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Operation and Maintenance of Offshore Wind Farms

-A study for Systecon AB

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Preface

This master thesis is the final part of our master's degree at Lund University, Faculty of Engineering. The thesis was carried out during the spring of 2011 at Systecon AB in Malmö, in collaboration with the Division of Production Management at Lund University, Faculty of Engineering.

It has been a great pleasure to write a master thesis within the highly-topical field of O&M of offshore wind farms, where new information is published daily and people on all sides show big interest. Thanks to this we have been provided with knowledge from best practice and from people with state-of-the-art competence.

First we would like to thank Systecon AB and Pär Sandin for letting us write the thesis at Systecon's office in Malmö. We are very grateful for all valuable experiences they have provided us with, such as participation in courses and in the Nordic Wind Power Conference.

We would also like to thank all involved persons, whom shared their experiences and thoughts. Especially Hans Ahlmann who enthusiastically followed our work with valuable comments and guidance.

Finally we want to take the opportunity to thank our supervisor Olle Stenius at Lund University, Faculty of Engineering, who has shown big interest and supported us throughout the study.

Lund, June 2011

Ulrika Möller

Catarina Hersenius

Abstract

Title	Operation and Maintenance of offshore wind farms -A study for Systecon AB
Authors	Catarina Hersenius and Ulrika Möller
Supervisors	PhD student Olle Stenius, the Division of Production Management, Department of Industrial Management and Logistics at Lund University, Faculty of Engineering. Pär Sandin, vice president and head of sales, Systecon AB.
Objective	The main objective is to investigate in what way O&M of offshore wind farms can be modelled in Systecon's simulation tool, SIMLOX. The interim objective is to understand how maintenance of offshore wind farms is carried out and how this is related to costs and revenues.
Theory	Theory mainly covers the areas of O&M, offshore wind power, life cycle profit and maintenance strategies. Theory also presents existing simulation tools for O&M of offshore wind farms.
Conclusions	The authors stated that accessibility is the most significant feature for O&M of offshore wind farms. In brief, wind speed has impact on wind turbine reliability, choice of transportation mode and wind farm accessibility. Decreased reliability, vessels restricted from performing O&M tasks and low accessibility are factors that drive O&M costs. Furthermore wind enables energy production and thus wind is a value driver too. Embracing a life cycle profit approach enhances the support organisation to support business and focus on revenue. Energy yield increases if O&M tasks are performed at low wind speed; hence it's a maintenance performance indicator that captures the embracement of a life cycle profit approach. The authors summarized what operators demand from a simulation tool. The summary was presented in the apple framework that consists of key functionalities and key outputs. Above all the investigation of key functionalities and key outputs showed that SIMLOX has the capability to model wind as both a cost and value driver. This relationship is important to regard since it's characteristic for O&M of offshore wind farms. Further, this is something that hasn't been ceased in any of the competitors' simulation tools that have been investigated in this report. The investigated simulation tools merely capture wind speed in a restrictive manner.
Keywords	O&M, maintenance strategies, life cycle profit, offshore wind farms, simulation tools, weather conditions, and energy yield.

Abbreviations

ADT	Administrative Delay Time
BOM	Business Oriented Maintenance
CBM	Condition Based Maintenance
CMS	Condition Monitoring System
CM	Corrective Maintenance
EBIT	Earning Before interest and taxes
ECN	Energy research Centre of the Netherlands
FRT	Failure rate
ILS	Integrated Logistics Support
ISP	Independent Service Providers
KPI	Key Performance Indicator
LCC	Life Cycle Cost
LCP	Life Cycle Profit
LTH	Lunds Tekniska Högskola
MDT	Mean Down Time
MLDT	Mean Logistics Delay Time
MPI	Maintenance Performance Indicators
MPM	Maintenance Performance Measurements
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MWT	Mean Waiting Time
OM	Opportunistic Maintenance
OMCE	Operation and Maintenance Cost Estimator
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
PI	Performance Indicators
PM	Preventive Maintenance
RCM	Reliability Centered Maintenance
ROA	Return On Assets
SCADA	Supervisory Control and Data Acquisition
SMART	Specific, Measureable, Attainable, Realistic and Timely

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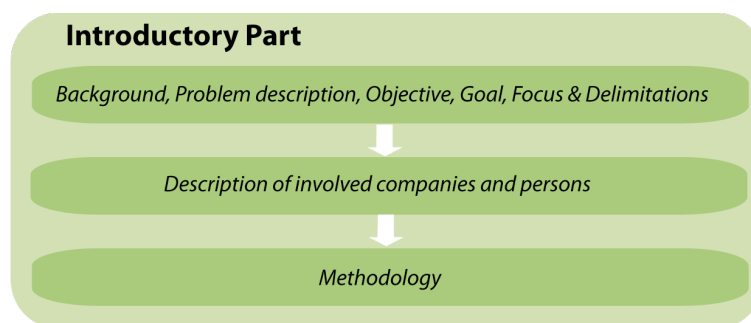
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INTRODUCTORY PART



Chapter 1: Introduction
Chapter 2: Methodology

1 Introduction

This chapter explains how the need of this report is linked to objective and goal. The chapter consists of background and problem description followed by objective, goal and target group. Finally an outline is presented that guides the reader throughout the composition of the report.

1.1 Background

There is an international on-going effort to lower the usage and dependence of fossil fuels¹. In order to support this the European Commission has come up with a proposition for countries within the EU that involves growth in renewable energy². One of the stated goals in the proposition is that 20% of energy consumption shall origin from renewable energy sources in 2020³.

Wind power is a source of renewable energy⁴. EU encourages offshore wind power because it has a lot of advantages compared to onshore wind power⁵. Research has shown that countries within EU ought to make large investments in offshore wind power to be able to meet the targets by 2020⁶.

Wind power is often considered as an expensive source of energy, but the technical development of wind farms has made wind power a more competitive source of energy⁷. Offshore wind power is in an initial phase where most wind farms that have been built are pilot projects⁸. Because of higher prices of combustibles and improved technology, wind power is gaining more economical competitiveness⁹. Operation and maintenance (O&M) costs of offshore wind farms make up to about 30% of the kWh price. Regarding onshore wind power the same cost is calculated to 10-15%. This indicates that there is a large potential in cost-savings by reducing the costs for O&M of offshore wind power.¹⁰

Systecon is a Swedish company that offers consultancy and software within the areas of system logistics, maintenance and cost-effectiveness. Systecon focuses on technical systems and the support organisation, among others within the area of energy.¹¹

Spare parts logistics is an important factor to consider in O&M of offshore wind farms. A master thesis within this field has previously been written for Vattenfall in collaboration with Systecon AB. Except from this, Systecon has little experience from working with wind power, but they are aware of the future need of cost-effective

¹ Svensk Vindenergi (2007) p.2

² Comission of the European Communities (2007) p.18

³ Ibid., p.3

⁴ *Svensk Vindkraft Förening*

⁵ Svensk Vindenergi (2007) p.11

⁶ Vasilakos and Green (2011) p.496

⁷ Svensk Vindenergi (2007) p.7

⁸ Esteban et al (2011) p.449

⁹ EWEA (2004) p.13

¹⁰ Braam et al (2003)

¹¹ *Systecon*

maintenance of offshore wind power. Hence, Systecon wants to investigate if they can become a player on this market.

1.2 Problem Description

The future demand of offshore wind power due to the EU Commission's proposition will put completely new requirements on maintenance of wind farms. Maintenance¹² of offshore wind farms is complex and consequently the related costs and profits are too. Knowledge about cost and value drivers is essential to be able to maintain offshore wind farms cost-effectively. Hence the following questions will firstly be answered:

- Which factors are the most characterising for maintenance of offshore wind farms?
- What maintenance approach is suitable for offshore wind farms?

Systecon is aware of the future demand of cost-effective maintenance of offshore wind farms. The company lacks knowledge and experience about this new and complex field of maintenance and thus how applicable their tools are within this field. The following questions will be answered in order to give Systecon further insight in this area.

- What do operators of offshore wind farms demand from simulation tools?
- How can O&M of offshore wind farms be modelled appropriately with Systecon's simulation tool?

1.3 Objective and Goal

The main objective is to investigate in what way O&M of offshore wind farms can be modelled in a simulation tool. The interim objective is to understand how maintenance of offshore wind farms is carried out and how this is related to costs and revenues.

The goal is to clarify how Systecon's simulation tool should be applied in order to be successful in the area of maintenance of offshore wind farms.

1.4 Focus and Delimitation

Focus is put on the main characteristics of O&M of offshore wind farms. The impact of weather condition on O&M will also be emphasized in the report. The line of argument will highlight the value of O&M throughout the report; O&M costs will not be regarded alone.

Since Lindqvist and Lundin previously have used Systecon's tools for spare parts optimization for wind turbines onshore, this aspect will be de-emphasized in this report. Another delimitation is that construction and planning phase, when investment decisions are made, won't be regarded. This delimitation will facilitate a more in depth investigation of the operational phase when the wind farm is running.

¹² Maintenance concepts in this report also include repair and service.

This report will not regard health and safety issues related to maintenance of offshore wind farms. It's a highly important aspect to consider, but very difficult to simulate.

1.5 Target Group

This report is primarily written for Systecon AB: Anna Gabrielsson, Magnus Andersson and the company tutor Pär Sandin. It will also be of interest for other companies within the fields of maintenance, system logistics and wind power: Vattenfall, E.ON and Dong Energy.

The report will also make a contribution to the academia. Therefore it's likewise written for the Division of Production Management, Department of Industrial Management and Logistics at Lund University, Faculty of Engineering (LTH) and Olle Stenius, tutor at LTH.

1.6 Disposition of the Report

Figure 1 illustrates how the report is structured and its different parts: Introductory Part, Part I, Part II, Part III and Closing Part. Part I, Part II and Part III will be performed in chronological order. Key findings from Part I constitute information to Part II and key findings from Part II constitute information to Part III. The research questions will be answered according to Figure 2.

Questions

<p>Part I Which factors are the most characterising for maintenance of offshore wind farms? What maintenance approach is suitable for offshore wind farms?</p> <p>Part II What do operators of offshore wind farms request from a simulation tools?</p> <p>Part III How can O&M of offshore wind farms be modelled appropriately with Systecon's simulation tool?</p>
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Figure 1: Questions to be answered in the report

Introductory part presents background, problem description, objective and goal, focus and delimitations, a description of involved companies and persons and methodology. This part includes information that frames all the other parts in the report. Part I introduces the reader to offshore wind farms and O&M. It also describes O&M of offshore wind farms in practice. Part II explains different maintenance strategies and experiences from O&M simulations. It will also enlighten how competitors simulate O&M of offshore wind farms. Part III describes the development of a simulation model in Systecon's simulation tool. Closing Part analysis key findings from Part I, II and III all together. The final conclusions are presented in this part together with discussion and recommendations.

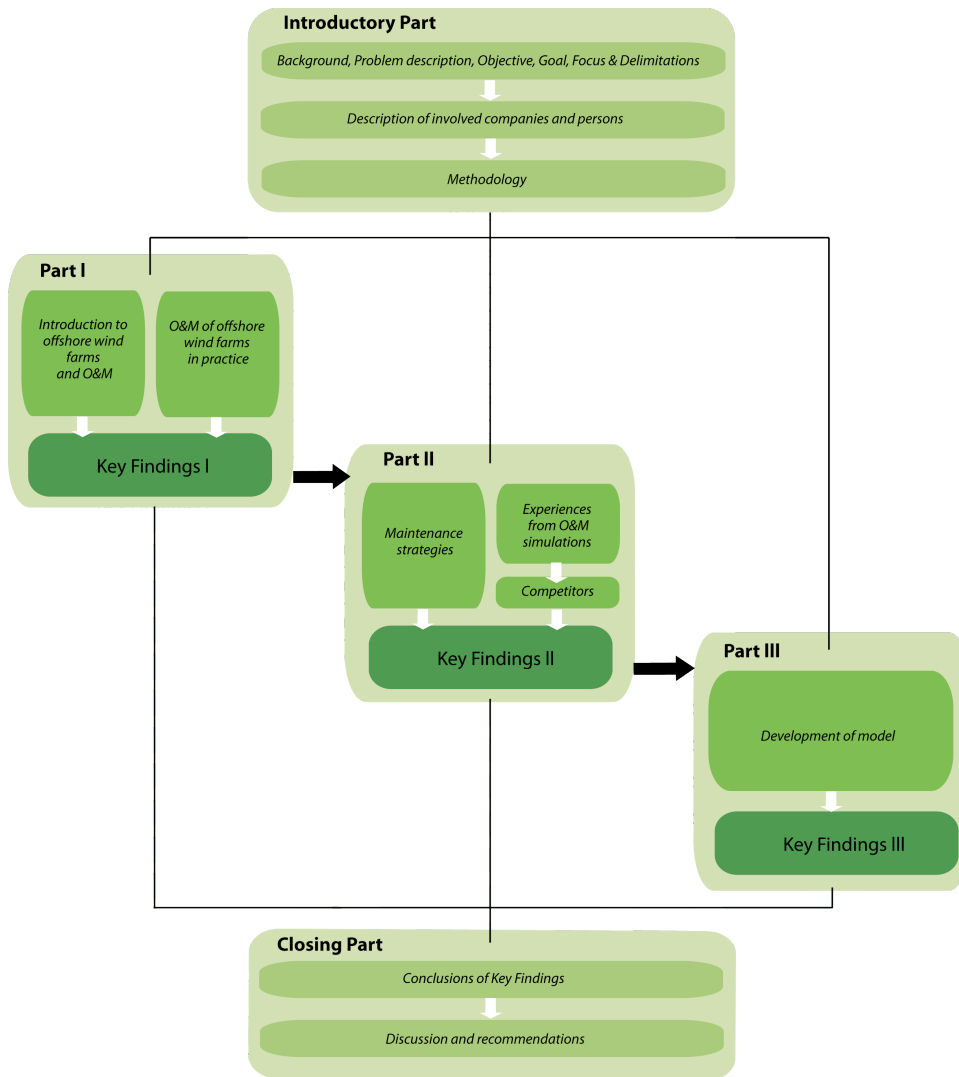


Figure 2: Disposition of the report

2 Systecon and Involved Experts

In this chapter Systecon AB is presented, but also an introduction to Systecon's toolbox. Experts that have been engaged in the composition of the report and provided the authors with important sources of information are also presented.

2.1 Systecon AB

Systecon was founded in the 1960's and has since then developed state of the art competence within the fields of system logistics and engineering and O&M. Systecon offers consultancy services, software solutions and education within these areas. Energy, rail and defence are the main fields where service, education and solutions are applied. Systecon has a broad customer basis all over the world. Some of the customers are: E.ON, Royal Air Force, SAAB Aircraft, SL and Volvo Cars.¹³

The head office is located in Stockholm; there is also one office in Malmö and one in Gothenburg. Systecon has a subsidiary company in the United Kingdom and an international network with representatives in among others Germany, Australia, China and Japan.¹⁴

2.1.1 Integrated Logistics Support Toolbox

During the 90's Systecon strengthened its role within the field of integrated logistics support (ILS). This resulted in assignments in industries such as energy production, information systems and public transport. Systecon's range of products includes OPUS10, SIMLOX and CATLOC. OPUS10 is an optimization tool for spare parts assortments and the support organisation. CATLOC is a flexible calculating tool for cost analysis and investment calculations. SIMLOX is a simulation tool that can be used as a complement to OPUS10 or independently. This report only considers SIMLOX, which is further described in Chapter 13.

¹³ Systecon AB's web site

¹⁴ Ibid.

