NTNU – Trondheim
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Vessel fleet size and mix for maintenance of offshore wind farms

A stochastic approach

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Oppgavetekst/Problembeskrivelse The purpose of this thesis is to develop model(s) and solution method(s) to determine an optimal fleet size and mix to be used in the execution of operations and maintenance in the offshore wind industry. The thesis will be based on a stochastic solution approach to be able to capture uncertain factors, e.g. weather conditions and turbine failures, and by this create realistic and robust solutions. The model(s) will then be analysed, and simulations will be used to evaluate different aspects of the solutions and the model(s).	
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a Stochastic Approach

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Master Thesis
Managerial Economics and Operations Research
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NTNU
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Norwegian University of Science and Technology
Faculty of Social Sciences and Technology Management
Department of Industrial Economics and Technology Management

Preface

This master thesis is the final step in achieving a Master of Science degree at the Norwegian University of Science and Technology (NTNU). The degree specialisation is Applied Economics and Optimization at the department of Industrial Economics and Technology Management. This thesis has been written in cooperation with researchers at SINTEF and MARINTEK as a part of the scientific projects Norwegian Research Centre for Offshore Wind Technology (NOWITECH) and Far Offshore Operation and Maintenance Vessel Concept Development and Optimisation (FAROFF) where one intermediate aim is the development of decision support tools to enable more cost effective operation and maintenance activities for offshore wind farms.

We have received much appreciated help and guidance while working with this thesis, both from professors at NTNU as well as industry contacts. We would like to give special thanks to our supervisors Associate Professor Lars Magnus Hvattum from NTNU and Elin Espeland Halvorsen-Weare from SINTEF for their good and inevitable counselling throughout the project. We would also like to thank Bjørn Mo Østgren, Operations and Maintenance Manager for Offshore Wind at Statkraft. Due to limited literature and data available on maintenance of offshore wind farms, his cooperation has been a key part of gaining a better insight into the industry, as well as obtaining realistic input data for the model.

Trondheim, June 8, 2012

Christian Gundegjerde Ina Blomseth Halvorsen

Abstract

In recent years the global installed capacity of offshore wind has increased rapidly, due to the world's green electricity demand. Increasing developments in the offshore wind sector has led to fewer possible locations for new wind farms, forcing the developers to move further and further away from shore. This shift from near-shore to far-shore wind farm locations, increases the complexity and costs of executing operations and maintenance, which can account for 25% of the production cost of power.

The vessels and helicopters that are used to execute preventive and corrective maintenance activities are expensive, and a crane vessel can easily cost USD 40 000 per day. The potential savings in determining an optimal fleet size and mix for the execution of maintenance activities on an offshore wind farm are therefore considerable. Using a joint fleet for more than one wind farm, is a way of achieving savings in order to obtain cost-efficient projects. However, uncertain factors, such as turbine failures requiring corrective maintenance, vessel spot rates, electricity prices and weather conditions limiting the accessibility of the vessels, raise the need for decision support tools.

In this thesis we investigate the possibility of using operations research to determine an optimal fleet size and mix for one or several offshore wind farms. The decisions to be made are how many vessels to acquire or rent in order to meet a given maintenance schedule, in addition to determining whether offshore station concepts are economically viable. Strategic decision support tools in terms of both a deterministic and a stochastic optimisation model are developed and will be presented. Based on different scenarios including turbine failures, vessel and helicopter spot rates, electricity prices and weather conditions, the stochastic model determines the optimal fleet size and mix that should be used to execute maintenance operations on one or several offshore wind farms.

A computational study proves that the stochastic model is able to solve problems for real world wind farms with more than 400 wind turbines. Further, the value of the stochastic solution and the expected value of perfect information suggest that the stochastic model gives solutions that are fairly well hedged against possible future outcomes, and returns solutions that perform significantly better than the solutions from the deterministic model. In addition, the stochastic model is shown to have a great economical applicability, in terms of determining the willingness to pay for additional wave capacity of the vessels, the possible savings of using offshore station concepts and the potential savings in using a joint fleet on several offshore wind farms.

The stochastic optimization model addressing the fleet size and mix problem for offshore wind is the first of its kind, and this thesis has proven that the model has a real world value in terms of being a great strategic decision support tool taking into account the inherent uncertainties of the problem. The model does, however, not consider the logistics of spare parts or the tactical day-to-day utilisation of the given fleet, thus further work is suggested on these issues.

Sammendrag

De siste årene har global innstallering av offshore vindkraft hatt en kraftig økning, på grunn av verdens etterspørsel etter grønn elektrisitet. Økende utbygging av offshore vindkraft har begrenset områdene for nye vindparker, hvilket tvinger utviklerne til å flytte lenger og lenger vekk fra land. Dette skiftet fra near-shoretil far-shorelokasjoner for vindfarmer, øker kompleksiteten og kostnadene ved utføring av drift og vedlikehold, som kan utgjøre 25 % av produksjonskostnaden for kraft.

Fartøyene og helikoptre som brukes til å utføre forebyggende og korrektive vedlikeholdsaktiviteter er dyre, og et kranfartøy kan koste mer enn 40 000 USD per dag. De potensielle besparelsene ved å bestemme optimal flåtestørrelse og flåtemiks for utførelse av vedlikehold på en offshore vindpark kan derfor ansees som betydelige. Å bruke en felles flåte for mer enn en vindpark er én måte å oppnå besparelser på, og kan sørge for kostnadseffektive prosjekter. Usikre faktorer, som turbinsvikt som krever korrigerende vedlikehold, spotpriser på fartøy, strømpriser og værforhold som begrenser tilgjengeligheten til fartøyene, øker behovet for beslutningsstøtteverktøy.

I denne avhandlingen undersøker vi muligheten for å bruke operasjonsanalyse for å bestemme optimal flåtestørrelse og flåtemiks for utførelse av vedlikeholdsaktiviteter på én eller flere offshore vindparker. Beslutningene som skal foretas er hvor mange fartøy som burde leies eller anskaffes for å møte en gitt vedlikeholdsplan, i tillegg til å avgjøre hvorvidt et moderskipskonsept kan være økonomisk lønnsomt. Strategiske beslutningsstøtteverktøy i form av både en deterministisk og en stokastisk optimeringsmodell er utviklet og vil bli presentert. Basert på ulike scenarier, inkludert turbinfeil, spotpriser på fartøy og helikoptre, strømpriser og værforhold, bestemmer den stokastiske modellen optimal flåtestørrelse og flåtemiks som bør brukes til å utføre vedlikeholdsoperasjoner på en eller flere offshore vindparker.

En beregningsorientert studie beviser at den stokastiske modellen er i stand til å løse problemer for virkelige vindparker med mer enn 400 vindturbiner. Videre, tyder verdien av den stokastiske løsningen og den forventede verdien av perfekt informasjon på at den stokastiske modellen gir løsninger som er godt sikret mot mulige fremtidige utfall, og returnerer løsninger som presterer vesentlig bedre enn løsningene fra den deterministiske modellen. I tillegg har den stokastiske modellen vist seg å ha en stor økonomisk anvendbarhet, i form av å avgjøre villighet til å betale for ekstra bølgekapasitet på fartøyer, mulige besparelser ved bruk av moderskip og potensielle besparelser ved bruk av en felles flåte på flere offshore vindparker.

Den stokastiske optimeringsmodellen som tar opp flåtestørrelse- og flåtemiksproblemet for offshore vind er den første i sitt slag, og denne avhandlingen har vist at modellen har en reell verden verdi i form av å være et godt strategisk beslutningsstøtteverktøy som tar hensyn til den iboende usikkerheten i problemet. Modellen vurderer imidlertidig ikke logistikk av reservedeler eller optimal skiftordning for vedlikeholdspersonell, og videre arbeid består av blant annet disse spørsmålene.

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1 Introduction

The world's electricity demand is increasing rapidly. An expected growth in the global electricity demand of 35 % from 2010 to 2035 (Figure 1), combined with governmental policies to reduce CO_2 emissions, will require a new focus on renewable electricity sources. The EU 20-20-20 targets include reduction of greenhouse gas emissions by at least 20 % compared to 1990 levels. Reduction of coal fired electricity and an increase in renewable energy is crucial to meet this and other environmental targets (IEA, 2010).

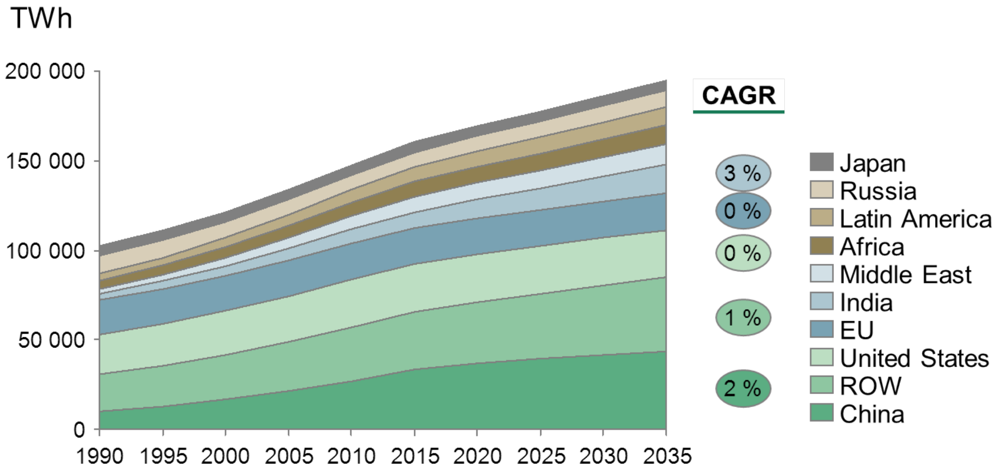


Figure 1: *World electricity demand forecast. Based on the IEA World Energy Outlook 2010 scenario that takes into account the policy commitments and plans announced around the world (IEA, 2010). Note: Data converted from million tonnes of oil equivalents (Mtoe) to TWh using IEA converting tables. Compounded annual growth rate (CAGR) calculated from 2010-2035.*

The International Energy Agency (IEA), expects wind energy to play an important role in the renewable electricity mix in the years to come. However, the expected increase of renewable power generation will depend on whether different governmental policies will be achieved. The IEA have presented three different scenarios, in which the compounded annual growth rate (CAGR) for power generation from wind energy, range between 8 % and 11 % as illustrated in Figure 2. The *current policies scenario* assumes no change in policy as of mid-2010, the *new policies scenario* takes account of the broad policy commitments and plans announced around the world, and the *450 scenario* is based on the goal of 450 parts per million of CO_2 equivalent in the atmosphere. The major difference between the three scenarios is the substitution of coal-fired power generation with renewable energy sources (IEA, 2010).

Within the past 10 years, the global installed capacity of offshore wind has increased rapidly, from 65 MW in 2000, to 4175 MW in 2011 as illustrated in Figure 3. The growth is expected to continue, and different forecasts for offshore wind capacity in the EU in 2020, range between 38 and 64 GW, compared to approximately 3.2 GW in the EU in 2010 (Figure 4). Offshore wind sites are not unlimited. To enable such a strong growth, offshore wind developers will have to move further and further away from shore. Dogger Bank, the largest

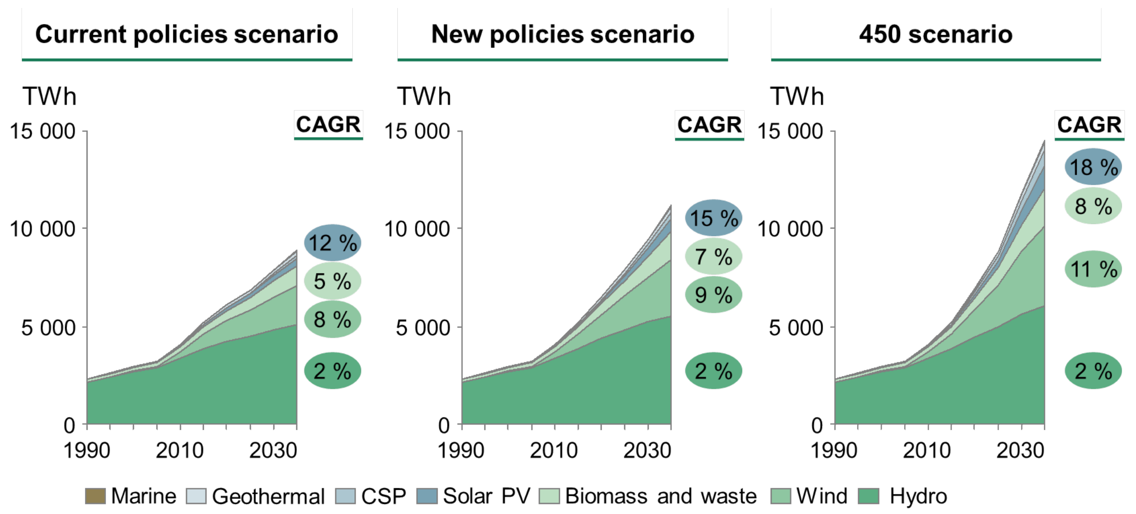


Figure 2: *Renewable power generation. Based on IEA World Energy Outlook 2010 (IEA, 2010). Note: CAGR is calculated from 2010-2035, and extrapolation has been done using CAGR.*

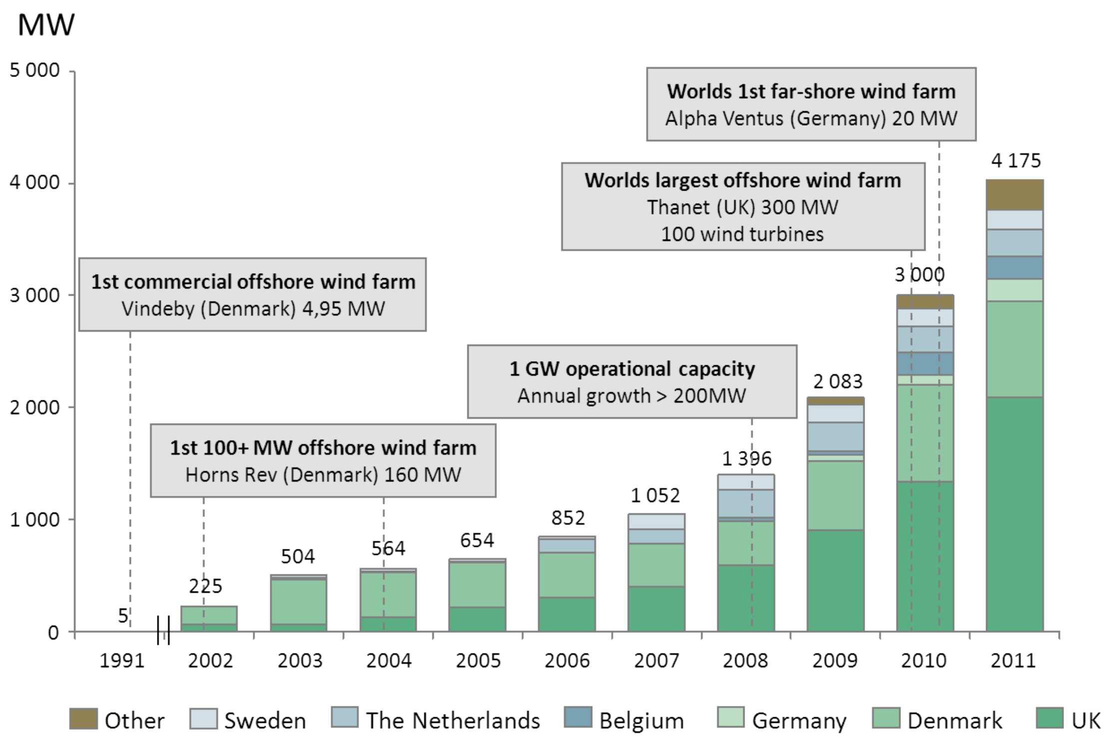


Figure 3: *Development of global offshore wind capacity. Source: EWEA (2009a) and 4C Offshore (2011)*

zone in the third license round for UK offshore wind farms, is located off the east coast of Yorkshire, between 125 and 290 kilometres offshore (Forewind, 2011). In comparison, the Belgian wind farm Belwind, is located 46 kilometres off the coast of Zeebrugge, and is currently the wind farm located farthest away from shore, if we only take into account fully operational wind farms (Belwind, 2012).

Heavy winds and salty sea make offshore wind turbines more exposed to break downs than onshore wind turbines. Furthermore, rough weather conditions and

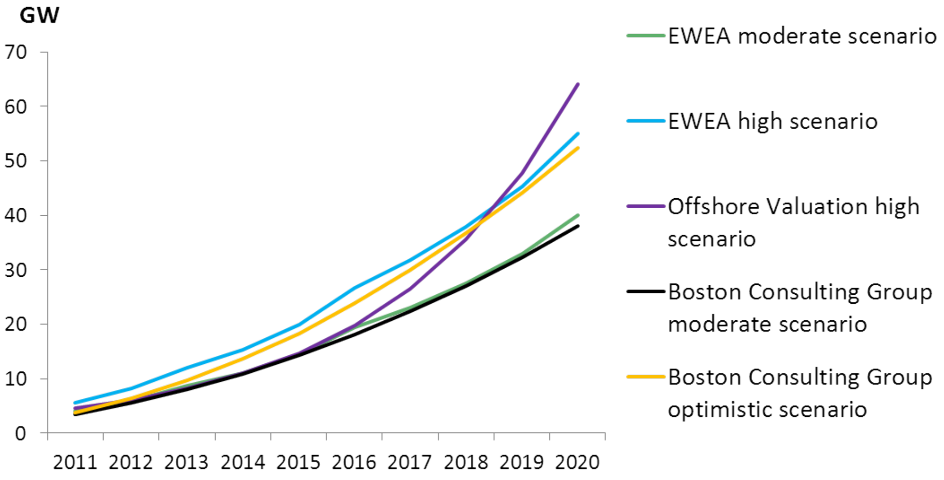


Figure 4: *Overview of different forecasts for offshore wind developments. Source: EWEA (2009b) , The Offshore Valuation Group (2010), The Boston Consulting Group (2011).*

greater distances from shore lead to lower accessibility of the wind farm, and makes operations and maintenance of an offshore wind farm difficult and expensive to perform. Operators are highly dependent on weather windows to be able to perform different maintenance activities. The further away from shore, the longer the weather windows must be, to successfully perform the maintenance activities.

One of the challenges in the offshore wind industry today, is the need of financial support through different governmental support mechanisms. For an offshore wind farm project to be profitable, the levelised cost of energy must be below the given support scheme (BCG, 2011). The cost of Operations and Maintenance (O&M) can easily make up for 20 % - 25 % of the total power production cost, as illustrated in Figure 5 (Renewable UK, 2011). According to Wind Energy Updates latest Operations and Maintenance report, wind farm owners could face O&M costs up to EUR 100 000 - EUR 300 000 per wind turbine per year (Bussiéres and Cavaco, 2011). The same report concludes that corrective maintenance, as a result of break down on a turbine, makes up for 66 % of the total O&M costs. The losses in revenue as a result of unavailability of the turbine is often of equal size, and comes in addition to the maintenance costs. However, these losses depend upon the electricity price, and can vary considerably from day to day.

In the execution of maintenance operations of an offshore wind farm, the choice of fleet mix can make a great impact on the O&M costs. A helicopter can have a variable cost of 1000 USD/hour (Conklin and Decker, 2011), and a crane vessel can easily cost 40 000 USD/day (Kaiser and Snyder, 2011). The vessel spot rates for maintenance vessels can deviate with up to 60 % from year to year, and makes it difficult to determine whether vessels should be contracted today or in a year (Østgren, 2012). Choosing an optimal fleet mix however, is not necessarily easy. The weather conditions at the specific site, wave height and wind speed in particular, will affect the choice of vessels, and are highly uncertain. Some vessels can access the foundation of the turbine when the wave height is up to 1 meter, while catamarans can generally access the turbine in wave heights up to 1.5 or even 2

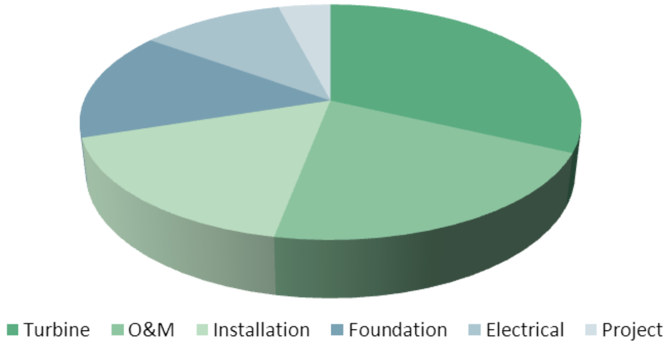


Figure 5: *Breakdown of cost of energy into key elements. Source: Renewable UK (2011).*

meters. Helicopters can access the turbine independently of wave conditions, but require wind speeds less than 18 m/s (Østgren, 2012).

Another factor that has to be taken into account, is the distance from shore. For many of the offshore wind farm projects currently under planning, a harbour or a platform at sea serving as a station for transportation out to the wind farm(s) with accommodation for personnel, storage of spare parts and shelter in emergency situations, could be economically viable depending on the distance from shore. With such a concept, the required weather window for successfully performing a maintenance activity would be reduced considerably.

Whether to rent a vessel or helicopter on a short term, or rent it on a long term but at a lower day rate, is a decision that must be deliberately examined. The optimal decision will depend on the size of the wind farm and the maintenance strategy. A strategy with a high focus on preventive maintenance will require more planned visits to each wind turbine than a run-to-failure strategy. Then again, little focus on preventive maintenance will lead to a higher failure frequency, which again might require even more visits than that of a highly preventive strategy.

Making the right decisions is crucial in the planning phase of an offshore wind farm project. Improvements of only 1 % in the O&M costs can make a relatively big impact on the revenue, given the numbers above. One way of achieving these savings is for several offshore wind farm operators to cooperate on a joint fleet, in order to achieve economies of scale. A model determining the fleet size and mix that is able to serve more than one offshore wind farm can thus be very attractive.

The problem of deciding the optimal fleet size and mix for O&M on one or several offshore wind farms will be addressed in this thesis, and will be referred to as the Fleet Size and Mix Problem in Offshore Wind, FSMPOW. This thesis will address the FSMPOW using operations research (OR).

Offshore wind is a relatively new technology, and the number of publications on this subject is limited, which suggests that advanced OR is not in extensive use today. Considering the complexity of choosing a fleet size and mix, and the high economic impact of these decisions, wind farm developers should to a greater extent take advantage of operations research tools.

To address the FSMPOW, we will first develop a deterministic model. Not to neglect the inherent uncertainty of the problem, including unplanned failures with the following need of corrective maintenance, uncertainties in electricity prices, vessel spot rates and weather conditions, we will develop a stochastic node formulation of the FSMPOW. This will give decision makers considerable decision support when determining the fleet size and mix to execute maintenance activities on one or several offshore wind farms.

In the next section, different aspects regarding operations and maintenance within the offshore wind industry is described. In Section 3 a in-depth description of the FSMPOW is given. Relevant literature is reviewed in Section 4. A deterministic mathematical formulation of the FSMPOW is presented in Section 5, before presenting a stochastic node formulation of the FSMPOW in Section 6. In Section 7 we present the methods that have been used during the computational study. We continue with presenting the results from the computational study in Section 8. Section 9 sums up the results in a conclusion, before further work on the FSMPOW is discussed in Section 10.

2 Maintenance of Offshore Wind Farms

Offshore wind is a relatively new technology, and the execution of maintenance operations on offshore wind turbines is very different from O&M on onshore wind turbines. In this section we will try to give the reader an impression of the O&M process for offshore wind turbines, as this will give a better understanding of the problem description that will be presented in the next section.

2.1 Preventive Maintenance

Preventive maintenance is conducted to extend the life time of a turbine, and to keep the number of failures at a reasonable level. A preventive maintenance operation can include visual inspections, changes of consumables (greasing, lubrication, oil filters), oil sampling and re-tightening of bolts (Besnard et al., 2009). The frequency at which preventive maintenance should be executed, will depend upon the maintenance strategy developed for the specific wind farm. An optimal maintenance strategy is based on the types of turbines being used, because the costs of spare parts and failure frequencies will vary between different turbine producers and models. However, some preventive maintenance strategies suggest 1 - 2 visits to each turbine every year. The preventive maintenance operations generally take 1-2 days per turbine, and normally require 2 maintenance personnel transported to the turbine by either a vessel or a helicopter. It is common to have a major overhaul of each wind turbine every 5 years, which normally requires around 100 man hours (Van Bussel et al., 2001).

Considering the fairly high failure rates of offshore wind turbines and the high downtime cost, having no maintenance strategy at all would reduce the availability of the wind farm considerably, and thus not be an option (Van Bussel and Schöntag, 1997).

2.2 Corrective Maintenance

If a wind turbine faces a break down, corrective maintenance has to be executed. A break down can happen for a number of different reasons, and the frequency at which they happen will vary dependent on turbine manufacturer and model. Considering offshore wind being a relatively new technology, little research has been done on this specific matter. However, a number of articles have been written on failure rates for onshore wind turbines. The German Wind Energy Measurement Program did a research on 1500 onshore turbines in Germany over 10 years from 1997 - 2006, where they collected valuable data on failure rates (Milborrow, 2010). Although these might not be entirely representative for offshore wind turbines, they give an impression of how failure rates and days out per failure influence the total downtime of a wind turbine. This is illustrated in Figure 6.

The electrical system is the most common source for failure, with 0.55 incidents per year. Although the turbine is generally back into operation after only 1.5 days, the high failure rate leads to a long total downtime. The gearbox, on the other hand, has a relatively low failure rate, only 0.13 incidents per year. When a gearbox fails however, the outage time is much longer, normally over 6 days.

Although increased focus on preventive maintenance can reduce the number

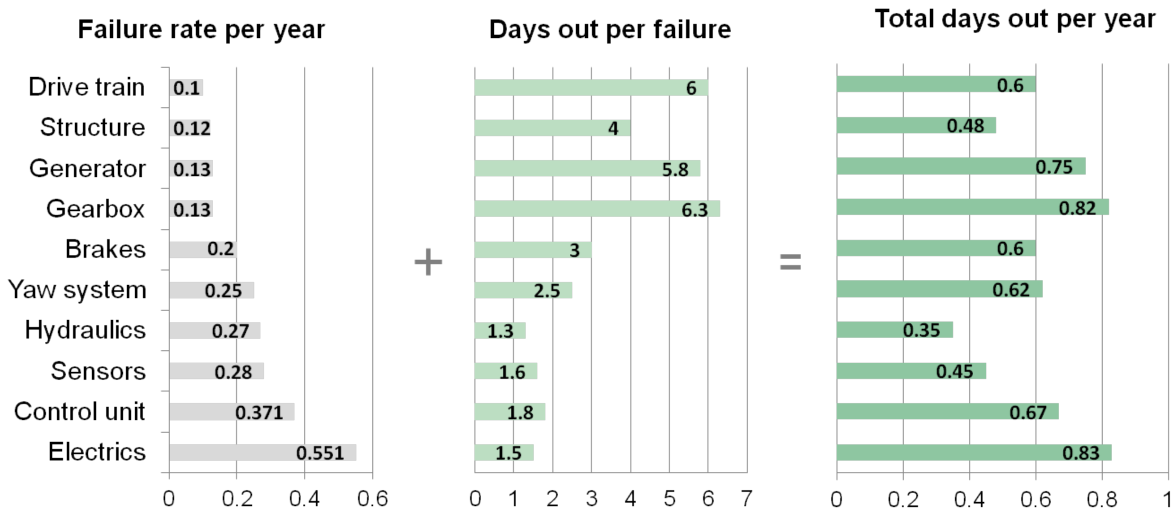


Figure 6: *Average failure rates and days out per failure for onshore wind turbines. Research done on 1500 onshore turbines in Germany over 10 years (1997-2006) by the German Wind Energy Measurement Programme (Milborrow, 2010)*

of failures on a wind turbine, a complete mitigation of the risk is highly unlikely. That being said, it is possible to limit the downtime by focusing on the several factors influencing the actual time required to get a turbine back in operation. The total downtime of a turbine can roughly be divided into four parts, as illustrated in Figure 7. After a failure occurs, getting hold of the right vessels and spare parts can take time. Once the required vessels are in place, one have to wait for an appropriate weather window, and this waiting time will depend upon the specifications of the vessel. The distance from the base of the vessel to the offshore wind farm and the speed of the vessel will determine how much time is spent in transport. Once the vessel is located at the turbine, the maintenance task can be executed, and the time required will vary dependent on the type of failure (Allwood and Sharp, 2006).

Offshore wind power producers in the UK receive approximately EUR 100 per MWh of produced power in support (Ofgem, 2011). A 5 MW turbine can thus have a downtime cost of EUR 12 000 per day, and this is without considering

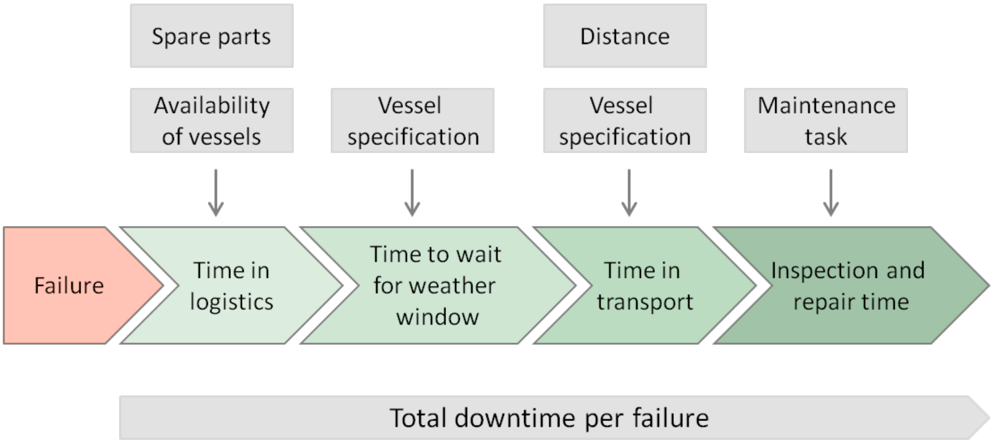


Figure 7: *Factors influencing the downtime after a failure occurs*

the electricity price. Figure 7 illustrates the great influence vessels make on the downtime of a turbine after a failure has occurred. Having vessels with the right specifications available can reduce the downtime considerably, and emphasises the importance of the FSMPOW.

2.3 Vessels and Helicopters Used for Maintenance in Offshore Wind

For preventive maintenance, which normally consists of transporting personnel with a limited need of equipment, small supply vessels like the WindCat, Fob Lady, Fob Swath 1 and SWATH Tender are used today (Figure 8). These vessels can also transport smaller parts, and the SWATH Tender, currently used at BARD offshore wind farm located 100 km off the German coast, can carry 12 passengers and has a maximum deck load capacity of 1.5 tonnes. RIB's (Rigid Inflatable Boats) are only used for short distances, and in good weather conditions. For intermediate sized components like main bearing and yaw drive, a larger supply vessel is required for transportation (Gardner et al., 2009).

(a) FOB SWATH 1. Photo: Odfjell Wind AS

(b) SWATH Tender. Photo: www.elbe-pilots.de

Figure 8: *Vessels used for maintenance on offshore wind farms*

For replacing large components like blades, the generator or the nacelle, a crane vessel is required. The jack-up barge Odin, lifts itself over the surface by placing its four legs on the seabed as illustrated in Figure 9(a). The jack-up barge can lift up to 500 tonnes and stay offshore for weeks (HOCHTIEF, 2011).

However, the jack-up concept puts a restriction on the water depth. Crane vessels on the other hand, can operate at any water depth, and the multipurpose crane vessel Rambiz, which did the installation at the Beatrice wind farm in UK, can lift up to 3300 tonnes as illustrated in Figure 9(b) (Scaldis N.V., 2011).
Increasing investments in offshore wind has led to developments in the offshore wind vessel industry and there are a number of new concepts for deeper waters and harsher environments on their way.

Currently the vessels used for offshore wind maintenance cannot, and should not, operate in significant wave heights above 1.5 m - 2.5 m, and wind speeds over 18 m/s (Østgren, 2012). For the regions around the Baltic sea, this restriction should not affect the accessibility of the wind farm to a great extent. In the North Sea however, the number of days in which the wave height is more than 2 meters is considerably higher. Data we have gathered on wave heights from the Ekofisk field

(a) Jack-up barge Odin
Photo: Island Shipping 2007

(b) Crane vessel Rambiz
Photo: Scaldis salvage and marine contractors N.V.

Figure 9: *Crane vessels used for maintenance activities on offshore wind farms*

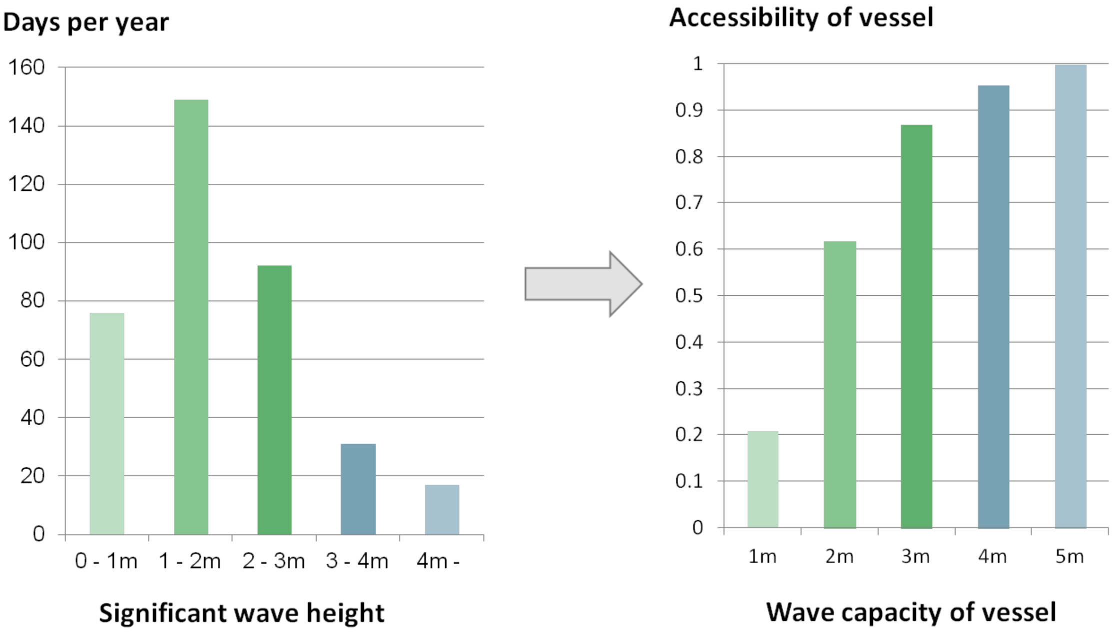


Figure 10: *Wave heights and vessel accessibility for the Ekofisk area in the North Sea*

in the North Sea (Norwegian Meteorological Institute, 2012), show that the wave height is below 2 meters 225 days of the year, giving a vessel with wave capacity of 2 meters only an accessibility of 61 % as illustrated in Figure 10. If the wave capacity of the vessel were increased to 3 meters however, the accessibility would be increased to 86 %.

