FACULTY OF SCIENCE AND TECHNOLOGY

MASTER THESIS

Study programme:

Industrial Asset Management

The spring semester, 2022

Open

Author:
Ine Høines

Ine Høines
....
(signature author)

Supervisor(s):

Faculty supervisor: Idriss El-Thalji

Industrial supervisor: Petter Sveindal

Thesis title:

Modelling analysis of maintenance logistics optimization for a floating wind park: A case study for Utsira Nord

Credits (ECTS): 30

Keywords:

Utsira Nord,
Floating offshore wind
Maintenance logistic
Service operation vessel (SOV)
Crew transfer vessel (CTV)
Shoreline
Cost/availability/emissions
Modelling and simulation

Pages: 80

+ appendix: 1

Stavanger, 15.06.2022

Modelling analysis of maintenance logistics optimization for a floating wind park: A case study for Utsira Nord

By

Ine Høines

Thesis is submitted to the Faculty of Science and Technology
University of Stavanger
In Fulfillment of the Requirements for the degree of
Master of Science (MSc) in Industrial Asset Management

FACULTY OF SCIENCE AND TECHNOLOGY

University of Stavanger

Year 2022

Abstract

The global society is part of a climate challenge that requires the development of will, understanding and technology. The United Nations has given the climate challenge its sustainability goal, saying, "Goal 13: Take urgent action to combat climate change and its impacts" [1]. There will not be sufficiently developed energy production today in the context of future electrification of the Norwegian everyday life and industry. Norway needs to invest in more green energy production not to become an import nation of energy, but; an export nation. On June 12th, 2020, the Utsira Nord area was opened by the Government by royal decree for energy production from floating offshore wind [2].

By taking a closer look at the well-known concept of Operating expenditures, one can see clear advantages and challenges related to floating offshore wind [3]. It shows how important it is to optimise the maintenance strategy for the industry, and this is the basis for this thesis. There are many logistics solutions, and many factors influencing the choice that is hard to know beforehand. Therefore, it will depend on each wind farm to decide the best alternative to provide maintenance services. Hence, this thesis aims to investigate the following questions:

- *How to utilize modelling and simulation method for selection of optimal maintenance logistics strategy for a wind farm at Utsira Nord*
- *What will be an optimal maintenance logistics strategy for an imaginary Utsira Nord wind farm, seen from cost-benefit perspective and emission perspective*

A case study has been carried out based on an imaginary wind farm at Utsira Nord to answer the research questions. Shoreline software is used to create simulations, and analyses potential technical solutions. The research is executed in the following steps: (1) extract stakeholder requirements and acceptance criteria and define the purpose of the simulation model, (2) systems analysis of the wind park, maintenance program and logistic vessels, (3) collect and extract failure and maintenance data from existing offshore wind parks, (4) collect technical and economic data for several logistic maintenance vessels, (5) design and prepare the simulation cases, (6) perform the simulation cases and visualise the results, (7) verification and validation, including sensitivity analysis and (8) evaluate and select the most optimal logistic vessel alternative based on cost/availability and emissions

When it comes to the most optimal vessel for the case wind park, the result clearly shows that the service operation vessel provides more benefits in terms of overall grading for cost/availability and emissions. It comes out far better than the crew transfer vessel because of the sensitivity associated with the maximum wave height for this vessel. This causes a significantly higher downtime for the wind farm, and the analysis shows that the case can increase its turnover by € 13,844,000 by using a service operation vessel in favour of a crew transfer vessel concerning lost production.

The method used to carry out the analysis and simulation can be used as a starting point to provide the most optimal maintenance logistics strategy for each park. It can be common service operation vessel for several parks within the same field, several crew transfer vessels or make use of other logistical possibilities such as helicopters.

Acknowledgements

This thesis was written at the University of Stavanger as a finalization of my master's degree in Industrial Asset Management. The thesis was written in collaboration with Deep Wind Offshore.

In this chapter, I will use the opportunity to show my gratitude to people who have been an essential help in realizing this thesis.

First, I must show my gratitude to my internal supervisor Idriss El-Thalji. He was an indispensable resource throughout the period, and supported me with all his knowledge and time for the thesis to succeed. I am grateful for all the engagement, ideas, discussions and encouragements that are far more than what could be expected.

Secondly, I would like to thank Deep Wind Offshore for providing me with the case for the thesis. My external supervisor, Petter Sveindal, has always been available for discussions and ideas whenever needed.

Finally, I want to show tremendous gratitude to my family and friends who have continually encouraged, supported and cheered me on throughout my academic years.

Ine Høines

Ine Høines

Kopervik, 15.06.2022

List of content

ABSTRACT ..... **III**

ACKNOWLEDGEMENTS ..... **V**

LIST OF FIGURES ..... **VIII**

LIST OF TABLES ..... **X**

LIST OF APPENDIXES ..... **XI**

LIST OF ABBREVIATIONS ..... **XII**

1 INTRODUCTION **1**

1.1 CLIMATE 1
1.2 RENEWABLE ENERGY 1
1.3 ENERGY SHORTAGE 2
1.4 WIND ENERGY 3
1.5 OFFSHORE WIND 3
1.6 UTSIRA NORD 4
1.7 MAINTENANCE AND MAINTENANCE LOGISTIC 5
1.8 PROBLEM DESCRIPTION 7
1.8.1 Research needs and gaps 7
1.8.2 Research questions 9
1.8.3 Methodology 9
1.8.4 Scope of the thesis 10
1.8.5 Project plan 10
1.8.6 Thesis structure 13

2 THEORETICAL BACKGROUND **14**

2.1 FLOATING WTGS 14
2.2 MAINTENANCE 15
2.2.1 Scheduled 15
2.2.2 Corrective 16
2.3 VESSELS 16
2.3.1 CTV 16
2.3.2 SOV 17
2.4 SHORELINE 18
2.5 STANDARDS 20

3 RESEARCH METHODOLOGY AND DESIGN **24**

4 DATA COLLECTION **29**

4.1 THE CASE STUDY COMPANY 29
4.2 DATA SOURCES 30

5 ANALYSIS AND RESULTS **31**

5.1 STEP 1 – ANALYSIS AND DATA 31
5.1.1 System analysis 31
5.1.2 Failure data WTG 32
5.1.3 Vessels 35
5.1.4 Stakeholder analysis and criteria 38
5.2 STEP 2 - INPUT 39
5.2.1 Bases 39
5.2.2 Assets 41
5.2.3 Logistic 45
5.2.4 Personnel 49
5.2.5 Strategy 55
5.3 STEP 3 – OUTPUT 58
5.3.1 Scenario 1 - CTV, 1 year, 100 runs. 58
5.3.2 Scenario 1 - SOV, 1 year, 100 runs 59

5.3.3 Fuel consummation and fuel emissions 60
5.3.4 Lost production vs Lost sale 62
5.3.5 Sensitivity analysis........ 63
5.3.6 Pugh matrix - criteria-based decision matrix........ 65
5.4 STEP 4 - VALIDATION ANALYSIS FOR EXAMPLE 66

6 DISCUSSION 67

6.1 ANSWERS TO THE RESEARCH QUESTIONS 67
6.2 WHAT'S INNOVATIVE ABOUT THE THESIS? 69
6.3 WHAT COULD MAY HAVE CHANGED THE RESULT?........ 70
6.4 HOW CAN SCENARIO 2 WITH THE SOV BE IMPROVED........ 71
6.5 CHALLENGES AND LIMITATIONS OF THE PROJECT 72
6.6 SHORELINE........ 73
6.7 VALIDATION DURING DIFFERENT PHASES........ 73
6.8 FUTURE WORK........ 74

7 CONCLUSION........ 76

REFERENCES 78

APPENDICES........ 81

List of figures

Figure 1: World electricity generation by power station type 2
Figure 2: Map of the location of the field Utsira Nord 4
Figure 3: Past and expected development of WTGs 5
Figure 4: Offshore wind farm operating expenditures (OPEX) 6
Figure 5: An overview of five of the most common foundations, two bottom-fixed and three floatings 15
Figure 6: The maintenance categories section used in the thesis 15
Figure 7: Sprinter 26, Commander 27 and Sprinter 28 from Wave Craft by Umoe Mandal ... 16
Figure 8: Illustration of an SOV, this particular is from Edda Wind 17
Figure 9: Diagram showing some typical ERP modules 19
Figure 10: Demo of ports 19
Figure 11: Demo of means of logistics 20
Figure 12: process for maintenance implementation 21
Figure 13 Maintenance management loop developed by the Norwegian Petroleum Directorate 21
Figure 14: Maintenance planning process 23
Figure 15: Sequency of this case study 27
Figure 16: System analysis of the turbine 32
Figure 17: The locations of the different bases 40
Figure 18: Rregistration of base in Shoreline 41
Figure 19: Overview of assets in Shoreline 42
Figure 20: Scheduled maintenance task in Shoreline 43
Figure 21: Corrective maintenance task in Shoreline 44
Figure 22: Overview of information added for CTV 46
Figure 23: Overview of information added for SOV in Shoreline 47
Figure 24: Chosen campaign period for the CTV 49
Figure 25: Registration of non-campaign personnel in Shoreline 51
Figure 26: Registration of campaign personnel in Shoreline 52
Figure 27: Chosen campaign period for the SOV 53
Figure 28: Registration of non-campaign personnel in Shoreline 54
Figure 29: Registration of campaign personnel in Shoreline 55

Figure 30: Strategy for CTV in Shoreline 56
Figure 31: Strategy for SOV in Shoreline 56
Figure 32: Work order priority for both scenarios 57
Figure 33: Illustration of what is done by the author 69
Figure 34: Utsira (island) and Killingøy 71

List of tables

Table 1: The two scenarios being discussed in this analysis 7
Table 2: Existing research and keywords 8
Table 3: Ideal project plan (orange is the weeks it was supposed to be done, with blue being the week it should be finished) 11
Table 4: Realistic representation of how the project progressed 12
Table 5 Research methodology step and philosophy 26
Table 6 : The data collection methods 30
Table 7: Failure rates /WTG/year 33
Table 8: Repair time 33
Table 9: Required technician 34
Table 10: Fuel information for the scenarios 35
Table 11: Emission data for the fuel 37
Table 12: Stakeholder analysis and key acceptance criteria 39
Table 13: Average (avg.) distribution of wave height for one year 45
Table 14: Selected data in Shoreline for CTV 46
Table 15: Selected data in Shoreline for SOV 48
Table 16: Output data for the CTV from Shoreline 59
Table 17: Output data for the SOV from Shoreline 60
Table 18 Fuel in 24 hours for CTV 60
Table 19 Fuel in 4 weeks and 24 hours for SOV 61
Table 20: Emissions from fuel in 24 hours for CTV 61
Table 21 Emissions from fuel in 4 weeks and 24 hours for SOV 62
Table 22: Sensitivity analysis for the different wave heights for the CTV 64
Table 23: Pugh matrix for evaluating the two scenarios 65

List of appendixes

Appendix 1: data collected for failure rates, repair time and required technicians for the WTG 81
Appendix 2: data collected for CTV 81
Appendix 3: data collected for SOV 81

List of abbreviations

Avg.	Average
CAPEX	Capital expenditures
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CTV	Crew transfer vessel
DWO	Deep Wind Offshore
EDF	Electricité de France
ERP	Enterprise resource planning
ETS	Emissions trading system
FMEA	Failure Mode and Effects Analysis
Heli	Helicopter
HLV	Heavy lift vessel
HSE	Health, safety and environment
IEA	The International Energy Agency
IRENA	The International Renewable Energy Agency
Kn	Knot (unit)
KWh	Kilowatt-hour
LCOE	Levelized cost of electricity
MCR	Major component replacements
MFO	Marine fuel oil
MGO	Marine gas oil
MW	Megawatt
N_2O	Nitrous oxide
NVE	The Norwegian Water Resources and Energy Directorate
O&M	Operations and maintenance
OPEX	Operating expenses
PWh	Petawatt-hour
SOV	Service operation vessel
TWh	Terawatt-hour
UN	The United Nations
W2W	Walk to work
WTG	Wind turbine generator

1 Introduction

This chapter aims to introduce the theme and find the essence of what the thesis includes. Furthermore, it is examined which research hole is associated with the research questions, which method is used to answer them, the scope, the project plan, and the project's structure.

1.1 Climate

The global society is part of a climate challenge that requires the development of will, understanding and technology. *The United Nations* (the UN) has given the climate challenge its own sustainability goal, saying, "Goal 13: Take urgent action to combat climate change and its impacts" [1]. It is partly due to increased emissions after the Industrial Revolution. In parallel with technological developments, greenhouse gas emissions have also increased. A significant contributor to the world's greenhouse gases is burning oil, gas, and coal, the energy carriers on which a large part of society is built. These energy carriers are used for, among other things, fuelling cars and other engines, heating homes and water and cooking. Therefore, new energy carriers must be found and developed as the first step to reach a joint achievement of the UN Sustainable Development Goal number 13. *The International Energy Agency* (IEA) cites figures that by 2024, 30% of all energy will be renewable [4]. These figures are also supported by claims that the projects within solar and wind will lead to a startling pace.

1.2 Renewable energy

The definition of renewable energy is often used as resources that can supplement us with energy naturally from nature's cycle. It is often seen as a source of continuous supply for which there will be no end date. Commercial extraction of these sources will be sustainable and essential in reducing greenhouse gases. Many renewable energy sources can already help phase out oil, gas and coal. The challenge with many known renewable energy sources is that they are based on factors not controlled by human influence, such as solar radiation, rain and wind. It shows that the diversity of carriers is essential in providing energy to countries with different geographical locations and conditions. However, Figure 1 shows how the development of energy resources is expected to develop towards 2050, and offshore wind is comprehensible the largest, with more than 55 PWh/year.

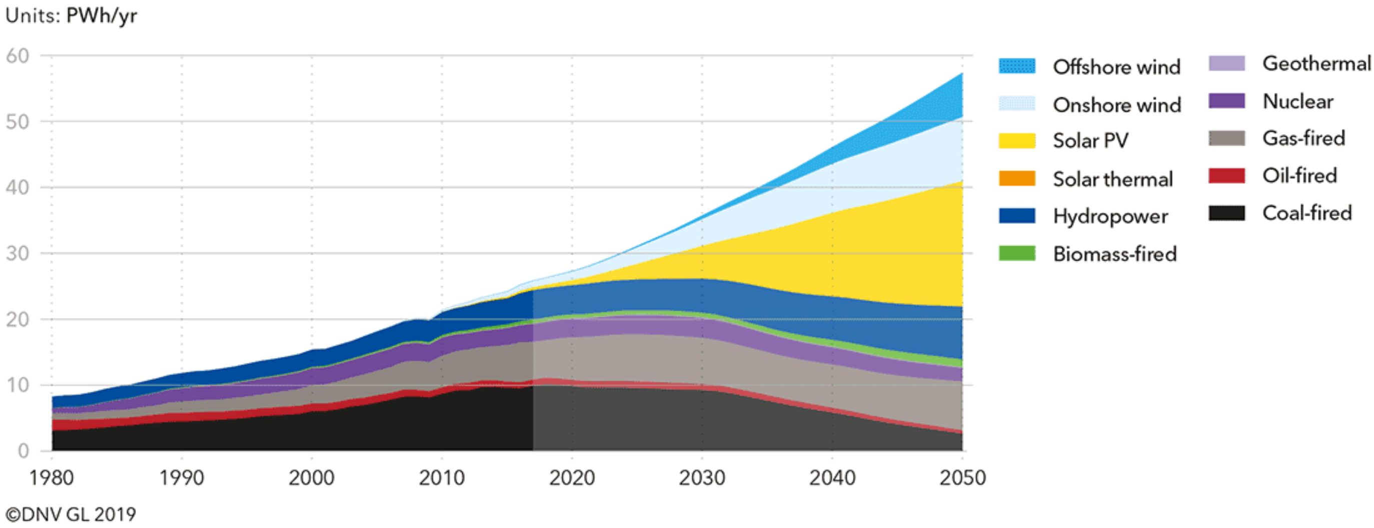


Figure 1: World electricity generation by power station type [5]

1.3 Energy shortage

There will not be sufficiently developed energy production in Norway in the context of future electrification of Norwegian everyday life and industry. This is considering that Norway has mainly used renewable energy for several years in the form of hydropower. On the one hand, it is not the extensive revolution to restrike the entire energy production that is the most significant task; on the other hand, it is to meet the increased energy demand from electrification. Figures from Statnett show that the Norwegian energy consumption is expected to grow from the current level of 140 TWh to 180-190 TWh between 2040-2050 [6]. Recent figures from T*he Norwegian Water Resources and Energy Directorate* (NVE) shows that Norway's energy consumption increased by more than double of the increased energy production for 2021 [7][8]. As a result of these expected values, it is evident that Norway needs to make more investments in green energy production to not become an import nation of energy, but; an export nation. Wind energy is one of the options that can contribute to this.

1.4 Wind energy

As a result of increased demand, it has been seen that the commercial and economic aspect related to wind power has developed in a positive context. Analyses conducted by T*he International Renewable Energy Agency* (IRENA) show that prices for commercial wind-generated electricity will decrease by 35-37% from 2015 to 2025 [9]. It will result in wind power becoming more attractive in the global market because of the reduced costs. The technology is waiting for the various nations to invest, as the first 15 MW offshore wind turbine generator (WTG) has been installed[10].

Over time, an increasingly marked resistance has been built against onshore wind farms in Norway. During the settlement of Haramsøy, large demonstrations were held where the police had to get involved in helping the developer gain access to the given concession area [11]. A direct cost analysis will show that onshore wind is more economically sustainable than offshore wind. However, by looking at cost in the context of other conflicts of interest, offshore wind will be the most sought after in the future.

1.5 Offshore Wind

From an international perspective, commercial floating offshore wind parks have already begun to operate. Hywind Scotland, consisting of five WTGs with a total capacity of 30 MW, was put into production outside the coast of Peterhead in Scotland in 2017 [12]. The floating WTGs on Hywind Scotland have been shown to have the highest capacity factor of all wind parks throughout the United Kingdom. Deep-sea areas will have more constant access to wind, resulting in a higher capacity factor. Also, in other European countries, floating technology has been adopted, such as on the coast of Viana do Castelo in Portugal, where Windfloat Atlantic was put into production in 2020. There are currently no parks operating in Norway from a national commercial context. However, Equnior is planning to start production at Hywind Tampen in 2022. This park aims to start the electrification of the Norwegian continental shelf. Suppose Norway want to join in on the competition to become world-leading in offshore wind, especially floating offshore wind; it is high time for the process development to accelerate.

1.6 Utsira Nord

On June 12th, 2020, the Utsira Nord area was opened by the Government by royal decree for energy production in the form of offshore wind [2]. This call of proposals marks the start of what is part of history's first concession for offshore wind on the Norwegian shelf. Utsira Nord, shown in Figure 2, covers an area of over 1,000 square kilometres, with a planned redevelopment of 1,500 MW spread over at least three different concessions [13]. The depth of the field, with an average of 276 m, results in it needing the technology for floating offshore wind [11][14]. The distance to shore is less than 20 km, which means that the accessibility to the field is high [15].

Figure 2: Map of the location of the field Utsira Nord [16]

1.7 Maintenance and maintenance logistic

Looking at the well-known concepts of capital expenditures (CAPEX) and operating expenses (OPEX), one can see clear advantages and challenges related to floating offshore wind. Highlighting the differences is essential to distinguish these concepts and what they embrace. CAPEX aims to classify cash flow for buying direct or upgrading assets. OPEX is operating expenses incurred by a company by operating and maintaining the already generated assets from CAPEX.

It has already been documented that the CAPEX per installed MW has decreased significantly in already established wind farms. Historically, it has been shown that Equinor has already had a CAPEX reduction of 70% per installed MW between their Hywind Demo (2.3 MW), now called UNITECH Zefyros, and Hywind Scotland (33 MW) [12]. The company has embarked what its ambition of a future CAPEX reduction of 40% per installed MW from Hywind Scotland to Hywind Tampen (88 MW). Figure 3 below shows the expected development of floating wind cost reduction according to Equinor.

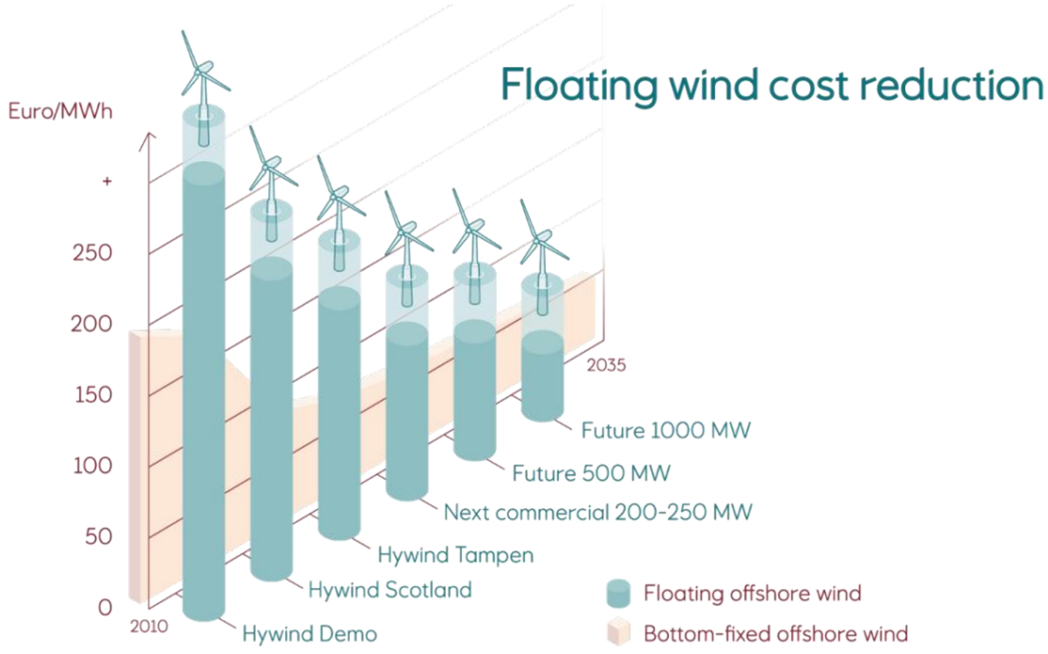


Figure 3: Past and expected development of WTGs [12]

However, there is a significant challenge regarding OPEX for offshore wind. Therefore, finding which factors are essential contributors indicates the tremendous potential for improvement is imperative. Figure 4 shows a distribution for OPEX, with 38% going to maintenance. This graph is for general offshore wind, and it is theoretically easier to carry out maintenance on bottom fixed WTGs than floating ones. Towing the floating WTGs into shore for major component replacement (MCR) is common. This will cost a lot in vessels and resources, but it will also require more extended downtime of the energy production. Therefore, the percentage for maintenance is expected to be even higher for floating offshore wind. It shows how important it is to optimize the logistic maintenance strategy for offshore wind, and is the basis for this thesis.

