Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Trygve Thomas Aamodt

Gone With the Wind?
Offshore Wind Data Management in the North Sea

Feasibility study of a database recording operational data from multiple offshore wind operators in the North Sea

Master's thesis in Reliability, Availability, Maintainability and Safety
Supervisor: Jørn Vatn
Co-supervisor: Wanwan Zhang
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RAMS
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Preface

This is a master thesis in RAMS at NTNU as part of the study program Engineering and ICT. The thesis was carried out during the autumn semester 2021 and January 2022. The thesis has been carried out as part of the FME Northwind research project (Norwegian Research Centre on Wind Energy), and is intended as a feasibility study looking at establishing an operational database for all offshore wind operators in the Norwegian exclusive economic zone. The idea for the thesis came to life after the realizing the difficulty of accessing relevant data from existing wind farms. Consequently, this thesis is meant to be an encouragement of cooperation for the industrial partners at FME Northwind. Hopefully describing a foundation of data that could produce interesting research for years.

The intended readers are industrial and scientific members of FME Northwind, as well as interested parties. The thesis is not meant to be overly technical.

Oslo, 2022-01-20

Trygve Aamodt

Trygve Thomas Aamodt

Acknowledgment

I would like to thank Jørn Vatn for being my supervisor and guiding me to help find a meaningful subject to explore. Having periodic supervisions was helpful. Additionally I would like to thank Viggo Gabriel Borg Pedersen at NTNU for also contributing his time to discuss the thesis. I would also like to thank my partner Marte, for standing with me through both hard and easy times that naturally occur during a master thesis. Lastly I would like to thank my parents for their support, and especially my father Geir who helped me greatly during the last days ensuring the thesis came out in one piece.

T.T.A.

Executive Summary

Offshore wind is seen as a viable solution for renewable energy production at large scale. The Norwegian exclusive economic zone is an area well suited due for floating and bottom-fixed turbines, having favorable weather, demand and industrial competence. FME Northwind is a Norwegian research project aiming to make offshore wind profitable, looking at multiple engineering disciplines. Among them RAMS(Reliability, Availability, Maintainability and Safety). This thesis is looking at the possibility of FME Northwind establishing a common database for all industrial partners in the project. In order to better understand the true cost of operating a offshore turbine, and to hopefully find patterns in sensor data correlating with degradation over time. Similar projects are explored, as well as research discussing data management practices. Additionally, research proposing analytic methods for utilizing data is reviewed. Lastly, data storage and management is considered. Generally there are no technological limitations, but rather a lack of standard regarding data collecting practices that is not in place. A similar standard exist in the oil and gas sector ISO 14 224, and many point to it as a source of inspiration. The concept of a database should be implemented, and is more or less a given in the age of digital twins. However, ensuring research partners access is essential to fully utilize the data.

Contents

Chapter 1

Introduction

1.1 Background

The need for renewable energy sources that operate on scale can hardly be needed to justified anymore. Although Norway already has a close to renewable electricity production due to its favorable terrain and precipitation, providing excellent conditions for hydro power. The European grid is still powered by a majority of fossil foul sources according to the International Energy Agency **IEA** (IEA, n.d.) as of 2019. Consequently, Norway finds itself at an opportune moment, with a large windy coast, marine competence from the oil and gas sector and significant future demand for renewable energy from the European continent. This also coincides with the European Commission's ambition of a 15% interconnection instantaneous capacity between member states by 2030 (European Commission, 2016), which means that a country must be able to export up to 15% of their total production. The rational behind this goal is to better utilize renewable energy sources, because their peak production rarely occur simultaneously as peak demand. Thus underpinning the energy transition needed to take place in order to reach emissions goals. Examples would be countries in the Mediterranean exporting solar, British isles wind, and Norway offshore wind as well as hydro during low power generation. As stated by (Soares-Ramos et al., 2020) installed capacity have increased significantly over the last 20 years as seen in figure 1.1, and the European Commission aims at reaching around 100 GW of offshore wind capacity by 2030. Yet, data for the actual O&M costs of commissioned projects is not readily available (Irena, 2018). Where it is, care must be taken in extrapolating from historical O&M costs, as significant changes in wind turbine technology over the last decade must be taken into consideration. There is a need for research and innovation in order to meet said goals.

FME Northwind (Norwegian Research Centre on Wind Energy) is a research collaboration between universities and companies in Norwegian power industry. According to their website the main goal is to "bring forward outstanding research and innovation to reduce the cost of wind power and facilitate its sustainable development, which will grow exports and create new jobs." (FME Northwind, n.d.*a*). The research and industry partners of FME Northwind can be seen in figure 1.2 and 1.3, respectively. The research is divided into five work packages, where some packages overlap somewhat in terms of research scope. The work packages focus on operations (WP2) and asset management (WP4) (FME Northwind, n.d.*b*). Both areas of research share the underlying need for a digital twin or large data collection capabilities.

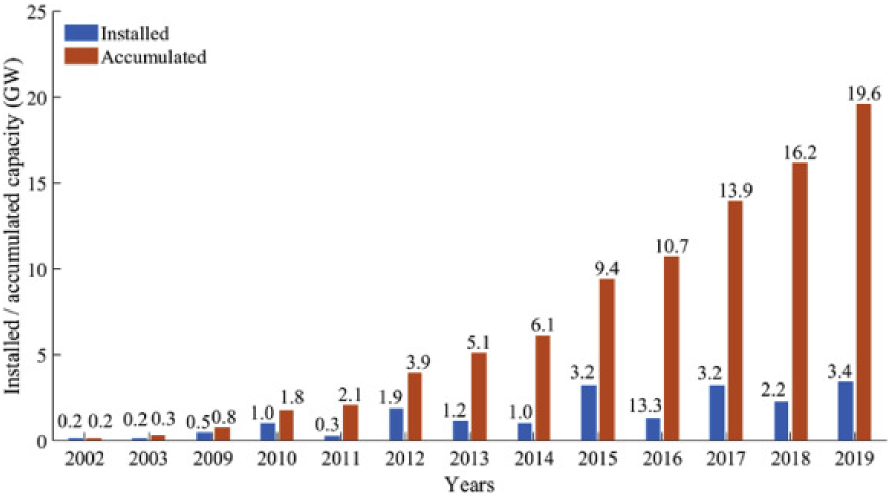


Figure 1.1: Yearly installed and accumulated capacity of large-scale European offshore wind farms (Soares-Ramos et al., 2020).

Digital twins, as stated by (Trauer et al., 2020) is an evolving concept, yet there are no one formal definition. Trauer and his coworkers identified three characteristics that is present is most cases: representation of a physical system, bidirectional data exchange and connection along entire lifeline. In order to facilitate cost reduction research for offshore wind, data is needed in order to achieve an understanding of true lifetime costs related to offshore windmills. Especially considering the first deep sea wind farm opened as recently as 2017 (The Engineer, 2017), and arguably the true cost is so far unknown.

If Norway is to remain an energy nation and be competitive in the growing offshore wind market there are several technologies that must be studied, understood and optimized. Most if not all are stated by FME Northwind research objectives (FME Northwind, n.d.*b*). Availability of excellent, updated and relevant data is crucial to create positive feedback loops: where research reduce costs, incentivising more installed capacity, meaning more data generation and analysis which again fuels the research for cost and operations optimizing. A visual representation is show at 1.4. Exactly this is one of the aims of Northwind, and this thesis will focus on the data collection part seen in 1.4.