Considering the high costs of downtime, effective access systems can be relatively expensive, and still favourable. In some cases, like in Horns Rev offshore wind farm in Denmark, Helicopters are used to transport engineers out to the turbines (Gardner et al., 2009). The helicopter cannot land, but can lower people to the top of the nacelle as illustrated in Figure 11. Although having a helipad that would allow helicopters to land is a different issue, the ability to lower engineers to the top of the nacelle has relatively little impact on the turbine design. Furthermore, the helicopters are not limited by the wave conditions, but they do require good visibility and acceptable wind speeds. Helicopter access is probably not profitable for many of the wind farms in operation today, with increasing distances from shore, the savings in time and the high accessibility compared to vessels can make helicopters economically viable (Tong, 2010).

Figure 11: *Engineer lowered onto the nacelle by a helicopter. Photo: Eurocopter*

2.4 Offshore Station Concepts

While moving further out to sea, the travel time will increase, and longer weather windows will be necessary to allow for maintenance to be executed. For many of the wind farms currently under planning, new concepts are in development. Forewind, a consortium comprising the four large energy companies Statoil, RWE, SSE and Statkraft, is planning the development of Dogger Bank. The wind farm field has a planned capacity of 9 GW, which is more than the double of the world's installed offshore wind capacity today. In addition to being the worlds largest offshore wind farm, it will be located the farthest away from shore, between 125 km and 290 km (Forewind, 2011). Due to the location and size of the Dogger Bank project, different offshore station concepts are being analysed (Østgren, 2012). One of these concepts consists in building a mother ship solution that can stay on-site, providing accommodation for the wind turbine maintenance and service personnel, with capacity for multiple catamaran work boats to transfer personnel out to the wind turbines. Two concepts that might give these opportunities are the Sea Wind maintenance vessel (Renewable Energy Focus, 2011) proposed by Offshore Ship Designers as illustrated in Figure 12(a) and Ulstein's X-bow concept designed for Sea Energy PLC (The Maritime Executive, 2012) as illustrated in Figure 12(b). These solutions also support helicopter operations including transport of personnel to and from shore (Renewable Energy Focus, 2011).

(a) Sea Wind maintenance vessel. Photo: Offshore Ship Designers

(b) Ulstein's X-bow concept. Photo: Ulstein Group

Figure 12: *Potential mother ship concepts.*

Another concept emerging is the Dutch *harbour at sea*, an artificial island with the purpose to reduce sailing times for installation and maintenance of the offshore wind turbines (Figure 13). The island would serve as a station for transporting, assembling and maintaining turbines, with hotel for personnel, storage of spare parts and a heliport among other things. Although the required investments in civil infrastructure are estimated to MEUR 1000, the harbour is intended to serve several offshore wind farms (Haven Eiland Duurzame Energie op de Noordzee, 2011).

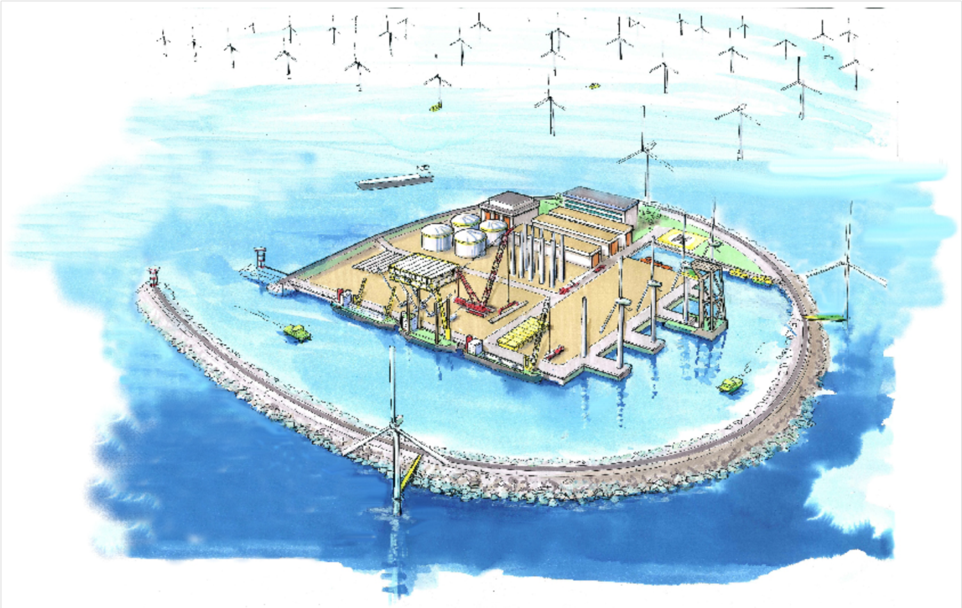


Figure 13: *A prospect of the Dutch harbor at sea. Photo: www.haveneilandopzee.nl*

3 Problem Description

In this section we will describe the different aspects that must be taken into account when wind farm operators want to determine an optimal fleet size and mix to execute maintenance activities for one or several offshore wind farms.

3.1 The maintenance activities

There are two different types of maintenance operations that have to be executed on an offshore wind farm: preventive maintenance operations and corrective maintenance operations. The preventive maintenance operations are planned, and the operator will have access to a maintenance schedule for each wind turbine, which is normally based on the point in time with minimum cost of replacement for each maintenance operation, as indicated in Figure 14. However, the preventive maintenance operations can be executed both before and after the scheduled point, but with increased cost. If a preventive maintenance operation is executed before the optimal point, this will incur costs as changing parts too often. On the other hand, if a preventive maintenance operation is delayed, this will increase the probability of failure and thus increase the expected downtime cost.

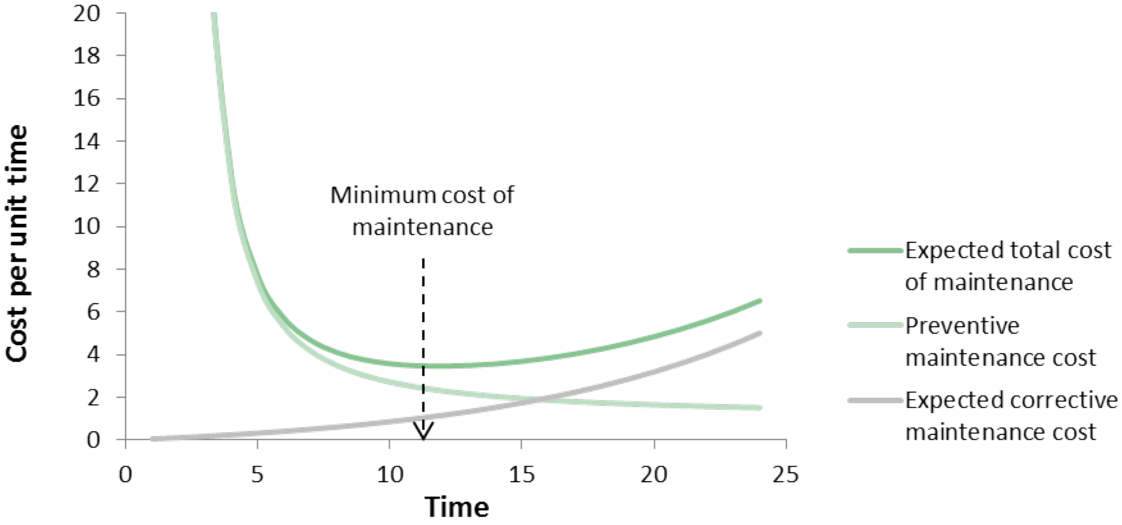


Figure 14: *Preventive and corrective replacement cost. Source: ReliaSoft Corporation (2011).*

In addition to the preventive maintenance operations, there are different types of unforeseen failures that can occur on each turbine throughout the planning period. The probability of each type of failure is assumed to be known, and is based on historical data for the type of turbine being used on the offshore wind farm. If a failure occurs, corrective maintenance should be executed as soon as possible to minimise the downtime costs.

3.1.1 Execution of the maintenance operations

The execution of each maintenance operation, both preventive and corrective, will consist of one or more *activities* as illustrated in Figure 15. These activities can be divided into three groups: transport of maintenance personnel, shipment of larger parts and equipment, and lifting activities. Each activity type will normally require different vessel types. The transport of maintenance personnel can be done by a crew transfer vessel (CTV), helicopter or supply vessel. The shipment of parts requires a supply vessel or a multipurpose vessel, and heavy lifts will require a crane vessel or a multipurpose vessel.

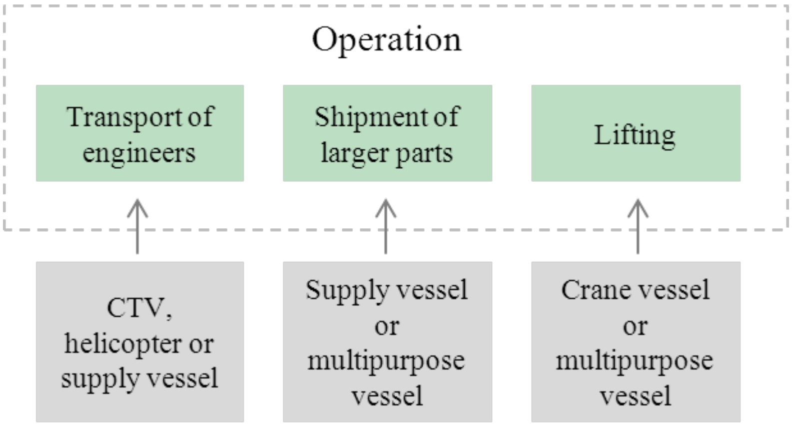


Figure 15: *Illustration of how an operation can consist of several activities with different vessel requirements*

The activities concerning transportation of maintenance personnel will require a CTV or helicopter with a certain crew size. The parts and equipment that need to be shipped will have a certain weight and size, and thus require a deck load (tonnes), and deck size (m^2). The activities consisting of a lift will require a crane vessel or a multipurpose crane vessel with a certain lifting capacity (tonnes). It will take a given number of hours to execute each of the maintenance activities. However, the execution time for some of the activities requiring maintenance personnel can be reduced, if the number of men working on the activity is increased from the minimum requirement. For example, the time required to re-tighten the bolts might be reduced if the size of the maintenance team is increased from two to three. On the other hand, there is a limit as to how many men that can be working on the same turbine at the same time. There is thus also a limit in the number of maintenance personnel that can work on the same activity while increasing the efficiency.

There are some preventive maintenance operations where a CTV or helicopter can have several teams working on different turbines at the same time. The CTV or helicopter drops off each team at their turbine, and picking them up when their job is done. For safety reasons not more than 4 teams should be working at different turbines at the same time. This is to allow the CTV or helicopter to have sufficient time to rescue the teams in case of bad weather or other emergencies.

3.2 Composition of the fleet

In the execution of the different maintenance activities one may have the ability to rent or acquire different types of CTVs, supply vessels, crane vessels and helicopters. These will have a given speed, deck load, deck size and crew capacity. In addition they will have operational and safety requirements in terms of different types of weather, for instance wind speed and wave heights. If the weather conditions exceed one of the operational requirements of a vessel, the vessel will not be able to execute any maintenance operations. If the weather conditions exceed the safety requirement of a vessel, the vessel must return to a safe haven.

The total cost of renting or buying a vessel or a helicopter is divided into a fixed cost and a variable cost. The variable cost will depend on the number of hours in operation, and the number of hours required for transportation to and from an offshore wind farm and between wind farms. Each vessel and helicopter type can either be rented or acquired. The lengths of the contracts for the vessels and helicopters that can be rented will vary from type to type. Some might have a lease term of a couple of weeks, and others might have lease terms of several months. If a vessel is acquired, the fixed cost will be the investment cost less the salvage value depreciated over the expected life time of the wind farm.

3.2.1 Current and future maintenance fleet concepts

According to Østgren (2012), O&M Manager for Offshore Wind at the Norwegian electricity company Statkraft, there are in general three different maintenance fleet concepts that can be used when executing maintenance activities on an offshore wind farm.

The first concept, which is mostly used today, consists of an onshore harbour to which all vessels and helicopters must return by the end of the day. The second concept is based on existing technology and consists of large CTVs, supply vessels or crane vessels that can stay offshore for several periods, only returning to shore in order to fill up with supplies, bunker up or to change the crew. The safe haven will in this case be a harbour onshore. Vessels that can stay offshore for several days normally require some time in preparation in the beginning of the contracting period, in addition to some time in demobilisation in the end of the contracting period.

The third concept consists of either a mother ship or a platform located close to the offshore wind farms, to reduce the distance that needs to be undertaken by the vessels and helicopters in the execution of the maintenance activities. Such an offshore station concept will have an annual fixed cost which is the investment cost less the salvage value, depreciated over the expected life time of the wind farm. The station will be placed at a certain distance from the offshore wind farm(s), and will have capacity limits in terms of number of helicopters, supply vessels and crane vessels. An offshore station is considered as a safe haven, which means that the vessels that belong to an offshore station do not have to return to shore in case of bad weather.

It is likely that the optimal fleet mix will be a combination of the concepts mentioned above, especially if the solution consists of a mother ship, which can not serve as a safe haven for crane vessels due to their size. Figure 16 illustrates possible routes for two different maintenance concepts. One vessel has origin at an onshore harbour and can stay offshore for several periods while the other vessel has origin at an offshore station and can thus only stay offshore for one period.

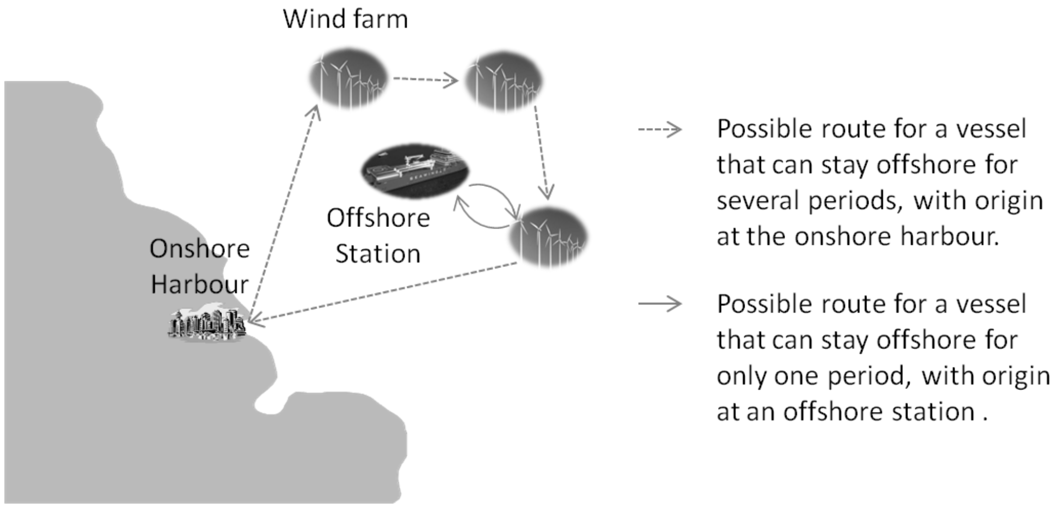


Figure 16: *Example of routes for maintenance vessels with three offshore wind farms and one offshore station.*

3.2.2 Adjustment of the fleet

Decisions involving acquirement or construction of new vessels, helicopters and offshore stations must be made at a reasonable time in advance of their usage. When it comes to the rental contracts an operator can, in theory, rent vessels and helicopters from the spot market on a day to day basis. This strategy is risky however, because the demand often exceeds supply in the summer months. Operators therefore try to make decisions of renting vessels several months in advance of the maintenance execution. Some vessel and helicopter types can, however, be contracted right before the maintenance execution. All rental contracts are binding, and the operator will only have a given budget to invest in vessels, offshore stations and helicopters.

Figure 17 illustrates the point of contracting and the periods of usage for a vessel type and a helicopter type. The vessel type can be contracted both in the beginning of year 1 and in the end of year 1 and the helicopter type can only be

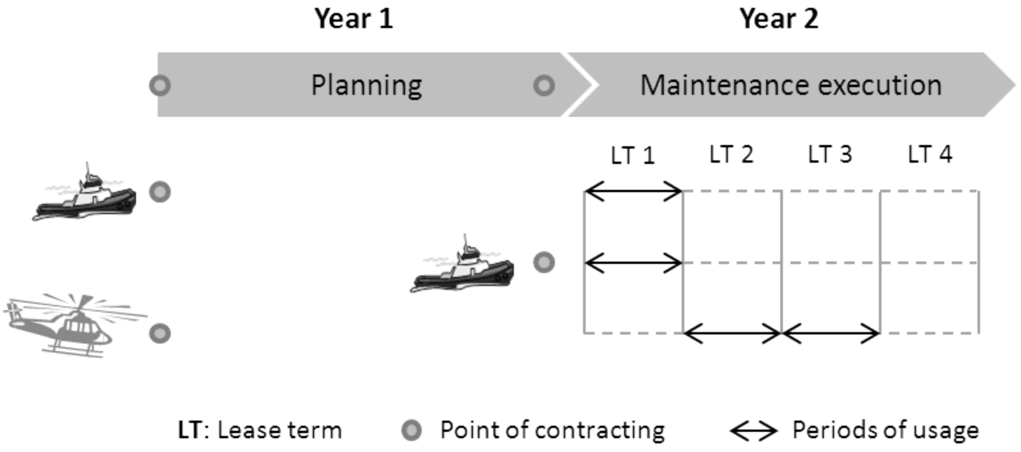


Figure 17: *Example of contracting point for a vessel type and a helicopter type*

contracted in the beginning of year 1. In this example one vessel is contracted in the beginning of year 1 and another in the end of year 2, both for usage in lease term 1. In addition, one helicopter is contracted in the beginning of year 1 for usage in lease term 2 and 3. In this example we have assumed that the vessel type and helicopter type have lease terms with equal lengths of 3 months.

3.3 Location aspect

The location of the offshore wind farms will determine the distance between the wind farms and the distance from each farm to the shore, and thus the time it will take to transport vessels, spare parts and maintenance personnel out to the wind farm(s) and between the wind farms. In addition, there will be a certain water depth in the area at which the wind farms are located, which will affect the types of vessels that can operate on each wind farm. The location of the wind farm(s) will have variable weather conditions in terms of wind speed and direction, wave height, wave period, wave direction, current direction and current speed.

Each wind farm will consist of a certain number of wind turbines, which are usually of the same type with the same production capacity (MW). This, in addition to the wind speed, will affect the output generated from the wind farm, and thereby also the downtime cost if a turbine faces a breakdown, or if a turbine is to be shut down for maintenance operations.

3.4 Uncertainty

There are several uncertain factors affecting the optimal fleet size and mix for executing the maintenance operations on offshore wind farms. In this thesis we will take into account uncertainties in weather, vessel spot rates, electricity prices and turbine failures to allow for robust solutions that will perform well when exposed to real uncertainty.

3.4.1 Weather

The area at which the wind farms are located will have a variable wind speed in addition to wave height, wave period etc., which are all highly uncertain. The wind speed will affect the generated output of each wind farm, which is why it is important to take into account the wind speeds when determining at which point the different maintenance activities should be executed. Figure 18 shows an approximation of the power output for a typical 5 MW wind turbine. The *cut-in speed* is the minimum wind speed at which the wind turbine will generate usable power and the *rated speed* is the minimum wind speed at which the wind turbine will generate its designated rated power. Finally, the *cut-out speed* is the wind speed at which the turbine is shut down for safety reasons (Puthoff and Sirocky, 1974).

Vessels and helicopters will have both operational limits and safety limits when it comes to wind speed, wave height, wave period etc. Wave heights are one of the most challenging aspects in the industry, because the vessels currently in the market cannot operate in significant wave heights of more than 2.5. If the weather conditions reach one of the operational limits of a vessel (or helicopter), the vessel will not be able to execute any maintenance activities. If the weather conditions

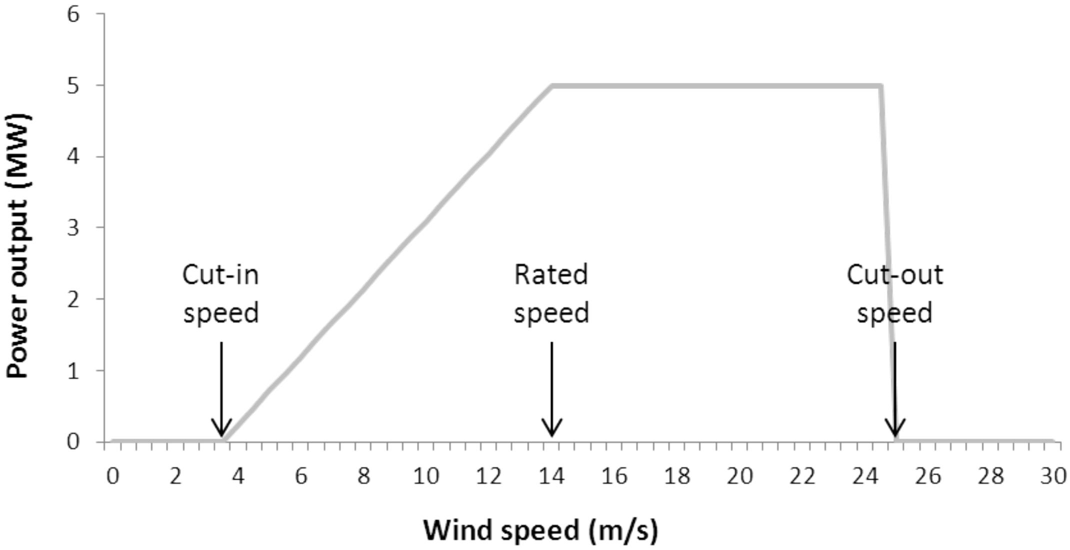


Figure 18: *Simplified power output curve as a function of wind speed for a 5 MW Siemens wind turbine. Based on Puthoff and Sirocky (1974) and specifications from Siemens (2011).*

reach one of the safety limits of a vessel, the vessel must return to a safe haven which is either shore or an offshore station dependent on the origin of the vessel.

3.4.2 Vessel spot rates

The price of a vessel contract will depend upon the spot rates in the market at the point of contracting, for the respective lease term. Short term rental of one month is generally 40 % - 60 % more expensive than a long term contract of one year (Østgren, 2012). As discussed in Section 3.2.2 some types of vessels and helicopters can be contracted close to the maintenance execution, referred to as the end of year 1 in Figure 17. The prices of these contracts will depend on the spot rates in the market at that point, and are therefore uncertain. The decision makers must therefore decide whether they should contract the vessels at a given price today, or if they should wait until a later stage, which can be favourable if the spot rates are expected to decline. They can, of course, contract some vessels today and some at a later stage.

3.4.3 Turbine failures

The number of failures each wind farm will experience is highly uncertain. A vessel fleet must thus be robust enough to handle the majority of the corrective maintenance operations as a result of failure, in addition to the planned preventive maintenance operations given from the maintenance strategy, in order to keep the availability of the wind farm at a reasonable level. The losses from one 5 MW turbine that fails to produce power can be up to EUR 12 000 per day in the UK, only from support (Section 2.2), and it should be evident that flexibility of the fleet is crucial to ensure high availability of the offshore wind farms.

3.4.4 Electricity price

The electricity price as well as the wind speeds will affect the revenue of each wind farm, or in other words, the downtime cost for wind turbines not operating. It is thus important to execute preventive maintenance activities in periods with low wind speeds and low electricity prices, when the downtime costs are low. If the wind speeds and electricity prices are expected to be low for several periods after a failure occurs on a turbine, it might be more profitable to use available vessels on more urgent maintenance activities than to get the turbine up and running immediately. Wind energy producers will in addition to the electricity price receive a feed in tariff per MWh of produced power as a support for producing renewable power, which in the UK is determined each year by the government (DECC, 2011). The support mechanism for offshore wind varies from country to country. Although a certain factor in the UK, it might be an uncertain factor in other countries.

3.5 Model Objective

The FSMPOW is a strategic decision problem, in which the offshore wind farm operator must make a long term decision based on the different aspects mentioned above. The planning horizon can be one year or even longer, thus the decisions made today will make a great impact on the future economics of the offshore wind farm(s). The solution to the FSMPOW should determine the optimal combination of vessels, helicopters and offshore stations that should be rented or acquired in the given time horizon, in order to execute the preventive and corrective maintenance activities at the lowest possible cost.

4 Literature Review

In the field of fleet composition and routing there exists a great amount of research, especially when it comes to land based problems (Hoff et al., 2010). Our work is related to the fleet size and mix problem (FSMP) in the offshore wind industry, where the number of operation research publications has been limited so far. Consequently, this literature study has been divided in two. First, publications on strategic fleet planning within the maritime industry are given. This to capture similarities and variations among FSM problems being solved by operations research. Second, we will discuss publications focusing on O&M in the offshore wind industry today.

4.1 Strategic fleet planning

Hoff et al. (2010) states that in decision models for strategic fleet management, it will not make sense to include routing aspects at a very detailed level, unless the transportation demand is highly predictable. That being said, the authors also highlight the fact that even in a strategic setting, decisions may involve some sort of tactical aspects due to the strong dependency between fleet composition and routing. They point out that integration of routing in fleet composition decisions is warranted, but that such integration increases the computational complexity of the problem. By including uncertainty, the complexity is likely to increase even more. Their survey shows that most of the fleet composition and routing problems today are solved as some sort of a FSM problem, where the traditional FSM problem is an extension to the basic classes of routing problems (specific types of the vehicle routing problem). This implies that the fleet size and mix problem is a problem where the optimal fleet is implicitly derived by solving an underlying routing problem. This also coincides with our impression from this literature study.

Several aspects of the maritime FSM problem differ from other transportation contexts (i.e. land-based) (Pantuso et al., 2012). Hoff et al. (2010) and Christiansen et al. (2004) indicate this in their surveys, and mention differences in capital costs, lead times, higher level of uncertainty and the lifetime of vessels. Earlier this was a problem due to the fact that most research was land-based, but during the last decade the interest for the maritime area has grown rapidly.

In general, for FSM problems, the major critique of today's research can be dividend in two. First, there is a trend to analyse problems that are too idealized and far from the requirements of the real world. Second, there is a lack of treating stochastic aspects (Hoff et al., 2010).

The papers to be presented in the first part of this survey are mainly related to the maritime FSM problem and are only a selection of the papers available. However, this should give the reader a brief introduction on the field of interest within FSM problems. For a more thorough overview of the literature, the reader is referred to the literature surveys presented by Hoff et al. (2010), Christiansen et al. (2004), Ronen (1993) and Pantuso et al. (2012).

4.1.1 Maritime FSMP publications

The pioneers of fleet size problems are Dantzig and Fulkerson. Their publication from 1954 deals with minimisation of the number of navy fuel oil tankers needed to guarantee a fixed set of schedules. The problem is modified by Bellmore et al. (1968) to include a utility for each delivery, as the number of fuel oil tankers is set to insufficient. Bellmore's problem is to maximise the sum of utilities associated with each schedule. The problem is shown to be equivalent to a transshipment problem.

A model determining the optimal number of ships to meet a given proposed task while ensuring the most profitable deployment of the fleet is presented by Bendall and Stent (2001). The idea behind the development of the model is to analyse the potential effects and savings of introducing a new high speed cargo vessel. The problem is formulated as a mixed integer problem and tested on a hub and spoke feeder service based in Singapore.

The problem of determining an optimal fleet in a real liner shipping problem along the cost of Norway, and the corresponding weekly routes for each ship is considered by Fagerholt (1999). The solution method consists of three phases, where a set partitioning problem (phase 3) is solving a set of generated routes (phase 1 and 2). The generation of routes is done with a dynamic programming algorithm. The problem studied is a fleet size problem, where the ships are given and the speed is equal for all the vessels. The solution method Fagerholt presents can also be adjusted to solve the fleet composition problem.

A new solution method for handling ships with different speeds is proposed by Fagerholt and Lindstad (2000). This solution algorithm is developed as a request from a Norwegian oil company, with the purpose of determining an optimal policy for the scheduling of supply vessels servicing a number of offshore installations from an onshore depot. A given vessel pool is used, which means that the model does not take into account the possibility of acquiring new vessels. Anyhow, the research show potential annual savings of $7 million in comparison with the solution used at that time.

Fagerholt (2001) considers another interesting subject when combining ship scheduling with soft time windows. Fagerholt introduces soft time windows instead of hard time windows to allow controlled window violations. The soft time windows, according to Fagerholt's finding, gives the possibility to obtain better schedules and significant reductions in the transportation costs.

Zeng and Yang (2007) present in the paper *Model integration Fleet Design and Ship Routing Problems for Coal Shipping* an integer programming model for solving both the fleet design and ship routing for a large Chinese coal corporation. The dependency between the fleet design and the ship routing is captured and solved by using a two phase tabu search algorithm on the IP model. In the numerical results presented, improvements in the coal shipping efficiency are indicated by using the proposed model.

A study of resource management for a merchant fleet is addressed in a paper by Pesenti (1995). Pesenti discusses and presents a problem involving decisions on purchase and usage of ships to meet customers' demand. A model for the considered problem is developed as a hierarchical model, and heuristic techniques which solve the problems at different decision levels are described.

In the article *Robust Supply Vessel Planning*, Halvorsen-Weare and Fagerholt (2011) address the problem of creating robust schedules to the supply vessel planning problem, which is undertaken by Halvorsen-Weare et al. (2012). The original problem is a maritime transportation problem in which a set of offshore installations require supplies from an onshore supply depot, a service performed by a fleet of offshore supply vessels. Before Halvorsen-Weare and Fagerholt (2011) incorporate robustness, a planning tool based on the deterministic supply vessel planning problem is implemented for real life use and indicate savings of MUSD 3. When robustness considerations are tested, meaning that solutions are capable to allow for unforeseen events, the results show even higher potential improvements in terms of costs.

4.1.2 FSMP publications addressing uncertainty

The number of publications utilising a stochastic optimisation approach in order to address the issue of uncertainty are to the authors knowledge limited, particularly within shipping. This coincides with the literature surveys by Alvarez et al. (2011) and Verderame et al. (2010). Most of the literature address deterministic fleet size and mix models, where a sample of the publications are to be found in the previous subsection.

Among the few papers including uncertainty, Alvarez et al. (2011) propose a mixed integer programming (MIP) model of the multi-period fleet sizing and deployment problem. Their model is developed to assist companies in risk handling within the trading process of ships (e.g. buying, chartering or selling), as well as the deployment of active ships to contracts and geographic markets.

List et al. (2006) illustrate how a robust optimisation model can be used to explore the effects of uncertainty on an equipment acquisition strategy within a fleet size problem. In their model, certain risk terms are introduced to hedge against scenarios that have a high total cost. This is, according to the authors, significantly different from the standard stochastic programming solution for this problem.

Du and Hall (1997) present an inventory-theoretic model to minimise the fleet size required to achieve a specified stock-out probability on trucks. The basis for their model is a hub-and-spoke transportation network with stochastic demands for shipments between the center hub and the outlying terminals.

Dong and Song (2009) consider the joint container fleet sizing and empty container repositioning problem in multi-vessel, multi-port and multi-voyage shipping systems with dynamic, uncertain and imbalanced costumer demands. A simulation-based optimisation tool is developed to find the vessel fleet size and the empty container repositioning.

4.2 Operation and Maintenance Publications

There are few authors addressing the problems with logistics and vessel utilisation/mix in the maintenance of offshore wind farms. Van Bussel and Bierbooms (2003) point out that the ability to maintain offshore wind turbines highly depends upon the access system being used. By using Monte Carlo simulations they estimate the availability of the DOWEC offshore wind farm. Their research addresses aspects affecting the availability, one of them is the problem of being too optimistic on the accessibility of offshore wind farms compared to onshore wind farms. Further, they argue that the changing weather conditions are one of the main issues reducing the accessibility. The main conclusions are that onshore availability levels are not feasible for remote offshore locations, and that new vessel types are needed for handling rougher weather conditions in order to increase the availability to an acceptable level. In the simulations, a given number of vessels is taken as input and must be changed manually. This reduces the ability of the model to determine the optimal number and combination of vessel types.

Van Bussel (1999) present, what the author calls, an expert system for calculating the assessment of offshore wind farm availability and the related O&M costs. The developed system uses an onshore wind turbine as starting point and calculates the offshore availability as a function of distance to shore, average storm percentage and the amount of money to be spent on maintenance. The calculations assume the use of a vessel traveling at the speed of 10 km/hour. In other words the system does not account for variation in vessel types or the uncertain weather conditions.

In the article *Operation and Maintenance Aspects of Large Offshore Wind farms*, Van Bussel and Schöntag (1997) analyse the O&M process for a large offshore wind farm trying to identify ways to reduce O&M related costs. They evaluate the use of new vessel types, the use of offshore platforms and alternative windmill designs. They use a Monte Carlo simulation to calculate the availability of the wind farm, and conclude that this simulation tool is of great value for the optimisation of O&M strategies. Also in this paper the authors leave out the determination of the optimal fleet size and mix for the execution of maintenance operations, as a fixed number of vessels is given as input to the simulation model.

