subassemblies.

To model this probability in WOMBAT, the Weibull distribution is employed. The Weibull distribution is specifically chosen for its flexibility and accuracy in representing various failure behaviors. The distribution is characterized by two key parameters:

- **Scale Parameter (λ)**: This parameter adjusts the distribution along the time axis, correlating with the expected life of a component (mean time between failures, or MTBF). Essentially, it stretches or compresses the distribution to reflect how long components are expected to last. The scale parameter is mathematically defined as::

$$\text{scale} = \frac{1}{\text{\# failures/system/year}} \tag{3.3}$$

- **Shape Parameter (β)**: This parameter determines the nature of the failure rate over time—whether it remains constant, decreases, or increases. By adjusting β, the Weibull distribution can model a wide range of failure behaviors—from early-life failures to wear-out failures.
  - If $\beta = 1$, the distribution is exponential, indicating a constant failure rate over time (random failures).
  - If $\beta < 1$, the failure rate decreases over time (early failures, possibly due to manufacturing defects).
  - If $\beta > 1$, the failure rate increases over time (wear-out failures, such as those due to fatigue or corrosion).

Application in WOMBAT:
The practical application of the Weibull distribution involves generating random times to failure for each component. This is done using a random number generator that samples from the Weibull distribution according to its CDF. The process works as follows:

1. **Initialization:** When the simulation starts, each subassembly of the wind turbines and substructures is initialized with Weibull distribution parameters based on user-provided scale and shape values.
2. **Random Sampling:** For each subassembly, the random generator samples a time to the next failure from the Weibull distribution. This sampling process uses the CDF to determine the likelihood of failure at different points in time, ensuring that the generated failure times reflect realistic operational conditions.
3. **Failure Events:** Once a subassembly reaches its randomly generated failure time, it triggers a failure event. This event is logged, and a repair request is initiated in the repair management system, which then reduces the operational capacity of the wind turbine.
4. **Repair Process:** The repair management system assigns the repair task to the appropriate service equipment. After the repair is completed, the subassembly is reset, and a new time to failure is sampled from the Weibull distribution, continuing the cycle.

By combining the theoretical power of the Weibull distribution with the practical use of random sampling, WOMBAT can simulate realistic failure scenarios that support data-driven maintenance and operational strategies.

Example in the Code:
WOMBAT requires users to input the Weibull scale and shape parameters for each subassembly. For instance, if the shape parameter is set to 5 (indicating a random failure rate) and the scale parameter to 2 years (indicating an average failure time over 2 years), the model will generate five failures randomly through this 2-year meantime. Other examples of these values will occur in later chapters.

Practical Implications:
By using the Weibull distribution, WOMBAT can simulate a realistic range of failure times and maintenance needs for wind turbines, accounting for different failure behaviors (early, random, or wear-out). This helps evaluate the reliability of components and the effectiveness of various maintenance strategies.

Summary

- **Weibull Distribution Parameters**: Scale (MTBF) and Shape (failure rate behavior).
- **Model Initialization**: Subassemblies initialized with Weibull parameters.
- **Random Sampling**: Time to failure is sampled from Weibull distribution.
- **Failure Events**: Triggered based on sampled time, initiating repair processes.
- **Repair and Reset**: After repairs, the failure time is sampled, continuing the cycle.

This approach allows WOMBAT to provide detailed, scenario-based O&M cost-benefit analysis by modeling the realistic failure behavior of wind turbine, cable and substructure components over time.

3.1.4. Future Developments and Integration

3.1.4.1 Potential Enhancements in WOMBAT

Future work on WOMBAT involves enhancing its core capabilities and integrating it more closely with other tools from the National Renewable Energy Laboratory. Enhancements planned by NREL include incorporating more detailed anchor and mooring line simulations and integrating real-time monitoring data. These improvements will support the modeling of new or alternative mooring system configurations [43].

For this thesis, specific modifications have been made to WOMBAT to include detailed simulations of mooring lines and anchors, addressing the particular needs of floating offshore wind farms. These modifications allow WOMBAT to simulate the impact of different mooring configurations on O&M strategies more precisely. This capability ensures that the software can adapt to the evolving wind farm management and maintenance needs, particularly in the offshore sector, where the complexities and challenges are more pronounced. At the time of publishing the thesis, the modifications made to WOMBAT are on the public GitHub of WOMBAT by NREL [44].

As simulation technology advances, tools like WOMBAT can further impact O&M strategies by incorporating emerging technologies and more detailed modeling capabilities. For example, integrating data from real-time monitoring systems and using advanced analytics could enhance the predictive maintenance capabilities of WOMBAT.

3.1.5. Conclusion

3.1.5.1 Summary of WOMBAT's Impact on Wind Farm O&M

WOMBAT can be a powerful tool for optimizing O&M activities in wind farms. Its ability to simulate different maintenance strategies and analyze their cost impacts makes it invaluable for improving operational efficiency and reducing costs. The enhancements made in this thesis, particularly the detailed simulation of anchors and mooring lines, have expanded WOMBAT's capability to address the unique challenges of floating offshore wind farms. Continuous development and integration of simulation tools like WOMBAT will be crucial for the future of renewable energy operations, ensuring that wind farms operate efficiently and economically. For the integrated details of the workings of WOMBAT, the NREL report is suggested for further reading [43].

3.2. Adaptations to WOMBAT Software for Mooring integration

From the reports and presentation on WOMBAT, there has been an indication to expand the software's capabilities to include mooring configurations [42][43]. The work done for this thesis is in answer to this indication. This included massive additions to the existing code, going into every code file, cross-checking, and implementing code to make the modifications for mooring work. The code can be found on GitHub under the WOMBAT main [44]; it has its own available branch there. Due to the extent of the added code, it will not be given in the chapters; a snippet is given in the appendix and will be explained further in the chapter. This section has three subsections; in the first, the creation of the two wind farm scenarios data is explained (3.2.1). The second subsection explains the logic flowchart that was implemented with the additional mooring code modifications (3.2.2). In the third subsection, the consequences of failure in mooring components are made clear, subsection 3.2.3.

3.2.1. Creation of mooring layouts

Before a wind farm's operation and maintenance can be analyzed, its layout must first be created. Given the need to analyze multiple wind farms with different mooring configurations, manually creating these layouts was impractical. To address this, an algorithm was developed to automate the creation of wind farm layouts based on a set of predefined inputs.

Algorithm for Layout Generation:

The algorithm has been implemented in Python to generate wind farm layouts by taking several input parameters, including the number of turbines, spacing between turbines, and the mooring configuration (single-line or multiline anchors). These inputs are detailed in table 3.1, which lists the parameters for the algorithm and an example of these inputs.

Table 3.1: Input parameters for creating wind farm and mooring layouts.

Parameter	Example inputs
# of turbines	25
spacing turbines [m]	2160
# of turbines per string	5
# of strings per substation	5
Shared Anchor	TRUE & FALSE
Coordinates:	
latitude	19° 58’
longitude	-154
tolerance overlap anchor [m]	1
angles multiline anchor layout	90,210,330
angles single-line anchor layout	0,120,240

The algorithm generates two data files in CSV format, containing all necessary information for the wind farm layouts and mooring layout. Figures 3.3 and 3.4 below illustrate the difference between single-line and multiline anchor layout configurations.

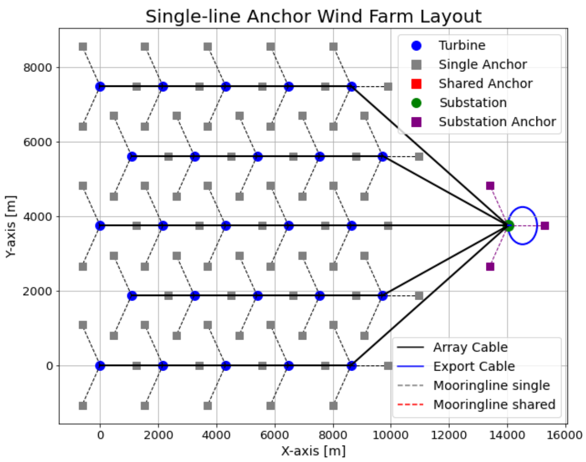


Figure 3.3: Automatically generated single-line anchor layout from example inputs.

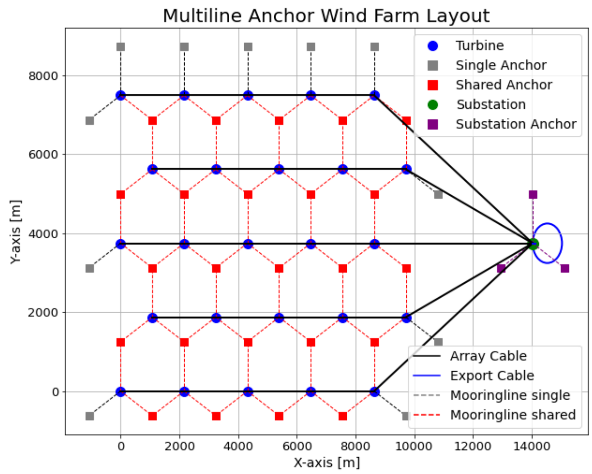


Figure 3.4: Automatically generated multiline anchor layout from example inputs.

The Python script's logic involves creating a grid of turbines based on the input parameters and then assigning mooring lines and anchors according to the chosen configuration. This automated process ensures consistency and accuracy in the layout generation, allowing for efficient analysis of various scenarios within the WOMBAT software.

3.2.2. Integration of Mooring Simulation in WOMBAT

WOMBAT has intensely interconnected codes, meaning that though there is a central mooring code, in order to make it work into the overall system, codes had to be added to nearly every other part of the software. Integrating mooring simulations within the WOMBAT framework involves a structured and systematic approach to ensure effective O&M for FOWFs. This section builds on the explanation provided in Section 3.1 about the WOMBAT software, the Weibull distribution and failure rates, focusing now on how these concepts are implemented specifically for mooring systems.

Figure 3.5 is a flowchart that depicts the process underlying the mooring simulation. This flowchart illustrates the fundamental steps involved in the simulation. It shows how various components of the WOMBAT code, such as `windfarm.py`, `repair_management.py`, `service_equipment.py`, `environment.py` and `port.py` (represented by grey boxes), are interwoven with the mooring part.

3.2.2.1 Description of the Flowchart

The flowchart illustrates the sequence of operations and decision points for managing the mooring system within the WOMBAT framework.

1. **Initialization Steps**:
   - **WindFarm** (Triangle, Blue): The simulation begins with initializing the `WindFarm` object, which encompasses the overall simulation environment. This is implemented in the `__init__` method of the `Windfarm` class in `windfarm.py`.
   - **SubassemblyData** (Rectangle, Blue): This is where detailed data of the specific subassembly mooring components are loaded. This is handled by the `_create_mooring_layout` methods in `windfarm.py`.
   - **Start Mooring Process** (Rectangle, Blue): The mooring simulation process is initiated by the `__init__` method of the `Mooring` class in `mooring.py`.

2. **Loading and Parsing Data**:
   - **Load YAML Files** (Rectangle, Blue): Configuration files containing mooring data are loaded using the `yaml` function in `windfarm.py`.

- **Parse YAML Files** (Rectangle, Blue): The data from the YAML files is parsed to extract the necessary information for the simulation, handled by `_yaml_data` in `windfarm.py`.

3. **Maintenance Detection**:
   - **Schedule Maintenance** (Rectangle, Green): Routine maintenance tasks are scheduled based on predefined intervals and conditions. This function comes from the `repair_management.py` code component.
   - **Maintenance Request** (Rectangle, Orange): The system keeps running until maintenance is triggered and requested, using functions `trigger_request` in `mooring.py`.
   - **Scheduled Maintenance** (Rectangle, Orange): The maintenance request is run in conjunction with the Repair Manager and Service Equipment, done with `run_single_maintenance` in `mooring.py`.
   - **Log Maintenance and Action** (Rectangle, Purple): Logging of events so far performed in the maintenance of mooring component is done with `log_event` as part of `mooring.py`.

4. **Failure Detection**:
   - **Monitor for Failures** (Rectangle, Yellow): The system keeps running until a failure is triggered by using function `trigger_request` in `mooring.py`.
   - **Failure Detected?** (Diamond, Yellow): This is a decision point to check if any failures have been detected; if yes, then the information is passed on to failure identification and repair.

5. **Failure Identification and Repair**:
   - **Identify Failure Type** (Rectangle, Yellow): If a failure is detected, the type of failure is identified by the `_create_processes` function in `mooring.py`.
   - **Repair Request** (Rectangle, Orange): A repair request is generated using the `register_repair` function in `repair_management.py`.
   - **Schedule Repair or Replacement** (Rectangle, Orange): Based on the repair request, either a repair or a replacement is scheduled by the `run_single_failure` function in `mooring.py`.
   - **Log Failure and Action** (Rectangle, Purple): The events identified and actions needed for the failed mooring component are logged with `log_event` as part of `mooring.py`.

6. **Shutdown Actions**:
   - **Determine Connectivity Action** (Diamond, Yellow): The necessary actions are determined based on the connectivity and impact on the overall system, this is handled by `stop_all_mooring_processes` function in `mooring.py`
   - **Shutdown Turbine/Turbines/Substation** (Rectangles, Red): Depending on the failure type and connectivity, turbines or substations may need to be shut down. This is also done in the `stop_all_mooring_processes` function of `mooring.py`.
   - **Perform Maintenance or Repair** (Oval, Green): The actual maintenance or repair work is simulated in the Repair Manager and Service Equipment software components. If tow-to-port is part of it then the Port component of the simulation adds input.
   - **Log Maintenance or Repair** (Rectangle, Purple): All actions taken are logged for reference using the `log_event` function in `mooring.py`.
   - **Turn Back on Apparatus** (Rectangle, Red): Once repairs are complete, the apparatus(ses) are turned back on by the `enable_mooring_operations` function in `service_equipment.py`.
   - **WindFarm** (Triangle, Blue): The system returns to a normal operational state until the next maintenance or failure is triggered.

The integration of mooring simulations within WOMBAT, as illustrated in the flowchart, highlights the comprehensive approach taken. The corresponding functions across `windfarm.py`, `mooring.py`, `repair_management.py`, and `service_equipment.py` are meticulously designed to handle each step of the process, ensuring robust and reliable operations. To be clear, the flowchart shows what is happening in the context of the tool's mooring component. The grey boxes already existed in the tool and were modified and added to. All the other color boxes are part of the mooring component, though similar to the logic of how cables integrate into the software, the mooring component stands on its own and is the modification.

Additionally, when it comes to multiline mooring configuration, the data distinguishing whether a single-line or multiline layout is loaded happens at the beginning in Subassemblydata (first blue box). This data trickles down the logic flow chart. Depending on the mooring type, different vessels could come from service equipment, and information on time and cost will come from the repair manager. The determine connectivity action (second yellow diamond) was built with multiline in mind and its consequences, which are explained in the next subsection. The single-line and multiline configuration is the data being processed through the mooring component; however, while writing the Python scripts, consideration was taken to build the code in such a manner that different configurations could also be applied. In this manner, other research with different layouts could be done, not limiting the mooring component to only these specefic ones.

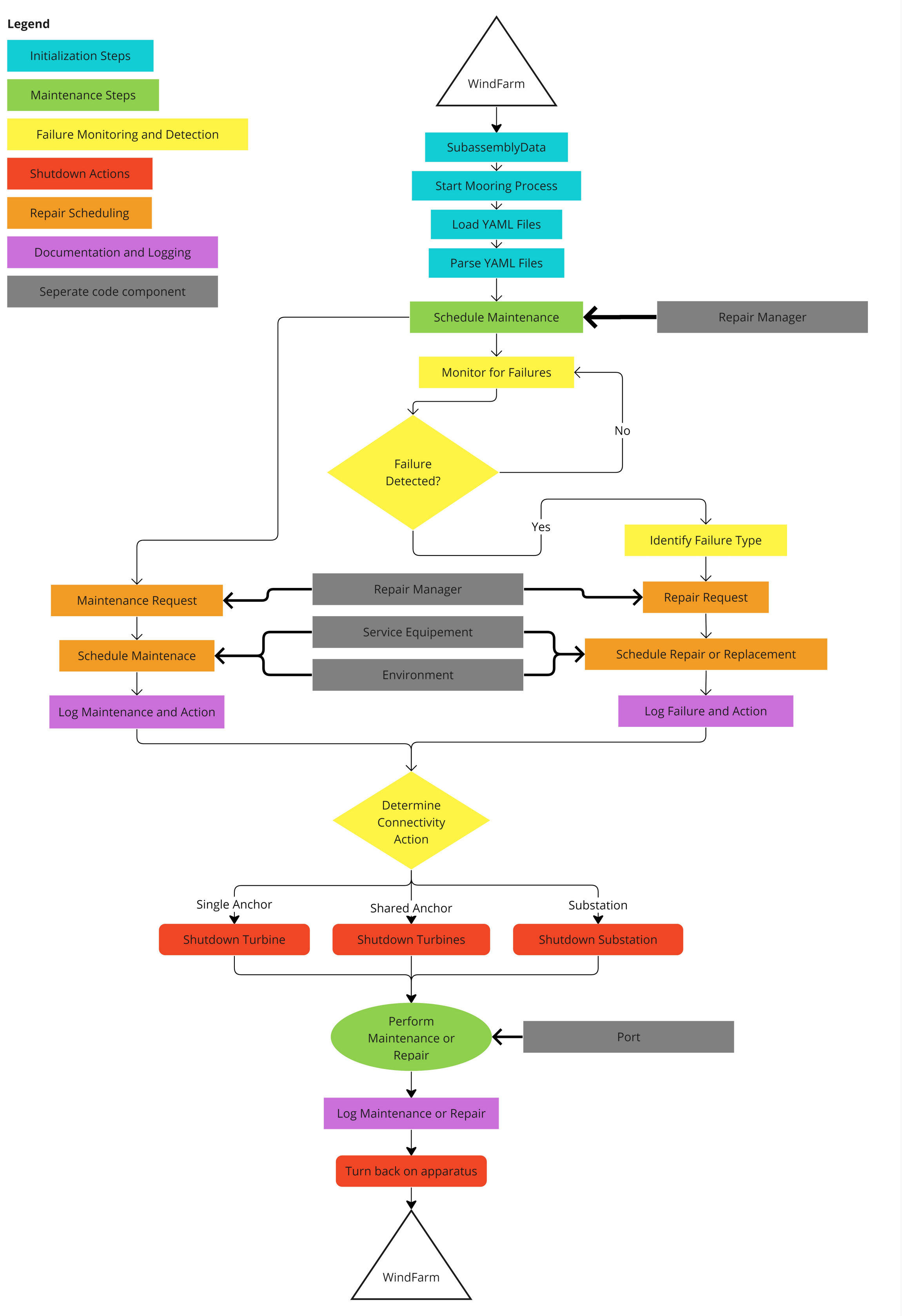


Figure 3.5: Logic flow chart of the mooring component of WOMBAT Software

3.2.3. Impact of Mooring System on Wind Turbine Shutdown

3.2.3.1 Definition of failure and replacement

The definition of failure within the mooring system is crucial for accurate simulation and response. In this context, two primary failure types are considered:

1. **Anchor Failure:** This occurs when an anchor loses its embedment to the seafloor. For multiline anchors, the failure results in the disconnection of all mooring lines attached to the anchor, affecting multiple turbines (typically three). For single-line anchors, the failure affects only the turbine connected to that anchor. These failures require the replacement of the failed anchor to restore functionality.

2. **Mooring Line Failure:** This involves the breaking of the mooring line itself, which can be due to fatigue, corrosion, or excessive load. When a mooring line fails, it is considered a critical failure necessitating immediate replacement to prevent drift and potential collisions.

These definitions are operationalized in WOMBAT using specific classes and methods in `mooring.py` and `repair_management.py`. The logic was outlined in the previous section with figure 3.5. It starts at number 4, failure detection, until the end of number 6, shutdown actions.

3.2.3.2 Connectivity of phased wind farm shut down

To mitigate the risks associated with mooring failures, an overly conservative two-phase shutdown protocol was developed. This system prepares for worst-case scenarios based on the wind farm's connectivity with multiline anchors. The rationale behind this conservative approach is to prevent potential collisions between partially untethered turbines and operational turbines.

The implementation of the phased shutdown process will be described in steps and with the help of Figure 3.6.

- **Direct Turbine Shutdown**: Represented by green circles, showing turbines directly affected by the anchor failure.
- **Indirect Turbine Shutdown**: Represented by purple circles, indicating secondary turbines at risk of being affected.

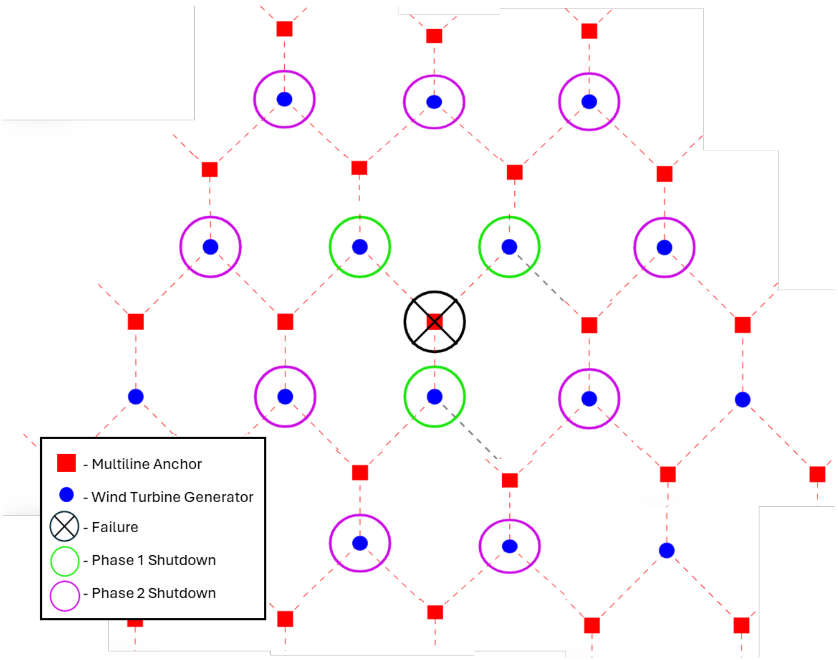


Figure 3.6: Illustration of the connectivity of a wind farm with a multiline anchor failure and the affected turbines in phased shutdown.

The implementation of the phased shutdown process involves two main phases managed by the `stop_all_mooring_processes()` method in `mooring.py`.

In **Phase 1 - Direct Shutdown**, initiated immediately after detecting a failure, all turbines directly connected to the failed anchor are shut down. This method ensures that turbines with a loose mooring line are taken offline to prevent collisions. The system identifies and logs all **directly affected systems** that need to be shut down due to the failure. This is achieved through logging the initiation of the shutdown process, interrupting processes within subassemblies of directly affected systems to safely stop them, and logging the action of direct impact and failure for each affected system.

Phase 2 - Indirect Shutdown assesses the connectivity map to identify secondary turbines at risk of collision due to the failure. These turbines are proactively shut down to mitigate potential cascading failures. The system identifies all **indirectly affected systems** due to shared mooring connections by gathering all anchors connected to directly affected systems, identifying all systems connected to these anchors, and logging the action of indirect impact and failure for each affected system.

The logic and detailed coding of this process, ensuring robust and fail-safe operation, are documented in Appendix C, showcasing the specific Python methods and algorithms implemented to handle these failures. In a multiline configuration as shown in figure 3.6, a multiline anchor failure results in 3 direct turbines and 9 indirect turbines being shut down. This highlights that an anchor failure in an overly conservative shutdown system could lead to a total of 12 turbines being shut off. This conservative approach is critical, as highlighted in literature by Hallowel et al. [33] [45], to prevent cascading failures and ensure the operational safety and efficiency of the wind farm.

By clearly defining failure types and implementing a structured, phased shutdown approach, WOMBAT ensures reliable and efficient management of floating offshore wind farms, enhancing overall system resilience and operational safety. For research where indirect shutdown is not desired, this feature can be altered easily in the Python code so that direct shutdown is the only logic implemented.

4
Cases and Simulations Setup

This chapter outlines the five case studies, the anchor layouts, and the wind farm scenario within them. Understanding this setup is critical for interpreting the results presented in subsequent chapters. Figure 4.1 serves as a navigational tool to keep track of which layout and scenario belong to which case study.

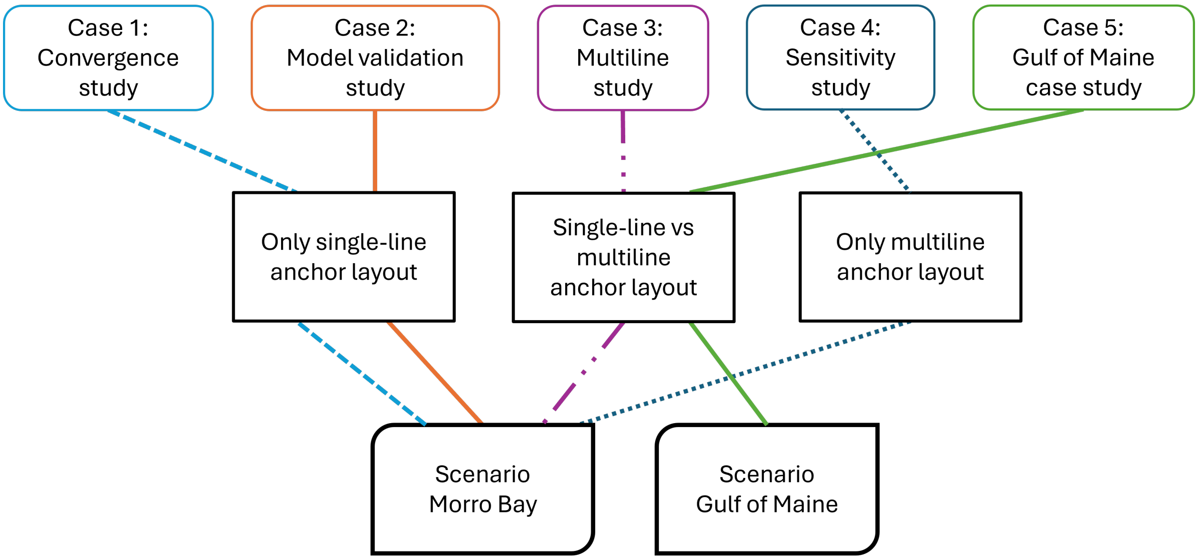


Figure 4.1: Navigational pane for case study and related anchor layout & scenario.

4.1. Case Studies Overview

The following case studies were conducted to evaluate the modifications made to the WOMBAT software and to evaluate a single-line vs multiline anchor layout.

- **Case 1: Convergence study** The study's objective is to determine the minimum number of simulations required for reliable results. This will be accomplished by running 50 simulations and monitoring convergence at intervals of 2 simulations.
- **Case 2: Model validation study** This study compares the improved software version to its original using the Morro Bay scenario and the data from the COREWIND report with a single-line anchor layout.
- **Case 3: Multiline layout study** This study compares single-line anchor versus multiline anchor layouts to determine which is more cost-effective, keeping other inputs constant in the Morro Bay scenario.

- **Case 4: Gulf of Maine study** This study evaluates the impact of different inputs, such as weather, wind farm life cycle duration, and port distance, using the same wind farm and mooring layout as the Morro Bay scenario.
- **Case 5: Sensitivity study** This study assesses the impact of different failure rate assumptions on wind farm performance by using four different mooring line failure rates sourced from the DeepStar 20401 Project, WFO Global Mooring White Paper, ASME Digital Collection - OMAE2014 and the COREWIND report. In this analysis, no repairs and anchor failures are applied for mooring.

4.2. Wind Farm Scenarios

Two wind farm scenarios are defined for the five upcoming simulations discussed in the subsequent chapters. To prevent repetition, the scenarios are predefined in this section. The array and mooring layouts for the two scenarios were created as described in section 3.2.1 and with the table 4.1.

Table 4.1: Input parameters for creating layouts for the Morro Bay and Gulf of Maine scenarios.