Research Partners

SINTEF
CENTRE HOST
NTNU
NGI
UiO
NINA

Figure 1.2: FME Northwind Research Partners

Industry Partners

ABB
AKER OFFSHORE WIND
AMON WIND
aibel
Baker Hughes
COGNITE
DNV

DR. TECHN. OLAV OLSEN ARTELIA GROUP
DOF Subsea
EDR MEDESO
EIDEL EIDSVOLL ELECTRONICS AS
NOR
Norsk olje&gass
Energi Norge

ENERGY INNOVATION
equinor
ESVAGT
Finnmark Kraft
FORCE TECHNOLOGY
Fred. Olsen Renewables
FUGRO

GFMS
Hafslund Eco
HAVdesign
Huisman
impello
KONGSBERG
Lloyd's Register

4subsea
TotalEnergies
Nexans
NKT
NOV
Norwegian Energy Partners
Norconsult

NorSea
OFFSHOREWIND
Odfjell Oceanwind
RENERGY
SFE
Statkraft
STORE NORSKE

SUSTAINABLE ENERGY
NORWEGIAN CATAPULT CENTRE
Sval
TrønderEnergi
VARD a Fincantieri company
windcluster NORWAY

Figure 1.3: FME Northwind Industry Partners

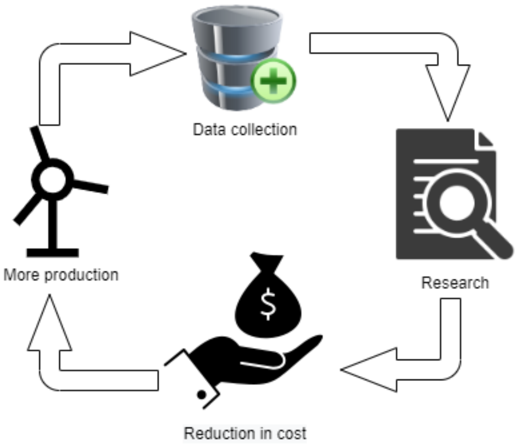


Figure 1.4: Proposal of feedback loop where research drives down cost of offshore wind.

This thesis will examine the potential of a database that records factors such as but not limited to: operational and environmental status, individual turbine sensor data and maintenance logs to name a few. I will ask three research questions and use literature to look for similar work and research into offshore wind turbine operations and maintenance **(O&M)**.

1.2 Research Questions

To examine the possibility of a database consisting of data collected from turbines in Norwegian waters, three questions are posed in an effort to explore and learn. Each question covers a different topic, believed to be the most relevant for readers concerned with the research possibilities enabled by this project. They are the following:

- What similar research has been done and are there equivalent projects?
- What ways are data used to benefit O&M for offshore wind?
- What solutions can be used to implement a research database?

1.3 Limitations

This thesis has a scientific perspective similar to a scoping review to get an overview of practices related to storing operations data for offshore wind turbines, what that data can be used to analyze and in what way can it be stored. The thesis is not intended to be technical related to either wind turbine technology or condition monitoring. Instead opting to examine papers discussing state-of-the-art technology relating to especially the condition monitoring field. Another limitation was the fact that most databases discussed in this paper are privately owned and operated. Consequently, it was difficult to write extensively about said databases without insight and experience. Thus, instead the thesis is designed to be superficial, and to shed light on certain problems and solutions. And to make the reader gain an understanding of where to seek more relevant information, and which parties that likely have most relevant experience in the field.

1.4 Thesis Structure

This thesis is divided into five chapters, with chapters 2, 3 and 4 dedicated to answering the posed research questions. Each chapters consists of sections exploring a topic related to the field within the chapter. Chapter 5 discusses and summarizes the findings from the previous chapters.

Chapter 2

Related Work

There exists more research than what is presented in this chapter. Nevertheless, I have selected topics which I believe is most relevant for the FME Northwind project and the Norwegian industry. Two different types of works will be discussed:

- Related research
- Existing databases

2.1 Related Research

There have been efforts to define a RAM(Reliability, Availability, Maintainability) database for offshore wind for years. That is, a database that records operational status including downtime and maintenance work for individual turbines on a wind farm. Hameed et al. looked at challenges regarding data collection for offshore wind in 2011 (Hameed et al., 2011). The authors arrived at, then as now, there is a need for a standardized RAM database in the industry, and the OREDA project, examined in section 2.2, was held up as the gold standard. The paper proposed an architecture and methods for analysis. Regarding the project as technologically feasible.

As the wind power industry matured, there has been a formalization in exploring the possibilities of a database. IEA Wind Task 33 was an expert working group with a focus on data collection and reliability assessment for O&M optimization of wind turbines. Their work lasted between 2012 and 2016, and their paper summarizes the key findings and recommendations (Hahn et al., 2017). In their report they concluded there is a high demand for better utilizing operational experience in order to optimize O&M, they also acknowledged that the same data could help optimize wind turbine design and risk management. Another point they made was no international standard exist on what data to collect and how to use it, unlike ISO 14 224, a standard for collection and exchange of reliability and maintenance data for equipment in the oil and gas sector developed by OREDA. In their report, the authors asked three questions. With a great deal of overlap to this thesis.

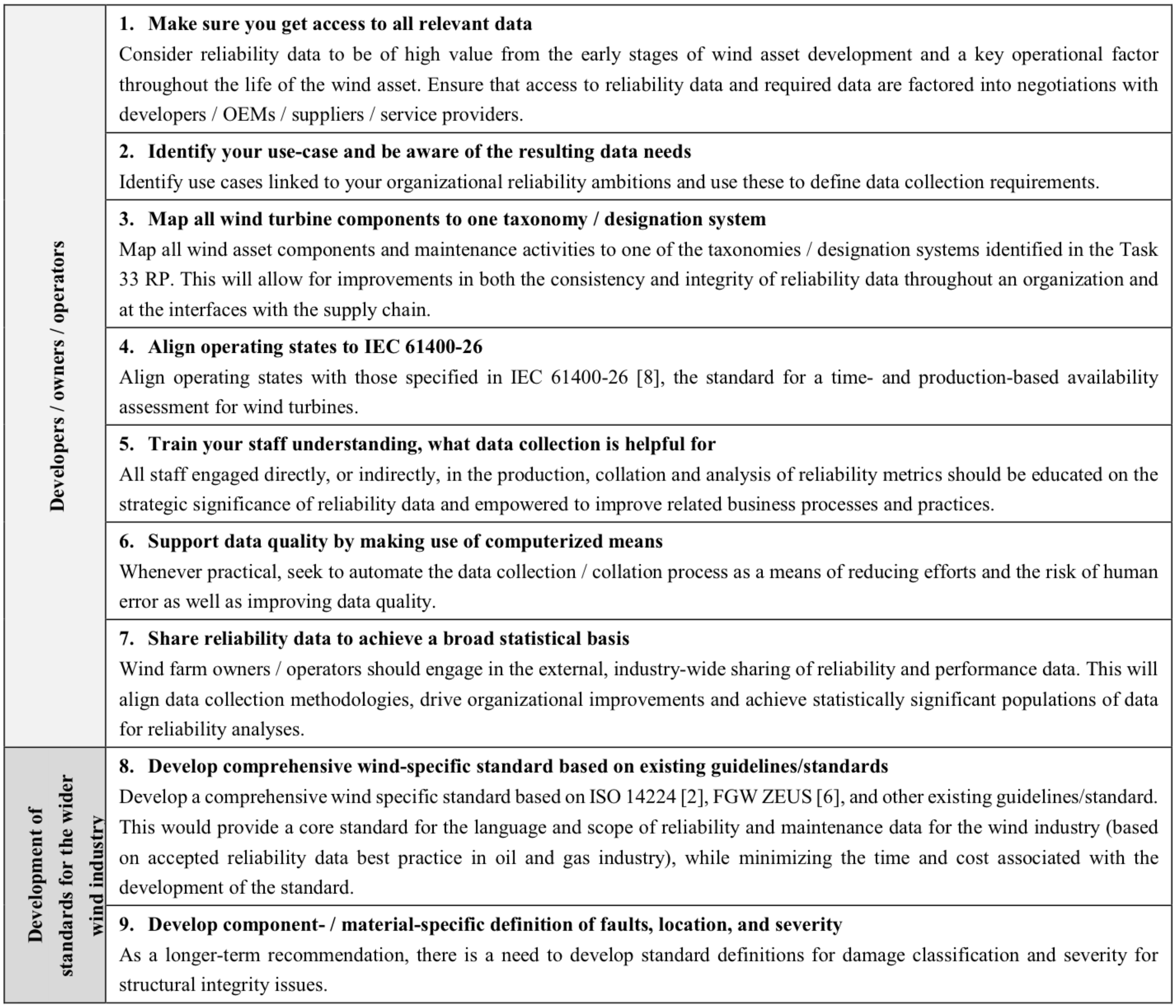
- Which information do operators and other stakeholders need?
- What analyses can provide the requested information?
- Which data has to get recorded to feed these analyses?