2.2 Description of Involved Experts

Håkan Borgström from Dong Energy

Borgström has an MSc in Mechanical Engineering. He currently works at the department of asset management at Dong Energy in Copenhagen. Borgström's work involves asset management of offshore wind farms. He has previously been employed at Systecon and has experience from working with Systecon's simulation tool. Borgström has published papers, in collaboration with professor emeritus Ahlmann, regarding maintenance issues at the corporate management level.

Francois Besnard from Chalmers/Vattenfall

Besnard is a PhD student, at the department of energy and environment at Chalmers. He's positioned at Vattenfall where he spends half the time on his research and half the time as an employee at Vattenfall. Besnard's licentiate thesis regards optimal maintenance management for wind power systems. Further, he has experience from working with O&M tools from the energy research centre of the Netherlands.

Hans Ahlmann from LTH

Ahlmann is professor emeritus at LTH, at the department of production management. Ahlmann has published numerous scientific papers and books and he was the one to present the life cycle profit approach. Many of his scientific papers consider the area of life cycle cost and life cycle profit. He has many years of experience working within the field of quality management.

Jörgen Svensson from LTH

Svensson is assistant professor at LTH, at the department of industrial electrical engineering and automation. Svensson has 15 years of experience of offshore wind power from working at E.ON.

3 Methodology

This chapter begins with short theory presentations of different method and research approaches that can be applied in academic theses. This is followed by theory about how information can be gathered and what factors that determine the quality of the study. Further on the study's practical modes of procedure is described, which puts the study in context with previous descriptions. In conclusion the credibility of the study is discussed.

3.1 Different Types of Studies

The level of ambition depends on how much knowledge there is within the problem area. Based on this, different types of studies can be chosen: explorative, descriptive, explanative and normative studies.¹⁵

3.1.1 Explorative Studies

This approach is used to get fundamental knowledge about the problem. Relevant variables and concepts are identified as: what does not belong to the problem and what can be excluded. Field study is a common method for this approach and the study can be qualitative as well as quantitative.¹⁶

3.1.2 Descriptive Studies

This approach is used to determine the characteristics of the research problem. Generally a theoretical approach is used on this type of study but it also becomes more common to proceed from empirics by data collection and systematization.¹⁷

3.1.3 Explanative Studies

Explanative studies are commonly explaining studies. The explanative approach can be used for more in depth research.¹⁸ It brings up problem where the actual choice of explanation is of importance¹⁹.

3.1.4 Normative Studies

The outcomes of studies using this approach are norms or acting proposals. How should e.g. a production line be designed to be as effective as possible? And what makes a system effective? The task for the researcher is to show different standing points, action plans and the consequences that follow.²⁰

3.2 Research Approaches

Depending on the researcher's fundamental view of knowledge, the research has different goals. This can be explained by three different approaches: the analytical, the actors and the systems approach.²¹

¹⁵ Wallen (1996) p.46

¹⁶ Ibid.

¹⁷ Ibid.

¹⁸ Björklund and Paulsson (2003) p.58

¹⁹ Wallen (1996) p.46

²⁰ Ibid.

²¹ Björklund and Paulsson (2003) p.59

3.2.1 The Analytical Approach

The analytical approach tries to completely clarify the objective truth. The observer has no impact or influence on the research object; it's assumed that no subjectivity exists. Arbnor and Bjerke argue that the analytical approach is based on the assumption that *the whole is the sum of its parts*. This implicates that if the researcher get to know the different parts, they can be added together to get the whole.²²

A prerequisite for the analytical approach is that given techniques are used in order to validate or falsify different hypothesis. The approach explains causal relationships, how effects and causes are connected. The result of using the analytical approach is generalising in order to make up to continuous research.²³

3.2.2 The Systems Approach

An observer with the systems approach means that reality is objective, but in contradiction to the analytical approach, *the whole is not the same as the sum of its parts*²⁴. The systems approach focuses on the relation between the parts because of the synergies that can be derived from it. The approach aims to explain the parts with knowledge about features from the whole.²⁵

This approach is built on the statement that analogies can be drawn to other studies with comparable structure. That is, if things agree in some respects, they probably agree in others. The systems approach explains the correlation of relationships and their driving forces and barriers. This results in findings about synergy effects in both unique and general cases.²⁶

System characteristics

The systems approach includes many ideas and concepts that are fundamental to know in order to understand the approach. It's important to realize that a *system* consists of a number of components and the relation between these. A system can be open or closed, dependent on the system boundary, which is illustrated in Figure 3. An open system is studied with its relationship to the environment, whereas a closed system is studied without this respect.²⁷ The connections between the components in a system can be tangible or abstract²⁸.

²² Arbnor and Bjerke (1994) p.65

²³ Ibid., p.72

²⁴ Björklund and Paulsson (2003) p.59

²⁵ Arbnor and Bjerke (1994) p.67

²⁶ Ibid., p.72f.

²⁷ Ibid., p.127f.

²⁸ Ibid., p.133

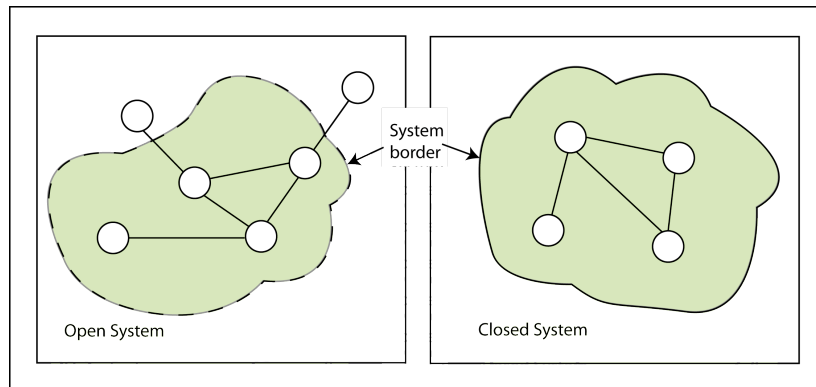


Figure 3: Illustration of an open and a closed system²⁹

Study orientation

There are two different study orientations that are possible to use within the systems approach: goal- means orientation or search- learn orientation. The goal- means orientation normally imply a more structured orientation where the researcher can plan the study in advance. To solve the problem, the researcher look for mean to achieve the system goal.³⁰ The common work procedure with a goal- means orientation is illustrated in Figure 4. It shows a problem from the real world that is identified by the researcher through analysis of the system. Thereafter, the researcher maps and finds the relationships in the real system and completes the problem by implementing the solution.³¹

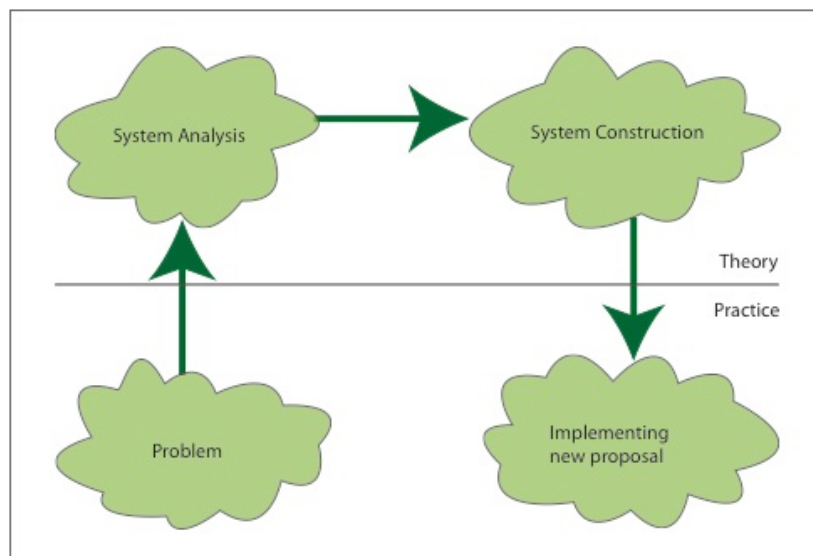


Figure 4: A general plan for a study with goal- means orientation³²

²⁹ Modified from Arbnor and Bjerke (1994) p.128

³⁰ Modified from Ibid., p.320f.

³¹ Modified from Ibid., p.321

³² Modified from Ibid., p.302

The search- learn orientation is not focused on a precise goal for the system. It's a more process based than structured way of gradually give rise to a conceptualisation of the problem. Thus, the researcher cannot plan the study completely in advance.³³

3.2.3 The Actors Approach

The actors approach is based on the assumption that reality is a social construction that influences and is influenced by its observer. Therefore, the observer's previous experiences and acting have an impact on the description of reality.³⁴ The actors approach is supported by the notion that *the whole is understood by the characteristics of its parts*. Thus, if the researcher knows significant features of the parts, the whole can be understood.³⁵

Use of the actors approach requires guidelines for interpretive practices and general assumptions about the function about the human consciousness. The approach tries to explain relations among the interpretations of actors. This explanation results in models or process models that describe different situations.³⁶

3.2.4 Research Approaches in Logistics and Maintenance

Gammelgaard discusses how the different research approaches can be applied in the context of studying the field of logistics. The analytical approach strives to find more common, time and value free explanations. The systems approach suggests that logistic relationships are too complicated and complex, so cause-effect relations are difficult to find. Therefore the systems approach tries to explain logistic systems with tangible maps and models. The actors approach proves that different terms within the field of logistics must be understood and used in different ways, dependent on the context.³⁷

The research approaches used within the field of logistics research are the analytical and the systems approach. The actors approach in logistics research has not been found, according to Gammelgaard.³⁸

Bouwer Utne argues that to make the right decisions about maintenance strategies for complex systems that consist of contradictive constraints and requirements a systems approach is to prefer. She refers to offshore wind farms as complex systems with these constraints.³⁹

3.3 Method Approaches

The choice of research approach concerns the relation between theory and empirics. Typically two method approaches are mentioned, the inductive and the hypothetical-deductive method.

³³ Modified from Arbnor and Bjerke (1994) p.325f.

³⁴ Björklund and Paulsson (2003) p.59

³⁵ Modified from Arbnor and Bjerke (1994) p.67

³⁶ Ibid., p.74ff.

³⁷ Gammelgaard (2004) p.488

³⁸ Ibid.

³⁹ Bouwer Utne (2010) p.368

3.3.1 Induction

The research starts off from data collection where patterns are sought and based on this, general and theoretical conclusions can be drawn. The data gathering shall be performed unbiased. Explorative studies often have to be inductive. In induction, an area can be studied without having any knowledge about existing theory. Instead the theory originates from the empirics that are collected, which is illustrated in Figure 5.⁴⁰

3.3.2 Hypothetical Deduction

In this method the theory is more important and independent than in induction. The theory makes the base and from this, predictions of the empirics are performed.⁴¹ The hypothesis is a proposed explanation that is beyond present knowledge. The hypothesis is later tested empirically through verification of the gathered data. Figure xxx shows how the theory is linked to empirics through verification.⁴²

3.3.3 Abduction

Abduction can be compared to induction but it requires more experience regarding the questions that are concerned i.e. experience from similar cases. One proceeds from possible relations or correlations and conclusions are drawn by elimination of factors. To support the conclusions, tests are performed. Abduction is a combination between deduction and induction, which involves movements between theory and practice.⁴³

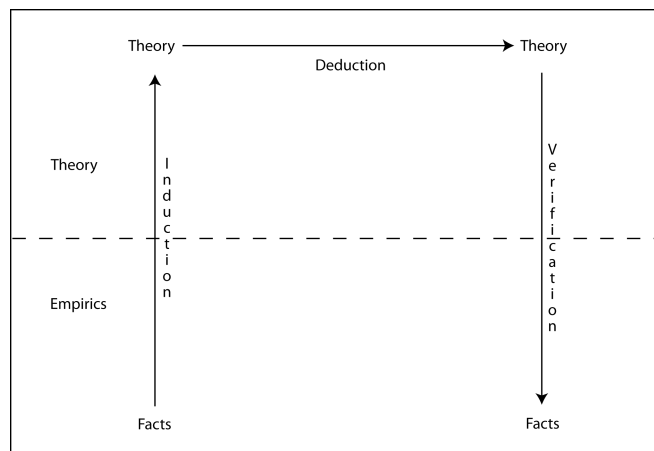


Figure 5: Illustration of inductive and deductive approach⁴⁴

3.4 Quantitative and Qualitative Approach

A qualitative study is mainly used when the researcher tries to get a more in-depth understanding. If the researcher wishes to generalize results, a quantitative study is to prefer. Information that can be measured or valued in numbers is generally used in

⁴⁰ Björklund and Paulsson (2003) p.62

⁴¹ Ibid.

⁴² Wallen (1996) p.48

⁴³ Ibid.

⁴⁴ Modified from Arbnor and Bjerke (1994) p.63

quantitative studies. Surveys and mathematical model are methods that are applicable in a quantitative study. Observations and interviews are methods more suitable for a qualitative study.⁴⁵ Table 1 shows distinctive aspects between quantitative and qualitative studies.

Table 1: Distinctive aspects between quantitative and qualitative studies summarized from Denscombe⁴⁶

	Quantitative	Qualitative
The analysing unit	Numbers	Words and pictures
Focus of the study	Specific	Holistic
Researcher impact	Objective	Subjectivity is difficult to avoid
Scope of project	Large-scale project	Small- scale projects

Denscombe highlights that quantitative and qualitative studies are not mutually exclusive⁴⁷. He also argues that it's the objective and how the information is analysed, not the practical modes of data collection, that decide if the study is qualitative or quantitative. The aim of a quantitative study is to generate numerical data. The observed data is converted to quantifiable information. On the other hand, qualitative studies aim to convert the observed data to information in written words, not numerically.

3.5 Primary and Secondary Data

There are two kinds of data to gather, secondary and primary data. Primary data is collected for the specific purpose of the study. Interviews and experiments are often sources to primary data.⁴⁸ Secondary data is collected by someone other than the user. Since secondary data is not gathered in the specific purpose of the study and the methods are unknown, it's important to question the information and the usage of the material.⁴⁹ Literature such as academic publications is an example of secondary data⁵⁰.

3.6 Research Methods

There are several methods to use in order to gather information. Different methods are typically connected to classificatory benefits and drawbacks.

3.6.1 Interview

An interview is a method that includes questioning. The questioning can be based on a phone-interview, via mail or personally at a meeting. An interview can be shaped

⁴⁵ Björklund and Paulsson (2003) p.63

⁴⁶ Modified from Denscombe (2009) p.320ff.

⁴⁷ Denscombe (2009) p.319

⁴⁸ Arbnor and Bjerke (1994) p.241

⁴⁹ Björklund and Paulsson (2003) p.70

⁵⁰ Höst et al (2006) p.98

differently depending on the choice and the answering respondents.⁵¹ An interview can be structured, semi- structured or unstructured. A structured interview contains an in advance fixed questionnaire. This kind of interview results in a more standardised method, that is easy to repeat and makes the analysis easier. An unstructured interview has no fixed questionnaire. A semi-structured interview has a questionnaire, but it's not strictly followed. Therefore, a semi- structured interviewer needs to be flexible.⁵² An interview is followed by the advantage that it's a good opportunity for the researcher to gain primary data. It's also the most flexible method for gathering data. The answering frequency is often high, due to the predetermined time for the interview, which increase the validity. A disadvantage is that it's a very time consuming method, especially the analysis of the collected data. This can be prevented by more standardized interviews. Another shortcoming is that the reliability of an interview is low.⁵³

3.6.2 Observation

There are many ways to perform an observation, the observer can participate in the observation or just observe it. Observation is always very time consuming. An advantage is that it's a method to gain more objective information.⁵⁴

3.6.3 Literature Study

Literature study is information in written text in books, papers and articles. This kind of information is seldom written with the same purpose as the researchers and is therefore commonly secondary data. It's consequently of great importance to be critical towards literature in order to increase the quality of the study.⁵⁵ Advantages with literature study are that they are often easy to access and contain a lot of information to low costs. Hence, it's a cost- effective method. The credibility of the literature used in the study is often difficult to confirm, which is the main downside with this method.⁵⁶

3.6.4 Conference and Lecture

Information can also be gathered at conferences and lectures. Information shared at these kinds of events varies a lot, dependent on participants and aim of the event. Common is that information is secondary data. Therefore gathered information must be reviewed and one must consider to whom the information is primary aimed at.⁵⁷ The main advantage is that little effort is needed in order to gather a lot of information⁵⁸.