Parameter	Morro Bay	Gulf of Maine
# of turbines	80	
spacing turbines [m]	2160	
# of turbines per string	10	
# of strings per substation	4	
Shared Anchor	TRUE & FALSE	
Coordinates		
latitude	35° 26’	43° 5’
longitude	-121° 53’	-69°
tolerance overlap anchor [m]	1	
angles multiline anchor layout	[90,210,330]	
angles single-line anchor layout	[0,120,240]	

4.2.1. Morro Bay

The definition of the Morro Bay wind farm scenario is based on the COREWIND report [46]. This scenario was selected for two main reasons: it was the only U.S. scenario available in the COREWIND report and is a commonly used example case for floating wind turbines in the United States. The scenario provides a comprehensive dataset, including the environmental conditions, wind farm layout, mooring layout, and component specifications, which are crucial for a more defined simulation. The input parameters and variables are in Appendix A. Additional data, such as weather information, is sourced from the original WOMBAT files on the GitHub server. For the Morro Bay scenario, the weather data covers 20 years of hourly data in wind speed and wave height. The Bureau of Ocean Energy Management (BOEM) indicated Morro Bay area allocation is depicted in Figure 4.2. The port for this simulation is Cambria, located 60 km (37 miles) away, as indicated by the orange dotted line. The simulation parameters for the Morro Bay scenario are as follows:

- Total capacity: 1.2 GW
- Coordinates: (35.26, -121.53)
- 80 X IEA 15 MW turbines
- 60 km distance to port
- Two offshore substations
- 20-year life span

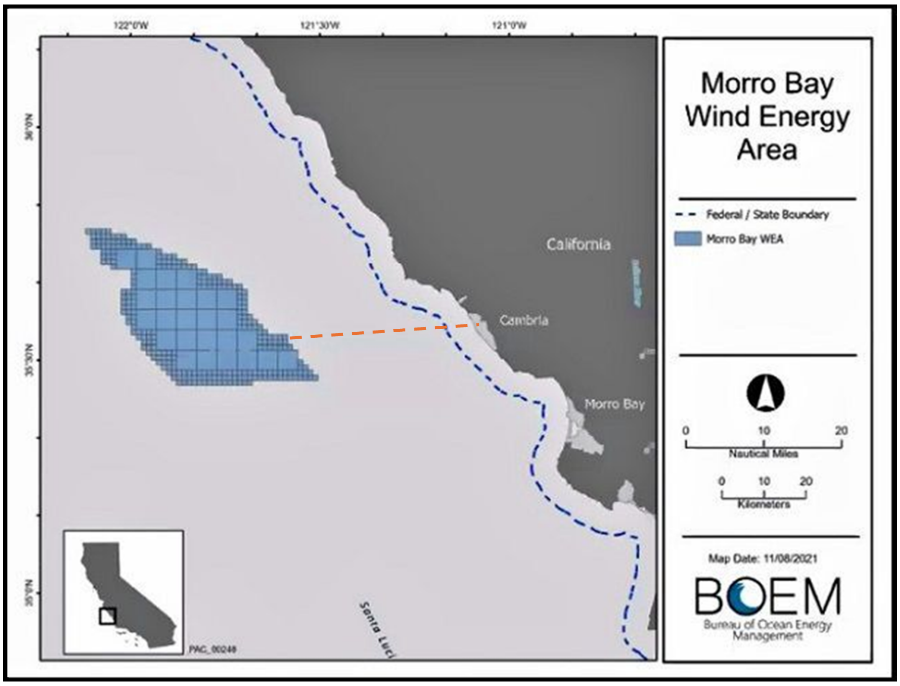


Figure 4.2: BOEM allocation of the Morro Bay site for wind energy. Modified image: [47]

4.2.2. Gulf of Maine

The Gulf of Maine (GoMe) scenario utilizes the same wind farm layout as the Morro Bay scenario, with changes in weather data, lifespan, and port location. GoMe offers a distinct set of metocean conditions, including colder water temperatures, unique wind patterns, and different wave heights. These variations enable an assessment of the influence metocean conditions have on maintenance operations. Weather data for this scenario was sourced from Buoy ST63236 [48] for a 30-year time span with hourly wind speed and wave height. The maintenance and failure rates remain consistent with those outlined in the COREWIND report [46], as detailed in Appendix A. The BOEM indicated Gulf of Maine area allocation is shown in figure 4.3, specifically focusing on lot OCS-A 0562 (blue encircled area). The port for this simulation is Portland, ME, located 113.94 km (70.8 miles) away, as shown in figure 4.4. Based on expert discussions at the IPF 2024 conference in New Orleans, the expected lifetimes of FOWFs have been extended to 25-35 years, reflected in the GoMe scenario. Additionally, GoMe has been a focal point for several research and development initiatives related to offshore wind energy, further justifying its selection as a comparative location. The simulation parameters for the Gulf of Maine scenario are as follows:

- Total capacity: 1.2 GW in OCS-A 0562
- Coordinates: (43.5, -69)
- 80 X IEA 15 MW turbines
- 113.94 km distance to port
- Two offshore substations
- 30-year life span

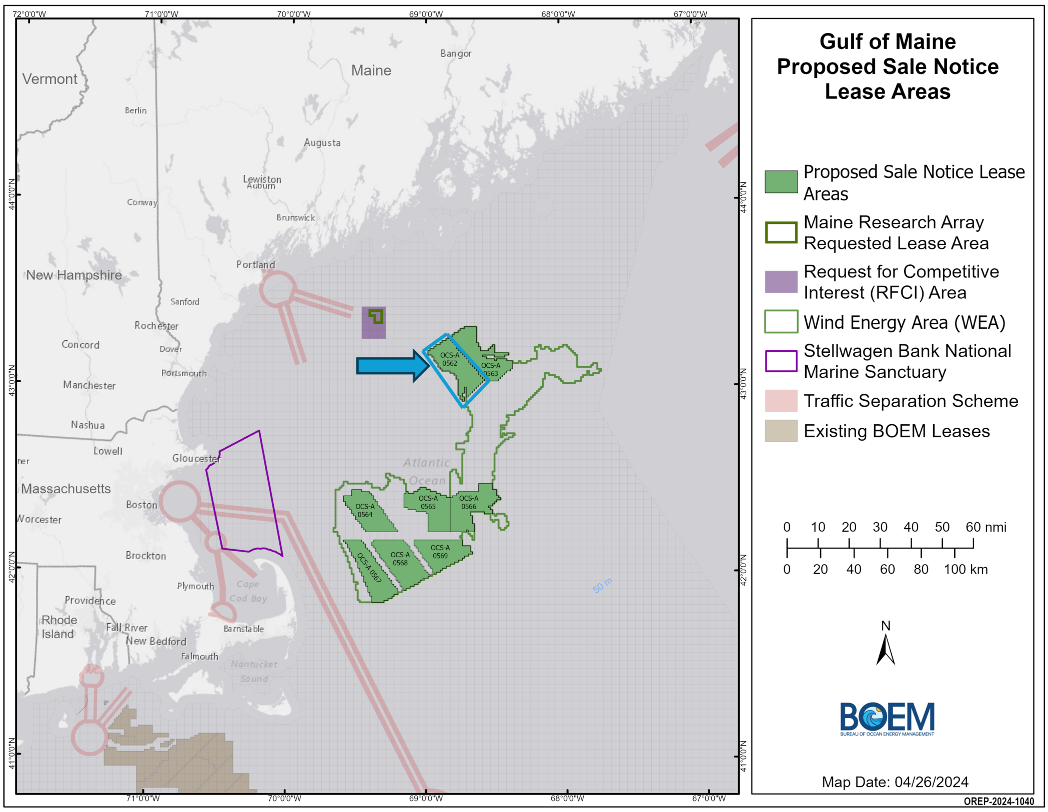


Figure 4.3: BOEM allocation of the Gulf of Maine site for wind energy. [49]

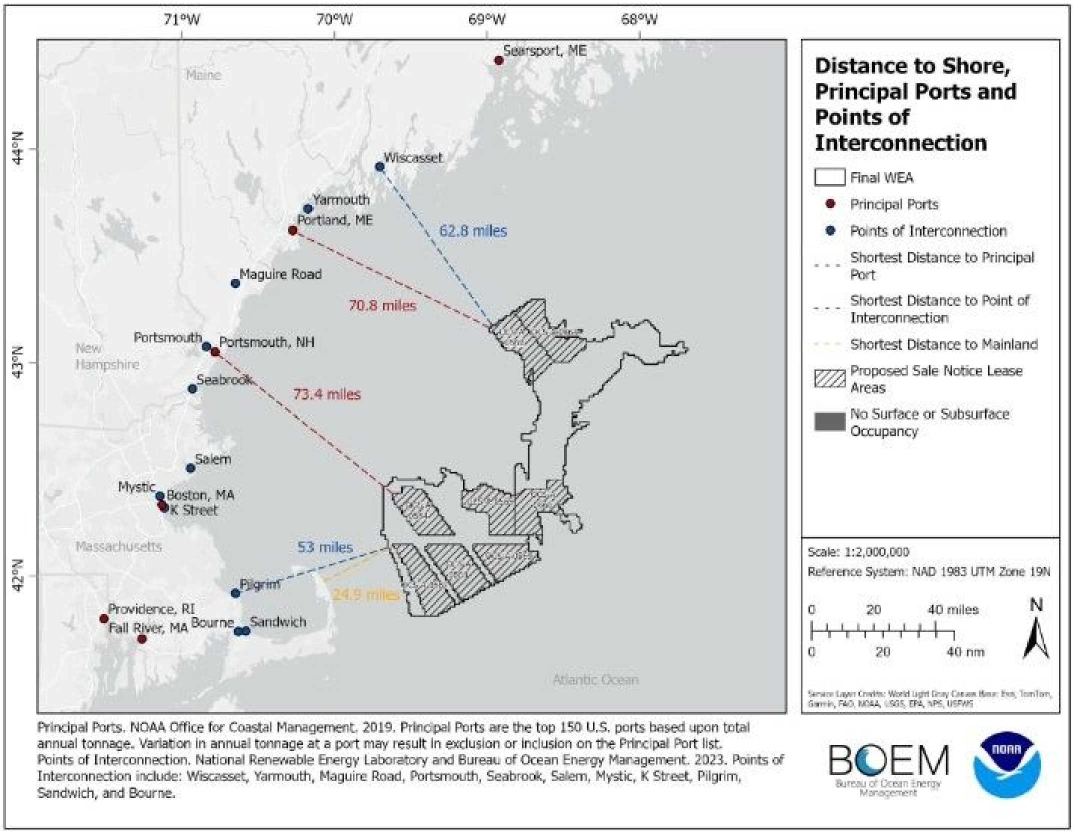


Figure 4.4: Port distance calculated by Power Advisory LLC for GoMe sites. [50]

4.3. Operation and Maintenance Strategies

A comprehensive overview of the operational and maintenance strategies used in WOMBAT can be found in Appendix E. These strategies include scheduled and unscheduled In-Situ maintenance, Tow-to-Port maintenance, and predictive maintenance. Each strategy is designed to address specific challenges and optimize the maintenance of offshore wind farms. In each case study, the software is programmed to perform scheduled In-Situ maintenance and request-based In-Situ repairs or unscheduled Tow-to-Port repairs.

4.4. Terminology for consistency

In this report, specific terminology is used to describe the different types of analyses conducted. Consistency in terminology is crucial for clarity and understanding. The terms used are defined as follows:

Case Studies: Distinct setups or configurations of wind farms, including specific environmental and operational parameters. Comprehensive analyses involving multiple simulations to address particular research questions.
Simulations: Individual runs of the WOMBAT software with specific input parameters and conditions.
Scenarios: A distinct wind farm location.
Mooring layout: Specification of the mooring layout, there are three possible options: only single-line anchor layout, only multiline anchor layout, or single-line vs multiline anchor layout.

5

Case 1: Convergence Study of the Simulation Software

5.1. Introduction

The convergence study aims to determine the number of simulations required to achieve a stable and reliable average sum of the results for offshore wind farm operations. This is crucial for ensuring the reliability of the simulation outcomes and optimizing computational resources. This is done by examining two primary metrics — Net Present Value (NPV) and Operational Expenditure (OpEx) — the goal is to identify the minimum number of runs required to achieve stable and reliable average results.

Specific Objectives of the Study:

1. **Identify the Point of Mean Stabilization:** Determine the number of simulation runs at which the mean of key metrics (NPV and OpEx) stabilizes.
2. **Reduce Computational Time and Resources:** Establish the minimum number of required simulations to reduce computational time and resources while maintaining the consistency of results.

Achieving convergence in the averages of the results is crucial as it ensures the reliability of simulation outcomes, reduces computational resources, and enhances the efficiency of decision-making processes.

To determine the optimal number of simulation runs, an in-depth analysis of the provided datasets was conducted, focusing on the mean, standard deviation, Coefficient of Variation (CV), and Standard Error of the Mean (SEM). Convergence is defined as the point where additional simulation runs result in negligible changes in the mean values of the key metrics. The results of this analysis will guide the optimal number of runs necessary for the case studies, thereby improving the efficiency and consistency of the simulation process.

5.2. Methodology

5.2.1. Overview of Methodology

This section outlines the methodology used to conduct the convergence study, focusing on the simulation setup, metrics for analysis, and the calculation of key statistical measures.

5.2.2. Simulation Setup

The simulations were conducted with the following parameters:

- **WOMBAT Version:** Modified
- **Scenario:** Morro Bay

- **Mooring Layout:** Single-line anchor
- **Input Data:** Appendix A
- **Number of Runs:** 50
- **Average Duration of Each Simulation:** 15 minutes
- **Per Run Simulation:**
  - In-Situ Repair: Utilizes a heavy lift vessel (HLV) for repairs conducted on-site.
  - Tow-to-Port Repair: Does not use an HLV; instead, the turbine is towed to the port for repairs.
- **Random Seed:** A seed number was used for each simulation to ensure reproducibility. In this case, the seed number 34 was multiplied by the run number (1-50) and then used in the random generator that is part of WOMBAT.

The choice of conducting 50 runs was based on the recommendation from the software creator to ensure a comprehensive and statistically significant analysis. Fifty runs provide a robust sample size that allows for detecting patterns and trends while minimizing the impact of outliers and random variations. Additionally, this sample size is sufficiently large to ensure the stability of statistical measures such as the mean, standard deviation, and confidence intervals. If 50 runs had not shown the pattern and trends expected for convergence, the number of runs would have been doubled, until a trend would appear.

For the analysis, runs were randomly grouped in sets of 2 to ensure variability and independence. The choice for sets of 2, rather than larger groupings such as sets of 5, allows for a more granular examination of convergence trends. Smaller sets increase the number of data points for the case study, enhancing the reliability of the convergence assessment and providing a more detailed view of how the metrics stabilize as the number of runs increases. The list of these groupings can be found in appendix D.

5.2.3. Statistical Measures

The analysis focuses on the mean, standard deviation, coefficient of variation, and standard error of the mean (SEM) to get to the confidence interval, which allows for the assessment of convergence for the simulation results.

1. **Calculation of Standard Deviation (σ)**:
The standard deviation (σ) for NPV and OpEx was calculated using the results from the 50 runs dataset.

2. **Calculation of Coefficient of Variation**:
For each set of runs (e.g., 2, 4, 6, ..., 50), the CV was calculated using the formula:

$$\text{CV} = \frac{\sigma}{\bar{X}}$$

where $\bar{X}$ is the mean of the sample, providing a normalized measure of dispersion relative to the mean.

3. **Calculation of Standard Error of the Mean**:
For each set, the SEM was calculated using the formula:

$$\text{SEM} = \frac{\sigma}{\sqrt{n}}$$

where n is the number of runs.

4. **Determination of the 95% Confidence Interval**:
The 95% confidence interval (CI) for the mean was determined using the SEM and the t-distribution critical value:

$$\text{CI} = \bar{X} \pm t_{\alpha/2,\,df} \times \text{SEM}$$

where $\bar{X}$ is the mean of the sample, $t_{\alpha/2,\,df}$ is the critical value from the t-distribution for a given confidence level (typically 95%) and degrees of freedom ($df = n - 1$).

The standard error of the mean provides a measure of how far the sample mean of the data is likely to be from the true population mean, making it essential for understanding the precision of the mean estimates. The 95% confidence interval offers a range within which the true mean is expected to fall, giving a clear indication of the estimate's reliability. The coefficient of variation is used to provide a normalized measure of dispersion relative to the mean, which helps compare the degree of variation between different datasets. This is particularly useful when the means of the datasets are significantly different. The standard deviation is crucial in determining the confidence interval as it measures the amount of variation or dispersion in a set of values. By using the standard deviation, the uncertainty and variability in the dataset can be quantified, thus ensuring the reliability and robustness of the simulation results.

5.2.4. Metrics for Analysis

The primary metrics compared in this study are net present value and operational expenditure. These metrics were chosen because they are critical for assessing the financial performance and operational efficiency of offshore wind farm operations.

- **Net Present Value:** NPV is a key financial metric that represents the difference between the present value of cash inflows and outflows over a period of time.
- **Operational Expenditure**: OpEx refers to the ongoing costs associated with the operation and maintenance of the wind farm.

These are the formulas for OpEx and NPV:

$$\text{OpEx} = F_C + P_f + E_C + L_C + M_C \tag{5.1}$$

where:

- F_C are the fixed costs revenue at time t.
- P_f are the port fees.
- E_C are the equipment costs.
- L_C are the labor costs.
- M_C are the material costs

$$\text{NPV} = \sum_{t=0}^{T} \frac{R_t - C_t}{(1+r)^t} \tag{5.2}$$

$$\text{NPV}_{\text{O\&M}} = \sum_{t=0}^{T} \frac{(P_t \times P_{\text{price}}) - \text{OpEx}_t}{(1+r)^t} \tag{5.3}$$

where:

- T is the total number of periods (e.g., months, years).
- R_t is the revenue at time t.
- C_t is the operational expenditure (OpEx) at time t.
- r is the discount rate.
- t is the specific period (e.g., month, year)
- P_t is the power production at time t in MWh.
- P_{price} is the price per MWh (offtake price).
- $OpEx_t$ is the operational expenditure at time t.

5.3. Results

5.3.1. Confidence Analysis

The following plots illustrate the confidence trends for the NPV and OpEx for In-Situ and Tow-to-Port.

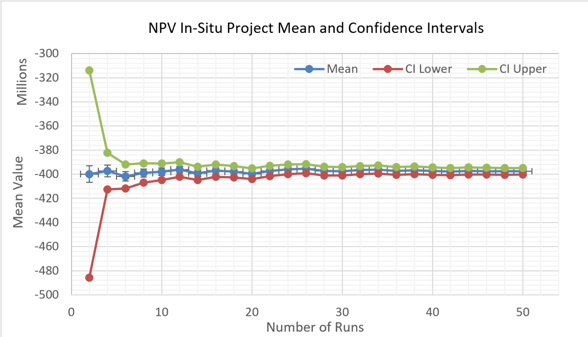


Figure 5.1: NPV In-Situ Project Mean and Confidence Intervals

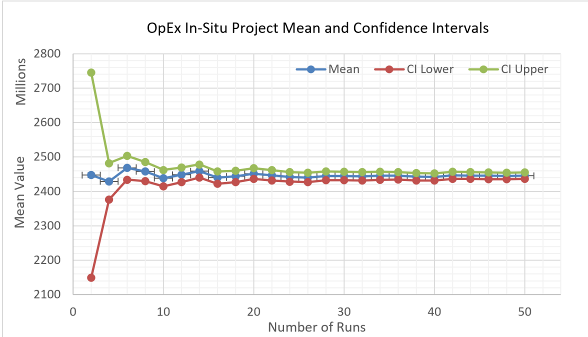


Figure 5.2: OpEx In-Situ Project Mean and Confidence Intervals

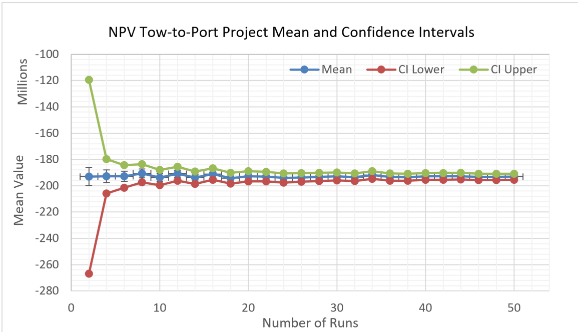


Figure 5.3: NPV Tow-to-Port Project Mean and Confidence Intervals

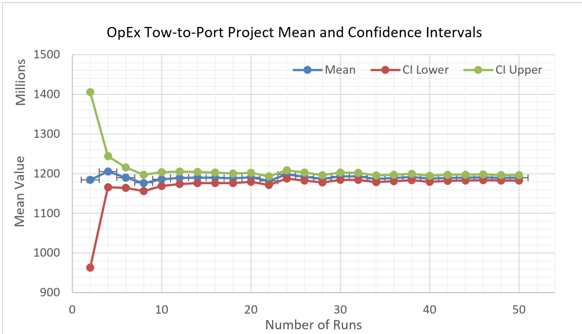


Figure 5.4: OpEx Tow-to-Port Project Mean and Confidence Intervals

Figures 5.1 to 5.4 illustrate the convergence analysis for the four key metrics: NPV In-Situ, OpEx In-Situ, NPV Tow-to-Port, and OpEx Tow-to-Port. Each figure consists of the following elements:

- Blue Line (Mean): This line represents the mean value of the metric across different numbers of simulation runs. It shows how the mean value stabilizes as the number of runs increases.
- Error Bars (SEM): The error bars around the mean represent the standard error of the mean, providing a measure of the precision of the mean estimate. Narrower error bars indicate greater precision.
- Green Line (CI Upper): This represents the upper bound of the 95% confidence interval for the mean.
- Red Line (CI Lower): This represents the lower bound of the 95% confidence interval for the mean.

These elements together provide a comprehensive view of how the metrics converge as the number of simulation runs increases.

In each of the four plots, as the number of runs increases, the confidence intervals narrow, indicating increased precision of the mean estimates. The number of runs after which the mean values and confidence intervals show minimal changes is considered the point of convergence, marking the minimum number of runs required to achieve stable and reliable average results.

Interpretation of results

The convergence analysis for NPV and OpEx metrics across both in-situ and tow-to-port projects consistently indicates that approximately 30 simulation runs are sufficient to achieve stable and reliable average results. This conclusion is drawn from the observation that beyond 30 runs, the mean values stabilize, and further increases in the number of runs yield negligible changes in these values.

For the NPV In-Situ Project, the mean value stabilizes around 30 runs, as indicated by the flattening of the blue line in the corresponding plot. The SEM decreases by approximately 74% from 2 runs to 30 runs and further reduces by 80% at 50 runs. The CI narrows significantly, reducing by about 18%, demonstrating that this number of runs is sufficient to provide stable mean estimates with high precision.

Similarly, for the OpEx In-Situ Project, the mean stabilizes at around 30 runs. The SEM decreases by approximately 74% from 2 runs to 30 runs and further reduces by 80% at 50 runs. The CI narrows by about 86%, suggesting that 30 runs provide a reliable estimate of the mean, ensuring the precision and stability of the results.

In the case of the NPV Tow-to-Port Project, the mean value also stabilizes around 30 runs. The SEM decreases by approximately 74% from 2 runs to 30 runs and further reduces by 80% at 50 runs. The CI narrows by about 29%, indicating increased precision and stability of the mean estimates. This reinforces the conclusion that 30 runs are adequate for obtaining reliable results.

For the OpEx Tow-to-Port Project, the mean value stabilizes at around 30 runs, with the SEM reducing by approximately 74% from 2 runs to 30 runs and further reducing by 80% at 50 runs. The CI narrows by about 86%, suggesting that this number of runs is sufficient to achieve stable and precise mean estimates.

Detailed analysis and reflection
The significance of the 30 runs convergence point is explained in 5 points:

1. Statistical Stability: The choice of 30 runs as the convergence point is based on achieving a balance between statistical stability and computational efficiency. Beyond 30 runs, the reduction in SEM is relatively small, indicating diminishing returns on additional runs. This point represents a practical threshold where the mean estimates are sufficiently stable, and further runs would not significantly enhance the precision.

2. Impact of Variability: The consistent 74% reduction in SEM across all metrics is indicative of the reduction in variability achieved through increasing the number of runs. This percentage suggests that the variability in the sample mean decreases substantially as the sample size grows, aligning with the principles of the Central Limit Theorem. The theorem states that as the sample size increases, the distribution of the sample mean approaches a normal distribution with reduced variance.

3. Complexity of Repair Scenarios: The slightly different percentage reductions in the CI for NPV metrics (18% for In-Situ vs. 29% for Tow-to-Port) can be attributed to the complexity and logistical challenges inherent in each scenario. Tow-to-Port repairs involve more complex logistics, including transportation coordination, travel times, and potential delays, leading to greater variability in the data. In contrast, in-situ repairs are more straightforward, leading to less variability and a smaller reduction in the CI.

4. Operational Dynamics: The operational dynamics of wind farm maintenance, including weather conditions, equipment availability, and repair crew efficiency, also contribute to the observed variability. The consistent reduction in SEM by 74% across all metrics indicates that the simulations are adequately capturing these factors, and increasing the number of runs helps in averaging out these variations.

5. Precision of Estimates: The narrowing of the confidence intervals by 86% for OpEx metrics indicates a high degree of precision in the cost estimates. This suggests that operational expenditure, being a cumulative metric influenced by multiple factors over time, benefits significantly from larger sample sizes. In contrast, the 18% and 29% reductions in CI for NPV metrics reflect the impact of discrete events such as major repairs or equipment failures, which may not average out as smoothly as continuous cost accruals.

6. Balancing Precision and Efficiency: While the SEM continues to decrease slightly up to 50 runs, achieving an additional 6% reduction (from 74% at 30 runs to 80% at 50 runs) comes at the cost of nearly doubling the number of simulations. This increase in computational effort does not proportionally enhance the precision of the results. The 30-run mark is chosen because it provides a substantial reduction in SEM (74%) and CI, ensuring stable and reliable mean estimates while optimizing computational resources. Beyond 30 runs, the incremental benefits in precision are outweighed by the increased computational cost.

5.4. Conclusion

5.4.1. Key Findings and Implications

The convergence study effectively identifies that 30 simulation runs are sufficient to obtain reliable and stable results for key metrics NPV and OpEx. The principal findings include:

- Stabilization of NPV and OpEx: Minimal variation in these metrics after 30 runs indicates stable and reliable outcomes. Specifically, the standard error of the mean was reduced by approximately 74% across the metrics, and the confidence intervals narrowed by 18% to 86%, highlighting the precision of the estimates.
- Resource Efficiency: Reducing the required simulations from 50 to 30 significantly decreases computational time and resources, reducing the total runtime from 12.5 hours to 7.5 hours. This efficiency enhances the practicality and manageability of the simulation process.
- Reliable Results: Ensuring convergence at 30 runs guarantees accurate and dependable results, forming a robust basis for decision-making.
- Further Validation: Additional studies should validate these findings across different scenarios and wind farm configurations to ensure broad applicability.

In conclusion, this convergence study establishes a defined number of simulations (30), providing a robust framework for coming cases that analyze the cost related to O&M. This methodological improvement will aid in optimizing computational resources while ensuring the reliability and accuracy of simulation outcomes.

6
Case 2: Model validation study

6.1. Introduction

6.1.1. Purpose of the Case Study

This chapter provides an in-depth analysis of how the results from the modifications made to the WOMBAT tool compare to the original. The primary objective is to validate the new WOMBAT code by comparing the outputs of the modified version with those of the original version under comparable conditions. The study aims to demonstrate that while disaggregating the mooring and anchoring system components may lead to different results, these results are more accurate and align more closely with reported data, thereby allowing for more fine-grained and precise modeling.

Although the failure rate is divided by three and the components are multiplied by three in the modified version, the expectation is that this adjustment should provide a more precise representation of real-world conditions. This case study is crucial for capturing the complexities and details of wind farm operations, providing an essential validation of the modified tool's enhanced capabilities.

The methodology described in chapter 3 provides context on the design considerations and the integration of mooring configurations in the simulation tool. As a reminder, the original version of WOMBAT did not include a detailed mooring layout. The mooring components were categorized under the turbine section and simulated as singular entities; with 80 turbines, a total of 80 sets of anchors and 80 sets of mooring lines were simulated. The modified version addresses this limitation by incorporating a more accurate representation of mooring configurations, which is expected to yield more precise and reliable results, reflected in OpEx and NPV.