They summarized their finding into nine recommendations as seen in table 2.1. All the recommendation are useful and valuable to keep in mind as one considers the issue. Although, one could argue that the most meaningful recommendation is that of a ISO standard, like that of the oil and gas industry.

Similar work was done in a PhD thesis by (Koltsidopoulos Papatzimos, 2020), the author claimed that neither academia nor industry had addressed the lack of data management in the offshore wind industry. The doctoral thesis discussed tools and methodologies to make offshore wind operations more data driven. Among the claims, similar to (Hahn et al., 2017), the author says the industry generates large quantities of data that are rarely utilized by the operators. Moreover, the thesis also argued for a open environment in terms of data sharing in the offshore wind industry. As well as encouraging collaboration between operators, claiming potential for a win-win situation not a loss of competitive advantage.

In the literature review, a common feature is usually to look at ways data from wind turbines can be used to lower O&M costs. That offshore wind is growing rapidly, there is a lack of standardization likely due to the fact that the industry is so new, and the operating environment differs from the onshore counterparts, meaning new factors to consider. Lastly, there now exist an IEA Wind Task 43, where one of the goals is data standards (IEA Wind Task 43, n.d.), though no report has been published so far.

Table 2.1: Wind Task 33 Recommendations (Hahn et al., 2017).



Developers / owners / operators	**1. Make sure you get access to all relevant data** Consider reliability data to be of high value from the early stages of wind asset development and a key operational factor throughout the life of the wind asset. Ensure that access to reliability data and required data are factored into negotiations with developers / OEMs / suppliers / service providers.
	2. Identify your use-case and be aware of the resulting data needs Identify use cases linked to your organizational reliability ambitions and use these to define data collection requirements.
	3. Map all wind turbine components to one taxonomy / designation system Map all wind asset components and maintenance activities to one of the taxonomies / designation systems identified in the Task 33 RP. This will allow for improvements in both the consistency and integrity of reliability data throughout an organization and at the interfaces with the supply chain.
	4. Align operating states to IEC 61400-26 Align operating states with those specified in IEC 61400-26 [8], the standard for a time- and production-based availability assessment for wind turbines.
	5. Train your staff understanding, what data collection is helpful for All staff engaged directly, or indirectly, in the production, collation and analysis of reliability metrics should be educated on the strategic significance of reliability data and empowered to improve related business processes and practices.
	6. Support data quality by making use of computerized means Whenever practical, seek to automate the data collection / collation process as a means of reducing efforts and the risk of human error as well as improving data quality.
	7. Share reliability data to achieve a broad statistical basis Wind farm owners / operators should engage in the external, industry-wide sharing of reliability and performance data. This will align data collection methodologies, drive organizational improvements and achieve statistically significant populations of data for reliability analyses.
Development of standards for the wider wind industry	**8. Develop comprehensive wind-specific standard based on existing guidelines/standards** Develop a comprehensive wind specific standard based on ISO 14224 [2], FGW ZEUS [6], and other existing guidelines/standard. This would provide a core standard for the language and scope of reliability and maintenance data for the wind industry (based on accepted reliability data best practice in oil and gas industry), while minimizing the time and cost associated with the development of the standard.
	9. Develop component- / material-specific definition of faults, location, and severity As a longer-term recommendation, there is a need to develop standard definitions for damage classification and severity for structural integrity issues.

2.2 Existing Databases

This section will examine existing databases recording data from wind turbines or similar in an offshore environment. Each mentioned database will be dissected to find what data is collect and at what frequency. Also, cases of studies related to the database will be discussed. Generally this section is here to enable the reader to gain an understanding in existing practices.

First, it is valuable to look at similar practices in other industries. The offshore oil and gas sector shares the same operating environment as offshore wind, and the experience from the oil and gas sector is therefore valuable for the offshore wind sector. The OREDA project started in 1981 by the Petroleum Safety Authority in Norway, and is a database shared by multiple operators in the oil and gas sector. The primary objective of the project was to collect reliability data for safety equipment (OREDA, n.d.). The latest phase of the project enabled cloud connectivity. Another important milestone for the project was the implementation of ISO standard 14 224 for collection and exchange of reliability and maintenance data for equipment. A standard largely inspired by the project. One must mentioned, that the OREDA project started the promotion of an ISO standard in 1993, 12 years before it was finalized. It is clear and stated in the report (Hahn et al., 2017), that the evolution of the ISO 14 224 standard has inspired the research group. A possible reason for not seeing a similar standard being developed so far, could be the fact that turbine manufacturers like Vestas and Siemens Gamesa make a substantial income from service including maintenance (Vestas, 2021)(Siemens Gamesa, 2021). Therefore, there is no clear incentive for them to share their data and in the long term loose valuable contracts, due to research institutions optimizing availability through available data.

Over the last years, there have emerged several RAM databases for offshore wind. In a recent published paper, (Cevasco et al., 2021) reviewed the state of the industry. The paper mentioned the work of (Hameed et al., 2011) and (Hahn et al., 2017), and explained 2 databases have been launched that are in line with the interest of FME Northwind.

- **SPARTA** (System Performance, Availability and Reliability Trend Analysis), UK
- **WInD-Pool** (Wind-Energy-Information-Data-Pool), Germany

SPARTA is a UK based database that provide anonymous operations data from several offshore wind operators. It was formed in 2013, with an aim to provide the operator partners with a better understanding of their assets. In their latest open report from 2018, the project envelops 9 operators, 22 wind farms, 1 445 wind turbines and 5 147 MW of installed capacity (SPARTA, 2018), tracking 529 KPIs(Key Performance Indicators). Listing all the KPIs is not practical, in summary the database records **downtime due to forced outages, lost energy production, number of forced outages, number of major system repairs, number of transfers**. Many of the KPIs are then derivations of those, for example: Downtime due to forced outages per turbine, and then again according to which subsystem of the turbine. The number of wind farms involved in the project is likely to have increased by 2021. The project has 3 principles to dictate their data collection and analysis: Anonymity, Transparency and Quality. In the mentioned report, the numbers of transfers, that can be looked at as a proxy for amount of work at sites, is steadily dropping over time as seen in figure 2.1. The report argues this is due to the industry maturing, perhaps in synergy with the SPARTA project. A search on Google Scholar on **"offshore wind" AND SPARTA** yielded 253 results.