3.6.5 Survey

Surveys are standardized questionnaires with given answering alternatives. Choice of survey target group how it's mediated depends on which questions the survey consists

⁵¹ Björklund and Paulsson (2003) p.68

⁵² Denscombe (2009) p.234

⁵³ Björklund and Paulsson (2003) p.70

⁵⁴ Ibid.

⁵⁵ Ibid., p.67

⁵⁶ Denscombe (2009) p.316

⁵⁷ Björklund, and Paulsson (2003) p.67

⁵⁸ Ibid., p.70

of.⁵⁹ Surveys enhance gathering of primary data. Disadvantageous is that low answer frequency and misunderstandings, due to badly developed surveys, decrease data reliability.⁶⁰

3.6.6 Experiment

Experiments are based on the use of a factious reality with given variables. In an experiment, variables can be varied and examined in a controlled manner. It's important to describe how the experiment is performed and which variables that are measured. Experiments are usually very time- and resource consuming and reality is difficult to reflect since it's often very complex.⁶¹ Advantageous is the possibility to perform experiments anew, which make it possible to establish reliability⁶². According to Lekvall and Wahlbin, experiments can be divided in laboratory experiments, field experiments and simulations⁶³.

3.7 Quality of the Study

Reliability, validity and objectivity are three different means that measure a report's credibility⁶⁴.

3.7.1 Reliability

Reliability explains to what degree surveying instruments can be trusted upon. This implicates to what extent an identical survey will generate the same result.⁶⁵ A prerequisite that research findings explain real situations is that the observed facts are reliable⁶⁶.

3.7.2 Validity

Validity is to what extent one measures what one is supposed to measure⁶⁷. It's important to differ between validity and reliability. Andersen highlights that research findings can be reliable, but reliability does not imply that the findings are valid.⁶⁸

Validity and reliability can be explained with a dartboard. Figure 6 consists of three different dartboards that illustrate different levels of validity and reliability. The dartboard on the left hand demonstrates both low validity and reliability. The dartboard in the middle exemplifies high reliability, but low validity and explains the fact that reliability does not imply validity. Finally, the dartboard on the right hand illustrates both high validity and reliability.⁶⁹

⁵⁹ Ibid., p.68

⁶⁰ Ibid., p.70

⁶¹ Björklund, and Paulsson (2003) p.69ff.

⁶² Ibid., p.71

⁶³ Lekvall and Wahlbin (1993) p.150

⁶⁴ Björklund and Paulsson (2003) p.59

⁶⁵ Ibid.

⁶⁶ Andersen (1994) p.91

⁶⁷ Björklund and Paulsson (2003) p.59

⁶⁸ Andersen (1994) p.92

⁶⁹ Björklund and Paulsson (2003) p.60

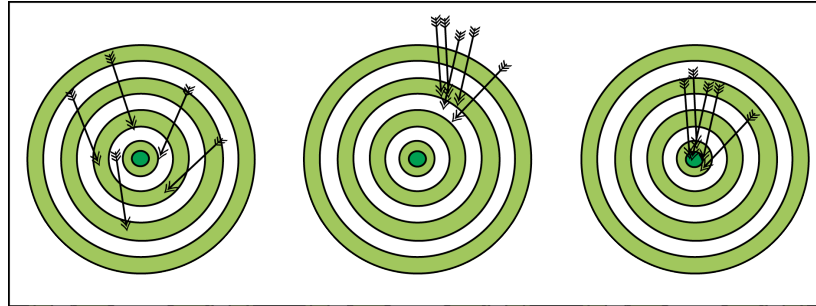


Figure 6: Illustration of validity and reliability⁷⁰

3.7.3 Objectivity

Objectivity is to what degree the researcher's valuations affect the results of the study. The objectivity can be increased by clear and well-defined motivation of different choices in the study. This makes it possible for the reader to create an own point of view to the research findings.⁷¹

3.8 Applied Methodology

Applied methodology puts the report in the context of presented methodology theories.

3.8.1 Different Types of Studies

An explorative study will be performed in order to reach the interim objective of the study. The interim objective is to understand how maintenance of offshore wind farms is carried out and how this is related to costs and revenues. This approach is chosen in order to gain fundamental knowledge about the problem. Fundamental knowledge is essential to understand variables and concepts and focus of the report.

The main objective is to investigate in what way O&M of offshore wind farms can be modelled in a simulation tool. To reach the main objective normative studies will be applied. It's an appropriate approach to use for answering questions about effectiveness. The choice is also motivated by the authors' search for action plans and the consequences that follows.

3.8.2 Research Approaches

The authors believe that the whole is *not* the same as the sum of its parts and that there are synergy effects in a logistic system. The analytical approach suggests that the whole is the sum of its parts; therefore this approach has been excluded. The actors approach suggests that the whole is understood by the characteristics of its parts. The authors believe that this description is too simplified for a logistics system; therefore the actors approach has been eliminated. This choice is further strengthened by Gammelgaard who argue that the actors approach has not yet been used within the field of logistics.

⁷⁰ Modified from Björklund and Paulsson (2003) p.60

⁷¹ Björklund and Paulsson (2003) p.59ff.

The research approach chosen is the systems approach. This approach aims to explain the parts with knowledge about features from the whole. The authors agree with Gammelgaard who suggests that logistic relationships are too complicated and complex to find cause-effect relations. The systems approach is therefore appropriate to use, because it focuses on the relation between the parts and synergies in a system. This choice is also improved by Bouwer Utne that chooses the systems approach for research of maintenance strategies for offshore wind farms.

System characteristics

The authors study an open system. This involves the system in context with its environment. Weather and wind are factors that have a significant impact on the system and therefore have to be taken into account. Figure 7 shows the regarded system in the study. The connections to factors outside the system boundary illustrates that the system boundary is open and that the system is linked to the environment.

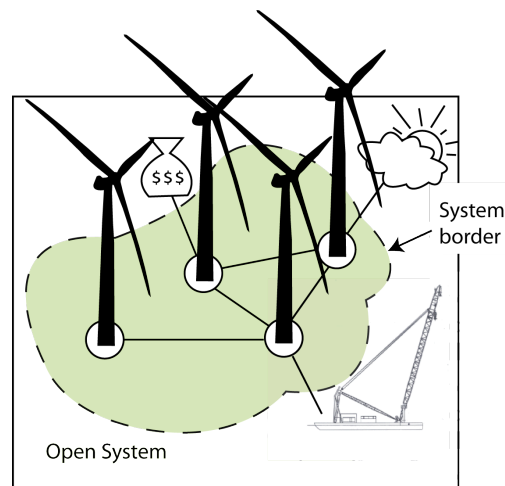


Figure 7: The offshore wind power farm is a system that is studied with its relationship to the environment.

Study orientation

The study is planned in advance and has an organized and structured approach. Hence, the authors have chosen the goal-means orientation and eliminated the search-learn orientation. The authors will look for means to achieve the system goal. The adapted work procedure for the goal-means orientation adapted in this report is shown in Figure 8. The figure explains that the problem is generated in practice, reality, but system analysis and system construction will both be performed in theory. Implementation of the authors' conclusion is beyond the study boundaries and consequently not a part of the study orientation.

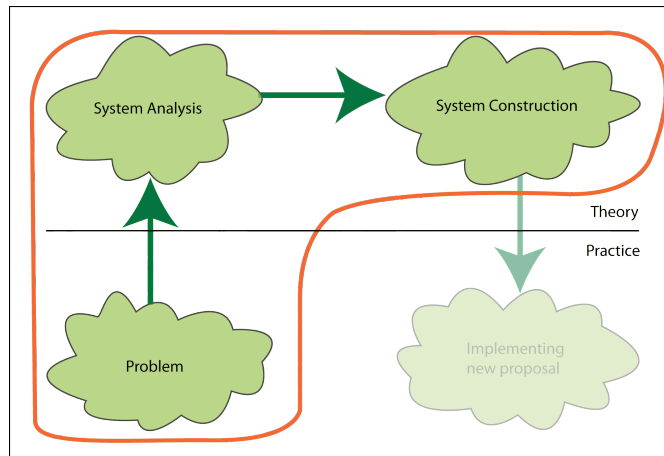


Figure 8: The goal-means orientation applied in the study

3.8.3 Method Approaches

Part I and Part II consists of both theory and empirics. Key findings from Part I constitute input to Part II. The method approach in Part I is deductive, since the authors have focused on theory in order to anticipate empirics. The method approach in Part II is of inductive nature; empirics from Part I have impact on theory in Part II. This clarifies that movements between theory and empirics are performed throughout the report. Hence, abduction, a combination of induction and deduction, is the method approach used in this report.

3.8.4 Quantitative and Qualitative Approach

Denscombe highlights that quantitative and qualitative studies are not mutually exclusive. The authors argue that this report is a striking example of this. Part I and Part II consists of analysis in words and pictures and the focus of the study is holistic. Research methods used, is among others, interviews, which further strengthen the use of a qualitative approach. In Part III a mathematical model is used and analysis concerns numbers rather than words and pictures. Focus of the study in Part III is more specific than in previous parts. The study objective in Part I and Part II is of qualitative nature conversely to Part III, where the objective is of quantitative nature.

3.9 Practical Modes of Procedure

Practical modes of procedure describe research methods used in practice. Chosen methods are discussed in terms of primary and secondary data. The research methods used in practice are presented in Figure 9. Figure 9 illustrates how research methods are connected to Part I, Part II and Part III, but also how information within these parts is gathered.

Research Methods in Practice

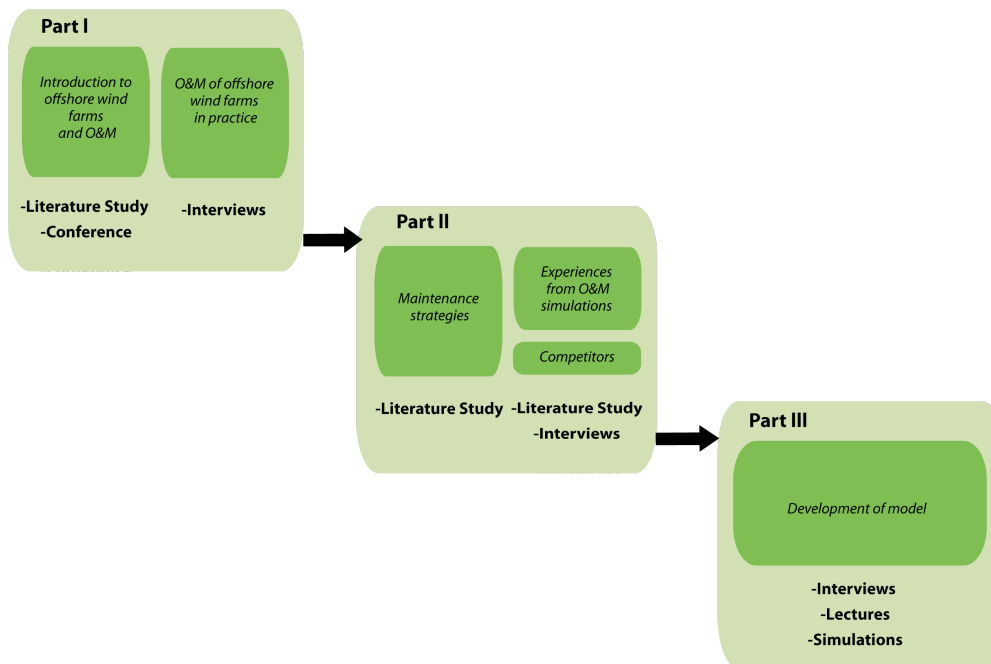


Figure 9: Research methods in practice

3.9.1 Part I

Literature study, interviews and information gathering at conference are the research methods used in Part I.

Literature Study

Information gathered from books, journal articles, conference proceedings, research publications, reports and theses constitute the literature study in Part I. Lund University's electronic library, LibHub, has been the major source for articles. Non-electronized articles and conference proceedings were provided by professor emeritus Ahlmann. Theses have been found at the LTH web page and most books at Lund University's libraries. Books, research publications, conference proceedings as well as reports have been browsed on Internet. Web based material from unknown sources have been avoided to a large extent. Reports from European Wind Energy Association (EWEA) have included contemporary information about the wind industry. Information used in the literature study is secondary, since it's not primarily written for the specific purpose of the report.

Conference

The authors visited the Nordic Wind Power Conference in Copenhagen, 2011-04-12 to 2011-04-13. The conference concerned O&M of wind farms, and best practice were presented during company presentations, which the authors participated in. The authors took notes and summarized the conference in order to gather information. Gathered information from the Nordic Wind Power Conference is secondary data, since the information presented wasn't aimed primarily to answer the research

problems. Even though little information from the conference is part of the report, the authors gained a deeper understanding of how O&M of offshore wind farms is performed in practice.

Interviews

Assistant professor Jörgen Svensson was interviewed at LTH, 2011-03-16. According to the authors, Svensson's practical experience from offshore wind farms at E.ON made him a preferable source of information. The performed interview was semi-structured, so more in depth questions could be asked on specific topics. The interview guide can be found in Appendix A.

Håkan Borgström was interviewed at Systecon's office in Malmö, 2011-04-19. Borgström has previously worked at Systecon and is presently employed by Dong Energy, where he works at the Department of Asset Management. The authors chose to interview Borgström, since he has experience of O&M of offshore wind farms, but also since he has knowledge about Systecon's simulation tool. The performed interview was semi-structured, so more in depth questions could be asked on specific topics. The interview guide can be found in Appendix B. Gathered information from the interviews is primary data, collected for the specific purpose of the study.

3.9.2 Part II

Literature study and interviews are the research methods used in Part II.

Literature Study

Information has been gathered as described in Part I, additional information was gathered from Systecon's educational supplies. This information was given when the authors participated in a course at Systecon⁷². Information collected during the lectures is primary data, since it concerns underlying theory behind Systecon's simulation tool. This information has been collected for the specific purpose of this study.

Interviews

Francois Besnard was interviewed at Systecon's office in Stockholm, 2011-05-16. Besnard's licentiate thesis regards optimal maintenance management for wind power systems. Further, he has experience from working with O&M tools from ECN. The authors argued that a person that can provide more information than Besnard for the aim of the report is difficult to find. He was also able to provide information from both the academia and the industrial life. The authors used Besnard's licentiate thesis in the literature study and knew that he had investigated O&M tools earlier. The performed interview was semi-structured, so more in depth questions could be asked on specific topics. The interview guide can be found in Appendix C.

Borgström was interviewed at Systecon's office in Malmö, 2011-04-19. Information has been gathered as described in Part I. Gathered information from the interviews is primary data, collected for the specific purpose of the study.

⁷² This will be further described in Section 2.9.3

3.9.3 Part III

Interviews, lectures and experiments at conference are the research methods used in Part III.

Lectures

The authors participated in a course at Systecon's office in Stockholm, 2011-03-07 to 2011-03-11. The course included practise of Systecon's simulation and optimization tools. Educational supplies were handed out during the lectures.

Simulations

Part III mainly consists of developing a model in Systecon's simulation tool. So simulations constitute the research method experiment.