Rademakers et al. (2008) describe an interesting O&M support tool developed to lower the O&M costs of offshore wind farms. The support tool is developed in an Excel environment using Visual Basic and uses long term average data to generate long term average values as output. It does not consider any logistic aspects. Some of the users of the model concluded that the tool represents the state-of-the-art.

All the references above use different types of simulation tools to analyse O&M of offshore wind farms. One publication using operations research is the article by Besnard et al. (2009). The article describes an opportunistic maintenance optimisation model for offshore wind systems, with the purpose of reducing the overall maintenance costs. The model is developed to help the maintenance managers decide when to execute preventive maintenance. It uses the advantage of wind forecasts and corrective maintenance tasks to perform preventive maintenance tasks at low costs. The authors demonstrates that this makes it possible to save major maintenance costs. The problem with logistics and transportation is mentioned as a future extension of the model, meaning implicitly that the model does not consider the fleet size and mix problem.

Except for this last article described there seems to be a lack of operations research models developed for the offshore wind industry regarding O&M. There are OR models developed for the optimal design of wind turbines, see Andrawus et al. (2007), but these are outside the scoop of this thesis.

4.3 Remarks

While knowing that operations research is a good means to achieve both effective and efficient maintenance in general (Dekker, 1996), the utilisation has, in the offshore wind industry, been limited so far. By this absence we can conclude that there is a great potential for operation research methods within the offshore wind industry. Our contribution, by analysing the FSMPOW, will put light on some of the problems within the industry today. In the next section we will present a deterministic model for solving the FSMPOW and in Section 6 we will present a stochastic node formulation of the FSMPOW, where we take into account the inherent uncertainties of the problem.

5 Mathematical Formulation, Deterministic

In this section we will present the deterministic model of the FSMPOW, which has been formulated as a mixed integer problem (MIP). Due to the relatively non-transparent contracting market for offshore wind maintenance vessels, and certain vessel types with abilities that increase the problem complexity, we will begin this section with presenting some of the main assumptions we have made while addressing the FSMPOW. In the next section we will present a three stage stochastic node formulation of the FSMPOW and the assumptions regarding uncertainty will be presented here.

Both helicopters, CTVs, supply vessels, multipurpose vessels and crane vessels will be treated in the model. For simplicity, we will use the collective term *vessel* in the rest of this thesis.

5.1 Assumptions

The underlying assumption for a deterministic formulation of the FSMPOW is assuming that all uncertain parameters are known, such as electricity prices, weather conditions and spot rates. Unforeseen failures requiring corrective maintenance operations will also be treated as known in the deterministic formulation.

The depth at the locations of the wind farms will not be taken into account in the model. This is because the depth will only affect which types of vessels that can be used on the different wind farms, and these vessel types can easily be excluded from the solution in the pre-processing of the data.

The time horizon will be divided into *periods* with equal length, typically the length of a working day (uniform time-discretisation). However, one may use non-uniform time discretisation without making any major changes to the model.

5.1.1 Splitting of The Maintenance Operations

Although preventive maintenance operations mainly consist of simple procedures requiring only one CTV with a limited crew size, some of the corrective maintenance operations might require several types of vessels, for instance both a supply vessel and a crane vessel. In this case we split these operations into *activities* in the pre-processing of the data, such that each activity entering the FSMPOW model will only require one type of vessel. This is explained further in Method of Computational Study in Section 7.

In the mathematical formulation we will not take into account that these activities might have inner dependencies, in terms of that some activities might have to be executed before others can start, or that some activities on a maintenance operation must be executed at the same time. However, we remind the reader that the FSMPOW is a strategic decision support tool for long term planning, and that implementing such constraints might only increase the problem size without actually improving the solution.

5.1.2 Vessel Properties

The vessels can either be rented or acquired. The length of a lease term can vary between different vessel types, but we assume that the placement of the lease terms are fixed, which means that if the length of a lease term is one month, it is not possible to rent the vessel from mid-January to mid-February.

All the vessel types will have a fixed and a variable cost. The variable cost will include the operational expenditures, mainly fuel, and will depend upon the vessel size and type. We assume that the vessel will have the same variable cost during transport as during maintenance execution. The fixed cost is the cost of having a vessel available, either if it is hovering at sea or at a harbour. If the vessel is rented, the fixed cost will include the cost of personnel, principal and interest payments on debt, insurance and return on investment. By this we assume that if a vessel is rented, the vessel with its crew will be at disposal for the entire contracting period. If a vessel is acquired, the fixed cost will be the investment cost less the salvage value depreciated over the expected life time of the wind farm(s) in addition to the cost of personnel, interest payments on debt and insurance.

Each vessel type will belong to either an onshore harbour or an offshore station. We will call this the *origin* of the vessel, and the origin will be denoted as $\{0\}$ in the mathematical formulation. If adjustments are to be made to the fleet, we assume that this will find place at the origin to each vessel type.

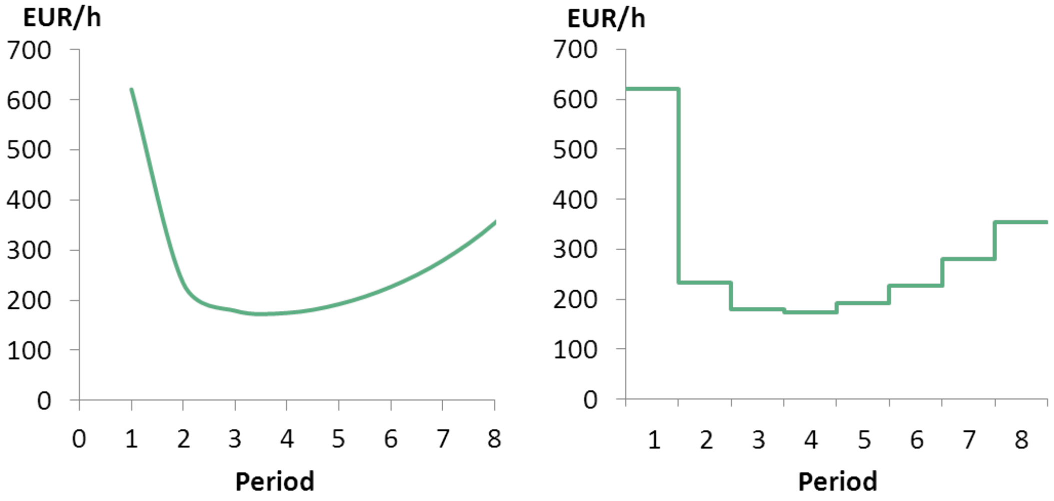
If a vessel that can stay offshore for several periods is rented, we assume that the preparation and demobilisation of the vessel will take one period, at the beginning and the end of the rental contract, respectively. Further, the vessels that can stay offshore for several periods are required to return to origin after a given number periods, to fill up with supplies, bunker up or to change crew. We assume that this will take one period, which means that the vessels will be unavailable for maintenance operations in this period.

To reduce the number of variables and identical solutions in the model, we will use one variable for each vessel type and lease term, x_{vl}, which can take integer values, to determine the number of vessels of type v that must be rented or acquired in each lease term. If the vessels are acquired there will only be one lease term, which means that the index l could have been removed for these vessel types, but we will keep the index on these vessel types for consistency. An alternative to integer variables would have been to introduce binary variables for each *vessel* available for rental, in each lease term. Such an approach could have given a number of identical solutions, however, considering that many wind farm operators today use a number of equal vessels in the execution of maintenance operations.

5.1.3 Downtime Cost

The expected downtime cost when executing the preventive maintenance activities will depend upon a number of different factors. First of all, the point of execution will determine the expected total cost of maintenance. Secondly, at the point of execution there will be a certain wind speed which will determine the potential generated output from the wind turbine, as illustrated in Figure 18. Finally, the particular support regime and the electricity price at the point of maintenance execution will define the lost revenue as a result of shutting down the wind turbine during the maintenance execution.

The expected total cost of maintenance is a continuous function, as illustrated in Figure 19(a). Considering that we are using uniform time-discretisation, the total cost of maintenance is simplified to a step function, where each interval is the length of a working period, as illustrated in Figure 19(b). For the same reason the wind speeds and electricity prices in the area are simplified to step functions. By this we assume that the wind speed and electricity price during one period is constant.



(a) Expected cost of maintenance (continuous) (b) Expected cost of maintenance (step function)

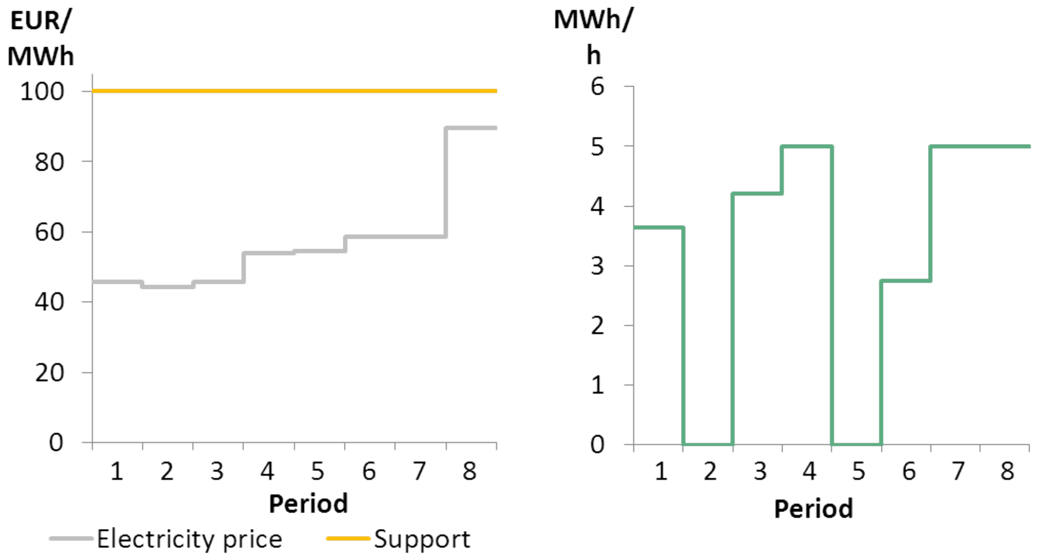
Figure 19: *Expected total cost of maintenance as a continuous function and a step function. Note: These figures are simply illustrations.*

The expected generated output is calculated from a power output curve as illustrated in Figure 18. The expected electricity price and support regime price (Figure 20(a)), together with the expected generated output (Figure 20(b)), determine the expected revenue from power generation, which is illustrated in Figure 20(c). By adding the expected cost of maintenance from Figure 19(b) with the expected revenue from power generation in Figure 20(c), we get the expected downtime cost for the preventive maintenance activities, which is illustrated in Figure 20(d).

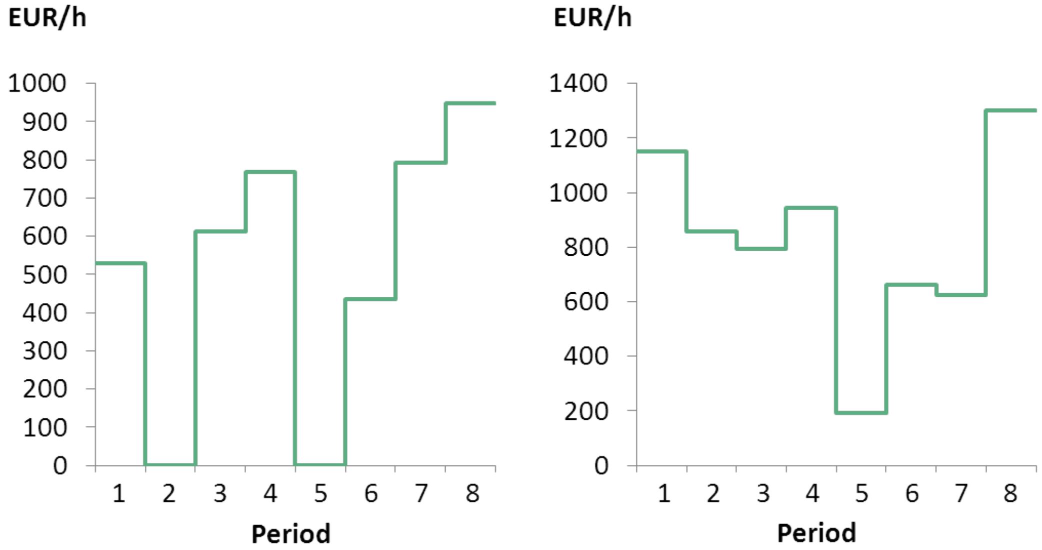
In theory, the preventive maintenance activities can be executed at any time, but to reduce the size of the problem we will introduce *hard time windows* in which the maintenance activities must be executed. The periods in which the downtime cost is low, can be viewed as a type of *soft time windows*. The maintenance activities must be executed within the hard time windows, and preferably within a soft time window.

The corrective maintenance activities will have a slightly different downtime cost function than the preventive maintenance activities. When a wind turbine faces a break down, there will be losses in revenue until the turbine is up and running again. The cost of delaying the execution of the corrective maintenance activity with for instance two periods will thus be two times the daily revenue. Figure 21 illustrates the downtime cost per hour for a corrective maintenance activity, if a failure happens in period 0. Let us call this cost C_{pif}^{CORR}.

There will be no binary variable in the model telling us whether a maintenance activity i is executed in period p or not. However, the FSMPOW model will



(a) Electricity price and support regime price (b) Expected generated output



(c) Expected revenue from power generation (d) Expected downtime cost for preventive maintenance activities.

Figure 20: *Calculating the expected downtime cost. The expected downtime cost for preventive maintenance activities in (d) is the sum of the expected cost of maintenance in 19(b) and the expected revenue from power generation in (c).*

determine the number of hours a vessel of type v spends on a maintenance activity i on wind farm f in period p, defined as t_{vpif}. For the model to calculate a downtime cost that is as correct as possible, we must multiply t_{vpif} by a downtime cost that takes into account the time required to perform maintenance activity i. This downtime cost will be defined as C^D_{pif} for both preventive and corrective maintenance activities in the model formulation.

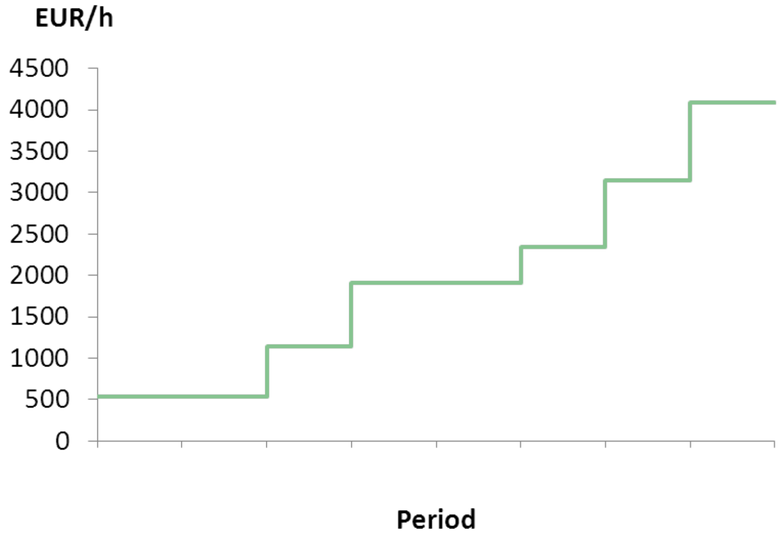


Figure 21: *Illustration of expected downtime cost for a corrective maintenance activity. Note: this is the downtime cost referred to as* C^{CORR}_{pif}*, in equation* (5.2).

The downtime cost C^D_{pif} for a corrective maintenance activity i on wind farm f in period p can be calculated from:

$$C^D_{pif} = \frac{HC^{CORR}_{pif}}{T^A_{if}}, \tag{5.1}$$

where H is the number of hours in a period and T^A_{if} is the time required to execute maintenance activity i on wind farm f. This gives the following property for a corrective maintenance activity i on wind farm f in period p:

$$\sum_{v \in V} C^D_{pif} t_{vpif} = \sum_{v \in V} \frac{HC^{CORR}_{pif}}{T^A_{if}} t_{vpif} = HC^{CORR}_{pif}, \tag{5.2}$$

which will always hold if:

$$\sum_{v \in V} t_{vpif} = T^A_{if}, \tag{5.3}$$

where V is the set of all vessel types. This means that the downtime cost for corrective maintenance activities will be correct if an activity is started and completed within the same period. If the activity is started in period 4, and completed in period 5, the cost can be underestimated, which follows from:

$$C^D_{pif} \leq C^D_{(p+1)if}. \tag{5.4}$$

Let us illustrate this by an example. If activity i on wind farm f is executed both in period 4 and period 5, the true downtime cost should be HC^{CORR}_{5if}. If $C^D_{4if} = C^D_{5if}$ we get:

$$\sum_{v \in V} \frac{HC^{CORR}_{4if}}{T^A_{if}} t_{v4if} + \sum_{v \in V} \frac{HC^{CORR}_{5if}}{T^A_{if}} t_{v5if} = HC^{CORR}_{5if}, \tag{5.5}$$

which is correct.

If $C^D_{4if} < C^D_{5if}$, on the other hand, we get:

$$\sum_{v \in V} \frac{HC^{CORR}_{4if}}{T^A_{if}} t_{v4if} + \sum_{v \in V} \frac{HC^{CORR}_{5if}}{T^A_{if}} t_{v5if} < HC^{CORR}_{5if}, \tag{5.6}$$

which will lead to an underestimation of the downtime cost. However, the main focus of the FSMPOW is not necessarily to determine the true costs, if not to force the model to execute the maintenance activities as soon as possible.

In theory the corrective maintenance activities can be executed at any point after a failure has occurred, but we will also here introduce hard time windows to reduce the problem size.

5.1.4 Efficiency Dependent on the Crew Size

There are some maintenance activities where the time required to perform the activity can be reduced if the number of maintenance personnel is increased from the minimum limit. There will be a maximum number of maintenance personnel that can be used to achieve reduction in execution time on an activity i on wind farm f, and we define the maximum number as E_{if}. Each vessel type will have a fixed crew size, and we define this as F_v. We can then define a new constant H_{vif}, which is the number of maintenance personnel from a vessel of type v working on maintenance activity i when achieving maximum efficiency, where $H_{vif} = min\{E_{if}, F_v\}$.

5.1.5 Activity Bundles

There are some preventive maintenance activities that can be executed in parallel. In this case a CTV or helicopter can drop off teams on different turbines, and pick them up at a later stage. For safety reasons, one vessel cannot operate on more than 4 turbines at the same time. We will introduce *activity bundles* to solve this problem. An activity bundle will be treated as all other activities, and will include a maximum of four different maintenance activities that can be executed at the same time by the same vessel. The periods in which an activity i on wind farm f can be executed will be defined as P^A_{if}. The periods in which an activity bundle can be executed will be defined by the intersection of P^A_{if} for the activities included in the bundle. The set A^B_f , will be defined as the set of activity bundles on wind farm f. Further, the set A^B_{if}, will be the set of activity bundles that maintenance activity i is included in. In the mathematical model it will be possible to choose whether an activity should be executed alone, as part of an activity bundle, or both. Figure 22 illustrates how the activity bundles can be created. Activity 1 and activity 2 can both be executed in periods 1 and 2, and can therefore be included in an activity bundle, namely activity 4. However, the periods in which activity 2 can be executed also overlap with activity 3, and a second activity bundle can be created for period 3, namely activity 5. If we assume that these activities belong to wind farm 1, the set A^B_f will be $A^B_1 = \{4, 5\}$. Further, we have $A^B_{11} = \{4\}$, $A^B_{21} = \{4, 5\}$ and $A^B_{31} = \{5\}$. The time windows for the activity bundles will in this case be $P^A_{41} = P^A_{11} \cap P^A_{11} = \{1, 2\}$ and $P^A_{51} = P^A_{21} \cap P^A_{31} = \{3\}$ as illustrated in the figure.

A maintenance activity i on wind farm f will require a minimum number of maintenance personnel, and we define this as M_{if}. When an activity bundle is

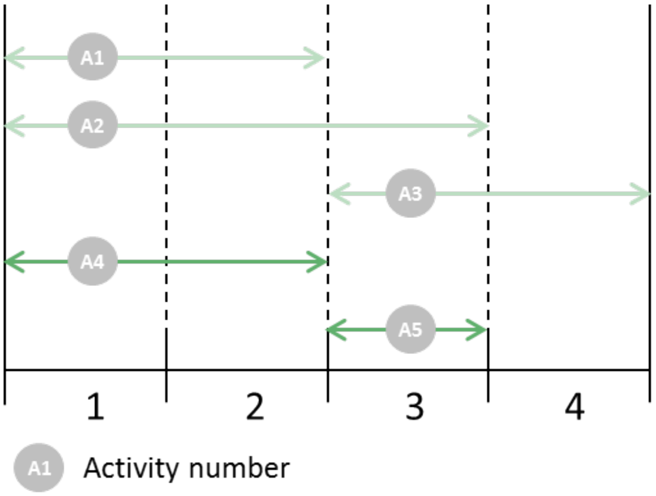


Figure 22: *Illustration of how activity bundles can be created.*

created, each activity in the bundle must be assigned a team which meets this minimum requirement. For simplicity, each activity i in an activity bundle will be assigned a team with size M_{if}.

The time required to execute a maintenance activity will be given in man-hours, and the variable t_{vpif} will determine the number of hours vessel type v spends on maintenance activity i on wind farm f in period p. To determine the number of man-hours that has been spent on an activity i included in activity bundle $\bar{i}$ we have to multiply $t_{vp\bar{i}f}$ by M_{if}. However, when a vessel is working on an activity bundle we can assume that some time will be lost in transporting the different teams out to their wind turbines. We define an efficiency constant E_v^V, which is the efficiency of vessel type v when working on an activity bundle, where $E_v^V \leq 1$. The effective time that has been spent on an activity i in bundle $\bar{i}$ will thus not be $t_{vp\bar{i}f} * M_{if}$, if not $t_{vp\bar{i}f} * M_{if} * E_v^V$. We therefore define a new constant, B_{vif} where $B_{vif} = E_v^V * M_{if}$.

As an example, let us assume that a vessel type v has efficiency $E_v^V = 0.9$ when working on an activity bundle. Further let us assume that activity i on wind farm f is included in activity bundle $\bar{i}$, and M_{if}=4. This gives $B_{vif} = 4 * 0.9 = 3.6$. If a vessel v works 10 hours on activity bundle $\bar{i}$, this corresponds to $10 * 3.6 = 36$ man-hours on activity i.

The downtime cost for an activity bundle i in period p, will be the sum of the downtime costs in period p for the activities that can be included in the bundle.

5.1.6 The routing aspect

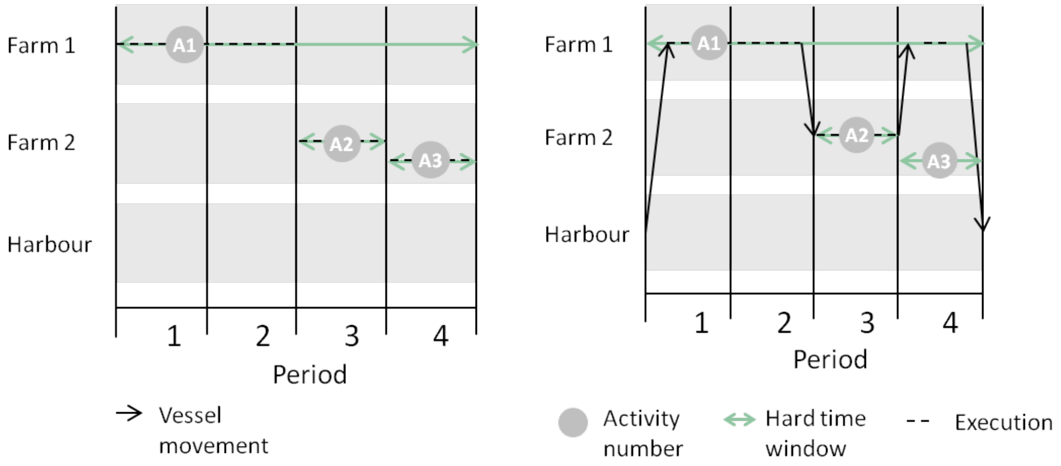
The FSMPOW can consist of one or several wind farms, with certain locations. This will determine the time required in transit between the wind farm(s) and shore, in addition to the time required in transit between the wind farms. The wind turbines at each offshore wind farm will have different locations, implying that there will be a routing problem between the different wind turbines. However, considering that the FSMPOW is a strategic decision problem, we will look at the wind farm as a whole, at which a number of maintenance operations should be performed. The actual wind turbine at which the operation must be executed is thus not of interest.

If the distances between the wind farms are sufficiently small, the problem can be simplified by treating the wind farms as one. If we are dealing with large distances, however, the routing problem must be taken into account. In this case we assume that one vessel will only operate on one wind farm each day. This means that there will not be a routing problem for the vessels that can stay offshore for only one period.

In addition to the dependency on the location of the wind farms, simplifications that can be made to the model will depend on the shift system that is used. Let us assume that a period is defined by one day. If a vessel can only operate during the day, the vessels that can stay offshore for several periods can simply relocate during the night. The distances undertaken by the vessels will affect the costs, but are not likely to affect the optimal fleet size and mix. In this case the routing problem does not have to be taken into account. A rolling shift system, on the other hand, implies that a vessel can operate 24 hours a day. In this case the time spent in transport should reduce the available operation time of the vessels on the wind farms. Considering that each vessel only can operate on one wind farm in each period, we assume that if a vessel is to travel from location f to location g, this can be done in the beginning of a period, in the end of a period, or both.

To illustrate the importance of including the routing problem in order to reduce the available operating time on the wind farms with the time spent in transit, we will use a simple example. Assume we have a wind farm field with two offshore wind farms, with a total of three activities to be completed. Activity 1 must be executed within the interval $\{1, 2, 3, 4\}$ and takes two periods to complete. Activity 2 must be executed within period 3, and this activity takes 1 period to complete. Activity 3 must be executed within period 4, and this activity also takes 1 period to complete. Figure 23(a) illustrates a possible solution if the routing problem and by this also the time spent in transit is not taken into account. Here, one vessel is used in period 1, 2, 3 and 4, and the vessel can stay offshore for several periods.

Figure 23(b) illustrates the same problem when the routing problem, and the time spent in transit is taken into account. The same vessel is used here as in the



(a) Without routing (b) With routing

Figure 23: *The routing problem for vessels that can stay offshore for several periods.*

previous solution. As the figure illustrates, the vessel travels from the harbour to wind farm 1 in the beginning of period 1, and operates on this wind farm in period 1 and 2. In the end of period 2 the vessel travels from wind farm 1 to wind farm 2, to execute maintenance activity 2 within the specified hard time window. The vessel returns to wind farm 1 in the beginning of period 4 to complete maintenance activity 1, before returning to the harbour at the end of the period. As the figure illustrates, activity 3 cannot be completed unless another vessel is included in the solution.

5.2 Definitions

We have used lower-case letters to represent variables and indices, and capital letters to represent constants.

Indices

v	Type of vessel or helicopter.
p	Period, where a period can typically be one day.
i	Maintenance activity number.
j	Offshore station number.
l	Lease term.
f, g	Wind farm, harbour or offshore station.
k	Type of restricting weather conditions.

Sets

F	Set of wind farms, $F : \{1, ..., \|F\|\}$.
P	Set of periods in the given time horizon. If the planning horizon is one year and a period is defined by one day, the number of periods will be 365.
J	Set of offshore stations.
V	Set of vessel types, including helicopters.
L_v	Set of lease terms for vessel type v, $L_v = \{1, ..., \|L_v\|\}$
A_f	Set of maintenance activities at wind farm f.
P_{if}^A	Set of periods in which the different maintenance activities can be executed at wind farm f. These periods are defined by the hard time windows. $P_{if}^A \subset P$.
P_{vl}^L	Set of periods in lease term l for vessel type v, where $P_{vl}^L \subseteq P$.
$P_{vl}^{\|L\|}$	The last period in lease term l, for vessel type v, where $P_{vl}^{\|L\|} \subset P$.
V_{if}^A	Set of vessel types that can perform maintenance activity i at wind farm f, where $V_{if}^A \subseteq V$.
V_j^J	Set of vessel types with restricted use to offshore station j, where $V_j^J \subseteq V$.
V^O	Set of vessel types that can only stay offshore for one period before returning to a safe haven, where $V^O \subseteq V$.
V^S	Set of vessel types that can stay offshore for several periods, where $V^S \subseteq V$.
A_f^L	Set of maintenance activities at wind farm f where $T_i > T^P$, and T_i is the time required to perform maintenance activity i, and T^P is the length of a period, $A_f^L \subseteq A_f$.
A_f^B	Set of activity bundles on wind farm f, where $A_f^B \subset A_f$.
A_{if}^B	Set of activity bundles at wind farm f that activity i can be included in, where $A_{if}^B \subseteq A_f^B$.
K	Set including different types of weather restrictions, for example $K = \{\text{wind speed, wave height}\}$.

Constants

T_{if}^{A}	Man-hours required to perform maintenance activity i at wind farm f.
T^{P}	Available operation time in a period. If a period is defined by one day, then the available operation time can typically be 12 or 24 hours dependent on the shift system.
T_{vf}^{T}	Time required in transport from origin of vessel type $v \in V^{O}$ to wind farm f and back again. The origin of a vessel type $v \in V^{O}$ can either be an offshore station or an onshore harbour.
T_{vfg}^{T}	Time required in transport from wind farm or harbour f to wind farm or harbour g for vessel type $v \in V^{S}$. A vessel type $v \in V^{S}$ will have origin at an onshore harbour.
K_{vk}^{O}	Operational requirement for vessel type v and weather category $k \in K$. If the weather conditions for category k exceeds the operational requirement, the vessel type will not be able to operate but can stay offshore until weather conditions improve.
K_{vk}^{S}	Safety requirement k for vessel type v and weather category $k \in K$. If the weather conditions for weather category k exceeds the safety requirement for vessel type v, the vessel type must return to a safe haven.
W_{pk}	Value of $k \in K$ in period p.
C_{vl}^{I}	Investment cost of renting or acquiring vessel type v in lease term l.
C_{vl}^{F}	Fixed cost of renting or acquiring a vessel of type v in lease term l. If the vessel is acquired there will only be one lease term, and the fixed cost will in this case be the investment cost less the salvage value, depreciated over the expected life time of the wind farm(s).
C^{B}	Investment budget for vessels and offshore stations.
C_{v}^{V}	Variable cost of vessel type v per hour in operation.
C_{pif}^{D}	Expected downtime cost if maintenance activity i on wind farm f is performed in period p. For a more thorough explanation see Section 5.1.3.
C_{j}^{I}	Investment cost of offshore station j.
C_{j}^{J}	Fixed cost of offshore station j for the planning period. If the offshore station is acquired, the fixed cost will be the investment cost less the salvage value, depreciated over the life time of the offshore wind farm(s).
C_{if}^{P}	Penalty cost per hour if maintenance activity i on wind farm f is not completed.
P_{v}^{M}	Maximum number of periods vessel type v can stay offshore.
Q_{jv}	Vessel capacity on offshore station j for vessel type v.

B_{vif}	Constant based on the efficiency of vessel type v when working on an activity bundle, and the minimum number of maintenance personnel needed on activity i on wind farm f. If E_v^V is the efficiency of vessel type v when working on an activity bundle, and M_{if} is the size of the maintenance team required to execute maintenance activity i on wind farm f, then $B_{vif} = E_v^V * M_{if}$. For a more thorough explanation, see Section 5.1.5.
H_{vif}	Number of maintenance personnel from vessel type v working on maintenance activity i on wind farm f when achieving highest possible efficiency. The reader is referred to Section 5.1.4 for a more thorough explanation.

Decision variables

x_{vl}	Number of vessels of type v rented or acquired in lease term l.
x_{vp}^J	Number of new vessels of type $v \in V^S$ joining the fleet in period p.
x_{vp}^L	Number of vessels of type $v \in V^S$ leaving the fleet in period p.
y_{vpf}	Number of vessels of type v located at wind farm or origin f in period p.
w_{vpfg}	The number of vessels of type v traveling from wind farm or harbour f to wind farm or harbour g in period p.
t_{vpfg}^M	Time used in transit in the beginning of period p from wind farm or harbour f to wind farm or harbour g for vessel type v. If the vessel type travels to a wind farm, this should reduce the available operating time at wind farm g.
t_{vpfg}^E	Time used in transit in the end of period p from wind farm or harbour f to wind farm or harbour g for vessel type v. If the vessel type travels from a wind farm in the end of period p this should reduce the available operating time at wind farm f.
t_{vpif}	The amount of time vessel type v spends on maintenance activity i on wind farm f in period p.
d_{if}	Variable that takes value if maintenance activity i on wind farm f is not completed. The variable d_{if} is continuous, and will determine the time remaining on activity i on wind farm f.

$$z_j = \begin{cases} 1 & \text{if offshore station } j \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

5.3 Mathematical model

The deterministic model will now be explained in detail, starting with the objective function and continuing with the different constraints. A plain version of the model is presented in Appendix B.1.

5.3.1 Objective Function

$$\min Z = \sum_{v \in V} \sum_{l \in L_v} C^F_{vl} x_{vl} + \sum_{j \in J} C^J_j z_j \tag{5.7a}$$

$$+ \sum_{f \in F} \sum_{i \in A_f} \sum_{v \in V^A_{if}} \sum_{p \in P^A_{if}} C^V_v t_{vpif} \tag{5.7b}$$

$$+ \sum_{f \in F} \sum_{i \in A_f} \sum_{v \in V^A_{if}} \sum_{p \in P^A_{if}} C^D_{pif} t_{vpif} + \sum_{f \in F} \sum_{i \in A_f \setminus A^B_f} C^P_{if} d_{if} \tag{5.7c}$$

$$+ \sum_{v \in V^S} \sum_{p \in P} \sum_{(f,g) \in F \cup \{0\} | f \neq g} C^V_v (t^M_{vpfg} + t^E_{vpfg}) + \sum_{v \in V^O} \sum_{p \in P} \sum_{f \in F} T^T_{vf} C^V_v y_{vpf}. \tag{5.7d}$$

The objective function calculates the fixed cost of the vessels and offshore stations that are rented or acquired, the variable cost of the vessels, the expected downtime cost, the penalty costs and the total transportation costs. Part (5.7a) is the fixed cost of the vessels being rented or acquired in lease term l and the fixed cost of the offshore stations. Part (5.7b) is the total variable cost, which is dependent on the amount of time spent on executing the maintenance activities with each vessel type on each wind farm, and the corresponding variable cost of utilising a vessel of type v.