The detailed representation of the mooring system's behavior and failure modes allows for better predictions of maintenance schedules and repair costs. The original model scheme was appropriate for single-line anchors because it was based on a straightforward, conventional layout where each turbine had its own set of independent anchors and mooring lines. This simple configuration did not involve any shared components, making it possible to model the system as singular entities without significant loss of accuracy.

However, this approach became inadequate when applied to multiline anchor systems, where anchors are shared between turbines. The shared nature of the anchors in multiline systems introduces complexities and interdependencies that the original model could not accurately represent. In a multiline system, the failure or performance of one anchor can directly affect the connected turbines, necessitating a much more detailed and interconnected modeling approach. The modified version of WOMBAT addresses this limitation by incorporating a far more detailed representation of the mooring configurations, ensuring that the unique dynamics of multiline anchor systems are accurately and comprehensively simulated.

6.2. Methodology

6.2.1. Overview of Methodology

This section outlines the methodology used to conduct the model validation study, focusing on the simulation setup and the analysis metrics. For clarification, the single-line mooring layout is implemented in the original WOMBAT version as it was before any modifications were made so, as a whole unit, as part of the floating substructure.

6.2.2. Simulation Setup

The simulations were conducted with the following parameters:

- **WOMBAT Version:** Original & Modified
- **Scenario:** Morro Bay
- **Mooring Layout:** Single-line anchor
- **Input Data:** Appendix A
- **Number of Runs:** 2 x 30
- **Average Duration of Each Simulation:** 15 minutes
- **Per Run Simulation:** In-Situ repair & Tow-to-Port.
- **Random Seed:** Seed number 24 was used for each simulation to ensure reproducibility.

Evaluating the key metrics of availability, power production, component failure, OpEx, and NPV.

Special attention in the simulation setup is the different failure rate components depending on the version. Since the modified model splits the mooring into a 3-line configuration, the original failure rates are divided by three, as seen in table 6.1. Additionally, the cost of the mooring components and the duration of repair are divided by three to reflect the component's individuality compared to the whole entity. The values in both the original and modified version were converted to Weibull parameters using Equation 3.3, with a shape parameter set to one. For reference, the Weibull parameters for the modified version can be found in Tables A.11 and A.12.

Table 6.1: Failure rates of mooring components depended on the software version.

Version	Failure rate	Major repair	Replace
Original	anchor [Failure/year]	0.015	0.0125
	mooring line [failure/year]	0.015	0.0125
Modified	anchor [failure/year]	0.005	0.0042
	mooring line [Failure/year]	0.005	0.0042

6.2.3. Metrics for Analysis

To compare the performance of the original and modified versions, the key outputs analyzed were availability, power production, component failure rates, OpEx, and NPV. Availability was chosen as it directly impacts the operational efficiency of the wind farm, reflecting the percentage of time the turbines are operational. Power production was analyzed to assess the overall energy output and the impact of downtime on energy generation. Component failure rates were included to understand the reliability and maintenance needs of the wind farm's infrastructure and, specifically, the mooring components. Operational expenditures were examined to evaluate the cost-effectiveness of the maintenance strategies and the overall operational costs. NPV was analyzed to assess the wind farm's financial viability and profitability.

The results displayed represent the average of 30 simulations unless specified otherwise, as determined by Case 1: Convergence study.

6.3. Results

6.3.1. Availability and power production

The performance comparison between the original and modified versions indicates some notable differences in availability and power production metrics. Below are the figures illustrating these differences:

Figure 6.1: Availability of wind farm comparing original and modified.

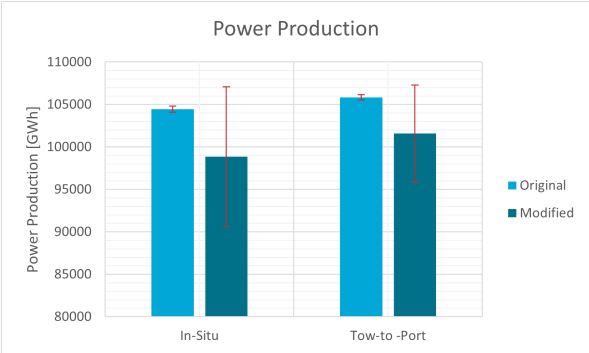


Figure 6.2: Power production of wind farm comparing original and modified.

Time-Based Availability seen in figure 6.1:

- The original software shows higher mean availability for both scenarios than the modified software.
- The modified software has a much larger standard deviation, indicating more variability in availability.

From power production in figure 6.2 for In-Situ and Tow-to-Port:

- The original software reports higher mean power production than the modified software.
- The standard deviation is significantly lower for the original software, suggesting more consistent power production.

6.3.2. Interpretation of availability and power production results

6.3.2.1 Simulation Stability and Reliability

The original version is a well-established tool that has been extensively validated for bottom-fixed offshore wind farms. It uses a simpler model where each turbine's mooring components are treated as singular entities. The modifications to include detailed mooring configurations in the new version introduced additional complexity, making the simulations more prone to variability and errors. This complexity likely contributes to the higher standard deviations and lower mean values observed in the modified version's results. Where as the original version possibly has overestimated the results due to its simplified nature.

6.3.2.2 Failure Rate Adjustments

In the modified version, the failure rates for mooring components are adjusted to reflect the new configuration. Despite these adjustments, the increased number of components and interactions could be a reason for the lower results of the modified version.

6.3.2.3 Higher Fidelity and Complexity

The modified version aims to provide higher fidelity by modeling floating offshore wind farms and their complex mooring systems in greater detail. While this is beneficial for accuracy, it also means the software must handle more data and more intricate interactions, which can introduce new sources of errors and increase the computational burden. This complexity might lead to the higher variability seen in the modified software's results.

6.3.2.4 Calibration and Tuning

The original version has been fine-tuned over time to provide stable and reliable results. In contrast, the modified version, which includes recent enhancements, might still require further calibration and tuning to achieve the same level of stability and proven reliability. This process takes time and more extensive testing than already performed.

6.3.2.5 Conclusion

The better performance of the original version can be attributed to its mature and stable nature, simpler modeling assumptions, and extensive validation for traditional wind farm setups. The modified version, despite offering higher fidelity and more detailed modeling capabilities, introduces complexities that result in higher variability and lower performance metrics. Further refinement, calibration, and optimization of the modified software are necessary to fully realize its potential benefits for floating offshore wind farms.

6.3.3. OpEx

The figures below illustrate the average annual and lifetime sum OpEx for In-Situ and Tow-to-Port scenarios, comparing the original and modified versions.

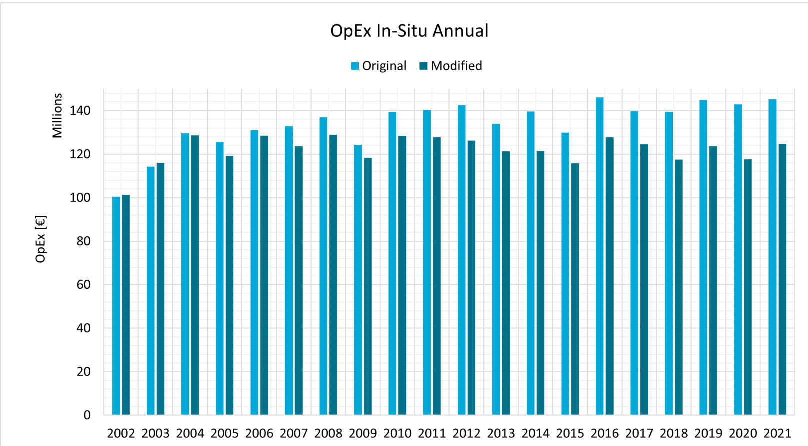


Figure 6.3: Annual OpEx for the In-Situ scenario using the original and modified version.

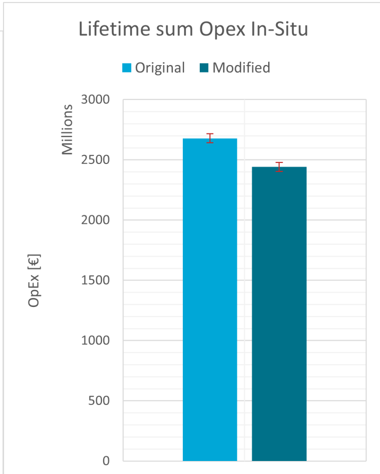


Figure 6.4: Lifetime sum OpEx for the In-Situ scenario using the original and modified version.

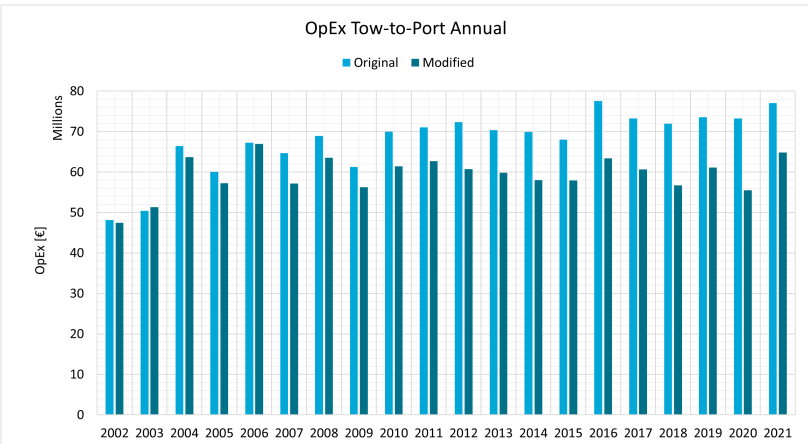


Figure 6.5: Annual OpEx for the Tow-to-Port scenario using the original and modified version.

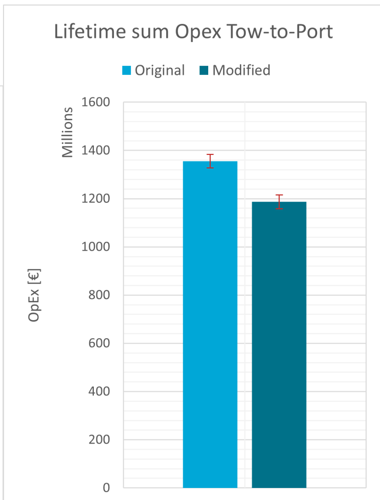


Figure 6.6: Lifetime sum OpEx for the Tow-to-Port scenario using the original and modified version.

6.3.3.1 Annual OpEx In-Situ

Figure 6.3 illustrates the annual OpEx for the In-Situ scenario. It is evident that the modified version generally results in lower OpEx compared to the original across the years 2002 to 2021. This trend suggests that the changes implemented in the modified version lead to cost reductions in operational expenditures. The annual OpEx remains relatively stable, with minor fluctuations, but consistently lower for the modified software.

6.3.3.2 Lifetime Sum OpEx In-Situ

Figure 6.4 presents the cumulative OpEx over the lifetime of the wind farm for the In-Situ scenario. The total OpEx for the modified software is significantly lower than that for the original software. This difference highlights the lower costs with the implementation of the modified version.

6.3.3.3 Annual OpEx Tow-to-Port

Figure 6.5 shows the annual OpEx for the Tow-to-Port scenario. Similar to the In-Situ scenario, the modified demonstrates lower annual OpEx than the original. This indicates that the improvements in the modified version also positively impact the operational costs when repairs are conducted by towing the turbines to the port.

6.3.3.4 Lifetime Sum OpEx Tow-to-Port

Figure 6.6 displays the lifetime sum of OpEx for the Tow-to-Port scenario. The modified software again results in lower cumulative costs compared to the original version, reinforcing the overall cost-effectiveness of the modifications over the operational lifetime of the wind farm.

6.3.4. Reasons for Performance Differences in OpEx

6.3.4.1 Failure Rate Adjustment

The modified version changes the failure rate by dividing it by a factor of three. This more granular approach results leads to a more precise prediction of component failures and subsequently lowers the overall operational expenditure.

6.3.4.2 Simulation Stability and Reliability

The original version, being a well-established tool, shows higher OpEx than the modified version. The modifications result in lower variability and more stable OpEx estimates.

6.3.4.3 Detailed Component Representation

The modified version includes enhanced modeling capabilities that provide a more detailed representation of the components and their interactions. This detailed modeling helps in identifying specific areas where cost savings can be achieved, possibly causing efficient scheduling of maintenance tasks and better resource allocation.

6.3.4.4 Reduction in Downtime

The improved capabilities of the modified version can lead to more efficient maintenance scheduling and reduced downtime. This allows for maintenance to be performed more effectively, minimizing the turbines' downtime.

6.3.4.5 Conclusion

The modified version generally shows lower OpEx compared to the original version. This improved performance can be attributed to the failure rate adjustment, detailed component representation, and reduction in downtime. These factors combine in the modified software to show a more cost-effective operation and maintenance of floating offshore wind farms.

6.3.5. NPV

The figures below illustrate the average annual and lifetime sum OpEx for In-Situ and Tow-to-Port scenarios, comparing the original and modified versions.

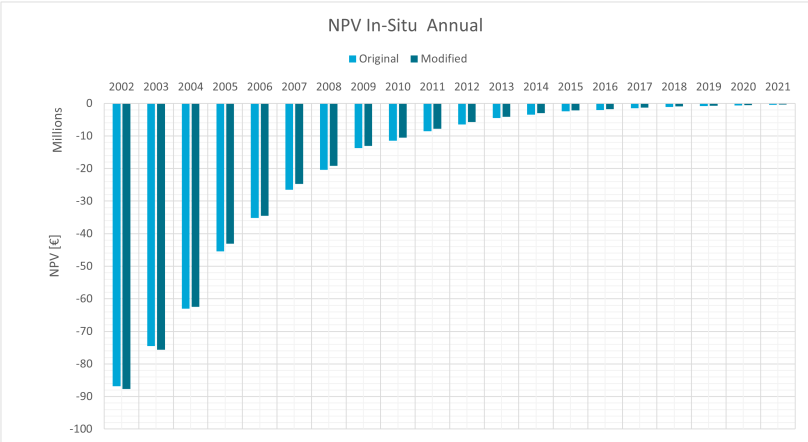


Figure 6.7: Annual NPV for the In-Situ scenario from 2002 to 2021, comparing original and modified version.

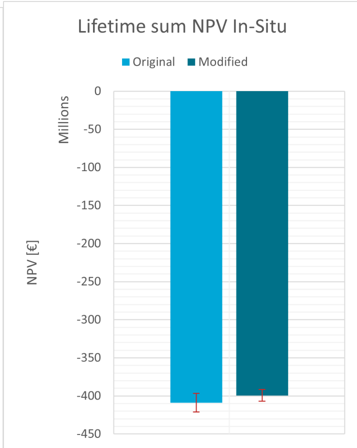


Figure 6.8: Cumulative NPV over the lifetime of the wind farm for the In-Situ scenario, comparing original and modified version.

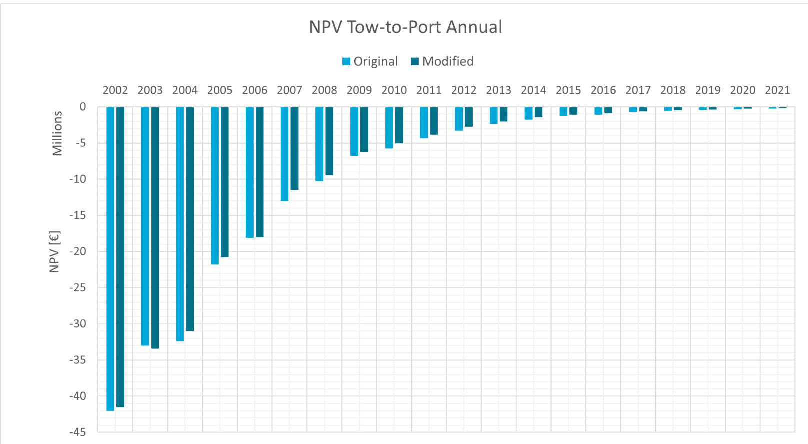


Figure 6.9: Annual NPV for the Tow-to-Port scenario from 2002 to 2021, comparing original and modified version.

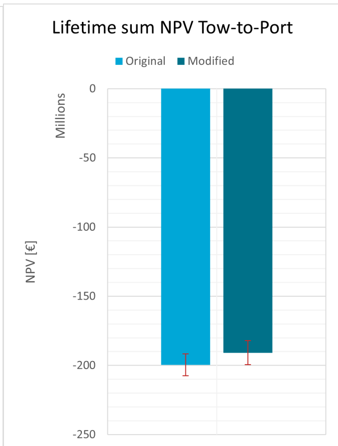


Figure 6.10: Cumulative NPV over the lifetime of the wind farm for the Tow-to-Port scenario, comparing original and modified version.

6.3.5.1 Annual NPV In-Situ

Figure 6.7 illustrates the annual NPV for the In-Situ scenario from 2002 to 2021. Both the original and modified version show a trend of increasing (less negative) NPV over time. The modified software generally exhibits a less negative NPV, indicating better financial performance.

6.3.5.2 Lifetime Sum NPV In-Situ

Figure 6.8 presents the cumulative NPV over the lifetime of the wind farm for the In-Situ scenario. The total NPV for the modified version is less negative than that for the original software, reinforcing the trend observed in the annual NPV results. This difference highlights the long-term financial benefits seen in the modifications made.

6.3.5.3 Annual NPV Tow-to-Port

Figure 6.9 shows the annual NPV for the Tow-to-Port scenario from 2002 to 2021. Similar to the In-Situ scenario, the modified version demonstrates a less negative NPV than the original software. This indicates that the changes made to the modified version reflect a higher NPV.

6.3.5.4 Lifetime Sum NPV Tow-to-Port

Figure 6.10 displays the lifetime sum of NPV for the Tow-to-Port scenario. The modified version again results in a less negative cumulative NPV than the original version, reinforcing the more precise nature of the modifications in the operational lifetime of the wind farm.

6.3.6. Reasons for Performance Differences in NPV

6.3.6.1 High component costs vs offtake price

The NPV remains negative in both scenarios due to the high costs of components compared to the offtake price of €80. Therefore, achieving the least negative NPV is the best financial outcome.

6.3.6.2 Failure Rate Adjustment

The failure rate for mooring components is adjusted in the modified software by considering individual components rather than treating the mooring system as a single unit. This more granular approach leads to more accurate predictions of component failures and subsequently lowers overall operational expenditure and, thereby, a higher NPV.

6.3.6.3 Simulation Stability and Reliability

The modifications result in more stability and lower variability in NPV estimates, contributing to a more predictable financial outcome over the project's lifetime.

6.3.6.4 Detailed Component Representation

The enhanced modeling capabilities in the modified version provide a more detailed representation of components and their interactions. This detail can helps identify specific areas for cost savings, such as more efficient maintenance scheduling and better resource allocation.

6.3.6.5 Reduction in Downtime

The improved modified version leads to reduced downtime and more efficient maintenance operations. This reduction in downtime minimizes the period turbines are offline, further lowering OpEx and improving NPV values.

6.3.6.6 Conclusion

The modified version generally shows better financial performance (less negative NPV) compared to the original version. This improvement is due to the failure rate adjustments, detailed component representation, and reduction in downtime, making the modified software more reflective of the real costs for the operation and maintenance of floating offshore wind farms.

6.3.7. Failure rates

6.3.7.1 Original and Modified failure rates

The failure rates for anchor and mooring line components were analyzed under two setups: the original setup and the modified setup. The failure rates for each component are summarized in Table 6.1.

6.3.7.2 Calculations for the Number of Failures

To understand the impact of these failure rates, the expected number of failures over the operational lifetime of the components was calculated. The following table show the results from formula 6.1 for the calculations of both the original and modified setups.

$$\text{Expected number of failure} = \text{failure rate} \times \text{\# of components} \times \text{lifetime farm} \tag{6.1}$$

original setup:
- Number of components: 80
- lifetime farm: 20 years

Table 6.2: Expected number of failures original

Failure type	calculation	result
Major anchor repair	$0.015 \times 80 \times 20$	24
Anchor replacement	$0.0125 \times 80 \times 20$	20
Major mooring line repair	$0.015 \times 80 \times 20$	24
Mooring line replacement	$0.0125 \times 80 \times 20$	20

modified setup:
- Number of components: 240
- lifetime farm: 20 years

Table 6.3: Expected number of failures modified

Failure type	calculation	result
Major anchor repair	$0.005 \times 240 \times 20$	24
Anchor replacement	$0.0042 \times 240 \times 20$	20.16
Major mooring line repair	$0.005 \times 240 \times 20$	24
Mooring line replacement	$0.0042 \times 240 \times 20$	20.16

It makes sense that the same values of results come from the original and modified version. Since the failure rate is divided by three, but at the same time, components of modified software also triple, leading to the same values.

6.3.7.3 Comparison with Observed Data

The calculated expected failures were compared with the observed data from the simulation results, as shown in Figure 6.11.

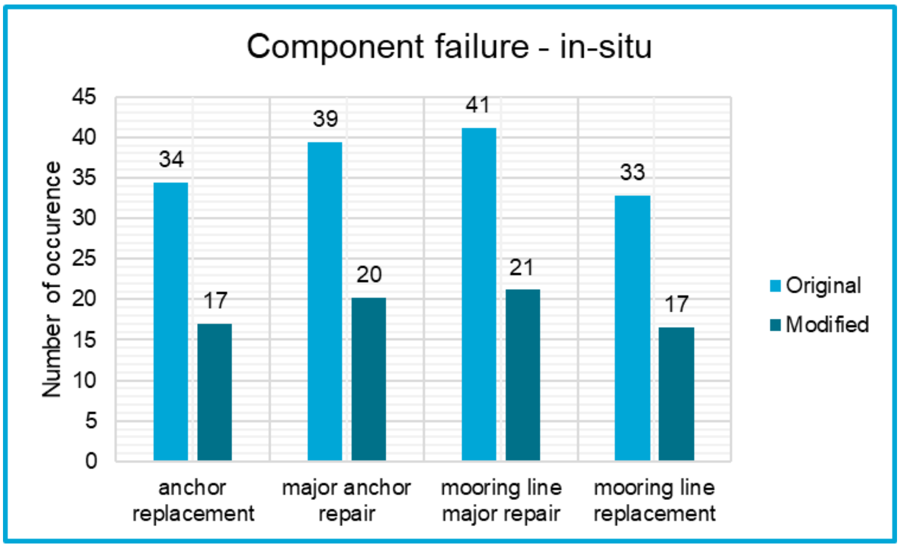


Figure 6.11: Occurrence of component failure of mooring components In-Situ.

Table 6.4: Observed vs expected number of failure occurrences

Failure type	expected	observed	type	% difference
Major anchor repair	24	39	original	62.5%
Anchor replacement	20	34	original	70%
Major mooring line repair	24	41	original	70.83%
Mooring line replacement	20	33	original	65%
Major anchor repair	24	20	modified	16.67%
Anchor replacement	20.16	17	modified	15.67%
Major mooring line repair	24	41	modified	12.5%
Mooring line replacement	20.16	17	modified	15.67%

The table shows that the observed modified values are closer to the expected values than the original values. The percentage difference makes this very clear.

The observed data for the modified setup closely aligns with the expected number of failures, validating that the software is a closer representative of the scenario. However, the observed failures for the original setup are significantly higher than the expected values. This has been brought to the original developer's attention.

6.4. Conclusion

This chapter has detailed the results of the significant enhancements made to the version to better simulate the operation and maintenance of floating offshore wind farms. By incorporating advanced mooring configurations, the modified version offers a more comprehensive and accurate analysis than the original version.

Key Enhancements and Findings

1. **Detailed Mooring Configurations:** The original version handled mooring components as part of the general turbine section without distinguishing between different mooring configurations. The modified software, however, introduces a detailed simulation of both single-line and multiline anchor systems, allowing for a precise representation of mooring layouts and their impacts on O&M activities.
2. **Improved Simulation Accuracy:** The enhanced simulation capabilities of the modified version provide a more accurate analysis of failure rates, repair times, and maintenance schedules. This precision is achieved through the integration of detailed mooring component models and the ability to simulate complex interactions within the mooring system.
3. **Comprehensive Case Studies:** The chapter presents a case study comparing the performance of the original and modified version using the Morro Bay scenario. Key metrics such as availability, power production, operational expenditure, and net present value were analyzed. The results demonstrated that the modified version offers a more detailed and reliable assessment of O&M costs and operational efficiency and most likely does not overestimate as the original version does.
4. **Enhanced Failure and Maintenance Modeling:** The modified version includes sophisticated modeling of failure mechanisms and maintenance strategies specific to mooring systems. This includes the ability to simulate the connectivity and interdependence of mooring components, allowing for a more precise assessment of how failures in one part of the mooring system can impact the related wind turbines. This feature is crucial for understanding the ripple effects of component failures and optimizing maintenance strategies to mitigate such risks.
5. **Software Utility and Flexibility:** The modifications have significantly increased the utility and flexibility of WOMBAT. The software can now simulate a wider range of scenarios and configurations, providing valuable insights for decision-making in the planning and operation of FOWFs.

6. **Implications for Future Research and Development:** The improvements made to WOMBAT set a foundation for further research and development in the field of offshore wind farm O&M simulation. Future work should focus on refining these models, integrating real-time data, and expanding the software's capabilities to include other aspects of wind farm operations.

In summary, the modifications to WOMBAT represent a substantial advancement in the simulation of O&M activities for floating offshore wind farms. The enhanced software provides a more precise and comprehensive tool for analyzing the complexities of mooring configurations, ultimately contributing to better decision-making and optimization of wind farm operations. Future research should build on these improvements to continue advancing the capabilities and applications of the version.

7

Case 3: Multiline layout study

7.1. Introduction

7.1.1. Purpose of the Study

This chapter provides a comparison of the mooring layouts, intending to answer the research question: ”Are multiline anchor layouts more cost-effective than single-line anchor layouts?” The aim is to evaluate the performance and cost implications of multiline anchor layouts compared to single-line anchor layouts.

The objective is to reflect on the outputs of the two layouts and to investigate leading factors in cost. Figures 7.1 & 7.2 gives a birds-eye view of the different layouts.

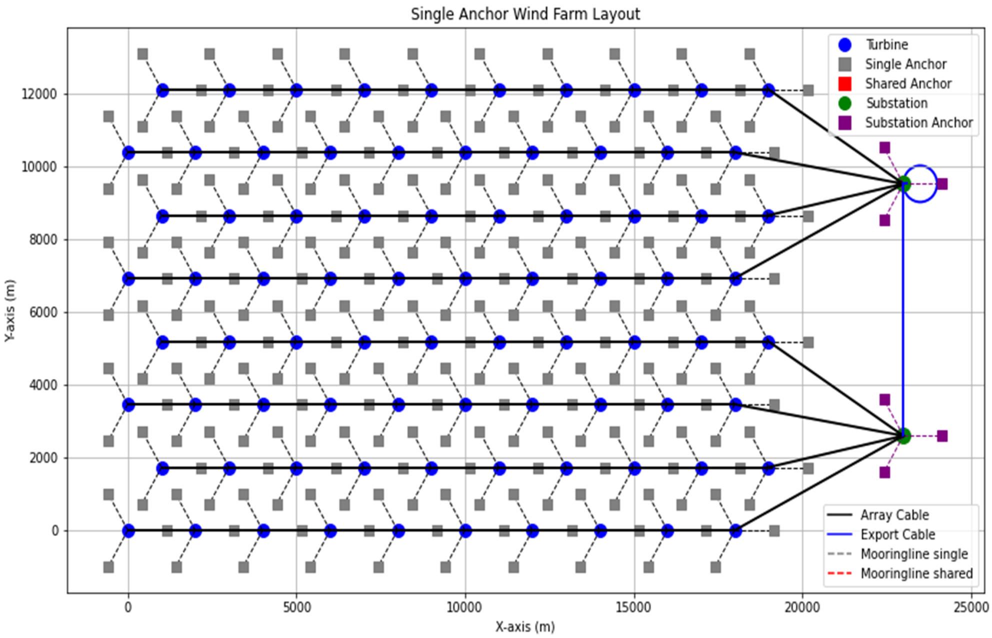


Figure 7.1: The single-line anchor layout for the Morro Bay scenario.