Interviews

The authors had the possibility to contact the model group at Systecon in Stockholm for questions and obscurities regarding the simulation tool. These interviews were practiced over phone and mail, but also when visiting Systecon's office in Stockholm, 2011-05-13 and 2011-05-16.

3.10 Credibility of the Report

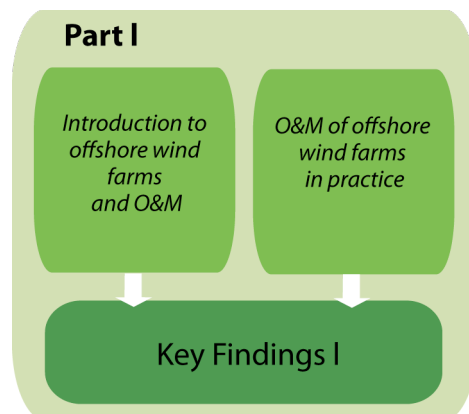
The authors have majorly used literature from known-sources within the field of O&M of offshore wind farms. In order to reach high credibility a vast search for literature has been performed in order to enable discrimination of deviating information. Since O&M of offshore wind farms is a relatively new field the authors have focused on contemporary sources of information. The authors had the possibility to contact professor emeritus Ahlmann, regarding any obscurities of his previous publications: articles and conference proceedings. This improves the report's reliability.

Interviewees have been chosen carefully in order to gather as much primary data as possible. To establish the authors' objectivity, the interviewees have reviewed the interview material afterwards. This also improves the report's reliability. The amount of primary data presented in the report increases validity.

Participation in the Nordic Wind Power Conference brought little information committed in the report. But it improved the authors' knowledge within the field of O&M of wind farms, which enhance reliability of the report and reliability of the developed simulation model.

The authors' attendance at the optimisation and simulation course at Systecon has been valuable for two reasons. Firstly, information from Systecon's educational supply has resulted in primary data. Secondly, the development of the simulation model has been less time-consuming. This increases both reliability and credibility of the report. The authors also had the possibility to contact the model group at Systecon for questions regarding the simulation tool. The simulation model has also undergone quality checks and simulations have been replicated ten times in order to achieve significant results. This improves reliability of the simulation model.

PART I



Chapter 4: Wind Power in General
Chapter 5: Introduction to Maintenance
Chapter 6: O&M of Offshore Wind Farms
Chapter 7: O&M of Offshore Wind Farms in Practice
Chapter 8: Key Findings Part I

4 Wind Power in General

This part describes the basics of wind power. It gives the reader some insight into the functionality of a wind turbine, its components, the wind power market and wind variations.

4.1 Wind Power by 2011

Wind power has been a source of energy for more than three millenniums. The first wind turbines for generation of electricity were developed in the early 20th century. But it's first in the past 20 years that wind power has been considered as one of the most important renewable and sustainable energy sources. The attention to offshore wind power is notably higher in Europe than the rest of the world. The main factors for this are that countries are running out of onshore sites and that EU targets for renewable energy have to be reached.⁷³ Figure 10 shows the total installed wind power capacity in Europe by the end of 2010.

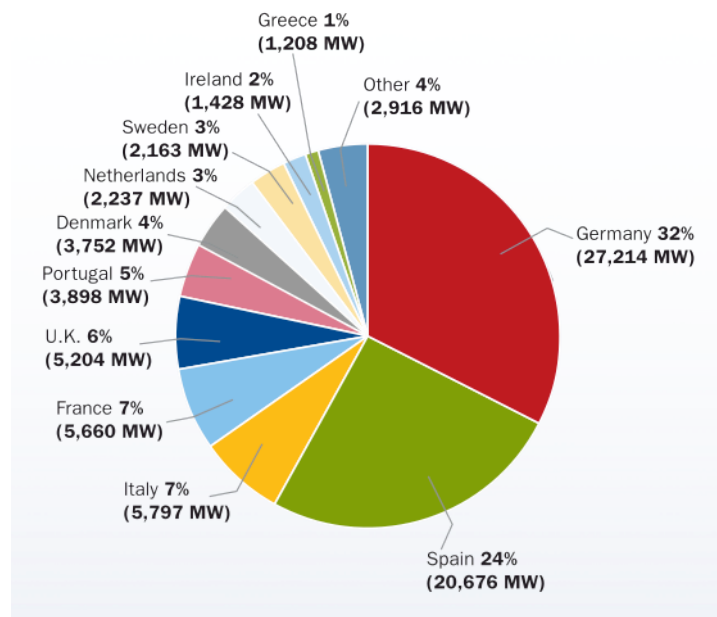


Figure 10: EU member state market shares for total installed capacity at the end of 2010⁷⁴

The world's largest offshore wind farm in operation is Thanet Offshore Wind Farm. The wind farm is situated in the sea outside UK. It consists of 100 turbines with a total capacity of 300MW. Vattenfall is the company that has performed the project.⁷⁵ The largest permission for offshore wind has been acquired Scottish Power and

⁷³ Ackermann, T. (2005) p.479

⁷⁴ EWEA (2010) Wind Power-2010 European Statistics, p.10

⁷⁵ Peters, E. (2010), p.45

Vattenfall. The permission comprises rights to install 7200 MW on the coast of East Anglia. The project is still in its initial phase.⁷⁶

4.2 Wind Turbine Functionality

Power stations generate power when the wind speed is 4-25 m/s. Stronger or lighter winds do not generate any electricity⁷⁷. Wind turbines start to generate power at the so-called cut-in speed. When the speed is below this point, the blades are prevented from rotating.⁷⁸ Wind turbines generate maximal power at different wind speeds, depending on what wind speed the turbine is designed to generate maximal power at. That is, when the rated power (maximum power output) is reached the turbine confines the input from the rotor blades. The turbine will then generate the same power for higher wind speeds. This type of regulation is called power control.⁷⁹ When the winds are too strong the blades will automatically slow down due to safety reasons, this is called the cut-out wind speed. Figure 11 exemplifies a power curve where the important characteristics, rated power, cut-in and cut-out speed can be identified.⁸⁰

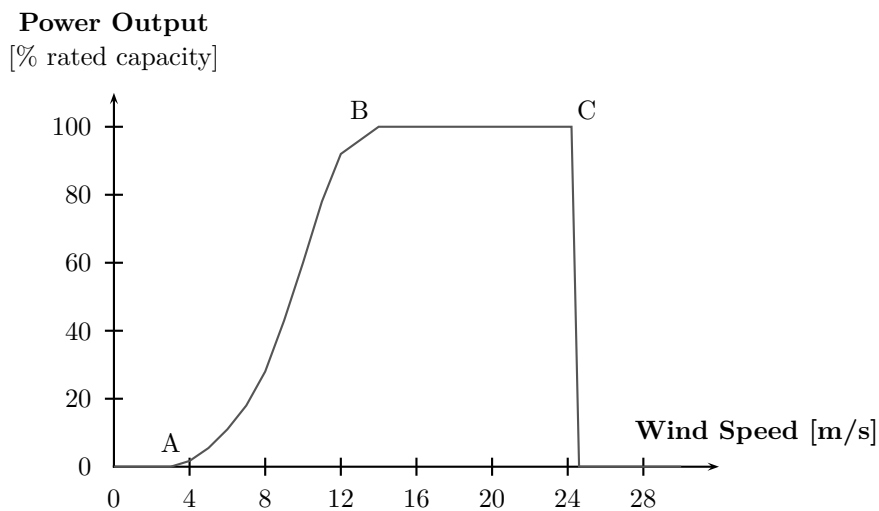


Figure 11: An example of a power curve. A is the cut-in speed, B is the rated power and C is the cutout speed.⁸¹

Generally the winds are stronger during the winter period, which means that the production of electricity follows the electricity demand. During periods with high wind power generation, an excess of power can occur. If the wind power station is connected to a grid, a limited amount of the power excess can be stored in water reservoirs.⁸² Figure 12 shows a common distribution of wind speeds. The parameters

⁷⁶ *East Anglia Offshore Windfarm Zone*

⁷⁷ Energimyndigheten (2001) En översikt- Vindkraft, p.2

⁷⁸ Besnard (2009) p.6

⁷⁹ Krohn et al (2009) p.49

⁸⁰ Besnard (2009) p.6

⁸¹ Modified from Besnard (2009) p.6

⁸² Gielson (2001) p.2

are different dependent on which geographical area that is measured, the distribution nearly always fit a Weibull distribution.⁸³

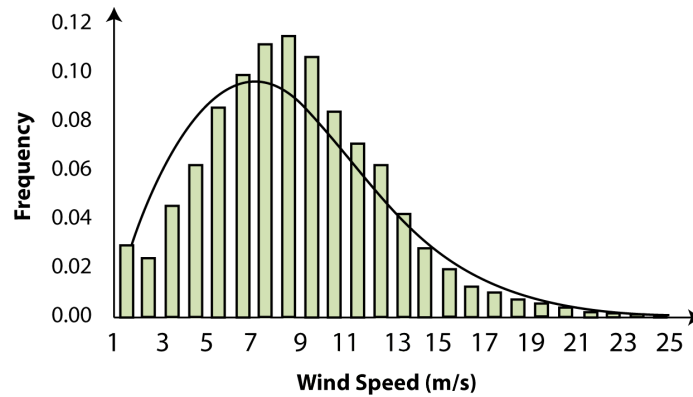


Figure 12: Wind speed frequency distribution⁸⁴

4.2.1 Wind Turbine Components

The blades and the hub are parts of the rotor, which is shaped to rotate at fixed or variable speeds. The longer the blades the slower the rotation is and vice versa. There are wind turbines with both two and three blades. The blades are connected to the main shaft via a hub.⁸⁵ The nacelle encloses the gearbox, the generator and control and monitoring tools. The nacelle is located at the back of the rotor blades. The gearbox is used in order to make the speed of the main shaft correct for the generator. It's important that the rotor axis is placed towards the wind. This is the yaw drive's task. The control system is normally located in the tower and the nacelle and consists of a computer-based control panel. The control system monitors different functions in the wind turbine. In a wind farm, consisting of many wind turbines, the turbines are connected to a central monitoring computer. Figure 13 illustrates the principal components in a wind turbine.⁸⁶

⁸³ Redlinger (2002) p.12

⁸⁴ Modified from Redlinger (2002) p.12

⁸⁵ Redlinger (2002) p.52f.

⁸⁶ Ibid., p.54f.

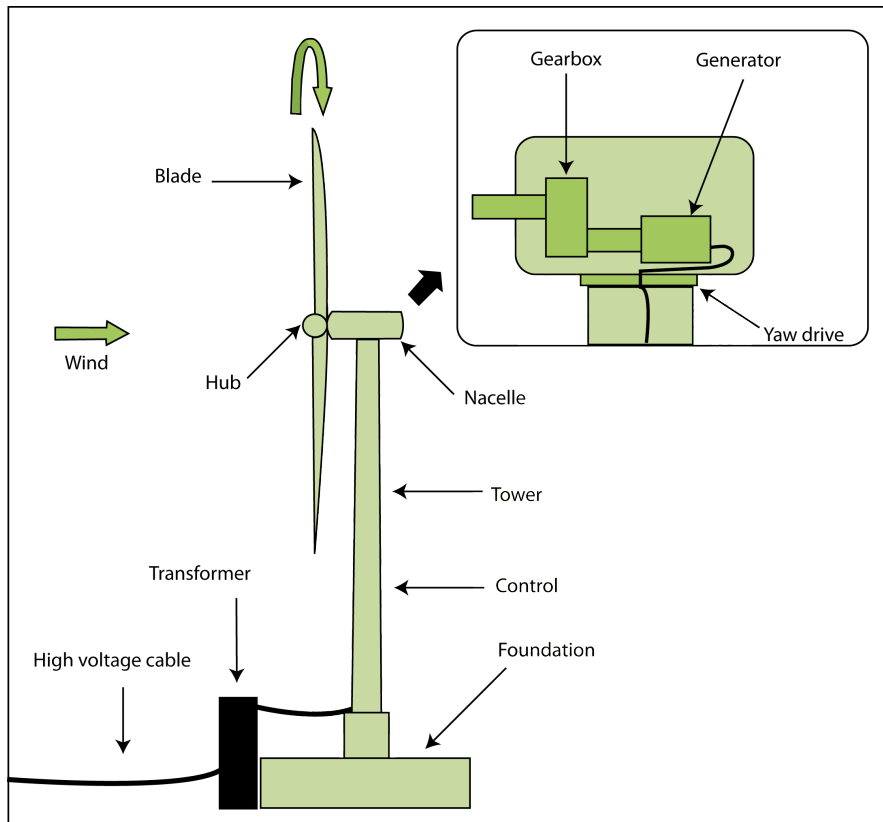


Figure 13: Principal components of a wind turbine⁸⁷

4.3 Seasonal and Diurnal Impacts on Wind Resources

Wind resources vary a lot from one year to another. The generated electricity can vary $\pm 15\%$ compared to the average production over long term. Ackermann implies that wind variability is a factor that characterizes wind energy. However there are significant seasonal and diurnal patterns (the variability on daily basis) in wind resources and therefore also in the power production. Research has shown that in Northern Europe the amount of electricity generated is larger in winter than in summer. The summer months in Northern Europe are also distinguished by stronger winds in the morning, than in the evening.⁸⁸

4.3.1 The Capacity Factor

The capacity factor describes the amount of electricity that is actually generated in relation to what theoretically can be generated.

$$\text{Capacity Factor} = \frac{\text{Electricity produced by generator}}{\text{Maximum theoretical production from generator}} \quad (1)$$

⁸⁷ Modified from Redlinger (2002) p.53

⁸⁸ Ackermann (2005) p.149ff.