The first term in part (5.7c) represents the expected downtime cost for the preventive maintenance activities and gives an estimate of the real downtime cost for the corrective maintenance activities. The second term in part (5.7c) serves as a penalty if a maintenance activity is not completed, and is introduced to avoid infeasible solutions.

The first term of part (5.7d) will calculate the traveling cost for the vessels that can stay offshore for several periods. This term takes into account all travels done by vessel type v between location f and g either in the beginning or the end of period p. The second term in (5.7d) applies for the vessel types that need to travel back and forth to the wind farm every day. This term multiplies the number of vessels of type v that are being utilised on wind farm f in period p with the traveling time and the variable operating cost of the vessel type.

5.3.2 Constraints

$$x_{vl} \leq Q_{jv} z_j, \qquad j \in J,\ v \in V_j^J,\ l \in L_v. \tag{5.8}$$

Constraints (5.8) restrict the availability of the vessels related to offshore station j. Vessel type v with restricted use to offshore station j can only be put into operation if offshore station j is acquired or rented. Furthermore, the number of vessels of type v that can be used is determined by the vessel capacity of offshore station j. The vessel types that belong to an offshore station must be rented for the whole planning horizon, and will thus only have one lease term.

$$\sum_{v \in V} \sum_{l \in L_v} C_{vl}^I x_{vl} + \sum_{j \in J} C_j^I z_j \leq C^B \tag{5.9}$$

The constraint (5.9) is the budget constraint, limiting the investments in vessels and offshore stations to the capital available, C^B.

$$\sum_{v \in V_{if}^A} \sum_{p \in P_{if}^A} H_{vif} t_{vpif} + \sum_{\bar{i} \in A_{if}^B} \sum_{v \in V_{\bar{i}f}^{ACT}} \sum_{p \in P_{\bar{i}f}^{ACT}} B_{vif} t_{vp\bar{i}f} + d_{if} \geq T_{if}^A, \qquad f \in F,\ i \in A_f \setminus A_f^B. \tag{5.10}$$

Constraints (5.10) ensure that all maintenance activities are executed within the hard time windows, and apply for all activities except for the activity bundles. If an activity i on wind farm f is not completed, the dummy variable d_{if} will take value in terms of the number of hours that is left on the activity. Certain activities can be executed in parallel with other activities on the same wind farm, in what we call an activity bundle. An activity i that can be executed in parallel with other activities can be a part of several activity bundles. The required execution time for such an activity can be divided between all bundles $\bar{i} \in A_{if}^B$, in addition to working on activity i alone. In the first term of (5.10), the constants H_{vif} take into account that the execution time of some activities can be reduced if the number of maintenance personnel is increased from the required number. These activities will have an execution time, T_{if}^A, given in man-hours. For activities such as heavy lifts, that have execution times independent of the maintenance team size, the constant H_{vif} will be 1. We refer to Section 5.1.4 for further explanation of the constants H_{vif}. To take into account that some time will be lost in transporting the different teams out to their turbine if an activity bundle is executed, the constants B_{vif} in the second term of (5.10), are based on the size of the maintenance team required on activity i, and an efficiency factor. We refer to Section 5.1.5 for a more thorough explanation of the constants B_{vif}.

$$\sum_{v \in V_{if}^A} t_{vpif} \leq T^P, \qquad f \in F,\ i \in A_f^L,\ p \in P_{if}^A. \tag{5.11}$$

It should be possible to reduce the execution time of an activity if the size of the maintenance team is increased from the required minimum. However, it should not be possible to reduce the execution time of an activity by introducing several vessels working in parallel on one activity at the same time. This is prevented by constraints (5.11), where the total time that can be spent on an activity i in period p is limited to the available operation time in a period, T^P. Constraints (5.11) only apply for the activities that take longer than a period. For the activities that take less than a period this will not be a problem.

$$\sum_{f \in F} y_{vpf} \leq x_{vl}, \qquad v \in V^O,\ l \in L_v,\ p \in P^L_{vl}. \tag{5.12}$$

Constraints (5.12) determine the number of vessels, v, where $v \in V^O$, that must be rented in each lease term. The total number of vessels of type v used in period p on all the wind farms must not exceed the number of vessels rented for this period.

$$\sum_{f \in F \cup \{0\}} y_{vpf} = x_{vl}, \qquad v \in V^S,\ l \in L_v,\ p \in P^L_{vl}, \tag{5.13}$$

$$x_{vl} - x_{v(l+1)} = x^L_{vp} - x^J_{vp}, \qquad v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl}, \tag{5.14}$$

$$y_{vp0} - y_{v(p+1)0} = \sum_{g \in F}(w_{vp0g} - w_{vpg0}) + x^L_{vp} - x^J_{vp}, \qquad v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl}, \tag{5.15}$$

$$y_{vpf} - y_{v(p+1)f} = \sum_{g \in F \cup \{0\} | f \neq g} (w_{vpfg} - w_{vpgf}), \qquad v \in V^S,\ l \in L_v,\ p \in P^{|L|}_{vl},\ f \in F, \tag{5.16}$$

$$y_{vpf} - y_{v(p+1)f} = \sum_{g \in F \cup \{0\} | f \neq g} (w_{vpfg} - w_{vpgf}), \qquad v \in V^S,\ l \in L_v,\ p \in P^L_{vl} \setminus P^{|L|}_{vl},\ f \in F \cup \{0\}. \tag{5.17}$$

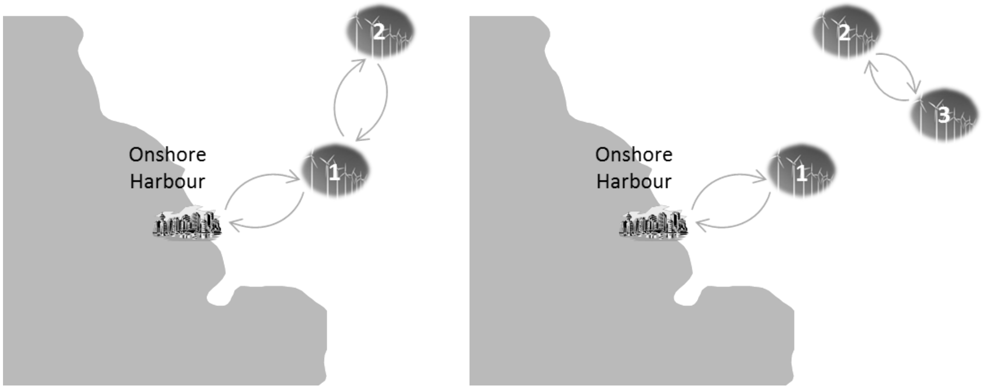
The constraints (5.13) - (5.17) are the balancing constraints for the vessel types that can stay offshore for several periods. Each vessel type $v \in V^S$ has an origin, denoted as $\{0\}$, which will be land based. The constraints (5.13) determine the number of each vessel type, v, located on each wind farm or at the origin, $\{0\}$, in each period. It should be possible to make adjustments to the fleet in the last period of a lease term, and this is enabled by the constraints (5.14), where the variables on the right hand side determine the number of vessels of type v leaving or joining the fleet in the respective periods. These constraints apply for all vessels that can stay offshore for several periods, and all lease terms except for the last lease term which is defined by $\{|L_v|\}$. Further, the constraints (5.15) - (5.17) determine the number of vessels of type v that travel from location f to location g in period p, namely w_{vpfg}. Adjustments of the fleet should be made at the origin, i.e. at a harbour, which is why constraints (5.15) only apply for the origin of vessel type v, and the periods in which it is possible to make adjustments to the fleet. Constraints (5.16) apply for all wind farms and the periods in which adjustments for the fleet can be made. Finally, constraints (5.17) apply for all wind farms, including the origin, but only for the periods where no adjustments of the fleet can be made, and thus complete the balancing constraints.

$$\sum_{f\in F} y_{vpf} \leq \sum_{f\in F} \sum_{\bar{p}\in\{p..p+P_v^M-1\}} w_{v\bar{p}f0}, \quad v \in V^S,\ p \in \{1,...,|P|-P_v^M+1\}, \tag{5.18}$$

$$y_{vpf} \leq \sum_{g\in F\cup\{0\}|f\neq g} \sum_{\bar{p}\in\{p..p+P_v^M-1\}} w_{v\bar{p}fg}, \quad v \in V^S,\ p \in \{1,...,|P|-P_v^M+1\},\ f \in F. \tag{5.19}$$

The vessels that can stay offshore for several periods are required to return to shore after a certain amount of time. P_v^M is the maximum number of periods vessel type v can stay offshore. Constraints (5.18) thus force the required number of vessels of type v to return to their origin, $\{0\}$, after P_v^M periods. If the distance to origin vary between different wind farms, however, there is a risk that only the vessels located at the closest wind farm will return to their origin. The constraints (5.19) thus force each vessel type to move to another wind farm or back to origin after P_v^M periods. This will ensure a constant movement of vessels between the different wind farms, and will give accurate solutions for up to two wind farms.

Figure 24(a) illustrates a problem with two wind farms, where wind farm 1 is located closer to the shore than wind farm 2. Constraints (5.19) force the vessels located at wind farm 2 to travel to wind farm 1 or to the onshore harbour. Figure 24(b) illustrates how constraints (5.19) will no longer be enough when the problem consists of three or more wind farms. If the vessels located at wind farm 2 are forced to move as a result of constraints (5.19), they might seek to move to the closest wind farm, which in this case is wind farm 3. However, this simplification is acceptable considering the FSMPOW is a strategic model.



(a) Problem with two offshore wind farms

(b) Problem with three offshore wind farms

Figure 24: *a) shows that constraints (5.19) give correct solution when the problem consists of no more than two wind farms. b) shows that a problem consisting of three or more wind farms can give inaccurate solutions.*

$$T^T_{vfg} w_{vpfg} \leq t^E_{vpfg} + t^M_{v(p+1)fg}, \qquad v \in V^S,\ p \in \{1, ..., |P| - 1\},\ (f, g) \in F \cup \{0\} | f \neq g. \tag{5.20}$$

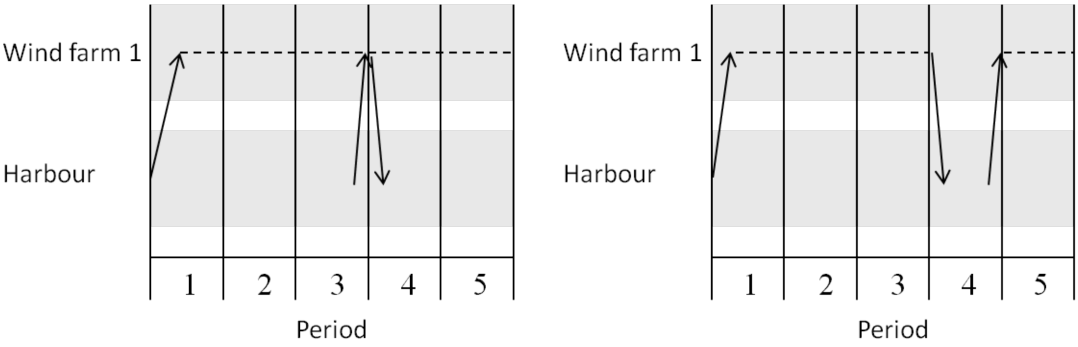
When a number of vessels of type v, where $v \in V^S$, with location f are to travel to location g in period p, this can either be done in the end of period p, in the beginning of period $p + 1$, or both in the end of period p and in the beginning of period $p + 1$. The transportation time from f to g should reduce the available operation time for vessel type v on wind farm f in period p if it decides to travel in the end of period p. If the vessel type decides to travel in the beginning of period $p + 1$, on the other hand, the available operation time should be reduced on wind farm g in period $p + 1$. The constraints (5.20) determine at which point vessel type v decides to travel, and the amount of time required in transportation time.

$$\sum_{g \in F \cup \{0\} | g \neq f} w_{vpfg} \leq y_{vpf}, \qquad v \in V^S,\ p \in P,\ f \in F \cup \{0\}, \tag{5.21}$$

$$\sum_{g \in F \cup \{0\} | g \neq f} w_{vpgf} \leq y_{v(p+1)f}, \qquad v \in V^S,\ p \in \{1, ..., |P| - 1\},\ f \in F \cup \{0\}. \tag{5.22}$$

If a vessel is forced to return to origin or to travel to another wind farm as a result of constraints (5.18) or (5.19), it should not be possible for this vessel to travel from f to g in the end of period p, and back to f in the beginning of period $p+1$. If a number of vessels travel *from* location f to g in period p, then constraints (5.21) ensure that these vessels must have been located at f in period p. At the same time, if a number of vessels travel *to* wind farm f in period p, then constraints (5.22) make sure that these vessels are located at f in period $p + 1$.

Figure 25(a) illustrates possible movements of a vessel with $P^M_v = 3$ if constraints (5.21) and (5.22) are not included. This solution does not violate constraints (5.18) or (5.19), because one vessel does indeed travel from the wind farm



(a) Solution without constraints. (b) Solution with constraints.

Figure 25: *Illustration of why constraints (5.21) and (5.22) are necessary, where the vessel type used can stay offshore for 3 periods.*

to the origin after 3 periods. Neither does it violate the balancing constraints (5.15)-(5.17). However, in this solution a fictitious vessel is created, allowing the rented vessel to stay offshore for more than the allowable number of periods. Figure 25(b) illustrates the movements of the same vessel if constraints (5.21) and (5.22) are added. The vessel is required to return to origin after 3 periods, and will thus not be able to operate in this period. These constraints also ensure that one period is used for preparation of the vessels in the beginning of the contracting time, and that one period is used for demobilisation of the vessel in the end of the contracting time.

$$\sum_{i \in A_f} t_{vpif} \leq T^P y_{vpf} - \sum_{g \in F \cup \{0\} | f \neq g} (t^M_{vpgf} + t^E_{vpfg}), \qquad v \in V^S, p \in P, f \in F, \tag{5.23}$$

$$\sum_{i \in A_f} t_{vpif} \leq (T^P - T^T_{vf}) y_{vpf}, \qquad v \in V^O, p \in P, f \in F. \tag{5.24}$$

Constraints (5.23) apply for the vessels that can stay offshore for several periods, and reduce the available operation time on wind farm f with the amount of time spent in transport in the beginning of a period from location g and in the end of a period to location g. Further, the constraints (5.24) reduce the available operation time on wind farm f for the vessel types that need to return to their origin on a daily basis.

$$\left(K^O_{vk} - W_{pk}\right) \sum_{f \in F} \sum_{i \in A_f} t_{vpif} \geq 0, \qquad p \in P, v \in V, k \in K, \tag{5.25}$$

$$\left(K^S_{vk} - W_{pk}\right) \sum_{f \in F} y_{vpf} \geq 0, \qquad p \in P, v \in V, k \in K. \tag{5.26}$$

The constraints (5.25) are operational constraints, ensuring that no operations can take place at any wind farm by a vessel type in periods in which either of the weather categories exceed the operational limit of the vessel type. Constraints (5.26) are safety constraints, forcing each vessel type to stay at the harbour of origin if either of the weather categories exceed the safety limits for the respective vessel type. The constraints (5.25) and (5.26) are not necessary in the model formulation if the variables t_{vpif} and y_{vpf} are only defined for the vessel types and periods at which safety and operational requirements are fulfilled.

$$x_{vl} \geq 0 \textit{ and integer,} \qquad v \in V,\ l \in L_v, \tag{5.27}$$

$$x^{L}_{vp} \geq 0 \textit{ and integer,} \qquad v \in V^{S},\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl},\ f \in \{0\}, \tag{5.28}$$

$$x^{J}_{vp} \geq 0 \textit{ and integer,} \qquad v \in V^{S},\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl},\ f \in \{0\}, \tag{5.29}$$

$$y_{vpf} \geq 0 \textit{ and integer,} \qquad f \in F,\ v \in V^{O},\ p \in P, \tag{5.30}$$

$$y_{vpf} \geq 0 \textit{ and integer,} \qquad f \in F \cup \{0\},\ v \in V^{S},\ p \in P, \tag{5.31}$$

$$w_{vpfg} \geq 0 \textit{ and integer,} \qquad v \in V,\ p \in P,\ (f,g) \in F \cup \{0\} \mid f \neq g, \tag{5.32}$$

$$t_{vpif} \geq 0 \qquad f \in F,\ i \in A_f,\ v \in V^{A}_{if},\ p \in P^{A}_{if}, \tag{5.33}$$

$$t^{M}_{vpfg} \geq 0 \qquad v \in V,\ p \in P,\ (f,g) \in F \cup \{0\} \mid f \neq g, \tag{5.34}$$

$$t^{E}_{vpfg} \geq 0 \qquad v \in V,\ p \in P,\ (f,g) \in F \cup \{0\} \mid f \neq g, \tag{5.35}$$

$$d_{if} \geq 0 \qquad f \in F,\ i \in A_f \setminus A^{B}_{f}, \tag{5.36}$$

$$z_j \textit{ is binary} \qquad j \in J. \tag{5.37}$$

Finally, constraints (5.27) - (5.35) impose non-negativity and integrality properties, and constraints (5.37) impose binary properties upon the respective decision variables.

6 Mathematical Formulation, Stochastic

In the previous section we presented a deterministic formulation of the FSMPOW, in which all parameters are assumed to be known. In this section we will begin with a presentation of the underlying assumptions for a stochastic model. We will then present a three stage stochastic node formulation of the FSMPOW, where the inherent uncertainties of the problem are taken into account.

6.1 Assumptions

The same assumptions that were discussed in Section 5.1 will apply for the stochastic model, except for, of course, the deterministic assumption. In the stochastic formulation of the FSMPOW, uncertainties in weather conditions, electricity prices, spot rates and turbine failures requiring corrective maintenance will be taken into account. We assume that the variable costs of the vessels are certain, although these might vary dependent on the fuel prices.

6.1.1 Number of stages

The most important decision in the FSMPOW is the type and number of vessels and helicopters that should be acquired or rented to execute the different maintenance operations on the wind farm(s) in question. An operator can, in theory, rent vessels and helicopters on the spot market on a day to day basis. This gives the operator flexibility to adjust the fleet dependent on weather conditions, electricity prices and the number of break downs to the turbines. A stochastic model allowing adjustments in the fleet on a day to day basis would require one stage for each period (or day). In addition to giving the problem high complexity, such a strategy would be risky considering that demand often exceeds supply in busy summer months.

We therefore assume a three stage structure of the problem, as illustrated in Figure 26, where adjustments to the fleet can be made at the first and second stages. The first stage is today, and at this stage the operator must decide upon the number of vessels that should be rented or acquired in each lease term with the spot rates existing in the market today. The second stage is at the beginning

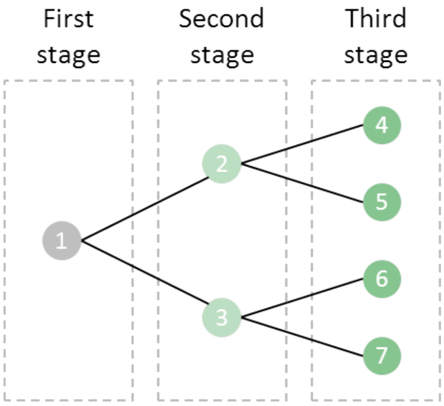


Figure 26: *Node tree showing the structure of the stochastic formulation of the FSMPOW*

of the maintenance execution, and at this stage new information about the vessel spot rates is obtained, and the operator makes a final decision in terms of vessel fleet size and mix to be used in the maintenance execution.

At the third and final stage, information about electricity prices, turbine failures and weather conditions is obtained. The operator now determines how the fleet that has been determined in the first and second stages should be used to execute the maintenance activities on the wind farm field, while minimizing the costs. In Figure 26, the third stage is represented by one set of nodes. However, this stage will consist of all the periods in the maintenance execution planning horizon. That is, if the maintenance execution planning horizon is one year, or 365 periods, we will have a stochastic model with 3 stages and 367 periods.

6.1.2 New sets and variables

The sets $\mathcal{N}^1$, $\mathcal{N}^2$ and $\mathcal{N}^3$ will include the nodes in the first, second and third stage, respectively. As opposed to the deterministic model presented in Section 5, we now have the possibility to adjust the fleet at two stages. A new set of variables will thus be introduced, where x_{vln}, $n \in \mathcal{N}^1$, are the number of vessels of type v that are rented or acquired in the root node in lease term l, and x_{vln}, $n \in \mathcal{N}^2$, are the vessels of type v that are rented in node n at the second stage for lease term l. Considering that only certain types of vessels can be rented in the second stage we introduce two new sets, where V^1 includes the vessel types that can be rented or acquired at the first stage and V^2 includes the types of vessels that can be rented at the second stage. If a vessel type can be acquired, this must happen at the first stage.

Some restrictions will require summation over the total number of vessels of type v that are rented or acquired at the first two stages. We will thus introduce a new set, $\mathcal{N}_n^A$, where $n \in \mathcal{N}^3$, which contains the ancestor nodes of node n. In Figure 26 we have $\mathcal{N}_4^A = \{1, 2\}$ and $\mathcal{N}_6^A = \{1, 3\}$.

6.1.3 Constraints and Stages

At the first stage we only have one set of constraints, namely the capacity constraints for the offshore stations, referred to as constraints (5.8) in the deterministic model. At the second stage we get two sets of constraints. First, we have the budget constraint, referred to as constraints (5.9) in the deterministic model. Second, we have the constraints determining the number of vessels leaving and joining the fleet in the end of each lease term l for vessel type v. These are referred to as constraints (5.14) in the deterministic model. All other restrictions from the deterministic model will appear at the third stage in the stochastic model, as these concern the execution of the maintenance activities.

6.2 Definitions

We have used the same notation as in the deterministic model. The sets, constants and variables which are dependent on the nodes will have an extra index, n, representing each node.

Indices

v	Type of vessel.
p	Period, where a period can typically be one day.
i	Maintenance activity number.
j	Offshore station number.
l	Lease term.
f, g	Wind farm, harbour or offshore station.
k	Type of restricting weather conditions.
n	Node.

Stochastic parameters

P_n	The probability of reaching node n.
$a(n)$	The preceding node of node n.

Sets

F	Set of wind farms, $F : \{1, ..., \lvert F \rvert\}$.
P	Set of periods in the given time horizon. If the planning horizon is one year and a period is defined by one day, the number of periods will be 365.
J	Set of offshore stations.
V	Set of vessel types, including helicopters.
L_v	Set of lease terms for vessel type v, $L_v = \{1, ..., \lvert L_v \rvert\}$
A_{fn}	Set of maintenance activities in node n at wind farm f.
P^A_{ifn}	Set of periods at which the different maintenance activities can be performed at wind farm f in node n. These periods are defined by the hard time windows and $P^A_{ifn} \subset P$.
P^L_{vl}	Set of periods in lease term l for vessel type v, where $P^L_{vl} \subseteq P$.
$P^{\lvert L \rvert}_{vl}$	The last period in lease term l, for vessel type v, where $P^{\lvert L \rvert}_{vl} \subset P$.
V^A_{ifn}	Set of vessel types that can perform maintenance activity i at wind farm f in node n, where $V^A_{ifn} \subseteq V$.
V^J_j	Set of vessel types with restricted use to offshore station j, where $V^J_j \subseteq V$.
V^O	Set of vessel types that can only stay offshore for one period before returning to a safe haven, where $V^O \subseteq V$.
V^S	Set of vessel types that can stay offshore for several periods, where $V^S \subseteq V$.
A^L_{fn}	Set of maintenance activities at wind farm f in node n in which $T_i > T^P$, where T_i is the time required to perform maintenance activity i, and T^P is the length of a period, $A^L_{fn} \subseteq A_{fn}$.
A^B_{fn}	Set of activity bundles on wind farm f in node n, where $A^B_{fn} \subset A_{fn}$.
A^B_{ifn}	Set of activity bundles at wind farm f in node n that activity i can be included in, where $A^B_{ifn} \subseteq A^B_{fn}$.
K	Set including different types of weather restrictions, for example wind speed and wave heights, $K = \{\text{wind speed, wave height}\}$.
$\mathcal{N}^1$	Set including the first stage node.
$\mathcal{N}^2$	Set of nodes in the second stage.
$\mathcal{N}^3$	Set of nodes in the third stage.
$\mathcal{N}^A_n$	Set of ancestor nodes in the first and second stages for node n, $n \in \mathcal{N}^3$.
V^1	Set of vessel types that can be rented at the first stage, where $V^1 \subseteq V$.
V^2	Set of vessel types that can be rented at the second stage, where $V^2 \subseteq V$.

Constants

T^A_{ifn}	Man-hours required to perform maintenance activity i at wind farm f in node n.
T^P	Available operation time in a period. If a period is defined by one day, then the available operation time can typically be 12 or 24 hours dependent on the shift system.
T^T_{vf}	Time required in transport from origin of vessel type $v \in V^O$ to wind farm f and back again. The origin of a vessel type $v \in V^O$ can either be an offshore station or an onshore harbour.
T^T_{vfg}	Time required in transport from wind farm or harbour f to wind farm or harbour g for vessel type $v \in V^S$. A vessel type $v \in V^S$ will have origin at an onshore harbour.
K^O_{vk}	Operational requirement for vessel type v and weather category $k \in K$. If the weather conditions for category k exceeds the operational requirement, the vessel type will not be able to operate but can stay offshore until weather conditions improve.
K^S_{vk}	Safety requirement k for vessel type v and weather category $k \in K$. If the weather conditions for weather category k exceeds the safety requirement for vessel type v, the vessel type must return to a safe haven.
W_{pkn}	Value of $k \in K$ in period p and node n.
C^I_{vln}	Investment cost of renting or acquiring vessel type v in lease term l in node n.
C^F_{vln}	Fixed cost of renting or acquiring a vessel of type v in lease term l in node n. If the vessel is acquired there will only be one lease term, and the fixed cost will in this case be the investment cost less the salvage value, depreciated over the expected life time of the wind farm(s).
C^B	Investment budget for vessels and offshore stations.
C^V_v	Variable cost of vessel v per hour in operation.
C^D_{pifn}	Expected downtime cost if maintenance activity i on wind farm f and node n is performed in period p. For a more thorough explanation, see Section 5.1.3.
C^I_j	Investment cost of offshore station j.
C^J_j	Fixed cost of offshore station j for the planning period. If the offshore station is acquired, the fixed cost will be the investment cost less the salvage value, depreciated over the life time of the offshore wind farm(s).
C^P_{ifn}	Penalty cost per hour if maintenance activity i on wind farm f in node n is not completed.
P^M_v	Maximum number of periods vessel type v can stay offshore.
Q_{jv}	Vessel capacity on offshore station j for vessel type v.

B_{vifn}	Constant based on the efficiency of vessel type v when working on an activity bundle, and the minimum number of engineers needed on activity i on wind farm f in node n. If B_v is the efficiency of vessel type v when working on an activity bundle, and B_{ifn} is the number of engineers required to execute maintenance activity i on wind farm f in node n, then $B_{vifn} = B_v * B_{ifn}$. For a more thorough explanation, see Section 5.1.5.
H_{vif}	Number of maintenance personnel on vessel type v working on maintenance activity i on wind farm f in node n when achieving highest possible efficiency. The reader is referred to Section 5.1.4 for a more thorough explanation.

Decision variables

x_{vln}	Number of vessels of type v rented or acquired in lease term l in node n, $n \in \mathcal{N}^1 \cup \mathcal{N}^2$.
x^J_{vpn}	Number of new vessels of type $v \in V^S$ joining the fleet in period p in node n, $n \in \mathcal{N}^2$.
x^L_{vpn}	Number of vessels of type $v \in V^S$ leaving the fleet in period p in node n, $n \in \mathcal{N}^2$.
y_{vpfn}	Number of vessels of type v located at wind farm or origin f in period p in node n, $n \in \mathcal{N}^3$.
w_{vpfgn}	The number of vessels of type v traveling from wind farm or harbour f to wind farm or harbour g in period p in node n, $n \in \mathcal{N}^3$.
t^M_{vpfgn}	Time used in transit in the beginning of period p from wind farm or harbour f to wind farm or harbour g for vessel type v in node n, $n \in \mathcal{N}^3$. If the vessel type travels to a wind farm, this should reduce the available operating time at wind farm g.
t^E_{vpfgn}	Time used in transit in the end of period p from wind farm or harbour f to wind farm or harbour g for vessel type v in node n, $n \in \mathcal{N}^3$. If the vessel type travels from a wind farm in the end of period p this should reduce the available operating time at wind farm f.
t_{vpifn}	The amount of time vessel type v spends on maintenance activity i on wind farm f in period p in node n, $n \in \mathcal{N}^3$.
d_{ifn}	Variable that takes value if maintenance activity i on wind farm f in node $n \in \mathcal{N}^3$ is not completed. The variable d_{ifn} is continuous, and will determine the time remaining on activity i on wind farm f.

$$z_j = \begin{cases} 1 & \text{if offshore station } j \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

6.3 Mathematical model

The stochastic node formulation of the FSMPOW will now be presented. This formulation include the same constraints as the deterministic model, and the reader is referred to Section 5.3 for a more thorough explanation of the constraints. We will begin with presenting the objective function, and will continue with the first stage restrictions. We continue with the second stage restrictions and finally we will present the third stage restrictions. A plain version of the stochastic model is presented in Appendix B.2.

6.3.1 Objective Function

$$\min Z = \sum_{n\in\mathcal{N}^1}\sum_{v\in V^1}\sum_{l\in L_v} C^F_{vln}x_{vln} + \sum_{j\in J} C^J_j z_j + \sum_{n\in\mathcal{N}^2} P_n \Big[\sum_{v\in V^2}\sum_{l\in L_v} C^F_{vln}x_{vln}\Big] \tag{6.1a}$$

$$+ \sum_{n\in\mathcal{N}^3} P_n \Big[\sum_{f\in F}\sum_{i\in A_{fn}}\sum_{v\in V^A_{ifn}}\sum_{p\in P^A_{ifn}} C^V_v t_{vpifn} \tag{6.1b}$$

$$+ \sum_{f\in F}\sum_{i\in A_{fn}}\sum_{v\in V^A_{ifn}}\sum_{p\in P^A_{ifn}} C^D_{pifn} t_{vpifn} + \sum_{f\in F}\sum_{i\in A_{fn}\setminus A^B_{fn}} C^P_{ifn} d_{ifn} \tag{6.1c}$$

$$+ \sum_{v\in V^S}\sum_{p\in P}\sum_{(f,j)\in F\cup\{0\}|f\neq g} C^V_v(t^M_{vpfgn} + t^E_{vpfgn}) + \sum_{v\in V^O}\sum_{p\in P}\sum_{f\in F} T^V_{vf} C^V_v y_{vpfn}\Big]. \tag{6.1d}$$

The objective function expresses the same as the objective function in the deterministic model. However, one term is added in part (6.1a) and this term reflects the fixed cost of the vessels that are rented at the second stage.

6.3.2 First stage constraints:

$$x_{vln} \le Q_{jv} z_j, \qquad n \in \mathcal{N}^1,\ j \in J,\ v \in V^J_j,\ l \in L_v. \tag{6.2}$$

Constraints (6.2) are the only set of restrictions for the first stage. These restrictions are to make sure that the capacity of the offshore station(s) are not exceeded, and express the same as constraints (5.8) in the deterministic model.

6.3.3 Second stage constraints:

$$\sum_{n'\in\mathcal{N}^1}\sum_{v\in V^1}\sum_{l\in L_v} C^I_{vln} x_{vln'} + \sum_{v\in V^2}\sum_{l\in L_v} C^I_{vln} x_{vln} + \sum_{j\in J} C^I_j z_j \le C^B, \qquad n \in \mathcal{N}^2, \tag{6.3}$$

$$\sum_{n'\in\{1,n\}} (x_{vln'} - x_{v(l+1)n'}) = x^L_{vpn} - x^J_{vpn},$$

$$n \in \mathcal{N}^2,\ v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl}. \tag{6.4}$$

At the second stage we have two sets of restrictions. Constraints (6.3) are the budget constraints for each second stage node, which express the same as constraints (5.9) in the deterministic model. Constraints (6.4) determine the number of vessels joining and leaving the fleet in each node at the second stage, and these constraints correspond to constraints (5.14) in the deterministic model.