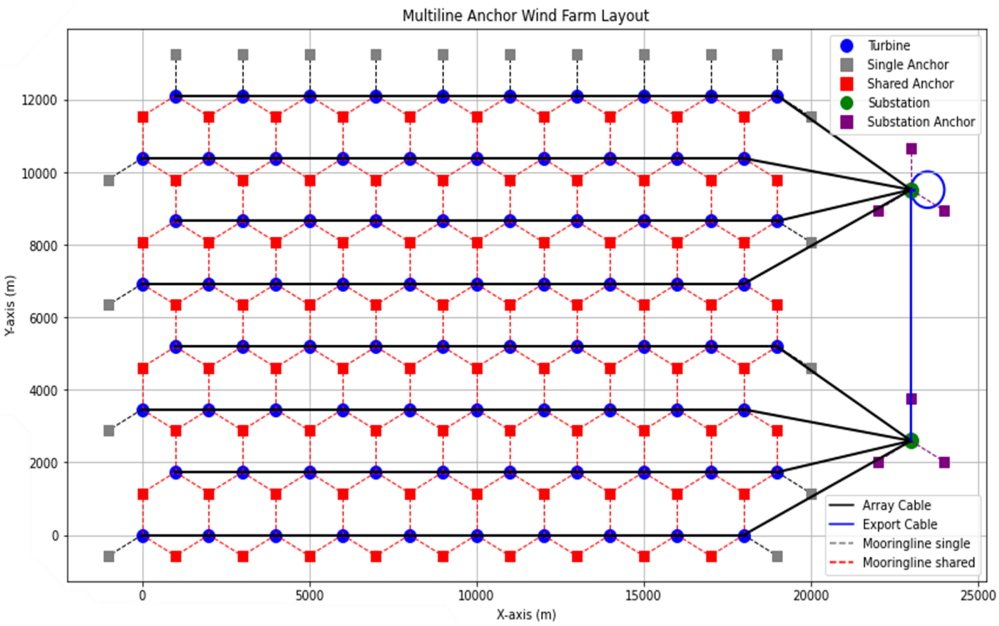


Figure 7.2: The multiline anchor layout for the Morro Bay scenario.

7.2. Methodology

7.2.1. Overview of Methodology

This section outlines the methodology used to conduct the multiline study, focusing on the simulation setup, and the metrics for analysis.

7.2.2. Simulation Setup

The simulations were conducted with the following parameters:

- **WOMBAT Version:** Modified
- **Scenario:** Morro Bay
- **Mooring Layout:** Single-line anchor & Multiline anchor
- **Input Data:** Appendix A
- **Number of Runs:** 2 x 30
- **Average Duration of Each Simulation:** 15 minutes
- **Per Run Simulation:** In-Situ repair & Tow-to-Port.
- **Random Seed:** Seed number 14 was used for each simulation to ensure reproducibility.

Evaluating the key metrics of availability, power production, component failure, OpEx, and NPV.

Special attention in the simulation setup is too the different number of components depending on the layout. Since the multiline layout decreases the number of anchors in the total wind farm, a check is performed that the correct number of components appear in each run. For clarity, the following table provides an overview.

Table 7.1: The number of anchors and mooring lines per layout.

	Single-line anchor layout	Multiline anchor layout
# of turbines	80	80
# of mooring lines	240	240
Single-line anchor	240	19
Multiline anchor	0	79
# of substations	2	2
# of mooring lines	6	6
Single-line anchor	6	6
Multiline anchor	0	0
Total		
# of anchors	246	104
# of mooring lines	246	246

7.2.3. Metrics for Analysis

The metrics analyzed are similar to the previous case: availability, power production, OpEx, NPV, and the number of mooring component failures. These metrics were chosen because they effectively measure the wind farm's cost-benefit and performance. The results displayed represent the average of 30 simulations unless specified otherwise, as determined by Case 1: Convergence study.

7.3. Results

7.3.1. Component maintenance occurrence

Figures 7.3 and 7.4 show the mean number of occurrences of maintenance tasks for both single-line and multiline anchor configurations for anchor replacements, major anchor repairs, mooring line major repairs, and mooring line replacements under both In-Situ and Tow-to-Port repair scenarios. The error bars represent the 95% confidence intervals, indicating the range within which the true mean is likely to fall.

7.3.1.1 Maintenance occurrences

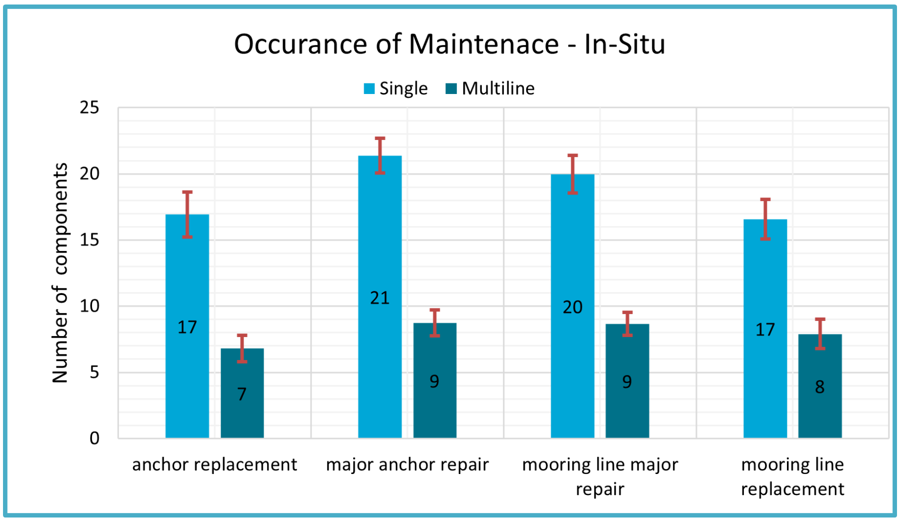


Figure 7.3: Occurrence of Maintenance - In-Situ

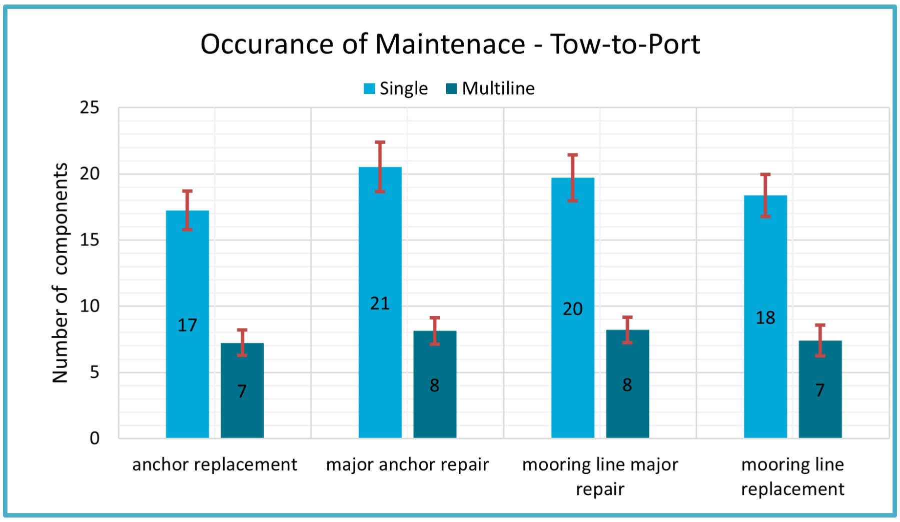


Figure 7.4: Occurrence of Maintenance - Tow-to-Port

For each component, single-line configurations show a higher mean occurrence compared to multi-line configurations. The 95% CI is larger for single-line configurations, indicating more variability in maintenance occurrences.

7.3.1.2 Discussion on Maintenance occurrences

Single-line anchor configurations result in higher maintenance task occurrences and more variability in these occurrences. Multiline configurations, despite their complexity, show lower mean maintenance occurrences due to the lower number of anchors in the layout.

Even though the failure rates are the same for both configurations, multiline layouts benefit from reduced maintenance occurrences for anchors because of their numbers. As seen in table 7.1, multiline has 104 anchors, of which 79 are multiline, compared to the single-line layout, which has 246 single-line anchors. An 81% difference in the number of anchors is reflected in the number of times maintenance occurs, all components are in the 80-90% range of difference between single-line and multiline.

However, there is a notable discrepancy in the number of mooring line repairs between single-line and multiline layouts despite the same number of mooring lines in both configurations, as seen in table 7.1. This discrepancy is likely due to the inherent sensitivity of the simulation model, which needs further investigation. The discrepancy happened despite using the same modified software, failure rates, and seed number. The code was even triple-checked for a possible bug error that might be the cause; however, none were found. This highlights the importance of conducting more case studies to see if this occurrence repeats itself.

7.3.2. Availability and Power Production

The performance comparison between single-line and multiline anchor layouts indicates differences in both availability and power production metrics. Figures 7.5 and 7.6 illustrate the mean values for time-based availability and power production under both In-Situ and Tow-to-Port repair scenarios. The error bars represent the 95% confidence intervals.

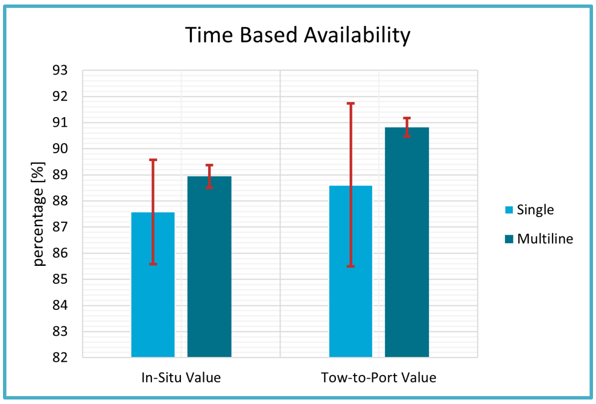


Figure 7.5: Availability of wind farm comparing single-line and multiline.

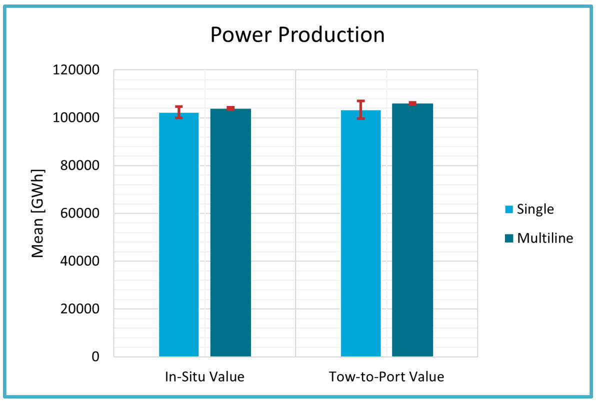


Figure 7.6: Power production of wind farm comparing single-line and multiline.

Multiline anchors show higher availability and slightly higher power production, indicating more consistent operational performance and reduced downtime. Additionally, multiline anchors have a narrower CI range.

7.3.2.1 Discussion on Availability and Power Production

Time-Based Availability: Multiline configurations demonstrate higher mean availability compared to single-line configurations in both In-Situ and Tow-to-Port scenarios. The narrower 95% confidence intervals for multiline configurations suggest more consistent operational performance. The higher availability in multiline configurations can be attributed to the lower number of anchors, reducing the frequency of maintenance and thus minimizing downtime.

The larger 95% confidence intervals for single-line configurations indicate greater variability in the time-based availability. This increased variability may result from these two factors. One is that single-line configurations have a significantly higher number of anchors, leading to a greater probability of maintenance events and operational disruptions. Leading to point two, the larger number of maintenance events in single-line configurations likely results in more operational disruptions, contributing to the wider range of availability outcomes. The larger confidence interval also implies that with the mean availability for single-line configurations being lower, there is more uncertainty in the data. This means that the true availability for single-line configurations could occasionally outperform the multiline configurations, but this is less likely due to the higher variability and lower mean values observed.

For both the Tow-to-Port maintenance strategies, the CIs are larger than for In-Situ. This can be explained due to the nature of the maintenance strategy. Tow-to-Port operations involve moving the entire turbine to a port facility, which introduces additional variables such as transit time, weather conditions during transit, and the availability of port facilities. These factors can significantly affect the duration and success of maintenance activities, leading to greater variability in the availability outcomes for Tow-to-Port scenarios.

Power Production: Multiline configurations consistently show higher mean power production compared to single-line configurations under both In-Situ and Tow-to-Port scenarios. The narrower 95% confidence intervals for multiline configurations indicate more stable and predictable power production. The increased power production can be directly linked to the higher availability of turbines in multiline configurations, leading to less downtime and more operational hours.

Simulation Stability and Reliability: The observed higher availability and power production in multiline configurations highlight the benefits of reduced anchor numbers, which directly impact the frequency of maintenance tasks and overall turbine downtime. This aligns with the fundamental design advantage of multiline configurations, less anchors, which lower the number of maintenance performed and thereby enhance operational efficiency.

Conclusion: The analysis shows that multiline configurations outperform single-line configurations in both availability and power production. The reduced number of anchors in multiline configurations leads to fewer maintenance occurrences, higher availability, and, consequently, higher power production.

These findings underscore the operational benefits of multiline anchor layouts for floating offshore wind farms.

7.3.3. Operational Expenditure

Figures 7.7 till 7.10 illustrate the differences in annual and project-level OpEx between single-line and multiline anchor configurations for both In-Situ and Tow-to-Port repair scenarios.

7.3.3.1 OpEx

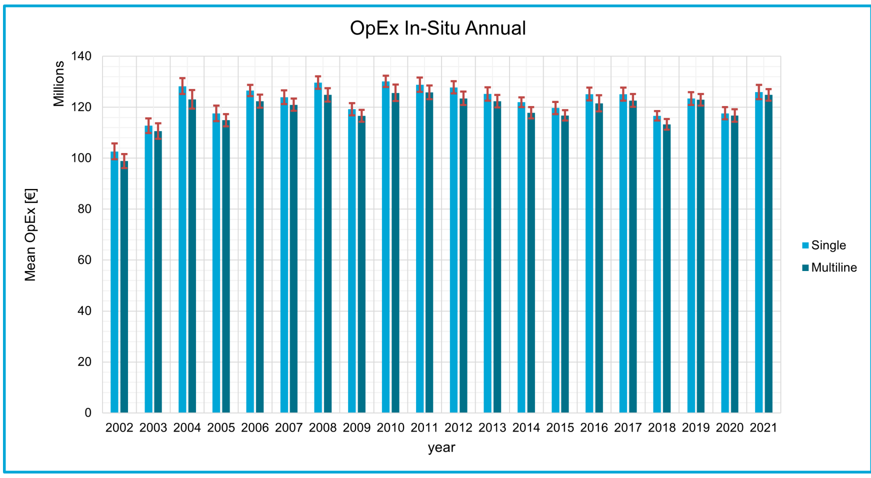


Figure 7.7: Annual OpEx for the In-Situ scenario comparing single-line vs. multiline wind farm layout.

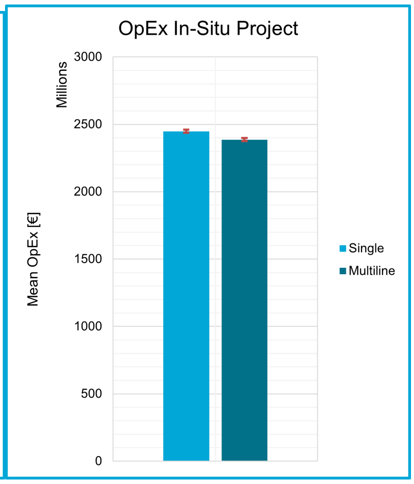


Figure 7.8: Lifetime sum OpEx for the In-Situ scenario comparing single-line vs. multiline wind farm layout.

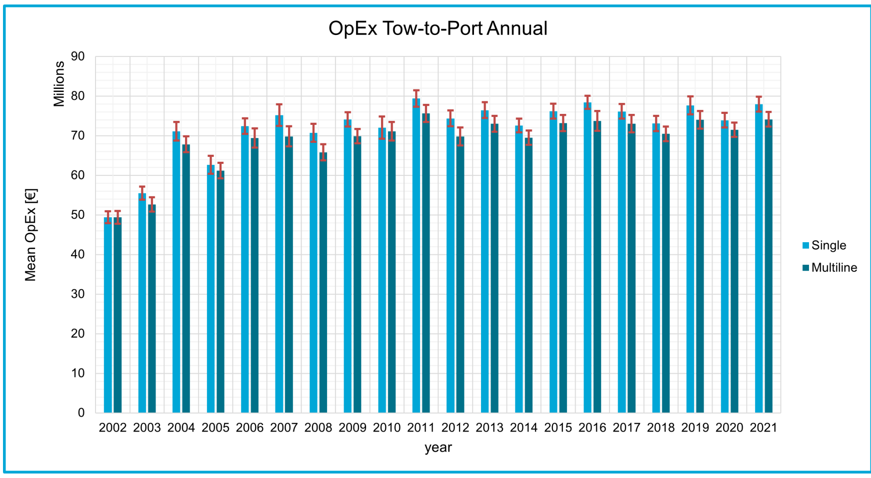


Figure 7.9: Annual OpEx for the Tow-to-Port scenario comparing single-line vs. multiline wind farm layout.

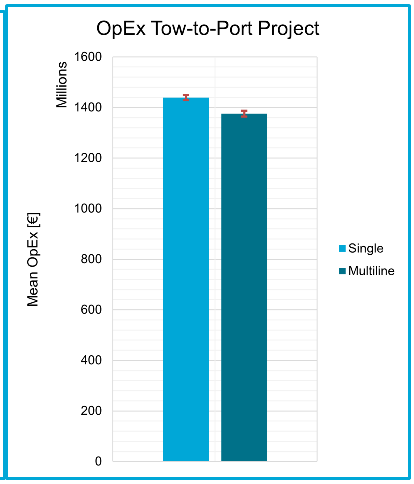


Figure 7.10: Lifetime sum OpEx for the Tow-to-Port scenario comparing single-line vs. multiline wind farm layout.

The average mean annual and project OpEx for single-line configurations is higher than those for multiline configurations both for In-Situ and Tow-to-Port.

7.3.3.2 Discussion on OpEx

From the OpEx, three analyses can be observed. First is the lower OpEx for multiline configurations. Across both annual and project-level analyses, multiline configurations consistently show lower mean OpEx compared to single-line configurations. This reduction in OpEx can be attributed to the lower number of anchors required for multiline configurations, which reduces the frequency and cost of maintenance activities. Second is the greater variability in single-line configurations. The larger 95% confidence intervals for single-line configurations, especially in Tow-to-Port operations, suggest greater variability in operating costs. This increased variability is likely due to the higher number of maintenance events and the associated operational disruptions that are more prevalent in single-line configurations. The third is in the Tow-to-Port vs. In-Situ operations. The OpEx for Tow-to-Port operations is generally lower than for In-Situ operations. A reason for this can be the high daily charter cost for HLV compared to the costs of two tugboats and towing to port operations. Another is the comprehensive nature of Tow-to-Port maintenance, where turbines are brought to port facilities for extensive repairs, potentially reducing the frequency of minor In-Situ interventions. However, the logistical complexities and variability introduced by Tow-to-Port operations result in broader confidence intervals, indicating more uncertainty in cost predictions.

Overall, the findings highlight the cost-efficiency of multiline configurations, particularly in reducing operational expenditures and providing more predictable maintenance costs. Additionally, Tow-to-Port has a lower OpEx and would be preferable for large maintenance than an In-Situ strategy. This conclusion is reflected in the industry where Equinor has chosen to tow all turbines back to port for a 'heavy maintenance' in the Hywind Scotland floating wind farm in 2024 [51].

7.3.4. Net Present Value (NPV)

Figures 7.9 and 7.10 provide a detailed view of the average annual and project-level net present value for both single-line and multiline anchor configurations under in-situ and Tow-to-Port scenarios.

7.3.4.1 NPV

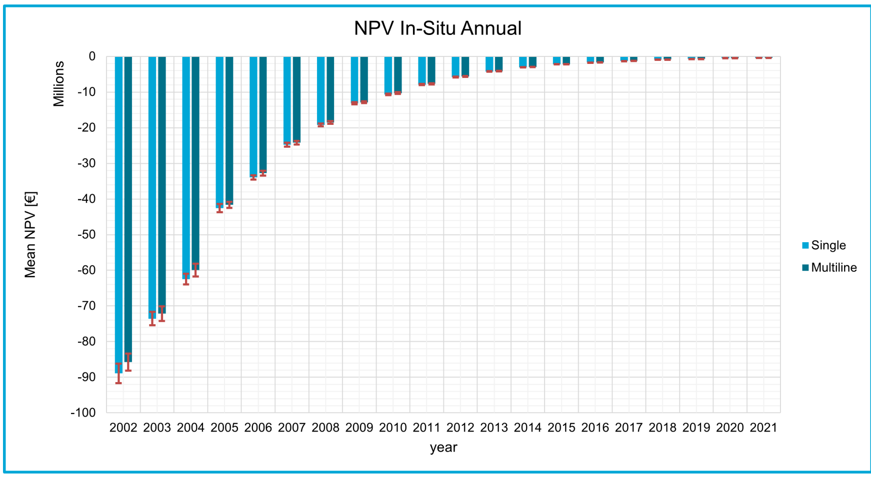


Figure 7.11: Annual NPV for the In-Situ scenario comparing single-line vs multiline wind farm layout.

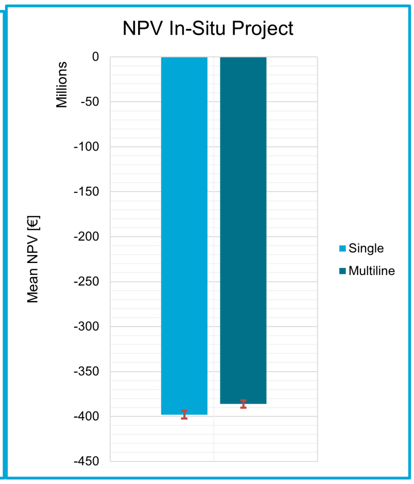


Figure 7.12: Lifetime sum NPV for the In-Situ scenario comparing single-line vs multiline wind farm layout.

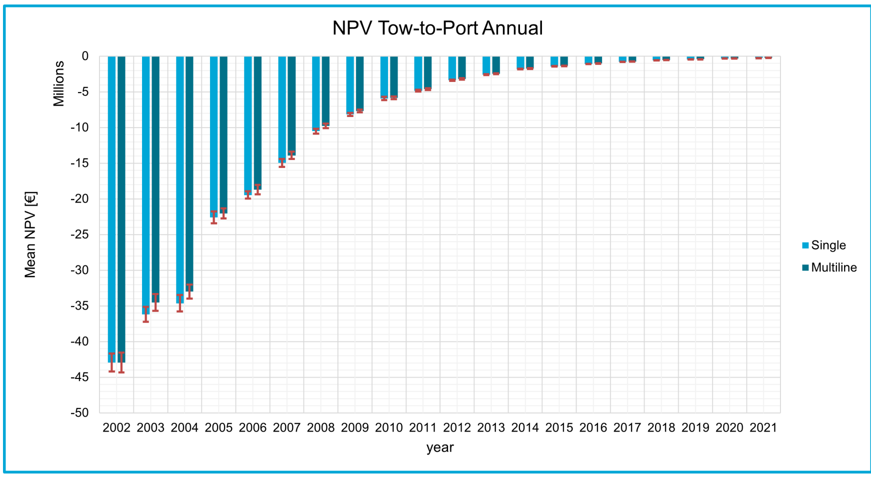


Figure 7.13: Annual NPV for the Tow-to-Port scenario comparing single-line vs multiline wind farm layout.

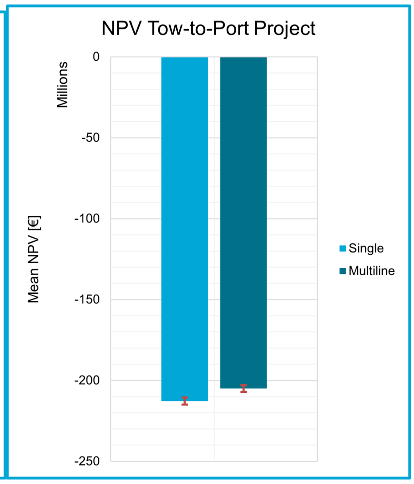


Figure 7.14: Lifetime sum NPV for the Tow-to-Port scenario comparing single-line vs multiline wind farm layout.

The annual NPV for single-line configurations shows significant negative values initially, with relatively narrow 95% confidence intervals; multiline configurations follow the same curve and have slightly wider intervals, indicating more variability. At the project level, single-line configurations have a total NPV of about -€400 million for In-Situ and -€212 million for Tow-to-Port operations, with narrow confidence intervals indicating stable predictions. In contrast, multiline configurations have a slightly better total NPV of around -€375 million for In-Situ and -€205 million for Tow-to-Port operations, with narrower confidence intervals, suggesting more consistent cost predictions.

7.3.4.2 Discussion on NPV

The negative NPV values observed for both single-line and multiline configurations throughout the entire project duration underscore the high costs associated with floating wind farms. These costs include significant expenditures on components and maintenance, which are not fully offset by the revenue generated from energy production. This persistent trend highlights that the revenue from these floating wind farms does not cover the substantial capital expenditure required for floating structures, anchoring systems, and the logistical complexities of maintenance. This is where as mentioned in the introduction chapter, government incentives could facilitate a higher price for power and possibly a lower cost of components. Until the industry grows to economies of scale, lowering costs for floating wind and mooring components.

The average annual and project-level NPVs for single-line and multiline configurations are quite similar, with multiline configurations generally showing slightly better performance. This improvement can be linked to the lower operational expenditures observed for multiline configurations. The slightly better NPV performance of multiline configurations can also be attributed to their operational efficiencies over time despite their initial higher variability. This suggests that multiline configurations may offer the potential for better long-term financial performance as operational efficiencies improve and maintenance practices are optimized. The alignment of lower OpEx with better NPV highlights the importance of operational cost management in achieving better overall financial performance in floating wind farms.

Additionally, the output reflects the better performance of Tow-to-Port operations compared to In-Situ operations in terms of NPV. It can be attributed to several factors. Tow-to-Port operations often result in more controlled and efficient maintenance processes. By performing large component maintenance at port facilities, there is a reduction in the logistical complexities and risks associated with offshore repairs. This method can lead to more consistent and shorter maintenance durations, minimizing downtime and associated costs. Furthermore, the ability to use specialized equipment and personnel at port facilities can enhance the quality and efficiency of maintenance activities, contributing to the overall better financial performance of Tow-to-Port operations. This is reflected in both the lower OpEx and the improved NPV for Tow-to-Port scenarios.

Overall, multiline configurations demonstrate marginally better financial performance compared to single-line configurations, particularly when considering Tow-to-Port maintenance strategies. These findings underscore the potential benefits of multiline systems for long-term viability and cost-effectiveness in floating wind farm operations.

7.4. Conclusion

This chapter has provided a comprehensive analysis of the operational and financial performance of single-line and multiline mooring configurations for floating offshore wind farms. Through detailed simulations and evaluations, several key findings have emerged that address the research question regarding the cost-effectiveness and operational efficiency of these configurations.

Firstly, the analysis of availability and power production metrics consistently indicated that multiline configurations outperform single-line configurations. The higher availability and power production observed in multiline setups can be attributed to the reduced number of anchors, which leads to fewer maintenance occurrences and less downtime. This fundamental design advantage of multiline anchors significantly enhances operational efficiency and stability, as evidenced by the narrower confidence intervals in availability and power production metrics for multiline configurations.

Secondly, the evaluation of operational expenditures highlighted the cost-efficiency of multiline configurations. The lower average mean OpEx observed for multiline setups, both annually and over the project lifetime, underscores the economic benefits of reducing the number of anchors. This reduction translates into lower maintenance costs and more predictable expenditure patterns, making multiline configurations a more viable option for long-term financial planning and risk management in FOWFs.

Thirdly, the net present value analysis provided insights into the overall financial performance of the configurations. Although both configurations exhibited negative NPVs, reflecting the high costs associated with floating wind farms, multiline configurations showed slightly better performance. This marginally better NPV can be linked to the operational efficiencies and lower OpEx of multiline configurations, reinforcing their potential for better long-term financial outcomes.