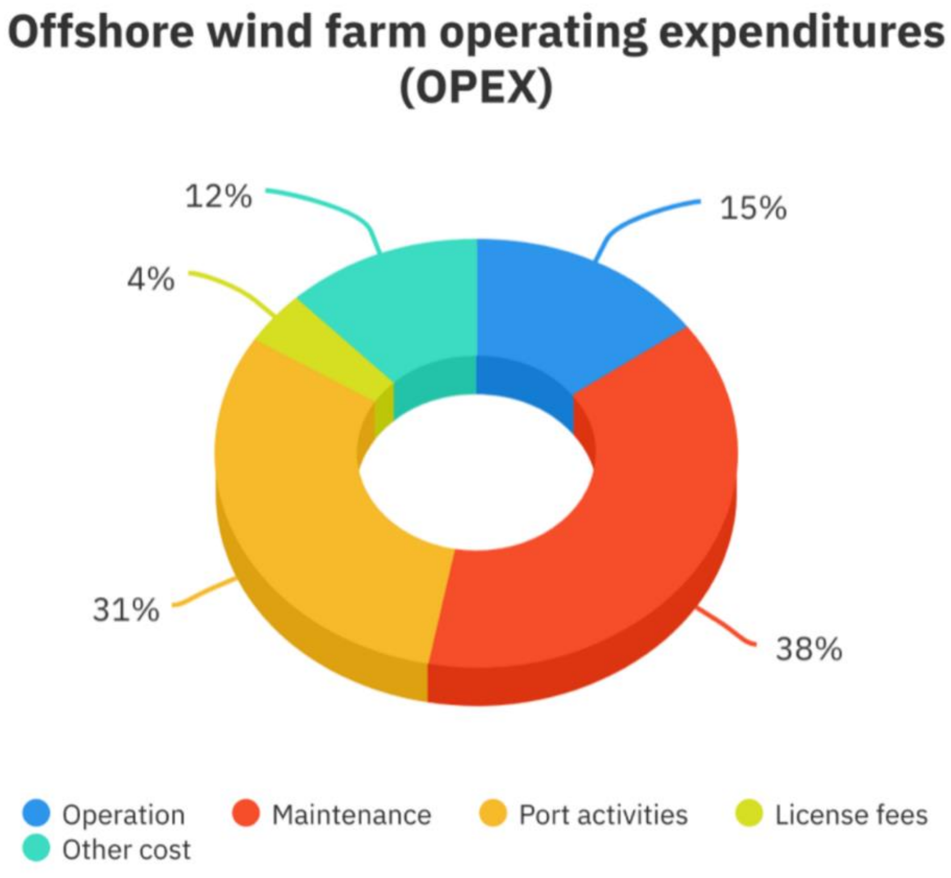


Figure 4: Offshore wind farm operating expenditures (OPEX) [3]

There are significant variations in the pros and cons of various strategies for maintenance logistics. The concession requirements may also impact what is chosen for Utsira Nord, as the indications are based on qualitative requirements in favour of quantitative requirements [17]. Qualitative requirements can often be seen as a beauty contest, where set requirements are more important than providing the best financial offer. It is done to build up the surrounding industry and strengthen it to become a leader in floating offshore wind. Since these requirements are not set when this master's thesis is carried out, it will preferably be cost/availability and emissions that is the starting point of the analysis of the different strategies for maintenance logistics.

The research paper is a comparative case study of two scenarios that compare a crew transfer vessel (CTV) and a scenario using a service operation vessel (SOV). These are two of the alternative scenarios that will be relevant to use on a wind farm on the Utsira Nord field. The various limitations and costs differing for each of them are shown in Table 1.

Table 1: The two scenarios being discussed in this analysis

	CTV	**SOV**
Speed	+- 20 kn	+- 12 kn
Wave height limitation	1,5 - 2.5 m	2,5 - 3.5 m
Personnel	Base onshore	Base offshore
Day rate	Low	High

1.8 Problem description

1.8.1 Research needs and gaps

A thorough literature study was carried out to form an impression of the research gap within the topic. Scopus was used as the central database in the searches for the thesis, as it is a digital tool that contains large amounts of publications at the same time as it is built up systematically.

Wind power is a vast and complex topic, and offshore wind will have even greater irregular conditions. As a result, most of the publications will be slightly irrelevant to other projects. On the other hand, many good sources of information about other projects can be used beneficially. The keywords used are shown in Table 2.

Table 2: Existing research and keywords

«Limit to» search in Scopus	**Document results**	**Relevant**
TITLE-ABS-KEY (maintenance AND logistic AND offshore AND wind) AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "United Kingdom") OR LIMIT-TO (AFFILCOUNTRY , "Norway") OR LIMIT-TO (AFFILCOUNTRY , "Denmark")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018))	13	1
TITLE-ABS-KEY (operations AND maintenance AND offshore AND wind AND parks) AND (LIMIT-TO (AFFILCOUNTRY , "Norway")) AND (LIMIT-TO (DOCTYPE , "cp"))	3	1
TITLE-ABS-KEY (sov AND ctv AND offshore AND wind)	1	0
TITLE-ABS-KEY (marine AND logistic AND offshore AND wind) AND (LIMIT-TO (AFFILCOUNTRY , "Norway"))	6	2

“Marine logistics decision support for operation and maintenance of offshore wind parks with a multi method simulation model” by Ole-Erik Vestøl Endrerud and Jayantha P. Liyanage was one of the relevant results [18]. It discusses a lot of the same questions as this thesis. However, the trend since the article was written in 2014 has been enormous. At the same time, a significant gap is distinguished between the problem where this task looks at a given area, with ERA5 weather data, while the article uses data from Germany in its analyses.

“Testing the Robustness of Optimal Vessel Fleet Selection for Operation and Maintenance of Offshore Wind Farms” by Iver Bakken Sperstad, Magnus Stålhane, Iain Dinwoodie, Ole-Erik Vestøl Endrerud, Rebecca Martin and Ethan Warner also discusses maintenance logistics [19]. Also in this article, the data is old, and during the work on this thesis it was found that many of the values were insufficient to use in 2022. The approach is also different, where Shoreline will be central to the assessment in this analysis.

None of these articles considers the emissions that occur when using these vessels. No other research was found that takes this into account. It is also important to point out how extremely variable the different wind parks are apart, where the location is a decisive factor. Each park is unique, with varying factors such as weather conditions and distance from shore. As a result of the distinctive wind parks, there is no established template for how maintenance logistics should be built up.

1.8.2 Research questions

The primary purpose of the thesis is to answer the question as follows:

1. *How to utilize modelling and simulation method for selection of optimal maintenance logistics strategy for a wind farm at Utsira Nord*
2. *What will be an optimal maintenance logistics strategy for an imaginary Utsira Nord wind farm, seen from cost-benefit perspective and emission perspective*

1.8.3 Methodology

The method for this case study is built up in several steps, based on IEC 60300-3-14:2004. A literature study will be carried out, providing an overview of the analysis's theories. In the research, analyses will be carried out for the system and the stakeholders' criteria. Furthermore, data needed to carry out the analysis will be collected. The cases must be built up in the software Shoreline before the simulations can be carried out. Data from the simulations are analysed and assessed against the criteria. Furthermore, validation is carried out to check that the interpretation of the data is correct.

1.8.4 Scope of the thesis

This master's thesis is prepared in a short period of 5 months, from January 15th to June 15th. The short period naturally entails a delimitation of how in-depth the work can be in context to familiarising yourself with entirely new topics.

The start of the period was heavily influenced by the Covid-19 pandemic, where the country was shut down with orders for obligatory home office. This lockdown limited the possibility of direct communication, which meant it took longer to obtain the needed resources.

It was decided early in the period to move away from looking at the entire wind farm as one, with foundation, inter-array cables, substation and export cables. This was replaced by looking isolated at the WTG, because the scope of data collection became more remarkable than what was possible to obtain for the available period.

Data collection remained a significant challenge, which delayed the work continuously throughout the period. As a result of a competition filled industry, it is understandable that it is withdrawn with its data to some extent. However, research such as this thesis, which is not carried out internally by a wind farm operator, will have significant problems obtaining updated data. Therefore, the used data are older and for far less scaling of WTGs than what is relevant for the future. This will affect the result, but it will still respond to its intent on how to conduct an analysis using Shoreline and extract results from it in the context to cost, availability and emissions.

1.8.5 Project plan

Early in the project, an ideal project plan was set up to be followed, as shown in Table 3. It is strongly influenced by optimism about a smooth and continuous working period without any unexpected challenges affecting the progress. Naturally, this was not realistic to perform without unforeseen challenges, especially missing access to data had a significant impact on the progress. Table 4 therefore, shows a more realistic representation of the project plan as it was carried out.

Table 3: Ideal project plan (orange is the weeks it was supposed to be done, with blue being the week it should be finished)

	JAN			FEB				MAR				APR				May				June		
Week #	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
TASK																						
Read past theses and find what already exists in the research field																						
Writing introduction part 1																						
Contact various resources for data collection																						
Writing introduction part 2 (Research &Methodology)																						
Theories of offshore wind and maintenance																						
Theories about the methods used(standards)																						
Theories of application (incl. shoreline)																						
Chapter 3, what is the research design																						
Description of DWO, system, problem																						
Build the wind farm for Utsira Nord in Shoreline																						
Create the different scenarios for the wind farm and run comparisons																						
Investigate emissions related to the different scenarios																						
Write result-analyse chapter																						
Write discussion																						
Draw conclusions																						
Deadline for my first submission																						
Task Auditing																						
Final submission to the university																						

Table 4: Realistic representation of how the project progressed

	JAN			FEB				MAR				APR				May				June		
Week #	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
TASK																						
Read past theses and find what already exists in the research field	■	■	■	■	■	■																
Writing introduction part 1	■	■	■	■	■	■																
Contact various resources for data collection	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Writing introduction part 2 (Research &Methodology)				■	■	■	■	■									■	■				
Theories of offshore wind and maintenance						■	■				■	■	■	■								
Theories about the methods used(standards)						■	■							■	■							
Theories of application (incl. shoreline)						■	■				■	■	■	■								
Chapter 3, what is the research design								■	■	■						■	■	■	■			
Chapter 4, data collection								■	■	■						■	■	■	■	■		
Build the wind farm for Utsira Nord in Shoreline						■	■	■	■	■	■	■	■	■	■	■						
Create the different scenarios for the wind farm and run comparisons									■	■	■	■	■	■	■	■						
Investigate emissions related to the different scenarios					■	■						■	■	■	■	■	■					
Write result-analyse chapter														■	■	■	■	■	■			
Write discussion																		■	■			
Draw conclusions																			■			
Deadline for my first submission																			■			
Task Auditing																			■	■	■	■
Final submission to the university																						■

1.8.6 Thesis structure

Chapter 2 – is a literature study that aims to describe the theoretical basis of the thesis. Theories on the topic, application and methods used in the structure are described.

Chapter 3 - describes the research methodology and the design used to answer the research questions asked. It describes the research philosophy, approach and strategy used, and the factors associated with data selection.

Chapter 4 – explains the case company, and what sources are used to retrieve and validate the data.

Chapter 5 – the analysis and result chapter thoroughly review what is produced in the thesis, how it is produced, and what results can be extracted from the produced material.

Chapter 6 – is a discussion chapter that looks at the results from the previous chapter, discusses limitations and challenges discovered in the preparation of the thesis and what factors could contribute to a different or a better result. Finally, it is examined which future research work can be carried out on this topic.

Chapter 7 – the conclusion chapter uses the results and the various steps that have been completed to answer the research questions, which is the primary purpose of the thesis.

2 Theoretical background

This chapter aims to present a literary presentation of theories that are central to being familiar with for the analysis. It is divided into five approaches representing the division of progress of the task: floating WTGs, maintenance, vessels, Shoreline and the use of standards.

2.1 Floating WTGs

The wind has been exploited as a driving mechanism in processes long before the birth of Christ. An example of this known history is from China about 4,000 years ago, where the process was to store water in artificial ponds [20]. It is one of several examples that highlight what was the beginning of an adventure that lay ahead.

When offshore wind is discussed, this embraces both bottom-fixed and floating WTGs offshore. Historically, fixed WTGs have been chiefly used globally; on the other hand, the future will consist of more floating ones. What distinguishes the two technologies is the distance to the ocean-bound where they will be located. Fixed WTGs are economically most satisfying out of the two alternatives, but will not be able to be used on fields where the sea depth is more than 50 m [21]. Figure 5 shows that floating WTGs can be installed in areas where the sea depth is over 50 m, up to as deep as 200-300 m [22].

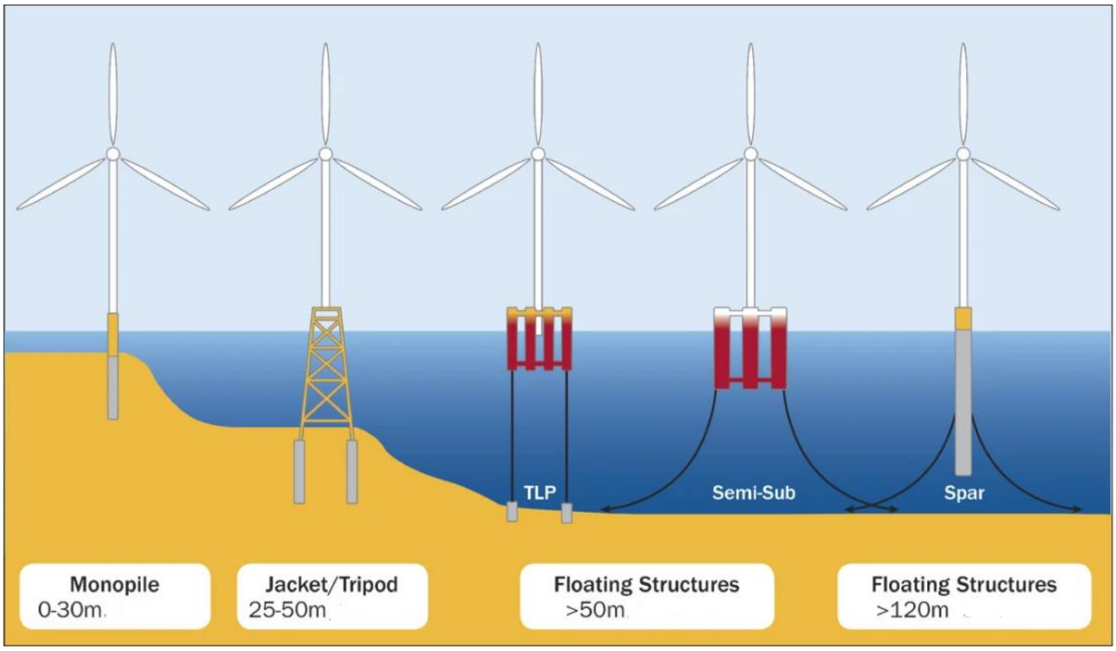


Figure 5: An overview of five of the most common foundations, two bottom-fixed and three floatings [23]

2.2 Maintenance

In this thesis, there are two central divisions of maintenance operations. Corrective and preventive-scheduled activities for the WTGs are used, as shown in Figure 6.

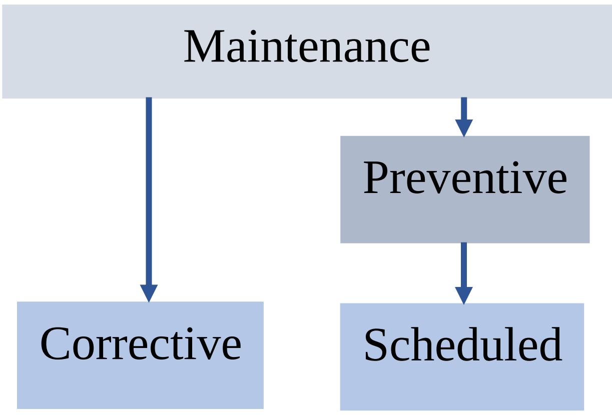


Figure 6: The maintenance categories section used in the thesis[24]

2.2.1 Scheduled

Scheduled maintenance work is done within a given time frame. It can be a one-time work order or occur at fixed intervals like every year. This maintenance work requires good knowledge of how the asset behaves throughout its lifetime to conduct preventive maintenance.

2.2.2 Corrective

Unplanned corrective maintenance is based on failure warnings because of a present failure. These occur spontaneously throughout the year and are not planned. This maintenance work can be costly, especially in industries such as offshore wind, where harsh weather conditions can be expected during the winter months.

2.3 Vessels

2.3.1 CTV

CTV is a vessel often used during offshore wind construction, maintenance, and operation. It differs from other vessels such as an SOV because it is specially designed for this industry, while others often operate across industries [25]. The added specifications allow it to efficiently transport technicians and smaller equipment out to the park from an operations and maintenance (O&M) base on land. Its material selections and scale allow it to run at high speed onto the field, enabling it to quickly get in and out of the base.

Wave Craft by Umoe Mandal is a business leasing CTV for the offshore wind industry, and the size range of their vessel is between 25 and 28 m [26]. Their three variants, shown in Figure 7, are partly distinguished regarding technicians' capacity. The Sprinter 28, their largest vessel under the renewable category, can carry 50 technicians. For larger wind farms, this will be essential. Utsira Nord, on the other hand, is divided into more minor concessions, presumed at 500 MW in this thesis, and thus will not have such a great need for capacity. On the other hand, Sprinter 26 and Commander 27 have an ability of between 12 and 24 technicians and are therefore more attractive to use in a park with 34 WTGs.

Figure 7: Sprinter 26, Commander 27 and Sprinter 28 from Wave Craft by Umoe Mandal [26]

There are pros for CTV when it comes to factors such as speed. On the other hand, there is a reason why this vessel is weaker than the larger vessels. The industry-standard has been that the maximum wave height should be about 1.5-2,5 m to operate with a CTV. This limit will be an explicit limitation when utilizing this as the main vessel of a maintenance logistics strategy.

2.3.2 SOV

Unlike a CTV, an SOV is much more than a way of transportation. Here one gets transport, at the same time as a hotel, workshop, and spare part tool. With a length that is often around 80 m, it has the opportunity to stay out on the field for an extended period with technicians constantly on board. The speed will naturally be somewhat lower, with a transiting speed usually around 12 knots. For example, looking something like Figure 8, the vessel also has good facilities to carry spare parts on board, allowing failures to be repaired efficiently. This option will help reduce downtime, as one does not have to spend time transporting out to the field for each visit.

Figure 8: Illustration of an SOV, this particular is from Edda Wind [27]

An SOV often has the capacity for around 40 technicians outside its crew. This capacity will be a considerable gain in using a vessel to accommodate many people on large wind farms. Furthermore, it is often the only option for fields located far from shore, where there is no possibility to use CTV for transport back and forth during regular working hours.

Given how vital health, safety and environment (HSE) is to safeguarding employees at all times, an SOV has many clear benefits. First, the size of the vessel makes its stability significantly higher than on a CTV, where it is known that people can quickly get seasick. The other thing that goes on security is how the technicians are transferred to the WTG. SOVs currently used for offshore wind are usually fitted with what is known as a walk-to-work bridge (W2W bridge). That would ensure staff a secure transmission platform on the WTG, unlike a CTV, where technicians must climb a ladder relatively close to the sea surface.

It shows many pros to using such a vessel for larger wind farms. However, there is a clear basis for the scaling at the park regarding cost. The vessel has a high cost due to its size, crew, and further. Therefore, it will be crucial to carry out analyses that look at cost in the context of accessibility. Digital tools such as Shoreline will help carry out such an analysis systematically.

2.4 Shoreline

Shoreline is a software developed by Ole Erik Vestøl Endrerud when working on his PhD at the University of Stavanger, and it was established in 2014 [28]. He discovered a shortage in the industry when optimizing corporate assets, increasing efficiency and making it more sustainable for the future. The software aims to reorganize the industry's attitudes towards separate processes from being "good enough" to the currently known enterprise resource planning (ERP) systems.

ERP is a system that will manage the primary business process in a unified and systematic manner and is often seen as a software for corporate governance [29]. Here, data can be collected, stored and used to take a historical approach to optimize processes. Following Industry 4.0, these management systems are often provided as a cloud-based solution. This will naturally increase availability as one can use the data anytime. Figure 9 below shows how the elements systematically interact within the software.

Figure 9: Diagram showing some typical ERP modules [29]

The software is designed to build a wind farm digital, and the first step is to add available ports and means of logistics. Many limitations must be included in the software for the vessels and helicopters (heli). It goes on both cost and availability and restrictions that reframe weather. In simulations, historical data is used to simulate the availability of these vessels based on the limitations set. Figure 10 below shows an overview of a demo of ports, and Figure 11 shows a demo of means of logistics, which can be further pressed to set values for the different parameters.