6.3.4 Third stage constraints:

$$\sum_{v \in V^A_{ifn}} \sum_{p \in P^A_{ifn}} H_{vifn} t_{vpifn} + \sum_{\bar{i} \in A^B_{ifn}} \sum_{v \in V^A_{\bar{i}fn}} \sum_{p \in P^A_{\bar{i}fn}} B_{vifn} t_{vp\bar{i}fn} + d_{ifn} \geq T^A_{ifn}$$
$$n \in \mathcal{N}^3,\ f \in F,\ i \in A_{fn} \setminus A^B_{fn}, \quad (6.5)$$

$$\sum_{v \in V^A_{ifn}} t_{vpifn} \leq T^P,$$
$$n \in \mathcal{N}^3,\ f \in F,\ i \in A^L_{fn},\ p \in P^A_{ifn}. \quad (6.6)$$

Most of the restrictions appear at the third stage. First we have constraints (6.5), which make sure that all maintenance activities are executed within the hard time windows. If an activity i on wind farm f in node n is not completed, the dummy variable d_{ifn} will take value in terms of the number of hours that is left on the activity. These restrictions correspond to constraints (5.10) in the deterministic model. Further, we have constraints (6.6), preventing several vessels to work in parallel on the same maintenance activity at the same time, equivalent to constraints (5.11) in the deterministic model.

$$\sum_{f \in F} y_{vpfn} \leq \sum_{n' \in \mathcal{N}^A_n} x_{vln'}, \qquad n \in \mathcal{N}^3,\ v \in V^O,\ l \in L_v,\ p \in P^L_{vl}, \quad (6.7)$$

$$\sum_{f \in F \cup \{0\}} y_{vpfn} = \sum_{n' \in \mathcal{N}^A_n} x_{vln'}, \qquad n \in \mathcal{N}^3,\ v \in V^S,\ l \in L_v,\ p \in P^L_{vl}. \quad (6.8)$$

Constraints (6.7) and (6.8) determine the number of vessels that must be rented or acquired at the first and second stage, and correspond to constraints (5.12) and (5.13) respectively, in the deterministic model. The right hand side of the constraints sum over $\mathcal{N}^A_n$, which is the set of all ancestor nodes for node n at the third stage.

$$y_{vp0n} - y_{v(p+1)0n} = \sum_{g \in F} (w_{vp0gn} - w_{vpg0n}) + x^L_{vpa(n)} - x^J_{vpa(n)},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl}, \quad (6.9)$$

$$y_{vpfn} - y_{v(p+1)fn} = \sum_{g \in F \cup \{0\} | f \neq g} (w_{vpfgn} - w_{vpgfn}),$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ l \in L_v,\ p \in P^{|L|}_{vl},\ f \in F, \quad (6.10)$$

$$y_{vpfn} - y_{v(p+1)fn} = \sum_{g \in F \cup \{0\} | f \neq g} (w_{vpfgn} - w_{vpgfn}),$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ l \in L_v,\ p \in P^L_{vl} \setminus P^{|L|}_{vl},\ f \in F \cup \{0\}. \quad (6.11)$$

Further, we have the balancing constraints (6.9) - (6.11), which determine the movement of vessels between wind farms and harbour for the vessels that can stay offshore for several periods. These constraints correspond to constraints (5.15) - (5.17) in the deterministic model.

$$\sum_{f \in F} y_{vpfn} \leq \sum_{f \in F} \sum_{\bar{p} \in (p,...,p+P^M_v-1)} w_{v\bar{p}f0n},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in \{1,...,|P| - P^M_v + 1\}, \quad (6.12)$$

$$y_{vpfn} \leq \sum_{g \in F \cup \{0\} | g \neq f} \sum_{\bar{p} \in (p,...,p+P^M_v-1)} w_{v\bar{p}fgn},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in \{1,...,|P| - P^M_v + 1\},\ f \in F. \quad (6.13)$$

Constraints (6.12) force each vessel type, where $v \in V^S$, to return to origin after P^M_v periods in node n. Constraints (6.13) force each vessel type where $v \in V^S$to travel to another wind farm or back to origin after P^M_v periods in node n. These constraints express the same as constraints (5.18) - (5.19), respectively, in the deterministic model.

$$T^V_{vfg} w_{vpfgn} \leq t^E_{vpfgn} + t^M_{v(p+1)fgn},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in \{1,...,|P|-1\},\ (f,g) \in F \cup \{0\} | f \neq g. \quad (6.14)$$

Further we have constraints (6.14), which determine the time spent in transport by vessel type v in node n when moving from location f to location g in period p. The constraints determine whether the vessel type travels in the end of period p, the beginning of period $(p+1)$, or both, in the same way as constraints (5.20) in the deterministic model.

$$\sum_{g \in F \cup \{0\} | g \neq f} w_{vpfgn} \leq y_{vpfn},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in P,\ f \in F \cup \{0\}, \quad (6.15)$$

$$\sum_{g \in F \cup \{0\} | g \neq f} w_{vpgfn} \leq y_{v(p+1)fn},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in \{1,...,|P|-1\},\ f \in F \cup \{0\}. \quad (6.16)$$

Constraints (6.15) and (6.16) correspond to constraints (5.21) and (5.22) in the deterministic model, and prevent the vessels that are forced to change location to do this between two periods. In addition, these constraints ensure that one period is used at the beginning and at the end of a contract, in order to prepare and demobilise the vessels.

$$\sum_{i \in A_{fn}} t_{vpifn} \leq T^P y_{vpfn} - \sum_{g \in F \cup \{0\} | f \neq g} (t^M_{vpgfn} + t^E_{vpfgn}),$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in P,\ f \in F, \quad (6.17)$$

$$\sum_{i \in A_{fn}} t_{vpifn} \leq (T^P - T^T_{vf}) y_{vpfn},$$
$$n \in \mathcal{N}^3,\ v \in V^O, p \in P,\ f \in F. \quad (6.18)$$

Further, constraints (6.17) and (6.18) correspond to constraints (5.23) and (5.24) in the deterministic model, and reduce the available operation time for vessel type v on wind farm f with the time used in transport for the respective vessel type to wind farm f.

$$\left(K^O_{vk} - W_{pkn}\right) \sum_{f \in F} \sum_{i \in A_{fn}} t_{vpifn} \geq 0, \quad n \in \mathcal{N}^3,\ p \in P,\ v \in V,\ k \in K, \quad (6.19)$$

$$\left(K^S_{vk} - W_{pkn}\right) \sum_{f \in F} y_{vpfn} \geq 0, \quad n \in \mathcal{N}^3,\ p \in P,\ v \in V,\ k \in K. \quad (6.20)$$

Constraints (6.19) and (6.20) correspond to constraints (5.25) and (5.26) in the deterministic model, and are the operational and safety restrictions. As described in the deterministic model, these restrictions are not necessary in the model formulation if the variables t_{vpifn} and y_{vpfn} are only defined for the nodes, vessel types and periods at which safety and operational requirements are fulfilled.

$$\begin{aligned}
x_{vln} &\geq 0 \textit{ and integer}, & v \in V^1,\ l \in L_v,\ n \in \mathcal{N}^1, && (6.21)\\
x_{vln} &\geq 0 \textit{ and integer}, & v \in V^2,\ l \in L_v,\ n \in \mathcal{N}^2, && (6.22)\\
x^L_{vpn} &\geq 0 \textit{ and integer}, & v \in V^S,\ l \in L_v \setminus |L_v|,\ p \in P^{|L|}_{vl},\ n \in \mathcal{N}^2, && (6.23)\\
x^J_{vpn} &\geq 0 \textit{ and integer}, & v \in V^S,\ l \in L_v \setminus |L_v|,\ p \in P^{|L|}_{vl},\ n \in \mathcal{N}^2, && (6.24)\\
y_{vpfn} &\geq 0 \textit{ and integer}, & v \in V^O,\ p \in P,\ f \in F,\ n \in \mathcal{N}^3, && (6.25)\\
y_{vpfn} &\geq 0 \textit{ and integer}, & v \in V^S,\ p \in P,\ f \in F \cup \{\mathit{0}\},\ n \in \mathcal{N}^3, && (6.26)\\
w_{vpfgn} &\geq 0 \textit{ and integer}, & v \in V,\ p \in P,\ (f,g) \in F \cup \{\mathit{0}\} \mid f \neq g,\ n \in \mathcal{N}^3, && (6.27)\\
t_{vpifn} &\geq 0 & n \in \mathcal{N}^3,\ f \in F,\ i \in A_f,\ v \in V^A_{ifn},\ p \in P^A_{ifn}, && (6.28)\\
t^M_{vpfgn} &\geq 0 & v \in V,\ p \in P,(f,g) \in F \cup \{\mathit{0}\} \mid f \neq g,\ n \in \mathcal{N}^3, && (6.29)\\
t^E_{vpfgn} &\geq 0 & v \in V,\ p \in P,(f,g) \in F \cup \{\mathit{0}\} \mid f \neq g,\ n \in \mathcal{N}^3, && (6.30)\\
d_{ifn} &\geq 0 & n \in \mathcal{N}^3,\ f \in F,\ i \in A_{fn} \setminus A^B_{fn}, && (6.31)\\
z_j &\textit{ is binary} & j \in J. && (6.32)
\end{aligned}$$

Finally, the constraints (6.21) - (6.30) impose non-negativity and integrality properties, while constraints (6.32) impose binary properties upon the respective decision variables. Considering that the stochastic model allows for the rental of vessels at two stages, constraints (6.21) apply for the first stage node, and the vessel types that can be rented or acquired at this stage. Constraints (6.22) apply for the second stage nodes, and the vessels that can be rented at this stage. Both constraints (6.21) and (6.22) correspond to constraints (5.27) in the deterministic model. Constraints (6.23)-(6.32) correspond to constraints (5.28) - (5.37) in the deterministic model.

7 Method Of Computational Study

The previous sections have in detail explained the development of both a deterministic and a stochastic model for solving the FSMPOW. In the following two sections we will mainly focus on the stochastic node formulation of the FSMPOW, thus when referring to the model this implies the stochastic node formulation.

In order to evaluate the applicability of the developed model on a real life wind farm, the limitation of the model in terms of solution time and number of wind turbines must be determined. Furthermore, the robustness of the solutions, that is, how the solutions perform when exposed to more uncertainty, must be investigated. Finding an optimal solution for a given number of scenarios is of no economical benefit if the solution does not perform relatively well for a greater number of scenarios. A computational study addressing these issues will be presented in Section 8.

To be able to analyse the results of the computational study, the model must be tested with an appropriate set of input data. Furthermore, variations in the scenarios are important when determining the robustness of the solutions. In Section 7.1 we will discuss how the input data that is not exposed to uncertainty has been gathered. In Section 7.2 we will discuss how the uncertain parameters have been gathered and pre-processed and how scenarios have been generated. Finally, in Section 7.3 the procedures we have used for calculating the value of stochastic solution (VSS) and the expected value of perfect information (EVPI) will be presented. In order to generate realistic scenarios, best practice for the offshore wind industry has been pursued where possible.

7.1 Selection of Critical Input Parameters

In the computational study we assume that Stage 1 is at the beginning of year 1, Stage 2 is at the end of year 1 and Stage 3 is the maintenance execution year stretching over year 2. Year 2 is assumed to have 360 periods (days). This is illustrated in Figure 27.

Two potential offshore wind farms, located in the North Sea, 100 and 130 kilometres from shore , respectively, will be included in the computational study, together with a number of different vessel types, helicopters and offshore station concepts as a basis for our scenario generation. The number of wind turbines at each wind farm will be changed during the computational study depending on the purpose of the different tests.

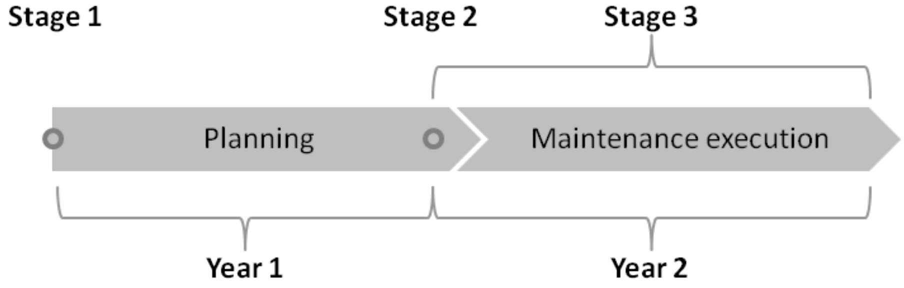


Figure 27: *Illustration of the stages used in the computational study.*

Relevant distances are summarised in Table 1. Notice that an offshore station concept is included in the table. This will be further discussed in the next section.

	Distances [km]
Distance to/from shore to wind farm 1	100
Distance to/from shore to wind farm 2	130
Distance between the farms	20
Distance to/from offshore station to wind farm 1	10
Distance to/from offshore station to wind farm 2	10

Table 1: *The distances used in the computational study.*

7.1.1 Vessels and Offshore Stations

Offshore wind is, as stated in Section 1, a relatively new technology and our model is therefore developed to handle various of vessel types and vessel concepts. Data for the different vessel types is based on Østgren (2012) and Kaiser and Snyder (2011). Considering the non-transparent contracting market for offshore wind maintenance vessels, the fixed and variable costs for different contracts are based on the estimated day rates in Østgren (2012) and Kaiser and Snyder (2011). Fluctuation in vessel spot rates from stage 1 to stage 2 will be further discussed in Section 7.2.2, as the spot rates are exposed to uncertainty.

Data for helicopters is gathered from Østgren (2012) and Conklin and Decker (2011). To also capture new concepts, as described in Section 2, a set of reasonable data is included for vessel types and offshore station concepts that do not exist today, but that can be interesting for the future.

It is important to keep in mind that an offshore wind farm operator will have access to all this data. The main purpose of the computational study is not to analyse the costs themselves, but to determine how the model can be used to carry out economical analysis.

Throughout the computational study, 9 vessel and helicopter types, all with different characteristics, will be used. Some of the main characteristics are listed in Table 2. The multipurpose vessel (vessel number 8) can execute both heavy lifts and transport large parts. Inputs not discussed but included in the computational study are: weight restrictions, areal restrictions, vessel speed, the stage at which the vessels and helicopters can be rented or acquired, and fixed and variable cost. These inputs can be studied in the CD enclosed.

An offshore station concept is included in the input data in order to capture the impact of such a station. The concept is in the computational study supposed to represent some sort of mother ship solution as described in Section 2.4. Characteristics for this mother ship are presented in Table 3.

Vessel number	Vessel type	Personnel	Wave restriction (in operation) [m]
1	CTV (small)	12	1,5
2	CTV (large)	24	2,0
3	CTV (small)	12	1,5
4	Supply vessel (small)	40	2,5
5	Supply vessel (large)	70	2,5
6	Helicopter 1	7	-
7	Helicopter 2	9	-
8	Multipurpose vessel	100	2
9	Jack-up rigg	150	2,5

Vessel number	Lift capacity [Metric tons]	Max time spent offshore [periods]	Lease length [periods]	Wave restriction (safety) [m]	Wind restriction (safety) [m/s]
1	0	1	360	1,5	20
2	0	1	30	2,5	25
3	0	1	30	1,5	30
4	0	20	30	3,5	30
5	0	20	30	4	30
6	0	1	30	-	20
7	0	1	360	-	20
8	250	20	360	3,5	30
9	400	20	360	4	35

Table 2: *The characteristics for the vessel types used in the computational study. Note: The wind restriction (in operation) is 18 m/s for all the vessel types and is not included in the table.*

Offshore station concept	Belonging vessel types	Vessel capacity [ref. column 2]
Mother ship concept	1 and 7	4 and 2

Table 3: *The characteristics for the offshore station concept used in the computational study. The cost of acquiring is not listed here. This can be studied in the CD enclosed.*

7.1.2 Maintenance Activities

Our study of the offshore wind industry shows that a preventive maintenance operation is on average conducted 1-2 times a year for each wind turbine. In the computational study the preventive maintenance strategy includes 2 visits to each turbine each year. The number of corrective maintenance operations on each wind farm is calculated based on the probability of failures for land-based wind turbines (Milborrow, 2010). Four different types of failures have been selected, with associated failure rates taken from Figure 6 in Subsection 2.2, this giving a total of five different types of maintenance operations, which are summarised in Table 4.

Type Of Maintenance	Operation Type	Failure rate
Preventive Maintenance	General Maintenance	-
Corrective Maintenance	Gearbox	0.13
Corrective Maintenance	Hydraulic	0.27
Corrective Maintenance	Electric	0.55
Corrective Maintenance	Brakes	0.20

Table 4: *The operations, with associated failure rates, used in the scenario generation.*

The maintenance operations are further divided into different activities, as discussed in Section 5.1. We assume that a preventive maintenance operation consists of only one activity, namely that of human interaction, whereas a corrective maintenance operation may consist of up to three different activities. Therefore a total of three different activities are included in our input data, one requiring human interactions and two others requiring lifting or transport capacity. The connection between an operation and its activities is illustrated in Figure 28.

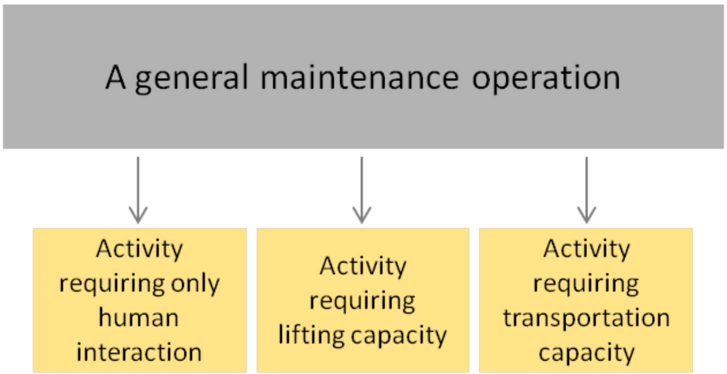


Figure 28: *An illustration of a general maintenance operation and its belonging activities.*

Preventive maintenance operations with overlapping execution windows (i.e. hard time windows) are mounted into activity bundles. By including activity bundles into the computational study we are opening up the possibility for a better utilisation of the vessel fleet. However, the efficiency of a vessel is reduced and restricted by an efficiency parameter, defined as E_v^V in the model formulation, when working on an activity bundle. In our analysis this has been fixed to 0,9 for all vessel types. This means that if a vessel spends 10 hours on an activity bundle, 1 hour will be lost in transporting the different maintenance teams out to their turbines. The idea behind the activity bundles and the efficiency parameter are explained in Section 5.1.5.

7.2 The Generation of Scenarios and Pre-Processing of Input Data

Both the deterministic and the stochastic model are formulated such that pre-processing and calculation of input data given by the user is required before entering the optimisation software. The vessel spot rate scenarios, electricity price scenarios and the weather scenarios are generated in Excel sheets. These scenarios, in addition to all other required input data, are exported to a `C++` application. The application is written for simplicity and flexibility, and will be referred to as the `FSMPOW_generator`. The `FSMPOW_generator` generates a preventive maintenance schedule and corrective maintenance scenarios, in addition to pre-processing all the input data such that it is readable for the optimization software Xpress MP.

An outline of the how the scenario generation is performed and the interaction between Excel, the `FSMPOW_generator` and the optimisation software Xpress-MP, is illustrated in Figure 29.

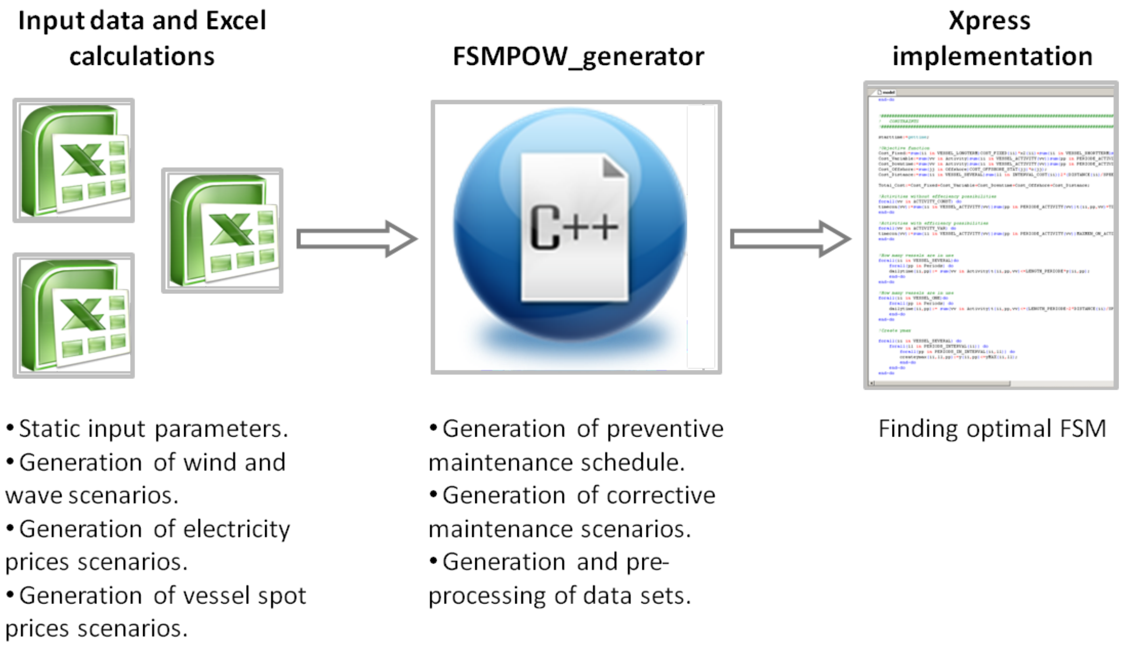


Figure 29: *The interaction between all the elements involved in the pre-processing and calculation of input parameters needed.*

In the following sections, the pre-processing and calculations of importance will be studied in detail. First, the structure of the node tree used in the computational study will be explained. Second, the Excel calculations will be discussed. Third, the architecture of the `FSMPOW_generator` will be addressed, along with some of the generated sets. As for the less important sets and parameters, the reader is referred to Appendix A.

7.2.1 The Structure of the Node Tree

There are four different parameters bringing uncertainty to our model: Spot rates for vessels, turbine failures, electricity prices and weather conditions. These uncertain parameters are revealed at different stages in the node tree. The vessel spot rates will be revealed at the second stage. At the third stage, the electricity prices, weather conditions and turbine failures are revealed.

Each second stage node will split into a number of third stage nodes, and each of these nodes will have a unique combination of scenarios, as illustrated in Figure 30. However, the same scenarios will be found in node 5, 8 and 9 in the figure, as the spot prices at stage 2 will not affect the weather conditions, electricity prices or turbine failures. We could have generated a number of third stage nodes such that all combinations of weather scenarios, electricity price scenarios and corrective maintenance scenarios were included. However, this would reduce the variation of uncertainty within the tree.

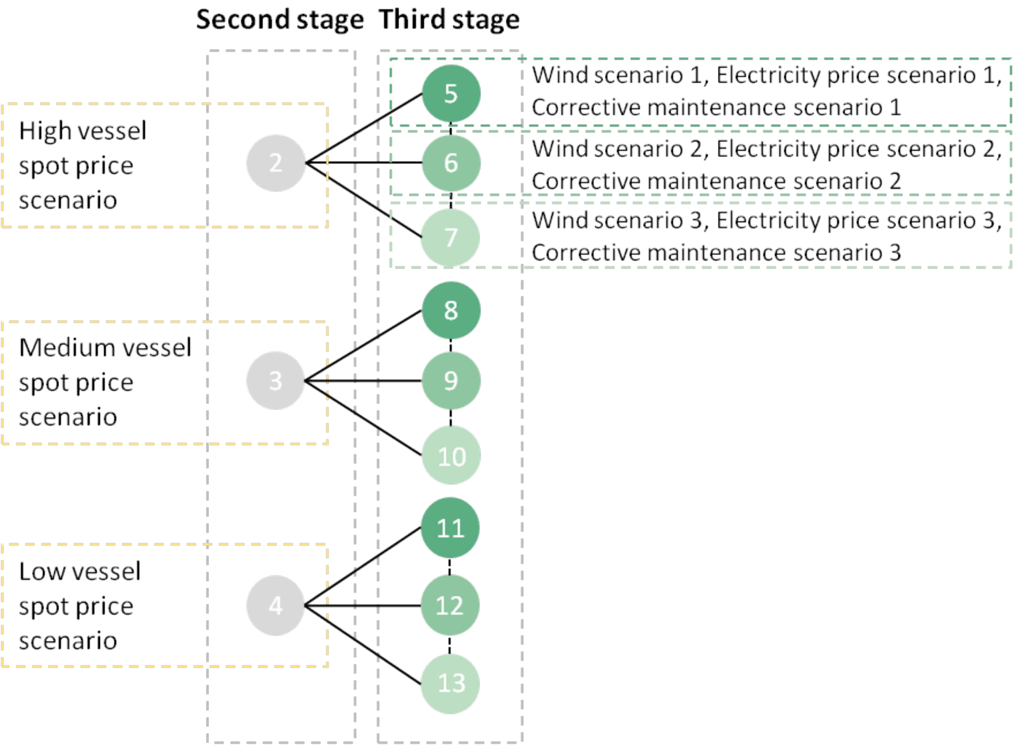


Figure 30: *The figure illustrates where and how the different scenarios are allocated. The third stage nodes with similar colours contain the same scenarios.*

The probabilities of reaching the second stage nodes will be discussed in the next section. We assume that there is an equal probability of reaching each of the succeeding third stage nodes from a second stage node, owing to the fact that we have no foundation for telling whether one scenario is more likely to happen than another.

7.2.2 Fluctuation in Vessel Prices

The price of renting or acquiring a vessel or a helicopter is highly dependent on the point of contracting, the length of the lease term, and the time of usage. If the timing is right the savings can be considerable. In our model, it is possible to contract vessels or helicopters at the first and the second stage depending on the vessel types. The spot rates at the second stage are uncertain, and we have assumed, unless other is specified, that there are three outcomes of the vessel spot rates at the second stage, namely high case, medium case and low case. The spot rates are assumed to fluctuate equally for all the vessel types. The probability of the medium case is 0.5, and these prices are identical to those at the first stage. Based on Østgren (2012) the high and low cases have been fixed to + 60% and - 60 %, respectively, both with the probability of 0.25. The probabilities used for the different second stage scenarios are listed in Table 5.

Scenario	Probability
High price scenario	25%
Middle price scenario	50%
Low price scenario	25%
Deterministic scenario	100%

Table 5: *Probabilities for reaching a node at the second stage.*

7.2.3 Weather scenario generation

Both the deterministic and stochastic formulation of the FSMPOW allow for a number of weather inputs, such as wind speed, wave height, wind direction, wave direction etc. For simplicity, we have decided to focus only on wind speed and wave height in our computational research, as these are the main factors affecting the accessibility of the different vessel types and helicopters. Wave heights will only affect the accessibility of the vessels, while the wind speed will mainly affect the accessibility of the helicopters. In addition, the wind speed will determine the generated output of the wind farm.

As a starting point for the scenario generation of wind speeds and wave heights, historical data from the Ekofisk field in the North Sea from 2005 to 2010 have been used (Norwegian Meteorological Institute, 2012).

Wind Speed Scenario Generation

The two-parameter Weibull distribution is used to model wind speed, where one parameter is the shape parameter k (dimensionless) and the other is the scale parameter c (m/s) (Vallee et al., 2007). The cumulative Weibull distribution function of the wind speed v is given by:

$$F(v;c,k) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right], \tag{7.1}$$

and the Weibull probability density function is given by:

$$f(v;c,k) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right]. \tag{7.2}$$

Figure 31 illustrates the probability density of the Weibull distribution with different scale factors c, and the shape factor k fixed to 3. In Spahic et al. (2009) the authors analyze data obtained from the North Sea, and they conclude that the annual wind speed can be approximated by the Weibull shape parameter $k = 2.17$.

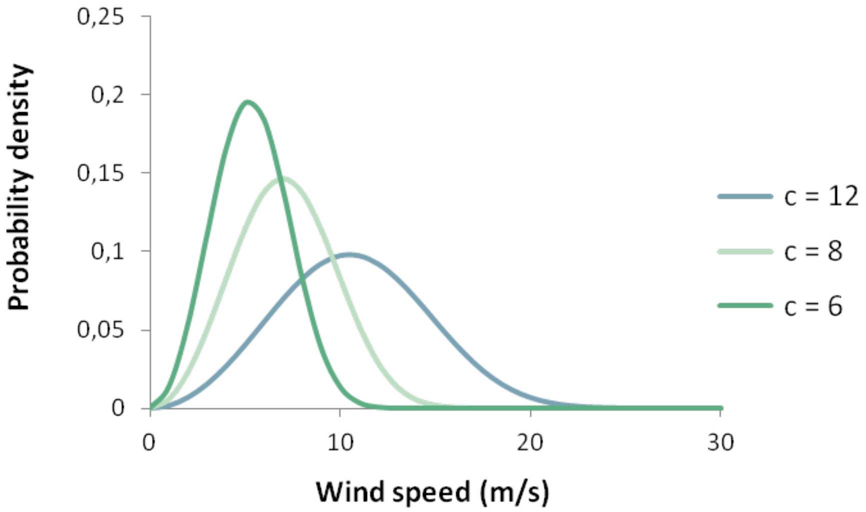


Figure 31: *Probability density of the Weibull distribution with shape factor $k = 3$.*

In Bhattacharya and Bhattacharjee (2009), the authors conclude that a good estimate for the scale parameter c can be obtained from:

$$c = 1.128\bar{v} \mid 1.4 \leq k \leq 4, \tag{7.3}$$

if the shape parameter k ranges from 1.4 to 4, where $\bar{v}$ is the mean wind speed. Based on these two findings we will use $k = 2.17$ and determine the scale parameter c from Equation (7.3).

In the Ekofisk field, the weather conditions are rougher in winter than in the summer. We thus estimate the mean wind speed $\bar{v}$, for each month of the year, based on the historical data from the Ekofisk field. The mean wind speed and the corresponding scale parameter can be found in Table 6. To generate a random 2-parameter Weibull distributed wind speed v in Excel we use the formula from Wittwer (2004):

$$v = c\left[-LN(1 - RAND())\right]^{\left(\frac{1}{k}\right)}, \tag{7.4}$$

where $k = 2.17$ and c for the different months is given in the Table 6.

Month	Mean wind speed $\bar{v}$	Scale factor c
January	10.87	12.26
February	8.70	9.81
March	8.91	10.05
April	7.16	8.07
May	6.73	7.60
June	6.12	6.90
July	6.11	6.89
August	6.96	7.85
September	7.92	8.94
October	8.24	9.29
November	9.97	11.25
December	8.82	9.95

Table 6: *Mean wind speed $\bar{v}$ and corresponding scale factor c used in the wind speed scenario generation.*

Significant Wave Height Scenario Generation

Calculations we have made on the historical data set show that wave heights are highly correlated with wind speeds, with correlation factors in the range $[0.73, 0.86]$. Figure 32 illustrates the high dependency between wind speed and significant wave height in the month of January 2010. To capture this dependency, we have assumed a correlation factor of 1 between wind speeds and wave heights in the scenario generation.

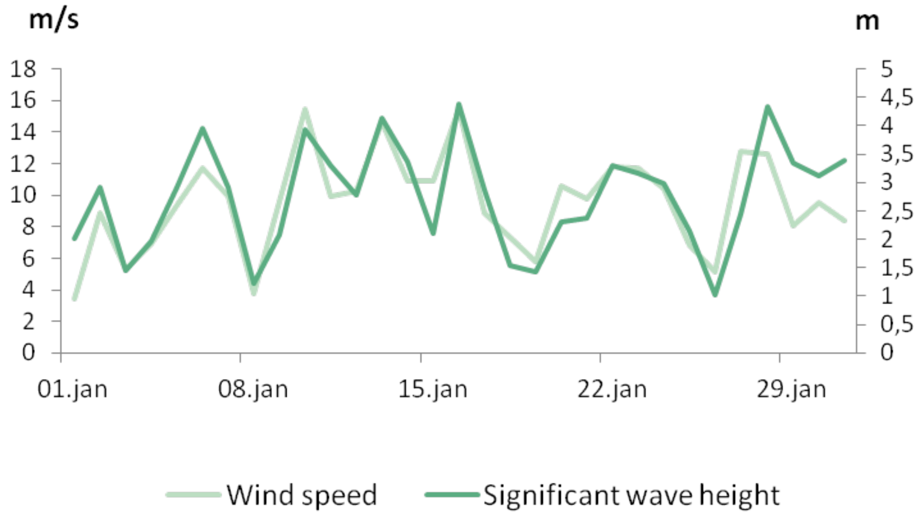


Figure 32: *Wind speed and significant wave height in January 2010. Based on data from Norwegian Meteorological Institute (2012).*

With a correlation factor of 1 there is only need for the generation of wind scenarios, and the corresponding wave scenarios can be generated by dividing wind speeds with the mean division factor $\bar{d}$. Based on the historical data from the Ekofisk field, the mean division factor has been calculated to $\bar{d} = 4.3$.

7.2.4 Electricity price scenario generation

For the generation of electricity price scenarios we have used daily prices from Nordpool Spot (2012) for the year of 2010 as a starting point. These prices are referred to as $S_1, ..., S_{360}$. In order to get a smoother basis for the scenario generation, we have used exponential smoothing according to equations (7.5) and (7.6) (Brown et al., 1961). The parameter α has been set to 0.6.

$$\bar{P}_1 = S_1, \tag{7.5}$$

$$\bar{P}_t = \alpha \bar{P}_{t-1} + (1 - \alpha) S_t. \tag{7.6}$$

The set of prices $\bar{P}_t$ are now used as a base case for the scenario generation. Each scenario can deviate from the base case within the interval $[-\delta, \delta]$, where δ is the allowable deviation. In addition we add some noise to each day in the scenario generation. Each day in a scenario can deviate within the interval $[-\eta, \eta]$, where η is the allowable noise in EUR/MWh. The price P_{st} in scenario s on day t is thus given by:

$$P_{st} = \bar{P}_t(1 + \delta \xi_s) + \eta \xi_{st}, \tag{7.7}$$

where ξ_s and ξ_{st} are uniformly distributed random numbers in the interval $[-1, 1]$. The noise parameter η has been set to 5 EUR/MWh, and the deviation δ is fixed to 0.5 in the scenario generation, unless other is specified. This means that we assume possible deviations of ± 50 % in the electricity price from the base case. Figure 33 illustrates four different electricity price scenarios during the maintenance execution planning horizon.

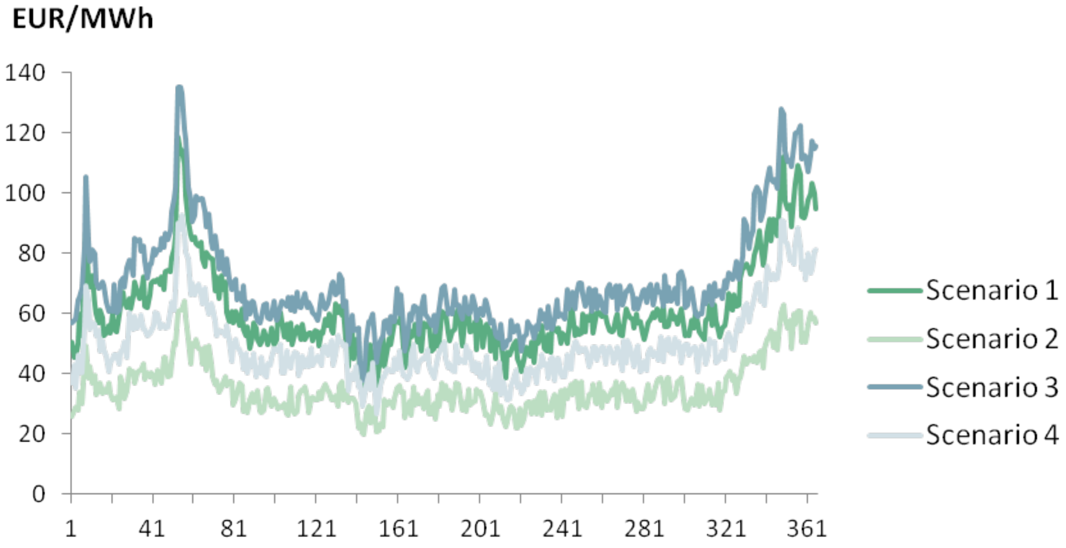


Figure 33: *Electricity price scenario generation based on equation* (7.7).