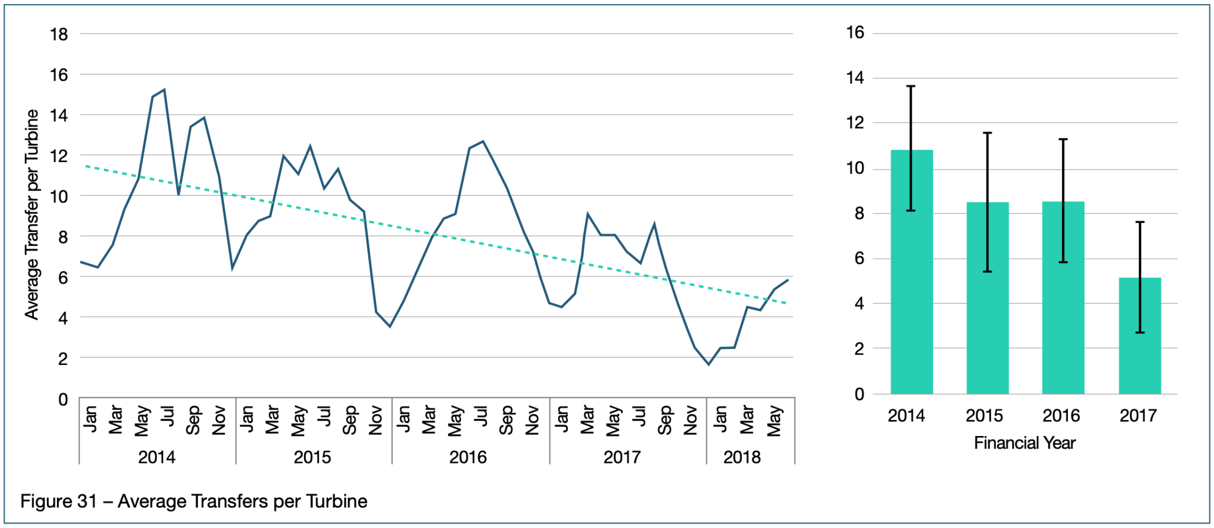


Figure 2.1: Average Transfers per Turbine(SPARTA, 2018)

WInD-Pool (Wind-Energy-Information-Data-Pool) is the German equivalent of SPARTA. The database operates very similar to its British counterpart. A collaboration of operators that report their operations in a standardized form, then having it collected by a trusted third party who anonymizes the data in order to ensure fairness between the operators (WInD-Pool, n.d.*c*). Figure 2.2 shows the relationship between partners for the WInD-Pool project. The project started in 2008 as a concept and has evolved over the years, including changing names from WMEP. The project has existed in its current form since 2016. Figure 2.3 shows how the data is collected, anonymized and distributed. While SPARTA provides a list of KPIs that is being tracked, WiND-Pool only states the minimum data requirement needed in for partners to join the project. Said requirements can be seen in table 2.2. How WiND-Pool manages data can be seen in figure 2.3. With a description provided by the project.

Searching for **"offshore wind" AND WInD-Pool** on Google Scholar yields 33 results, and **"offshore wind" AND WMEP** yields 358. A possible indication that WiND-Pool has been more successful in contributing to scientific works compared to the SPARTA project. In a paper written by Scheu and coworkers, they investigated component reliability in offshore wind farms and they used data from both the WinD-Pool and SPARTA databases (Scheu et al., 2017).

It was not possible to find the architecture of the databases, one can assume they operate differently from each other. Nevertheless, their objectives are the same: help operators reduce cost of operations by better understanding their assets. And consequently both should be consulted if and when similar projects are initiated.

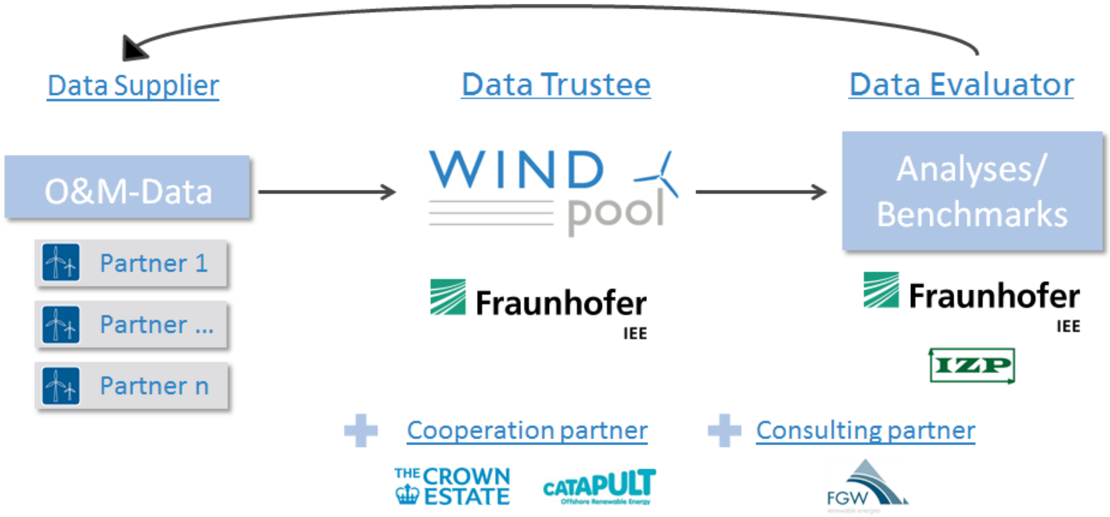


Figure 2.2: Structure and Partners of the WInD-Pool (WInD-Pool, n.d.c).