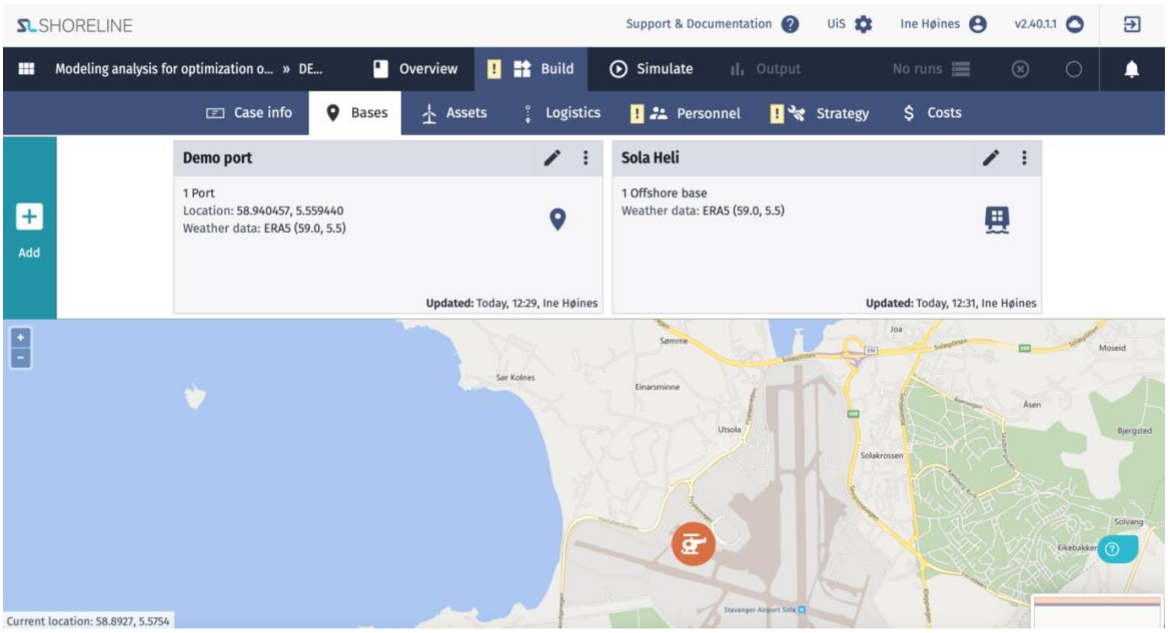


Figure 10: Demo of ports

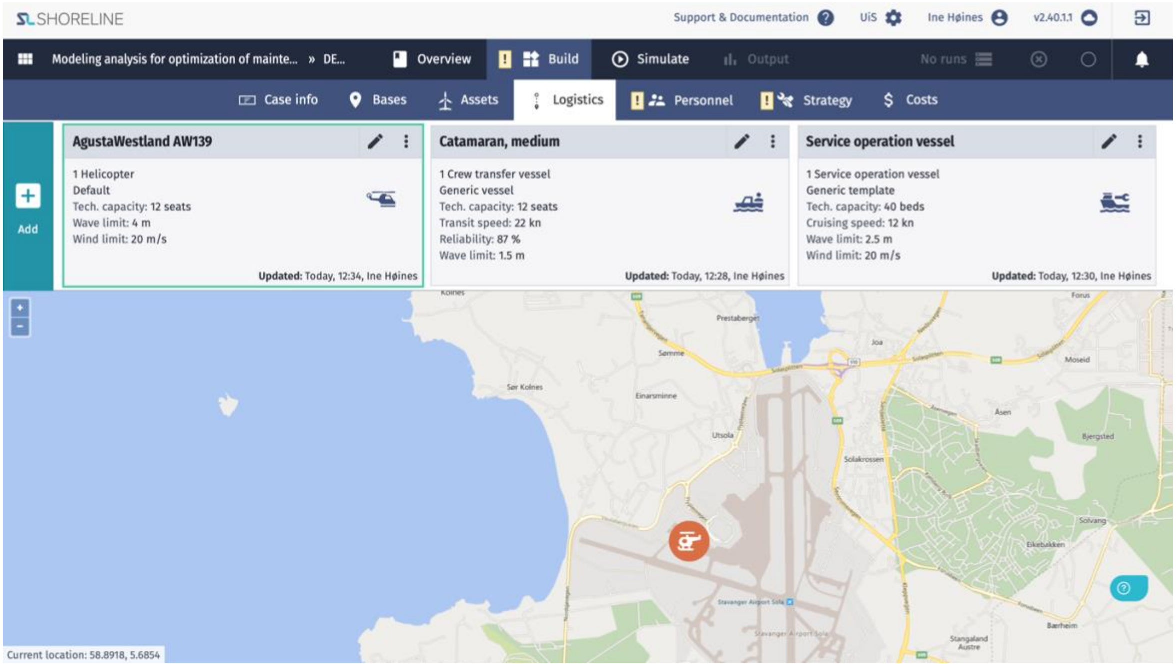


Figure 11: Demo of means of logistics

Furthermore, various assets such as WTGs, cables, foundations and other assets are added when constructing the wind park in Shoreline. These assets have different parameter limitations, scheduled maintenance, corrective maintenance, and vessels' need. Therefore, it will be necessary to connect these so that the software is familiar with, for example, which vessel is required for the various failures. A systematic approach to this information will help optimize the operation of the park. Finally, personnel are added both inside (scheduled maintenance) and outside (corrective maintenance) campaigns and the strategy for the case.

2.5 Standards

Figure 12 from the standard IEC 60300-3-14:2004 shows a process for maintenance implementation [30]. This process description has apparent similarities to the maintenance loop published by the Norwegian Petroleum Directorate in 1998, shown in Figure 13 [31]. Both figures show the same process where goals and resources are first looked at for the object before entering a planning and preparation phase. Furthermore, the activity will be carried out according to the given descriptions and requirements, and reported back for analysis and any further improvements. The result of these loops entails continuous improvement and optimization. This thesis focuses on the highlighted areas of Figure 12, within the planning and preparation phase.

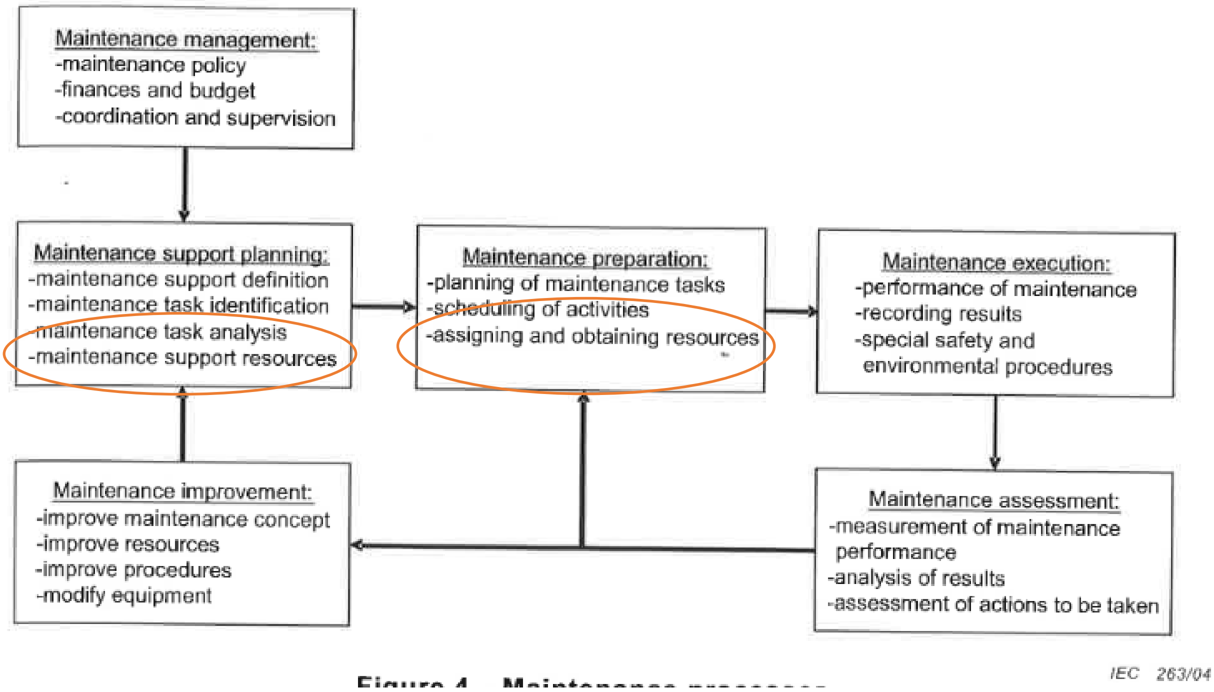


Figure 12: process for maintenance implementation [30]

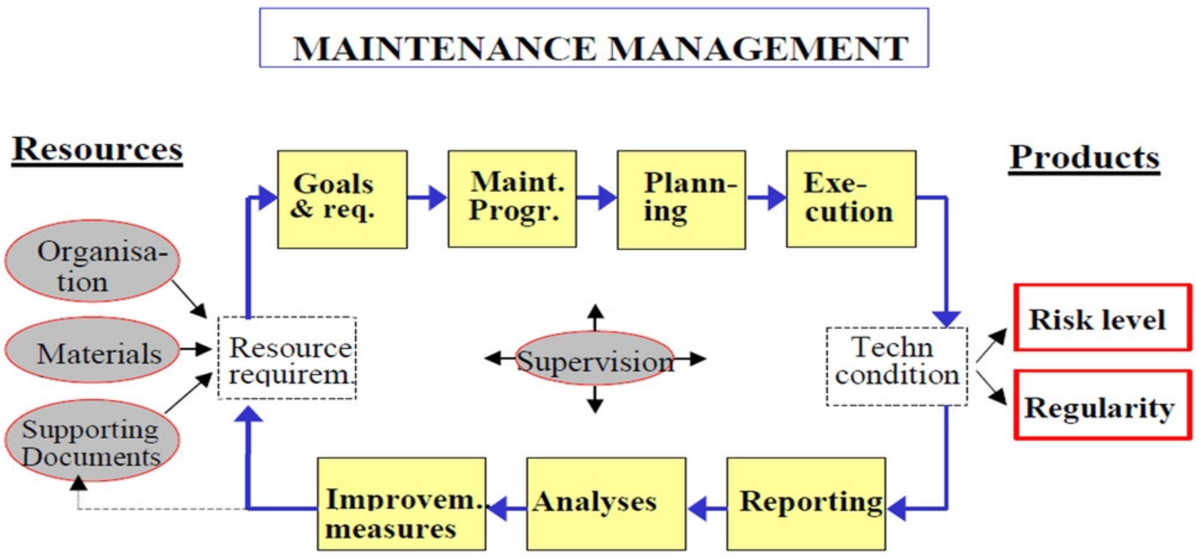


Figure 13 Maintenance management loop developed by the Norwegian Petroleum Directorate [31]

In the thesis, the standard IEC 60300-3-14:2004 has been used as a tool for systematic work towards the set goal. Figure 14 from the standard shows the same sequence used in the analysis [30]. The "determination of maintenance support" is the primary purpose of finding out, especially which means of transport will optimize it.

Furthermore, the sequence goes to "maintenance task definition", where various activities for collecting data such as "FMEA", "manufacturer recommended tasks", and "experience with similar items" are appointed as methods for collecting data for preventive and corrective maintenance tasks. It was attempted to contact manufacturers such as Siemens Gamesa and Vestas to obtain information about failure rates, scheduled maintenance to maintain the warranty and similar information. As a result of very little response from the companies, which mainly referred to their websites for information they were willing to share, it was inappropriate to use this as data in the analysis. Therefore, it was chosen to use "experience with similar items" in the analysis.

The failures have been divided into categories, or levels of repair, further elaborated in Chapter 5.1.1. It is done to distinguish which faults can use several means of transport and which will need special hazards to carry out the maintenance work. This part is essential to map in the thesis, as for this reason, it does not need to be considered in the analysis as it will be the same for both scenarios.

Finally comes "identification of maintenance support resources", where the analysis uses the software Shoreline to compare the two scenarios with the CTV and SOV. Here the various advantages and disadvantages will be identified to determine the best alternative for an imaginary 500 MW wind farm at Utsira Nord.

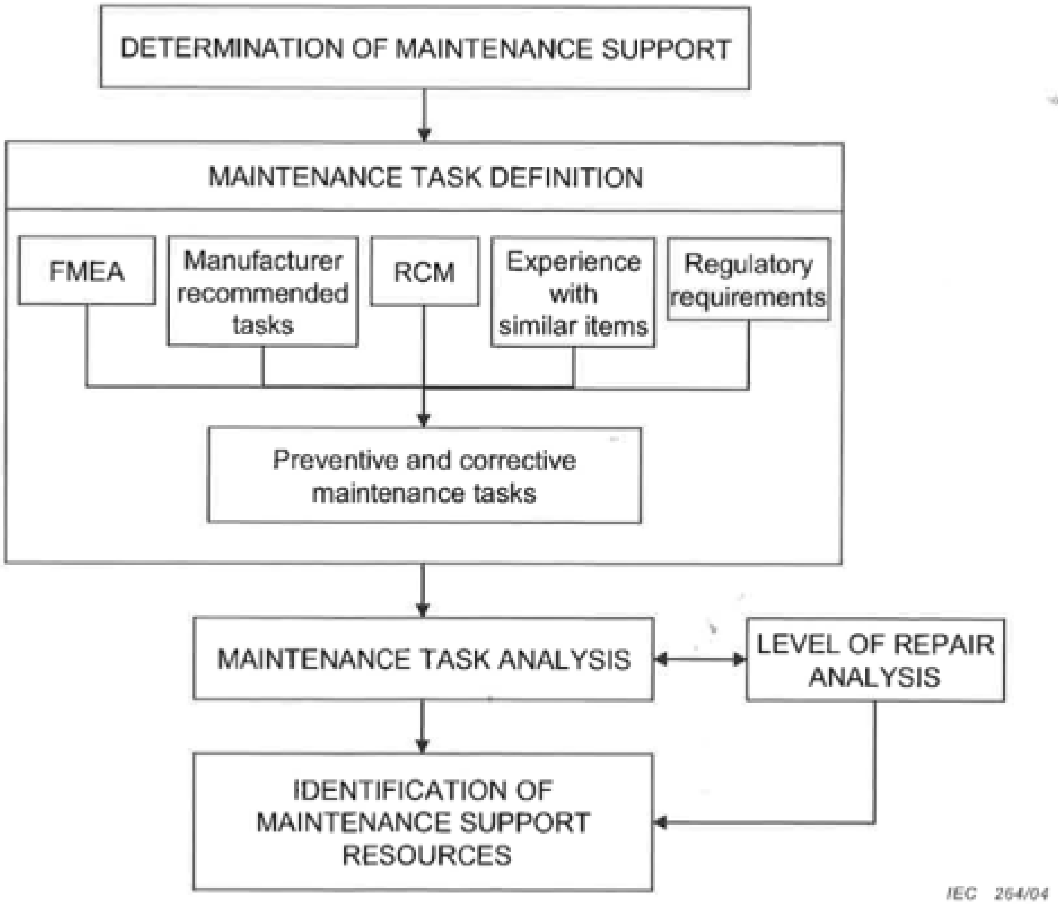


Figure 14: Maintenance planning process [30]

3 Research methodology and design

This chapter describes the research methodology purposefully designed to answer the research questions. It describes the main research steps and associated research philosophy, approach and strategy used, and the factors associated with data selection.

Research steps

The primary purpose of this thesis is to answer the following questions:

1. *How to utilize modelling and simulation method for selection of optimal maintenance logistics strategy for a wind farm at Utsira Nord*
2. *What will be an optimal maintenance logistics strategy for an imaginary Utsira Nord wind farm, seen from cost-benefit perspective and emission perspective*

The straightforward optimal approach would be to collect the required data from the wind park that is being analysed. Afterwards, it would be used to estimate the production performance, availability and emissions for the different maintenance logistic alternatives (e.g. CTV, SOV). However, three fundamental problems have created challenges in designing the research methodology of this thesis.

First, Utsira Nord is still in the early project phase, making historical data unavailable. Also, several relevant technical specifications, such as the turbine type, have not been decided yet. Therefore, there is a need to use data from other operating wind parks (with similar technical, i.e.operational conditions) and utilise a modelling and simulation approach to predict production performance, availability and emissions for several potential maintenance logistic alternatives.

Secondly, this case study requires involvement from several stakeholders to enable a practical evaluation of the existing and future logistics alternatives. Examples of involvement are potential operators that should come up with specific requirements and performance indicators. Furthermore, potential maintenance service providers shall estimate the potential major and minor failures. Lastly, vessel service providers shall also provide technical and economic specifications of their possible services. Therefore, three systems are the subject of analysis in this thesis: (1) the wind farm by itself, (2) the WTGs and its maintenance program (corrective and scheduled events), (3) the logistic vessel and its technical capacity, capabilities and limitations.

Third, the logistic maintenance alternatives for different scales and floating offshore wind parks are still under exploration. Important factors that need to be considered are for example distance from shore as well as weather conditions. Therefore, exploring the logistic maintenance alternatives is part of this thesis and requires a semi-structured interview with several vessel service providers.

In summary, the research methodology combines the case study and modelling and simulation methods. It also considers several systems (wind farm and WTG, maintenance program, vessels) as the subject of analysis. Furthermore, it depends on qualitative data, such as requirements and interpretation of technical specifications, and quantitative data, such as failure rates, capabilities, cost-related data, and CO_2-related data.

A research methodology of a six-step process has been designed and planned to be able to answer the research questions, considering the previously mentioned issues. Further, one will look at these steps and then explain the research approach and activities applied to ensure reliable and valid data sources, data analysis and results. The research steps are as follows:

1. Extract stakeholder requirements, acceptance criteria and define the purpose of the simulation model

2. Systems analysis of the wind park, maintenance program and logistic vessels

3. Collect and extract failure and maintenance data from existing offshore wind parks

4. Collect technical and economic data for several logistic maintenance vessels

5. Design and prepare the simulation cases

6. Perform the simulation cases and visualise the results

7. Verification and validation, including sensitivity analysis

8. Evaluate and select the most optimal logistic vessel alternative based on cost/availability and emissions

Table 5 shows the relationship between the different steps and the philosophical view. In the table's first steps, "critical realism" and "pragmatism" remain primarily used. These philosophical views well describe this part of the thesis, the main purpose of which was to acquire as much and thorough information as possible on the various topics. As the task moves to conduct simulations and interpret data, the table shows a change in the philosophical views used. "Interpretivism" is repeated in the last three steps, which are about how humans subjectively process the data.

Table 5 Research methodology step and philosophy

Steps/ core activity	Philosophical View
Extract stakeholder requirements, acceptance criteria and define the purpose of the simulation model	Critical realism
Systems analysis of the wind park, maintenance program and logistic vessels	Critical realism Pragmatism
Collect and extract failure and maintenance data from existing offshore wind parks	Critical realism Pragmatism
Collect technical and economic data for several logistic maintenance vessels	Critical realism Pragmatism
Design and prepare the simulation cases	Positivism Pragmatism
Perform the simulation cases and visualise the results	Constructivism and Interpretivism
Verification and validation, including sensitivity analysis	Positivism and Interpretivism Postmodernism
Evaluate and select the most optimal logistic vessel alternative based on cost/availability and emissions	Interpretivism

Research approach

Since the analysis is built up of two cases, the starting point for the simulation modelling, the abduction approach has been used. It is central as the data collected for the thesis is not generic for all wind parks. As a result, the conclusion will be based on and correct for this case with this data, however, it does not necessarily need to be the valid alternative for other wind farms.

The analysis is based on:

One case, 2 scenarios, 100 runs per simulation, 1 year per simulation

Research Strategy

As previously mentioned, quantitative and qualitative data were used to perform the simulations. There are qualitative data such as requirements and interpretation of technical specifications, and quantitative data such as failure rates, capabilities, cost-related data, and CO_2e-related data. The research strategy used is therefore mixed research strategy.

Research Method

A case study contains only one unit to be examined, while a comparative case study is used if several units are compared [32]. In this thesis, two different cases, CTV and SOV, will be analysed separately before being systematically compared and measured against each other. The sequence is shown in Figure 15.

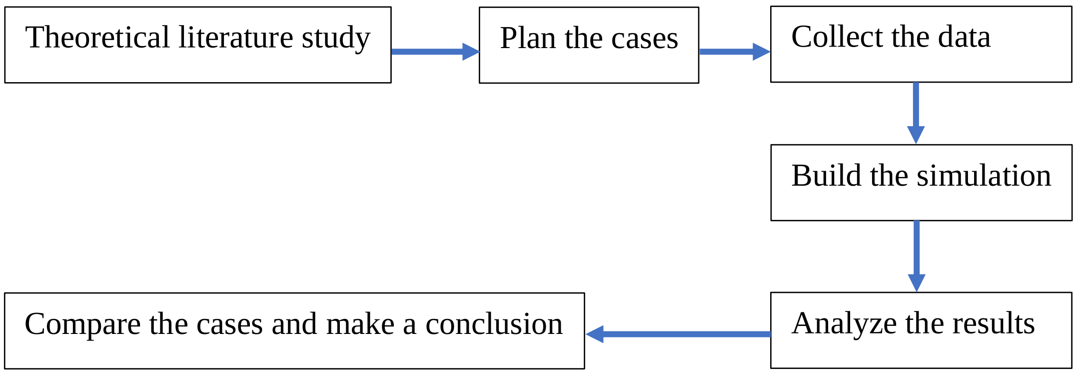


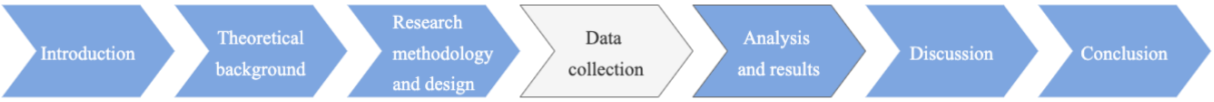
Figure 15: Sequency of this case study

Primary vs secondary Data Source:

To better understand where the data used in the research originates, it is common to divide the data into primary and secondary [33]. It easily distinguishes whether the source has been obtained directly in this context or if others have already collected it. Primary data is collected directly by the author to carry out the purpose of the research, often through, for example, field examination or interview. Secondary data is documented data from others, such as in a report or a book. It is possible to choose both approaches of data retrieval or choose one of them.

In this thesis, it was first attempted to obtain primary data from various players in the industry, both operators of wind farms and different support functions. It was a significant challenge because of a competition-focused industry that will not disclose its data. As a result, it was decided to go for secondary data already documented in reports. It was then checked against some of the aforementioned players and validated to be within the expected interval.