The wind access and wind speed for wind turbines are the two most important factors for determining the capacity factor. Sinden argues that these factors are more important than for example shut down for maintenance.⁸⁹ Ackermann also implies that the wind resource is strongly linked to the electricity that can be generated and thus the capacity factor. There is a great significance in the capacity factor over one year for onshore and offshore wind farms. The factor onshore is normally 20-40% and offshore 45-60%.⁹⁰

It's preferable to use larger generators in windy locations. This results in a lower capacity factor than if a smaller generator was chosen, even if the total annual produced power is higher. This is called *the capacity factor paradox*.⁹¹

4.3.2 Seasonal and Diurnal Impacts on the Capacity Factor

Sinden has studied how seasonal and diurnal patterns in wind power affect the capacity factor onshore. Figure 14 shows that the average monthly wind power capacity factor over one year is 30%. The summer season (June, July and August) make a contribution of 17% of electricity production in one year, while the winter season (December, January and February) make a contribution of 33%. Figure 15 shows the daily variability based on winter, spring, summer and autumn. The diurnal variability shows that the average daily summer capacity factor is 20% and the corresponding average winter capacity factor is 38%. It also shows how the capacity factor varies, dependent on the time of the day. Sinden completes his study with conclusions that wind power resources are highest during wintertime and during daytime, compared to night times.⁹²

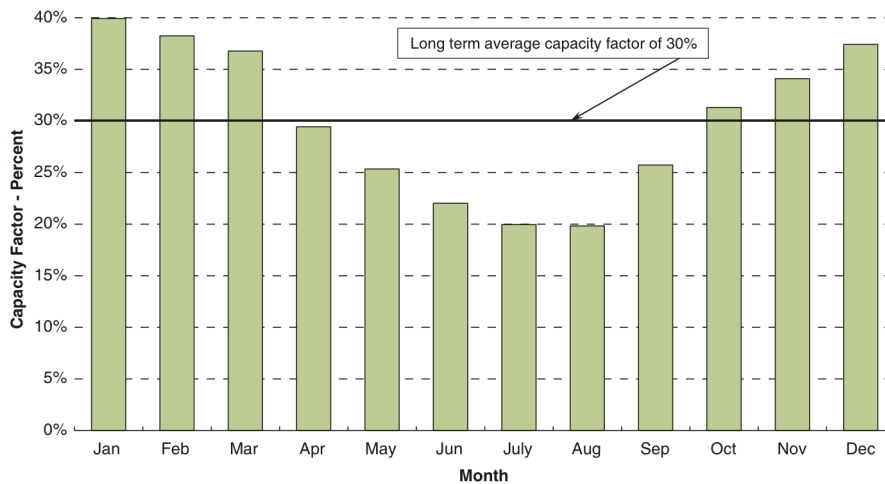


Figure 14: Average monthly wind power capacity factor⁹³

⁸⁹ Sinden (2007) p.3

⁹⁰ Ackermann (2005) p.199

⁹¹ *Danish Wind Industry Association*

⁹² Sinden (2005) p.4

⁹³ Sinden (2005) p.6

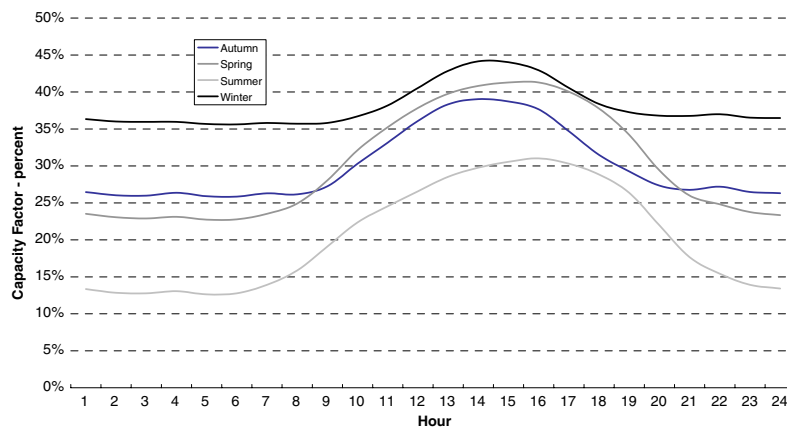


Figure 15: Average daily variability in the United Kingdom wind power capacity factor⁹⁴

4.4 Wind Power Market

Due to the deregulation of power markets, the markets within the North European countries are arranged in equivalent ways. There are five types of power markets existing within these North European countries: over the counter trading, the spot market, the intraday market, the regulating power market and the balancing market. The markets with the most significance for wind power are the spot market and the regulating market. The spot market determines prices one day ahead, given supply and demand conditions, while the regulating power market acts in real time.⁹⁵

4.4.1 Supply and Demand

Figure 16 shows a typical supply and demand curve. Power is an essential type of commodity that is difficult to interchange. This causes an inelastic demand, implying almost constant demand with increasing prices. This is illustrated by the almost vertical demand curve in Figure 16.⁹⁶

The power market portfolio consists of several types of technologies. This is illustrated in Figure 16. It shows the supply and demand curve in the power market during one year. The amount and cost of power, which a power technology can provide, decides the order of the supplying technologies. The supply curve within the power market is typically called *the merit order curve*. There is a difference between the costs of the power technologies. This cost consists of the technology used and the combustible material consumed. As seen in Figure 16, wind and nuclear power are the technologies with the lowest marginal costs. That the marginal cost for wind power is scarce depends most on the non-consuming of combustible material. The wind is the substitute in this case. The power price on the spot market is influenced by wind power in two ways:⁹⁷

⁹⁴ Ibid., p.5

⁹⁵ EWEA (2010) Wind Energy and Electricity Prices, p.9

⁹⁶ Ibid., p.10

⁹⁷ Ibid., p.10f.

The merit order effect implies that the price of power normally is low in periods with high wind and vice versa.

If the power supply is larger than the demand of power, wind power is the technology preferred to generate power due to its low environmental impact. It's neither economically advantageous to lower the production of wind.

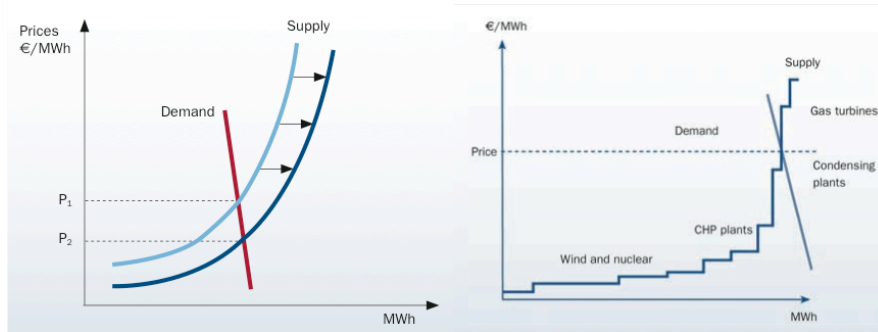


Figure 16: Typical supply and demand curves and Annual supply and demand curves in the power market⁹⁸

4.4.2 The Power Consumption

Svensk Energi compiles statistics of the monthly power in Sweden. The statistics clearly demonstrates that the power consumption is higher during months of winter than summer. The Figure 17 also shows how wind power production follows the demand.⁹⁹

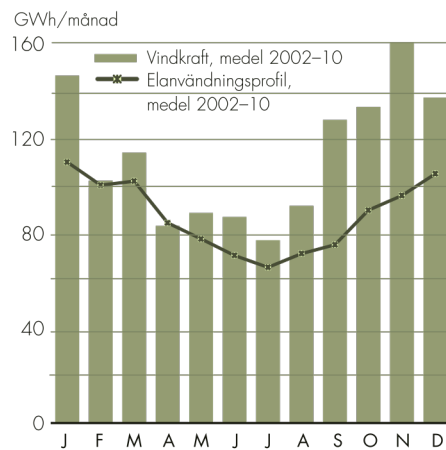


Figure 17: Monthly power consumption profile and wind power production in Sweden, 2002-2010¹⁰⁰

⁹⁸ Ibid., p.9f.

⁹⁹ Svensk Energi (2010) p.2

¹⁰⁰ Svensk Energi (2010) p.2

5 Introduction to Maintenance

This chapter introduces the reader to maintenance theory. Conceptions such as life cycle cost and life cycle profit, maintenance performance measurement and efficiency theory are presented.

5.1 Life Cycle Cost & Life Cycle Profit

An important conception to consider at the planning phase of an investment is the life cycle concept. It's central to understand that future running costs are dependent on decisions taken at the time of the planning phase. The costs at the planning phase are often surpassed by costs of maintenance.¹⁰¹ With these facts on hand, the importance of calculating costs during the entire life cycle is emphasized.

The total cost of owning and maintaining a manufacturing unit, the Life Cycle Cost (LCC).¹⁰²

The costs during a life cycle are often illustrated with an iceberg. Over the sea level the acquisition costs are viewable, but under the sea level there are costs for spares, maintenance, education, dismantlement etcetera. It's easy to only focus on the most apparent costs over the water surface, but one must remember that all costs must be considered.¹⁰³

Ahlmann highlights that it's not enough to focus on costs alone. He means that beside the costs of an investment, the future revenue of this investment must be taken into account. Most industrial enterprises aim to generate revenue. Life Cycle Profit (LCP) is according to Ahlmann therefore an essential extension of LCC. How costs and benefits vary over time is illustrated in Figure 18, which also demonstrates the LCP calculation.¹⁰⁴ Important to remember is that all costs that are related to maintenance are not necessarily direct cost of maintenance rather cost due to lack of maintenance. An example of costs due to lack of maintenance is revenue losses.¹⁰⁵

¹⁰¹ Ahlmann (2002) p.2

¹⁰² Ibid., p.3

¹⁰³ Bergman and Klefsjö (2007) p.149

¹⁰⁴ Ahlmann (2002) p.4

¹⁰⁵ Ahlmann (2011-03-14) LTH

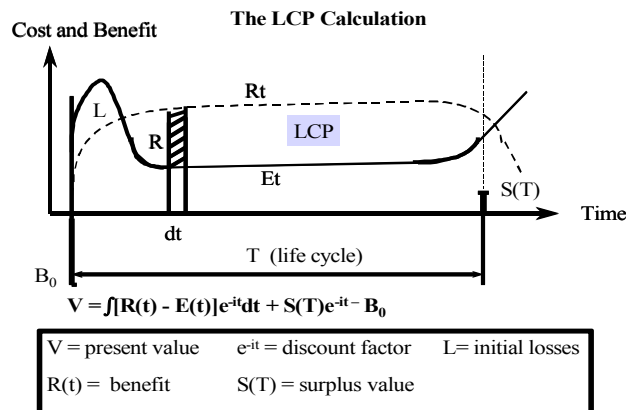
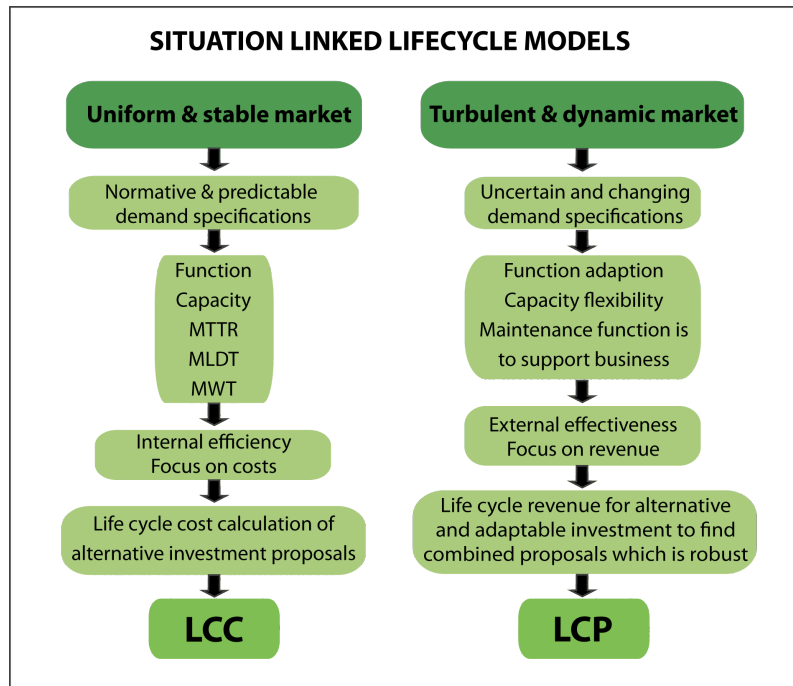


Figure 18: The LCP Calculation¹⁰⁶

LCP is more suited for production strategy and dynamic market situations. Figure 19 shows situation linked lifecycle models. That is, when LCC and LCP are appropriate to use.¹⁰⁷ Figure 19 shows that LCC is to prefer when demand is predictable and normative and LCP when demand is uncertain and changing. The LCC perspective will focus on costs and thus internal efficiency. On contrary, LCP will enhance focus on revenue and external effectiveness.¹⁰⁸



¹⁰⁶ Ahlmann (2002) p.4

¹⁰⁷ Ahlmann (2002) p.4

¹⁰⁸ Ibid.

Figure 19: Situation linked Lifecycle Models¹⁰⁹

5.2 Maintenance in Theory

Parida and Kumar argue that there has been a paradigm shift in maintenance. Companies considered maintenance to be a necessary evil a hundred years ago, but today maintenance is considered as an important and integral part of business processes. Figure 20 illustrates this paradigm shift in maintenance.¹¹⁰

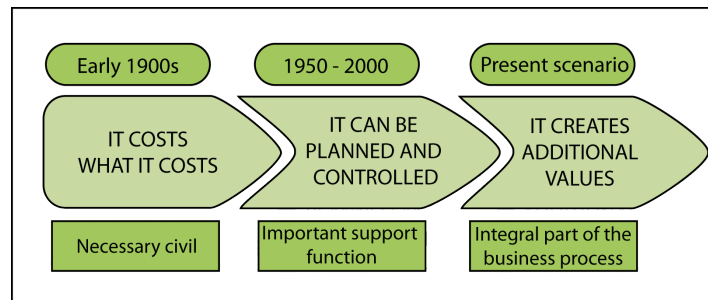


Figure 20: Paradigm shift in maintenance¹¹¹

The definition of maintenance according to International Electrotechnical Commission is:

The combination of all technical and administrative actions, including supervision, intended to retain an item, or restore it to a state in which it can perform a required function.¹¹²

Today, maintenance is considered a very important factor for companies in order to retain profitability over long term. It's seen as something that creates value. Maintenance makes up to a great part of the total costs within certain industries that are asset-intensive. For these industries, the cost of maintenance is a substantial part of the total operational cost.¹¹³

The past years the output productivity has increased a lot due to competition within many industries. To be able to raise productivity, maintenance plays an important role. There are both direct and indirect costs of keeping equipment functional. The addition of indirect and direct costs makes the total costs of maintenance. Direct costs of maintenance are the actual costs for maintenance operations while indirect costs are for example loss of good will and customer satisfaction. The significant impact of maintenance on the overall business performance makes maintenance an important factor that companies cannot afford to disregard.¹¹⁴

¹⁰⁹ Modified from: Ahlmann (2002) p.4

¹¹⁰ Parida and Kumar (2006) p.240

¹¹¹ Ibid.

¹¹² Parida and Kumar (2006) p.239

¹¹³ Ibid., p.239f.

¹¹⁴ Murthy et al (2002) p.288

5.2.2 External and Internal Efficiency

Maintenance issues are traditionally associated with costs and it's seldom addressed at the corporate level. Besides the focus has always been on internal efficiency. By connecting the internal efficiency to market performance it becomes clearer how the maintenance function has a big impact on reaching financial goals and business objectives. Business-oriented maintenance (BOM) is a concept where maintenance issues are performed with a strong business focus. The concept translates strategy into action where the maintenance activities aim to maximize the LCP. Based on LCP and return on asset (ROA) strategic decisions are financially evaluated. The ROA is a measure that takes both internal and external efficiency into account.¹¹⁵

When actions are dependent of each other the result becomes multiplicative. If two actions are independent, the result is additive, which can be seen in Figure 21. By multiplying the effect of performed actions, it's possible to reduce the costs and at the same time increase the revenues.

The external efficiency is associated with the customer satisfaction and the internal efficiency is associated with the productivity. The multiplicative scenarios are those that move diagonally in the ROA graph in Figure 21.¹¹⁶

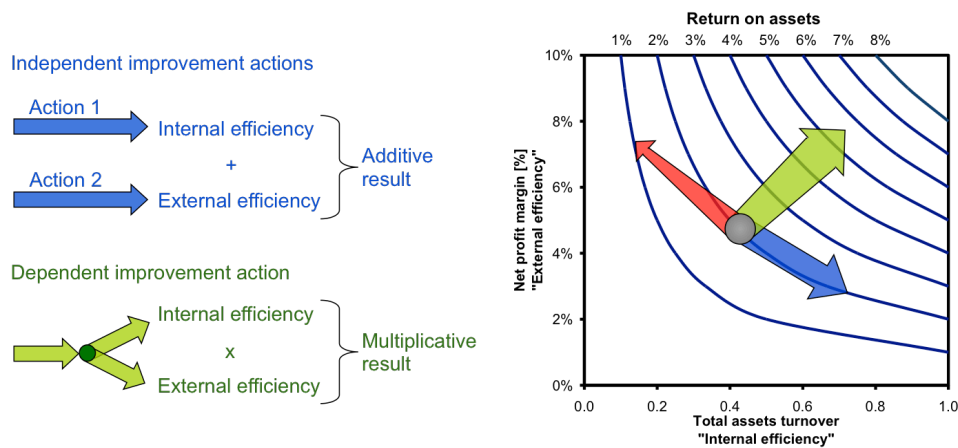


Figure 21: Additive and multiplicative result (left) and ROA graph and the diagonal way to financial success (right)¹¹⁷

5.3 Maintenance Performance Measurement

Performance measurement is commonly used within the field of operation management. It's defined by quantifying the efficiency and effectiveness of an action or process. There are four basic principles that are essential to know within the area of performance measurement:¹¹⁸

¹¹⁵ Ahlmann and Borgström (2010) p.1

¹¹⁶ Ahlmann (2002) p.5

¹¹⁷ Ahlmann and Borgström (2010) slide 17

¹¹⁸ Bourne and Neely (2003) p.3

- Performance measures have many dimensions. They can be both financial and non-financial, but also measure internal and external performance.
- Performance measurement are relevant within a given context, they cannot be done in separation from the context.
- Performance measurements are subjective in the way that they influence the environment they operated in.
- Performance measurement is primarily used to measure what is of interest for stakeholders, and not for the employees in the company.