Although not an uncertain factor, we will present the input data regarding support regime here, while this will be added to the electricity prices in the scenario generation. We have assumed a support regime as the one presently used in the UK, which is based on renewable obligations (RO). In the UK, every renewable energy producer receives a certain amount of renewable obligation certificates (ROCs) per MWh of produced power. The number of ROCs an operator will receive per MWh depends upon the type of renewable energy that is produced. Offshore wind power producers currently receive 2 ROCs per MWh of produced power. The certificates are then sold on the market, where the market price is fixed for one year (DECC, 2011). The current price is approximately EUR 50 per ROC, which gives an offshore wind farm producer 100 EUR/MWh in support, in addition to the electricity price (Ofgem, 2011).

7.2.5 The C++ Application

The `FSMPOW_generator` has five main objectives. First, constructing a node tree together with the associated probability of reaching each node, and allocating the scenarios generated in Excel to their respective nodes. Second, generating a preventive maintenance activity schedule, and a number of activity bundles, and allocating the maintenance schedule to all third stage nodes. Third, generating the corrective maintenance activity scenarios, and allocating them to the respective third stage nodes. Forth, pre-processing and generating all the sets required to run the implementation of the stochastic model.

The language used writing the application is `C++` and the application used in the development is Microsoft Visual Studio 2008. The `FSMPOW_generator` code can be found on the CD enclosed.

7.2.6 Maintenance Schedule

When using the FSMPOW model to analyse a real world scenario, the preventive maintenance schedule should be based on many dissimilar considerations, such as the type of wind turbines, accessibility, weather conditions, etc. (Vatn, 2011). These are all important factors for a real case offshore wind farm, but of less significance when creating a preventive maintenance schedule simply to evaluate the model. By relaxing these criteria, it is possible to generate preventive maintenance schedules with the `FSMPOW_generator`, only knowing the number of wind turbines at each wind farm, and the frequency at which preventive maintenance should be executed.

The `FSMPOW_generator` creates a maintenance schedule in three steps. This is done for the number of wind farms given as input to the application.

1. First, the application generates the preventive maintenance schedule for each wind turbine. And allocates this to all the third stage nodes. Given the assumption of two operations per wind turbine per year, the application selects two random "optimal" points in the time horizon, for each wind turbine and each farm, at which the operation should be executed. When this has been done for all the wind turbines, there will be a number of preventive maintenance activities evenly spread out throughout the time horizon (given that the number of wind turbines is relatively large).

   Based on the optimal execution point and the expected execution time of a given preventive maintenance operation, a time interval in which the operation must be completed is calculated. The completion time is rounded up to the closest integer period, before the `FSMPOW_generator` adds two times the adjusted completion time on each side of the optimal starting point. This process results in two randomly placed time intervals, for each wind turbine, in which the preventive maintenance operation has to be completed. These intervals represent the *hard time window* for the activities.

We will illustrate this process with an example. First, a random optimal starting point is selected within the total number of periods. Assume that the optimal starting point is in period 20. If the activity takes 15 hours, the adjusted completion time becomes one period (period 20), and the hard time window is then to include the optimal starting period ± 2 periods, which is two times the adjusted completion time for the optimal starting point. The result of this example gives us a hard time window starting in 18 and ending in 22. In the case of larger completion time, the time windows would have been longer.

2. Second, for each farm, the generated preventive maintenance schedule is sorted from the first starting hard time window to the last.
   The `FSMPOW_generator` then checks if the first operation has an overlapping time interval with the next three operations in the sorted list. If any of the following operations have an overlapping time interval with the first, they are merged into a bundle. The time interval for this bundle activity will be set to the periods in which the underlying activities are overlapping. If a bundle is created, the application continues with the first preventive operation not yet in a bundle, and repeats the process. For safety reasons, an activity bundle will include a maximum of four maintenance activities. For simplicity we have assumed that one activity only can appear in one bundle. If no overlapping periods are found between the active and the following activities, the application will jump to the next activity in the sorted list. The `FSMPOW_generator` stops the bundling when it has checked all the preventive maintenance operations on each farm. While generating the activity bundles, a set is created for each preventive maintenance activity, including the activity bundle that activity i is included in. This set is known as A^B_{ifn} in the model formulation. In addition, a set including all the activity bundles on wind farm f is created. This set is known as A^B_{fn} in the model formulation.

3. Third, a given number of corrective maintenance scenarios are generated and allocated to their respective nodes, as illustrated in Figure 30. In each scenario, for each farm and each wind turbine and corrective maintenance activity type, the `FSMPOW_generator` generates a uniformly distributed random number in the interval [0,1], and adds the corrective maintenance operation if the number is less than the expected failure rate, given in Table 4, for the given operation. If an operation is added, a random point of occurrence is generated. The operation is then split into the respective activities, all with the same point of occurrence. The hard time windows for all the belonging activities of an operation is created by taking the period of occurrence and adding the 9 subsequent periods. Hence, the `FSMPOW_generator` generates

between 0 and 4 different corrective maintenance operations for each wind turbine, consisting of up to 3 activities, each with associated time windows.

When the three steps have been completed, the `FSMPOW_generator` has created a complete maintenance schedule for each third stage node, consisting of preventive and corrective maintenance activities, in addition to the bundle activities. If the application is run for more than one wind farm a complete maintenance schedule is generated for each wind farm. The maintenance schedule is referred to as P^{A}_{fin} in the model formulation. Figure 34 illustrates possible composition of a maintenance schedule over a 8 period planning horizon.

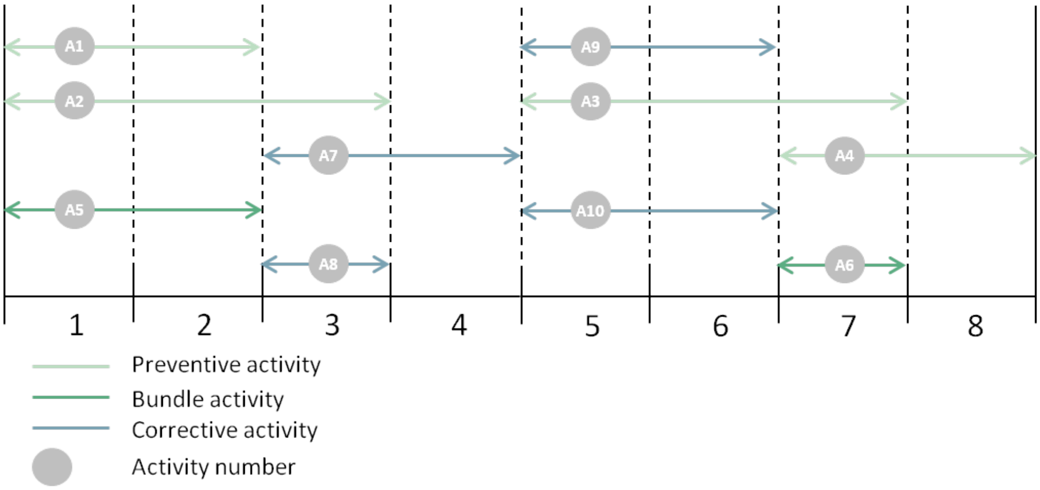


Figure 34: *An example of a maintenance schedule*

7.2.7 Vessel Determination

The FSMPOW model has, as mentioned above, been implemented such that the set of vessel types with possibility to execute each of the maintenance activities must be generated. In this process the `FSMPOW_generator` investigates the requirements of each activity on each farm and each node, and compares them with the characteristics of the vessel types available. If a vessel type fulfils all the specifications of an activity, it is added to the set of vessels that can perform this activity. By running the `FSMPOW_generator` on all the activities and farms, including the bundle activities, a complete set, linking all the generated activities together with possible vessel types, is created. This set is referred to as V^{A}_{ifn} in the model formulation. Some vessel types are dependent on an offshore station concept. An additional set, linking these vessel types to the offshore station concept, is created by the `FSMPOW_generator`. This set is referred to as V^{J}_{j} in the model formulation.

In the model formulation, the constraints (6.19) can be excluded from the model formulation if the variables t_{vpifn} are only defined for the periods in which the weather conditions allow vessel type v to operate. For each node, wind farm and period, the `FSMPOW_generator` will determine whether vessel type v can operate, based on the weather in the specific period and the operation capacity in terms of wind speeds and wave heights for vessel or helicopter type v. The generator will create a set for each third stage node and vessel type, including all the periods in which vessel type v can operate. This set is not included in the model formulation, but will be referred to as `PERIODS_OPERATION` in the Xpress formulation.

Further, the constraints (6.20) can be excluded if the variables y_{vpfn} are only defined for the nodes, farms and periods in which vessel type v can stay offshore, for safety reasons. If the weather conditions in a period, p, and node, n, exceed either the wind speed safety limit or the wave height safety limit of a vessel type v, the vessel type must return to its origin. The `FSMPOW_generator` will create a set for each third stage node and vessel type, including all the periods in which vessel type v can stay offshore. This set is not included in the model formulation, but will be referred to as `PERIODS_SAFETY` in the Xpress formulation.

In the Xpress formulation the variables t_{vpifn} will only be created for vessel type v in node n and period p, if p is included in the set `PERIODS_OPERATION(n,v)`. In the same manner, the variables y_{vpfn} will in the Xpress formulation only be created for wind farm f, vessel type v, node n and period p, if p is included in the set `PERIODS_SAFETY(n,v)`.

7.2.8 Other Determined Parameters

Downtime Cost: Closely related to the time windows generated in the maintenance schedule, are the cost of early start or delays in the execution of the preventive maintenance activities. Completing an activity before the optimal execution point implies the risk of fixing something not in the need of repair, whereas delayed execution increases the risk of a fatal failure on the wind turbine, and thus increases the expected downtime cost. The `FSMPOW_generator` tries to capture the costs of either executing too early or too late according to the theory of time windows described in Section 5.1.3. The expected total cost of maintenance is assumed to grow exponentially both before and after the optimal execution point. Further, for each third stage node, the expected power generation (Figure 20(b)) is calculated based on the wind speed in each period, and the simplified power output curve shown in Figure 18 in Section 3.4.1. The expected power generation in addition to the electricity price scenario and the ROC price gives the expected revenue from power generation. The application then merge the expected cost of maintenance and the expected revenue from power generation, giving a downtime cost for the interval in which the preventive maintenance activity can be executed. This interval will look similar to the illustration in Figure 20(d) in Section 5.1.3.

The downtime cost of corrective maintenance represents the loss in earnings due to a wind turbine breakdown. For each of the corrective maintenance activities in a node at the third stage, the `FSMPOW_generator` calculates the downtime cost by taking the accumulated loss in electricity sales for the subsequent periods in the hard time window and adds it to the current period. This is done for all the periods in the hard time window, as illustrated in Figure 21 in Section 5.1.3.

When it comes to the activities in a bundle the downtime cost is calculated by taking the downtime cost for the overlapping intervals for each of the belonging activities and adding them together. The `FSMPOW_generator` does this and links the accumulated interval costs to the current bundle activity.

To sum up, the `FSMPOW_generator` creates a set containing intervals with downtime costs corresponding to each of the time windows for every activity generated in the maintenance schedule generation. This process is done for all wind farms and all third stage nodes. The set created is referred to as C^D_{pifn} in the model formulation.

Maximum Usage of Men: As described in Section 5.1.4 there might be some maintenance activities where the time required to perform the activity can be reduced, if the number of maintenance personnel is increased from the minimum given demand. The necessary calculations in the determination of the constants H_{vif} is done with the `FSMPOW_generator` and returned as a set readable for the optimisation software. This is done for all the activities requiring human interaction, for the rest the constant is set equal to one.

Efficiency bundles: The efficiency of a vessel is assumed to be reduced when operating on a bundle. This is taken into account by the `FSMPOW_generator`. The efficiency constant (E^V_v in the model formulation) is read as input and multiplied with the minimum number of required maintenance personnel for the activities included in an activity bundle. This is repeated for all the activity bundles and then linked to the different vessel types. The result is a set, referred to as B_{vifn} in the model formulation, defining how efficient a maintenance team from a vessel type will be, when working on an activity bundle.

Penalty Costs: The cost of not completing an activity, in this respect also the superior operation, will highly affect the results in terms of availability. Consequently, the calculations of the penalty cost is done with respect to the possibility of changing it. Two user given inputs, preventive penalty constant and corrective penalty constant (resp. C^P and C^C), enables this possibility. The `FSMPOW_generator` calculates the penalty cost by adding the cost of not producing, i.e. the expected revenue from power generation, for the subsequent 90 periods after the optimal execution point. The calculated cost are then multiplied with the proper penalty constant depending on whether the cost belongs to a preventive or a corrective activity. The penalty cost is in the model formulation referred to as C^P_{ifn}.

Other Important Sets: The `FSMPOW_generator` generates a number of other sets connecting lease terms, vessel contracts, constants and other input data. A brief explanation of these sets is given in Appendix A.

7.3 Evaluating the models

Stochastic models have a reputation for being computationally demanding, and often requiring specific solution methods. It can therefore be useful to have tools for evaluating whether using a stochastic model is necessary, or if it is sufficient to use for example a deterministic approach where the effort instead is aimed at determining uncertain parameters. Two methods of evaluation are presented in this section: the value of the stochastic solution and the expected value of perfect information. Both of these measures will be used to evaluate the models, and since the goal of these models is to minimize the costs, the notation below is made in regards to a minimization problem.

7.3.1 Expected Value of Perfect Information

The expected value of perfect information, EVPI, is defined by Birge and Louveaux (1997) as the measure of the maximum amount a decision maker would be willing to pay in return for complete information about the future, thereby removing all uncertainty. The parameter EVPI is estimated in the same manner for a multistage stochastic problem as for a two stage stochastic problem.

The value SP, denotes the optimal solution to the stochastic problem. If each scenario in the stochastic problem is solved independently, then the value WS is the expected value of the set of solutions to the scenario problems, which is referred to as the wait-and-see solution. This solution represents the expected solution if all uncertainty is resolved. The set of scenario problems is often referred to as the WS model.

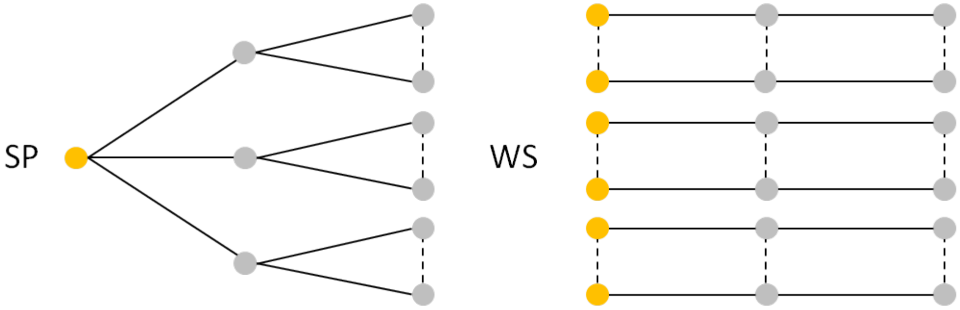
To estimate the EVPI, the stochastic problem is solved, giving SP, as indicated in Figure 35(a). Then the wait and see problem is solved, where each path in the node tree is solved as a deterministic problem as illustrated in 35(b), giving WS. For a minimization problem we have:

$$EVPI = SP - WS. \tag{7.8}$$

EVPI, obtained by comparing the wait-and-see approach to the here-and-now approaches, give an indication as to whether it is worth making an effort to reduce the uncertainty present in the problem. A small EVPI indicates that there will be little savings when reaching perfect information. For a minimization problem we have the general property:

$$WS \leq SP, \tag{7.9}$$

which is valid since the optimal solution of the uncertain parameters is always better than or equal to the stochastic solution of the same outcome (Birge and Louveaux, 1997).



(a) Solving the stochastic problem (b) Solving the wait and see problem

Figure 35: *Illustration of how the expected value of perfect information (EVPI) is calculated.*

7.3.2 Value of Stochastic Solution

The value of stochastic solution (VSS) measures the value of using a stochastic approach instead of a deterministic approach. Calculating the VSS for a two stage problem involves solving the expected value problem, EV, and then solving the SP with a fixed first stage solution from the EV problem. This gives the expected value of using an expected value approach, EEV. The value of the stochastic solution can then be calculated from:

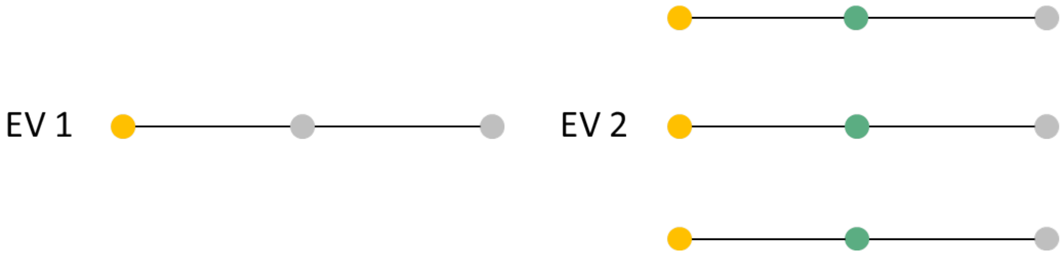
$$VSS = EEV - SP. \tag{7.10}$$

For a minimization problem we have the general property:

$$SP \leq EEV \tag{7.11}$$

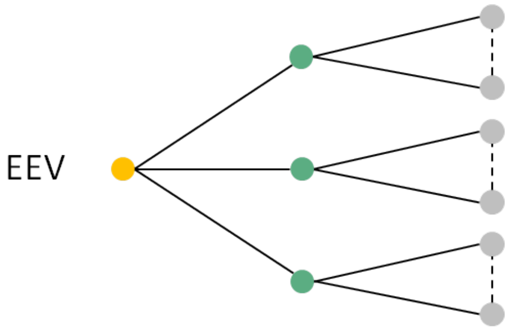
which holds for all stochastic problems, or SP is not the optimal solution to the stochastic problem, because the expected value solution also is valid for the stochastic problem, and could therefore have been chosen to obtain a better solution (Birge and Louveaux, 1997).

Calculating the VSS for a three stage stochastic model is not straightforward, because decisions are not only made at one stage. The question is thus which variables to fix at each stage. A trivial approach would be to fix only the first stage decisions. Such an approach would not be sufficiently beneficial to the stochastic FSMPOW model, however, considering that vessels can also be rented at the second stage. In Birge (1995), the author determines the VSS of a three stage, four period financial planning problem. Birge determines the EV by solving the



(a) The first stage solution is determined, based on the expected values in the second and third stages.

(b) The second stage solutions are determined, based on the expected value in the third stage.



(c) The EEV is determined by using the solutions from EV 1 and EV 2.

Figure 36: *Determining the VSS for the three stage FSMPOW.*

mean value problem for all three stages, and he implements these decisions in all stages when solving the EEV. Using this strategy when determining the VSS of the FSMPOW would imply the rental of the same number of vessels in all the nodes at the second stage, and would be advantageous for the stochastic model.

We have therefore used another approach, introduced by Escudero et al. (2007), where we take into account that the deterministic model should be able to make decisions at the second stage, based on the new information obtained about the vessel spot prices at this stage. Let EV1 be the optimal solution to the expected value problem at the first stage, or the EV1 problem, as illustrated in Figure 36(a). Further, let EV2 be the optimal solution to the expected value problem at the second stage (the EV2 problem), when the first stage variables have been fixed to the optimal solution from the EV1 problem, as indicated in Figure 36(b). Finally, let EEV be the expected value of using the first stage decisions obtained from the EV1 problem and the second stage decisions obtained from the EV2 problem, as indicated in Figure 36(b). The value of stochastic solution can now be determined by (7.10).

7.3.3 Determining the Mean Value Scenarios

When calculating the EV 1 and EV 2, mean value scenarios are used, as illustrated in Figure 36. At the second stage, only the vessel prices are revealed, and the mean value scenario is determined simply by calculating the average vessel prices based on the probability of the second stage nodes. At the third stage we have three uncertain factors, namely weather, electricity prices and the number of failures requiring corrective maintenance operations.

It is difficult to define a mean value weather scenario for the purpose of calculating the VSS. Creating a scenario based on the average wind speed and wave height each day would not add any value to the expected value problem, as this would neglect the variation in weather conditions, and thus underestimate the impact of wind speeds and especially wave heights. It is important to keep in mind that it is not necessarily the weather scenarios themselves, if not the combination of weather scenarios and the placement of the maintenance activities that affect the execution of the maintenance activities. Based on this we believe that it is impossible to create a mean value weather scenario that would benefit the expected value problem any better than a randomly generated scenario. The mean value weather scenario will therefore be generated as usual. The mean value electricity price scenario, however, will be calculated as the average electricity price in each period over the scenarios that are being included in the respective VSS problem instance. Finally, to determine the mean value scenario for the corrective maintenance activities (the preventive maintenance activities are known), we have generated the expected number of failures on each wind farm, based on the failure rates presented in Section 7.1.2.

7.4 The Implementation of the Model

The FSMPOW model is implemented in the algebraic modelling language `Mosel` using the commercial software FIFO$^{\mathrm{TM}}$Xpress Optimization Suite by Dash Optimization. While testing the model we have used a computer cluster solution with a AMD Opteron 2431 CPU 2,4 GHz and 24 GB RAM. The model implementation can be found on the CD enclosed.

8 Computational Study

Our intention with the FSMPOW model has been to develop a model capable of solving real world problems in order to reduce the costs of executing O&M, and by this making offshore wind more competitive against other energy sources. The purpose with this computational study is to evaluate whether the FSMPOW model can be used as a strategic decision support tool on a real offshore wind farm project.

In Section 8.2 we will look at the technical aspects of the stochastic model. Here we will evaluate the limitations of the model in terms of problem size, and determine an appropriate penalty cost of not completing a maintenance activity. We continue with evaluating the stochastic model in terms of VSS and EVPI, in addition to evaluating how the solution to the stochastic model performs when exposed to more uncertainty in Section 8.3. Finally, in Section 8.4, we will demonstrate how the model can be used in economical analysis. Here we will analyse the economies of scale when utilising one fleet for more than one wind farm, look into how the variations in electricity price affect the optimal fleet size and mix, and round this section up with a study on the wave capacities of the vessels.

8.1 Aspects of the Solution

When reading this computational study it is important to keep in mind that the different solutions to the FSMPOW model highly depends upon the given input data, and the scenarios that have been generated. To compensate for this, we will run several problem instances where necessary.

Further, it is important to keep in mind that some of the data used in the scenario generation is based on second hand sources, which might lead to inaccurate cost pictures. However, our intention with this computational study is not to perform an extensive economical analysis of the logistics in offshore wind, but to determine how the FSMPOW model can be used as an economical support in decision making.

Throughout this computational study, the costs in addition to the *availability* of the wind farm(s) will be used to evaluate the solutions. We define availability as the percentage number of maintenance activities that are completed. An availability of 100 % indicates that all maintenance activities have been completed successfully.

8.2 Technical aspects to the FSMPOW model

According to Østgren (2012), there is a need for an optimization model that can determine the optimal fleet size and mix for a wind farm containing 150 to 300 wind turbines. In this section we will determine the limitation of the FSMPOW in terms of number of wind turbines and activities on one wind farm, and continue with determining an appropriate penalty cost if an activity is unfinished.

8.2.1 Limitations in Problem Size

In this section we will analyse the limitations of the FSMPOW stochastic model in terms of solution times and problem size. We will focus on problems including one wind farm, and the problem size will be tested in terms of number of wind turbines. Seven problem instances with a different number of wind turbines will be solved, all with input data corresponding to Section 7. The penalty cost has been fixed to zero if an activity cannot be executed because of weather conditions. If an activity can be executed, the penalty cost is set to the value of the cheapest vessel type that can execute the respective maintenance activity. All problem instances have 3 second stage nodes and in total 27 scenarios. Information about the different problem instances can be found in Table 7.

Problem instance	Number of turbines	Number of activities	Number of rows	Number of columns	Global entities
1	100	380	704876	833531	181316
2	150	584	755657	1010420	183773
3	200	755	805688	1179620	184220
4	250	956	858881	1362293	184883
5	300	1168	858881	1362293	184883
6	350	1338	911909	1558835	185174
7	400	1487	960440	1705523	185249

Table 7: *Problem instances used when testing the impact of problem size on solution time.*

We solve the problem instances applying a time limit of 12 hours and a target gap of 1 %. From Table 8 we can see that all problem instances except for number *7* are solved to the target gap of 1 %. However, there is not necessarily a correlation between problem size and the solution times. Although all the problem instances have the same scenarios in terms of vessel prices, weather and electricity prices, the number of maintenance activities and the placement of these will of course vary from instance to instance. Our experience is that the placement of activities can affect the solution times just as much as the number of activities. If we look at problem instance 2, the respective solution time is almost 4 times the solution time of problem instance 5 and only half the size in terms of the number of activities.

From Table 8, we can see that some of the problem instances reach 10 % and 1% gap at the same time. This is also illustrated in Figure 37 where we can see that the model keeps finding new solutions until the optimality gap is around 15 %. At this point the best bound is increased significantly, which reduces the optimality gap to 1 %. This is clear tendency for all problem instances, and is a result of the MIP structure of the FSMPOW.

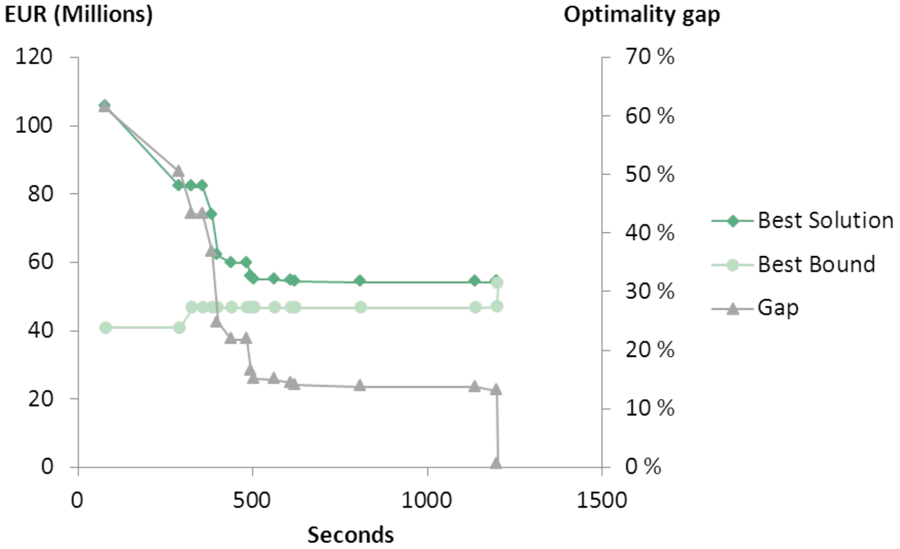


Figure 37: *Solution process of problem instance 1.*

It is worth mentioning that problem instance 7 was solved to optimality by performing a tuning session with Xpress Tuner, and implementing the parameters COVERCUTS = 0 and HEURDIVESTRATEGY = 5. This gave a gap of 0.59 % in 38497 seconds, and demonstrates how tuning can be a useful tool for the stochastic FSMPOW model.

The FSMPOW model is a strategic planning tool developed to support offshore wind farm operators when determining the fleet size and mix to be used for execution of maintenance operations a wind farm. The model is not intended for tactical and operational day-to-day planning, thus by being able to solve problem instances of up to 400 wind turbines with 27 scenarios, we can consequently conclude that the solution times must be seen as reasonable and within the time limits one should expect for a long-term planning tool.

Knowing that the world's largest offshore wind farm, Walney, consist of 102 wind turbines (Dong Energy, 2012), and that the FSMPOW model is able to solve a similar case, we can conclude that for now, the model can be used for solving real cases. Further analysis will complete and support this statement later in this computational study.

Problem instance	Time to 10 % gap	Time to 1 % gap	Optimality gap
1	1200	1201	0,46 %
2	11896	12591	0,89 %
3	518	1391	0,16 %
4	2385	3844	0,65 %
5	3175	3178	0,71 %
6	5058	5107	0,64 %
7	36252	43208	9,70 %

Table 8: *Problem instances and solution times. Optimality gap is set to 1 %, and target time to 12 hours or 42300 seconds.*

Although not presented here, the effect of increasing the number of scenarios on the solution time is more or less exponential (Table 13 in Appendix C). When it comes to increasing the number of wind farms, without increasing the total number of wind turbines, this does increase the solution times. However, one can expect the same increase in time to 15 % gap when going from 100 to 200 turbines on one wind farm, as when increasing the total number of wind turbines on two farms with 100 turbines (Table 14 in Appendix C).

8.2.2 Determining an Appropriate Penalty Cost

In the previous test, the penalty cost was set to zero if a maintenance activity could not be executed because of weather limitations. If an activity could be executed, the penalty cost was set to the value of the cheapest vessel type that could execute the respective maintenance activity. This resulted in a solution with 100 % availability of the wind farm, but high vessel costs compared to a deterministic solution, due to the high penalty costs. Even though the solution of a stochastic model gives 100 % availability, the optimal fleet will never give 100 % availability when exposed to real uncertainty. In this section we will determine an appropriate penalty cost, such that the availability of a wind farm is above 98 %.

As described in Section 7.2.8, the penalty cost, i.e. the cost of not executing a maintenance activity, is based on the lost generation cost for the subsequent 90 periods after the optimal execution point, which again is multiplied by a preventive maintenance constant, C^P for the preventive maintenance activities, and a corrective maintenance constant C^C for the corrective maintenance activities. The constants C^P and C^C are determined by the user. If the constants are too high, the model will try to execute all maintenance activities, which might result in an overestimation of the fleet size. If the constants are too low, however, it will not be worthwhile to execute the maintenance activities, which leads to an underestimation of the fleet size.

In order to analyse the constant C^P without the influence of vessels used on the corrective maintenance activities, the penalty cost for the corrective maintenance activities must be fixed to zero. The same applies when evaluating the corrective penalty constant. We therefore have to execute two separate tests.

Determining the Preventive Maintenance penalty Cost

To determine an appropriate value of C^P, we use a case with 100 wind turbines and three scenarios in which the corrective constant is fixed to zero. Considering that the solutions are highly dependent on the scenarios, we generate 4 problem instances, where the only differences are the third stage scenarios. We then run the same four problem instances with different values of C^P.

Figure 38 illustrate the average results over the four problem instances for different values of C^P. As we can see, the penalty cost reaches a minimum at $C^P = 0.02$. When $C^P < 0.02$ the availability is below the limit of 98 %. When $C^P = 0.02$, on the other hand, the availability is 99.2 %, which is above the limit. The preventive maintenance activity constant is therefore set to 0.02, as this is expected to give average availability above 98 %, at the same time as the penalty cost and the total fixed cost are kept at a minimum.

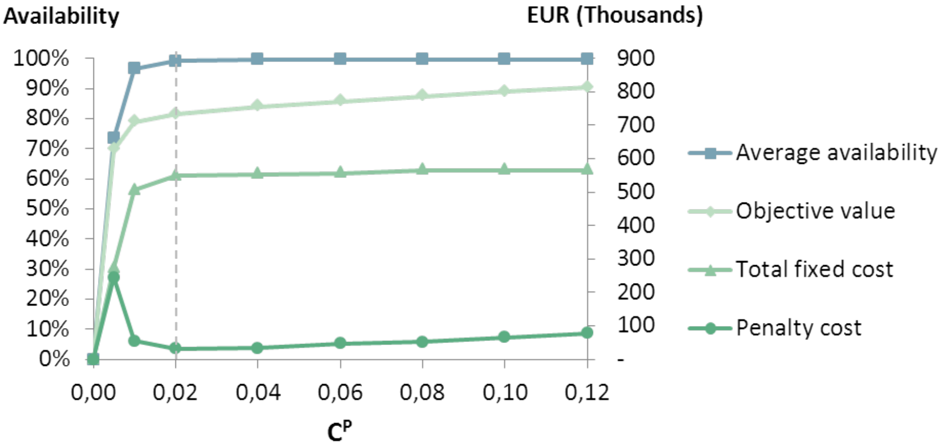


Figure 38: *Average availability, objective value, total fixed cost and penalty cost as a function of the preventive penalty cost constant,* C^P. *Results are the average values over the four problem instances.*

Determining the Corrective Maintenance penalty Cost

To analyse the corrective maintenance activity penalty cost constant, C^C, we again generate four problem instances, all with 100 wind turbines, 3 second stage nodes and 3 third stage nodes, but with different third stage scenarios. The constant C^P is fixed to zero. We then run the four problem instances for different values of C^C.

Figure 39 illustrates the average values over the four problem instances for different values of C^C. The objective value deserves some explanation. With values below 0.5, only CTVs are in the solution, and these are used to execute the activities requiring the transfer of maintenance personnel. When C^C is in the interval $[0.5, 0.7]$, some of the problem instances have a crane vessel in the solution, while the others take the penalty cost. When the constant reach 0.8, all problem instances have a crane vessel in the solution, and the average availability is above the limit of 98 %. Based on these results the constant C^C will be fixed to 0.8 for the rest of this computational study.