4 Data collection



This chapter goes through the case study company, and how the data used in the thesis is obtained and validated

----

4.1 The case study company

"We make clean electricity and empower coastal communities by harnessing the ocean winds." [34]

"Our business model is all about collaboration – with local communities, leading suppliers, national authorities, and supportive investors. Get to know our owners." [34]

Deep Wind Offshore (DWO) is an offshore wind company newly established in Haugesund[34]. The company has active ambitions to create a society that will benefit collectively, as the two quotes from their web page show. Its knowledge of vital and central owners with a multidimensional background in the maritime and energy sectors can benefit the company significantly. DWO has a joint venture with *Electricité de France* (EDF) for their project on Utsira Nord.

Knutsen Group is a fully integrated shipping with its head quatres in Haugesund. With its 120-year history, the company has the most valuable fleet in Norway[35]. They have built up a healthy environment in technology development, and see offshore wind as a future industry that should need their expertise. There are many specific projects within the offshore wind market where the Knutsen Group can utilize their broad knowledge.

Haugaland Kraft was formed as a merger in 1998, between *Haugesund Energi* and *Karmsund Kraftlag*[36] . Daily, they work with the production, transmission, and sale of electric power simultaneously as they also expand and operate fibre networks. The company draws on a lot of knowledge and experience in electric power, which will be an essential resource in developing wind power at Haugalandet.

Sunnhordaland Kraftlag is a subsidiary of *Haugaland Kraft*. With the ambition of ensuring stable and sufficient electric power to the inhabitants and industry in what was then Sunn- and Midthordaland, they were established in 1946 [37]. The company has for several years been named one of the country's most well-run and profitable energy companies.

4.2 Data sources

As mentioned in Chapter 3, primary and secondary data sources are distinguished. Table 6 lists the methods used to collect data and which strategies have been used to validate this data. It increases the credibility of the used information if it can be referred to as approximately equal data from several sources.

Table 6 : The data collection methods

	Data collection	**Validity**
Extract stakeholder requirements, acceptance criteria and define the purpose of the simulation model.	Experts and literature study	Online literature
Systems analysis of the wind park, maintenance program and logistic vessels	Literature study	Two expert opinions
Collect and extract failure and maintenance data from existing offshore wind parks.	Literature study	Two expert opinions
Collect technical and economic data for several logistic maintenance vessels.	Experts and literature study	Expert opinion and comparisons

5 Analysis and results

This chapter will review the natural frequency of the development of the thesis. Step 1 is to map the system, failure rates, criteria, and additional data. In step 2, shell this data be used to fill in the missing factors in the software Shoreline. The results from the analyses in the software will be presented in step 3. Finally, a validation analysis is presented to compare the results of this analysis against other analyses.

5.1 Step 1 – analysis and data

5.1.1 System analysis

Systematically, the maintenance objects are divided into two categories in the first round, replacements and repairs. The main reason for such an approach of the division is that these maintenance tasks require very different maintenance logistics to prepare the maintenance.

MCR stands for major component replacements, representing failures that require the replacement of large components to fix the failure. These failures will have major consequences for the operation of an offshore wind farm, as the downtime in anticipation of spare parts and resources will be great. The errors happen at such rare intervals that it is highly likely that these large components will not be in the project's O&M base for such a small wind farm. Since these failures will require far larger vessels than an SOV or CTV, they will not be considered in this analysis.

This analysis uses three allocations of repair, classified under major repair, minor repair and no cost data. The components considered in this analysis are shown in Figure 16. The division is taken from the article "Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines" by James Carroll, Alasdair McDonald and David McMillan [38]. It was decided to be the best source available for failure rates possible to obtain. The data is somewhat old and based on far smaller WTGs than the 15 MW relevant in this case study. Therefore, it is expected that this will affect the analysis results.

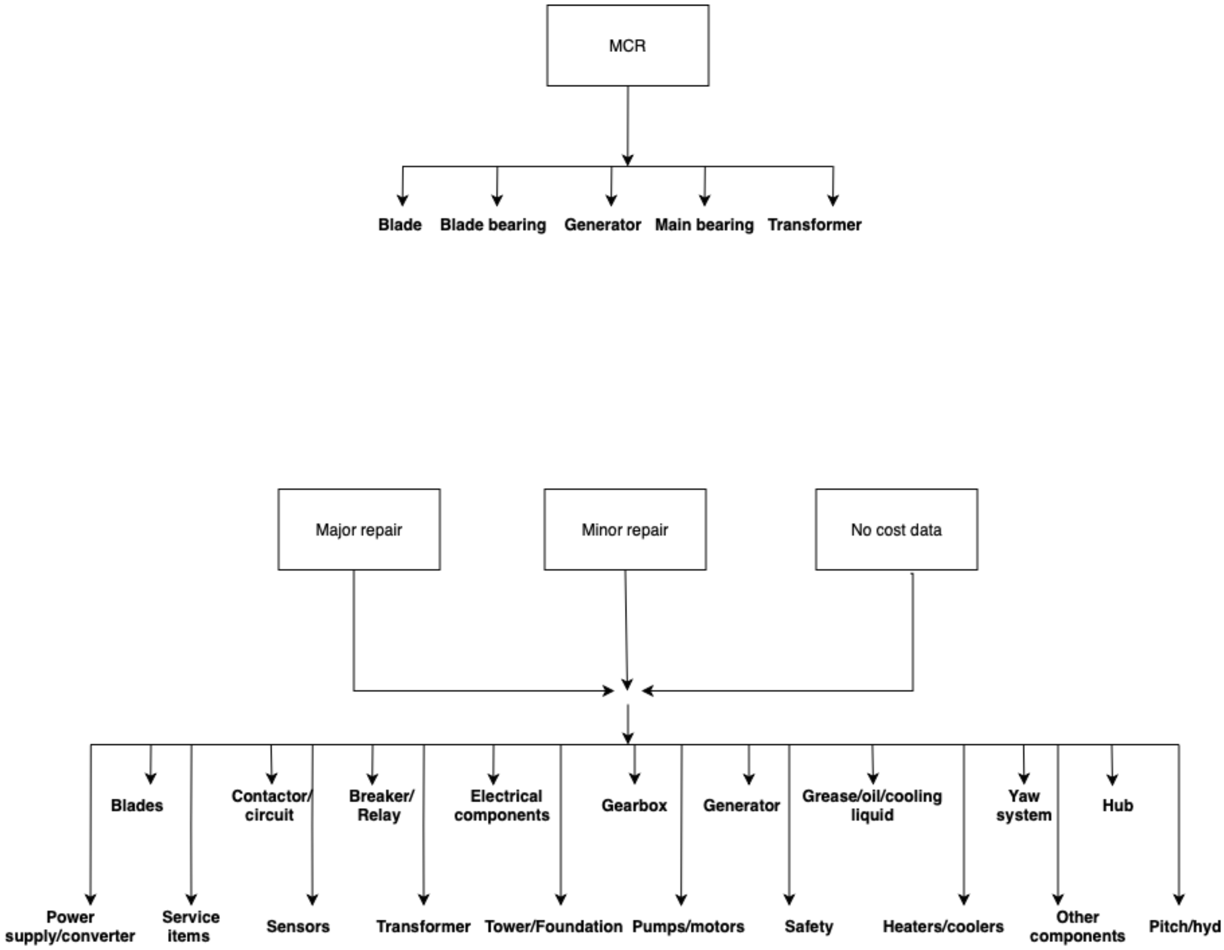


Figure 16: System analysis of the turbine

5.1.2 Failure data WTG

Essential factors to perform the analysis are to get crucial data on the frequency of failures, the number of technicians to fix them, and how many hours this takes. The data from Table 7, Table 8 and Table 9 is taken from the article by Carroll, McDonald and McMillan [38]. An overview of the data collected can also be found in Appendix 1.

Table 7: Failure rates /WTG/year

Components	Failure rates /WTG/year		
	Major repair	*Minor repair*	*No cost data*
Blades	0.01	0.456	0.053
Contactor/ circuit breaker/ Relay	0.054	0.326	0.048
Electrical components	0.016	0.358	0.059
Gearbox	0.038	0.395	0.046
Generator	0.321	0.485	0.098
Grease/oil/cooling liquid	0.006	0.407	0.058
Heaters/coolers	0.007	0.19	0.016
Hub	0.038	0.182	0.014
Other components	0.042	0.812	0.15
Pitch/hyd	0.179	0.824	0.072
Power supply/converter	0.081	0.076	0.018
Pumps/motors	0.043	0.278	0.025
Safety	0.004	0.373	0.015
Sensors	0.07	0.247	0.029
Service items	0.001	0.108	0.016
Tower/Foundation	0.089	0.092	0.004
Transformer	0.003	0.052	0.009
Yaw system	0.006	0.162	0.02

Table 8: Repair time

Components	Repair time		
	Major repair	*Minor repair*	*No cost data*
Blades	21	9	28
Contactor/ circuit breaker/ Relay	19	4	5
Electrical components	14	5	7
Gearbox	22	8	7
Generator	24	7	13
Grease/oil/cooling liquid	18	4	3
Heaters/coolers	14	5	5

Hub	40	10	8
Other components	21	5	8
Pitch/hyd	19	9	17
Power supply/converter	14	7	10
Pumps/motors	10	4	7
Safety	7	2	2
Sensors	6	8	8
Service items	0	7	9
Tower/Foundation	3	5	6
Transformer	26	7	19
Yaw system	20	5	9

Table 9: Required technician

Components	**Required technicians**		
	Major repair	*Minor repair*	*No cost data*
Blades	3	2	2
Contactor/ circuit breaker/ Relay	3	2	2
Electrical components	3	2	2
Gearbox	3	2	2
Generator	3	2	2
Grease/oil/cooling liquid	3	2	2
Heaters/coolers	3	2	3
Hub	4	2	2
Other components	3	2	2
Pitch/hyd	3	2	3
Power supply/converter	2	2	3
Pumps/motors	3	2	3
Safety	3	2	2
Sensors	2	2	3
Service items	0	2	2
Tower/Foundation	1	3	2
Transformer	3	3	3
Yaw system	3	2	2

5.1.3 Vessels

5.1.3.1 Fuel consumption

Table 10 below is used to calculate fuel consumption for both scenarios. The data is taken from the article "Setting a benchmark for decarbonising O&M vessels of offshore wind farms" by Dr Anthony Gray [39]. For secondary fuel, a modern SOV is expected to have access to an electric hybrid facility that can be used when the vessel is idle offshore. As a result, the fuel consumption of an SOV will be relatively low when in the field. On the other hand, it is way higher when transiting than a CTV.

Table 10: Fuel information for the scenarios[39]

	Scenario 1	**Scenario 2**
Vessel type	CTV	SOV
Primary fuel	MFO (Marine fuel oil)	MGO (Marine Gas Oil)
Secondary fuel	None	Electric
Fuel Consumption per hour, transiting	320 litres/hour	1,000 litres/hour
Fuel Consumption per hour, when idle offshore (in-field)	130 litres/hour	120 litres/hour

Based on the data from vessels speed and Table 10, fuel consumption can be counted in litres/km:

$$\text{Fuel consumption in transit}_{\text{CTV}} = \frac{320\ \frac{litres}{hour}}{41\ \frac{km}{hour}} = \mathbf{7,8}\,\frac{\textbf{Litre}}{\textbf{km}}$$

Equation 1

$$\text{Fuel consumption in transit}_{\text{SOV}} = \frac{1{,}000\ \frac{litres}{hour}}{22\ \frac{km}{hour}} = \mathbf{45,5}\,\frac{\textbf{Litre}}{\textbf{km}}$$

Equation 2

5.1.3.2 CTV

Much of the data is based on assumptions and expectations of developments in the future. The day rate of € 3,000 is based on the information that the expected day rate for an SOV is 8-10 times greater than for a CTV [40]. The data collected for the CTV is shown in Appendix 2.

5.1.3.3 SOV

Edda Wind was contacted for the day rate of an SOV to hear what kind of thoughts they had about expecting prices for around year 2030 [41]. They responded that a day rate of € 30,000 could be expected. It will naturally be highly based on assumptions about the future, such as large parts of the other data. The data collected for the SOV is shown in Appendix 3.

5.1.3.4 Fuel emissions

It is necessary to get an overview of the emission of the different fuels to calculate the emissions associated with the various vessels. Table 11 below shows the different emissions and the total CO_2e for average transit and when idle offshore [39].

Table 11: Emission data for the fuel [39]

	Scenario 1 (MFO)	Scenario 2 (MGO)
CO_2 produced at average transit speed	948.7 kg CO_2/hours	2,737.8 kg CO_2/hours
CH_4 produced at average transit speed	0.4 kg CH_4/hours	0.7 kg CH_4/hours
N_2O produced at average transit speed	14 kg N_2O/hours	36.9 kg N_2O/hours
CO_2e produced at average transit speed	999.1 kg CO_2e/hours	2,775.4 kg CO_2e/hours
CO_2 produced when idle offshore (in-field)	400 kg CO_2/hours	328.5 kg CO_2/hours
CH_4 produced when idle offshore (in-field)	0.2 kg CH_4/hours	0.1 kg CH_4/hours
N_2O produced when idle offshore (in-field)	5.7 kg N_2O/hours	4.4 kg N_2O/hours
CO_2e produced when idle offshore (in-field)	405.9 kg CO_2e/hours	333.0 kg CO_2e/hours

5.1.4 Stakeholder analysis and criteria

A Stakeholder analysis has been prepared in Table 12, to get an overview of the decisive factors for the criteria in the analysis. The main stakeholders connected to the case have been set up to map their needs. Furthermore, the needs are related to the requirements needed to achieve the needs. Based on this, the criteria necessary to consider in the analysis to optimize maintenance logistics are made.

The stakeholders have different priorities in the project, but they all have essential roles that must be considered to operate in a secure, social, political and economic context. For the owners, it was naturally as high a profit as possible that is the need. It is achieved by reducing downtime and choosing low-cost solutions, resulting in cost-effective criteria.

For those who are to be transported out to do the maintenance work, it is crucial that it takes place safely and reliably. It involves some reliability to the operation going in weather that can ensure optimal working conditions. However, the transport out to the WTGs and the transition onto the turbines shall occur according to given HSE standards.

On the other hand, the customer has entirely different needs associated with the case. Low prices will be central for customers to buy electricity, primarily known that floating offshore wind will have higher prices than what has been known historically in Norway. Furthermore, the customer needs to ensure continuous power according to its needs. Therefore, it will be critical to repair failures to ensure uptime in the shortest possible time.

In a socio-political context, the demand for reduced emissions is extreme, which is also the main factor for the rapid development of renewable energy sources today. Therefore, it will be necessary to consider the emissions associated with the maintenance logistics. It may be challenging to set priorities between costs and emissions, but this factor could create enormous costs in the future as the price of the CO_2 quota increases drastically.

Table 12: Stakeholder analysis and key acceptance criteria

Stakeholder	Needs	Requirements	Criteria
Owners	High profit	Low downtime and most affordable option	Cost and availability
Operators/ maintenance team	Reliable transport, comfortable and safe	Is reliable to be able to transport when the work is needed, the journey must be as comfortable as possible, and the transfer on to the WTG must be safe	Security and reliability
Entrepreneurs	Comfortable and safe	The journey must be as comfortable as possible, and then transfer to the WTG must be safe	Security
Costumer	Affordable power, access to power when needed	Optimization of production cost, low downtime	Availability and cost
Society	Environmentally friendly	Low emissions and sustainable	Environment

5.2 Step 2 - Input

5.2.1 Bases

The first thing that was decided in executing the thesis was to map out what opportunities for bases exist in the local area. It should be of a decent size to accommodate vessels on different scales, while at the same time, it should be possible to build the O&M base there. Two ports belonging to Karmsund Havn were visited, Killingøy and Husøy, and a visit to Gismarvik Næringspark.

Gismarvik Næringspark is not of great interest for this case as various companies will share the quay area. Therefore, it was clarified early on that this area might be relevant for construction but not for O&M for this imaginary case.

The area and development opportunities on Husøy are in themselves stimulating. It is located so that there are two passages out to Utsira Nord, both of which have clear height restrictions as e result of a bridge in the north and high-voltage lines in the south. It will not cause any problem in day-to-day operation, as the height restrictions are far higher than what SOV and CTV needs. The distance out to the field, on the other hand, is longer than if it is placed on Killingøy.

As a result, Killingøy is the base used in this imaginary case, shown in Figure 17. The area has been developed as a subsea and offshore base for the oil and gas sector, with key players such as Deep Ocean within the gates. It is centralized in the far north of the passage through Karmsundet and is, therefore, the area closest to the wind farm. Karmsund Havn has an accessible location at the base of a suitable size for the imaginary project. It is also possible to dock with SOV and CTV. This cost is not considered because the base fee will be the same for both scenarios.

Figure 17: The locations of the different bases

In Shoreline, it is necessary to set coordinates for the location of the base of Killingøy, shown in Figure 18. From the base's location to the field, one can set up a custom route, making it possible to calculate the distance out to the field. The simulation conducted in Shoreline is also based on weather data to calculate availability. Therefore, under the tab "weather", there is a need to download an ERA5 weather file with historical data dating back to 1979.

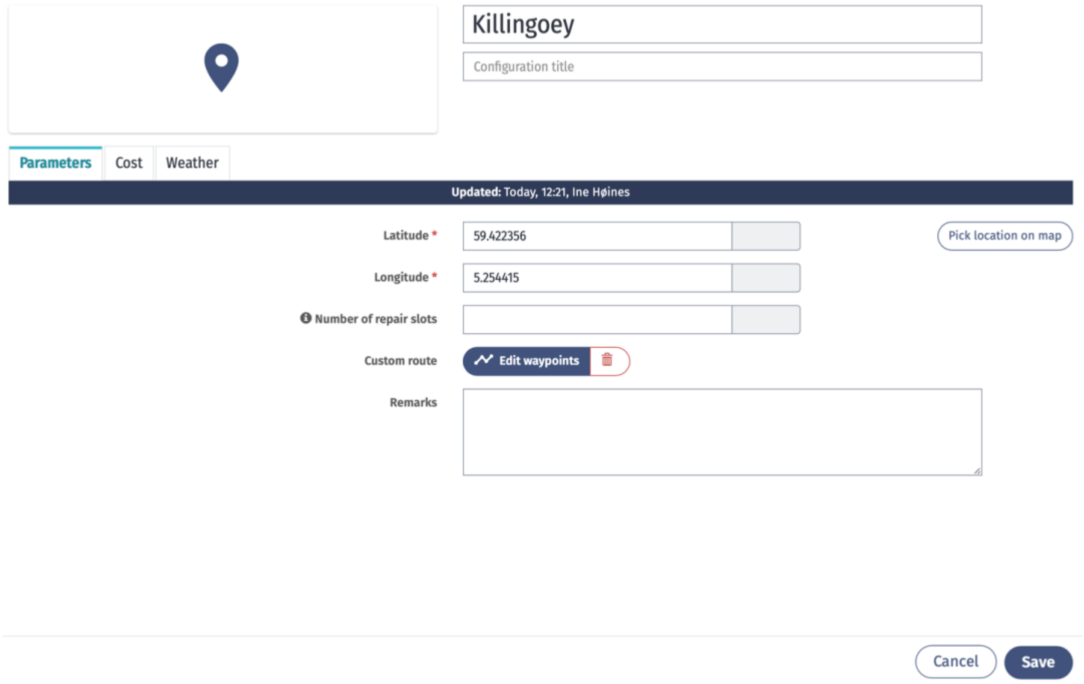


Figure 18: Rregistration of base in Shoreline

5.2.2 Assets

The next step is to set up the assets associated with the specific project. WTGs are analysed isolated in this project, but this tab is where foundations, cables, and other similar assets are registered in complete projects.

The tab consists of seven sub-tabs, which form the basis for all the calculations made in the analysis:

- Parameters
- Weather criteria
- Power curve
- Scheduled Maintenance
- Corrective Maintenance
- Weather

Figure 19 displays an overview of some of the information entered. As already described, the imaginary park consists of 34 WTGs of 15 MW each. Again, ERA5 historical weather data has been used, which stretches back to 1979, to support the reliability of the analysis. From Figure 19 one can also see that one scheduled task and 54 corrective tasks have been registered on each of the WTGs in this wind farm.

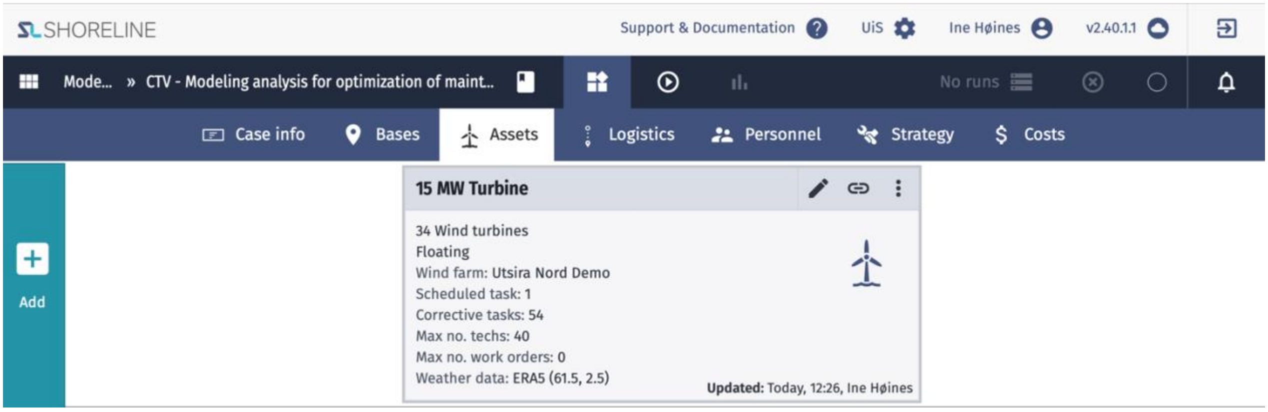


Figure 19: Overview of assets in Shoreline

Scheduled maintenance is recorded by entering a start date for the work, shown in Figure 20. It marks the start of a campaign, where additional resources are often contracted to carry it out. Moreover, a recurrence must be determined for the interval of the maintenance work, whether it occurs only the first year, every year, every fourth year, etc. In this case, the scheduled maintenance is set to occur every year. The production loss during the work is set to 100%.