The comparison between In-Situ and Tow-to-Port maintenance strategies further elucidated the advantages of Tow-to-Port operations. Despite the logistical complexities, Tow-to-Port maintenance demonstrated lower overall OpEx and better NPV outcomes. This can be attributed to the comprehensive nature of repairs performed at port facilities, which reduce the frequency of In-Situ interventions and associated operational disruptions. As well as the lower logistical complexity and risk of repairing in port compared to doing the same maintenance task out at sea.

In conclusion, this case study has shown that multiline mooring configurations offer superior operational and financial performance compared to single-line setups for floating offshore wind farms. The findings support the adoption of multiline configurations to achieve higher availability, lower operational costs, and improved financial viability. Additionally, Tow-to-Port maintenance strategies have proven to be more cost-effective, suggesting that they should be preferred for major maintenance activities. These insights contribute to the broader understanding of effective O&M strategies for FOWFs and provide a robust basis for future research and practical implementation in the industry.

8

Case 4: Gulf of Maine study

8.1. Introduction

8.1.1. Purpose of the Study

This chapter expands on the comparison of the mooring layouts, to see if the results from the previous chapter can be can be confirmed for different conditions. This simulation is different in 2 aspects. The first is a lifetime of 30 years, as industry experts predict and are working on the basis that this will be the lifetime of a FOWF. The second, the location change, has two consequences, it leads to different metocean input values. This will influence the operation of the wind turbines and the ability of the vessels as they have operational constrictions. Additionally, the distance to the port has changed (from 60 to 114 km), impacting the operational constrictions on vessels and time spent in transport.

The aim is still to evaluate the multiline anchor layout performance and cost implications compared to the single-line anchor layout and to see the effect the two changed conditions have on the results. The objective is to reflect on the outputs of the two layouts and to investigate leading factors in cost.

8.2. Methodology

8.2.1. Overview of Methodology

This section outlines the methodology used to conduct the Gulf of Maine study, focusing on the simulation setup, and the metrics for analysis.

8.2.2. Simulation Setup

The simulations were conducted with the following parameters:

- **WOMBAT Version:** Modified
- **Scenario:** Gulf of Maine
- **Mooring Layout:** Single-line anchor & Multiline anchor
- **Input Data:** Appendix A
- **Number of Runs:** 2 x 30
- **Average Duration of Each Simulation:** 45 minutes
- **Per Run Simulation:** In-Situ repair & Tow-to-Port.
- **Random Seed:** Seed number 14 was used for each simulation to ensure reproducibility.

Evaluating the key metrics of availability, power production, component failure, OpEx, and NPV.

Special attention in the simulation setup is the different conditions. The duration of each simulation is, on average, 45 minutes. The increase in simulation time is expected with an additional 10 years of wind farm lifetime, change in distance traveled to the wind farm, and change in metocean input.

8.2.3. Metrics for Analysis

The metrics analyzed are the same as the two previous cases: availability, power production, OpEx, NPV, and component failure rates. These metrics were chosen because they effectively measure the wind farm's cost-benefit and performance. The results displayed represent the average of 30 simulations unless specified otherwise, as determined by Case 1: Convergence study.

8.3. Results

8.3.1. Component maintenance occurrence

This section analyzes the maintenance occurrences for mooring components in both single-line and multiline anchor layouts. Figures 8.1 and 8.2 display the mean number of occurrences of maintenance tasks for both single-line and multiline anchor configurations for anchor replacements, major anchor repairs, mooring line major repairs, and mooring line replacements under both In-Situ and Tow-to-Port repair scenarios. The error bars represent the 95% confidence intervals, indicating the range within which the true mean is likely to fall.

8.3.1.1 Maintenance occurrences

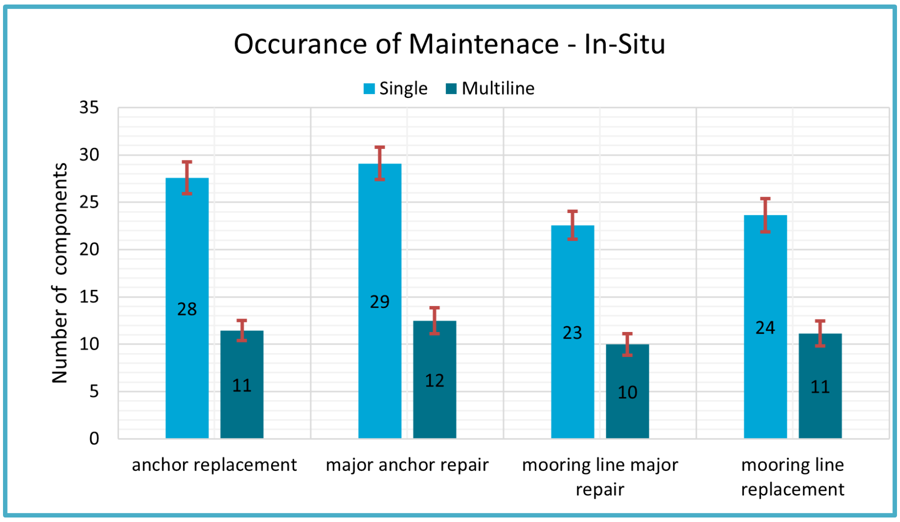


Figure 8.1: Occurrence of Maintenance - In-Situ

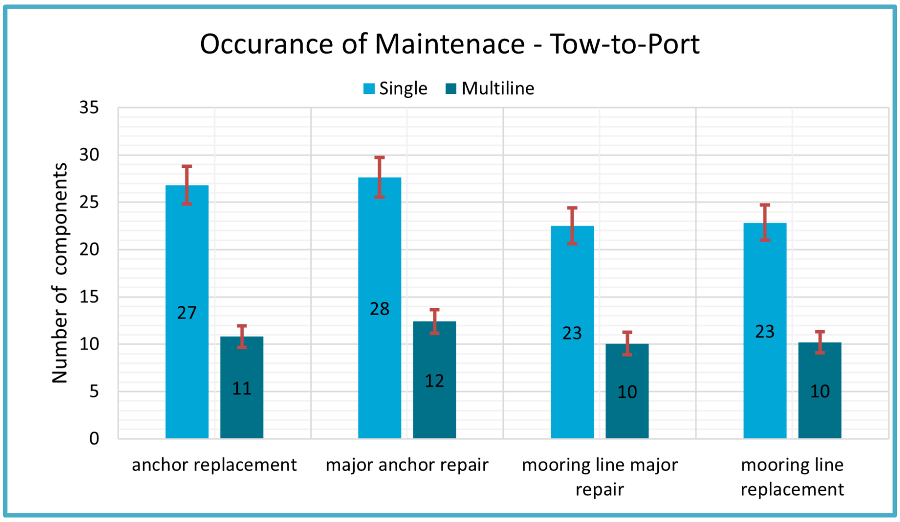


Figure 8.2: Occurrence of Maintenance - Tow-to-Port

For each component, single-line configurations demonstrate a higher mean occurrence of maintenance tasks than multiline configurations. The 95% CI is larger for single-line configurations, indicating greater variability in maintenance occurrences.

In detail, single-line anchor replacements occur on average 27 or 28 times compared to 11 times for multiline configurations. This trend is consistent across all anchor maintenance categories; for mooring lines, it is close to a 23 or 24 to 11 ratio. Notably, the 95% confidence intervals for single-line configurations are broader, signifying higher variability in the number of maintenance occurrences.

8.3.1.2 Discussion on Maintenance occurrences

The higher frequency of maintenance in single-line configurations underscores the increased demands placed on these systems, which can be correlated to the greater number of anchors in use, leading to more failure points. Conversely, the reduced maintenance in multiline configurations suggests that these systems benefit from having fewer components, which inherently decreases the chances of component failure and the need for repairs.

When comparing these results to Case Study 3 (Morro Bay), the Gulf of Maine scenario exhibits higher maintenance occurrences, which can be attributed to the additional 10 years of operational life factored into this study. Multiplying the maintenance occurrences from Case 3 by a factor of 4/3 to account for the extended operational period brings the values in line with those observed in this case, validating the influence of operational lifespan on maintenance frequency.

However, the persistent discrepancy in the maintenance of mooring line repairs between single-line and multiline layouts across both case studies suggests that this difference is likely inherent to the simulation design rather than being driven by environmental conditions. This consistency across different scenarios highlights the robustness of multiline configurations in reducing maintenance demands, regardless of the operational context, but also the need to develop and improve on the software to bring it more inline with expected outcomes. Where no matter the scenario, if the simulation has the same number of mooring lines with the same failure rates, then the same maintenance occurrences should happen.

8.3.2. Availability and Power Production

The performance comparison between single-line and multiline anchor layouts indicates differences in both availability and power production metrics. Figures 8.3 and 8.4 illustrate the mean values for time-based availability and power production under both In-Situ and Tow-to-Port repair scenarios. The error bars represent the 95% confidence intervals, providing insight into the variability and reliability of the data.

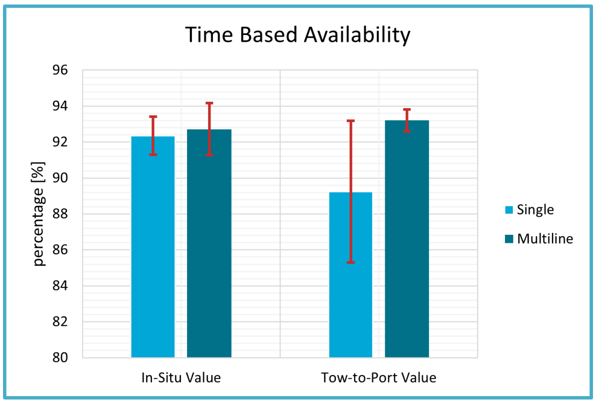


Figure 8.3: Availability of wind farm comparing single-line and multiline for GoMe.

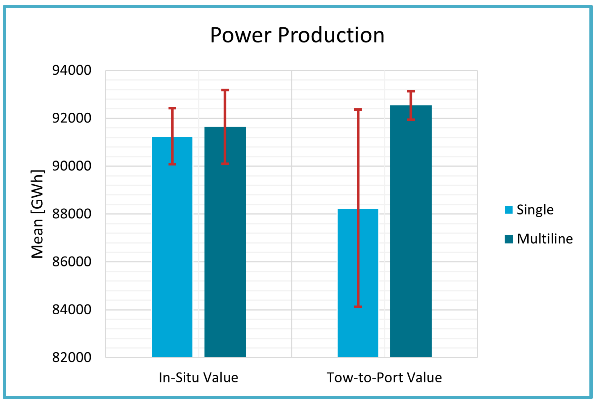


Figure 8.4: Power production of wind farm comparing single-line and multiline for GoMe.

Multiline configurations demonstrate superior performance in both time-based availability and power production, reflecting more consistent operational performance and reduced downtime. The narrower confidence intervals for multiline configurations suggest a lower degree of variability, further emphasizing their reliability.

However, the single-line configuration in the Tow-to-Port scenario shows a noticeable dip in both availability and power production, with significantly lower averages and a broader range of confidence intervals. This suggests increased variability and potential operational challenges under these conditions.

8.3.2.1 Discussion on Availability and Power Production

Time-Based Availability:
Regarding time-based availability, multiline configurations show higher mean availability than single-line configurations in both In-Situ and Tow-to-Port scenarios. The 95% CIs for single-line configurations are significantly larger, indicating greater variability and less consistency in maintaining availability. More investigation is needed with extra simulations to determine the cause of the dip in the mean value of single-line Tow-to-Port availability with a large CI span, possibly, it is the distance to port that is causing this, and/or the metocean influence on turbine and vessel performance conditions and/or there is a cause outside the location parameter but to do with the lifetime of the wind farm. Looking at the data, no clear singular event was found to be the cause, testing these possible reasons as the singular changing input could lead to a cause.

This trend is consistent with the findings from Case Study 3. However, the overall availability in the Gulf of Maine scenario is higher than in Morro Bay, reflecting the different environmental conditions. The increased distance to the port in the Gulf of Maine may not have hindered the availability of multiline, or its negative impact is less than the positive impact of the metocean conditions. With these factors, multiline configurations continue demonstrating superior performance in maintaining higher availability, underscoring their robustness and reliability in different marine environments.

Power Production:
When examining power production, multiline configurations consistently outperform single-line configurations regarding mean power production. For instance, multiline configurations have a mean power production of approximately 91,644 GWh in the In-Situ scenario, compared to 91,252 GWh for single-line configurations. The 95% CIs for multiline configurations are narrower, indicating more consistent power production. This pattern holds true for Tow-to-Port scenarios as well, with multiline configurations showing higher mean power production (92,534 GWh) compared to single-line configurations (88,242 GWh). Compared to the Case 3 study, the Gulf of Maine scenario shows lower power production for both configurations. Relating it to availability, it means that it produced more within what was possible compared to Case 3. Looking at the weather data for case 3, 86.13% of the weather falls within the cut-in and cut-out wind speeds. For this case, the weather is only within those boundaries 73.81% of the time. Meaning that the 10-year longer lifetime of the GoMe wind farm did not make it able to produce more power. This will be expanded on in a subsequent section.

8.3.3. Operational Expenditure:

Figures 8.5 till 8.8 illustrate the differences in annual and project-level OpEx between single-line and multiline anchor configurations for both In-Situ and Tow-to-Port repair scenarios. The figures show the mean annual OpEx and the sum project across the 30-year operational lifetime, with error bars representing the 95% confidence intervals, which give insights into the variability of the data.

8.3.3.1 OpEx

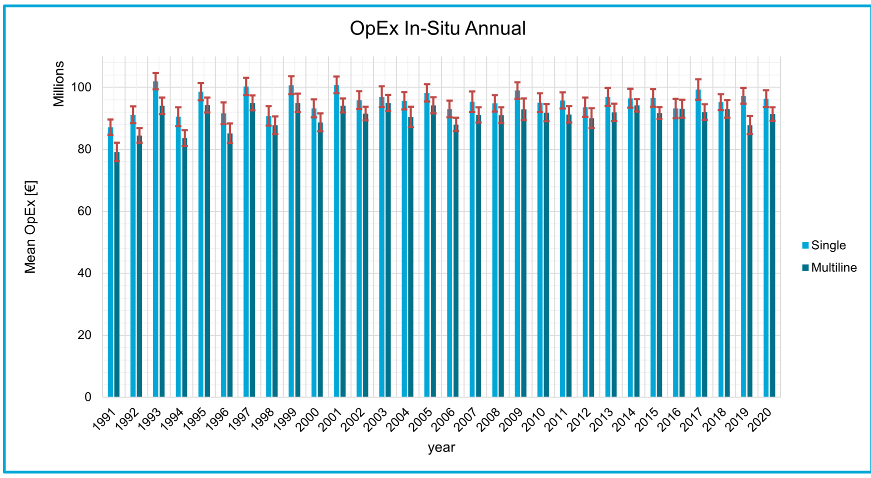


Figure 8.5: Annual OpEx for the In-Situ scenario comparing single-line vs multiline wind farm layout.

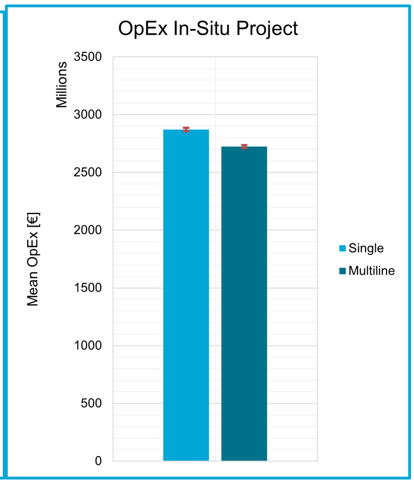


Figure 8.6: Lifetime sum OpEx for the In-Situ scenario comparing single-line vs multiline wind farm layout.

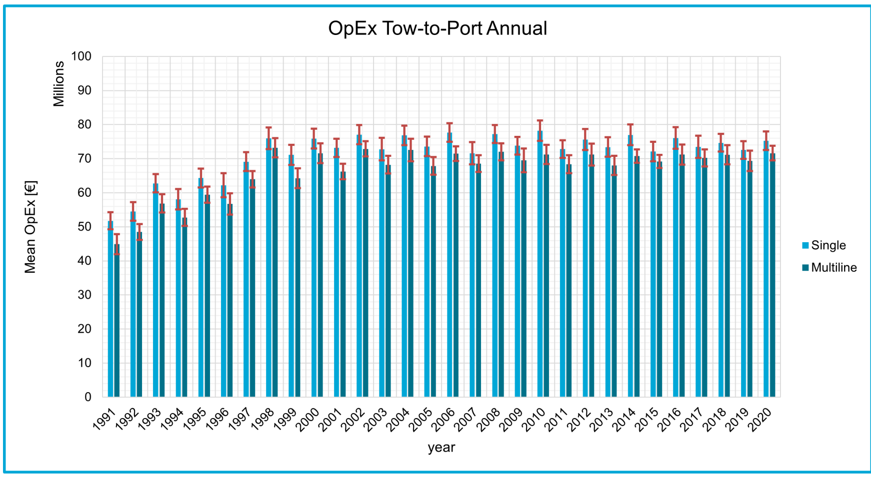


Figure 8.7: Annual OpEx for the Tow-to-Port scenario comparing single-line vs multiline wind farm layout.

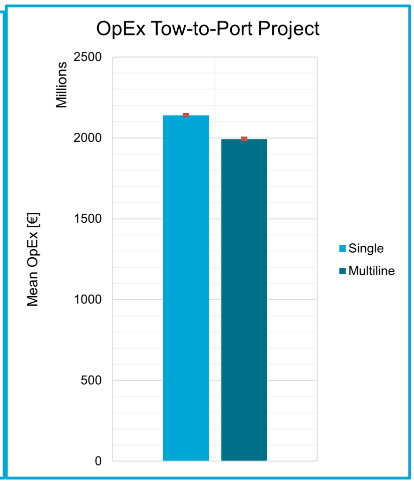


Figure 8.8: Lifetime sum OpEx for the Tow-to-Port scenario comparing single-line vs multiline wind farm layout.

The average mean annual and project OpEx for single-line configurations is higher than those for multiline configurations both for In-Situ and Tow-to-Port.

8.3.3.2 Discussion on OpEx

The operational expenditures for both In-Situ and Tow-to-Port projects reveal consistent patterns between single-line and multiline configurations. As shown in the figures for In-Situ projects, single-line configurations exhibit a higher mean OpEx of €2,871 million, compared to around €2,723 million for multiline configurations. This trend is further illustrated in the annual breakdown, where single-line configurations consistently incur higher costs yearly. The error bars in these figures, representing the 95% confidence intervals, are slightly larger for single-line configurations, indicating greater variability in annual OpEx.

For Tow-to-Port projects, depicted in the mean OpEx for single-line configurations is around €2,140 million, whereas it is approximately €1,993 million for multiline configurations. The annual trend shows that single-line configurations maintain higher operational costs, averaging around €70 million annually, compared to the slightly lower and more stable costs for multiline configurations. The error bars in these figures also suggest more variability for single-line configurations.

The higher OpEx for single-line configurations in both In-Situ and Tow-to-Port projects can be primarily attributed to their increased maintenance requirements due to the higher number of anchors. Single-line configurations necessitate more frequent interventions and repairs, increasing overall operational costs. The slightly larger error bars, indicating greater variability, reflect the unpredictable nature of these maintenance events. Conversely, multiline configurations benefit from fewer components, reducing the frequency of maintenance events. This results in lower overall and annual OpEx.

In Tow-to-Port scenarios, the trend persists. Multiline configurations demonstrate lower and more stable OpEx, underscoring their economic advantages in both maintenance strategies.

When comparing these In-Situ results to the Multiline layout study (Case 3), the trends remain consistent. Both case studies indicate higher OpEx for single-line configurations across all years. In this case, Gulf of Maine (Case 4), the relative difference in OpEx between single-line and multiline configurations is slightly larger, suggesting that the metocean conditions in this region and distance to port for travel times might exacerbate the maintenance demands and thereby cost for single-line configurations. However, the overall conclusion that multiline configurations are more cost-effective remains robust across both case studies.

For Tow-to-Port, the findings are similarly aligned. Both case studies show that single-line configurations incur higher OpEx than multiline configurations. The project OpEx values are higher in the Gulf of Maine, reflecting potentially different environmental conditions and the longer distance to the port. Despite these differences in magnitude, the overarching finding that multiline configurations offer a more cost-effective solution is consistent. This comparison highlights the resilience and economic efficiency of multiline configurations in diverse environmental conditions and locations, reaffirming their superiority in minimizing operational expenditures.

8.3.4. Net Present Value

Figures 8.9 till 8.12 illustrate the differences in the average annual and project-level NPV between single-line and multiline anchor configurations for both In-Situ and Tow-to-Port repair scenarios.

8.3.4.1 OpEx

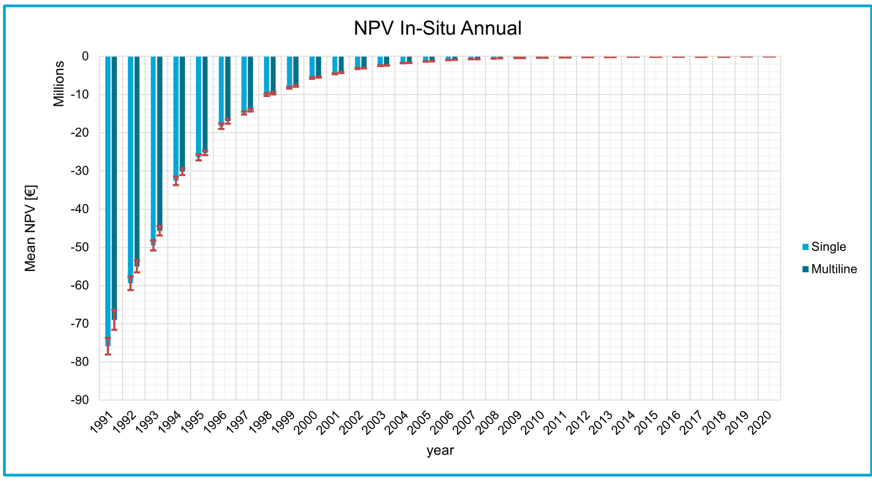


Figure 8.9: Annual NPV for the In-Situ scenario comparing single-line vs multiline wind farm layout.

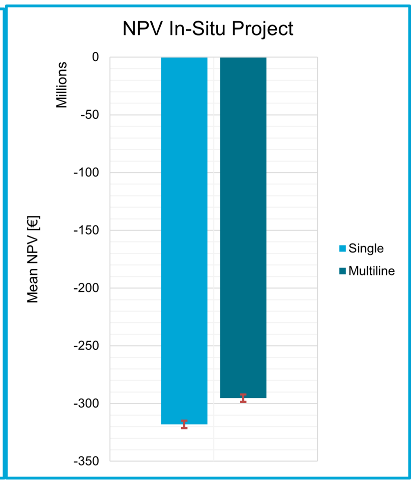


Figure 8.10: Lifetime sum NPV for the In-Situ scenario comparing single-line vs multiline wind farm layout.

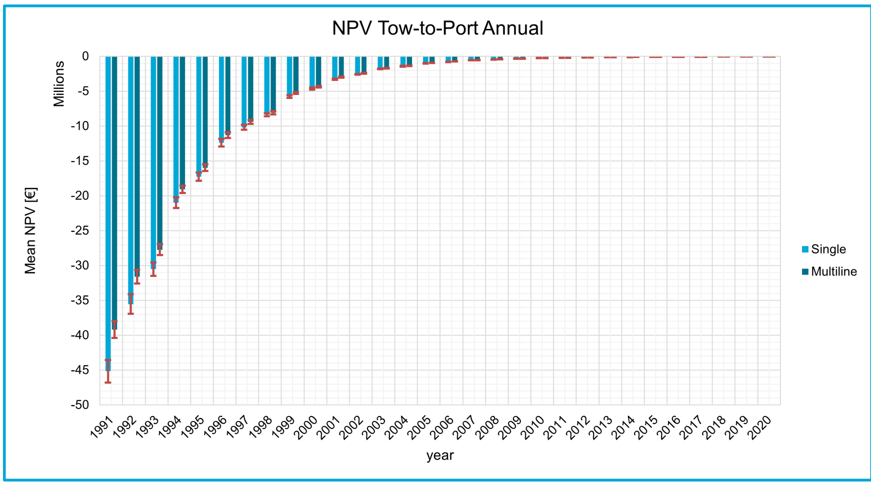


Figure 8.11: Annual NPV for the Tow-to-Port scenario comparing single-line vs multiline wind farm layout.

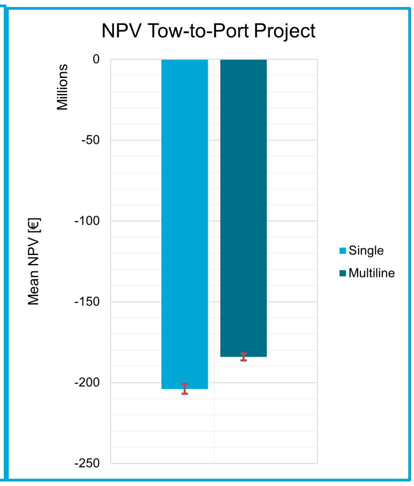


Figure 8.12: Lifetime sum NPV for the Tow-to-Port scenario comparing single-line vs multiline wind farm layout.

The mean annual and project NPV for single-line configurations is higher than those for multiline configurations both for In-Situ and Tow-to-Port.

8.3.4.2 Discussion on NPV

For In-Situ operations, the annual NPV and project-level NPV reveal that multiline configurations generally exhibit better financial performance than single-line configurations. The annual NPV for multiline configurations shows a consistent upward trend over the years, with narrower 95% confidence intervals indicating more stable financial outcomes. Specifically, the project-level NPV for multiline configurations is around -€295 million, whereas for single-line configurations, it is about -€318 million.

For Tow-to-Port operations, the annual NPV and project-level NPV also highlight that multiline configurations outperform single-line configurations. The annual NPV trend for multiline configurations is consistently higher than that for single-line configurations. The project-level NPV for multiline configurations is approximately -€184 million compared to -€204 million for single-line configurations. This trend underscores the financial advantage of multiline configurations in both operational contexts.

The preferable financial performance of multiline configurations, as reflected in higher NPVs and narrower confidence intervals, underscores their long-term economic advantages. The reduced maintenance costs and higher power production of multiline configurations contribute to lower operational expenditures and improved revenue streams, making them more financially viable.

The reduced frequency of maintenance interventions for multiline configurations, due to fewer components, minimizes downtime and enhances operational efficiency. This efficiency directly translates into more predictable and stable financial performance, as evidenced by the narrower CIs and higher mean NPV values.

In both Case Study 3 and Case Study 4, multiline configurations outperform single-line configurations in terms of NPV. The average annual and project-level NPVs for multiline configurations are consistently higher, indicating better financial performance. However, the Gulf of Maine scenario introduces different metocean conditions and transport/travel distances that impact the overall financial dynamics. Despite these conditions, the superior performance of multiline configurations remains evident, reinforcing their economic feasibility across varying environmental contexts. Overall, the analysis of NPV in the Gulf of Maine scenario further corroborates the findings from Case Study 3, demonstrating the financial advantages of multiline configurations in enhancing the long-term viability and cost-effectiveness of floating wind farms. This consistency highlights the robustness of multiline designs, making them a preferable choice for floating wind farm projects in diverse marine environments.

8.3.5. Metocean conditions and their impact on operations

The effectiveness of offshore wind farm operations is significantly influenced by local metocean conditions. In this section, the weather data from Morro Bay and the Gulf of Maine are compared, focusing on wind speed and wave height distributions. These factors are crucial not only for determining energy production potential but also for planning and executing maintenance operations.

Figures 8.13 and 8.14 compare wind speed and wave height histograms for Morro Bay and the Gulf of Maine. The data indicate that Morro Bay experiences a broader range of wind speeds, with significant occurrences in the 6-12 m/s range, and a notable frequency of wave heights around 1-2 meters. Conversely, the Gulf of Maine shows a higher frequency of low wind speeds coupled with lower wave heights, which has implications for both energy production and maintenance operations.