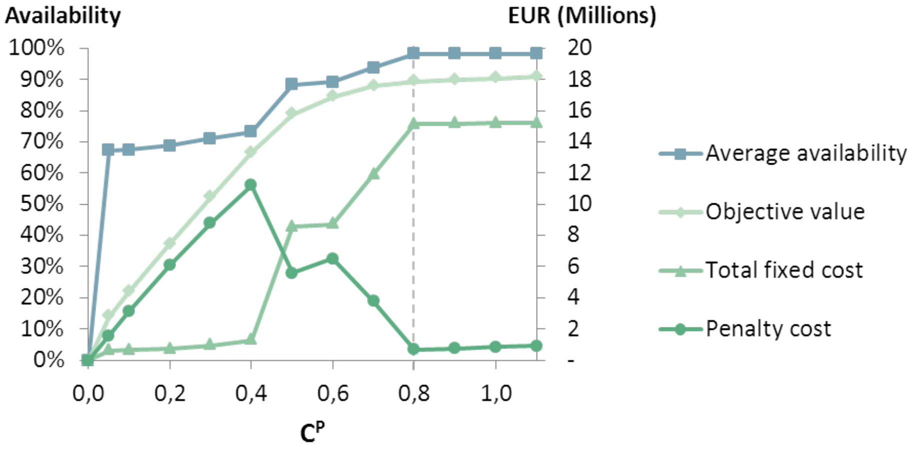


Figure 39: *Average availability, objective value, total fixed cost and penalty cost as a function of the corrective penalty cost constant,* C^C.

The results from this test are based on a given set of input data. Appropriate values of C^P and C^C will depend upon vessel prices, electricity prices, variable costs etc. It is therefore important to adjust these values according to the input data that is being used. Considering that we will mainly use the same input data throughout this computational study, the constants C^P and C^C will be fixed to 0.02 and 0.8, respectively.

8.3 Evaluating the Stochastic Model

In this section we will evaluate the stochastic model in terms of EVPI, VSS and further look at how the solution to the stochastic model performs when exposed to more uncertainty.

8.3.1 EVPI and VSS

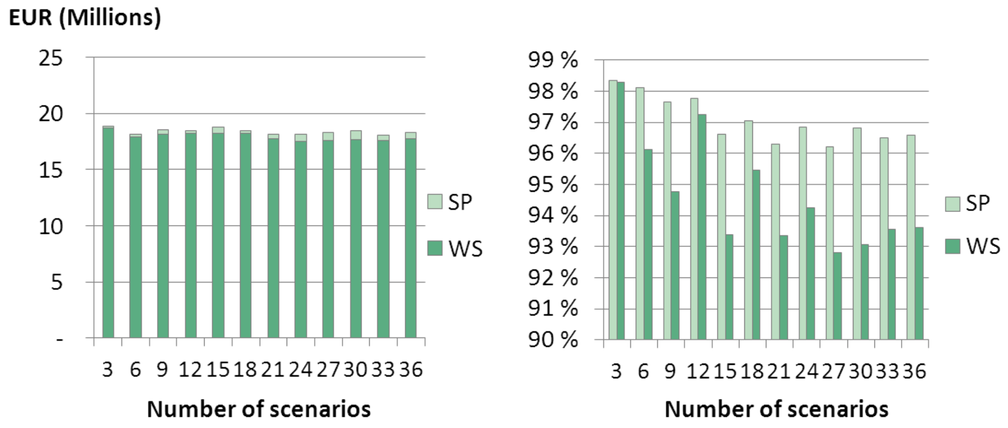
EVPI compares the solution to the wait and see problem with the solution to the stochastic problem. Attaining complete information about weather conditions, spot rates and turbine failures is not possible, making the EVPI a purely theoretical measurement for the FSMPOW. The VSS measures the expected value of using a stochastic model rather than a deterministic model.

We will evaluate the EVPI and VSS for 12 different cases, all with 3 second stage nodes, one wind farm and 100 wind turbines, but with an increasing number of scenarios. Considering possible variations between different problem instances for the same case, due to uncertainty, each case will be solved with 4 different problem instances. The procedure we use for calculating the EVPI and the VSS can be found in section 7.3.1 and 7.10, respectively. The stochastic problems as well as the EV 1 problems, the EV 2 problems and the WS problems are solved to an optimality gap of 1 %, while the EEV problems are solved to optimality. Table 9 give the average results for the different cases.

Case number	Number of scenarios	EVPI [EUR]	EVPI (%)	VSS [EUR]	VSS (%)
1	3	122 817	0.65 %	91 505	0.48 %
2	6	222 283	1.22 %	478 873	2.57 %
3	9	355 377	1.92 %	1 516 240	7.56 %
4	12	274 052	1.48 %	1 541 533	7.70 %
5	15	581 039	3.09 %	1 240 003	6.19 %
6	18	288 956	1.56 %	973 791	5.00 %
7	21	415 304	2.28 %	2 189 607	10.74 %
8	24	644 219	3.55 %	3 100 782	14.59 %
9	27	672 423	3.68 %	3 522 252	16.15 %
10	30	759 872	4.11 %	2 958 779	13.81 %
11	33	458 742	2.54 %	1 634 452	8.30 %
12	36	490 414	2.68 %	2 572 181	12.34 %

Table 9: *Average EVPI and VSS for the different cases.*

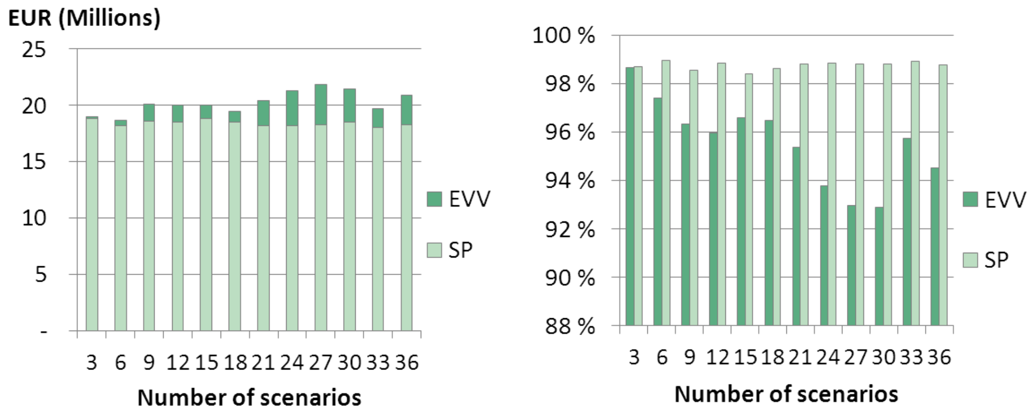
Both EVPI and VSS are positive in all cases, which coheres with property (7.9) and (7.10), respectively. Our results suggest an increasing EVPI with an increasing number of scenarios, which is as expected. However, the EVPI for the different cases is not particularly high compared to the SP value (Figure 40(a)). The main reason for the different values of WS and SP, is higher investments in the fleet when solving the stochastic problem. When solving the wait-and-see-problem, it is more profitable to reduce the availability, and to pay the penalty costs instead of investing in more vessels, or vessels with higher wave capacity. Consequently, the availabilities when solving the stochastic problems are considerably higher than those for the wait-and-see-problems, as illustrated in Figure 40(b).



(a) WS and SP for a different number of scenarios (b) Worst availability of WS problem and the stochastic problem

Figure 40: *Average results of the wait-and-see problems and the stochastic problems.*

The VSS is considerably higher than the EVPI. This indicates that the solution to the stochastic problem is fairly adequately hedged against either of the future outcomes. From Figure 41(a) we can see that there is an increasing VSS with an increasing number of scenarios. Due to a limited sample size of 4 problem instances we get an unexpectedly low VSS when we have 33 scenarios. However, the results show that there is a clear increasing tendency in VSS when the number of scenarios are increased, which means that there is indeed a value of using a stochastic formulation as opposed to a deterministic formulation. Figure 41(b) show that the average availability of the wind farm when the fleet size and mix is determined by solving the expected value problem is considerably low. The average availability of the stochastic problem, however, is above the target of 98 % in all cases. The low availability of the EEV problem leads to high penalty costs, which is the main reason for the high value of the stochastic problem.



(a) EEV and SP for a different number of scenarios (b) Average availability of the EEV problem and the stochastic problem

Figure 41: *Average results of the VSS test over the four problem instances for a different number of scenarios.*

When looking further into the different solutions of the EV1, EV2 and the stochastic problem for case number 10, 11 and 12, we get a better understanding of what the deterministic model is doing wrong. We conclude that there are two main reasons for the high VSS value. First, the deterministic model does in some cases not rent a crane vessel. Instead it rents one vessel of type 4 which is a supply vessel unable to perform corrective maintenance activities requiring a lift. The stochastic model, on the other hand, rents one multipurpose crane vessel at the first stage in all cases (vessel type 8).

Second, the deterministic model tends to rent vessel type 3 in almost all second stage nodes and months of the year. Vessel type 3 has a wave capacity of 1.5 meters. The stochastic model, on the other hand, tends to only rent vessel type 3 in the summer months of June and July, and rents vessel type 2 for the rest of the year, which has a wave capacity of 2 meters. Consequently, the stochastic vessel fleet can handle rougher weather conditions than the deterministic vessel fleet. In addition, the stochastic fleet is able to execute corrective maintenance activities requiring heavy lifts, while the deterministic model, in some cases, does not have this ability. Similar to both models however, is the rental of vessels with higher wave capacity in the low-price node at the second stage than in the medium and high-price nodes.

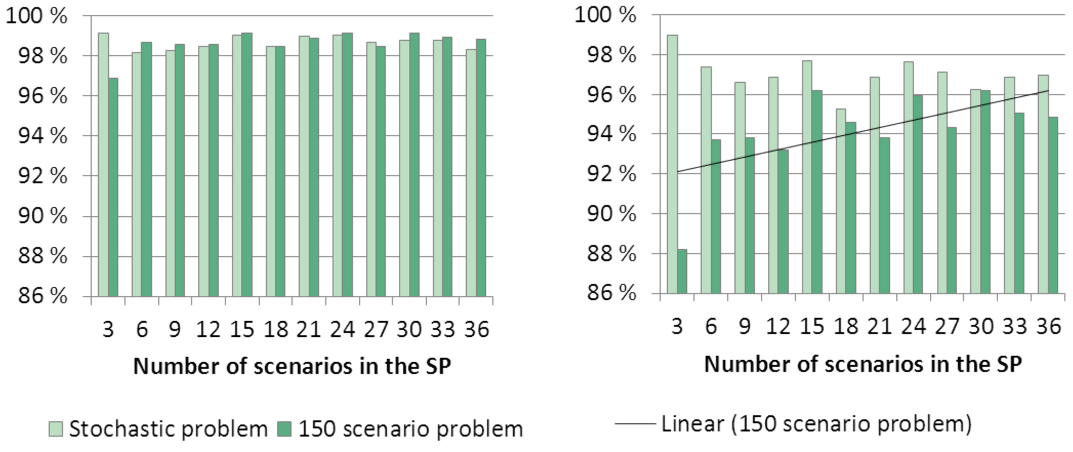
Based on the results from this test we can conclude that the value of using a stochastic model when solving the FSMPOW can be significant compared to using a deterministic model, especially in terms of availability of a wind farm. Furthermore, our willingness to pay for information about the future is relatively low. The question is, though, how will the stochastic solution perform if the solution is fixed and tested on an increasing number of third stage nodes? This will be discussed in the next section.

8.3.2 Testing the Number of Scenarios

In the previous section we concluded that there is a great value in using a stochastic model as opposed to a deterministic model when solving the FSMPOW. In this section we want to determine how the stochastic solution responds to a higher level of uncertainty, and if possible, the number of scenarios that is necessary in the stochastic model, in order to get robust solutions. We use the following procedure: first a problem instance, with a given number of scenarios, is solved with the stochastic model. Then, the first and second stage variables are locked, before solving a 150-scenario problem with the first and second stage variables from the stochastic solution.

The stochastic problem is run to an optimality gap of 1 % for all problem instances. The 150-scenario problem is run to optimality, due to its reduced complexity when fixing the first and second stage variables.

When evaluating the results from the stochastic model and the 150-scenario problems, we will look at three different aspects. First, the expected availability of the 150-scenario problem is interesting, while this can give an indication of the robustness of the stochastic problem solution when exposed to a high level of uncertainty. Second, the objective values indicate whether the estimated third stage costs from the stochastic problems are correct. Third, it is interesting to look at the actual fleet size and mix that is chosen in the different cases. If the



(a) Expected average availability (b) Expected worst availability

Figure 42: *Availability of the 150 scenario problems compared to the stochastic problem when a different number of scenarios have been tested.*

number of scenarios is high enough, there should be no changes in the fleet size and mix if further increasing the number of scenarios.

Figure 42(a) show the expected average availability of the solution of the stochastic problem and the 150-scenario problem for a different number of scenarios. The figure shows that the expected average availability of the stochastic fleet when exposed to more uncertainty is above the limit of 98 % when 6 or more scenarios are used in the stochastic problem. Furthermore, the results suggest that the expected average availabilities of the fixed fleets tend to be higher in the 150-scenario problem than in the original stochastic problem. This is because nodes with low expected availability give less deflection in the 150-scenario problem than in the original stochastic problem. Figure 42(b) show the expected worst availability for the stochastic problem and the 150 scenario problem. As the number of scenarios increase, the worst availability in the 150-scenario problem improve, which is as anticipated.

When an optimal number of scenarios are used in the stochastic problem, there should be little or no difference in the expected worst availability between the solution to the stochastic problem and the solution to the 150-scenario problem. From the figure we can see that the deviation in expected worst availability between the stochastic problem and the 150-scenario problem is decreasing with an increasing number of scenarios in the stochastic problem. For the problem instance with 30 scenarios the deviation is approximately 0. The question is: how large can we accept this deviation to be? Is an expected aggravation in worst availability of 2 % acceptable for a fleet determined by a stochastic model? This is not up to us to determine, but indeed an interesting question.

Figure 43 show the objective values of the stochastic problem for a different number of scenarios, and the respective objective value of the 150 scenario problem. Considering that the stochastic problem was not solved to optimality, we have included the best integer solution and the best bounds for the stochastic problem solutions. The results suggest that in most cases, the stochastic model gives a relatively good estimate of the expected third stage costs. In some cases, the stochastic model overestimates the expected third stage costs, and only in one case does the model underestimate the expected third stage costs. Although difficult to spot from the figure, there is a tendency of improved third stage cost estimate when increasing the number of scenarios. The question is whether a good estimate of the third stage costs is important, as long as the fleet size and mix is optimal, also for the 150 scenario problem.

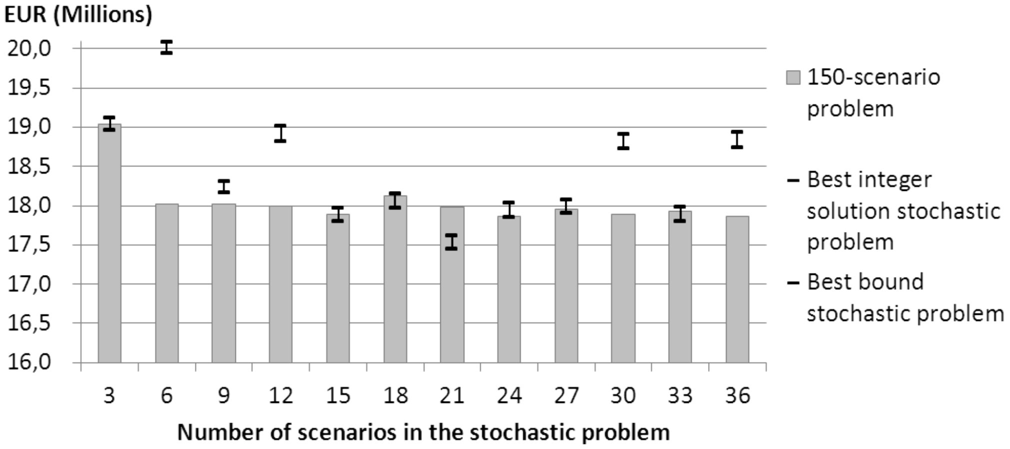
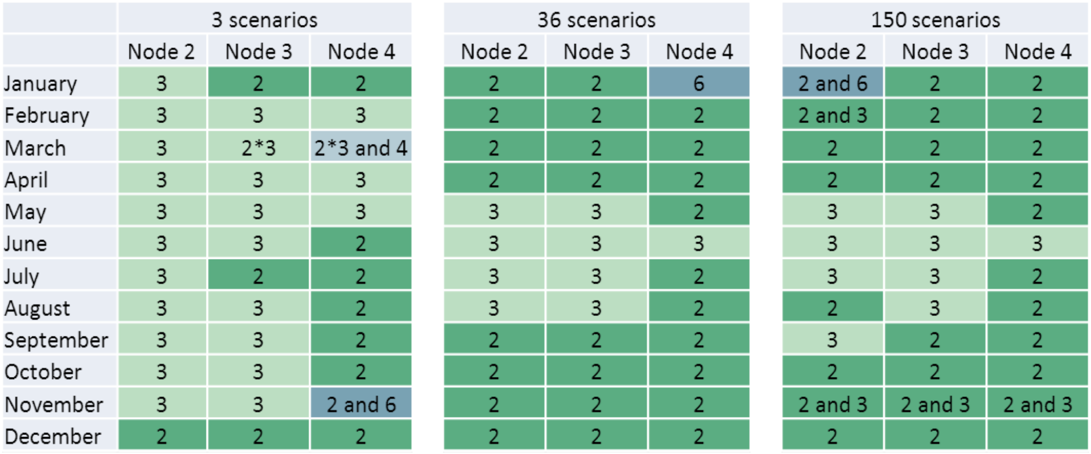


Figure 43: *Expected objective values of the stochastic problem for a different number of scenarios, and the respective expected objective values for the 150 scenario problem.*

Whether the fleet size and mix determined from a 36 scenario problem is also optimal for the 150-scenario problem, cannot be proven unless the 150 scenario problem is solved. We are not able to solve the 150-scenario problem to a 1 % optimality gap, however, we are able to solve the problem to an optimality gap of 9.46 %. This gives us an indication of the optimal fleet size and mix for this problem, and gives us the possibility of comparing the fleet size and mix in this solution to the optimal solutions from the problems with a smaller number of scenarios. Figure 44 illustrate the fleet available at each of the third stage nodes for the problems solved with 3, 36 and 150 scenarios, respectively. In addition to the vessels illustrated in the figure, a crane vessel is rented at the first stage in all cases. The colour codes have been added based on the vessel with the highest wave capacity available in each month in the second stage nodes.

By looking at the fleet size and mix determined for the different number of scenarios, we get an impression of how the fleet changes with an increasing number of scenarios. The model goes from selecting vessel type 3 in almost all lease terms and second stage nodes (except for node 4) for the 3-scenario problem, to selecting vessel type 3 only during the summer months, and vessel type 2 for the rest of the year in the 150-scenario problem. The solution with 36 scenarios is actually not that different from the 150-scenario solution, and definitely more similar to the 150-scenario solution than the 3-scenario solution. We must, however, keep in mind that the 150-scenario problem was not solved to optimality.

Based on the results from this test we can conclude that the solution from a stochastic model with more than 6 scenarios give an expected average availability above the target of 98 % when exposed to more uncertainty. However, in order to improve also the expected worst availability of the solution, the number of scenarios should be increased further. Our results indicate that the expected third



	3 scenarios			36 scenarios			150 scenarios		
	Node 2	Node 3	Node 4	Node 2	Node 3	Node 4	Node 2	Node 3	Node 4
January	3	2	2	2	2	6	2 and 6	2	2
February	3	3	3	2	2	2	2 and 3	2	2
March	3	2*3	2*3 and 4	2	2	2	2	2	2
April	3	3	3	2	2	2	2	2	2
May	3	3	3	3	3	2	3	3	2
June	3	3	2	3	3	3	3	3	3
July	3	2	2	3	3	2	3	3	2
August	3	3	2	3	3	2	2	3	2
September	3	3	2	2	2	2	3	2	2
October	3	3	2	2	2	2	2	2	2
November	3	3	2 and 6	2	2	2	2 and 3	2 and 3	2 and 3
December	2	2	2	2	2	2	2	2	2

(a) 3 scenarios (b) 36 scenarios (c) 150 scenarios

Figure 44: *Optimal vessel fleet size and mix for problems solved with a different number of scenarios. Note: the 150-scenario problem in b) was solved to an optimality gap of 9.46 %. Colour codes have been applied based on the available vessel type with the highest wave capacity in each month.*

stage costs when using the stochastic model are often correctly estimated, and in very few cases underestimated, which means that the model gives an offshore wind farm operator predictability in terms of the maintenance execution costs. When solving the 150-scenario problem we get a fleet size and mix that is similar to the solution of the 36-scenario problem, but not identical.

We therefore conclude that 36 scenarios is not necessarily optimal (nor is it not optimal, considering the 150-scenario problem was not solved to optimality), but 36 scenarios give a solution that can be considered as good enough, given our input data.

8.4 Economical Case Studies

In this section we have conducted several case studies to illustrate and motivate the applicability of the stochastic model. First we will evaluate the economies of scale when utilising one fleet for more than one wind farm. Thereafter we have look at how the vessel fleet changes with respect to differences in the electricity price. Further, we will assess the willingness to pay for additional wave capacity of a vessel, while this can reduce both the downtime and penalty cost of an offshore wind farm. Finally, we will determine the willingness to pay for an offshore station.

8.4.1 Economies of Scale

Reducing O&M costs in the offshore wind industry, such that offshore wind can be competitive against other fossil fuel energy sources has been our greatest motivation of developing the FSMPOW models. A possible way of reducing O&M costs is for several offshore wind farm operators to use a joint fleet for executing the maintenance operations on all their farms.

In this section we will demonstrate how the FSMPOW stochastic model can be used to analyse the savings in using a joint fleet on two wind farms, as opposed to having two separate fleets. Our case consists of 2 wind farms containing 100 wind turbines each, 3 second stage nodes and in total 15 scenarios. Considering that the solution depends highly on the scenarios, a total of 4 problem instances have been solved, all with different third stage scenarios.

The solution strategy is as follows: first the problem instance is solved for both wind farms, which gives the solution of the *joint fleet*. The same problem instance is then solved for each farm, separately. The costs for each farm are added, which gives the solution of the *separate fleets*. Table 10 summarize the main findings.

Solution of separate fleets		**Solution of joint fleet**		**Annual savings of joint fleet**
Total objective value [EUR]	Total fixed cost [EUR]	Objective value [EUR]	Fixed cost [EUR]	[EUR]
37 085 369	30 408 000	23 684 564	16 096 500	13 400 805
36 586 501	30 435 000	23 036 446	16 357 500	13 550 055
36 576 536	30 513 000	23 775 514	16 030 500	12 801 022
37 388 353	30 397 501	24 958 450	15 867 001	12 429 903

Table 10: *Results from the four problem instances when testing a joint fleet on two wind farms.*

The results suggest that approximately 50 % of the fixed costs can be cut if the two wind farms share one fleet. This is explained by the overcapacity of the fleets when solving the problem for each farm, separately. Each farm needs one crane vessel, but the joint fleet does not require two crane vessels. The same applies for the smaller vessels, where the joint solution in most cases suggest one smaller vessel for each lease term, while the solutions to each farm in total suggest two. Consequently, the solution to the joint fleet gives higher downtime costs and penalty costs than the separate fleet solution, but the savings in investment costs more than offsets the increase in downtime and penalty costs.

Given our input data, the annual savings in using a joint fleet on two wind farms with 100 turbines each, can reduce the total costs with approximately 35 %. This emphasizes the benefit of developing the FSMPOW model in such a way that it can handle more than one wind farm.

8.4.2 Changes in Electricity Prices

It has been argued, in this thesis, that the uncertainty and impact of the electricity price affects the determination of the optimal fleet size and mix. The intention with this analysis is to determine and support this assumption by analysing the investments in the fleet when changing the electricity prices.

To be able to execute this analysis, new sets of electricity prices must be calculated. Instead of calculating random scenarios, the *base case* electricity price is multiplied with a factor forcing the prices up and down. The values are set to 0.6, 1.0, 1.5 and 2.0. Considering the influence of the scenarios on the solutions, four data sets, with 100 wind turbines, 3 second stage nodes and 27 scenarios are generated for each of the electricity price factors.

Our results suggest an increase in expected average availability of the wind farm with an increasing electricity price, which is as expected. This is because the electricity price has a direct influence on the cost of not executing a maintenance operation, because a higher electricity price leads to a higher downtime cost, thus also a higher penalty cost. Figure 45 illustrates the relationship between availability and electricity price.

When increasing the number of executed operations, there is a need for more vessels to fulfil these tasks. In Figure 46 we see this tendency in terms of an increasing total fixed cost. However, our results suggest that a decrease in electricity price by 40 %, from 1 to 0.6, only reduce the average fixed cost by approximately 1 %. It is therefore natural to question whether the electricity price should be included in the stochastic model if the deviations in electricity prices are expected to be small. In this analysis the reader should be aware of how the input data affects the results from the model. The impact of the electricity prices on the fleet size

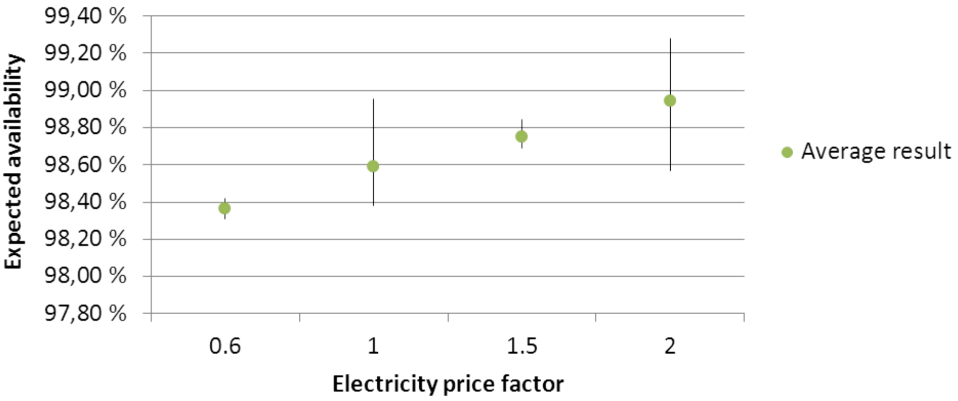


Figure 45: *Results showing how expected availability changes with respect to electricity prices. The vertical lines represents the variations in the four different problem instances run for each of the electricity price factors.*

and mix will depend upon the prices of the vessels, turbine size, and not at least the support regime. We have assumed a support regime that gives the operator EUR 100 per MWh of produced power, compared to an average electricity price at the base case of EUR 50 per MWh. This is not unusual for the offshore wind industry, however, and explains why wind farm operators in Germany, for instance, generate power although the electricity prices drop below zero (van Loon, 2010). Another set of input data, and another support regime, could therefore have given both higher and lower impacts on the fleet when changing the electricity price.

Given our input data, we can conclude that the electricity price does influence the fleet size and mix determination, and should therefore be included in the stochastic model.

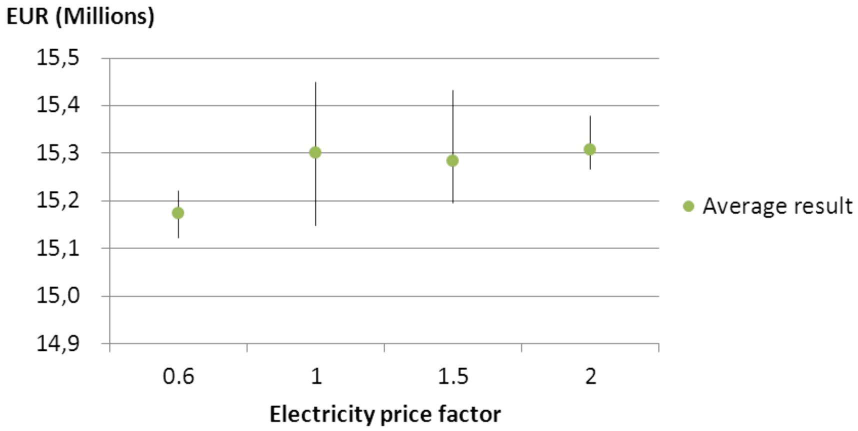


Figure 46: *Results showing how the investment in the vessel fleet, in terms of total fixed cost, changes with respect to electricity prices. The vertical lines represents the variations in the four different test run for each of the four factors.*

8.4.3 The Impact of Wave Capacity

One of the greatest challenges in the offshore wind industry is the harsh weather conditions, due the impact of wave heights on the accessibility of the vessels. Increasing the wave height capacity of a vessel can decrease the downtime cost because the fleet will be more flexible to execute maintenance operations in periods with low downtime costs (i.e. the soft time windows). In addition, an increased wave capacity can result in higher availability of the wind farm, which means lower penalty costs, because the fleet has more flexibility to execute the maintenance activities within the hard time windows. But how much should an operator be willing to pay for an additional wave capacity of 1 meter? In this section we will show how the model can be used to answer this question.

We will use 5 different cases in this test, all with 100 wind turbines, 3 second stage nodes and 15 scenarios, but with an increasing wave capacity for vessel type 2. Vessel type 2 is a CTV, with a wave capacity of 2 meters. This vessel type can execute all the preventive maintenance activities, in addition to some of the corrective maintenance activities. In order to analyse the wave capacity of vessel type 2 alone, we reduce the wave capacities for all other vessels that can execute the same activities as vessel type 2, to 2 meters. Considering variability in results due to uncertainty, every case will be solved with 6 problem instances, where the only difference is the corrective maintenance scenarios.

When increasing the vessel capacity of vessel type 2, this will only impact the downtime cost and penalty cost for the activities that vessel type 2 can execute, i.e. the downtime cost for the activities requiring a heavy lift, will not be affected by increasing the wave capacity of vessel type 2. In this analysis we will thus only present the downtime costs and penalty costs for the activities that can be executed by the vessel type in question. Table 11 show the most important findings.

Case number	**Wave capacity** [m]	**Average expected downtime cost** [EUR]	**Average expected penalty cost** [EUR]
1	2.0	686 411	52 415
2	2.5	498 890	2 941
3	3.0	388 447	5 568
4	3.5	341 659	2 930
5	4.0	310 684	4 529
6	4.5	300 998	5 012

Table 11: *Problem instances and average results when increasing the wave capacity of vessel type 2.*

The increase in wave capacity of vessel type 2 mainly affects the downtime costs and the penalty costs, which is as expected. Figure 47 illustrate how the downtime cost and penalty cost decrease when the wave capacity of the vessel type is increased. As we can see, the penalty cost is reduced to a minimum when the wave capacity is 2.5 meters. At a wave capacity of 2.5 meters our results suggest that the fleet has enough flexibility to execute the majority of the maintenance activities within the hard time windows, but not sufficient flexibility to execute the maintenance activities within the soft time windows. Thus, when increasing the wave capacity further, this only give impact on the downtime costs.

The downtime cost and penalty cost can be viewed as the alternative cost in terms of acquiring or developing vessel types with higher weather capacity. Our results suggest that an operator should be willing to pay approximately EUR 230 000 for increasing the wave capacity of vessel type 2 from 2 meters to 2.5 meters. How much you are willing to pay for an additional 0.5 meters of wave capacity, however, depends on the current capacity of your vessel, according to our results. This is as expected. When increasing the wave capacity from 4 to 4.5 meters, for instance, the total downtime and penalty costs only decrease with 3 %, which most likely does not offset the investment cost.

Comparing the results from this case with the vessel accessibility from Figure 10 in Section 2.3, which is based on the same weather data, points out the importance of an optimisation model when determining the optimal wave capacity of the vessels. One cannot determine the *availability* of a wind farm as a function of wave capacity by simply looking at the *accessibility* of the vessels. Such an approach is far too simplified, and does not take into account the flexibility time windows give to the fleet. Although not presented here, our results from this analysis suggest that even a wave capacity of 2 meters give expected preventive maintenance availability far above 90 %, although the same wave capacity only gives accessibility of approximately 60 %.

The results from this analysis suggest that the FSMPOW model is a great decision support tool when selecting an appropriate capacity of a fleet, while it takes into consideration the trade-off between downtime costs and increased weather capacity costs of the vessels.

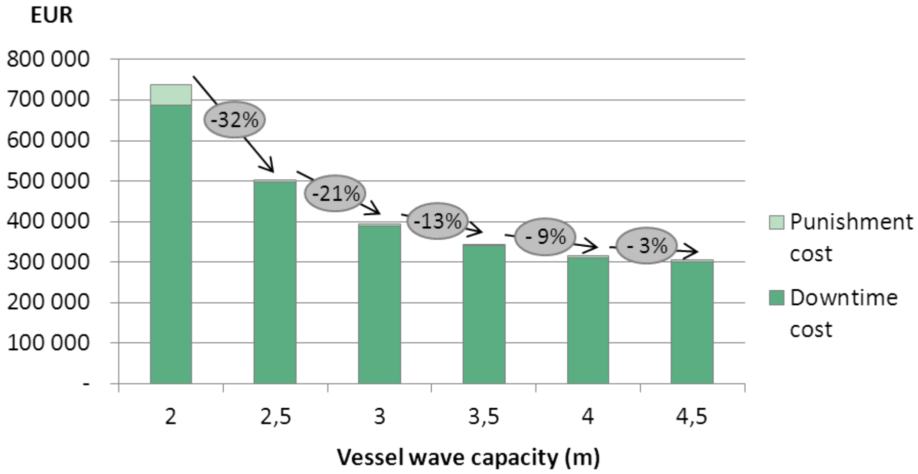


Figure 47: *Average expected downtime cost and penalty cost for different wave capacities of vessel type 2. Note: these results only include the costs for the activities that can be executed by vessel type 2.*

8.4.4 The Willingness to Pay for an Offshore Station Concept

In the previous tests, the offshore station is not selected, due to the high investment cost. In this section we demonstrate how the model can be used to analyse the willingness to pay for such a concept.

We analyse four cases, with 100, 200, 300 and 400 wind turbines respectively. Four problem instances are generated for each case, and tested when the offshore station (OS) is not included, and when the OS is included, but free of charge. Vessel type 2 and 6 are assumed to have the same specifications as vessel type 1 and 7 that belong to the offshore station, in order to get comparable results. The distance to shore is set to 200 km, which is approximately the location of Dogger Bank. Considering that introducing an offshore station will only affect the costs of the activities that vessel type 1 and 7 can execute, we will only present these costs. All tests are run to an optimality gap of 1 %.