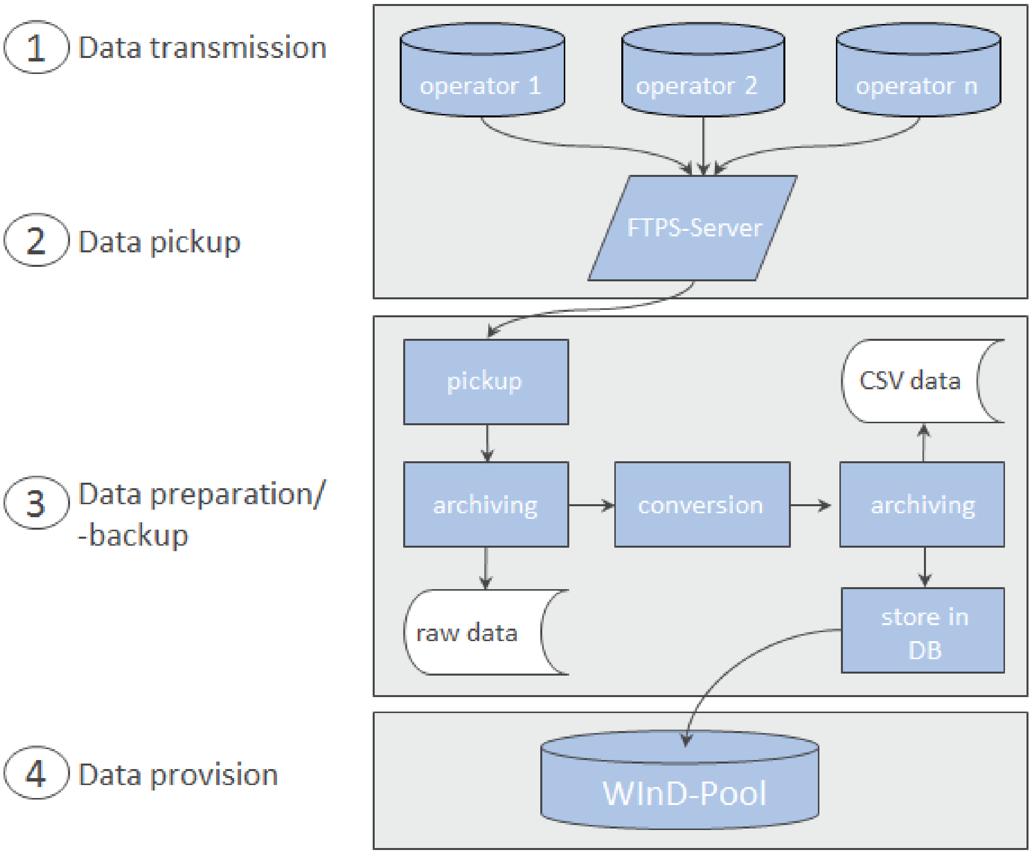
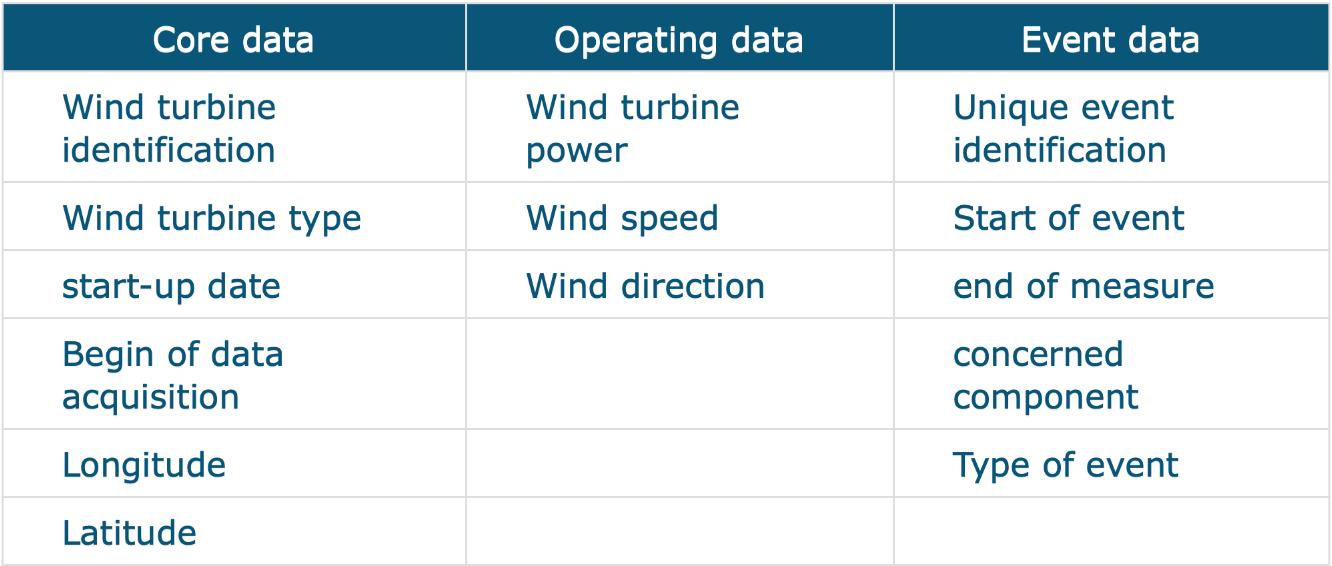


Figure 2.3: The data is transmitted over an encrypted connection and secured by an FTPS certificate.The data retrieved automatically in one-hour intervals and transmitted by TLS-Tunnels. Afterwards, the information from the FTPS-server is deleted (WiND-Pool, n.d.a).

Table 2.2: Minimum data requirements WinD-Pool, ensure that the development of standard benchmarks and analyses are possible (WiND-Pool, n.d.*b*).



Core data	Operating data	Event data
Wind turbine identification	Wind turbine power	Unique event identification
Wind turbine type	Wind speed	Start of event
start-up date	Wind direction	end of measure
Begin of data acquisition		concerned component
Longitude		Type of event
Latitude		

Chapter 3

Potential Use Cases

This chapter will discuss a few areas of research, where literature supports there is a potential: usually reducing cost and increasing profits. The chapter has been divided into three sections: condition monitoring, operations and farm optimization. Each section is related to an area of research, where the goal is to avoid overlapping such that the research is as broad as possible given the constrains of this thesis.

The selection of chosen topics is seen as the most useful combination relevant for FME Northwind at the time of writing. Although, one could say the selection is rather obvious because it is so relevant in the industry. Operators need state of the art technologies in order to accurately estimate the health of their equipment. Consequently reducing the operations cost, both in terms of materials and the cost for labor. In addition to cost reduction, there is naturally an incentive to increase power production, by for instance wind farm optimization.

Lastly, in order to limit the scope of the literature search, and in an effort to keep the material as relevant as possible, it would be pragmatic to define what subsystems in a wind turbine degrades fastest and at what cost. In their paper, (Dao et al., 2019) looked at 18 public wind turbine databases, likely similar to what this paper proposes. Five of the databases were from offshore wind farms. Their study included a measure to look at critical parts and sub systems of wind turbines based on downtime as seen in figure 3.1. They observed that the downtime compared between offshore and onshore was quite consistent, and the largest downtime contributors were gearbox, generator, and blades & hub for both onshore and offshore wind turbines. This is a useful observation because research on critical sub systems on onshore wind turbines remains relevant for offshore installations. However, all offshore turbines from the datasets had an output rating between 2 and 6 MW, while new proposed offshore turbines designed by Siemens, Vestas and GE are in the 13 to 15 MW range. The results should not be used as a rule, but it is helpful to keep in mind, in order to know which sub system or part to focus on. Thus, in section

3.1 studies looking at the critical parts referenced in figure 3.1 will be regarded as relevant.

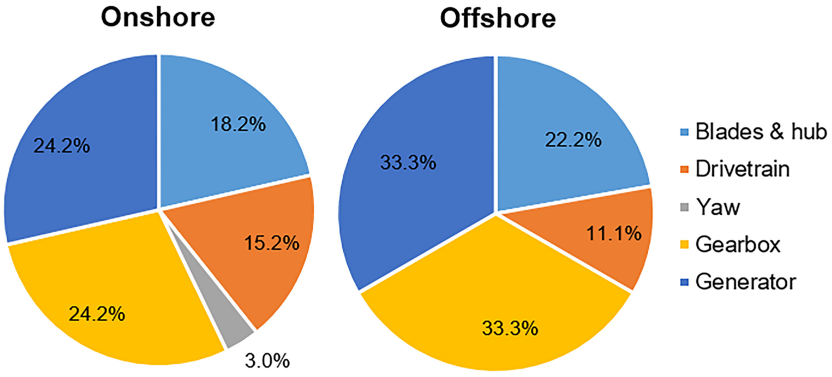


Figure 3.1: Critical components in term of downtime (Dao et al., 2019)

3.1 Condition Monitoring

Using the definition provided by (Dunn, 2009): *Condition Monitoring is taken to mean the use of advanced technologies in order to determine equipment condition, and potentially predict failure. It includes, but is not limited to, technologies such as: Vibration Measurement and Analysis, Infrared Thermography , Oil Analysis and Tribology, Ultrasonics and Motor Current Analysis.* Condition monitoring, being closely linked to operations, due to the fact that in order to optimize maintenance on a wind farm there is a need to know the state or condition of each individual wind turbine. Therefore, before said optimization is possible, a foundation for condition monitoring must be in place. In this section, state-of-the-art condition monitoring methods will be presented. Explaining what data is being used, and the analysis done. While the next section 3.2 will explore the ways operations and maintenance can be optimized given adequate condition monitoring is taking place. What is important to keep in mind, is that the aforementioned databases, SPARTA and WiND-Pool are RAM databases, designed to record operational status and environmental factors. Neither includes rich sensor data that could facilitate the connection between failure and patterns in sensor data emerging before the failure, thus enabling more precise failure predictions. Figure 3.2 shows intuitively how the process works by simplifying it.