Furthermore, choosing which vessel will be used to carry out the scheduled maintenance is necessary. Here, in Scenario 1, it will be checked off for CTV, while in Scenario 2, it will be checked off for SOV. When planning the crew, how many technicians and what skills they should have must be documented. Lastly, is a field where the number of man-hours is set and how long the repair time is. It is also possible to add spare part costs into this tab, but as it will be the same for both scenarios, it is chosen not to be included in the analysis

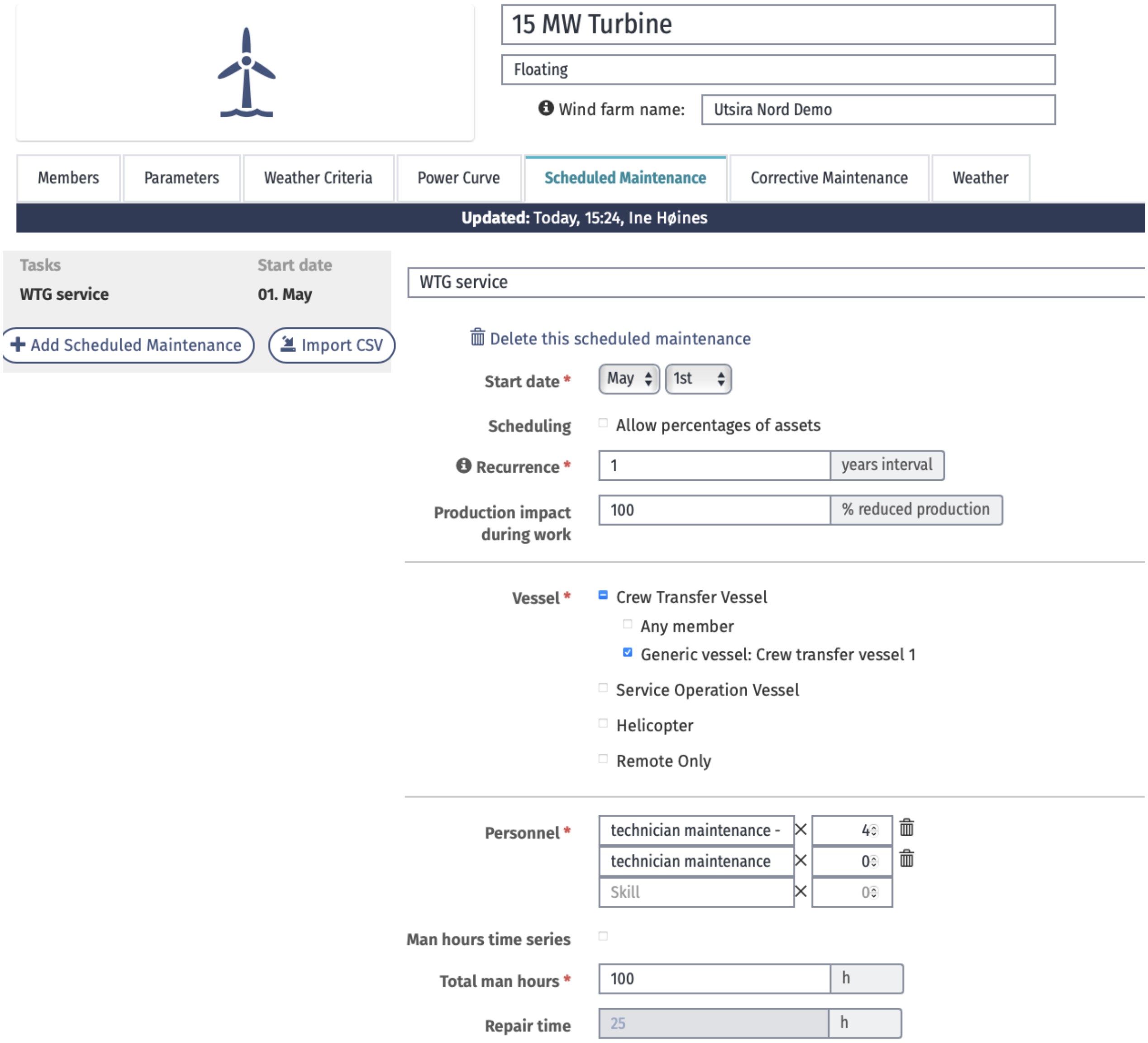


Figure 20: Scheduled maintenance task in Shoreline

The same data is also mainly used under corrective maintenance regarding vessels, personnel and how long it takes to repair the failure, as shown in Figure 21. However, there is a distinction in the introduction of severity, distribution, annual failure rate, production impact from failure and production impact from work. All the corrective tasks are critical and with exponential distribution in this analysis. There is also 100% reduced production both during the failure and during the work of repairing it. There are two different methods for the annual failure rate by which it can be documented. If one has access to detailed data that can show the failure rate for each year in the expected lifetime of the WTG, it is possible to register it year by year, which will provide a better estimate for each year. The average failure rate per year is used with the available data in this thesis.

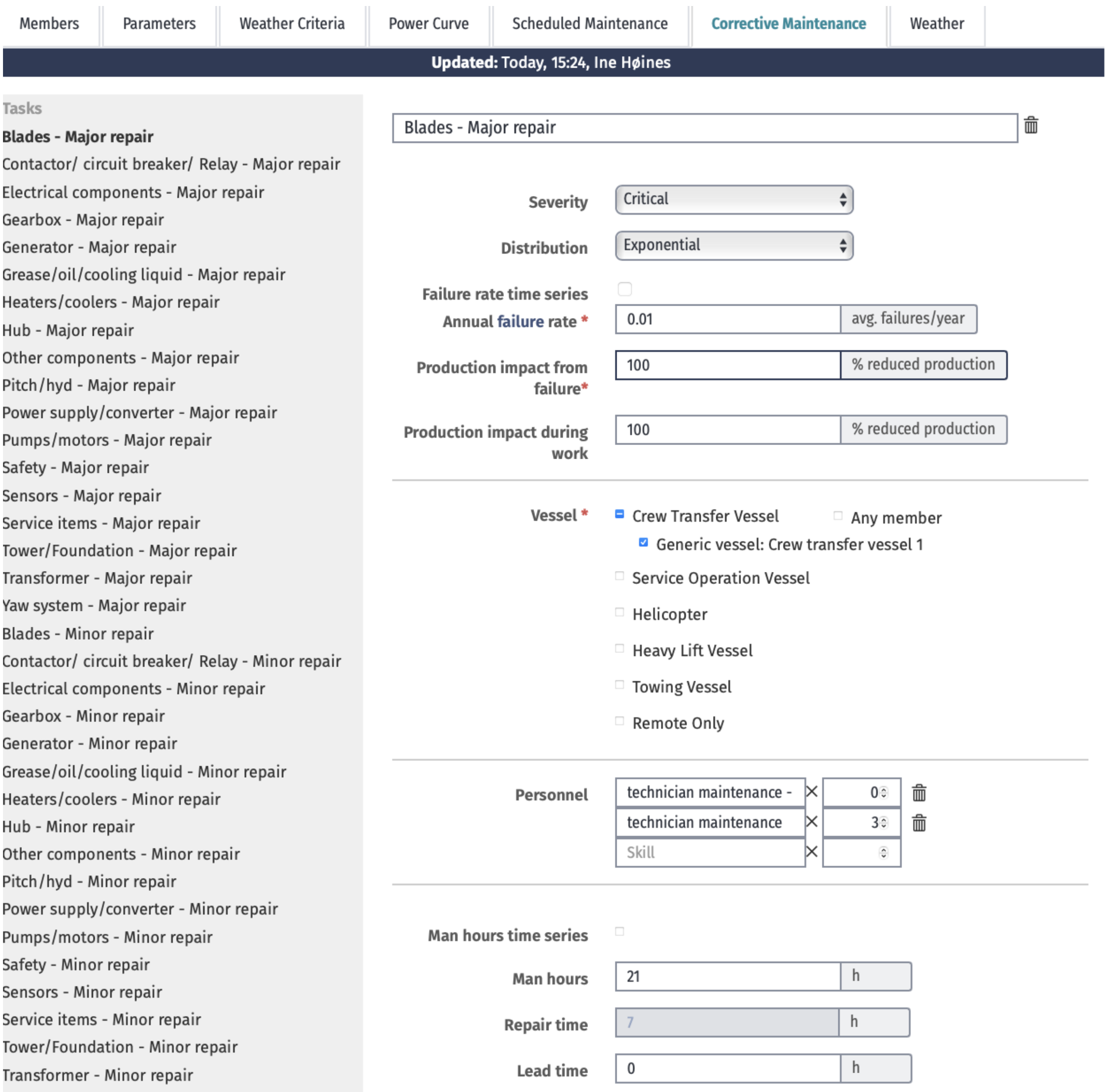


Figure 21: Corrective maintenance task in Shoreline

5.2.3 Logistic

Under the tool "logistics", there are many options for different solutions and needs. Examples of the alternatives are CTV, SOV, Heavy lift vessel (HLV), Heli, Towing vessel, Cable installation vessel and more. In the next two sub-chapters, a closer look will be made at how to register a CTV and an SOV.

Table 13 was made from historical data between 1957-2016 from The Norwegian Meteorological Institute [42]. The table shows that 63% of the year will be a higher wave height than 1,5 m. This wave height is often rendered as the industry standard for CTV, but at the same time, most experts also state that they operate up to 2.5 m. Therefore, the maximum wave height is set to 2.5 m for CTV in this analysis, which means that, on average it is available 67% of the year based on the wave height. Developments in this area are also expected to increase rapidly now that offshore wind is one of the fastest-growing industries.

The wave height limit is somewhat higher for SOV, which is around 3.5 m. Based on the table prepared below, the average availability of 77% can be summed up for the wave height. The W2W bridge to the WTGs makes the transfer less risky in bad weather.

Table 13: Average (avg.) distribution of wave height for one year

Hs	Avg. days in a year	Avg. hours in a year	% Of occurrence in an avg. year
< 1.5 m	136.4	3,273.7	37 %
1.5 – 2 m	60.8	1,460.3	17 %
2 – 2.5 m	47.3	1,135.8	13 %
2.5 – 3 m	35.7	858	10 %
> 3 m	84.4	2,034.1	23 %

5.2.3.1 Scenario 1 - CTV

Several different CTVs can be selected in Shoreline. In this analysis, it was chosen to use "Catamaran, medium". The main factors for the vessel is summarized in Figure 22 below.

Figure 22: Overview of information added for CTV

Table 14 shows all the data that has been selected for the CTV in this case. There are eight tabs with the names: members, parameters, capacity, performance, weather criteria, fuel consumption, cost and activity parameters. Each of these tabs has different factors that need to be assigned a value, shown on the right side of the table. These values are crucial in the analysis, such as the "Significant wave height access limit – 2.5 m" limiting the availability of the vessel based on the historical weather data selected for the area.

Table 14: Selected data in Shoreline for CTV

Members		
	Crew transfer vessels	Add 1
Parameters		
	Crew size	2
Capacity		
	Technician capacity	12 seats
Performance		
	Cruising speed	22 kn
Weather Criteria		
	Significant wave height access limit	2,5 m
Fuel Consumption		
	Fuel unit	Litre-unit
	Fuel consumption in transit	7,8 litre/km

	Fuel consumption when idle offshore	130 litre/hour
Cost		
	Day rate	€ 3,000
	Fuel cost	2 €/litre
Activity Durations		
	Lead time	10 minutes
	Connection time	5 minutes
	Disconnection time	1 minute
	Personnel transfer time per technician	5 minutes
	Equipment transfer timer	10 minutes
	Mobilising time per port visit	30 minutes
	Demobilising time per port visit	30 minutes

5.2.3.2 Scenario 2 - SOV

For Scenario 2 with the SOV, there is only one option in Shoreline; the choice is thus apparent. A summary of the factors is shown in Figure 23 below.

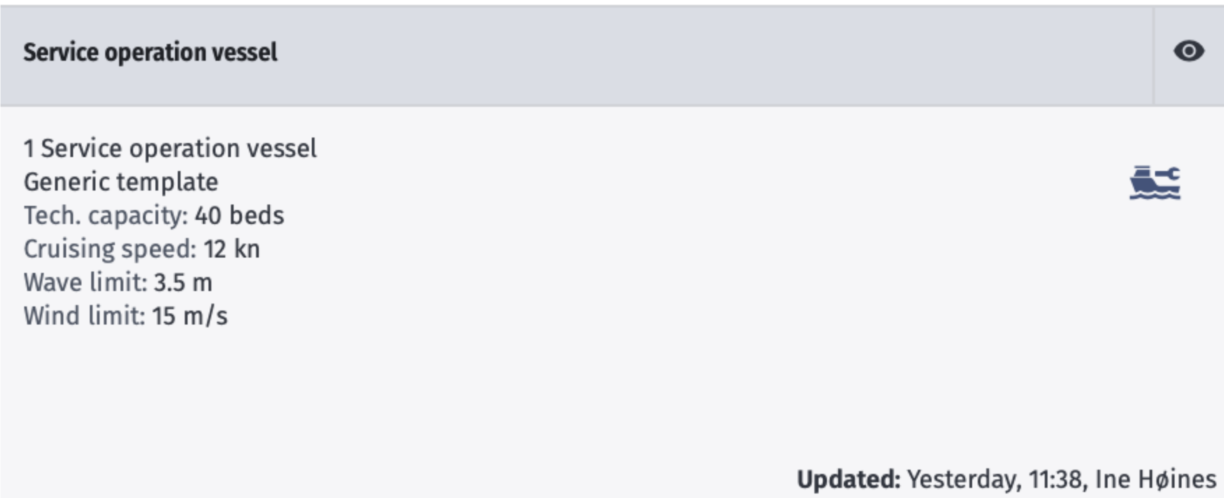


Figure 23: Overview of information added for SOV in Shoreline

Table 15 shows all the factors used for logistics in scenario 2 with an SOV in the analysis. There are significant differences that distinguish the SOV from the CTV. First, the essential difference is that the SOV stays on the field for 28 days instead of transporting staff daily to the port. It will affect the day rate, which is expected to be around € 30,000 around the start-up of the field at Utsira Nord.

Table 15: Selected data in Shoreline for SOV

Members		
	Service Operation vessels	Add 1
Parameters		
	Crew size	10
Capacity		
	Technician capacity	40 seats
Performance		
	Cruising speed	12 kn
	Dynamic positioning transit speed	5 kn
	Dynamic positioning activation time	20 minutes
Weather Criteria		
	Significant wave height access limit	3,5 m
	Wind speed access limit	15 m/s
	Wind speed limitation reference height	200 m
Fuel Consumption		
	Fuel unit	Litre-unit
	Fuel consumption in transit	45,5 litre/km
	Fuel consumption when idle offshore	120 litre/hour
Cost		
	Day rate	€ 30,000
	Fuel cost	2 €/litre
Activity Durations		
	Time between going to port	28 days
	Lead time	1 hour
	Connection time	10 minutes
	Disconnection time	5 minutes
	Personnel transfer time per technician	2 minutes
	Equipment transfer timer	10 minutes
	Mobilising time per port visit	30 minutes
	Demobilising time per port visit	30 minutes

5.2.4 Personnel

5.2.4.1 Scenario 1 – CTV

For personnel, it is necessary to set up crews that meet the skills added to the various maintenance tasks under the WTG in Assets. It was demanded that personnel for scheduled tasks had the skill "maintenance operator – campaign" and corrective tasks needed personnel with the skill "maintenance operator".

It is necessary to set up a campaign period to carry out scheduled maintenance, during which 25 working hours for four technicians will be carried out for all 34 WTGs. This resulted in the well-known "trial and error" method, where the goal was to find the period length that completed all the work orders while not using unnecessary resources. Some simulations did not have enough time to complete all the work orders, and it was then necessary to return to the input to extend the campaign period. The maintenance window is added to the summer months because it is the time of year with the calmest condition, and the lowest energy production. For CTV, it is set for May 1st to July 10th shown in Figure 24.

Figure 24: Chosen campaign period for the CTV

To register personnel, shown in Figure 25, it was also necessary to follow the "trial and error" method. There should be enough personnel to carry out as many maintenance tasks as possible while reducing unused resources by the most significant margin. After several attempts, the number of full-time personnel with this skill was set to eight in Scenario 1, with their home base at Killingøy. These will work outside the campaign, which means they work all year round. The simulation is based on 12 hours shifts, with two shifts, thus allowing for 24 hours of operations. No rotational plane has been established, however, these are minor factors for the results and have not been seen as something this master's thesis will solve.

The annual salary for technicians has been set to €65,000 per person, after conversations with various experts at the heart of the industry. This salary is an isolated estimate, which does not necessarily have to represent what will be relevant for these jobs in 2030. Here the same applies to working hours and rotation plans. The industry will determine and optimise it using several factors that have not been prepared. It can be expected that this annual salary may be higher according to the strategies chosen for the personnel.

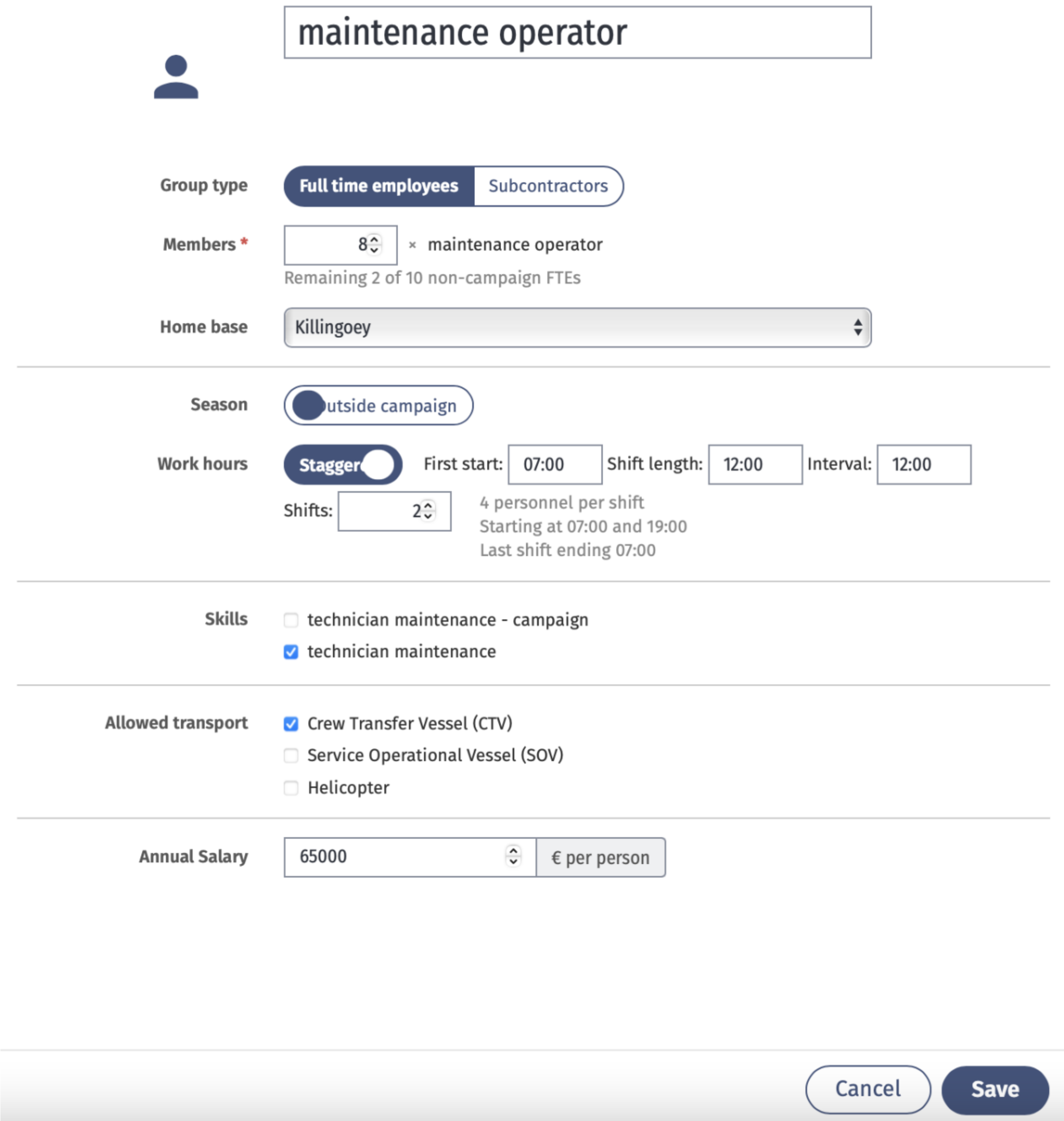


Figure 25: Registration of non-campaign personnel in Shoreline

When "maintenance operator - campaign" is detected, shown in Figure 26, no significant differences distinguish these technicians from those with the "maintenance operator" skill. There are 24 technicians, divided into two shifts of 12 hours each, with the same assumptions for rotation plans and pay as the "maintenance operator". What distinguishes the two is that "maintenance operator - campaign" has both skills and is now registered as "within campaign".