From the results we can see that there are considerable savings in transportation time when using an offshore station (Figure 48). In addition to the direct influence on the transportation costs, the time saved in transport affects the solution in a number of different ways. First, it gives more flexibility to the fleet and enables the execution of more activities within the hard time windows. The result is higher availability, and lower penalty costs. Secondly, the reduction in transportation time reduces the reaction time of the vessels when a turbine breaks down, which leads to lower downtime costs. In addition, there will be a faster reaction time when waiting for a weather window, which can reduce the downtime costs even further.

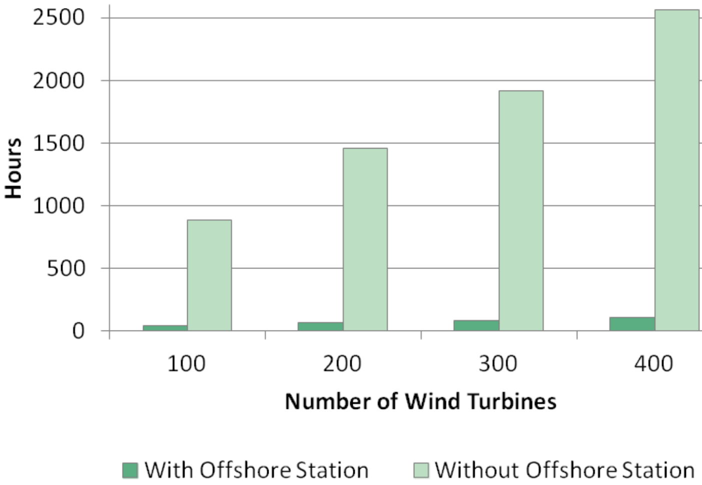


Figure 48: *Transportation time with and without the Offshore Station.*

Table 12 show the downtime cost, transportation cost and penalty cost for the solution with and without an offshore station. In addition to savings in transportation, downtime and penalty costs are smaller savings in variable costs.

The results show, not surprisingly, that all the mentioned costs increase with an increasing number of wind turbines. On average the sum of all the costs are 25 % lower when using an Offshore Station. The highest total savings is achieved for the case with 400 wind turbines (Figure 49), where the total savings are approximately EUR 1 000 000 per year or EUR 2500 per wind turbine per year. However it is not the numbers here that are interesting, but how the model can be used as a decision support tool when determining whether to invest in an Offshore Station or not, and alternatively how many wind turbines that are needed for such a concept to be profitable.

Number of Turbines	**Downtime Cost**		**Transportation Cost**		**Penalty Cost**	
	With OS [EUR]	Without OS [EUR]	With OS [EUR]	Without OS [EUR]	With OS [EUR]	Without OS [EUR]
100	567337	621689	3963	38370	8770	26702
200	1080344	1184932	6768	60887	23225	276411
300	1754439	1991950	8484	84617	77470	616327
400	2445920	2871822	6309	106349	116031	541779

Table 12: *Average transportation, downtime and penalty costs with or without the use of an Offshore Station (OS).*

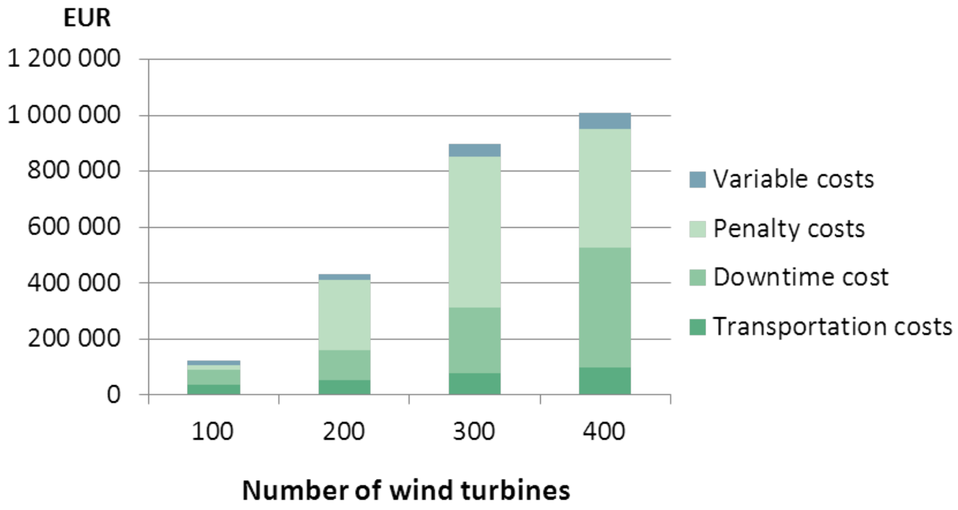


Figure 49: *Potential yearly savings when using the Offshore Station.*

9 Conclusion

One of the problems in the offshore wind industry today is the need for financial support through different support systems. Whether to invest in an offshore wind farm or not, will depend on whether a developer can operate profitably given a support scheme. Thus, the focus on possible savings to achieve a super-profit is a prioritised subject in the industry. Operations and maintenance is one of the areas where such savings are possible, especially through an optimal choice of fleet size and mix to be used on one or several offshore wind farms. In this thesis we have discussed this complex problem where the decisions to be made can make a great impact on the economical aspect of an offshore wind farm. Our literature study indicates that these decisions today are to a great extent based on excel sheets and Monte Carlo simulations. Given the complexity of the problem and the consequences of the decisions, the need for operations research should be quite clear.

In this thesis we have defined the fleet size and mix problem for maintenance operations on offshore wind farms, the FSMPOW. Further, we have used both a deterministic and stochastic approach to develop a decision support tool, which can assist the operator of an offshore wind farm when making strategic decisions regarding the FSMPOW. The stochastic model is the first, according to our literature study, decision support tool developed of its kind with an operations research approach.

The computational study gave promising results in terms of the problem sizes that the stochastic model was able to solve. Within reasonable solution times the model solves real world sized problems. When analysing the robustness of the solution to the stochastic model, we found that the model was able to generate solutions that performed very well when exposed to a high level of uncertainty. Our results suggested that a model with 36 scenarios gave relatively similar solutions in terms of fleet size and mix as a model with 150 scenarios. By this we concluded that the stochastic model is able to find good solutions with a solvable number of scenarios.

One of the main challenges of moving further away from shore, is the impact rough weather conditions have on the availability of a wind farm. The value of using the stochastic model on the FSMPOW was proven to be significant compared to using a deterministic model, due to ability of the stochastic model to hedge against uncertain weather conditions, among other things. Furthermore, the stochastic model proved to be of great support when determining the willingness to pay for additional wave capacity of a vessel type, in order to increase the accessibility and the availability of the wind farm.

When analysing the offshore station concept to a closer extent, we found that such a concept enables a more efficient vessel fleet in terms of reducing the downtime of a wind farm, and thereby also the costs. Further, when analysing the economies of scale, we found that relatively large savings can be achieved when combining a vessel fleet for two offshore wind farms.

As a final remark, the key findings from this study have not been the results themselves, if not the different ways in which the model can be used as a strategic decision support tool by offshore wind farm operations when facing ever-changing uncertain parameters and greater distances to shore.

10 Further Work

This thesis raises several questions that need to be further investigated. The stochastic FSMPOW model has been developed as a strategic planning tool, and does not cover the tactical day-to-day utilisation of the optimal fleet, including the issues of appropriate staffing. A suggestion for further work is the investigation of the operational deployment problem, given a predetermined vessel fleet, and the allocation of personnel needed in order to execute the maintenance activities. An operational planning model could take advantage of more accurate electricity prices and weather forecasts, to determine the optimal execution point of preventive and corrective maintenance activities, when power generation as a function of wind speed is taken into account.

Another interesting subject for further work is the tactical issue of spare parts logistics. We have not incorporated this aspect in our model, but the issue is highly relevant for an offshore wind farm operator. The development of a tactical logistic model, to be used together with the stochastic FSMPOW model, is therefore a natural continuation and supplement to our model.

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A Calculation of Input Parameters

This appendix contains a description of every parameter given in the complete dataset, and how they are calculated within the `FSMPOW_generator`. For a deeper study the reader is referred to the `C++code` enclosed with this project.

A.1 Scalar Data

nVessels: The number of vessel types, given in the input files. In the model formulation this is referred to as $|V|$.

nPeriods: The number of periods, given in the input files. In the model formulation this is referred to as $|P|$.

nActivity: The maximum number of activities on one wind farm, calculated after the maintenance schedule is generated. This parameter is only used in the calculations by the optimisation software.

nOffshore: The number of offshore station concepts, given in the input files. In the model formulation this is referred to as $|J|$.

nFarms: The number of wind farms, given in the input files. In the model formulation this is referred to as $|F|$.

nNodes: The number of nodes in the node tree. This is calculated given input of second and third stage nodes. This parameter is only used in the calculations by the optimisation software.

MAXMEN_ON_ACTIVITY: See explanation in Subsection 7.2.8. In the model formulation this is referred to as H_{vif}.

OFFSHORE_VESSELCAP: Is the upper bound on each vessel type a offshore station concept can use. In the model formulation this is referred to as Q_{jv}.

COST_DOWNTIME: See explanation in Subsection 7.2.8. In the model formulation this is referred to as C^{D}_{pifn}.

COST_OFFSHORE_STAT: Is the fixed cost of an offshore station. This is given as input to the application and no calculations are necessary. In the model formulation this is referred to C^{J}_{j}.

INVESTMENT_COST_OFFSHORE_STATION: Is the investment cost of an offshore station. This is given as input to the application and no calculations are necessary. In the model formulation this is referred to as C^{I}_{j}.

TIME_ACTIVITY: Is the required time to perform each of the generated activities. The required time is given in the input files for the given type of activity. In the model formulation this is referred to as T^{A}_{ifn}.

COST_FIXED: Is the fixed cost of renting or acquiring a vessel. These costs are given in the input files. In the model formulation this is referred to as C^F_{vln}.

INVESTMENT_COST: Is the investment cost of renting or acquiring a vessel. These costs are given in the input files. In the model formulation this is referred to as C^I_{vln}.

COST_VAR: Is the hourly operating cost for each vessel type when executing maintenance on a windmill. This is given in the input files. In the model formulation this is referred to as C^V_v.

TRANS_TIME_SEV: Is the time required in transport from/to the habour to/from a wind farm or the time required in transport between two wind farms. This parameter is calculated by taking the distance between the two locations and dividing it by the speed of the current vessel type. This calculation is done for all the vessel types able to stay offshore for more than one period. The parameter is referred to as T^T_{vfg} in the model formulation.

TRANS_TIME_ONE: Is the time required in transport from/to the habour to/from a wind farm. This calculation is done similar to TRANS_TIME_SEV, but only for vessel types able to stay offshore for less than one period. The parameter is referred to as T^T_{vf}.

MAXPERIODS_VESSEL: Is the maximum number of days each vessel type can stay offshore before returning to dock. This is given in the input files. In the model formulation this is referred to as P^M_v.

LENGTH_PERIOD: The number of hours available in each period. Specified in the input files. In the model formulation this is referred to as T^P.

EFFICIENCY_BUNDLE: See explanation in Subsection 7.2.8. In the model formulation this is referred to as B_{vifn}.

BUDGET_COST: Is the investment budget for vessels and offshore stations. This is given in the input files. In the model formulation this is referred to as C^B.

COST_PUNISH: See explanation in Subsection 7.2.8. In the model formulation this is referred to as C^P_{ifn}.

A.2 Sets

Here are all the pre-processed sets needed for the FSMPOW model summarised.

PROBABILITY: Is the probability of reaching a specific node. The probabilities are calculated as described in Subsection 7.2.1. In the model formulation this is referred to as P_n.

NODES_FIRST: Set including the first stage node. In the mode formulation this is referred to as $\mathcal{N}^1$.

NODES_SECOND: Set including the second stage nodes. The number of second stage nodes are given in the input files, whereas the application allocates them into a set readable for the optimisation software. In the model formulation this set is referred to as $\mathcal{N}^2$.

NODES_THIRD: Set including the third stage nodes. The number of third stage nodes are given in the input files, whereas the application allocates them into a set readable for the optimisation software. In the model formulation this set is referred to as $\mathcal{N}^3$

PRECEDING: is the stochastic parameter identifying the preceding node for all the third stage nodes. The application creates this set by reading in the number of third stage nodes and allocating them to the preceding second stage nodes. The set is referred to as $a(n)$ in the model formulation.

NODES_A: Set of ancestor nodes in the first and second stage for all the nodes in the third stage. The application create this set by reading in the number of third stage nodes and allocating them to the preceding first and second stage nodes. This set is referred to as $\mathcal{N}_n^A$.

NODES_N: Set of ancestor nodes in the first and second stage for all the node in the second stage. This set is created similar to NODES_A. The set is not referred in the model formulation. It is only used in the implementation of the model.

PERIODS_ACTIVITY: See Subsection 7.2.6. In the model formulation this is referred to as P_{ifn}^A.

VESSEL_ACTIVITY: See Subsection 7.2.7. In the model formulation this is referred to as V_{ifn}^A.

VESSEL_OFFSHORE: See Subsection 7.2.7. In the model formulation this is referred to as V_j^J.

PERIODS_LEASE: Set of periods in each lease term for all the vessel types. The application generates this set by dividing the total periods over the number of lease term for each vessel, and allocating them equally out on each lease term. If it is not possible to divide equally the remainder periods will be allocated to the last lease term. In the model formulation this set is referred to as P_{vl}^L.

PERIODS_LEASE2: Is the same set as PERIODS_LEASE minus the last period in each lease term. This set is not referred in the model formulation. It is only used on the implementation of the model.

LAST_PERIOD_LEASE: Set containing the last period in each lease term for all the vessel types. This set is generated by the application by fetching the last period from the set PERIODS_LEASE. In the model formulation this is referred to as $P_{vl}^{|L|}$

ACTIVITY_FARM: Set of maintenance activities belonging to a wind farm in one of the third stage nodes. This set is created by the application by analysing the created maintenance schedules. The generation of these schedules are described in Subsection 7.2.6. In the model formulation this is referred to as A_{fn}.

ACTIVITY_LARGE: Set of maintenance activities belonging to a wind farm in one of the third stage nodes, where the completion time for each activity is greater than the length of one period. This set is created by the application by analysing the created maintenance schedules. The generation of these schedules are described in Subsection 7.2.6. In the model formulation this is referred to as A^L_{fn}.

VESSEL_SEVERAL: Set of vessel types that can stay offshore for several periods. This is given in the input files. In the model formulation this is referred to as V^S.

VESSEL_ONE: Set of vessel types that can stay offshore for only one period. This is given in the input files. In the model formulation this is referred to as V^O.

VESSEL_FIRST: Set of vessel types that can be rented at the first stage. This is given in the input files. In the model formulation this is referred to as V^1.

VESSEL_SECOND: Set of vessel types that can be rented at the second stage. This is given in the input files. In the model formulation this is referred to as V^2.

ACTIVITY_IN_BUNDLE: See Subsection 7.2.6. In the model formulation this set is referred to as A^B_{ifn}.

ACTIVITY_BUNDLE: See Subsection 7.2.6. In the model formulation this set is referred to as A^B_{fn}.

LEASE_TERMS: Set of lease terms for all the vessel types. Depending on the length of the lease terms for each vessel type, given in the input files, the application calculates the number of lease terms for each vessel type.. The set is referred to L_v in the model formulation.

LEASE_TERMS2: Is the same set as LEASE_TERMS minus the last lease term for each vessel type. This set is not referred in the model formulation. It is only used in the implementation of the model.

PERIODS_OPERATION: See Subsection 7.2.7. In the model formulation this set is referred to as K^O_{vk}.

PERIODS_SAFETY: See Subsection 7.2.7. In the model formulation this set is referred to as K^S_{vk}.

B Plain version of the mathematical formulations

This appendix contains a plain version of both the deterministic and the stochastic mathematical formulations without explanations. It is added for readers preferring to read the whole model without interruptions. For the thoroughly prepared mathematical formulations see Section 5 and Section 6.

B.1 The deterministic model

$$\min Z = \sum_{v \in V} \sum_{l \in L_v} C^F_{vl} x_{vl} + \sum_{j \in J} C^J_j z_j \tag{B.1a}$$

$$+ \sum_{f \in F} \sum_{i \in A_f} \sum_{v \in V^A_{if}} \sum_{p \in P^A_{if}} C^V_v t_{vpif} \tag{B.1b}$$

$$+ \sum_{f \in F} \sum_{i \in A_f} \sum_{v \in V^A_{if}} \sum_{p \in P^A_{if}} C^D_{pif} t_{vpif} + \sum_{f \in F} \sum_{i \in A_f \setminus A^B_f} C^P_{if} d_{if} \tag{B.1c}$$

$$+ \sum_{v \in V^S} \sum_{p \in P} \sum_{(f,g) \in F \cup \{0\} | f \neq g} C^V_v (t^M_{vpfg} + t^E_{vpfg}) + \sum_{v \in V^O} \sum_{p \in P} \sum_{f \in F} T^T_{vf} C^V_v y_{vpf}. \tag{B.1d}$$

Subject to:

$$x_{vl} \leq Q_{jv} z_j, \qquad j \in J,\ v \in V^J_j,\ l \in L_v. \tag{B.2}$$

$$\sum_{v \in V} \sum_{l \in L_v} C^I_{vl} x_{vl} + \sum_{j \in J} C^I_j z_j \leq C^B \tag{B.3}$$

$$\sum_{v \in V^A_{if}} \sum_{p \in P^A_{if}} H_{vif} t_{vpif} + \sum_{\bar{i} \in A^B_{if}} \sum_{v \in V^{ACT}_{\bar{i}f}} \sum_{p \in P^{ACT}_{\bar{i}f}} B_{vif} t_{vp\bar{i}f} + d_{if} \geq T^A_{if},$$
$$f \in F,\ i \in A_f \setminus A^B_f. \tag{B.4}$$

$$\sum_{v \in V^A_{if}} t_{vpif} \leq T^P, \qquad f \in F,\ i \in A^L_f,\ p \in P^A_{if}. \tag{B.5}$$

$$\sum_{f \in F} y_{vpf} \leq x_{vl}, \qquad v \in V^O,\ l \in L_v,\ p \in P^L_{vl}. \tag{B.6}$$

$$\sum_{f \in F \cup \{0\}} y_{vpf} = x_{vl}, \qquad v \in V^S,\ l \in L_v,\ p \in P^L_{vl}, \tag{B.7}$$

$$x_{vl} - x_{v(l+1)} = x^L_{vp} - x^J_{vp}, \qquad v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl}, \tag{B.8}$$

$$y_{vp0} - y_{v(p+1)0} = \sum_{g \in F} (w_{vp0g} - w_{vpg0}) + x^L_{vp} - x^J_{vp},$$
$$v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl}, \quad \text{(B.9)}$$

$$y_{vpf} - y_{v(p+1)f} = \sum_{g \in F \cup \{0\} | f \neq g} (w_{vpfg} - w_{vpgf}),$$
$$v \in V^S,\ l \in L_v,\ p \in P^{|L|}_{vl},\ f \in F, \quad \text{(B.10)}$$

$$y_{vpf} - y_{v(p+1)f} = \sum_{g \in F \cup \{0\} | f \neq g} (w_{vpfg} - w_{vpgf}),$$
$$v \in V^S,\ l \in L_v,\ p \in P^L_{vl} \setminus P^{|L|}_{vl},\ f \in F \cup \{0\}. \quad \text{(B.11)}$$

$$\sum_{f \in F} y_{vpf} \leq \sum_{f \in F} \sum_{\bar{p} \in \{p..p+P^M_v-1\}} w_{v\bar{p}f0}, \qquad v \in V^S,\ p \in \{1, ..., |P| - P^M_v + 1\}, \quad \text{(B.12)}$$

$$y_{vpf} \leq \sum_{g \in F \cup \{0\} | f \neq g} \sum_{\bar{p} \in \{p..p+P^M_v-1\}} w_{v\bar{p}fg},$$
$$v \in V^S,\ p \in \{1, ..., |P| - P^M_v + 1\},\ f \in F. \quad \text{(B.13)}$$

$$T^T_{vfg} w_{vpfg} \leq t^E_{vpfg} + t^M_{v(p+1)fg},$$
$$v \in V^S,\ p \in \{1, ..., |P| - 1\},\ (f, g) \in F \cup \{0\} | f \neq g. \quad \text{(B.14)}$$

$$\sum_{g \in F \cup \{0\} | g \neq f} w_{vpfg} \leq y_{vpf}, \qquad v \in V^S,\ p \in P,\ f \in F \cup \{0\}, \quad \text{(B.15)}$$

$$\sum_{g \in F \cup \{0\} | g \neq f} w_{vpgf} \leq y_{v(p+1)f},$$
$$v \in V^S,\ p \in \{1, ..., |P| - 1\},\ f \in F \cup \{0\}. \quad \text{(B.16)}$$

$$\sum_{i \in A_f} t_{vpif} \leq T^P y_{vpf} - \sum_{g \in F \cup \{0\} | f \neq g} (t^M_{vpgf} + t^E_{vpfg}),$$
$$v \in V^S, p \in P,\ f \in F, \quad \text{(B.17)}$$

$$\sum_{i \in A_f} t_{vpif} \leq (T^P - T^T_{vf}) y_{vpf}, \qquad v \in V^O, p \in P, f \in F. \tag{B.18}$$

$$\left(K^O_{vk} - W_{pk}\right) \sum_{f \in F} \sum_{i \in A_f} t_{vpif} \geq 0, \qquad p \in P,\ v \in V,\ k \in K, \tag{B.19}$$

$$\left(K^S_{vk} - W_{pk}\right) \sum_{f \in F} y_{vpf} \geq 0, \qquad p \in P,\ v \in V,\ k \in K. \tag{B.20}$$

$$\begin{aligned}
x_{vl} &\geq 0 \textit{ and integer}, & v \in V,\ l \in L_v, && \text{(B.21)}\\
x^L_{vp} &\geq 0 \textit{ and integer}, & v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl},\ f \in \{0\}, && \text{(B.22)}\\
x^J_{vp} &\geq 0 \textit{ and integer}, & v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl},\ f \in \{0\}, && \text{(B.23)}\\
y_{vpf} &\geq 0 \textit{ and integer}, & f \in F,\ v \in V^O,\ p \in P, && \text{(B.24)}\\
y_{vpf} &\geq 0 \textit{ and integer}, & f \in F \cup \{0\},\ v \in V^S,\ p \in P, && \text{(B.25)}\\
w_{vpfg} &\geq 0 \textit{ and integer}, & v \in V,\ p \in P,\ (f,g) \in F \cup \{0\} \mid f \neq g, && \text{(B.26)}\\
t_{vpif} &\geq 0 & f \in F,\ i \in A_f,\ v \in V^A_{if},\ p \in P^A_{if}, && \text{(B.27)}\\
t^M_{vpfg} &\geq 0 & v \in V,\ p \in P,\ (f,g) \in F \cup \{0\} \mid f \neq g, && \text{(B.28)}\\
t^E_{vpfg} &\geq 0 & v \in V,\ p \in P,\ (f,g) \in F \cup \{0\} \mid f \neq g, && \text{(B.29)}\\
d_{if} &\geq 0 & f \in F,\ i \in A_f \setminus A^B_f, && \text{(B.30)}\\
z_j &\textit{ is binary} & j \in J. && \text{(B.31)}
\end{aligned}$$

B.2 The stochastic model

$$\min Z = \sum_{n \in \mathcal{N}^1} \sum_{v \in V^1} \sum_{l \in L_v} C^F_{vln} x_{vln} + \sum_{j \in J} C^J_j z_j + \sum_{n \in \mathcal{N}^2} P_n \left[\sum_{v \in V^2} \sum_{l \in L_v} C^F_{vln} x_{vln} \right] \tag{B.32a}$$

$$+ \sum_{n \in \mathcal{N}^3} P_n \left[\sum_{f \in F} \sum_{i \in A_{fn}} \sum_{v \in V^A_{ifn}} \sum_{p \in P^A_{ifn}} C^V_v t_{vpifn} \right. \tag{B.32b}$$

$$+ \sum_{f \in F} \sum_{i \in A_{fn}} \sum_{v \in V^A_{ifn}} \sum_{p \in P^A_{ifn}} C^D_{pifn} t_{vpifn} + \sum_{f \in F} \sum_{i \in A_{fn} \setminus A^B_{fn}} C^P_{ifn} d_{ifn} \tag{B.32c}$$

$$\left. + \sum_{v \in V^S} \sum_{p \in P} \sum_{(f,j) \in F \cup \{0\} | f \neq g} C^V_v (t^M_{vpfgn} + t^E_{vpfgn}) + \sum_{v \in V^O} \sum_{p \in P} \sum_{f \in F} T^V_{vf} C^V_v y_{vpfn} \right]. \tag{B.32d}$$

First stage constraints:

$$x_{vln} \leq Q_{jv} z_j, \qquad n \in \mathcal{N}^1,\ j \in J,\ v \in V^J_j,\ l \in L_v. \tag{B.33}$$

Second stage constraints:

$$\sum_{n' \in \mathcal{N}^1} \sum_{v \in V^1} \sum_{l \in L_v} C^I_{vln} x_{vln'} + \sum_{v \in V^2} \sum_{l \in L_v} C^I_{vln} x_{vln} + \sum_{j \in J} C^I_j z_j \leq C^B, \qquad n \in \mathcal{N}^2, \tag{B.34}$$

$$\sum_{n' \in \{1,n\}} (x_{vln'} - x_{v(l+1)n'}) = x^L_{vpn} - x^J_{vpn},$$
$$n \in \mathcal{N}^2,\ v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P^{|L|}_{vl}. \tag{B.35}$$

Third stage constraints:

$$\sum_{v \in V^A_{ifn}} \sum_{p \in P^A_{ifn}} H_{vifn} t_{vpifn} + \sum_{\bar{i} \in A^B_{ifn}} \sum_{v \in V^A_{\bar{i}fn}} \sum_{p \in P^A_{\bar{i}fn}} B_{vifn} t_{vp\bar{i}fn} + d_{ifn} \geq T^A_{ifn}$$
$$n \in \mathcal{N}^3,\ f \in F,\ i \in A_{fn} \setminus A^B_{fn}, \tag{B.36}$$

$$\sum_{v \in V^A_{ifn}} t_{vpifn} \leq T^P,$$
$$n \in \mathcal{N}^3,\ f \in F,\ i \in A^L_{fn},\ p \in P^A_{ifn}. \tag{B.37}$$

$$\sum_{f \in F} y_{vpfn} \leq \sum_{n' \in \mathcal{N}^A_n} x_{vln'}, \qquad n \in \mathcal{N}^3,\ v \in V^O,\ l \in L_v,\ p \in P^L_{vl}, \tag{B.38}$$

$$\sum_{f \in F \cup \{0\}} y_{vpfn} = \sum_{n' \in \mathcal{N}^A_n} x_{vln'}, \qquad n \in \mathcal{N}^3,\ v \in V^S,\ l \in L_v,\ p \in P^L_{vl}. \tag{B.39}$$

$$y_{vp0n} - y_{v(p+1)0n} = \sum_{g \in F} (w_{vp0gn} - w_{vpg0n}) + x^{L}_{vpa(n)} - x^{J}_{vpa(n)},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ l \in L_v \setminus \{|L_v|\},\ p \in P_{vl}^{|L|}, \quad \text{(B.40)}$$

$$y_{vpfn} - y_{v(p+1)fn} = \sum_{g \in F \cup \{0\} | f \neq g} (w_{vpfgn} - w_{vpgfn}),$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ l \in L_v,\ p \in P_{vl}^{|L|},\ f \in F, \quad \text{(B.41)}$$

$$y_{vpfn} - y_{v(p+1)fn} = \sum_{g \in F \cup \{0\} | f \neq g} (w_{vpfgn} - w_{vpgfn}),$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ l \in L_v,\ p \in P_{vl}^{L} \setminus P_{vl}^{|L|},\ f \in F \cup \{0\}. \quad \text{(B.42)}$$

$$\sum_{f \in F} y_{vpfn} \leq \sum_{f \in F} \sum_{\bar{p} \in (p, \ldots, p + P_v^M - 1)} w_{v\bar{p}f0n},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in \{1, \ldots, |P| - P_v^M + 1\} \quad \text{(B.43)}$$

$$y_{vpfn} \leq \sum_{g \in F \cup \{0\} | g \neq f} \sum_{\bar{p} \in (p, \ldots, p + P_v^M - 1)} w_{v\bar{p}fgn},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in \{1, \ldots, |P| - P_v^M + 1\},\ f \in F. \quad \text{(B.44)}$$

$$T^{V}_{vfg} w_{vpfgn} \leq t^{E}_{vpfgn} + t^{M}_{v(p+1)fgn},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in \{1, \ldots, |P| - 1\},\ (f, g) \in F \cup \{0\} | f \neq g. \quad \text{(B.45)}$$

$$\sum_{g \in F \cup \{0\} | g \neq f} w_{vpfgn} \leq y_{vpfn},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in P,\ f \in F \cup \{0\}. \quad \text{(B.46)}$$

$$\sum_{g \in F \cup \{0\} | g \neq f} w_{vpgfn} \leq y_{v(p+1)fn},$$
$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in \{1, \ldots, |P| - 1\},\ f \in F \cup \{0\}. \quad \text{(B.47)}$$

$$\sum_{i \in A_{fn}} t_{vpifn} \leq T^P y_{vpfn} - \sum_{g \in F \cup \{0\} | f \neq g} (t^M_{vpgfn} + t^E_{vpfgn}),$$

$$n \in \mathcal{N}^3,\ v \in V^S,\ p \in P,\ f \in F. \tag{B.48}$$

$$\sum_{i \in A_{fn}} t_{vpifn} \leq (T^P - T^T_{vf}) y_{vpfn},$$

$$n \in \mathcal{N}^3,\ v \in V^O, p \in P,\ f \in F. \tag{B.49}$$

$$\left(K^O_{vk} - W_{pkn}\right) \sum_{f \in F} \sum_{i \in A_{fn}} t_{vpifn} \geq 0, \qquad n \in \mathcal{N}^3,\ p \in P,\ v \in V,\ k \in K, \tag{B.50}$$

$$\left(K^S_{vk} - W_{pkn}\right) \sum_{f \in F} y_{vpfn} \geq 0, \qquad n \in \mathcal{N}^3,\ p \in P,\ v \in V,\ k \in K. \tag{B.51}$$

$$x_{vln} \geq 0 \textit{ and integer}, \qquad v \in V^1,\ l \in L_v,\ n \in \mathcal{N}^1, \tag{B.52}$$

$$x_{vln} \geq 0 \textit{ and integer}, \qquad v \in V^2,\ l \in L_v,\ n \in \mathcal{N}^2, \tag{B.53}$$

$$x^L_{vpn} \geq 0 \textit{ and integer}, \qquad v \in V^S,\ l \in L_v \setminus |L_v|,\ p \in P^{|L|}_{vl},\ n \in \mathcal{N}^2, \tag{B.54}$$

$$x^J_{vpn} \geq 0 \textit{ and integer}, \qquad v \in V^S,\ l \in L_v \setminus |L_v|,\ p \in P^{|L|}_{vl},\ n \in \mathcal{N}^2, \tag{B.55}$$

$$y_{vpfn} \geq 0 \textit{ and integer}, \qquad v \in V^O,\ p \in P,\ f \in F,\ n \in \mathcal{N}^3, \tag{B.56}$$

$$y_{vpfn} \geq 0 \textit{ and integer}, \qquad v \in V^S,\ p \in P,\ f \in F \cup \{0\},\ n \in \mathcal{N}^3, \tag{B.57}$$

$$w_{vpfgn} \geq 0 \textit{ and integer}, \qquad v \in V,\ p \in P,\ (f,g) \in F \cup \{0\} \mid f \neq g,\ n \in \mathcal{N}^3, \tag{B.58}$$

$$t_{vpifn} \geq 0 \qquad n \in \mathcal{N}^3,\ f \in F,\ i \in A_f,\ v \in V^A_{ifn},\ p \in P^A_{ifn}, \tag{B.59}$$

$$t^M_{vpfgn} \geq 0 \qquad v \in V,\ p \in P, (f,g) \in F \cup \{0\} \mid f \neq g,\ n \in \mathcal{N}^3, \tag{B.60}$$

$$t^E_{vpfgn} \geq 0 \qquad v \in V,\ p \in P, (f,g) \in F \cup \{0\} \mid f \neq g,\ n \in \mathcal{N}^3, \tag{B.61}$$

$$d_{ifn} \geq 0 \qquad n \in \mathcal{N}^3,\ f \in F,\ i \in A_{fn} \setminus A^B_{fn}, \tag{B.62}$$

$$z_j \textit{ is binary} \qquad j \in J. \tag{B.63}$$

C Additional results

This appendix shows additional results of testing the problem size of the stochastic model. Table 13 shows the results from increasing the number of scenarios for one wind farm with 100 turbines. The time limit has been fixed to 32 000 seconds for all problem instances. Table 14 shows the results of increasing the number of wind farms from one to two. All problem instances have been run with a time limit of 32 000 seconds.

Number of Scenarios	**Number of Activities**	**Solution Times [Seconds]**	**Time to 10% gap**	**Optimality gap**
30	432	32001	1102	2.65%
60	440	30859	4183	7.16%
90	461	32033	15483	5.16%
120	444	31848	17628	9.46%
150	446	19864	31843	9.59%

Table 13: *The table show how the solution times and optimality gap increases with an increasing number of scenarios.*

Number of Wind turbins (Farm 1)	**Number of Wind turbins (Farm 2)**	**Solution Times [Seconds]**	**Time to 15% gap**	**Optimality gap**
100	0	31220	72	0.83%
200	0	32002	1500	4.40%
300	0	32003	6544	5.75%
50	50	32001	1246	3.36%
100	100	32202	2808	9.03%
150	150	32069	7081	14.07%

Table 14: *The table shows the solution times for problem instances with one and two wind farms, with an increasing number of wind turbines.*