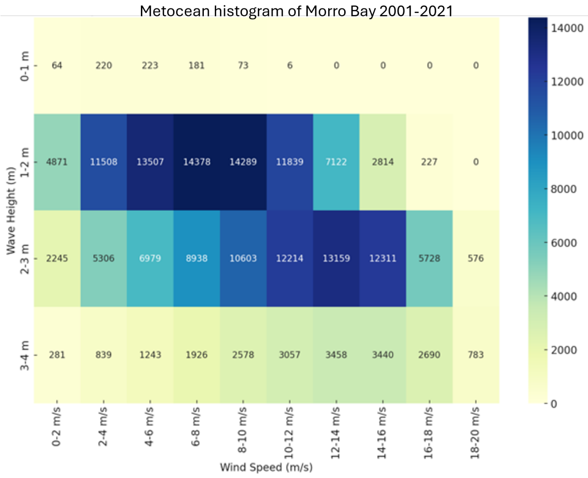


Figure 8.13: Metocean histogram for the Morro Bay scenario

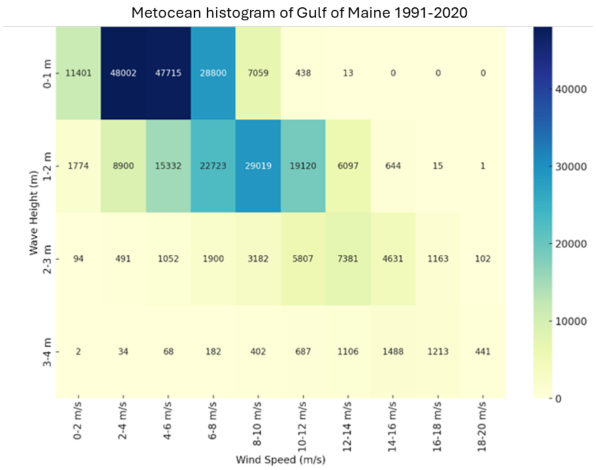


Figure 8.14: Metocean histogram for the Gulf of Maine scenario

8.3.5.1 Impact on wind turbine operations

The wind speed distribution in Morro Bay shows fewer occurrences of wind speeds below the cut-in speed of 4 m/s, leading to fewer periods with no power production. The significant presence of wind speeds within the 4-10 m/s range supports steady power production as wind speeds increase. Additionally, the strong occurrence of wind speeds in the 10-25 m/s range allows turbines to operate at maximum efficiency more frequently, resulting in higher overall power production. The minimal occurrences of wind speeds above the cut-out speed of 25 m/s imply that turbine shutdowns due to extreme wind speeds are likely rare, maintaining high availability.

In the Gulf of Maine, the wind speed distribution reveals a higher frequency of wind speeds in the 0-4 m/s range, resulting in more frequent periods of no power production. Although there is a substantial presence of wind in the 4-10 m/s range, contributing to moderate power production, the lower frequency of wind speeds in the 10-25 m/s range reduces the opportunities for turbines to operate at peak efficiency compared to Morro Bay. GoMe also had a few number of times of wind speeds exceeding 25 m/s, minimizing the risk of turbine shutdowns, and enhancing turbine availability despite the lower power production.

8.3.5.2 Impact on maintenance operations

Wave height distribution is a critical factor in determining the operational limits of maintenance vessels. In Morro Bay, the frequent occurrence of wave heights around 1.2 meters, particularly at moderate wind speeds, presents more challenges for maintenance operations compared to the Gulf of Maine. The operational limits for the vessels indicate that:

- Max Wind Speed: Most vessels, including anchor handling vessels (AHV), VSG (Vessel Support Group, the AHVs for multiline anchors), and Tugboats, can operate in wind speeds up to 20 m/s. Crew Transfer Vessels (CTV) are limited to 16 m/s, and Heavy Lift Vessels have a stricter limit of 10 m/s.

- Max Wave Height: AHV, VSG, and Tugboats can operate in wave heights up to 2.5 meters, while CTVs, HLVs, and Diving Support Vessels are limited to 2 meters.

Given these constraints, Morro Bay's wave conditions more frequently reach the operational limits for CTVs and HLVs, potentially causing delays in maintenance activities. In contrast, the Gulf of Maine's conditions, with generally lower wave heights and wind speeds, result in fewer operational disruptions, making maintenance weather windows more likely.

8.3.5.3 Comparitive analysis and implications

The comparative analysis between Morro Bay and the Gulf of Maine highlights the distinct metocean challenges at each site and their implications for wind turbine availability, power production, and maintenance.

The overall availability in the Gulf of Maine is higher than in Morro Bay, despite the increased distance to the port. This higher availability is primarily due to the more stable wind conditions in the Gulf of Maine, where there are fewer occurrences of extreme wind speeds (above 25 m/s) that could lead to turbine shutdowns. In Morro Bay, the variability in wind speeds and the harsher wave height conditions contribute to a more frequent need for weather delays, which could reduce availability.

The Gulf of Maine has lower overall power production compared to Morro Bay despite its higher availability. This is explained by the wind speed data, which shows that in the Gulf of Maine, only 73.81% of the time falls within the cut-in and cut-out wind speeds, whereas in Morro Bay, this percentage is higher at 86.13%. Consequently, the wind farm in Morro Bay produces more power within the available time frame due to more favorable wind conditions.

In summary, while the Gulf of Maine benefits from higher availability due to its more stable wind conditions and lower wave heights, Morro Bay achieves higher power production due to more time spent in optimal wind speed ranges. These findings suggest that for maximizing power production, Morro Bay's metocean conditions are more favorable, whereas the Gulf of Maine offers more stable operations with fewer risks of turbine shutdowns due to extreme conditions and weather delays.

8.4. Conclusion

The Gulf of Maine study, detailed in Case Study 4, extends the analysis of multiline anchor configurations in floating offshore wind farms by incorporating different metocean conditions, port distance, and an extended operational life of 30 years. This study reaffirms the findings from the previous case study and provides further insights into the performance and financial viability of multiline configurations under varying environmental conditions.

8.4.1. Summary of Key Findings

The primary findings from this case study are as follows:

1. Occurrence of Maintenance: Single-line configurations consistently exhibited higher maintenance occurrences across all categories (anchor replacement, major anchor repair, mooring line major repair, and mooring line replacement) compared to multiline configurations. This trend was observed in both In-Situ and Tow-to-Port maintenance scenarios.

2. Time-Based Availability: Multiline configurations demonstrated higher mean availability than single-line configurations. The 95% confidence intervals for single-line configurations were significantly larger, indicating more variability and less consistency in maintaining availability.

3. Power Production: Multiline configurations outperformed single-line configurations regarding mean power production. In the In-Situ scenario, multiline configurations achieved a mean power production of approximately 91,644 GWh, compared to 91,252 GWh for single-line configurations. The advantage was even more pronounced in the Tow-to-Port scenario, with multiline configurations generating 92,534 GWh compared to 88,242 GWh for single-line setups. The narrower 95% confidence intervals for multiline configurations indicate more reliable and consistent power output.

4. Operational Expenditure: Multiline configurations resulted in lower OpEx compared to single-line configurations in both In-Situ and Tow-to-Port scenarios. The difference was particularly significant in the Tow-to-Port scenario, where multiline setups consistently maintained lower operational costs throughout the project's lifetime. The reduced maintenance requirements of multiline configurations directly contributed to these lower expenditures.

5. Net Present Value: Multiline configurations exhibited better financial performance with higher NPVs compared to single-line configurations. For In-Situ operations, the project-level NPV for multiline configurations was approximately -€295 million compared to -€318 million for single-line configurations. Similarly, in the Tow-to-Port scenario, the NPV for multiline configurations was about -€184 million compared to -€204 million for single-line setups. These results underscore the financial advantages of multiline configurations, especially in more challenging operational contexts.

8.4.2. Comparison to case study 3

When comparing the Gulf of Maine results to those from the Morro Bay scenario in Case Study 3, the trends in performance remain consistent. Multiline configurations continue to demonstrate enhanced performance in terms of maintenance occurrences, availability, power production, OpEx, and NPV. The Gulf of Maine scenario, characterized by an extended operational life, greater distance to port, and different metocean conditions, further validates the robustness of multiline anchor designs. Despite the additional complexities introduced by the Gulf of Maine conditions, multiline configurations maintain their operational and financial advantages, reinforcing their suitability for FOWFs across diverse marine environments.

8.4.3. Implications for Future Research

The findings from the Gulf of Maine study highlight the importance of considering different environmental conditions and operational lifetimes in the design and evaluation of FOWFs. Future research should continue to explore the performance of multiline configurations under various scenarios, incorporating real-time data and advanced monitoring systems to enhance the accuracy and applicability of simulation models. Additionally, further studies should investigate the long-term benefits and challenges, including multiline's impact on environmental sustainability and cost-efficiency.

In conclusion, this study reinforces the case for adopting multiline anchor configurations in FOWFs, demonstrating their ability to enhance operational performance and financial viability even under complex and challenging marine conditions. As the industry evolves, the robust performance of multiline configurations across different scenarios suggests that they offer a reliable and cost-effective solution for future offshore wind farm developments.

9

Case 5: Sensitivity study

9.1. Introduction

Sensitivity analysis is a vital process in evaluating the reliability and robustness of floating offshore wind farms. It helps in understanding how variations in input parameters affect the simulation outcomes, particularly focusing on the operation and maintenance costs and performance metrics. This chapter delves into the impact different failure rates of mooring lines have on the performance of FOWFs, addressing the need for accurate failure rate data and the implications of varying these rates.

9.1.0.1 Rationale for Sensitivity Analysis

The sensitivity study is motivated by concerns raised in the feedback received regarding the reliability of failure rate data from various sources. The COREWIND report, often referenced, bases its failure rates on ”interviews and in-house expertise” without utilizing more widely recognized studies and published reports. This has led to the selection of alternative, more reliable data sources for this analysis. The following issues were highlighted:

- **Discrepancy in Failure Rates:** The COREWIND report assigns the same failure rate for anchors and mooring lines, which is inconsistent with industry observations where anchor failures are rare.
- **Lack of Real Case Data:** The COREWIND report does not reference recognized studies like the DEEPSTAR® projects, which provide extensive real-case data on mooring failures.
- **Expert Feedback:** Industry experts, such as those from Vryhof, indicate that anchor failures in permanent mooring systems are virtually nonexistent, with the majority of failures occurring in mooring lines, particularly at the splash zone.

Given these points, this sensitivity analysis uses alternative, more reliable failure rate data to provide a robust evaluation of FOWF performance. Additionally, the failure rate for anchor replacements is set to zero, reflecting industry feedback that anchor failures are rare in permanent mooring systems. Vryhof has not had a reported anchor failure since 1972, a record of 50+ years.

9.2. Methodology

9.2.1. Overview

The sensitivity analysis utilizes the modified WOMBAT software to simulate the O&M of FOWFs under different failure rate scenarios. Three distinct failure rate data points are used to represent a range of potential outcomes:

- **DeepStar 20401 Project:** This project provides a comprehensive analysis of mooring line failures in the offshore oil and gas industry, offering valuable insights with a failure rate of approximately 2.4×10^{-2} per line per year [35].
- **WFO Global Mooring White Paper (2023):** This study reports single-line failure rates around

2.5×10^{-3} per line per year, reflecting advancements in mooring technology and improved maintenance practices [52].

- **ASME Digital Collection - OMAE2014:** This detailed study on mooring line failure rates in floating offshore wind turbines reports single-line failures at 9.2×10^{-3} per line per year [53].

In this sensitivity study, the focus is specifically on analyzing the failure rates of mooring lines rather than incorporating repair rates. This approach is taken due to several key reasons. Firstly, the data on failure rates is more readily available and reliable, particularly from comprehensive studies such as the DeepStar 20401 Project, the WFO Global White Paper, and the ASME Digital Collection. In contrast, detailed and accurate data on repair rates, especially minor repairs, is significantly scarcer. The variability in repair methodologies, costs, and downtimes across different studies and real-world scenarios adds another layer of complexity that could compromise the consistency and comparability of the sensitivity analysis.

Moreover, focusing solely on failure rates allows for a clearer understanding of the impact of mooring line failures on the operational and maintenance strategies of floating offshore wind farms. It simplifies the modeling process and helps in isolating the direct effects of a singular failure rate on the overall system performance and costs. This targeted analysis is crucial for developing robust and reliable mooring systems, as it highlights the areas that require the most attention for improving resilience and reducing downtime. Future research can build on this foundation to incorporate repair rates once more comprehensive and standardized data becomes available.

9.2.2. Simulation Setup

The simulations were conducted with the following parameters:

- **WOMBAT Version:** Modified
- **Scenario:** Morro Bay
- **Mooring Layout:** Multiline anchor
- **Input Data:** Appendix A & changed failure inputs
- **Number of Runs:** 4 x 30
- **Average Duration of Each Simulation:** 15 minutes
- **Per Run Simulation:** In-Situ repair & Tow-to-Port.
- **Random Seed:** Seed number 4 was used for each simulation to ensure reproducibility.

For clarification, table 9.1 shows per sources in increasing failure rate order, the failure rate, and the Weibull scale used in the simulations. This means that table A.11 with the failure rates of the anchors will not used, and table A.12 with the failure parameters of mooring lines have for the replacement category the values in the table below. COREWIND is added as a last row of the table as a reference point.

Table 9.1: Depending on the source the change in mooring line failure rates and Weibull scales

Source	Failure Rate	Weibull Scale	Weibull Shape
Deepstar	0.024	41.67	1
ASME	0.0092	108.70	1
WFO	0.0025	400	1
COREWIND	0.0042	240	1

The results displayed represent the average of 30 simulations unless specified otherwise, as determined by Case 1: Convergence study.

9.3. Results

9.3.1. Component maintenance occurrence

Figures 9.1 and 9.2 show the mean number of occurrences of maintenance tasks for mooring line replacements under both In-Situ and Tow-to-Port repair scenarios. The error bars represent the 95% confidence intervals, indicating the range within which the true mean is likely to fall.

9.3.1.1 Maintenance occurrences

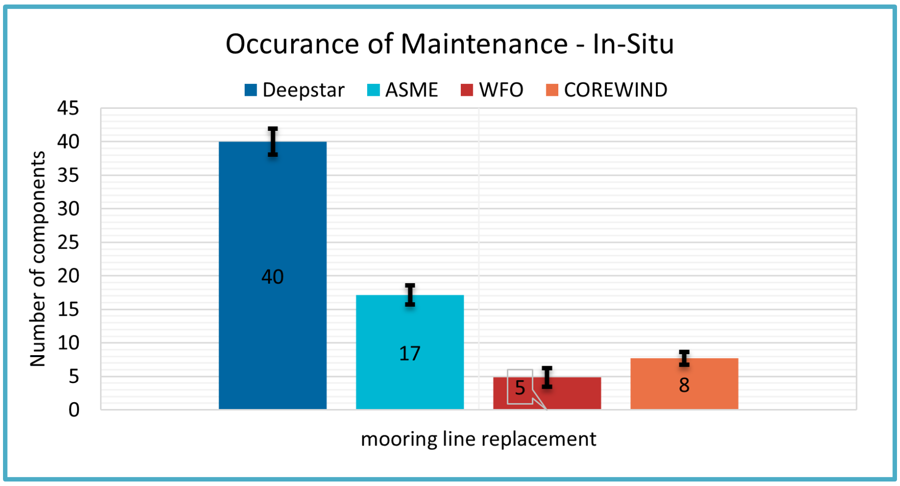


Figure 9.1: Occurrence of mooring line replacement - In-Situ

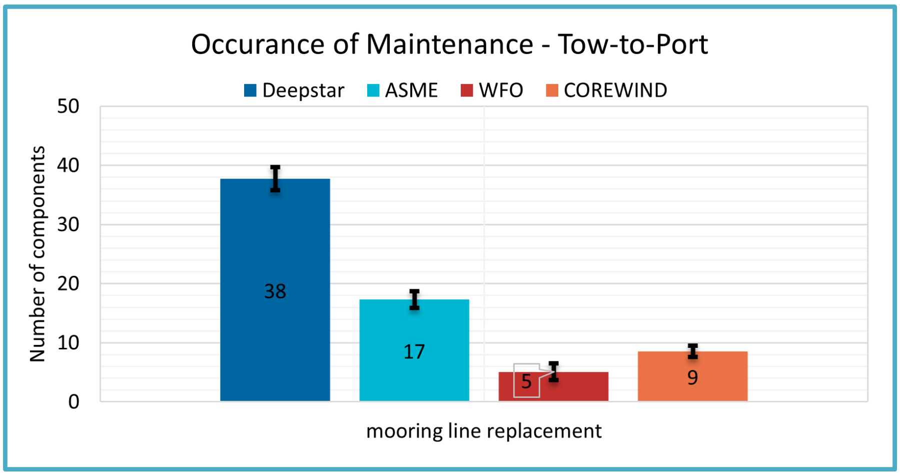


Figure 9.2: Occurrence of mooring line replacement - Tow-to-Port

Both figures show how the frequency of these maintenance events varies across the different failure rates provided by Deepstar, ASME, WFO, and COREWIND which is expected. The data indicates that Deepstar has the highest number of maintenance occurrences for In-Situ, reflecting its more conservative failure rate estimates. This is followed by ASME, which also shows a significant number of maintenance events. WFO and COREWIND, result in fewer occurrences, suggesting a more optimistic outlook on maintenance needs. A similar trend is observed with Tow-to-Port.

9.3.1.2 Discussion on Maintenance occurrences

These figures illustrate the critical role that failure rate data plays in determining the frequency of maintenance activities, a direct correlation. Conservative failure rates like those from Deepstar lead to more frequent interventions, which can significantly increase operational costs.

The implications of these maintenance occurrences are significant. Higher failure rates result in more frequent maintenance, which can disrupt operations and increase downtime. The lower maintenance occurrences in WFO and COREWIND suggest a more streamlined operation but may underestimate the actual need for maintenance if their failure rates are too optimistic. The choice between In-Situ and Tow-to-Port strategies has no influence on the failure rates.

9.3.2. Availability and Power Production

Figures 9.3 and 9.4 illustrate the mean values for time-based availability and power production under both In-Situ and Tow-to-Port repair scenarios. The error bars represent the 95% confidence intervals.

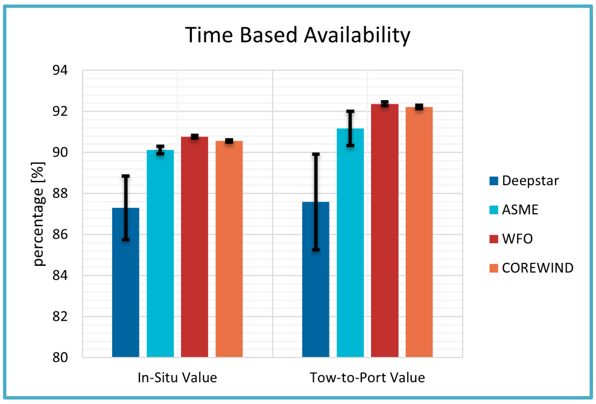


Figure 9.3: Availability of wind farm comparing single-line and multiline.

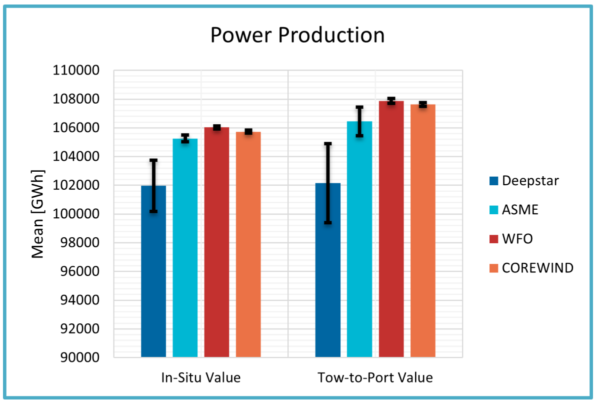


Figure 9.4: Power production of wind farm comparing single-line and multiline.

The bars in figure 9.3 show that time-based availability generally decreases as the failure rates increase. The figure shows that the In-Situ strategy has lower availability across all failure rate sources than Tow-to-Port. Deepstar, with its higher failure rates, leads to the lowest availability, reflecting the frequent need for repairs and the resulting downtime. The Tow-to-Port strategy shows slightly better availability than the In-Situ approach across all failure rates. However, it does seem for Deepstar that a high failure rate can lead to such significant maintenance that the choice of strategy has no impact. This suggests that Tow-to-Port may better manage the operational disruptions caused by mooring line failures, except for those in the range of Deepstar, though it still suffers from reduced availability under high failure rates.

Figure 9.4 clearly shows a correlation between the time-based availability and the wind farm's power output. For In-Situ, power production is lower, consistent with its reduced availability. As availability drops due to frequent maintenance interruptions, the overall energy output diminishes, which directly affects the farm's revenue potential. Similar to the availability results, the Tow-to-Port strategy maintains higher power production levels across failure rate sources except for Deepstar.

9.3.2.1 Discussion on Availability and Power Production

Time-Based Availability:
The results indicate that the Tow-to-Port strategy generally provides higher availability than the In-Situ strategy across all failure rate sources. This advantage is particularly evident in cases with higher failure rates, such as those provided by Deepstar. These findings have significant implications for wind farm operators. The varying failure rates of the mooring line demonstrate the importance of having precise values in the model. The total availability range goes from 87% to 92%, over the lifetime of a farm, which can significantly impact the revenue it makes. A single input has such an impact on the consequence that the model and outputs are only as accurate as the inputs. Using a failure rate that is overly conservative could cause the wind farm to spend money on resources it does not need (like an extra CTV), while an underestimation could lead to operators not having enough capability and capacity to deal with downtime and it being extended.

Power Production:
Figure 9.4 clearly illustrates the impact of mooring line failure rates on power production. The Tow-to-Port strategy consistently outperforms In-Situ in terms of energy output, aligning with the higher availability seen in Figure 9.3. This suggests that Tow-to-Port is a more robust strategy for managing

the operational disruptions caused by frequent maintenance needs, especially under low failure rate scenarios.

However, the power production figures also reveal the limitations of even the Tow-to-Port strategy when dealing with conservative failure rate estimates like those from Deepstar. The substantial drop in power production under these conditions indicates that overly conservative failure rates can severely limit the wind farm's economic potential.

For wind farm operators, these findings underscore the importance of balancing failure rate estimates with operational strategies. While conservative estimates ensure reliability and preparedness, they may come at the cost of reduced power production and, consequently, lower financial returns. Conversely, more optimistic estimates can enhance power output but carry the risk of unexpected maintenance needs if actual failure rates are underestimated.

9.3.3. Operational Expenditure:

Figures 9.5 till 9.8 illustrate the differences in average annual and project-level OpEx between the different failure rates configurations for both In-Situ and Tow-to-Port repair scenarios.

9.3.3.1 OpEx

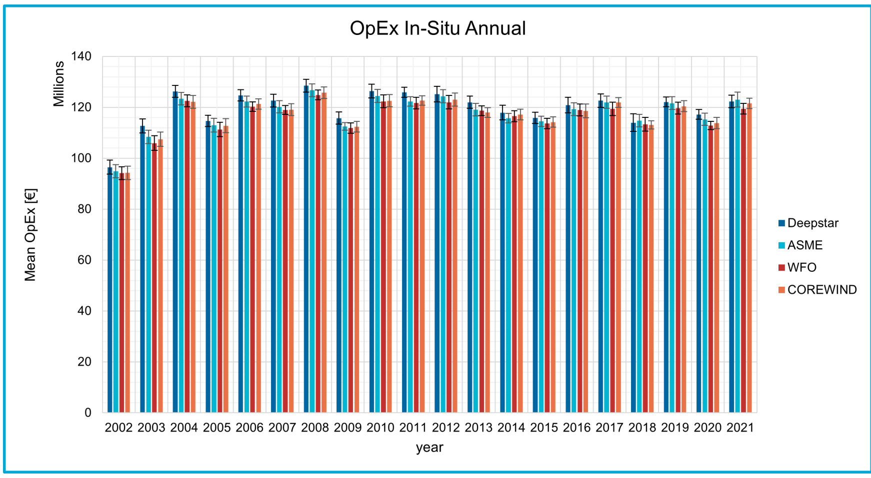


Figure 9.5: Annual OpEx for the In-Situ scenario comparing mooring line failure rates.

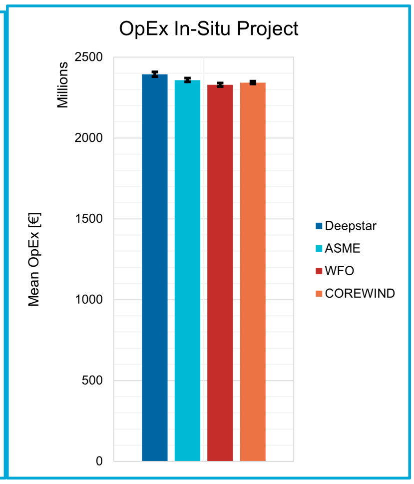


Figure 9.6: Lifetime sum OpEx for the In-Situ scenario comparing mooring line failure rates.

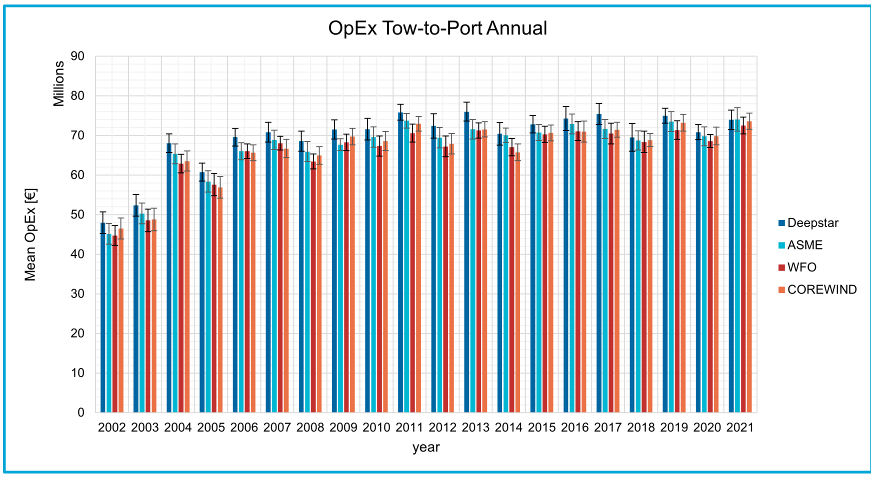


Figure 9.7: Annual OpEx for the Tow-to-Port scenario comparing mooring line failure rates.

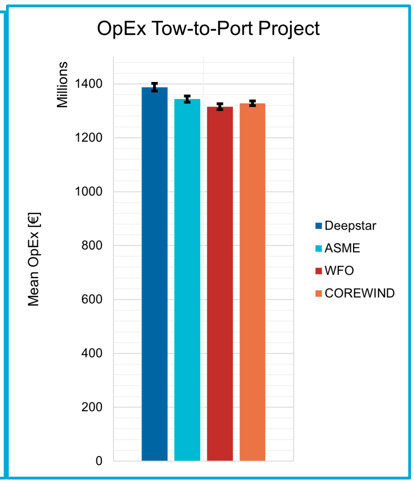


Figure 9.8: Lifetime sum OpEx for the Tow-to-Port scenario comparing mooring line failure rates.

Annual OpEx (Figures 9.5 and 9.7):
The annual OpEx is highest for Deepstar with In-Situ, reflecting the frequent maintenance activities required due to higher failure rates. ASME also shows elevated annual OpEx, though less severe than Deepstar. In contrast, WFO and COREWIND, with their lower failure rates, result in lower annual OpEx. The confidence intervals for the In-Situ strategy tend to be wider, indicating greater variability and uncertainty in these estimates, particularly for Deepstar.

The annual OpEx in the Tow-to-Port strategy is generally lower to that of the In-Situ strategy. However, Deepstar still has the highest annual OpEx under Tow-to-Port, suggesting that even if the number of maintenance events is similar, the costs associated with each strategy may be higher due to the logistics involved. WFO and COREWIND continue to exhibit the lowest annual OpEx, benefiting from lower failure rates. The confidence intervals for the Tow-to-Port strategy are slightly narrower, suggesting more predictable costs, though they remain influenced by the underlying failure rate data.