As defined by (Dunn, 2009), vibration analysis is one way to monitor equipment. Searching for *"wind turbine vibration analysis"* yields 37 results in Google Scholar. There exist a notable amount of research in the field, but the potential is likely higher. And consequently it should be noted that recording vibration data from wind turbines is an important part of the data base. Due to the fact the the combination of vibration data as well as maintenance data will provide a link between the state of equipment before failure. In a review of offshore wind maintenance

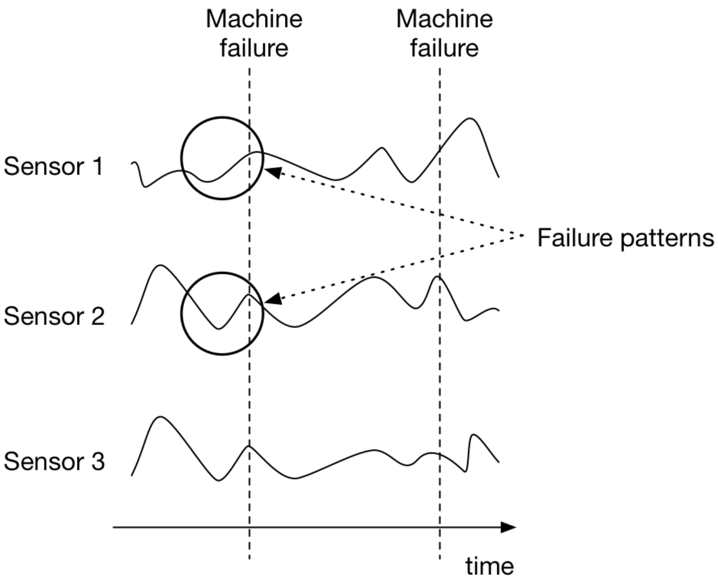


Figure 3.2: Example of how machine learning uses data to predict failure (MANTIS, n.d.).

and operations, (Ren et al., 2021) argues vibration analysis can be used to detect faults in components such as gearbox, bearing, rotor and blade, tower, generator and main shaft (Caselitz and Giebhardt, 2005). Yet argues that vibration analysis demands additional wiring complexity, and that vibration signals are not capable of detecting incipient faults due to low signal to noise ratio. However, vibration analysis remains a powerful tool to monitor wind turbines (Wang et al., 2016).

Machine learning has positioned itself as an alternative condition monitoring method apposed to the more traditional methods (e.g. vibration analysis, strain measurement, thermography and acoustic emissions). In a review of machine learning for condition monitoring on wind turbines, (Stetco et al., 2019) found studies looking at blade fault detection, generator temperature monitoring, power curve monitoring, etc. The models mostly used Supervisory control and data acquisition (SCADA) data, while a few also used images and audio signals. Interestingly, the paper noted that "A major hindrance to progress is a lack of large public datasets where new models could be developed, evaluated and compared.", a healthy remainder that before advanced techniques can be used, a proper foundation of open data must exist. That paper further elaborates on evaluating the models, and their development. There was no mention of models in use by operators, and it seems the research is still in the development stage.

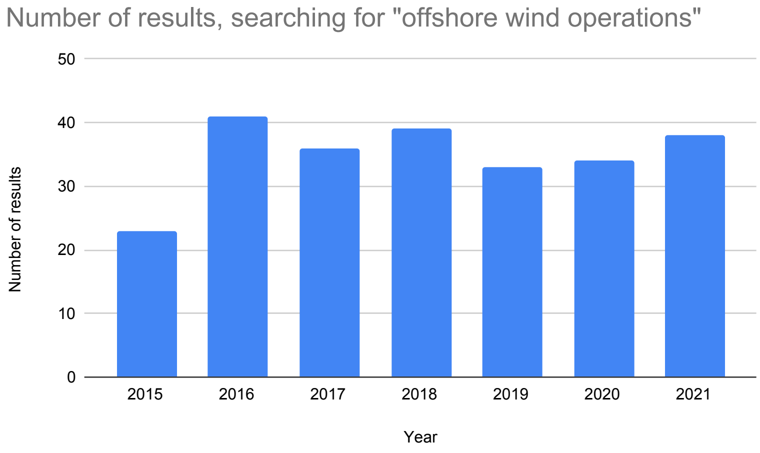


Figure 3.3: Number of published papers found on Google Scholar, searching for "offshore wind operations".

3.2 Operations

As mentioned in 3.1 this section will explore how operations and maintenance(O&M) can be optimized. This is assuming there is an accurate estimate for each individual wind turbine, elaborated in 3.1. Operations is comprised of multiple problems, and addressing all of them is neither possible nor useful. Instead, certain examples will be highlighted. In addition, figure 3.3 shows the amount of research dedicated to offshore wind operations. Like vibration analysis mentioned in section 3.1, the amount of research is notable, yet has a potential to grow as the industry matures.

An example of operations research is maintenance fleet size optimization. Finding an optimal number of vessels that is required in order to carry out necessary maintenance, while utilizing each vessel as much as possible. In their paper, (Stålhane et al., 2021) used a stochastic model, taking into account strategic uncertainty in the long term and operational uncertainty in the short term. Thus, creating a model able to assist the operator with decisions regarding: number, placement, charter length, and types of vessels to charter in order to meet maintenance demand. Uncertainty regarding future electricity prices and subsidies is taken into account. Assuming the maintenance assets are already in place. There are other methods suggested in order to optimize operations and reduce cost. (Rinaldi et al., 2020) used genetic algorithms to optimize the maintenance assets, considering reliability metrics of offshore wind turbines and the characteristics of the maintenance fleet. Meaning, already existing wind farms can better utilize their fleet by collecting reliability data of the turbines in order to accurately determine the turbine reliability. The paper concludes reliable optimization require an extensive knowledge of all the economic and technical characteristics of the offshore project. The paper was not able to reach the aim of automating part of the decision making process, and an interpretation and engineering judgement of the optimization results was necessary.

3.3 Farm Optimization

The annual produced power by a offshore wind farm is intuitively linked to the availability of the turbines, or the proportion of time where the turbine can perform as intended. Achieving a higher availability will result in more power produced. The previous sections have discussed methods to increase availability, this section will discuss how wind farm data can be used to look for new optimizing possibilities. Considering the wake effect, where wind consumes energy while passing through the rotor of a wind turbine, its speed is lower behind the turbine, which decreases the outputs of other downstream wind turbines (Hau, 2013). Optimizing for the wake can be done at two separate occasions of the wind farm life cycle. In the design process of the farm, where the optimal layout is calculated considering the offshore environment. And additionally during operations, where data regarding turbine settings, power output and position becomes especially interesting. For optimal layout, (Markarian et al., 2019) deployed a genetic algorithm to optimize the wind farm layout considering multiple factors that include different hub heights, rotor diameters, variable induction factors, power and capacity factor curves. For three different wind scenarios: constant wind–constant direction, constant wind–variable direction and variable wind–variable direction. The calculated efficiency derived from the model was 96.71%, 97.96% and 97.51%, respectively. In another study (Yang et al., 2019) used an annealing algorithm to optimize a layout in order to achieve wake affect uniformity. Using wind conditions from an actual wind farm. The model was compared to a layout optimized for energy output, with a small difference. Meanwhile, the layout would yield operational stability across the wind farm. Operational stability is a benefit perhaps most sough after in offshore working environments. And understanding the process of degradation can be very helpful. Bad weather can for example be a limiting factor, making the farm inaccessible.