Maintenance performance measurement (MPM) is performance measurement within the context of maintenance. It's of significant importance to know how well the maintenance process performs. One common MPM used by companies is to measure the maintenance productivity. Productivity is a good example of a MPM that measures both *effectiveness* and *efficiency*. Efficiency is doing the things right and effectiveness is doing the right things. The cost of maintenance is very different dependent on which industry that performs the maintenance. Therefore the measurement maintenance productivity is a good measurement for comparison between different industries.¹¹⁹ Independent of what industry and what is to be measured, it's very important that MPMs are SMART: Specific, measurable, attainable, realistic and timely. There is a surge in many companies for MPM, the main reasons for this follows in order of importance:¹²⁰

- **Measuring value created by maintenance:** It's important to understand the value that is created by the maintenance process and that the maintenance process is aligned with business goals and objectives.
- **Justifying investment:** If there is a return on the invested resources.
- **Revising resource allocations:** How the resources can be used more effectively and if there is a need for further investments.
- **Health safety and environmental (HSE) issues:** It's important to understand of maintenance affect the HSE issues.
- **Focus on knowledge management:** Companies within the field of maintenance need to know if the knowledge within the company is effectively used.
- **Adapting to trends in O&M strategies:** To be able to compare results within industries MPMs are used.
- **Organizational structural changes:** More flat, compact and process based organizational structures need MPM to understand how well the maintenance services are carried out in the organization.

¹¹⁹ Ibid., p.18f.

¹²⁰ Parida and Kumar (2006) p.245f.

5.3.1 Maintenance Performance Indicators

For evaluation of a system's or process' performance, performance indicators (PI) are used. A set of metrics makes the product of an indicator. A PI indicates the performance level achieved. The achieved performance can be measured from one to multiple aspects; dependent on what performance measurement the performance indicator is a product of.¹²¹

Maintenance performance indicators (MPI) are performance indicators in the context of maintenance. MPIs are used in order to evaluate the effectiveness of the maintenance activities. It's of great importance that MPIs consist of and are related to performance measurements that concerns both process inputs and outputs. MPIs can be used for benchmarking and to understand the performance of the employees.¹²²

Johansen argues that the most important PI's at Vattenfall regards safety and earnings before interest and taxes (EBIT). Typical PI's that have an impact on EBIT are availability, wind speed, accessibility, lost production and mean time between failures (MTBF).¹²³

¹²¹ Parida and Kumar (2006) p.242

¹²² Ibid.

¹²³ Johansen, B. (2011-04-13) Nordic Wind Power Conference

6 O&M of Offshore Wind Farms

This chapter foremost explains reliability, availability, maintainability and logistics supportability. Weather, O&M costs, service agreements and monitoring and control of wind turbines are clarified in order to give the reader a more comprehensive understanding of offshore wind power.

6.1 Comparison of Onshore and Offshore Wind Power

Offshore wind power has many advantages compared to wind power onshore. The main advantage is that winds are stronger offshore and therefore increase the productivity.¹²⁴ Due to better wind conditions offshore, 50% more power can be produced¹²⁵. Unfortunately stronger winds also result in higher O&M costs. Repairs are about five to ten times more expensive offshore compared to onshore. The main reasons for this are the costs of vessels and unsuitable weather conditions for reparation.¹²⁶ The offshore wind sector has become a distinct sector of the wind industry the last years. Onshore wind power is approaching maturity today and research within this area is mainly focused on improvements regarding reliability and efficiency.¹²⁷ The offshore wind industry lacks commercial experience and operational expectations are at present associated with uncertainties¹²⁸.

Offshore and onshore wind turbines are based on the same technology, but the size differs. Onshore turbines that are installed today have a height of 100 to 120 metres and offshore turbines are in the upper end of this scale, 115 to 120 metres.¹²⁹

It's not only the size of offshore wind power that differs from onshore. There is also an important obvious difference when it comes to installation and O&M. The accessibility to offshore wind farms is often limited. During periods, it's common that the whole farm is inaccessible due to harsh weather conditions. This in combination with complex logistics issues may result in long downtimes and reduced availability. When the site is accessible, the offshore maintenance is not only more costly, it's also much more time consuming. The transport to the site is very expensive and requires specialist equipment and careful timetabling in order to pinpoint preferable weather conditions.¹³⁰ Onshore lifting actions are performed relatively easy; the equipment can often be sourced locally with short notice. The offshore environment obstructs this kind of actions and the equipment required is scarce and very costly.¹³¹ This results in high uncertainties concerning the economical return of the projects. O&M costs of offshore wind farms make up to about 30% of the kWh price. Regarding onshore

¹²⁴ Breton and Moe (2009) p.646

¹²⁵ *Svenskenergi*

¹²⁶ Breton and Moe (2009) p.646

¹²⁷ EWEA (2009) Oceans of Opportunity, p.43

¹²⁸ Morgan et al

¹²⁹ BWEA Briefing Sheet- Offshore Wind (2005)

¹³⁰ Ibid.

¹³¹ Van Bussel et al (1997)

wind power the same cost is calculated to 10-15%. This indicates that there is a large potential in cost-savings by reducing this part of the cost of offshore wind power.¹³²

6.2 Availability Theory

Generally the objective of the maintenance actions is to maximize the availability and minimize production losses¹³³. With a proper support organization the availability of the wind power system can be relatively high. Onshore wind has a high operational availability nowadays. Regarding the offshore environment, there is a lot of factors that obstruct the maintenance work, which leads to very long downtimes and high costs.¹³⁴ Availability is a function of the system reliability, maintainability and supportability, which is shown in Figure 22¹³⁵.

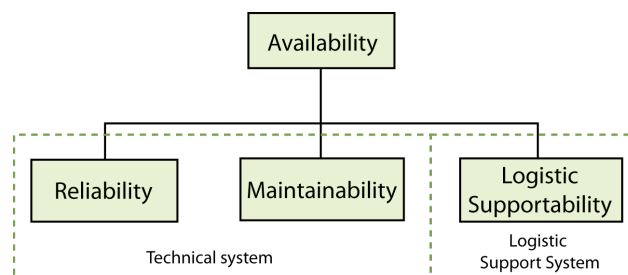


Figure 22: Availability as function of reliability, maintainability and supportability¹³⁶

The offshore operator has many daily critical decisions to make. Decisions that are related to: alarms, prioritizing of preventive actions, usage of vessels according to current weather conditions and availability of O&M crew.¹³⁷

6.2.1 Reliability

Reliability is the ability of a system to perform required tasks under given conditions. For a wind turbine that is the ability of producing power that corresponds to the actual wind conditions according to its nominal power curve. The failure rate, which is a basic measure of reliability, is highly dependent of how well the wind turbine is designed and the quality of the components together with stress load.¹³⁸ Turbine manufacturers try to make wind turbines more reliable for offshore environment. Reliability increases with reduction of components in wind turbine and higher component quality.¹³⁹

The parameters with greatest impact on reliability are:

- Component quality
- Stress and load

¹³² Braam et al (2003)

¹³³ Bouwer Utne (2010) p.369

¹³⁴ Van Bussel and Zaaijer (2001) p.120

¹³⁵ Vindforsk (2010) RAMS, p.12

¹³⁶ Systecon Educational Supplies (2011)

¹³⁷ Rademakers et al (2008)

¹³⁸ Van Bussel and Zaaijer (2001) p.120

¹³⁹ Rademakers et al (2009) p.11

- Environment
- Structure
- Equipment handling
- Faulty replacements
- Probability for secondary failures

Reliability is often expressed as the MTBF, which is $1/\lambda$. The failure rate, λ , is normally number of failures per hour. As time passes, the components ages and consequently the failure rate changes. This change often follows a so-called bathtub curve, which is illustrated in Figure 23. The failure rate is normally relatively high in the first part of the curve due to defects from installation and manufacturing. In the middle part the reliability has increased and the infant failures have been eliminated. Wear out failures is still rare which makes this to the “best period”. Finally comes the third period where the failure rate increases significantly due to high age and wear out.¹⁴⁰

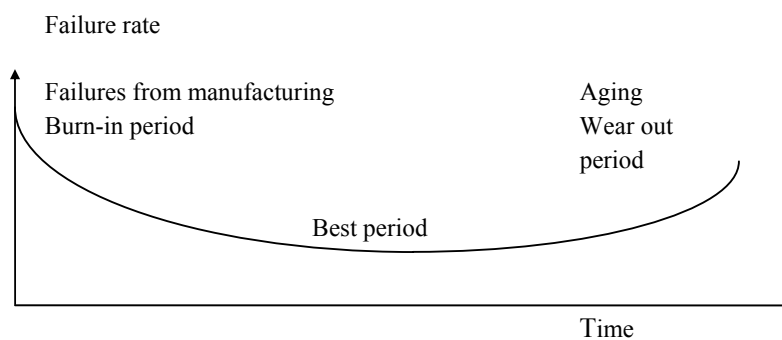


Figure 23: Bathtub curve divided into three periods¹⁴¹

Assumed that the failure rate is constant over time and does not depend on the age of the components, it follows an exponential distribution. In contrast to this memoryless distribution, the Weibull distribution has a parameter α as scales the distribution in time. The second parameter in the Weibull distribution is β . When $\beta > 1$, the failure rate is increasing, when $\beta = 1$ the failure rate is constant and when $\beta < 1$, the failure rate is decreasing. When $\beta = 1$, the Weibull distribution is equivalent to the exponential distribution. This is illustrated in Figure 24 below.¹⁴²

¹⁴⁰ Systecon Educational Supplies (2011)

¹⁴¹ Ibid.

¹⁴² Besnard (2009) p.17

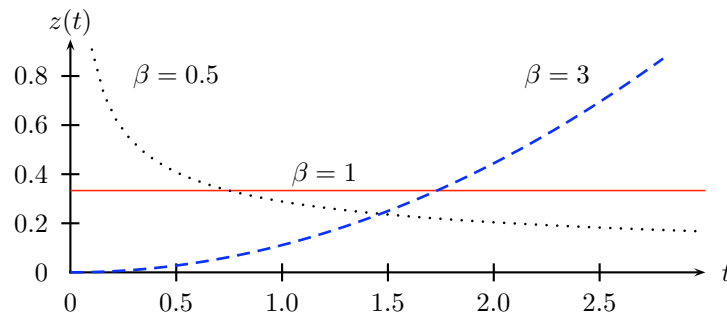


Figure 24: Failure rate of a Weibull distribution with $\alpha=3$ and $\beta=0.5, 1, 3$.
The failure rate λ is denoted as $z(t)$.¹⁴³

Spare Parts

Previously a master thesis of spare parts optimization for offshore wind turbines has been carried out. It demonstrated that spare part costs constitute a little part of the total support costs during a system's life cycle. Still, Lindqvist and Lundin have found that by choosing an optimal spare part strategy costs can be reduced. Central reordering and pooling strategy is more cost efficient [*sic!*] than local storage. They also found that gearboxes, generators, rotor blades and transformers are components associated with the highest spare part costs. Inventory levels of wind turbine spare parts are difficult to optimise. This difficulty depends on complicating factors such as long lead times related to e.g. crane ships.¹⁴⁴

6.2.2 Maintainability

Maintainability refers to the ease and efficiency of repair and maintenance issues. It's often expressed as time needed to complete the maintenance actions, measured as the Mean Time To Repair (MTTR). MTTR does not include logistics waiting time for logistics support resources. Parameters that have an impact on maintainability are:¹⁴⁵

- Fault indication
- Possibility to localize a fault
- Accessibility
- Replacement and repair times

Accessibility

An offshore wind farm is periodically not accessible due to harsh weather conditions when it might be irresponsible or not allowed to go to the site and perform maintenance actions. The accessibility is the percentage of time that the offshore farm can be accessed. What influence the accessibility are weather conditions, transport mode and equipment used. Information about actual weather conditions and accurate weather forecasts are essential factors to be able to plan the transportation and landing of the O&M crew.¹⁴⁶ The site might be inaccessible by boat or helicopter for one or

¹⁴³ Ibid., p.18

¹⁴⁴ Lindqvist and Lundin (2010) p.82

¹⁴⁵ Vindforsk (2010) RAMS, p.4

¹⁴⁶ Van Bussel and Bierbooms (2003) p.383

two months per year. Parameters like significant wave height, wind speeds and visibility determine if the site is accessible or not. Dependent on what type of equipment that is used these parameters have different levels of impact.¹⁴⁷ How waves behave depends on wind directions and underwater landscape¹⁴⁸.

Docking is considered the most critical part for accessing the wind turbine. Often weather condition allows the personnel to depart from mainland, but not to dock. This results in return to mainland without accomplished mission.¹⁴⁹ Dependent on current conditions; different access methods for the O&M crew is used. Large components require special lifting and transport equipment such as a barge for transportation and jack up or crane vessels for the lifting actions. Smaller components, tools and O&M crew are often transported by boat or helicopter. These vessels are showed in Figure 25 and Figure 26.¹⁵⁰ According to Besnard transportations are usually outsourced activities¹⁵¹.



Figure 25: Jack-up vessel and boat¹⁵²



Figure 26: Helicopter¹⁵³ and barge¹⁵⁴

¹⁴⁷ Braam et al (2003)

¹⁴⁸ Besnard (2009) p.32

¹⁴⁹ Borgström (2011) Dong Energy

¹⁵⁰ Van Bussel and Bierbooms (2003) p.383

¹⁵¹ Besnard (2009) p.32

¹⁵² *Maritime & Energy*

¹⁵³ *Power-technology*

¹⁵⁴ *Icebergan*

Restrictions regarding maximum significant wave height and wind speed are normally set for different access methods.¹⁵⁵ Access by boat is a relatively cheap expense, but also well proved for transfer at narrow waters. On the other hand, boat is unfeasible for high significant wave heights. Significant wave height is the height of the highest third of the waves. Jack-up vessels offer steady platforms over the waves and can also transport heavy equipment. In order to offer a steady platform, jack-up vessels require solid sea floor. These vessels are also very expensive and sensitive to significant wave heights during deployment and retraction.¹⁵⁶

Helicopters can access the wind farm up to wind speeds about 20 m/s, when the accessibility of water-borne vessels is limited. Helicopters are consequently less affected by bad weather conditions and can rapidly transfer both equipment and personnel. On the other hand, helicopter demand qualified workforce and is very expensive. Flying require good visibility and to be able to reach a wind farm, the turbine must be closed. To be able to land on a wind farm, the farm must be supplied with helipads.¹⁵⁷

The wind power operator usually has restrictions for maintenance activities. These restrictions also depend on weather conditions. Wind constraints are exemplified in Table 2.