Project OpEx (Figures 9.6 and 9.8):
The cumulative project OpEx in In-Situ is significantly higher for Deepstar, consistent with the trend seen in the annual figures. The project-wide cost burden under Deepstar is substantial, which could impact the overall financial sustainability of the wind farm. WFO and COREWIND maintain lower project OpEx, reflecting their reduced failure rates and fewer maintenance demands over the project's life. The wider confidence intervals observed for Deepstar suggest greater uncertainty in the long-term cost predictions, possibly due to the higher variability in maintenance needs.

The cumulative project OpEx remains highest for Deepstar, although the Tow-to-Port strategy does help mitigate some of the cost impacts compared to In-Situ. The long-term cost efficiency of WFO and COREWIND is evident, as they continue to have the lowest project OpEx, indicating better financial outcomes over the project's lifetime. The narrower confidence intervals for COREWIND in this strategy suggest a more confident estimation of long-term costs, though this might not fully capture all potential risks.

9.3.3.2 Discussion on OpEx
Figures 9.5 through 9.8 clearly demonstrate the impact of mooring line failure rates on both annual and cumulative project OpEx. The consistently higher OpEx observed with Deepstar data across both strategies underscores the financial burden of conservative failure rate estimates. While these estimates may provide a robust safety margin, they do so at the expense of predicting significantly higher operational costs, which can strain the wind farm's financial resources both annually and over the entire project duration.

The confidence intervals add further depth to this analysis, indicating that the In-Situ strategy, particularly when paired with conservative failure rates like Deepstar, introduces more variability and uncertainty in cost predictions. This could suggest that while the strategy might be effective in certain conditions, it carries a higher financial risk due to the potential for unexpected costs. In contrast, the Tow-to-Port strategy, with its slightly narrower confidence intervals, offers more predictable cost outcomes, though it still cannot fully mitigate the financial impacts of higher failure rates.

WFO and COREWIND's lower OpEx, annual and project-wide, highlights the financial benefits of using more optimistic failure rate estimates. Their narrower confidence intervals suggest a higher degree of confidence in these estimates, which might reflect more stable and predictable operational conditions. However, the possibility remains that these optimistic estimates could underestimate potential risks, leading to unforeseen expenses if actual failure rates exceed predictions.

In summary, choosing the failure rate data and maintenance strategy has significant implications for OpEx. While conservative estimates like Deepstar's provide a safeguard against failures, they also introduce higher costs and greater uncertainty. On the other hand, optimistic estimates from WFO and COREWIND enhance financial performance by reducing OpEx and offering more predictable cost outcomes, but they require careful management of potential risks. Therefore, wind farm operators must carefully balance these factors to optimize both financial performance and operational reliability.

9.3.4. Net Present Value

Figures 9.9 till 9.12 illustrate the differences in annual and project-level NPV between single-line and multiline anchor configurations for both In-Situ and Tow-to-Port repair scenarios.

9.3.4.1 OpEx

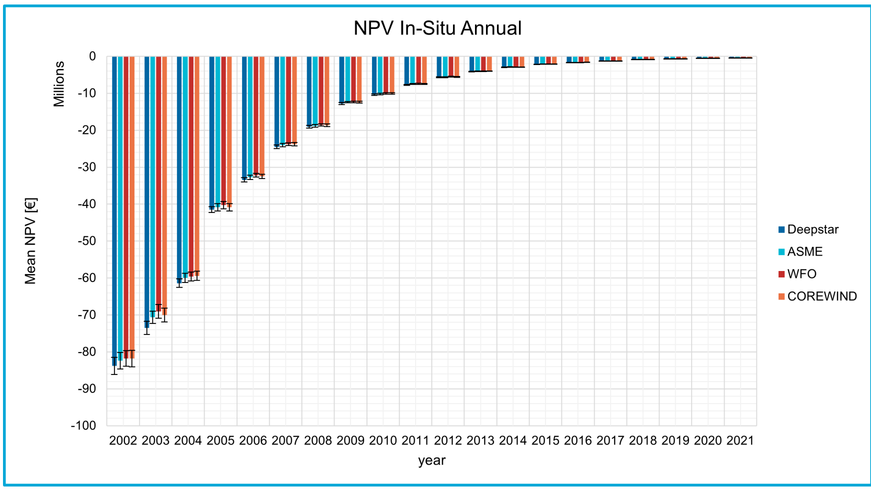


Figure 9.9: Annual NPV for the In-Situ scenario comparing mooring line failure rates.

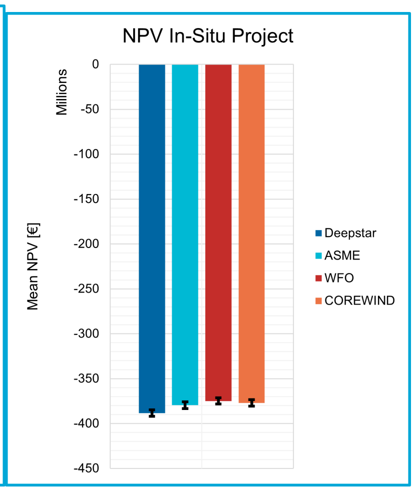


Figure 9.10: Lifetime sum NPV for the In-Situ scenario comparing mooring line failure rates.

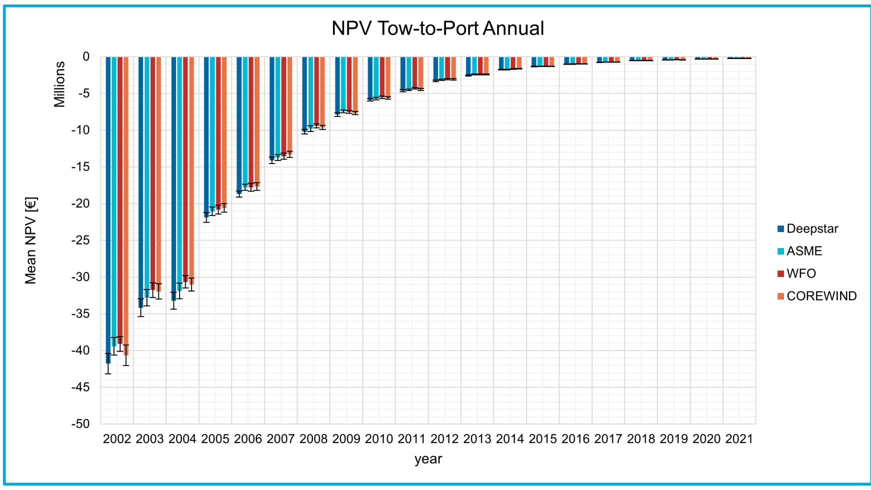


Figure 9.11: Annual NPV for the Tow-to-Port scenario comparing mooring line failure rates.

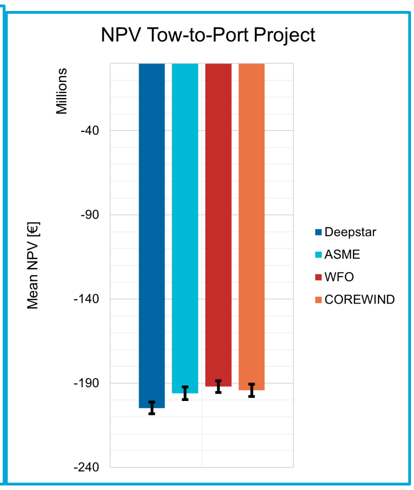


Figure 9.12: Lifetime sum NPV for the Tow-to-Port scenario comparing mooring line failure rates.

Annual NPV (Figures 9.9 and 9.11):
In the In-Situ strategy, Deepstar consistently shows the most negative NPV across all years, reflecting the high operational costs associated with its conservative failure rates. This results in a gradual improvement in NPV over time, though the overall financial performance remains challenging. WFO and COREWIND display a more favorable annual NPV, particularly in the later years, due to higher availability and lower operational costs. ASME's NPV trajectory falls between these extremes, improving over time but remaining more negative than WFO and COREWIND. The confidence intervals for Deepstar are notably wider, indicating greater variability and uncertainty in financial projections under this conservative scenario.

When examining the Tow-to-Port strategy, the trend is similar, with Deepstar again having the most negative annual NPV, although the differences between Deepstar and the other sources are less pronounced than in the In-Situ strategy. WFO and COREWIND continue to perform better, with their annual NPV becoming less negative more rapidly compared to Deepstar and ASME. The confidence intervals for the Tow-to-Port strategy are narrower compared to the In-Situ strategy, suggesting more predictable financial outcomes, though Deepstar still exhibits significant uncertainty.

Project NPV (Figures 9.9 and 9.11):
In terms of cumulative project NPV, as shown in Figures 9.11 and 9.12, the In-Situ strategy (Figure 9.11) shows that the project NPV for Deepstar is the most negative, underscoring the financial strain imposed by conservative failure rate estimates. The overall project value under Deepstar is significantly lower than the other sources, indicating a challenging financial outlook. COREWIND and WFO demonstrate the least negative project NPV, suggesting that their more optimistic failure rates lead to better long-term financial performance. The project NPV under these sources is closer to break-even, though still negative. ASME's project NPV falls in the middle, being more negative than COREWIND and WFO but less so than Deepstar. The confidence intervals for Deepstar's project NPV are wide, indicating significant variability in potential outcomes, which reflects the high level of uncertainty associated with its failure rates.

For the Tow-to-Port strategy (Figure 9.12), the overall trend is one of less negative project NPVs across all data sources compared to the In-Situ strategy, highlighting the cost-saving benefits of this maintenance approach. Although Deepstar remains the most negative, the gap between Deepstar and the other sources is reduced compared to the In-Situ strategy. COREWIND and WFO again show the least negative NPVs, with more favorable financial outcomes over the project's life. The confidence intervals are narrower for the Tow-to-Port strategy, suggesting a more predictable financial performance, though Deepstar still shows significant uncertainty.

9.3.4.2 Discussion on NPV
The NPV analysis, illustrated in Figures 9.9 through 9.12, highlights the profound impact of failure rate data on both annual and cumulative project NPV. The consistently more negative NPVs associated with Deepstar's conservative estimates emphasize the financial burden these failure rates impose, potentially deterring investment and straining the project's financial resources. The comparison between the In-Situ and Tow-to-Port strategies reveals that while the latter generally leads to improved financial outcomes, the choice of failure rate data remains a critical determinant of the overall project viability. COREWIND and WFO's more optimistic failure rates offer more favorable NPV outcomes, suggesting better financial performance and lower risk over time. However, these optimistic estimates may underestimate potential risks, leading to unforeseen costs if actual failure rates exceed predictions. The confidence intervals, particularly those associated with Deepstar, reveal a higher level of uncertainty in financial performance, especially under the In-Situ strategy. This underscores the importance of carefully balancing conservatism and financial performance when selecting failure rate data and maintenance strategies. The analysis suggests that achieving an optimal financial outcome for floating offshore wind farms requires a thoughtful approach to selecting failure rate data and maintenance strategies, weighing the trade-offs between conservative and optimistic estimates.

9.4. Discussion

9.4.1. Implications of Using Oil and Gas Data
Using failure rate data from the oil and gas industry, such as the DeepStar 20401 Project, provides a robust baseline for understanding mooring line reliability. However, it is crucial to acknowledge the differences between the oil and gas sector and FOWFs. The oil and gas industry operates in different environments with distinct operational parameters, which may not fully represent the conditions experienced by FOWFs.

As highlighted in the FOW-CoE report [54], several key differences must be considered:

- Installation Numbers: The total number of FOW installations is expected to exceed that of oil and gas installations, potentially leading to more frequent failures due to the increased number of installations.
- Mooring Tension Spectra: The loading on FOW systems is more dynamic and variable compared to the relatively static loading on oil and gas installations.

- Risk Profiles: The absence of onboard personnel and hydrocarbons in FOW systems may lead to different risk acceptance levels and, consequently, different failure rates.
- Monitoring and Maintenance: Oil and gas platforms benefit from continuous monitoring and maintenance, which may not be as feasible or frequent for FOW systems.

9.4.2. Expert Feedback

Feedback from industry experts, such as Vryhof, emphasizes that anchor failures are virtually nonexistent in permanent mooring systems. The majority of failures occur in mooring lines, particularly at the splash zone. This feedback supports the decision to set the anchor replacement failure rate to zero in the sensitivity analysis.

9.5. Conclusion

This case study presented a detailed sensitivity analysis that evaluated the impact of varying mooring line failure rates on the operational and financial performance of floating offshore wind farms. This analysis compared two maintenance strategies — In-Situ and Tow-to-Port — using failure rate data from four sources: Deepstar, ASME, WFO, and COREWIND.

A key finding of the analysis is that maintenance occurrences were consistent across both the In-Situ and Tow-to-Port strategies, dependent on the failure rate data source. Meaning that the choice of maintenance strategy does not affect the frequency of maintenance events but instead influences their financial and operational implications.

Regarding availability and power production, higher failure rates, particularly those from Deepstar, led to reduced availability and lower power production. These effects were more pronounced in the In-Situ strategy, where the strategy resulted in more significant downtime.

Financially, the analysis revealed that the In-Situ strategy typically resulted in higher operational expenditures due to the frequent and necessary maintenance interventions. This led to a more negative net present value, especially when using conservative failure rates like Deepstar's. While the Tow-to-Port strategy leads to slightly better financial predictability and improved availability, albeit with similarly negative NPVs across all scenarios.

In conclusion, this sensitivity study underscores the importance of selecting accurate failure rate data and choosing a maintenance strategy that best aligns with the specific operational context of the wind farm. The study also demonstrated the significant impact a singular failure data input can have on an entire wind farm's cost and performance.

10 Discussion

10.1. Mooring Modifications to the software

The mooring enhancements made to the WOMBAT software significantly improved its capability to simulate multiline anchors in terms of operation and maintenance strategies. The key modification can integrate details of the mooring configurations, allowing the software to distinguish between single-line and multiline anchor systems and, thereby, their consequences. The integration involved substantial changes to the original code. The modification was crucial in providing a realistic and comprehensive analysis of the cost-benefit implications of different mooring configurations, thereby optimizing the O&M processes for FOWFs.

10.2. Case 1: Convergence study

Interpretation of simulation results

Case 1 focused on determining the minimum number of simulation runs required to achieve stable and reliable results for offshore wind farm operations. The convergence study indicated that approximately 30 simulation runs were necessary to achieve stable and reliable average results for both net present value and operational expenditure metrics. The findings indicate that after 30 runs, additional simulations have a negligible impact on the mean values, ensuring that the results are statistically robust and reliable. Additionally, the finding ensures that the results of subsequent simulations are based on statistically robust data, providing confidence in the reliability of the cost-benefit analysis for different mooring configurations.

Advantages and limitations of the simulation model

The primary advantage of the convergence study is establishing a robust foundation for further simulations. By identifying the number of runs needed for reliable data, the study enhances the credibility of the simulation results. However, a limitation is that the study focuses solely on the number of runs without considering the potential variability in input data quality. Ensuring high-quality input data remains crucial for the accuracy of the simulation outcomes.

Applicability and adaptability of model findings

The convergence findings from this study are crucial for optimizing simulation resources in future case studies. By establishing that 30 runs are sufficient, future studies can allocate resources more effectively, ensuring both time and cost efficiency.

Future enhancements and potential extensions of the simulation

Future enhancements could involve developing methods to dynamically determine the convergence point during simulations, reducing the computational resources required. Additionally, extending the convergence study to include sensitivity analysis on input data quality would provide a more comprehensive understanding of the factors influencing simulation reliability.

10.3. Case 2: Model validation study

Interpretation of simulation results

The study on the modified WOMBAT tool aimed to evaluate its performance compared to the original version by simulating the operation and maintenance costs of a floating offshore wind farm with a single-line anchor layout. The results indicated that the modified version, which integrates detailed mooring configurations, provides more precise and reliable estimates of operational expenditures and net present value than the original version.

Advantages and limitations of the simulation model

The modified WOMBAT simulation model offers several advantages, including a more detailed and realistic analysis of different mooring configurations and their cost-benefit implications. The modification allows for a precise representation of single-line mooring layouts, enhancing the precision of the simulation. The detailed modeling of failure rates, repair times, and maintenance schedules provides a more comprehensive analysis of O&M activities. However, the increased complexity of the modified tool can introduce variability and errors. Additionally, the detailed simulations demand more computational resources, potentially limiting their use for preliminary studies or smaller projects.

Applicability and adaptability of model findings

The enhanced precision and detailed mooring configurations make the modified WOMBAT tool highly applicable for floating offshore wind farms with similar setups. However, the tool's performance should be validated in other scenarios and configurations to ensure its adaptability and reliability across different conditions.

Future enhancements and potential extensions of the simulation

Future enhancements should focus on further calibrating and tuning the modified WOMBAT tool to improve its stability and reliability. Additionally, expanding the tool's capabilities to include the integration of real-time operational data can significantly enhance its utility for broader applications in offshore wind farm management.

10.4. Case 3: Multiline layout study

Interpretation of simulation results

The multiline layout study compared the cost-effectiveness of multiline anchor systems against single-line anchor systems. The results showed that multiline mooring configurations consistently demonstrate better operational and financial performance, with higher availability, lower operational costs, and fewer occurrences of maintenance across all mooring components compared to single-line setups.

Advantages and limitations of the simulation model

The multiline configurations significantly reduce the number of anchors and associated costs, leading to substantial savings. The study demonstrated that multiline layouts enhance operational efficiency by improving turbine availability and reducing maintenance needs. Additionally, the findings are specific to the Morro Bay scenario and need validation in different environmental conditions to ensure broad applicability.

Applicability and adaptability of model findings

The findings from the multiline layout study are applicable to offshore wind farms, considering the adoption of multiline anchor systems. The demonstrated cost savings and operational benefits provide a compelling case for their implementation. However, further studies in different scenarios are necessary to confirm these benefits under varying conditions. That it has only been done once so far in the commercial floating wind farms, shows that companies see the potential of a multiline configuration.

Future enhancements and potential extensions of the simulation

Future research should explore integrating real-time data and advanced monitoring systems to better manage the complexities as well as have more accurate input data of multiline anchor systems. Additionally, expanding the simulation to include different environmental conditions (such as direction-based loading and failure due to metocean conditions) and longer operational lifetimes can provide deeper insights into the long-term benefits and challenges of multiline mooring configurations.

10.5. Case 4: Gulf of Maine study

Interpretation of simulation results

The Gulf of Maine study involved simulating the operational and maintenance strategies for a floating offshore wind farm with multiline anchor configurations. This case study extended the operational life to 30 years and included different metocean conditions and a greater distance to the port compared to the Morro Bay scenario from Case Study 3.

The results of the Gulf of Maine study demonstrated that multiline configurations continue to show superior performance compared to single-line configurations across several key metrics.

Advantages and limitations of the simulation model

The primary advantage of the simulation model used in the Gulf of Maine study is its ability to compare to case 3. The comparison was informative in continuing the conclusion of better cost-benefit results for multiline anchors. A limitation is that only two scenarios and case studies were compared. To further prove the benefit of multiline anchors, additional cases need to be run.

The extended operational life and different metocean conditions in the Gulf of Maine scenario also highlight the model's flexibility and applicability in diverse environments. Despite these advantages, the increased computational demands of the model may limit its use for preliminary studies or projects with limited resources.

Applicability and adaptability of model findings

The findings from the Gulf of Maine study are highly applicable to FOWFs considering the adoption of multiline anchor systems. The demonstrated operational and financial benefits provide strong evidence for their implementation in diverse marine environments. However, further validation in different scenarios and environments is necessary to ensure the broad applicability and reliability of the results.

Compared to Case Study 3, the Gulf of Maine study reinforces the benefits of multiline configurations under different environmental conditions. Despite the additional complexities introduced by the Gulf of Maine conditions, multiline configurations maintained their superior performance, highlighting their robustness and adaptability.

Future enhancements and potential extensions of the simulation

Future research should focus on further refining the simulation model to enhance its accuracy and reliability. This includes integrating real-time operational data and advanced monitoring systems to better manage the complexities of multiline anchor systems. Additionally, extending the simulation to include different environmental conditions and longer operational lifetimes can provide deeper insights into the long-term benefits and challenges of multiline mooring configurations.

Exploring the environmental sustainability and potential ecological impacts of multiline configurations should also be a priority. Understanding these aspects can support more informed decision-making and promote the broader adoption of multiline anchors in FOWFs.

10.6. Case 5: Sensitivity study

Interpretation of simulation results

The sensitivity analysis conducted provided critical insights into the impact of varying mooring line failure rates on the operational and financial performance of floating offshore wind farms. The results demonstrated that maintenance occurrences remained consistent within each failure rate source across both the In-Situ and Tow-to-Port strategies. This means that, for a given source, such as COREWIND, the number of maintenance events was similar or nearly identical regardless of whether the In-Situ or Tow-to-Port strategy was employed. This consistency indicates that the choice of mooring line failure impacts the number of maintenances and, thereby, the financial and operational implications in FOWFs.

Regarding availability and power production, higher failure rates led to reduced availability and lower power production. These effects were more pronounced in the In-Situ strategy, where the downtime was more significant. Financially, the analysis revealed that the In-Situ strategy typically resulted in higher operational expenditures, which led to a more negative net present value, especially when using conservative failure rates. The Tow-to-Port strategy provided slightly better financial predictability and improved availability, albeit with similarly negative NPVs across all scenarios.

Advantages and limitations of the simulation model
The model's ability to consistently reflect maintenance occurrences across different strategies adds credibility to its findings. However, there are also notable limitations, especially concerning the failure rates employed in the simulation. The accuracy and reliability of the results heavily depend on the validity of these failure rates, particularly those from COREWIND, which were a core component of the analysis in this and other case studies.

A major limitation is that the failure rate data may oversimplify certain assumptions, which may not fully reflect the real-world complexities of floating offshore wind farms and their mooring components. This sensitivity study showed that altering a single input can significantly impact the results. More data on FOWFs, especially their mooring components, is required for drawing definitive conclusions. While the simulation model offers valuable insights, its findings should be cautiously interpreted and validated against real-world data whenever possible.

Applicability and adaptability of model findings
The findings from this case study provide important insights into the real-world operation of offshore wind farms, particularly regarding how varying mooring line failure rates influence maintenance strategies and financial outcomes. The consistent maintenance occurrences across both In-Situ and Tow-to-Port strategies, dependent on the failure rate data source, indicate that the model's outcomes are reliable for understanding the financial and operational impacts of these strategies.

This case study highlights the critical role that accurate input values, such as mooring line failure rates, play in predicting operational expenditures and Net Present Value. The model demonstrates that selecting the correct failure rate data is crucial, as higher failure rates directly correlate with increased OpEx and more negative NPVs. These findings emphasize that the accuracy of input data significantly affects the reliability of the model's predictions and, consequently, the decision-making process for maintenance strategies.

The adaptability of the model to different operational scenarios, including varying failure rates and maintenance strategies, underscores its value as a decision-making tool in the offshore wind industry. By ensuring that the input data is accurate and reflective of real-world conditions, the model can be effectively applied to various wind farm projects, helping operators optimize their maintenance approaches and enhance the long-term economic sustainability of their investments.

Future enhancements and potential extensions of the simulation
The findings from this sensitivity study underscore the importance of accurate failure rate data in predicting the operational and financial performance of floating offshore wind farms. To enhance the reliability and applicability of the simulation model, several future enhancements and extensions could be considered.

Firstly, integrating more comprehensive and up-to-date failure rate data for floating offshore wind farms, particularly for mooring components, would significantly improve the accuracy of the model's predictions. Given that the study showed the substantial impact that varying mooring line failure rates can have on financial outcomes, collecting real-world data from existing FOWFs would help to validate and refine the model. This would also address the limitations related to potential oversimplifications in the current failure rate data.

Secondly, expanding the scope of the simulation to include a wider range of environmental conditions and stressors on mooring lines would provide a more robust analysis of how these factors influence maintenance needs and financial performance. Incorporating even more site-specific conditions, such as wave and wind directions and seabed characteristics, could lead to more tailored and accurate predictions for specific offshore wind farm locations. If this enhancement could play a factor in determining which component fails, it could simulate the real-world scenario more closely.

Another potential extension could involve the development of hybrid maintenance strategies that combine elements of both In-Situ and Tow-to-Port approaches. By simulating scenarios where maintenance strategies are dynamically adjusted based on real-time data or predictive analytics, the model could offer more flexible and optimized maintenance planning. This would allow for better balancing of operational costs and downtime, potentially leading to improved financial outcomes.

Finally, future research could explore the long-term implications of technological advancements in mooring systems and maintenance technologies. As the industry evolves, incorporating innovations such as advanced monitoring systems, automated maintenance technologies, or improved materials for mooring lines could significantly alter failure rates and maintenance strategies. By simulating these advancements, the model could provide insights into the future landscape of offshore wind farm operations.

Addressing these areas would enhance the simulation model's predictive accuracy and extend its applicability to a broader range of scenarios, making it an even more valuable tool for optimizing the operation, and maintenance of floating offshore wind farms.

11
Conclusion

11.1. Summary of Key Findings

This thesis explored the operation and maintenance dynamics of floating offshore wind farms equipped with multiline anchors, focusing on the cost-benefit analysis using the modified WOMBAT simulation tool. The research findings highlight several key insights that advance the understanding of multiline mooring systems in the context of FOWFs.

Multiline Anchors: Cost and Stability Benefits

The case studies reveal that multiline anchors can reduce operational expenditures and negative net present value in floating offshore wind projects. By using a single anchor to distribute the mooring loads of three turbines, multiline anchors reduce the number of required anchors, leading to lower O&M costs. The simulations indicate that multiline anchors contribute to a more stable mooring system, decreasing the frequency and cost of maintenance interventions.

Case Study 3: Multiline Layout Study

In Case Study 3, the cost-effectiveness and operational performance of multiline anchor systems were compared against single-line systems in the Morro Bay scenario. The results demonstrated that multiline systems consistently outperformed single-line configurations in terms of availability, power production, and OpEx. Multiline anchors led to fewer maintenance occurrences, enhanced turbine availability, and lower overall operational costs. The analysis concluded that multiline configurations offer superior financial and operational benefits, making them a viable option for floating wind farms.

Case Study 4: Gulf of Maine Study

The Gulf of Maine study (Case Study 4) extended the analysis of multiline anchor configurations by incorporating different environmental conditions, port distances, and an extended operational life of 30 years. The results confirmed the findings from the Morro Bay scenario, showing that multiline configurations maintained their superior performance even under more challenging conditions. Despite the increased distance to the port and the different metocean environment, multiline anchors continued to deliver better operational stability, higher availability, and improved financial performance compared to single-line configurations. This case study underscores the robustness of multiline systems across two diverse environmental scenarios.

Case Study 5: Sensitivity Study

Case Study 5 provided a sensitivity analysis focused on the impact of varying mooring line failure rates on the performance of FOWFs. The study validated the reliability of the simulation outcomes by showing that maintenance occurrences and financial outcomes were consistent across different failure rate assumptions. Although the failure rates influenced the number of maintenance events and overall operational costs, the fundamental benefits of multiline configurations remained intact. This study highlighted the importance of accurate input data, particularly in predicting operational expenditures and financial viability under different failure scenarios.

11.2. Contributions to the Offshore Wind Industry

This thesis contributes significantly to the offshore wind industry by providing a detailed evaluation of multiline mooring systems. The research offers an analysis of how multiline anchors can enhance the cost-effectiveness and reliability of FOWFs. The insights from the simulations and case studies provide a strong foundation for future developments.

The findings from case studies 3 and 4, in particular, highlight the potential of multiline anchors to transform the economics of floating offshore wind farms. By demonstrating their cost-effectiveness and stability across different environmental conditions, this research supports the broader adoption of multiline systems in the offshore wind industry.

11.3. Implications of the Research

The implications of this research extend beyond the immediate findings of cost reductions and improved maintenance efficiency. The successful implementation of multiline anchors in FOWFs could have far-reaching impacts on the renewable energy sector.

Economic Implications

The results from case studies 3 and 4 suggest that multiline anchors could help lower the levelized cost of energy for floating wind farms, making them more attractive to investors and policymakers. This could drive further investment in offshore wind, supporting the transition to a low-carbon energy future.

Environmental Implications

The use of multiline anchors can potentially reduce the seabed footprint of offshore wind farms, minimizing environmental impact. The results from case study 4, in particular, highlight the adaptability of multiline systems to various environmental conditions, which could lead to more sustainable offshore wind farm designs.