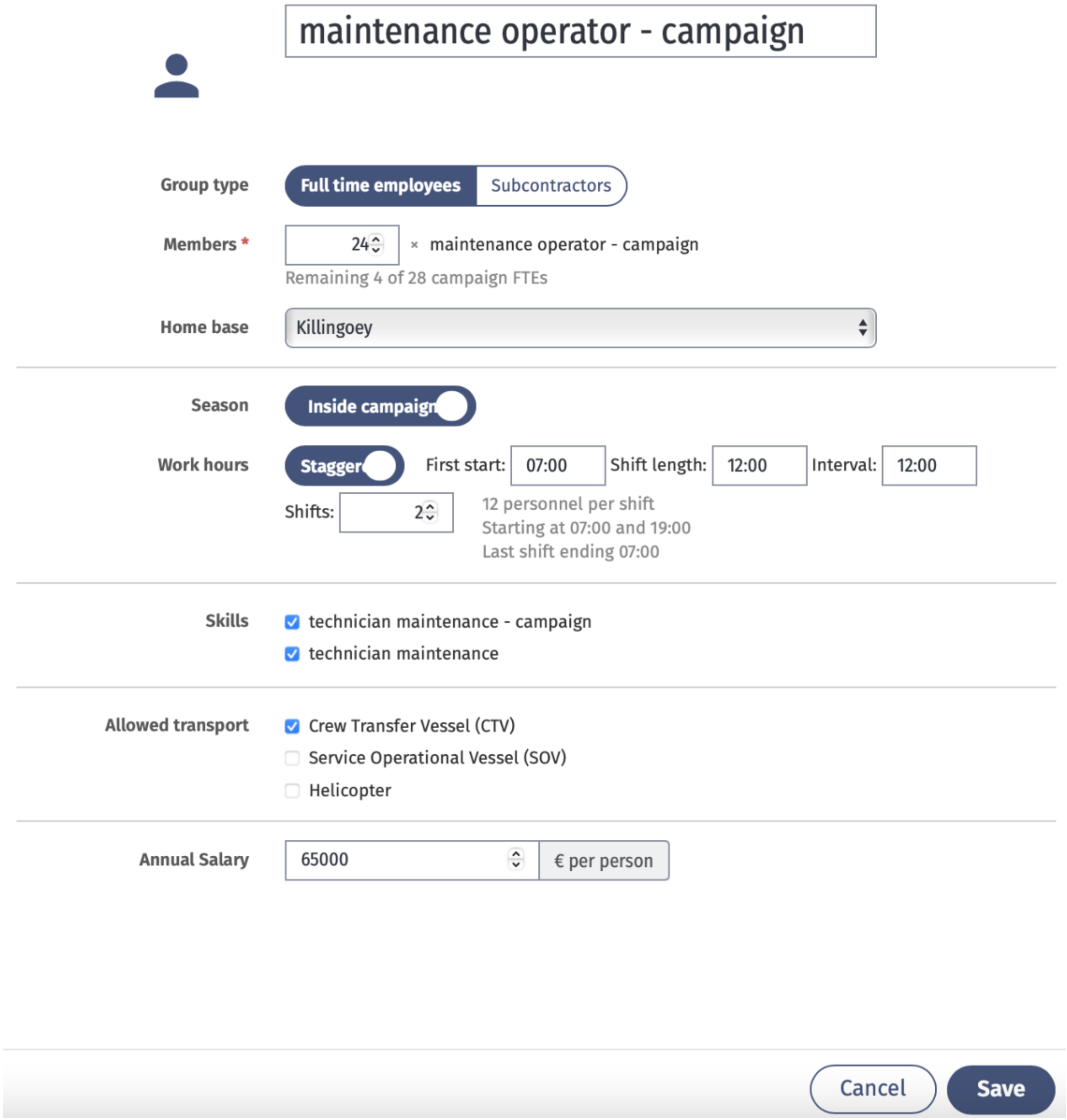


Figure 26: Registration of campaign personnel in Shoreline

5.2.4.2 Scenario 2 - SOV

For the SOV, the annual campaign will be concluded from May 1st to July 5th after trial and error, as shown in Figure 27. This strategy will give zero unfinished work orders and add a small safety margin.

Figure 27: Chosen campaign period for the SOV

Regarding "maintenance operator," for the SOV, shown in Figure 28, it will have many of the same assumptions in Scenario 2 as in Scenario 1. The only thing that distinguishes them is that there are only half as many workers on the SOV compared to the CTV, because there is only one shift here compared to two shifts. It is because the maximum number of workers on each of the maintenance tasks was four on one of the tasks. Therefore, four technicians are on board to perform all tasks. In opposition to Scenario1, where there must be twice as many, eight, to provide sufficient technicians on each shift to perform all types of maintenance tasks.

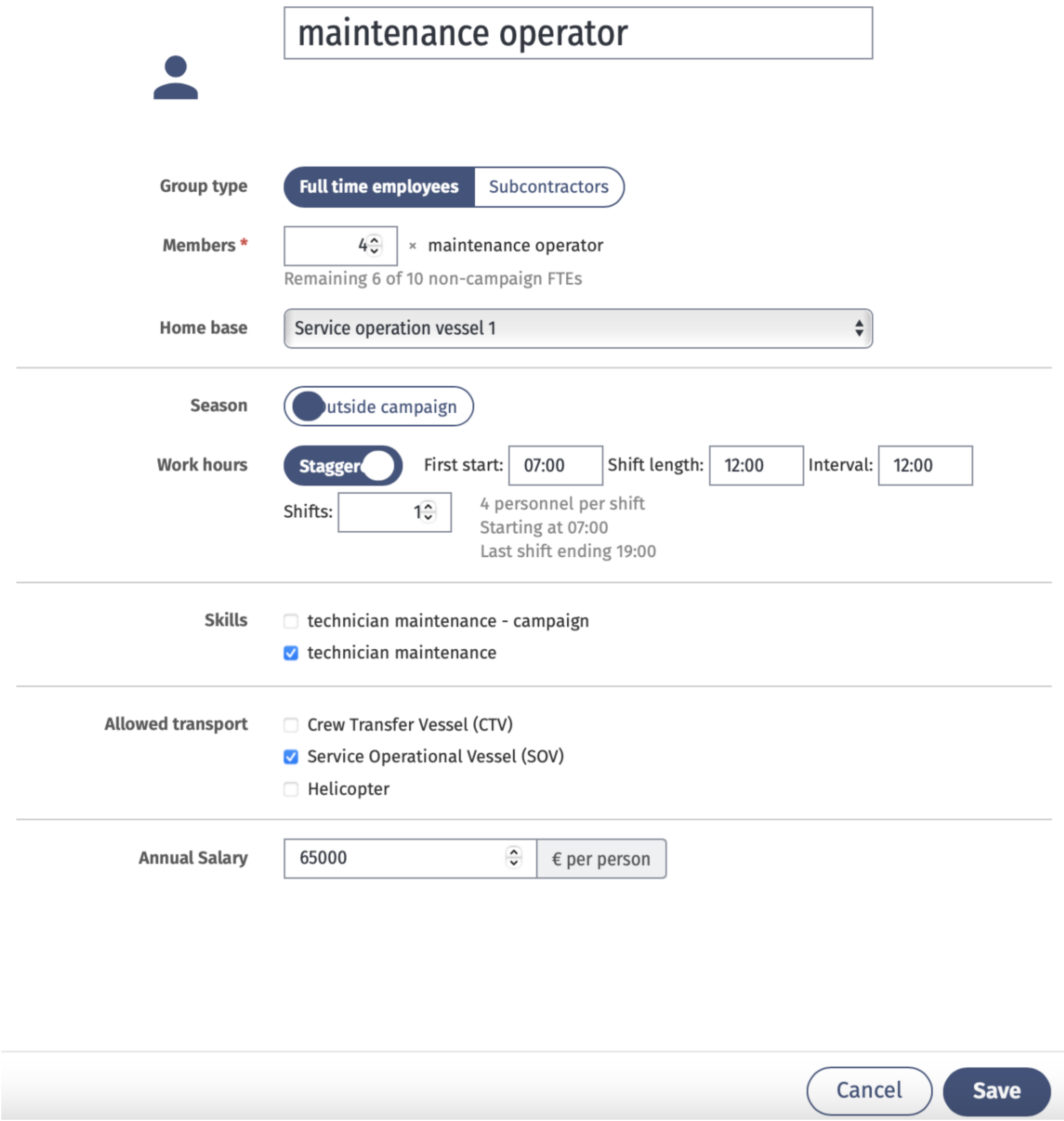


Figure 28: Registration of non-campaign personnel in Shoreline

For "maintenance operator - campaign", Figure 29, there are also apparent similarities to the information in Figure 26 for Scenario 1. The only difference here is that it is just one shift, with 28 workers. It was determined through the "error and trial" method. Initially, there was room for 40 technicians on board, but through visualizations, it was discovered that it was a lot of wasted time dropping off and picking them up on the WTGs within the working hours.

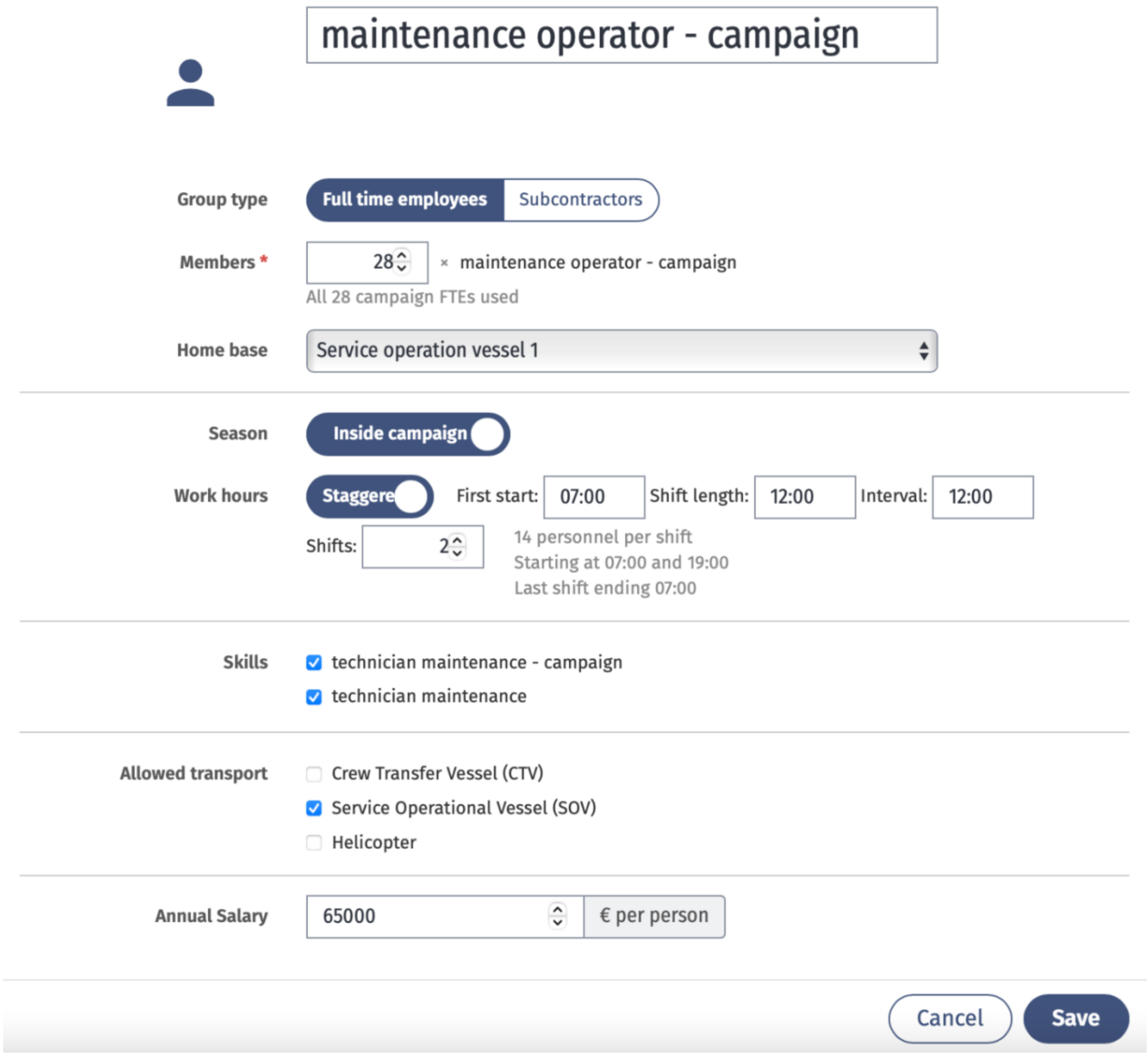


Figure 29: Registration of campaign personnel in Shoreline

5.2.5 Strategy

The “Strategy” tab in Shoreline consists of specific factors that will limit the maintenance of the case. Examples of factors that need to be clarified are the "emergency response limit", determining how far the vessel can move away from the WTG where it has been dropped off technicians. This tab is almost identical to Scenario 1 (Figure 30) and Scenario 2 (Figure 31). The only difference between the two figures is that Scenario 2 has a "Crew change strategy", as the crew lives on board the vessel for an extended period.

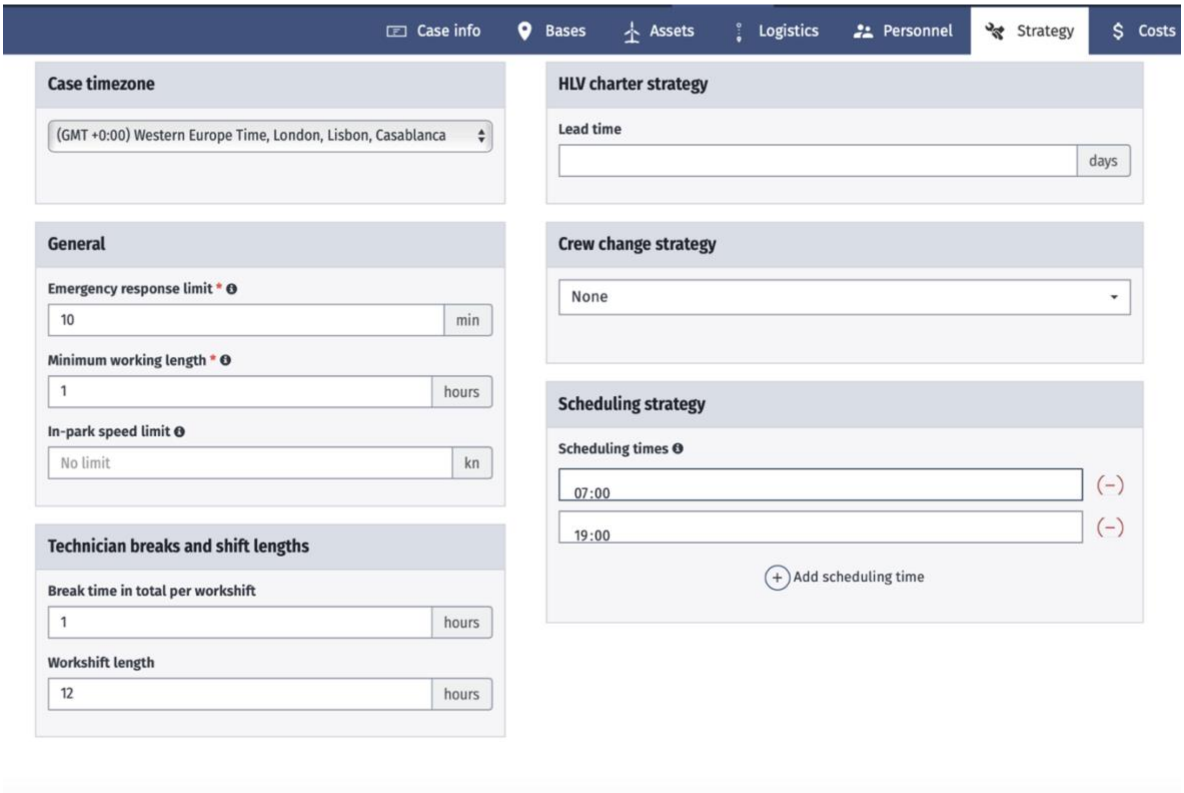


Figure 30: Strategy for CTV in Shoreline

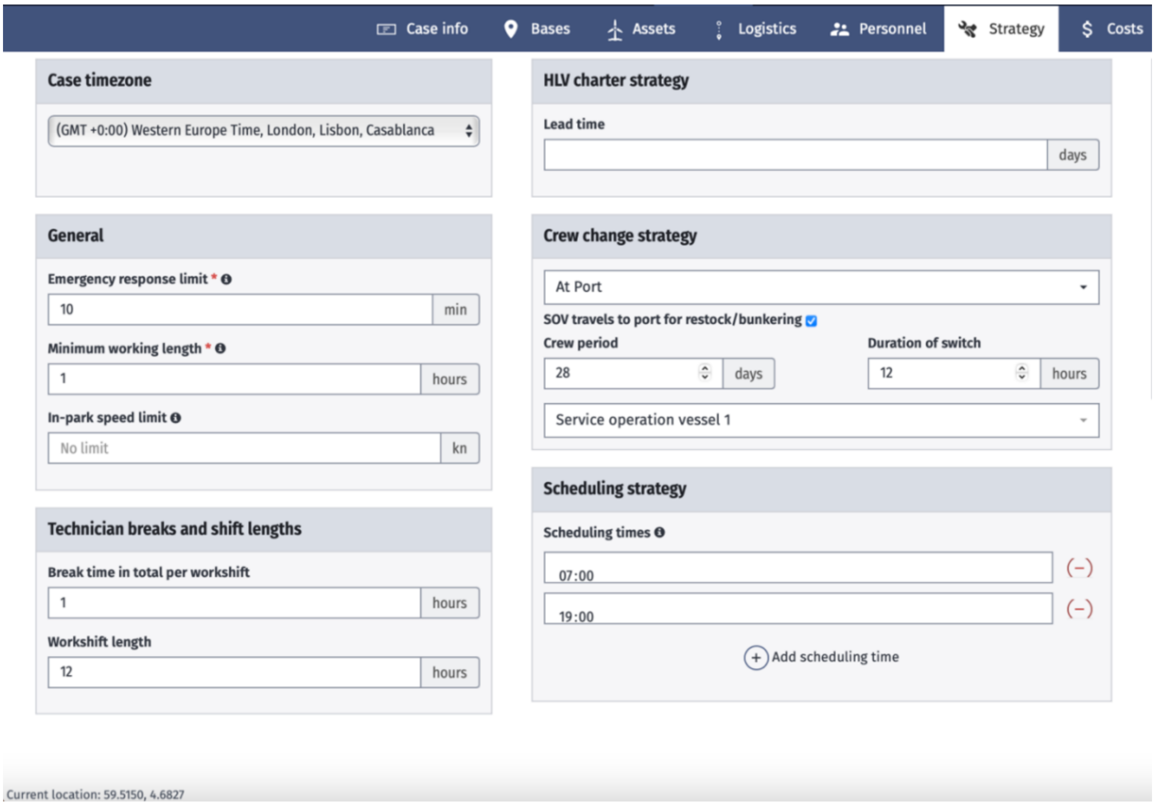


Figure 31: Strategy for SOV in Shoreline

Under "Strategy", it is also possible to set priorities for the work orders that are both corrective and scheduled. The priorities used in both scenarios in this thesis are shown in Figure 32.

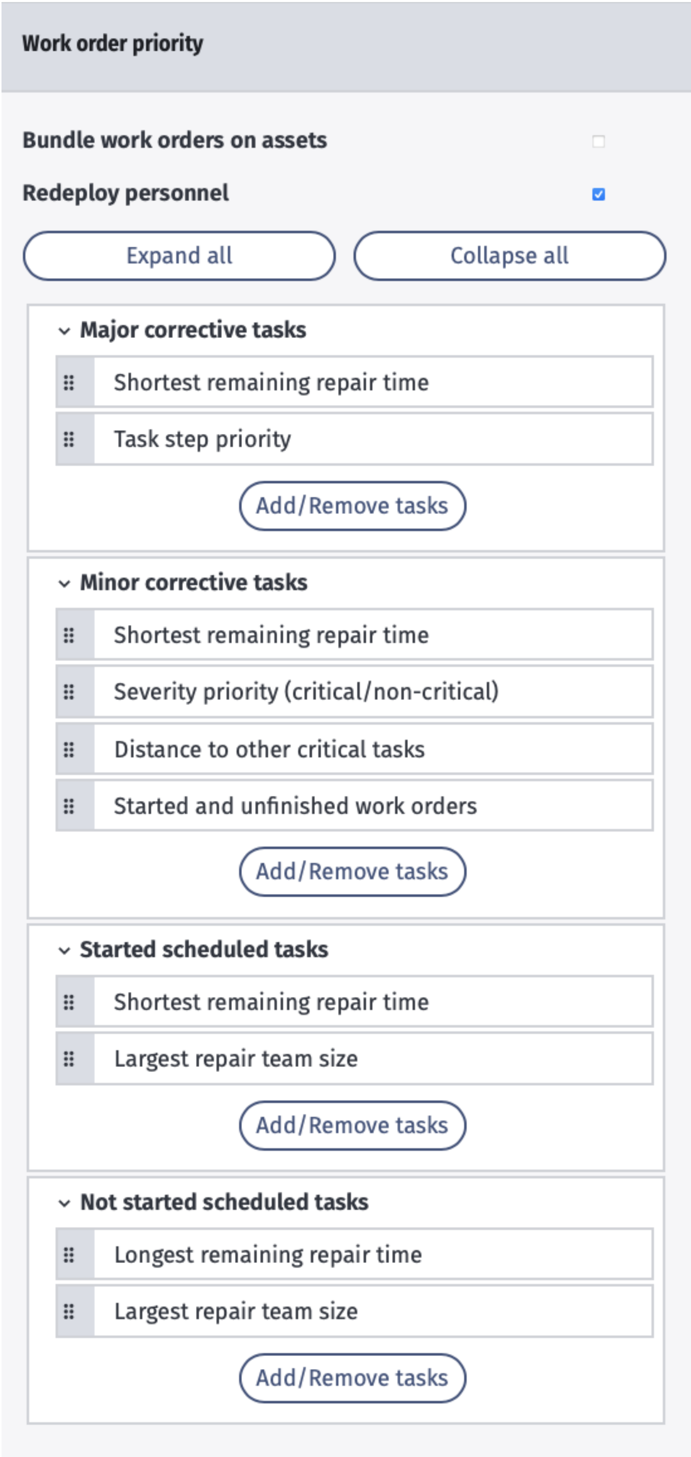


Figure 32: Work order priority for both scenarios

5.3 Step 3 – Output

Shoreline describes the outputs from its reports as:

"

TBA Loss (%) *- downtime / possible uptime, where downtime is the time an asset is non-operational, and possible uptime is the total time in the period measured*.