Table 2: Example of wind constraints for maintenance activities¹⁵⁸

Wind speed [m/s]	Restrictions
≥30	No access site
≥20	No climbing turbines
≥18	No opening of the roof doors
≥15	No working on the roof of the nacelle
≥12	No work in the hub
≥10	No lifting roof of nacelle
≥7	No blade removal
≥5	No climbing on the met masts

6.2.3 Logistic Supportability

Supportability is the support organization's ability to supply the required resources to be able to perform maintenance actions. This is a measurement of the effectiveness in the support organization. The Supportability is measured as the Mean Waiting Time (MWT), which includes both Mean Logistics Delay Time (MLDT) and Administrative Delay Time (ADT). MLDT refers to the resources waiting time and ADT refers to the time it takes to organize the maintenance resources.¹⁵⁹ The organizing work for the repair action consists of:¹⁶⁰

- Selection of support vessels and hoisting equipment

¹⁵⁵ Van Bussel and Bierbooms (2003) p.383

¹⁵⁶ Stewart (2008) p.277

¹⁵⁷ CA-OWEE (2011) Offshore Wind Energy- Ready to Power a Sustainable Europe, p.37f.

¹⁵⁸ Besnard (2009) p.32

¹⁵⁹ Borgström (2006) p.28

¹⁶⁰ Rademakers (2008)

- Spare parts logistics
- Crew mobilization
- Provide appropriate maintenance equipment

6.2.4 Availability

Availability (A) is the percentage of time that the system is able to operate satisfactorily, that is when it's not down for maintenance. The availability can be calculated in many different ways and therefore it's important that the measure is relevant to the actual situation.¹⁶¹ In general the availability is expressed as:

$$A = \frac{\text{Time when equipment is operable}}{\text{Total time}} \quad (2)$$

Operational availability (A_o) is the percentage of time that the system is able to operate satisfactorily, when required. It considers all maintenance down time; both active maintenance time and waiting time are included. The mean down time (MDT) is a sum of mean time to repair (MTTR) and mean waiting time (MWT).¹⁶²

$$MDT = MTTR + MWT \quad (3)$$

$$A_o = \frac{MTBM}{MTBM + MDT} \quad (4)$$

(Where MTBM is the Mean Time Between Maintenance)

The availability is strongly dependent of the reliability. When having a low reliability the availability decreases distinctly due to maintenance down time. On the contrary, if the system has a high reliability, the system does not necessary have a high availability. Even though the failure rates are very low, which means high reliability, the maintenance work can be very time consuming (Figure 27). This contributes to a poor availability. It's challenging to find a proper balance between investment costs and costs of maintenance work. The investment costs increases the reliability and the cost of maintenance increases the maintainability, which both affect the availability of the system. Since the accessibility is always below 100% when it comes to offshore environment, it's preferable to focus on high reliability.¹⁶³

The system downtime due to failure of a specific component varies a lot. Figure 27 below shows that different components have different impact on the downtime.

¹⁶¹ Systecon Educational Supplies (2011)

¹⁶² Borgström (2006) p.27

¹⁶³ Van Bussel and Zaaijer (2001) p.120

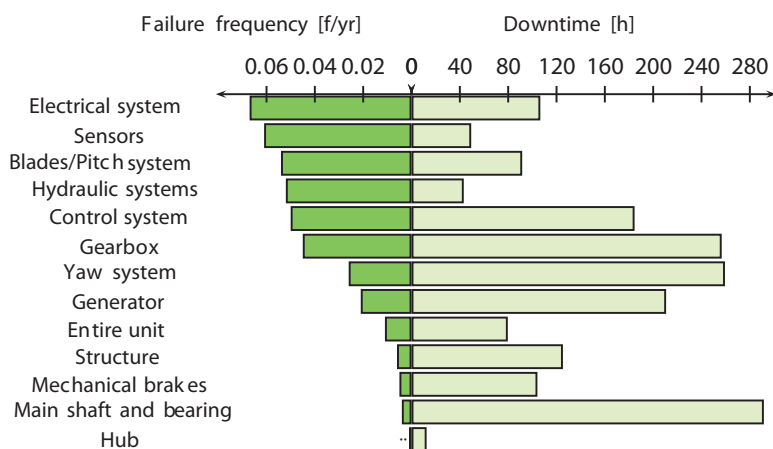


Figure 27: Average failure frequency and downtime per system and failure in Sweden 2000-2004¹⁶⁴

6.3 Weather Forecasts

There are different types of forecasts, depending on the time frame of the forecast. *Nowcasting* is weather prognosis from present time till two hours in the future. Now casting is very detailed. Very short prognoses consider weather from two to twelve hours ahead and medium term prognoses from two to ten days ahead. There are monthly prognoses, but they focus on the development of temperature. The rule to apply is the longer the prognosis; the less detailed is the information. Forecasts over long term are used as planning foundation while forecasts over shorter terms are used for decision-making.¹⁶⁵

Besnard et al write that there are forecast models that are developed to predict wind power production ten days ahead. Longer forecasts are of interest for planning of maintenance.¹⁶⁶ It's made known that 14 days is a constraint for weather predictability. Forecasts for longer periods therefore have to be based on historical data.¹⁶⁷ It's important to remember that:

A wind power model cannot be better than its weather input data¹⁶⁸.

6.4 O&M Costs of Wind Power

O&M costs for wind power is the unifying name for costs that are related to insurance, regular maintenance, repair, spare parts and administration. O&M costs represent a considerable part of the total LCC. Costs for insurance and regular maintenance are easier to predict than costs for spare parts and repair. During the turbine lifetime the O&M costs increase, but it's significantly the costs for spare parts

¹⁶⁴ Modified from: Besnard (2009) p.37

¹⁶⁵ SMHI

¹⁶⁶ Besnard (2009) p.2

¹⁶⁷ Besnard (2009) p.7

¹⁶⁸ Ackermann (2005) p.380

and repairs that are correlated and increases with the wind turbine age.¹⁶⁹ Braam et al present that O&M costs depend on many varying factors:¹⁷⁰

- The size and reliability of wind turbines
- The choice of maintenance concept (e.g. hoisting equipment)
- Distance to land, water depth and the size of the wind farm
- The wind and wave climate

The costs of O&M can be broken down in several ways. Figure 28 shows how Energy Research Centre of the Netherlands (ECN) has chosen to breakdown the costs in cost drivers, such as material and labour costs.¹⁷¹ O&M costs are usually presented as a percentage of the investment costs. Van Bussel and Henderson suggest that it's more relevant to express the O&M costs as a percentage of the kWh costs. Figure 28 also shows how availability¹⁷² varies over seasons.¹⁷³

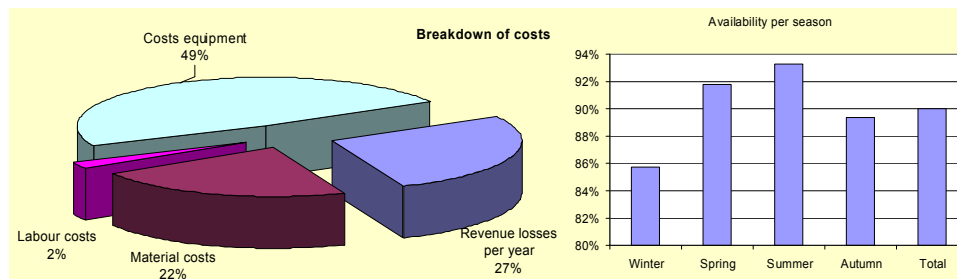


Figure 28: Breakdown of costs and availability per season¹⁷⁴

Bertling et al present the O&M cost structure for wind farms as:¹⁷⁵

- **Direct costs:** Staff, material, vessels, equipment
- **Indirect costs:** Revenue losses
- **Fixed costs:** Administration, O&M facilities, insurance, maintenance contracts

Phillips et al highlights the distinction between optimisation of O&M strategies and maximisation of wind farm availability. This distinction is illustrated in Figure X. Figure X shows that high availability can be achieved with high costs of O&M. Availability close to 100% results in almost infinite costs of O&M. The total O&M costs consist of O&M direct costs and revenue losses due to lost production. The “x” is the optimal point on the total O&M cost curve. It indicates the highest availability

¹⁶⁹ EWEA (2004) Wind Energy-the Facts, Costs & Prices, p.100

¹⁷⁰ Braam et al (2003)

¹⁷¹ Rademakers (2009) p.18

¹⁷² Van Bussel et al don't clarify calculation of availability

¹⁷³ Van Bussel et al (2001)

¹⁷⁴ Rademakers (2009) p.20

¹⁷⁵ Bertling et al (2011)

to the lowest possible operating cost. Figure 29 indicates that there are significant trade-offs regarding availability and total O&M costs.¹⁷⁶

A research that included 16 different enterprises in varying industries showed that direct maintenance costs and income losses varied in times of high and low demand¹⁷⁷. The revenues can be influenced in a larger extent than the costs according to Ahlmann. By using strategic decisions when it comes to maintenance actions, revenue losses can be reduced substantially. Maintenance actions should be performed at the moment when the revenue losses are minimal.¹⁷⁸ Revenue losses for onshore wind count for 2-25% of the O&M cost, depending on the time of the year. In August the revenue losses are about one third of the revenue losses in February, when the peak production occurs.¹⁷⁹

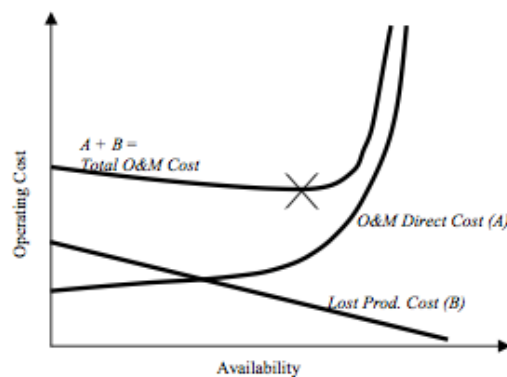


Figure 29: Indicative plot of wind farm O&M optimisation¹⁸⁰

6.5 Condition Monitoring and Control Systems

Condition monitoring systems (CMS) are commonly used within many industries. There is several different kinds of condition monitoring techniques, but interesting is that some of the techniques has proved to manage well under harsh conditions. Harsh condition is an important characteristic for a wind turbine. Braam et al. argue that condition monitoring has to be a part of the overall maintenance strategy in order to be value adding.¹⁸¹ A general definition of condition monitoring is:

Condition monitoring is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of developing failure¹⁸².

Condition monitoring can be performed in many ways. It's important to understand that the term involves online monitoring as well as non-online monitoring. An example of non-online monitoring is periodic inspections. The monitoring techniques have in common the purpose to determine the health of a system. If the intention is to

¹⁷⁶ Phillips et al

¹⁷⁷ Ahlmann (2002) p.5

¹⁷⁸ Ahlmann (2011-03-14)

¹⁷⁹ Langfeldt (2011-04-12) Nordic Wind Power Conference

¹⁸⁰ Phillips et al

¹⁸¹ Braam et al (2007) p.1

¹⁸² Ibid., p.2

monitor the health of a wind turbine two factors should be considered. The first factor is the life of the component. The monitoring is not useful if the life of the component exceeds the life of the wind turbine. The second factor is that it's wear of the component that affects the condition. Some components are *safe life components* that are components with a designed lifetime that exceeds the turbine lifetime once. Failure of safe life components depends on loading, quality or unpredictable factors. Failure of these components does not depend on wear.¹⁸³

Supervisory Control and Data Acquisition (SCADA) systems are used for observation and control of wind turbines. Sensors on the wind turbine are connected to the control system and supply the control systems with input. Sensors provide information about wind speeds and directions, temperatures etcetera. The control system constantly verifies the condition of the wind turbine. If the condition is not within tolerable limits alarms are generated. When the operator finds the alarm, he decides the arrangement needed.¹⁸⁴ False alarms from offshore wind turbines are not unusual. Ahlmann highlights that it's as important to put effort on maintaining these systems as the wind turbine¹⁸⁵.

6.6 Service Agreements and Warranties

Wind turbine manufacturers commonly offer a warranty period to the buyer. This warranty period is typically between two and five years. During this period the buyer, the wind farm operator, takes the opportunity to learn how maintenance of the wind turbine is carried out. Assumed this is agreed upon in the contract. When the time of warranty has come to an end a third party evaluate the contract and make sure that the warranty has been performed in consensus with the agreement.¹⁸⁶

When the warranty period has run out, the service of the wind turbine can be performed in different ways; by independent 3rd party service providers (ISPs), original equipment manufacturers (OEMs) or by the wind turbine owner's own service organisation. The options are related to different risks and costs.¹⁸⁷

¹⁸³ Braam et al (2007) p.2

¹⁸⁴ Besnard (2009) p.12f.

¹⁸⁵ Ahlmann (2011-03-14) LTH

¹⁸⁶ Besnard (2009) p.32

¹⁸⁷ Smee (2011-04-12) Nordic Wind Power Conference

7 O&M of Offshore Wind Farms in Practice

This chapter consists of information from interviews with Svensson and Borgström. The chapter presents how O&M of offshore wind farms is regarded and practiced, according to the experts.

7.1 Summary from Jörgen Svensson

The interview took place at LTH in Lund (2011-03-16). The interview guide can be found in Appendix A.

7.1.1 Comparison of Onshore and Offshore

There are few manufacturers that supply technique for offshore wind power. The market for offshore wind power is typically a sellers' market. On the contrary, more rivalry and several suppliers characterize the market for onshore wind power. Short experience of offshore wind power narrows the experiences of component quality. Another difference is that onshore wind farms commonly suffer from standstill due to low wind speed; this seldom occurs offshore where wind speeds often exceed the cut in speed. On the other hand it's less turbulent offshore even though the winds are stronger. It's significantly the environment that distinguishes offshore. Wind, waves, currents and salinity in air and water influence the choice of maintenance equipment and transportation mode.

7.1.2 Availability in Practice

There are three different types of availability. Production availability is the availability of a wind turbine at times when electricity can be generated. The contractual availability is the technical availability when planned service hours are subtracted. This availability is of interest for the supplier. The third availability is the technical availability. Technical availability is the part of time when the system is not down for maintenance or repair.

7.1.3 Reliability

There are many histories of wind farms suffering from bad quality and components with lower reliability than expected. One example is Nystedt in Denmark that experienced problem with gearboxes. Another example is Horns Rev in Denmark that had great problems with unpleasant component quality. Components and products for offshore wind farms require higher quality than the same components and products onshore. One reason for this is the high operational load and the degree of salinity in air and water. Another important reason for this is that maintenance offshore is more costly and time consuming. Maintenance operations offshore are therefore less desired. There are rarely no safe life components, but the components with the highest reliability are the foundation, the tower, the nacelle and cables.

Spare Parts

Manufacturers of offshore wind farms are few and there is no standardisation of components and products on the market. The operators of wind farms are therefore strongly dependent on spares from a specific supplier. This biased dependence put no pressure on the supplier. Spares have generally long lead times. Due to long lead times

and lack of component standardization, the spare part strategy is very important. The buyer of a wind farm might consider the wind farm as a black box. For some models the components are fixed and not changeable. This results in difficulties to find spares and components if reliability is lower than expected.

There are commonly no spares placed in offshore wind turbines. The most costly spare parts are large components such as the gearbox. There are other components with higher failure frequencies, but they are less expensive.

7.1.4 Maintainability

Most wind farms are designed for equipment handling accessibility. For example, Horns Rev in Denmark is equipped with helipads on top. Wind farms at sea with tide are typically supplied with ladders so the farms can be reached at times of ebb and flow. Maintenance equipment is dependent on the size of components and the surrounding environment.

There are good possibilities to localize a fault when it occurs. There are surveillance systems that give detailed localization of faults. These systems are commonly graphic. All faults cannot be read by surveillance systems, in these cases an operator must visit the wind farm to localize the fault manually. Generally, these systems contribute to better prerequisites to send operators with right equipment for the first visit.