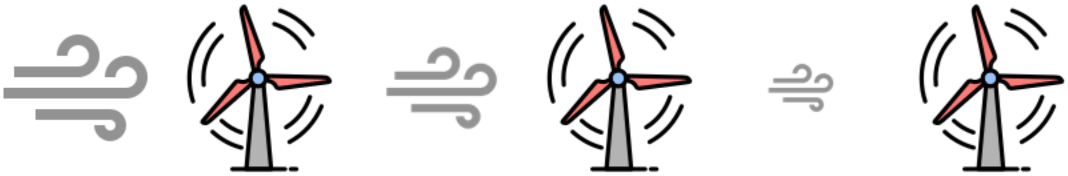


Figure 3.4: Simplified diagram showing the reduction of energy in the wind as wind turbines capture energy.

Chapter 4

Proposed Data Management

In this chapter, the question of how the data should be stored will be answered. So far, existing databases have been discussed. Both the SPARTA and WiND-Pool should be considered as potential successful projects that can serve as inspiration. Further, the remoteness of offshore wind will add a problem of connectivity and the ability to adequately transport information from the field to a secure database. Thus, some light will be shed on this potential problem. Lastly, potential suppliers will briefly be presented. Discussing positive and negative sides related different categories of providers.

4.1 Data Structure

The most pragmatic method to establish a working data structure is to draw inspiration from the two mentioned databases, SPARTA and WiND-Pool. As both instances, have the same aim as the proposed database of this thesis. However, there is a potential to expand the amount of captured data. And especially with regard to image and vibration analysis. Collecting sensor data concurrently as reliably data in the same framework, would provide an excellent base for research. Furthermore, recording the cost of maintenance operations and operations in general, is a pragmatic effort to reduce said cost in the future. Having the cost of operations, means optimizing for cost and not only availability. High available does not necessarily correlate with low operations cost. And the goal for operators will likely be to find the optimal combination of O&M costs and availability.

Another question the FME Northwind project must consider, is whether or not the data should be stored in a cloud or on an in-house data center. Using enterprise cloud services is a relatively new possibility, and could be used to the project's advantage. Removing the need for big data competence, and outsourcing to third party providers can assure more time is spent analysing data. Moreover, having the ability to scale the database when large quantities of data begin to accumulate is a problem out of mind using third party providers, as this is one of their main selling points.

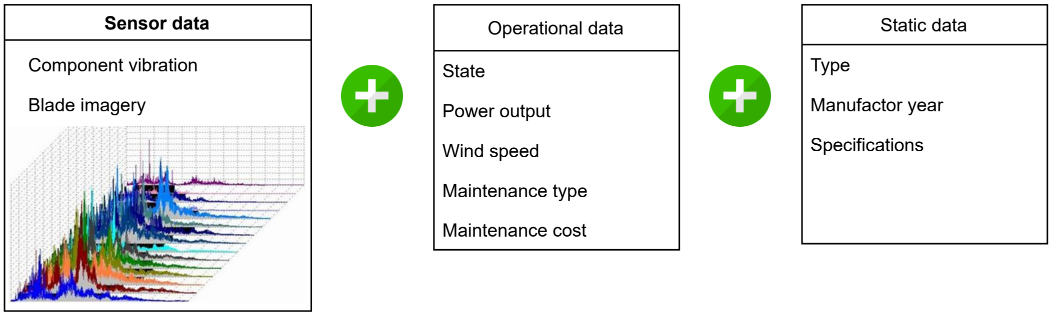


Figure 4.1: Proposed categories of data that should be recorded as an example. True list of data fields would be longer and more detailed.

A simplified proposal of what data to store is shown in figure 4.1. A combination of sensor, operational and static data. With this combination, analysis methods like machine learning would be possible, not only to wind turbines in general, but individually tailored to each specific type or model.

4.2 Connectivity

Receiving a reliable data stream is important to ensure the value of the project is realized. Thus, it is worth exploring solutions related to internet connectivity in remote operations. In a press release from 2020, the Norwegian government opened the application process for two areas in the Norwegian exclusive economic zone, as seen in figure 4.2. The area called Sørlige Nordsjø II is particularly a long distance from the Norwegian mainland. This problem is shared by other industries operating in offshore environments. For instance, the aquaculture industry can benefit from real-time monitoring of their farms. A solution was proposed by (Parri et al., 2020), using a Long Range Wide Area Network(LoRaWAN) network infrastructure for the remote monitoring of offshore sea farms. The paper concluded the technology could work reliably under worst case conditions for up to 8.33 km (Parri et al., 2020). However, with the rise of Low Earth Orbit(LEO) satellites providing internet access (Voelsen, 2021). It is possible the most straight forward solution is connecting the wind farm directly to the internet via a satellite internet provider, as seen in figure 4.3

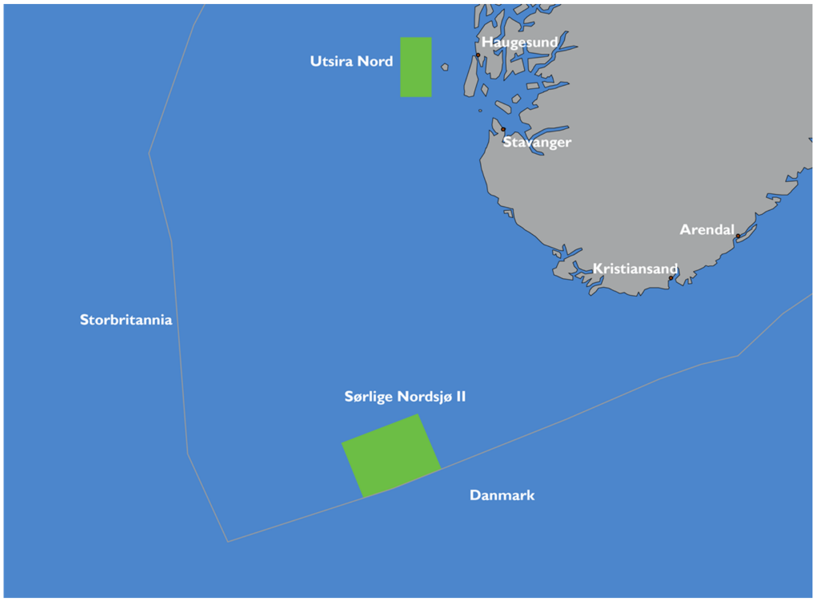


Figure 4.2: Areas in the Norwegian exclusive economic zone opened for offshore wind applications (Olje- og energidepartementet, 2020).