PBA Loss (%) *- lost production / potential production, where Potential production is the amount of energy an asset can produce if it was always operational (never fails or shuts down) and lost production is the amount of energy not produced when the asset has been down*

Lost production (MWh) *- is the energy not produced when an asset is non-operational but would be produced if it was operational.*

Downtime (h) *- the time the power production will be down due to specific components/services*

Net capacity factor (%) *–*

- *actual production [kWh] / SUM over assets (WTG rated capacity [kWh]*simulation Duration)*
- *Sum Of Case WTG Configurations (Number Of WTG Instances * Rated Powers * 8766*

Average total costs (€) *- shows the sum of costs on the main cost categories.*

" [43]

5.3.1 Scenario 1 - CTV, 1 year, 100 runs.

Table 16 below shows ten simulations of Scenario 1, with 100 runs per simulation. The values show that the simulations are approximately the same, indicating virtually consistent weather data. The total cost is for the day rate, personnel and fuel.

Table 16: Output data for the CTV from Shoreline

CTV							
Simulation	# Of runs	TBA Loss (%)	PBA Loss (%)	Lost production (MWh)	Downtime (h)	Net capacity factor (%)	Average total costs (€)
#1	100	9.8024	10.7970	307,243.03	29,275.4	56.7786	1,931,235
#2	100	9.7654	10.7751	306,619.40	29,165	56.7926	1,931,380
#3	100	9.7295	10.7301	305,339.44	29,057.8	56.8212	1,931,382
#4	100	9.9366	10.9394	311,293.83	29,676.2	56.6880	1,932,736
#5	100	9.8487	10.8339	308,291.52	29,413.8	56.7552	1,931,492
#6	100	9.9124	10.9322	311,089.47	29,603.9	56.6926	1,929,669
#7	100	9.9087	10.9427	311,387.69	29,593	56.6859	1,932,592
#8	100	9.6704	10.6385	302,731.08	28,881.2	56.8796	1,932,041
#9	100	9.7721	10.7312	305,369.28	29,185	56.8205	1,930,706
#10	100	9.7165	10.6915	304,241.11	29,019	56.8458	1,930,358

5.3.2 Scenario 1 - SOV, 1 year, 100 runs

The output from the simulation of using SOV to perform the maintenance tasks is summarized in Table 17. There are ten different simulations with 100 runs each. It is noticeable that the cost is much higher than what it is with a CTV, while the net capacity factor is just over 5% higher. In this scenario where the cost is so high, there are slightly larger deviations in the price of each simulation, but it is still very concise.

Table 17: Output data for the SOV from Shoreline

SOV							
Simulation	# Of runs	TBA Loss (%)	PBA Loss (%)	Lost production (MWh)	Downtime (h)	Net capacity factor (%)	Average total costs (€)
#1	100	4.2825	4.6029	133,537.09	12,790	61.9057	10,773 629
#2	100	4.2825	4.5906	133,180.05	12,789.8	61.9137	10,774 880
#3	100	4.3822	4.7242	137,054.41	13,087.7	61.8270	10,789 563
#4	100	4.2975	4.6178	133,967.09	12,834.6	61.8960	10,775 750
#5	100	4.3569	4.7051	136,500.86	13,012	61.8394	10,769 126
#6	100	4.3528	4.6711	135,514.36	13,000	61.8614	10,760 131
#7	100	4.2523	4.5668	132,488.73	12,699.7	61.9291	10,762 027
#8	100	4.2533	4.5678	132,459.53	12,687.3	61.9296	10,762 253
#9	100	4.3164	4.6402	134,616.86	12,891.2	64.8926	10,786 453
#10	100	4.2921	4.6118	133,795.2	12,818.7	61.8999	10,782 563

5.3.3 Fuel consummation and fuel emissions

The activities of the two vessels are very different when viewed from a holistic perspective. Scenario 1 with CTV will be in transit 4 hours a day, but Scenario 2 with SOV will be in transit 4 hours within 28 days. Table 18, Table 19, Table 20 and Table 21 below present the amount of time spent on the various activities and how much fuel consumption this will entail.

Table 18 Fuel in 24 hours for CTV

Fuel in 24 hours for CTV		
30 mins	Starting the day before departure	0 litres
1 hour	Transiting out from shore	320 litres
9 hours	Idle offshore	9 * 130 litres
1 hour	Transiting back to shore	320 litres
30 mins	Ending day after arrival	0 litres

	Total	1,810 litres
	(Two times a day) 24 hours	**3,620 litres**

Table 19 Fuel in 4 weeks and 24 hours for SOV

Fuel in 4 weeks and 24 hours for SOV		
24 h*7 days*4 weeks = 672 hours in 4 weeks		
12 hours	Crew change	0 litres
2 hours	Transiting out from shore	2 * 1,000 litres
656 hours	Idle offshore	656 * 120 litres
2 hours	Transiting back to shore	2 * 1,000 litres
	Total in 4 weeks	82,720 litres
	28 days in 4 weeks	
	Total for 1 day	**2,954 litres**

Table 20: Emissions from fuel in 24 hours for CTV

Emissions from fuel in 24 hours for CTV		
30 mins	Starting the day before departure	0
1 hour	Transiting out from shore	999.1 kg CO_2e
9 hours	Idle offshore	9 * 405.9 kg CO_2e
1 hour	Transiting back to shore	999.1 kg CO_2e
30 mins	Ending day after arrival	0
	Total	5,651.3 kg CO_2e
	(Two times a day) 24 hours	**11,302.6 kg CO_2e**

Table 21 Emissions from fuel in 4 weeks and 24 hours for SOV

Emissions from fuel in 4 weeks and 24 hours for SOV		
24 h*7 days*4 weeks = 672 hours in 4 weeks		
12 hours	Crew change	0
2 hours	Transiting out from shore	2 * 2,775.4 kg CO_2e
656 hours	Idle offshore	656 * 333 kg CO_2e
2 hours	Transiting back to shore	2 * 2,775.4 kg CO_2e
	Total in 4 weeks	229,549.6 kg CO_2e
	28 days in 4 weeks	
	Total for 1 day	**8,198.2 kg CO_2e**

By comparing Table 20 and Table 21, the daily emissions of CO_2e will be more than 3,000 kg CO_2e higher for the CTV than the SOV. Efforts are also being made in the EU toward shipping being included in the emissions trading system (ETS), which means that the industry must be prepared to buy quotas for its emissions [44]. There will then be a clear advantage with as little emissions as possible.

5.3.4 Lost production vs Lost sale

Comparing the two scenarios makes it possible to look at the difference between the average total cost in context to the downtime. The most expensive alternative will have the highest production, while the most affordable option will have the most increased downtime.

A simple calculation can show how much lost sales are in relation to the difference in the downtime between the two scenarios. The comparison is based on LCOE (Levelized cost of electricity) for floating offshore wind in Norway [45]:

$$Lost\ production\ in\ €_{CTV_{avg\ from\ 10\ simulations}}$$ Equation 2

$$= 307{,}361\ MWh * 1{,}000 \frac{KWh}{MWh} * 0.08 \frac{€}{KWh} = \ € \mathbf{24,588,880}$$

$$Lost\ production\ in\ €_{SOV_{avg\ from\ 10\ simulations}}$$ Equation 3

$$= 134{,}311\ MWh * 1{,}000 \frac{KWh}{MWh} * 0.08 \frac{€}{KWh} = \ € \mathbf{10,744,880}$$

$$Difference\ in\ lost\ production\ in\ €_{CTV\ vs\ SOV} = €\ 24{,}588{,}880 - €10{,}744{,}880$$ Equation 4

$$= \ €\mathbf{13,844,000}$$

Equation 4 shows that the difference in the downtime between the two scenarios is more than the total price for the vessel and personnel for the SOV isolated.

5.3.5 Sensitivity analysis

One of the main factors that are decisive for the outcome of Scenario 1 – CTV is the permissible wave height at which the vessel can operate. It was also known through Table 15 in Chapter 5.2.3. The sensitivity analysis for the different wave heights, shown in Table 22, shows how much impact this detail has on the result.

Table 22: Sensitivity analysis for the different wave heights for the CTV

CTV							
Wave height	# Of runs	TBA Loss (%)	PBA Loss (%)	Lost production (MWh)	Downtime (h)	Net capacity factor (%)	Average total costs (€)
1,5	100	30.3821	32.8405	934,516.67	90,738	42.7477	1,748,450
1,7	100	23.5078	25.5649	727,479.38	70,207,5	47.3788	1,799,324
1,9	100	19.5747	21.3882	608,628.28	58,461	50.0372	1,851,344
2,1	100	16.3256	17.9336	510,321.65	48,757.4	52.2362	1,879,155
2,3	100	12.0288	13.1611	374,516.02	35,924.7	55.2739	1,905,543
2,5	100	9.7165	10.6915	304,241.11	29,019	56.8458	1,930,358

With an isolated perspective on the difference between a maximum wave height (hs) of 2.5 m versus 2.3 m, the simulation shows the downtime increases by about 7,000 hours a year. This, in turn, corresponds to approximately 70,000 MWh. A short calculation with what is expected to be the minimum LCOE for floating offshore wind in Norway shows [45]:

$$Lost\ production\ in\ €_{hs=2,5\ vs\ 2,3} = 70{,}000\ MWh * 1{,}000\frac{KWh}{MWh} * 0.08\frac{€}{KWh} = €\ 5{,}600{,}000$$

Equation 5

It is based on historical figures and the minimum price relative to the expected cost. On the other hand, if energy prices in Southern Norway for the past six months are the base for the future energy prices, the average KWh spot price will be around 140 øre [46]. The lost production will then be worth:

$$Lost\ production\ in\ €_{hs=2,5\ vs\ 2,3} = 70{,}000\ MWh * 1{,}000\frac{KWh}{MWh} * 0.14\frac{€}{KWh} = €\ 9{,}800{,}000$$

Equation 6

It shows clear tendencies that there is a need for development within the industry, at least concerning the industry standard of 1.5 m, for a CTV to be relevant for consideration.

5.3.6 Pugh matrix - criteria-based decision matrix

To compare the results in a systematic method, they are inserted into a Pugh Matrix in Table 23. It is initially used in the planning phase and is often not what is most used as investment analysis. However, it is a primitive method of measuring the two scenarios against each other, where the criteria are taken from Table 12.

The matrix is designed so each scenario gets a grade between -, 0, and + based on how strongly it scores on the highlighted criteria. There may be several criteria or other stakeholders associated with the project, but these have not been selected here based on which are relevant in this context.

Table 23: Pugh matrix for evaluating the two scenarios

Pugh Matrix		
Criteria/scenario	*Scenario 1 CTV*	*Scenario 2 SOV*
Cost	**+** *(Avg total cost € 1,931,470)*	**-** *(Avg total cost € 10,778,456)*
Availability	**-** *(Avg lost production € 24,588,880)*	+ *(Avg lost production € 10,744,880)*
Environment	**-** *(365 days * 11,302.6 kg CO_2 e per day)*	**0** *(365 days * 8,198.2 kg CO_2e per day)*
Security	**-**	**+**
Reliability	**0**	**+**
+	1	3
0	1	1
-	3	1
Total	**-2**	**2**

5.4 Step 4 - Validation analysis for example

It was essential to validate the data and method to the extent possible during the work. As mentioned earlier, the data was validated against several experts based on whether it was within an approximate interval from their data. During the process, Shoreline Support was communicated with to find any errors in the simulation construction. Ultimately, it was wanted to validate that the output data was interpreted correctly.

An expert on the simulation method, a researcher in the field and an expert from an operator of offshore wind parks were contacted. All concluded that the output data had been interpreted correctly. Some also commented that the results were consistent with similar work discussing various logistics solutions they had done. Common to all the comments was that the wave height is the greatest sensitivity to the result.

6 Discussion

This chapter will discuss the findings of the analysis, and comment on any factors that could have yielded a different result. Various future measures are being looked at that may impact operations optimisation. Finally, it looks at challenges and deficiencies that have been discovered along the way as the thesis has developed.

6.1 Answers to the Research questions

The master thesis has two main research questions. The first research question:

How to utilize modelling and simulation method for selection of optimal maintenance logistics strategy for a wind farm at Utsira Nord

is more into the methodology of applying modelling and simulation approaches to solve maintenance logistic problems for real-world offshore wind farms. The methodology to conduct modelling and simulation approach is designed in chapter 3 and applied and validated throughout the analysis chapter. It consists of six steps, as follows.

1. System analysis to understand what data is needed to obtain
2. Criteria analysis to set the criteria by which the different scenarios are to be judged by
3. Collect the required technical and cost data as input in Shoreline
4. Use Shoreline software to simulate the different scenarios
5. Analyze the output report regarding the criteria
6. Perform analysis such as Pugh Matrix or multiple-criteria decision analysis to compare the data

This methodology manages to combine analysis steps that prepare technical, maintenance and cost data for simulation purposes, and connects simulation results into a multi-criteria decision making step answering the second research question:

What will be an optimal maintenance logistics strategy for an imaginary Utsira Nord wind farm, seen from cost-benefit perspective and emission perspective

Based on the simulation and the calculation made in Chapter 5, in this imaginary case, the SOV is the most optimal choice of vessels to support the maintenance logistics.

1. If seen in the context of lost production during downtime, the calculation will significantly differ from the day rates. The calculation made in the analysis shows that the case can increase its turnover by €13,844,000 per year by using an SOV in favour of a CTV concerning lost production.

2. Regarding emissions, SOV has far higher emissions in transit, with slightly lower when idle offshore (based on a hybrid with battery). However, the strategy with the SOV staying out on the field for an extended period means that the average daily emission for the SOV is 8,198.2 kg CO_2e, while there is 11,302.6 kg CO_2e a day for the CTV.

6.2 What's innovative about the thesis?

Even though Shoreline is used as a simulation tool, it is nevertheless important to point out that it is the author who is responsible for most of the work. Figure 33 illustrates this, where everything done by the author is on the left. It's only in one of the six steps where Shoreline does the work. To obtain and collect all the information going into the software, set criteria for how it should be assessed and compare the output, are activities Shoreline does not provide.

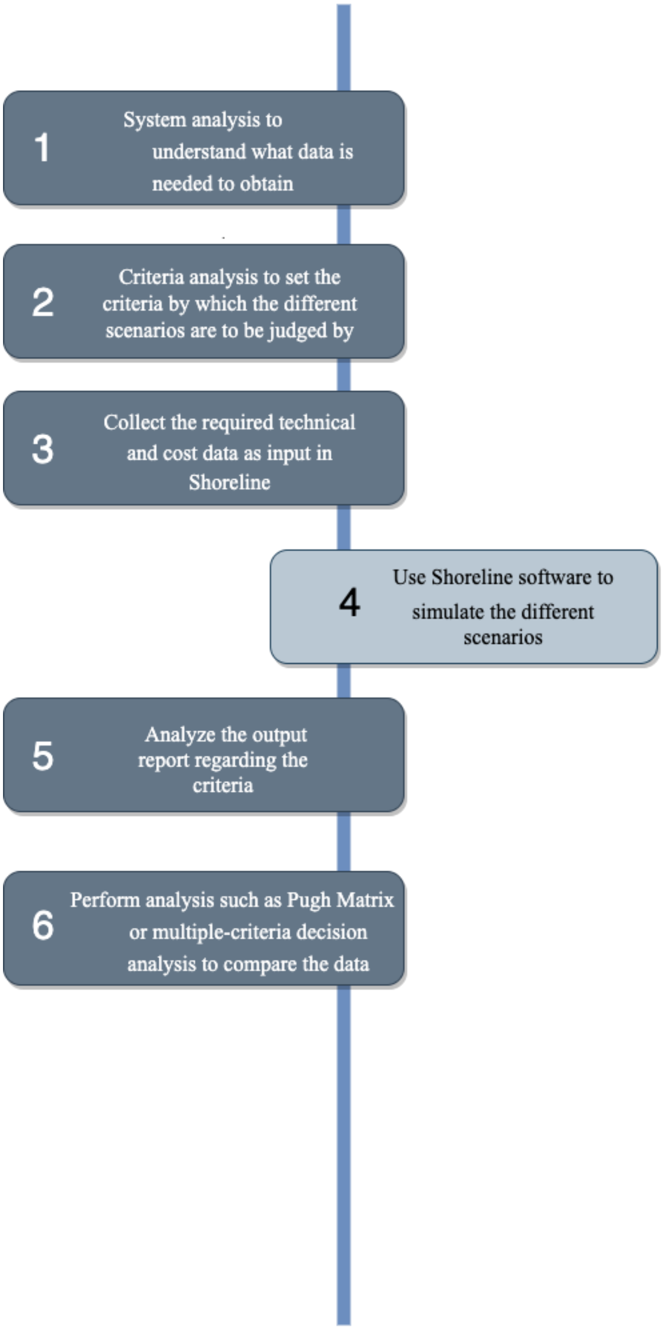


Figure 33: Illustration of what is done by the author

6.3 What could may have changed the result?

Having communicated with various companies and experts from the industry at the beginning of the project, it seemed that CTV was the preferred option. The result of the analysis was, therefore, a little surprising. Further, one will look at what factors may have contributed to SOV being the most optimal option in this case.

The first thing that destroys the possibilities for a CTV is that the significant downtime causes a considerable loss of production. Therefore, it is essential to reduce these levels for the vessel to be competitive. The sensitivity analysis shown in Chapter 5.3.5, Table 22 indicates how much outcome the maximum wave height has. It is an apparent problem for the industry, as the change must occur from the vessel's design phase. This factor requires the most extensive change, but other factors may also contribute to a change in the result.

The personnel strategy in this analysis was set as a result of communication with a support company for logistics services, which indicated that the strategy has not been fully prepared for the industry. It is understandable as it is a fact that it is a long time until this will be operational. The industry is highly likely to form an industry standard similar to the turnaround: four weeks on and four weeks off, two weeks on and two weeks off, or other ones that we are already familiar with in similar processes. The length of the workday, the number of workers simultaneously, and the number of shifts were determined by the trial-and-error method on how to get the most out of its staff. It was carried out primitively in Shoreline with few factors, and it is conceivable that there is the potential for improvement in this field. These factors may naturally influence the outcome positively but may also negatively impact it.

Another thing that has not been considered and that could have provided other output data was if the CTV was based on the island of Utsira. The base will then be closer to the field, shown in Figure 34, resulting in less time passing to transit. There will then be a need for a "hotel" where they live, similar to the type of rotation on the SOV, but they will be sleeping on Utsira.

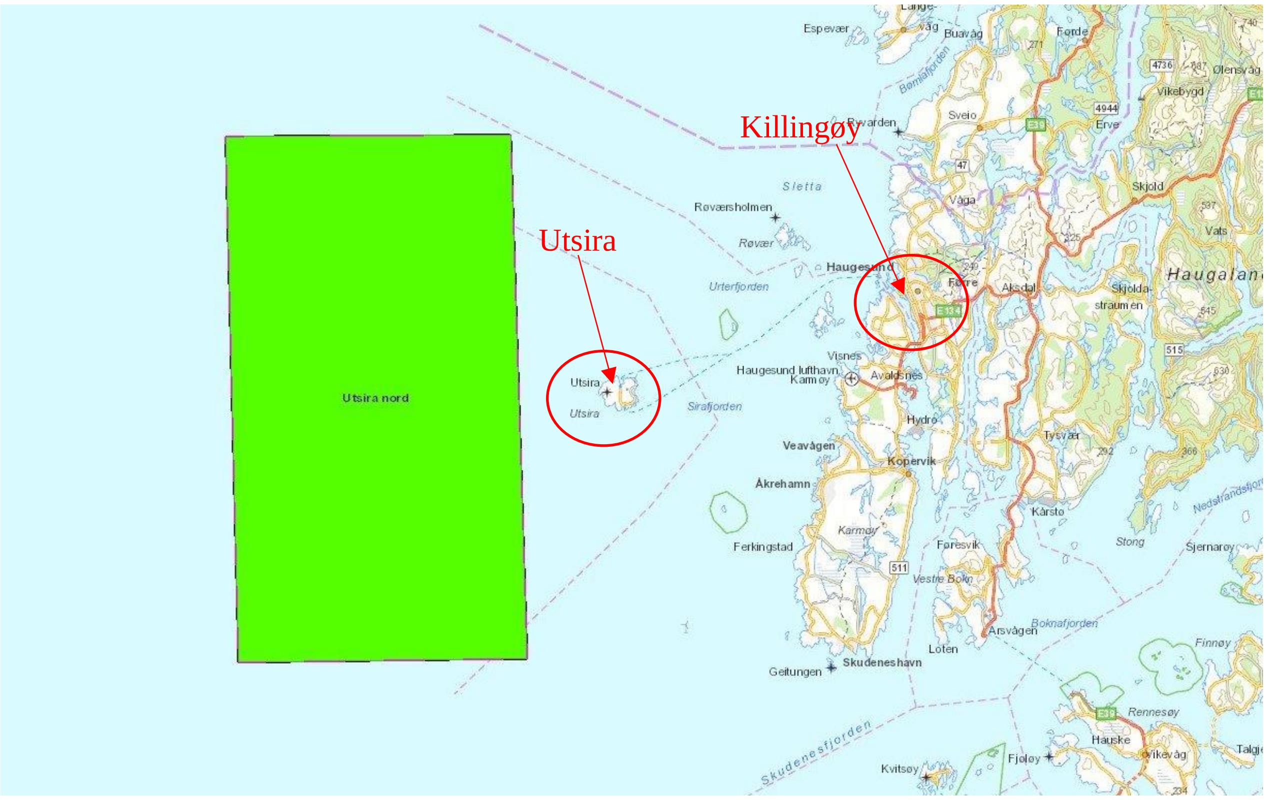


Figure 34: Utsira (island) and Killingøy [47]

6.4 How can Scenario 2 with the SOV be improved

It is not only scenario 1 with the CTV that has the potential for improvement; scenario 2 with the SOV can also be discussed. The day rate for the SOV is exceptionally high, especially if it is put in context to the fact that only 4/40 beds are used on board for technicians. It is naturally due to the scale of the project, where each concession is a maximum of 500 MW. The scope is also minimal compared to ScotWind, where the most significant concession out of the 17 awarded was 3,000 MW [48].