Strategic Deployment

The insights gained from Case Studies 3 and 4 imply that multiline systems could be strategically deployed in a wider range of environments, offering a reliable solution that balances cost and durability.

11.4. Limitations of the Study

While this research provides valuable insights, it is important to acknowledge its limitations. The study's reliance on simulations and modeled scenarios, while informative, may not capture all the complexities of real-world offshore wind farm operations. The assumptions made, particularly regarding failure rates and environmental conditions, could influence the generalizability of the findings.

Moreover, the focus on specific case studies, such as the Gulf of Maine and Morro Bay, means that the results may not be directly applicable to other offshore wind farm locations with different environmental and logistical challenges.

11.5. Recommendations for Further Research

Building on the findings of this thesis, several avenues for further research are recommended.

Empirical Validation

Empirical studies are needed to validate the simulation results and input values presented here. Field trials of multiline mooring systems in operational offshore wind farms would provide valuable data to corroborate the cost and performance benefits suggested by this research.

Advanced Monitoring and Materials

Future research could explore the integration of advanced materials and technologies into multiline mooring systems. For example, smart sensors and monitoring systems could enhance the reliability of these systems by providing real-time data on mooring line tension and anchor stability.

Comprehensive Environmental Assessment

A more comprehensive assessment of the environmental impacts of multiline anchors is needed. While this thesis has touched on the potential for reduced seabed disturbance, further studies could quantify these benefits and explore ways to minimize the ecological footprint of offshore wind farms.

Enhancing the WOMBAT Tool
There is significant potential to further develop the WOMBAT simulation tool to more accurately reflect real-world scenarios. Currently, the tow-to-port strategy is modeled as a reactionary, unscheduled response to failures. Future research could focus on developing this strategy into a planned, scheduled event where turbines are brought in for maintenance in a staggered manner. This would better simulate proactive maintenance strategies and could lead to improved cost management and operational efficiency.

Moreover, incorporating wind and wave direction into the simulation and making these factors influence which components need replacement would bring the model closer to real-world conditions. Such an enhancement would allow for more accurate predictions of maintenance needs and component wear, ultimately leading to more reliable operation and maintenance schedules for floating offshore wind farms.

11.6. Conclusion

In the simulated scenarios, multiline anchors have a cost-benefit advantage over single-line anchors for FOWF.

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A

Appendix

A.1. Input Parameters and Variables for the Simulation

This section outlines the various input parameters and variables used in the floating offshore wind farm simulation. The inputs are organized into the following categories: project, cables, substations, turbines, vessels, mooring, and weather data. It will be clearly indicated whether the inputs are consistent or if they are variable.

A.1.1. Project, Variable

The project library serves as the foundation for the simulation, containing essential configurations and plant and port data files. The configuration files exist twice, once with details of Morro Bay and one for the Gulf of Maine. The key project files hold the following:

1. **Array Configuration**: Specifies the array layout and configurations for the wind turbines, including the name, subassembly type, location, string number, and substation connection.
2. **Mooring Configuration**: Defines the parameters of the mooring configuration, detailing the name of the anchor, its location, its type (multiline or not), the turbines it connects to, and the mooring line names and types.
3. **Wind farm file**: A summary file that links all the input files for the wind farm simulation. For the tow-to-port scenario, the port input is added. This file includes:
    - Name windfarm
    - Weather file
    - List of the service vessels
    - The array wind farm layout file
    - The mooring layout file
    - The distance to port
    - The inflation rate
    - Workday start and end times
    - Start and end year
    - Project capacity [MW]
    - Port
4. **Port configuration**: This file contains the details of the port and the tugboats used for a tow-to-port scenario. It includes the name of the port, link to tugboat input files, the number of crews, the number of people per crew and their day rates, the maximum number of turbines possible in the port, and the annual port fee.

The project library provides all the necessary configuration files and links the various input files to create the model of the wind farms.

A.1.2. Vessels, Variable

Depending on the layout configuration, there is a set of vessel configuration files, each detailing the capabilities and operational limits of that vessel. The wind farm file specifies the type and number of each vessel assigned to the wind farm. Table A.1 shows the vessel list per layout configuration. The vessel support group is a stand-in for representing three anchor handling tugboats when it comes to repairing a multiline anchor.

Table A.1: Dependent on mooring layout, a list of the vessels assigned to them

Single-line layout	Multiline layout
Anchor Handling Vessels (AHV)	Anchor Handling Vessels
Cable Vessels (CAB)	Vessel Support Group (VSG)
Crew Transfer Vessels (CTV)	Cable Vessels
Diving Support Vessels (DSV)	Crew Transfer Vessels
Heavy Lift Vessels (HLV/LCN)	Diving Support Vessels
Tugboats (TUG)	Heavy Lift Vessels
	Tugboats

Each vessel configuration file includes critical specifications such as capacity, operational limits, and cost factors. Detailed parameters for each vessel type, including their equipment rate, capabilities, speed, strategies, and operational constraints, are provided in table A.2. These detailed specifications are essential for modeling the logistics, operational limits, and costs associated with the operation and maintenance of the wind farm. These operational limits are where the next section of weather ties is; the software reads this file to determine whether the vessel can operate or if it is on standby till a weather window opens up.

Table A.2: Parameters of the vessel inputs for WOMBAT

name	AHV	VSG	CAB	CTV 1-7	HLV 1	DSV	Tugboat 1,2
equipment_rate [USD]	66000	198000	75000	3500	290000	75000	30000
capability	AHV	VSG	CAB	CTV	LCN	DSV	['TOW']
speed [km/h]	24.08	24.08	25.93	37.04	20.37	29.63	37.04
strategy	requests	requests	requests	scheduled	requests	requests	requests
max_windspeed _transport [m/s]	20	20	99	16	10	99	99
max_windspeed _repair [m/s]	20	20	99	16	10	99	99
max_waveheight _transport [m]	2.5	2.5	2	2	2	2	2.5
max_waveheight _repair [m]	2.5	2.5	2	2	2	2	2.5
onsite	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE
mobilization_cost [USD]	530000	1590000	225000	0	325000	22500	N/A
mobilization_days	20	20	14	0	10	15	N/A
port_distance [km]	0	0	N/A	30	N/A	N/A	0
crew_transfer_time [h]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
n_crews	1	3	1	1	1	1	1
people's day rate [USD]	219.18	219.18	219.18	219.18	219.18	219.18	219.18
n_people per crew	10	10	10	3	5	10	5

A.1.3. Weather data, Variable

The CSV weather file contains hourly wind speed and wave height data for the duration of the wind farm's lifespan as modeled in the simulation. This data is used, as mentioned, for the vessel limits but also for calculating the power production of the wind turbines. The power production is based on the power curve from the 2020 ATB NREL reference model, which assumes a turbine capacity of 15 MW and a rotor diameter of 240 meters. The key parameters, tabular data, and power curve details are in Appendix B.1. The weather data serves as a fundamental input for the simulation runs, as is shown in Figure 3.2 in section 3.1.3. The simulation process relies on this data to run as the underlying timeline for the simulation. As specified in section 4.2Morro Bay has its own weather data, as does Gulf of Maine.

A.1.4. Failure and maintenance inputs

This section outlines the failure and maintenance inputs, detailing each component type separately. These inputs are used for all the case studies. The only variable inputs are the turbine and the mooring; the cables and substation stay the same no matter the scenario or case study. These inputs for failure include failure rates, costs, operation reduction, replacement, time for repair/replacement, and the needed service equipment. For maintenance, the inputs are the time for repair, material costs, frequency of occurrence, and the needed service equipment. The tables A.3 & A.4 give a description for each type of parameter. The detailed tables for each component type provide specific values necessary for the simulations. All of these values come from the COREWIND report D4.2 Floating Wind O&M Strategies Assessment [46].

Table A.3: Description of failure input parameters

Parameter Failure	Description
Description	Type of failure category
level	The severity of the failure, for failure repairs based on severity
materials	The cost of materials
operation reduction	Operation reduction, either [0,1]
replacement	Whether component needs to be replaced
scale	Scale of Weibull distribution
shape	Shape of Weibull distribution
time [hours]	Duration of repair time
service equipment	The service equipment assigned to this failure

Table A.4: Description of maintenance input parameters

Parameter Maintenance	Description
Description	The specific maintenance occuring
time [hours]	Duration for maintenance to occur
materials	The cost of materials
service equipment	The service equipment assigned to this maintenance
frequency	number of days till next occurance
level	The severity of the maintenance

A.1.4.1 Cables, consistent

The cable components include array and export cables, each with specific failure rates and maintenance inputs necessary for the simulations. An array cable is between turbines, while the export cable goes in between the substations and the mainland. Failure inputs are in table A.5 and maintenance inputs are table A.6.

Table A.5: Failure parameters for cable

Parameter Failure	Array Cable		Export Cable
Description	major repair	replacement	major repair
level	4	6	4
materials	30000	220000	30000
operation reduction	0	0	0
replacement	FALSE	TRUE	FALSE
scale	40	62.5	50
shape	1	1	1
time [hours]	240	360	60
service equipment	['CAB']	['CAB']	['CAB']

Table A.6: Maintenance parameters for cable

Parameter Maintenance	Array Cable	Export Cable
Description	n/a	subsea inspection
time [hours]	0	12
materials	0	500
service equipment	CTV	DSV
frequency	0	730
level	n/a	1

A.1.4.2 Substations, consistent

For failure with the substation, there is only a single and major repair as there is no record of a substation being replaced (table A.7). There is only a single maintenance parameter (table A.8), simplifying the simulation inputs for this component.

Table A.7: Failure parameters for substations

Parameter Failure	Substation	
Description	minor repair	major repair
level	2	4
materials	2000	220000
operation reduction	0	0
replacement	FALSE	FALSE
scale	5	100
shape	1	1
time [days]	12	60
service equipment	CTV	CTV

Table A.8: Maintenance parameters for substations

Parameter Maintenance	Substation
Description	annual inspection
time [hours]	24
materials	500
service equipment	CTV
frequency [days]	365
level	1

A.1.4.3 Turbines, variable

The turbine, due to its many components, has a large number of failure parameters seen in table A.10. For the tow-to-port condition for turbines, any LCN in the column service equipment becomes TOW for the tugboats. When tow-to-port is being modeled, there is a single different input parameter; all other components are carbon copies. Maintenance is broken into two parts: the turbine itself and the support structure (table A.9); in the support structure, mooring components are not included. Only in case 2, where the original WOMBAT software is compared to the modified version, is mooring still part of the turbine, but this is elaborated upon in chapter 6.

Table A.9: Maintenance parameters for turbines

Parameter Maintenance	**Turbine**	**Supporting Structure**	
Description	annual inspection	annual inspection	subsea inspection
time [hours]	24	24	12
materials	1500	600	500
service equipment	CTV	CTV	DSV
frequency [days]	365	365	730
level	N/A	N/A	N/A

Table A.10: Failure parameters for wind turbines

Parameter Failure Wind Turbine	Component	Description	Level	Materials [USD]	Operation Reduction	Replacement	Scale	Shape	Time [hours]	Service Equipment
Electrical System	Power Converter	Minor Repair	1	1000	0	FALSE	1.859	1	14	CTV
		Major Repair	3	7000	0	FALSE	2.959	1	28	LCN
		Replacement	5	55000	0	TRUE	12.99	1	170	LCN
	Power Electrical System	Minor Repair	2	1000	0	FALSE	2.793	1	10	CTV
		Major Repair	4	220000	0	FALSE	62.5	1	60	LCN
		Replacement	6	50000	0	TRUE	500	1	54	LCN
Hydraulic System	Pitch System	Minor Repair	1	500	0	FALSE	1.214	1	18	CTV
		Major Repair	3	1900	0	FALSE	5.587	1	38	CTV
		Replacement	5	14000	0	TRUE	1000	1	75	LCN
	Ballast Pump	Minor Repair	2	1000	0	FALSE	100	1	8	CTV
Yaw System	Yaw System	Minor Repair	1	500	0	FALSE	6.173	1	10	CTV
		Major Repair	3	3000	0	FALSE	166.7	1	40	LCN
		Replacement	5	12500	0	TRUE	1000	1	147	LCN
Rotor Blades	Blades	Minor Repair	2	6000	0	FALSE	2.193	1	18	CTV
		Major Repair	4	51732	0	FALSE	100	1	42	LCN
		Replacement	6	534000	0	TRUE	1000	1	864	LCN
Generator	Direct Drive Generator	Minor Repair	2	1000	0	FALSE	1.832	1	13	CTV
		Major Repair	4	14340	0	FALSE	33.333	1	49	LCN
		Replacement	6	236500	0	TRUE	111.1111	1	244	LCN
Supporting Structure	Marine Growth Removal	Minor Repair	1	1500	0	FALSE	8.33	1	40	CTV
	Buoyancy model	Replacement	6	100000	0	TRUE	30.3	1	40	CTV
Drive Train	Main Shaft	Minor Repair	2	1000	0	FALSE	4.329	1	10	CTV
		Major Repair	4	14000	0	FALSE	38.462	1	36	LCN
		Replacement	6	232000	0	TRUE	111.111	1	144	LCN

A.1.4.4 Mooring, variable

These failures and maintenance inputs were originally part of the turbine section. Since they have been split off, some overlapping inputs related to the support structure, which also applies to mooring components, have been kept under the turbine inputs. This is marine growth removal in failure and in maintenance the subsea inspection. No other maintenance is described as necessary for mooring; therefore, there are no maintenance inputs. For clarification, COREWIND has modeled the failure rate of mooring lines and anchors as one whole system with a single value. Since the modified software model has 'split' the mooring configuration into different types and into three individual mooring lines and three anchors, the failure rate was divided by 3 with the help of formula 3.3. Additionally the times for repair and the cost has also been divided by three. The anchor and mooring lines have been split into the following types: single, shared, and substation. Thereby the appropriate service equipment can be sent to the correct anchor or mooring line type. Depending on the case it will be made clear in that chapter if the tables below are used or changed inputs are implemented.

Table A.11: Failure parameters for anchors

Parameter Failure Anchor	**Single Anchor**		**Shared Anchor**		**Substation Anchor**	
Description	major repair	replacement	major repair	replacement	major repair	replacement
level	2	4	2	4	2	4
materials	25000	170666.67	25000	170666.67	25000	170666.67
operation reduction	0	0	0	0	0	0
replacement	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
scale	200	240	200	240	200	240
shape	1	1	1	1	1	1
time [hours]	80	120	80	120	80	120
service equipment	AHV	AHV	VSG	VSG	AHV	AHV

Table A.12: Failure parameters for mooring lines

Parameter Failure Mooring line	**Single Anchor Mooring line**		**Shared Anchor Mooring line**		**Substation Anchor Mooring line**	
Description	major repair	replacement	major repair	replacement	major repair	replacement
level	3	5	3	5	3	5
materials	6666.67	45000	6666.67	45000	6666.67	45000
operation reduction	0	0	0	0	0	0
replacement	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
scale	200	240	200	240	200	240
shape	1	1	1	1	1	1
time [hours]	80	120	80	120	80	120
service equipment	AHV	AHV	VSG	VSG	AHV	AHV

B

Appendix

B.1. 2020 ATB Reference NREL 15 MW 240D

Table B.1: Key Parameters of 2020 ATB NREL Reference 15MW 240D

Item	Value	Units
Name	2020 ATB Reference 15	N/A
Rated Power	15000	kW
Rated Wind Speed	11	m/s
Cut-in Wind Speed	4	m/s
Cut-out Wind Speed	25	m/s
Rotor Diameter	240	m
Hub Height	150	m
Drivetrain	Direct Drive	N/A
Control	Pitch Regulated	N/A
IEC Class		N/A

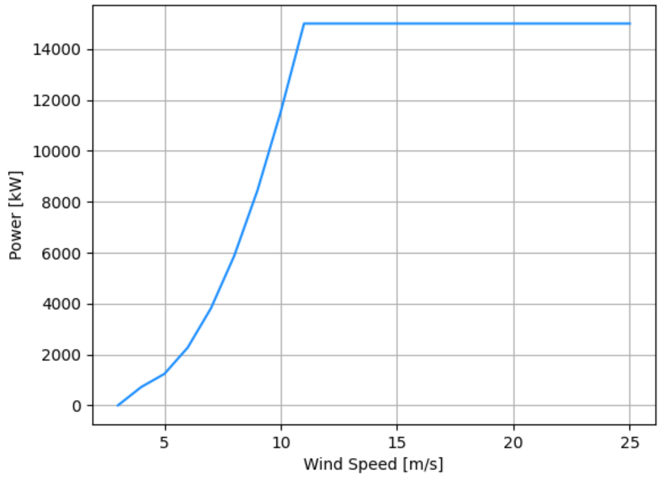

Figure B.1: Power curve of 2020 ATB NREL Reference 15MW 240D

Table B.2: Tabular data of 2020 ATB NREL Reference 15MW 240D

windspeed [m/s]	power [kw]
0	0
1	0
2	0
3	0
4	720
5	1239
6	2271
7	3817
8	5876
9	8450
10	11536
11	15000
12	15000
13	15000
14	15000
15	15000
16	15000
17	15000
18	15000
19	15000
20	15000
21	15000
22	15000
23	15000
24	15000
25	15000
26	0

C
Appendix

C.1. Python code for mooring logic

```python
        def stop_all_mooring_processes(self, failure: Failure | Maintenance) -> None:
        """Stops all turbines from producing power by creating an event for each system.
            mooring_failure and handles both direct and indirect impacts based on shared
            mooring connections."""
        logging_context = {
            "agent": self.mooring_id,
            "request_id": failure.request_id   #"some_unique_identifier",
        }

        # Log the start of the process
        self.env.log_action(
            system_id=self.mooring_id,
            system_name="Mooring System",
            action="Process Stop Initiated",
            reason="Connectivity failure triggered",
            additional="Starting shutdown of all connected systems",
            **logging_context
        )


        # Function to safely interrupt processes within subassemblies
        def safe_interrupt(system):
            for subassembly in system.subassemblies:
                for process in subassembly.processes.values():
                    if not process.triggered:  # Check if the process has not been triggered
                        try:
                            process.interrupt(cause="mooring failure")
                        except RuntimeError as e:
                            self.env.log_action(
                                system_id=system.id,
                                system_name=system.name,
                                action="Interrupt Failed",
                                reason=str(e),
                                **logging_context
                            )

        # Directly affected systems
        directly_affected_systems = set()
        for system_id in self.connected_systems:
            if self.windfarm.is_anchor(system_id):
               # Skip any shutdown logic for anchors since they don't influence power
                   production
               continue
            else:
                system = self.windfarm.system(system_id)
                if system.system_type == "turbine" or system.system_type == "substation":
                    system.mooring_failure = self.env.event()
```

```
                    safe_interrupt(system)
                    #system.interrupt_all_subassembly_processes()
                    directly_affected_systems.add(system_id)
                    self.env.log_action(
                        system_id=system_id,
                        system_name=system.name,
                        action="Direct Impact - Failure Triggered",
                        reason="Directly connected to failed mooring",
                        system_ol=0,
                        part_ol=np.nan,
                        **logging_context
                    )

       # Indirectly affected systems due to shared mooring connections
        indirectly_affected_systems = set()
        all_checked_systems = set(directly_affected_systems)  # Keep track of all checked systems
        anchors_to_check = set()

        # First, gather all anchors connected to directly affected systems
        for system_id in directly_affected_systems:
            anchors_to_check.update(self.windfarm.mooring_map.get_anchor_connections(system_id))

        # Now gather all systems connected to these anchors
        for anchor_id in anchors_to_check:
            connected_systems = self.windfarm.mooring_map.get_connected_turbines(anchor_id) + self.windfarm.mooring_map.get_connected_substations(anchor_id)
            for connected_system_id in connected_systems:
                if connected_system_id not in directly_affected_systems:
                    indirectly_affected_systems.add(connected_system_id)
                    all_checked_systems.add(connected_system_id)

        for system_id in indirectly_affected_systems:
            if self.windfarm.is_anchor(system_id):
                continue
            else:
                system = self.windfarm.system(system_id)
                if system.system_type == "turbine" or system.system_type == "substation":
                    system.mooring_failure= self.env.event()
                    safe_interrupt(system)
                    # system.interrupt_all_subassembly_processes()
                    self.env.log_action(
                        system_id=system_id,
                        system_name=system.name,
                        action="Indirect Impact - Failure Triggered",
                        reason="Affected by shared mooring connectivity",
                        system_ol=0,
                        part_ol=np.nan,
                        **logging_context
                    )

        # Log the completion of the process
        self.env.log_action(
            system_id="N/A",
            system_name="Global Mooring System",
            action="Process Stop Completed",
            reason="All relevant systems have been processed",
            additional="Shutdown complete",
            **logging_context
        )
```

D

Appendix

D.1. Convergence Study

D.1.1. Random sampling runs

Table D.1: Random sampling of runs by an interval of two

# Runs	Selected Runs
2	50, 19
4	22, 43, 25, 41
6	42, 7, 10, 19, 33, 43
8	16, 42, 37, 12, 36, 29, 40, 4
10	36, 21, 33, 2, 7, 29, 1, 15, 48, 20
12	3, 17, 43, 37, 9, 44, 19, 26, 5, 46, 25, 30
14	3, 21, 28, 47, 43, 40, 26, 23, 34, 49, 46, 17, 44, 7
16	27, 7, 22, 9, 46, 21, 28, 17, 5, 13, 8, 18, 41, 20, 32, 38
18	41, 44, 26, 47, 7, 35, 23, 1, 37, 34, 21, 39, 45, 33, 27, 49, 8, 2
20	30, 10, 21, 38, 32, 27, 3, 43, 26, 6, 20, 19, 37, 47, 14, 5, 18, 25, 24, 7
22	17, 1, 36, 2, 13, 21, 32, 8, 43, 35, 33, 46, 20, 14, 29, 41, 4, 23, 24, 12, 42, 47
24	34, 47, 2, 35, 17, 46, 18, 3, 23, 28, 11, 33, 30, 25, 39, 36, 20, 44, 16, 31, 22, 4, 48, 7
26	30, 24, 7, 39, 46, 3, 17, 22, 18, 13, 25, 38, 36, 11, 10, 44, 35, 48, 42, 9, 4, 1, 32, 27, 41, 29
28	3, 1, 30, 50, 45, 17, 43, 31, 12, 48, 40, 10, 23, 46, 29, 38, 19, 39, 20, 37, 36, 2, 21, 6, 44, 25, 4, 16
30	28, 21, 45, 47, 23, 27, 30, 33, 39, 44, 34, 25, 8, 22, 26, 46, 20, 37, 13, 7, 10, 42, 17, 11, 36, 35, 49, 9, 18, 14
32	32, 26, 22, 42, 23, 45, 9, 27, 39, 16, 36, 2, 19, 35, 38, 40, 31, 33, 8, 18, 49, 29, 48, 37, 11, 50, 41, 24, 20, 17, 7, 15
34	45, 25, 46, 28, 16, 37, 10, 23, 20, 49, 47, 32, 1, 9, 2, 24, 11, 26, 27, 34, 6, 17, 15, 40, 50, 12, 33, 30, 38, 36, 44, 14, 48, 18

36	27, 23, 46, 18, 49, 11, 30, 48, 15, 20, 13, 19, 35, 16, 9, 42, 33, 44, 21, 10, 50, 14, 38, 32, 2, 47, 22, 25, 37, 29, 8, 31, 40, 43, 41, 1
38	20, 49, 3, 33, 8, 12, 14, 18, 26, 19, 23, 22, 40, 9, 39, 46, 17, 36, 24, 6, 41, 7, 11, 21, 30, 37, 34, 16, 4, 47, 44, 50, 42, 15, 25, 43, 29, 1
40	25, 37, 31, 17, 23, 45, 41, 21, 1, 14, 30, 4, 2, 32, 33, 11, 50, 12, 13, 46, 6, 44, 15, 40, 38, 28, 48, 34, 36, 47, 19, 24, 49, 8, 5, 26, 20, 18, 29, 39
42	24, 40, 4, 49, 18, 6, 37, 15, 10, 32, 46, 26, 35, 3, 19, 25, 16, 50, 12, 36, 30, 44, 9, 21, 22, 7, 5, 34, 31, 11, 33, 47, 28, 42, 14, 39, 48, 2, 29, 1, 27, 17
44	38, 50, 21, 17, 33, 45, 4, 19, 18, 20, 2, 25, 42, 48, 29, 16, 30, 3, 10, 46, 5, 11, 12, 49, 15, 1, 47, 23, 27, 9, 34, 14, 22, 8, 36, 31, 43, 39, 26, 28, 35, 37, 24, 40
46	26, 44, 12, 33, 23, 29, 45, 32, 11, 35, 39, 2, 30, 4, 14, 24, 1, 17, 16, 5, 49, 34, 3, 40, 20, 50, 42, 15, 46, 41, 28, 18, 10, 22, 21, 36, 27, 37, 13, 47, 19, 9, 48, 7, 43, 25
48	19, 21, 47, 22, 27, 5, 32, 8, 20, 6, 29, 25, 45, 15, 42, 37, 9, 2, 44, 38, 35, 30, 24, 10, 18, 1, 43, 23, 46, 39, 16, 31, 49, 26, 3, 14, 13, 7, 4, 50, 34, 48, 36, 33, 41, 17, 12, 11
50	44, 39, 22, 8, 30, 38, 7, 9, 40, 24, 42, 28, 37, 3, 12, 45, 17, 36, 6, 47, 14, 27, 35, 33, 13, 10, 2, 23, 20, 1, 48, 50, 4, 29, 11, 32, 18, 5, 49, 15, 41, 16, 34, 43, 26, 25, 46, 19, 21, 31

E

Appendix

E.1. Operation and Maintenance Strategies

WOMBAT offers several operational and maintenance strategies that can be chosen or implemented in the model. These strategies enable users to tailor the maintenance and operational procedures to the specific needs and constraints of their wind farms, optimizing the balance between maintenance costs, downtime, and overall operational efficiency. WOMBAT's flexibility allows for modeling a wide range of scenarios and adapting to new technologies and methodologies as they are developed.

Effective operation and maintenance strategies are crucial for the sustainability and efficiency of wind farms. WOMBAT provides a suite of strategies designed to address the unique challenges of maintaining offshore wind farms. This section details these strategies, explaining their configurations, use cases, and the specific benefits they offer.

E.1.1. Scheduled In Situ Maintenance

- Description: This strategy involves pre-planned visits for maintenance and repairs at predetermined intervals.
- Configuration: Users provide a schedule specifying the start and end dates for each visit over the simulation period.
- Use Case: Useful for equipment like Crew Transfer Vessels (CTVs) that stay on-site for extended periods.
- Advantages: Ensures regular maintenance, reducing the likelihood of unexpected failures.
- Limitations: May result in unnecessary maintenance if the equipment is in good condition.

E.1.2. Request-Based In Situ Repairs

- Description: Service equipment is mobilized based on the accumulation of a specified number of repair requests.
- Configuration: A threshold for the number of repair requests is set, and once this threshold is met, the service equipment is dispatched.
- Use Case: Suitable for managing less frequent but necessary repairs to maintain operational efficiency.
- Advantages: Targets repairs based on actual needs, potentially reducing unnecessary maintenance trips.
- Limitations: May lead to higher downtime if repair requests accumulate slowly.

E.1.3. Downtime-Based In Situ Repairs

- Description: Mobilization of service equipment occurs when the total downtime exceeds a set threshold.

- Configuration: A downtime threshold is defined, triggering the deployment of service equipment when met.
- Use Case: Effective for minimizing the operational downtime impact by addressing issues promptly when downtime accumulates.
- Advantages: Helps in maintaining operational efficiency by addressing downtime proactively.
- Limitations: Requires precise downtime tracking and may lead to frequent repairs if thresholds are set too low.

E.1.4. Unscheduled Tow-to-Port Repairs

- Description: This strategy involves transporting the equipment to port for repairs, typically used for major repairs that cannot be performed on-site.
- Configuration: Triggered by a repair request threshold, similar to the request-based strategy, but specifically for offshore scenarios.
- Use Case: Essential for offshore wind farms where certain repairs require specialized port facilities.
- Advantages: Allows for comprehensive repairs that are not feasible offshore, ensuring equipment is thoroughly maintained.
- Limitations: High logistical costs and extended downtime due to transportation.