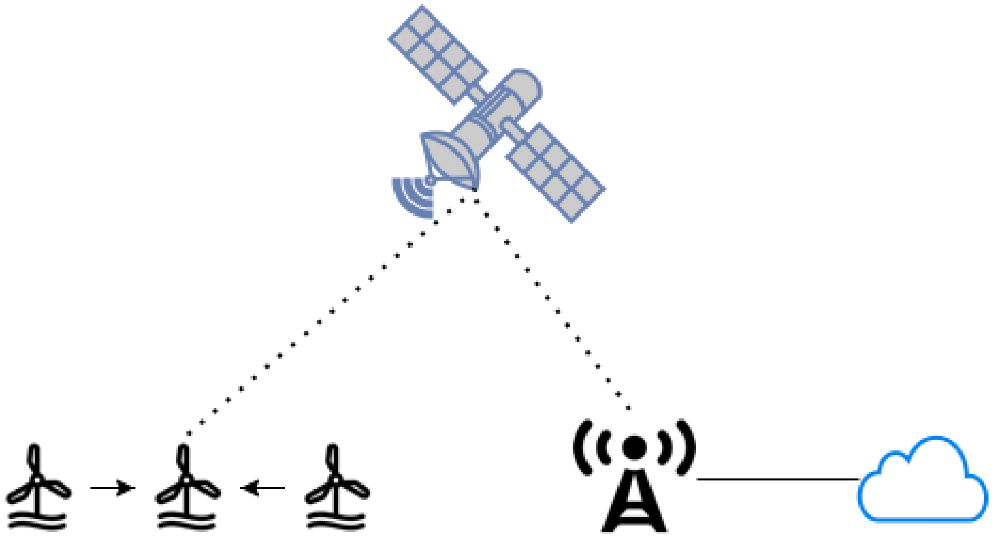


Figure 4.3: Simplified diagram, proposing communication between wind farm and cloud provider via low earth orbit satellites.

4.3 Potential Suppliers

The process of building and maintaining the database, can be solved in multiple ways. As discussed in section 4.1, should a database be created and maintained, one must decide if outsourcing the infrastructure is worth the cost. Assuming the answer is yes, there are several suppliers to choose from, in this section a few potential suppliers will be briefly presented.

Major suppliers

- Microsoft Azure
- Amazon Web Services
- Google Cloud Platform

All of the major suppliers provide tailored programs for research. Furthermore, these suppliers have in addition to simply storage also great analytical tools like machine learning and image processing baked into their services. This can have a significant impact, because not being technically familiar with the advanced tools like machine learning would not be a constraint. Instead these tools would be more accessible to wind turbine and maintenance experts. Lastly, is the track record for safety. Confidentiality is vital in order for the operators to be involved in the project, thus data security should be a high priority.

Platform as a Service(PaaS)

- Cognite
- Palantir

These companies work rather differently than their purely cloud providing counterparts. Focused towards industry costumers, companies like Cognite and Palantir offer software solutions that enable costumers to optimize their operations. Already experienced with enabling predictive maintenance to costumers, providing similar solutions to a research project might not be a big leap. However, it could be argued that these companies are better suited to be used in parallel to the research, having the operators enter agreements with them individually.

Chapter 5

Conclusions, Discussion, and Recommendations for Further Work

This final chapter will conclude and summarize what was found in the previous chapters. A discussion is also provided.

5.1 Summary and Conclusions

The thesis set out to answer three research questions.

- What similar research has been done and are there equivalent projects?
- What ways are data used to benefit O&M for offshore wind?
- What solutions can be used to implement a research database?

Overall, it seems clear that the technology needed to facilitate a RAM database for the FME Northwind project exists. In chapter 2 similar projects were examined and are already operating, including one in the UK(SPARTA) and one in Germany(WiND-Pool). Both of those databases records operational data such as state and downtime among several other factors. Yet, neither of the databases records sensor data in addition to the operational data. In an effort to future-proof itself FME Northwind should consider implementing sensor data as standard. This would enable advanced condition monitoring techniques to take place, discussed in chapter 3. In addition to existing data bases, there are studies looking at the potential for a standardized format for recording RAM information on offshore wind turbines. Several of these studies referenced the OREDA project, initiated by the Norwegian Petroleum Safety Authority in an effort to collectively reduce operational costs for involved partners. Consequently, the OREDA project should be viewed as a source of inspiration.

In chapter 3 a case was made for the implementation of sensor data to be recorded along side operational data. This would enable researchers to look for correlation between sensor patterns and turbine performance. Machine learning perhaps stands out as the ideal tool for analysing that kind of data. Not surprisingly however, there are several other analytical tools such as vibration analysis that could prove its worth. Another use case brought forward was optimizing operations, if understanding the true state and degradation of the turbines becomes a reality. Limitations of maintenance assets incentives the optimal use of said assets. One exiting possibility will be to regulate the settings of the turbines in order to extend time before needed maintenance by reducing the load in the turbine.

Lastly collection and storage of data was discussed in chapter 4. The challenge of recording and storing data from wind turbines is not a technical challenge in 2022. However, what is important to consider is whether to use an enterprise cloud system. What can make a difference in regards to storing the data is the ease of access it can provide. Intuitively, having fast and direct access would certainly be beneficial for the research partners at FME Northwind. Consequently, this would be a key difference in how this database would differ from SPARTA and WiND-Pool, being driven by research institutions, not private operators.

5.2 Discussion

Not surprisingly, the answer to the research questions posed in this thesis is that technology exists and equivalent projects have been initiated before. There is no technological reason not to implement a similar project as SPARTA in the North sea. As there are so many research partners involved, hungry for the opportunity to partake in important research like sustainable energy production is. What FME Northwind must consider is if a database can be initiated before a standard for data recording is in place. Discussed in chapter 2, there is currently no such standard. Many look at OREDA as a source of inspiration, and it could provide as a healthy starting point. However, the standards developed by OREDA did take several years to take the shape they are today. This could be the most valuable lesson to learn from OREDA. Initiating the projects is what matters most, and designing the project to organically evolve along with demand from both operators and research partners. Periodically expanding the scope of what data should be recorded.

Along with designing an architecture with continuous development as a feature. FME Northwind should also consider the accessibility of data to both industrial and research partners. Both SPARTA and WiND-Pool are private initiatives, without universities as research partners. Aspects such as ease of access and permissions should be considered in the design process. Simply put, if the research partners of FME Northwind wish to conduct research on offshore wind turbines they must take active part in the development of a RAM database, and ensure access for relevant personnel.

An observation that should be discussed is the fact that Equinor is a partner in FME Northwind, SPARTA and OREDA. Although Equinor is a large organization, and likely there is not one person associated with all of the different projects. That is valuable experience that should be used by FME Northwind.

5.3 Recommendations for Further Work

As elaborated in the discussion, there are no technological constraints to overcome in order to realize this project. As there likely are a few more years before the first offshore wind turbine is installed in Norwegian waters, there is still more time to expand upon this work. The most valuable work to continue with is the development of a standard like the ISO 14 224. Having that in place when the first turbine is installed will maximize the likely hood of project success. As other countries continue to install offshore wind, the condition monitoring technology will continue to evolve. Thankfully, this will happen independently of FME Northwind, and consequently developing a standard remains the most valuable action.

In the short and medium term it would be fruitful to initiate systematic reviews of state-of-the-art research in condition monitoring, operations, and farm optimization to understand the range of research topics and research questions. Additional, investigating the nexus between public participation and industry partner participation could also be a exiting. In the long term however, assuming wind farms in the North sea are installed and operating. I would suspect those farms could be operated autonomously and remotely, and thus research into that area can can be interesting.

The Norwegian offshore wind industry is facing an exciting future. In order to meet requirements for both the industry itself and the Norwegian authorities, it is necessary to establish efficient and optimal database solutions. This dissertation has shown that we have both solutions and technology to establish such a database.

Appendix A

Acronyms

KPI Key Performance Indicator

OEM Original Equipment Manufacturer

O&M Operations and Maintenance

OPEX Operating expenses

OREDA Offshore and Onshore Reliability Data

OWT Offshore Wind Turbine

RAMS Reliability, Availability, Maintainability, and Safety

SCADA Supervisory Control And Data Acquisition

SPARTA System Performance, Availability and Reliability Trend Analysis

WiND-Pool Wind-energy-Information-Data-Pool

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