The total planed installed capacity for Utsira Nord is currently 1,500 MW. The capacity distribution per concession is presently uncertain, but the decision is on the total capacity for the entire wind farm. What would be interesting for the companies that win the different concessions is to look at the possibility of using a common SOV. The capacity on board is more than large enough, with a typical vessel with about 40 beds. It will result in an apparent reduction in the day rate cost.

On the other hand, it will be necessary to include an "emergency response limit" in the assessment. In this analysis, it is set to ten minutes to ensure that the vessel is within this distance in the event of an emergency. It is uncertain whether there will be a standard that sets requirements for this or whether the industry itself is responsible for determining it. This factor may mean that a common SOV may be unable to drop off technicians at the various wind farms simultaneously. As a result, the downtime may increase somewhat because of the waiting period for the vessel to reach the park. Therefore, the reduced expenditure on the SOV must be assessed against lost income for lost production.

6.5 Challenges and limitations of the project

There was a significant challenge connected to collecting reliable data for this project. This challenge set a clear delimitation for the thesis because obtaining more data with the resources one had at the time was impossible. Naturally, this also affects the result, as the trends in the technical data are likely to change markedly with technological developments. It can be positive through improvements to existing technologies or possibly negative when scaling up to larger WTGs. Furthermore, one should consider how information sharing is handled in the oil and gas sector.

Offshore and Onshore Reliability Data (OREDA) was established as a project in 1981, and aims to create a real source of failure data, distribution of malfunctions and the repair time of equipment in the oil and gas sector [49]. Today, the organization consists of several companies from the industry, and it has been like this since 1983. The goal is to optimize and cost-streamline equipment by sharing technical data.

A similar project for the offshore wind industry could bring significant benefits. However, it requires that they join forces in an agreement to be transparent with their data, where there is now a great deal of secrecy attached to it. This solution could potentially bring enormous benefits to all stakeholders.

6.6 Shoreline

Shoreline was perceived as an orderly and structured software, which was systematic and user-friendly. This factor is crucial for companies to choose this product in favour of similar tools. On the other hand, there is potential for improvement to make customer processes relatively easier.

For start-ups or students, it can be difficult to build cases in Shoreline, as an extreme amount of data needs to be recorded inside the software. An example is "Equipment transfer time" or "Dynamic positioning activation time" for the vessel. Several assets are not included in this analysis, such as foundations, inter-array cables, substations and export cables, which also need the required data to do the analysis. Furthermore, it could also be problematic for new companies to access the necessary technical data for failure rates, required technicians and repair time for the WTGs. The following section will present a possible solution to this.

«SPARTA is a Joint Industry Project formed in 2013 that provides performance benchmarking for operational offshore wind farms. We aim to help owners and operators better understand relative performance of their assets.»[50] By entering into an agreement with SPARTA, Shoreline could potentially offer its customers a guide to the expected value. It will not act as a substitute for the input data but as a validation method that the data is within an expected range.

6.7 Validation during different phases

As mentioned earlier, there was little transparency and willingness to share information from the industry. However, several experts were willing to give validation on whether the data found was within an expected interval. It has been imperative to build credibility for the analysis. In particular, the research steps below (from Chapter 3) were necessary to validate, as there was a lack of available data that could be compared.

3. Collect and extract failure and maintenance data from existing offshore wind parks.

The data from the "Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines" used were somewhat weak in terms of scaling and age. Therefore, the data was validated by two major European offshore wind operators, who responded by saying that it was within a reasonable interval against their data.

4. Collect technical and economic data for several logistic maintenance vessels.

Edda Wind was helpful with data for the SOV regarding vessel data. The CTV, on the other hand, was difficult to retrieve data, and the day rates available were of such an old age that they were not accurate today. A method that used information about the day rate for a CTV being 8-10% of the day rate of the SOV was used. Furthermore, this information was used to compare whether the percentage share also applied to the older data. It validated that 8-10% was highly likely to be an accurate distribution.

5. Design and prepare the simulation cases

During the preparation of the cases in Shoreline, there were several discharges where it was clear that there were errors in input in the cases. Shoreline support was highly supportive, with quick responses after going through the case. It was an essential tool in the software where they detected an error in the input.

6. Perform the simulation cases and visualise the results

As a result of the fact that the author had no previous experience with using Shoreline and interpreting that data, it was desirable to get someone else’s view of the result. The result was validated against several resource experts within the relevant companies to validate that the output from the analyses was interpreted correctly. It helps to ensure that the conclusion of the thesis is as secure as possible.

6.8 Future work

Since the work is strongly characterized by delimitations and a lack of available data in the technical and economic aspects, there is a lot of future work that can be done on the topic.

1. For companies that already sit on the technical data from suppliers, this analysis can be run based on this data. It is extensive for external persons, such as students, as the data

is rarely shared. The simulations can be further developed if one has all relevant data and strong contacts with suppliers, e.g. WTGs, CTVs and SOVs.

2. As a result of this analysis only looking at the use of one vessel at a time, there will be good development opportunities for future work by examining whether availability increases if, for example, it is chosen more than one CTV.

3. What is very clear in the analysis is how strong impact the maximum wave height the vessel can operate in has. Therefore, it will be a reasonable basis for future work to investigate the development of CTVs for the future. The vessel is well suited for the industry, but further development is needed to be relevant in this case.

4. There are far more logistics opportunities, such as heli. Since there was limited data to get hold of, it was chosen to focus on the two scenarios of the SOV and the CTV. Future work may be to conduct a more extensive analysis to see how the other logistics options respond to cost/availability and emissions criteria.

7 Conclusion

Here the conclusion of the research questions will be presented

----

Concluding from Chapter 5 and Chapter 6, the research questions in this thesis can be answered:

"How to utilize modelling and simulation method for selection of optimal maintenance logistics strategy for a wind farm at Utsira Nord"

Chapter 5 demonstrates the approach one can use to find the optimized maintenance logistics strategy for a wind farm at Utsira Nord. This can be summarized in the following points:

1. System analysis to understand what data is needed to obtain
2. Criteria analysis to set the criteria by which the different scenarios are to be judged by
3. Get the required data for input in Shoreline
4. Use Shoreline to simulate the different scenarios
5. Analyze the output report regarding the criteria
6. Perform analysis such as Pugh Matrix or multiple-criteria decision analysis to compare the data

"What will be an optimal maintenance logistics strategy for an imaginary Utsira Nord wind farm, seen from cost-benefit perspective and emission perspective"

Based on the simulation and the calculation made in Chapter 5, it is clear that the SOV is the most optimal choice of vessels to support the maintenance logistics in this imaginary case.

1. If seen in the context of lost production during downtime, the calculation will significantly differ from the day rates. The calculation made in the analysis shows that the case can increase its turnover by € 13,844,000 per year by using an SOV in favour of a CTV concerning lost production.

2. Regarding emissions, SOV has far higher emissions in transit, with slightly lower when idle offshore (based on a hybrid with battery). However, the strategy with the SOV staying out on the field for an extended period means that the average daily emission for the SOV is 8,198.2 kg CO_2e, while there is 11,302.6 kg CO_2e a day for the CTV.

References

[1] “Goal 13 | Department of Economic and Social Affairs.” https://sdgs.un.org/goals/goal13 (accessed Jan. 14, 2022).

[2] O. energidepartementet, “Opner områder for havvind i Noreg,” *Regjeringa.no*, Jun. 12, 2020. https://www.regjeringen.no/nn/dokumentarkiv/regjeringa-solberg/aktuelt-regjeringen-solberg/aktuelt1/pressemeldingar/2020/opner-omrader/id2705986/ (accessed Feb. 01, 2022).

[3] “How to reduce maintenance costs for your wind farm.” https://www.samotics.com/reduce-maintenance-costs-for-your-wind-farm (accessed Mar. 24, 2022).

[4] “Renewables 2019 – Analysis.” Accessed: Mar. 17, 2022. [Online]. Available: https://www.iea.org/reports/renewables-2019

[5] “Rapid electrification.” https://eto.dnv.com/2019/rapid-electrification (accessed Mar. 17, 2022).

[6] Statnett, “Langsiktig markedsanalyse Norden og Europa 2020–2050,” Statnett, Oct. 2020. Accessed: Jan. 17, 2022. [Online]. Available: https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/lma/langsiktig-markedsanalyse-norden-og-europa-2020-50_revidert.pdf

[7] “Det eksepsjonelle kraftåret 2021,” *Statnett*, Jan. 06, 2022. https://www.statnett.no/om-statnett/nyheter-og-pressemeldinger/nyhetsarkiv-2022/det-eksepsjonelle-kraftaret-2021/ (accessed Jan. 28, 2022).

[8] “Kraftproduksjonen i Norge økte med 3,1 TWh i 2021 - NVE,” Jan. 27, 2022. https://nve.no/nytt-fra-nve/nyheter-energi/kraftproduksjonen-i-norge-okte-med-3-1-twh-i-2021/ (accessed Jan. 28, 2022).

[9] “The Power to Change: Solar and Wind Cost Reduction Potential to 2025,” ISBN 978-92-95111-97-4 (PDF), x 2016. Accessed: Jan. 28, 2022. [Online]. Available: https://www.irena.org/publications/2016/Jun/The-Power-to-Change-Solar-and-Wind-Cost-Reduction-Potential-to-2025

[10] Adnan Durakovic, “World’s Largest, Most Powerful Wind Turbine Stands Complete,” *Offshore Wind*, Nov. 12, 2021. https://www.offshorewind.biz/2021/11/12/worlds-largest-most-powerful-wind-turbine-stands-complete/ (accessed Jan. 31, 2022).

[11] K. M. H. Caroline Grundekjøn, “Stormen på øya: Kampen mot møllene,” *E24*, Aug. 29, 2020. https://e24.no/i/EWdqWG (accessed Jan. 31, 2022).

[12] “Hywind Scotland remains the UK’s best performing offshore wind farm - equinor.com.” https://www.equinor.com/en/news/20210323-hywind-scotland-uk-best-performing-offshore-wind-farm.html (accessed Mar. 22, 2022).

[13] T. D. N. Direkt, “Går mot utsettelse av Utsira Nord,” Nov. 19, 2021. https://finansavisen.no/nyheter/energi/2021/11/19/7776063/gar-mot-utsettelse-av-utsira-nord (accessed Feb. 01, 2022).

[14] “Havvinden kan varme over halvparten av norske boliger.” https://www.aftenposten.no/norge/i/rE4OMA/havvinden-kan-varme-over-halvparten-av-norske-boliger (accessed Mar. 21, 2022).

[15] “RWE, NTE og Havfram vil bygge ut havvind på Utsira Nord,” *Energi24.no*, Sep. 10, 2021. https://energi24.no/energi/rwe-nte-og-havfram-vil-bygge-ut-havvind-pa-utsira-nord (accessed Feb. 02, 2022).

[16] “Havvind-leiar: – Me er eit nisselueland – E24.” https://e24.no/det-groenne-skiftet/i/Vq19q1/havvind-leiar-me-er-eit-nisselueland (accessed Mar. 21, 2022).

[17] “Varsler egne krav til flytende havvind: – Vi ønsker å utvikle industri – E24.”

https://e24.no/olje-og-energi/i/9KdX8d/varsler-egne-krav-til-flytende-havvind-vi-oensker-aa-utvikle-industri (accessed Mar. 24, 2022).
[18] O.-E. V. Endrerud, J. P. Liyanage, and N. Keseric, “Marine logistics decision support for operation and maintenance of offshore wind parks with a multi method simulation model,” 2015, vol. 2015-January, pp. 1712–1722. doi: 10.1109/WSC.2014.7020021.
[19] I. B. Sperstad, M. Stålhane, I. Dinwoodie, O.-E. V. Endrerud, R. Martin, and E. Warner, “Testing the robustness of optimal access vessel fleet selection for operation and maintenance of offshore wind farms,” *Ocean Eng.*, vol. 145, pp. 334–343, Nov. 2017, doi: 10.1016/j.oceaneng.2017.09.009.
[20] Malcolm Grimston, *The Paralysis in Energy Decision Making:: 978-184995-167-8 -*. Whittles Publishing, 2016.
[21] L. Zhang, C. Michailides, Y. Wang, and W. Shi, “Moderate water depth effects on the response of a floating wind turbine,” *Structures*, vol. 28, pp. 1435–1448, Dec. 2020, doi: 10.1016/j.istruc.2020.09.067.
[22] Z. Lin, X. Liu, and S. Lotfian, “Impacts of water depth increase on offshore floating wind turbine dynamics,” *Ocean Eng.*, vol. 224, p. 108697, Mar. 2021, doi: 10.1016/j.oceaneng.2021.108697.
[23] H. Bailey, K. L. Brookes, and P. M. Thompson, “Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future,” *Aquat. Biosyst.*, vol. 10, no. 1, p. 8, Sep. 2014, doi: 10.1186/2046-9063-10-8.
[24] B. Hahn *et al.*, “Recommended practices for wind farm data collection and reliability assessment for O&M optimization,” *Energy Procedia*, vol. 137, pp. 358–365, Oct. 2017, doi: 10.1016/j.egypro.2017.10.360.
[25] “An Introduction to Crew Transfer Vessels.” https://www.4coffshore.com/support/an-introduction-to-crew-transfer-vessels-aid2.html (accessed Mar. 30, 2022).
[26] “Renewables,” *Umoe WAVECRAFT TM*. https://www.wavecraft.no/market/renewables-fast-crew-transfer-vessels/ (accessed Mar. 30, 2022).
[27] “Edda Wind wins Siemens Gamesa contract for SOV,” *Marine Log*, Dec. 28, 2021. https://www.marinelog.com/offshore/offshore-wind/edda-wind-wins-siemens-gamesa-contract-for-sov/ (accessed Mar. 28, 2022).
[28] “Company,” *Shoreline*. https://shoreline.no/company/ (accessed Jun. 10, 2022).
[29] Erwin, “Benefits of ERP Software Solutions,” *Pixal Vistas*, Jun. 26, 2021. https://www.pixelvistas.com/benefits-of-erp-software-solutions/ (accessed Apr. 06, 2022).
[30] IEC 60300-3-14:2004, “Application guide - Maintenance and maintenance support, IEC 60300-3-14:2004.”
[31] The Norwegian Petroleum Directorate, “The Maintenance Baseline Study: A Method for Self-Assessment of Maintenance Management Systems.” Norwegian Petroleum Directorate, 1998.
[32] E. Wæhle, S. Dahlum, and S. Grønmo, “case-studie,” *Store norske leksikon*. May 14, 2020. Accessed: May 22, 2022. [Online]. Available: http://snl.no/case-studie
[33] “Primære og sekundære datakilder - UTGÅTT - Markedsføring og ledelse 1 (LK06) - NDLA,” *ndla.no*. https://ndla.no/subject:1:433559e2-5bf4-4ba1-a592-24fa4057ec01/topic:2:183191/topic:2:105795/resource:1:93370 (accessed May 20, 2022).
[34] “Deep Wind Offshore,” *Deep Wind Offshore*. https://www.deepwindoffshore.com (accessed Apr. 19, 2022).
[35] “About Knutsen Group,” *Knutsen*. https://knutsenoas.com/about/ (accessed Apr. 19, 2022).
[36] “Bli kjent med konsernet Haugaland Kraft,” *Haugaland Kraft*. https://hkraft.no/om-haugaland-kraft/konsernet-haugaland-kraft/ (accessed Apr. 19, 2022).
[37] S. AS, “Historia vår | SKL – Rein, berekraftig energi,” *SKL*, Aug. 31, 2018.

https://skl.as/historia-var/ (accessed Apr. 19, 2022).
[38] “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines”, doi: 10.1002/we.1887.
[39] Dr Anthony Gray, “SETTING A BENCHMARK FOR DECARBONISING O&M VESSELS OF OFFSHORE WIND FARMS.” Feb. 2021.
[40] B. Hu and C. Yung, “Offshore Wind Access Report 2020,” 2020, Accessed: May 15, 2022. [Online]. Available: https://repository.tno.nl/islandora/object/uuid%3Ad6cefbf6-2916-42fc-bb3d-b2d713938e09
[41] Edda Wind, “SOV day rate,” 17.3.20222.
[42] 17 1 2017 | Modified 18.2.2021, “Portaler og datasett,” *Norwegian Meteorological Institute*. https://www.met.no/en/free-meteorological-data/tilgjengelige-datasett (accessed May 30, 2022).
[43] “Output explained overview,” Mar. 18, 2021. https://design.support.shoreline.no/support/solutions/articles/80000517784-output-explained-overview
[44] “Forsterket kvotesystem 2021-2030,” *Regjeringen.no*, Aug. 16, 2021. https://www.regjeringen.no/no/sub/eos-notatbasen/notatene/2021/aug/forsterket-kvotesystem-2021-2030/id2878386/ (accessed May 16, 2022).
[45] DET KONGELIGE OLJE- OG ENERGIDEPARTEMENTET, “Energi til arbeid – langsiktig verdiskaping fra norske energiressurser.” Jun. 11, 2021. Accessed: May 12, 2022. [Online]. Available: https://www.regjeringen.no/contentassets/3d9930739f9b42f2a3e65adadb53c1f4/no/pdfs/stm202020210036000dddpdfs.pdf
[46] “Historiske strømpriser | NorgesEnergi.” https://norgesenergi.no/hjelp/strompriser/historiske-strompriser/ (accessed May 12, 2022).
[47] “Havvind, Energi | Ønsker tempo og et større Utsira Nord.” https://www.h-avis.no/onsker-tempo-og-et-storre-utsira-nord/s/5-62-1286305 (accessed May 25, 2022).
[48] “ScotWind offshore wind leasing delivers major boost to Scotland’s net zero aspirations - News - Crown Estate Scotland.” https://www.crownestatescotland.com/news/scotwind-offshore-wind-leasing-delivers-major-boost-to-scotlands-net-zero-aspirations (accessed May 25, 2022).
[49] “OREDA.” https://www.oreda.com/about (accessed May 29, 2022).
[50] “SPARTA - System Performance, Availability and Reliability Trend Analysis.” https://www.sparta-offshore.com/SpartaHome (accessed May 26, 2022).

Appendices

Appendix 1: data collected for failure rates, repair time and required technicians for the WTG

Data below is from "Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines"

Components	Failure rates /WTG/year		
	Major repair	Minor repair	No cost data
Blades	0,01	0,456	0,053
Contactor/ circuit breaker/ Relay	0,054	0,326	0,048
Electrical components	0,016	0,358	0,059
Gearbox	0,038	0,395	0,046
Generator	0,321	0,485	0,098
Grease/oil/cooling liquid	0,006	0,407	0,058
Heaters/coolers	0,007	0,19	0,016
Hub	0,038	0,182	0,014
Other components	0,042	0,812	0,15
Pitch/hyd	0,179	0,824	0,072
Power supply/converter	0,081	0,076	0,018
Pumps/motors	0,043	0,278	0,025
Safety	0,004	0,373	0,015
Sensors	0,07	0,247	0,029
Service items	0,001	0,108	0,016
Tower/Foundation	0,089	0,092	0,004
Transformer	0,003	0,052	0,009
Yaw system	0,006	0,162	0,02

Components	Repair time		
	Major repair	Minor repair	No cost data
Blades	21	9	28
Contactor/ circuit breaker/ Relay	19	4	5
Electrical components	14	5	7
Gearbox	22	8	7
Generator	24	7	13
Grease/oil/cooling liquid	18	4	3
Heaters/coolers	14	5	5
Hub	40	10	8
Other components	21	5	8
Pitch/hyd	19	9	17
Power supply/converter	14	7	10
Pumps/motors	10	4	7
Safety	7	2	2
Sensors	6	8	8
Service items	0	7	9
Tower/Foundation	3	5	6
Transformer	26	7	19
Yaw system	20	5	9

Components	Required technicians		
	Major repair	Minor repair	No cost data
Blades	3	2	2
Contactor/ circuit breaker/ Relay	3	2	2
Electrical components	3	2	2
Gearbox	3	2	2
Generator	3	2	2
Grease/oil/cooling liquid	3	2	2
Heaters/coolers	3	2	3
Hub	4	2	2
Other components	3	2	2
Pitch/hyd	3	2	3
Power supply/converter	2	2	3
Pumps/motors	3	2	3
Safety	3	2	2
Sensors	2	2	3
Service items	0	2	2
Tower/Foundation	1	3	2
Transformer	3	3	3
Yaw system	3	2	2

Appendix 2: data collected for CTV

members		parameters		capacity		Performace		Weather criteria		Fuel Consumption		Cost		Activity Durations	
CTV	1	Crew size	2	Technician capacity	12	Crusing speed	22 kn	Significant wave height access limit	1.5 m	Fuel unit	litre-uni	Day rate	3 000 €	Lead time	10m
		Remarks						Lowest tide		Fuel consumption in transit	7.8 litre/km	Fuel cost	2 €/litre	Connection time	5m
										Fuel Consumption when pushing on asset		Mobilisation cost		Disconnection time	1m
										Fuel consumption when idle offshore	130 litre/hr	Port fee		Personnel transfer time per technician	5m
														Equipment transfer time	10m
														Mobilising time per port visit	30m
														Demobilising time port visit	30m

Appendix 3: data collected for SOV

members		parameters		capacity		Performace		Weather criteria		Fuel Consumption		Cost		Activity Durations	
SOV	1	Crew size	10	Technician capacity	40	Crusing speed	12 kn	Significant wave height access limit	3.5 m	Fuel unit	litre-unit	Day rate	30 000 €	Time between going to port	28d
		Remarks				Dynamic positioning trasnit speed	5 kn	Wind speed access limit	15 m/s	Fuel consumption in transit	45.5 litre/km	Fuel cost	2 €/litre	Lead time	1h
						Dynamic positioning activation time	20 min	Wind speed limitation reference height	200 m	Fuel consumption in DP mode (ton/hr)		Mobilisation cost		Connection time	10 m
						Reliability		Lowest tide		Fuel consumption in DP mode (ton/km)		Port fee		Disconnection time	5 m
										Fuel consumption when idle offshore	120 litre/hr			Personnel transfer time per technician	2 m
														Equipment transfer time	10 m
														Mobilising time per port visit	30 m
														Demobilising time port visit	30 m