The distance to the wind farm is of great significance and is strongly related to the time it takes to perform a maintenance or repair operation. Safety issues are a priority when it comes to maintenance of offshore wind farms. There are trade offs between maintenance operation time and the related risks.

Accessibility

Wind, waves, currents and sight deteriorate the accessibility of an offshore wind farm. If the temperature is too low and ice appears the wind farm cannot be reached. Different components have different requirements on the accessibility for repair and replacement actions. The choice of transportation means is based on the size of the component, what maintenance equipment that is needed, the urgency of the maintenance activity and the distance. Time to perform repairs and replacements depend on accessibility and are longer due to safety issues and surrounding environment. It's of great importance that the maintenance actions are performed on time. Semi-finished repair and replacements are not desirable. For some actions the work can be split in smaller parts.

7.1.5 Logistic Supportability

Maintenance actions are well documented with regard to reliability and safety. Good documentation has a positive impact on the learning curve. Accommodation and inventories offshore will probably be common in the future.

7.1.6 Costs and Profits and the Capacity Factor

The distribution of costs between work, maintenance equipment and components are highly varying. Components that are relatively cheap to buy and to handle can contribute to high costs due to revenue losses.

The capacity factor is determined during the planning phase of an offshore wind farm. It is later used as an indicator for what is expected. Calculation of the capacity factor:

$$\text{Capacity Factor} = \frac{\frac{\text{Planned Production (Wh)}}{\text{Installed effect (W)}}}{\text{Total production hours per year (h)}} \quad (5)$$

The generator power and the rotor diameter must be balanced in order to avoid the capacity factor paradox.

7.1.7 Maintenance in Practice

The worst thing that can happen is to be unprepared when failure occurs. To reduce the corrective maintenance that commonly is very costly, preventive maintenance is performed. Once a month supervision of the wind farm takes place where maintenance crew follows a checklist. This could be inspection of oil levels etc. Competent personnel can listen to the system in order to determine the condition. Once or twice a year more exhaustive maintenance actions of wind farms are performed. This maintenance of each wind turbine takes about two or three days. Yearly maintenance is throughout and commonly amount full-time job for the maintenance crew.

When planning maintenance actions, the safety is highly prioritized. There is generally a culture to improve the safety. Occurrences and accidents are therefore always well documented. Focus is also on minimizing costs and increase availability. The trade off between these factors has to be balanced. To consider the electricity price in planning of maintenance is something that should be done in larger extent when contracts with fixed price have run out.

Weekly weather forecasts are used as an indicator for planning of maintenance actions. To get a more detailed and reliable prediction, one-day forecasts are used. During summer months when wind speeds regularly are lower, safety for maintenance actions increases. This is the time of the year when maintenance actions preferably is performed. Maintenance crew typically departs early in the morning to be able to work in daylight.

7.2 Summary from Håkan Borgström

The interview took place at Systecon in Malmö (2011-04-19). The interview guide can be found in Appendix B.

7.2.1 The Price of Power

A major part of power produced by offshore wind turbines in Europe is subsidised. This results in well-known power prices for generated power and the fluctuations in market spot prices are therefore not considered in the logistics analyses. Market prices will probably be of greater relevance in the future, along with industry maturity.

7.2.2 Life Cycle Cost & Life Cycle Profit

Offshore wind is a dynamic market. Embracing the LCC perspective would only put focus on costs and result in emphasis on minimizing the O&M costs. This point of view doesn't focus on maximizing the value generation though an optimal balance

between O&M cost and production revenues. In order to consider this a LCP view must be adapted.

7.2.3 Internal and External Efficiency

The produced power is fed into one common grid, and it is therefore not relevant to talk about quality of the end product. Focus is on maximizing the value generation through an optimal balance between O&M cost and production revenues. The utilities goodwill benefits from that wind power is green energy.

7.2.4 O&M Costs

Some of the largest cost drivers are acquisition of major components, logistics and labour costs. The cost of a major component breakdown includes both purchase cost and replacement cost. Production losses could be major cost drivers too, but for a well-operated and maintained wind farm this should not constitute the largest cost.

7.2.5 Maintenance Performance Indicators

The yield concept is an important measure of production and is expressed as a percentage. The yield concept takes into consideration the wind resource and captures availability with regard to this. The concept enhances maintenance in times of low wind speed.

8 Key Findings Part I

This chapter analyses information from theory and interviews from previous chapters in Part I. The key findings are used as input to Part II and aims to answer the questions: Which factors are the most characterising for maintenance of offshore wind farms? What maintenance approach is suitable for offshore wind farms?

8.1 Distinct Patterns for Offshore Wind Farms

Since wind is the main production resource in offshore wind farms, it's of high importance to consider seasonal and diurnal wind patterns. According to theory, the power production can vary $\pm 15\%$ compared to the average production over long term. Planning maintenance with regard to wind patterns decreases revenue losses and consequently maximizes the production. The power curve, shows that maintenance ought to be avoided at wind speeds when the rated power is reached. The authors believe that it's important to point out that variations in wind speeds affect the production volume.

Performing maintenance during calm wind conditions, to the largest possible extent, is beneficial in many aspects. According to Langfeldt, there are large seasonal variations in revenue losses due to maintenance. Regarding onshore wind farms the revenue losses in August are about one third of the revenue losses during peak production. This distinct difference probably becomes even larger for offshore wind farms, where the O&M costs counts for a larger part of the kWh price according to Braam.

The merit order effect implies that the price of wind power is normally low in periods with high wind and vice versa. This is not the case regarding offshore wind since this source of energy commonly is subsidised according to Borgström. The price of offshore wind power is thus well known. With this knowledge, the authors claim that variations in the power market can currently be disregarded, concerning maintenance of offshore wind farms. One must consider that this is the actual case at present when the offshore wind industry is immature. Svensson claims that the electricity price should be considered in larger extent for planning of maintenance when contracts with fixed prices have run out. According to Borgström market prices will probably be of greater relevance in the future, along with industry maturity.

Wind power is a preferred energy source due to its low environmental impact. A consequence of this, in combination with fixed price for offshore wind power motivates that seasonal and diurnal variation in power consumption also can be disregarded for the time being. There are large profits to gain by maximized production in periods when the market price is high. This is also a future case when the offshore wind industry becomes a bigger player on the power market.

8.2 An Optimal Maintenance Approach

It's important to look at costs during the entire life cycle and "invisible" costs for O&M must not be forgotten. Ahlmann argues that focus on costs alone is not enough since enterprises aim to generate revenue; LCP is therefore a necessary extension of

LCC. Borgström claims that offshore wind is a dynamic market. A LCC perspective will only contribute to reduction of maintenance costs. In order to benefit from maintenance a LCP perspective is desirable. With these facts on hand, the situation linked lifecycle models can be regarded. The authors establish that a turbulent and dynamic market, that characterizes offshore wind power, must be approached with a LCP perspective. This approach will enhance the maintenance function to support business and focus on revenue and external effectiveness. Establishing the LCP approach further strengthens the paradigm shift in maintenance presented by Parida and Kumar. The present scenario is that maintenance creates additional value and makes an important factor for companies in order to retain profitability. This is aligned with the LCP approach.

Borgström and Ahlmann introduce the BOM concept where maintenance activities aim to maximize LCP. To be able to maximize ROA, dependent improvement actions that bring multiplicative results must be performed. According to Borgström a LCP approach will regard the optimal balance between O&M cost and production revenues. Consequently, the authors believe that a LCP approach will clarify benefits from maintenance at low wind speeds. This clarification will increase both internal and external efficiency. External efficiency is related to production volume, since produced power is fed into one common grid, and quality of the end product is not a matter of relevance. Total assets turnover constitute the internal efficiency. The authors claim that the LCP approach will put focus on BOM and increase ROA by clarification of the value that dependent improvement actions bring. Sub-optimization of maintenance costs can also be avoided with focus on revenue.

8.3 Applied Availability

Characteristics for offshore wind farms that concern reliability, maintainability and logistics supportability are shown in Figure 30.

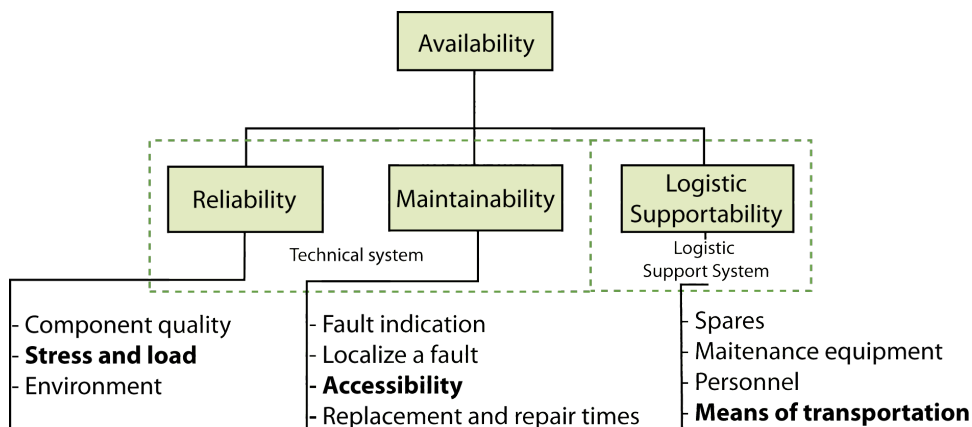


Figure 30: Offshore Wind Farm Characteristics

8.3.1 Reliability

Svensson argued that there are examples of wind farms suffering from components with lower reliability than expected. This is due to lack of experience of components

in offshore wind turbines. The component qualities and lack of “right” failure rates characterize offshore wind farms; failure frequencies are therefore related to significant uncertainties. Due to high wind speeds that characterize offshore environments, wind turbines suffer from higher stress and load than onshore. This results in higher failure frequencies and lower reliability for offshore wind turbines. Salinity in air and water typify offshore environments and has negative impact on component reliability. Since accessibility is related to high costs offshore; better component quality is therefore desired. This is difficult at present due to *the black box* problem presented by Svensson.

8.3.2 Maintainability

Today’s advanced control systems return an alarm when faults occur and it also enables remote fault localization. This is highly valuable since it’s very costly to access the wind farms. In this way appropriate maintenance equipment can be provided directly. On the other hand, these systems often give false alarms, which results in unnecessary visits. Trade-offs between acquisition of high quality control system and costs for transportation to the site must be considered. Concerning the replacement and repair times, Svensson argued that these times generally are longer offshore than onshore.

Distance to the wind farm is of great significance and downtimes are strongly related to waiting times for suitable weather windows. Since safety issues are a priority when it comes to maintenance of offshore wind farms, trade-offs between time of maintenance activities and the related risks are essential. The significant wave height, wind speed and visibility determine if the site is accessible. Regard to currents, ebb and flow must also be taken, especially when it comes to docking, which is the most critical part. The authors claim that accessibility is the major and most critical feature regarding maintenance of offshore wind farms. It generally affects all costs that are related to maintenance.

8.3.3 Logistic Supportability

Svensson says that good documentations and experience of maintenance actions have a positive impact on the learning curve and thus the organisation’s logistic supportability. The market for offshore wind power is typically a sellers’ market. Therefore, spare parts for offshore wind turbines characteristically have long lead times. Maintenance equipment must be adapted to wind and waves in the surrounding environment. There are also high requirements on personnel skills, especially skills and education related to different transportation vessels, safety and maintenance equipment. Accessibility is distinguishing for maintenance offshore and has direct impact on the choice of transportation mean. Modes of transportation must manage docking in harsh weather conditions. The choice of transportation mean is also affected by limiting values. Vessels are one of the major cost drivers and must therefore be chosen appropriately. Logistic supportability includes many trade-offs, which regards number of crews, shifts, working hours, competences and transportation means.

8.3.4 Wind -A Cost and Value Driver

The offshore environment is characterized by wind. Wind is a cost driver but it's also the main revenue driver. Figure 30 highlights (bolded) factors that directly depend on weather conditions. Wind worsens reliability of components by stress and load. Accessibility is also affected by weather conditions, which in turn have impact on transportation mean. These highlighted factors are associated with trade-offs, availability versus costs, which are complex by nature. This complexity denotes the fact that wind drives costs as well as revenues. It's in the authors' belief that the LCP approach will clarify trade-offs and the revenues associated with these.

8.4 O&M Costs

Theory shows that O&M costs can be broken down and expressed in different ways. Bertling et al present a cost distribution that differs between direct, indirect and fixed costs. Indirect and direct costs typically depend on stochastic variables in contrast to fixed costs. It's in the authors' belief that this distribution of costs supports the preferred LCP approach. Since revenue losses are expressed as indirect costs, this cost distribution encourages focus on BOM.

It's beneficial to understand seasonal trade-offs between revenue losses and direct O&M costs. By regarding total costs for O&M from a LCP perspective the authors reason that this trade-off will be easier to detect. It will also support reduction of both direct and indirect cost. Important to remember is that revenue losses can be influenced to a larger extent than costs. This is pursuantly to Ahlmann's research. Offshore wind farm is associated to large revenue losses due to lost production. The authors believe that embracing a LCP approach results in reduced revenue losses. Consequently, revenue losses for offshore wind farms can be influenced to some extent.

Some of the largest cost drivers are acquisition of major components, logistics and labour costs. Production losses could be major cost drivers too, but for a well-operated and maintained wind farm this should not constitute the largest cost, according to Borgström. Svensson argued that O&M costs for labour, maintenance equipment and spare parts vary. Spare parts that are relatively cheap to buy and handle might result in high costs due to revenue losses. Svensson highlighted that the distance between the wind farm and mainland is strongly related to the time it takes to perform maintenance actions. According to Braam et al the most common factors that drive costs are size and reliability of wind turbines, maintenance concept, distance to land, water depth and weather. Since costs depends on many different factors the distribution of costs between different wind farms differ. The authors emphasize that except from acquisition cost of components, it's the distance between the wind farm and mainland that affects and drives the costs, not least revenue losses.

8.5 Maintenance Performance Indicators

The capacity factor is commonly used in power plants. Svensson says that it's common to use the capacity factor in the planning phase of offshore wind farms. It's used as an indicator for future expectations. In theory the capacity factor is measured differently than what Svensson explains. The authors think that the concept is confusing since it's

used differently. Therefore the capacity factor should not be used as a MPI. This is further strengthened by not considering wind as a cost and value driver.

Another confusing MPI is availability, which can be calculated in several ways. Availability is key in order to generate power, but high availability during low wind speeds brings no value. According to the LCP concept a preferable availability must cease revenue and enhance maintenance during low wind speeds.

Johansen explained that the most important PI's for Vattenfall are EBIT and safety. He further clarifies that EBIT depends on factors such as availability, wind speed, accessibility, lost production and MTBF. The authors believe that EBIT is a desirable MPI since it enhances the LCP approach.

Dong Energy uses the yield-concept, which is widely used in the wind power industry at present. The authors claim that the yield concept is preferable since it considers wind as a cost and value driver. Further, the yield concept will reflect upon internal and external efficiency and is therefore an excellent MPI. An advantage is that it also ceases value created by maintenance, justifying investment and revising resources. According to the authors, the yield concept should be calculated as energy yield. The calculation is presented in Formula 6. Energy yield is a fraction of the sum of energy production over a given time divided by possible energy production over the same time. The possible production refers to how much power that is possible to produce according to current wind condition. The energy yield concept, presented in Figure 31, shows how wind as a cost and value driver is connected to availability and how these factors constitute the energy yield.

$$Energy\ Yield = \frac{\sum_t Energy\ Production(t)}{\sum_t Possible\ Energy\ Production(t)} \quad (6)$$

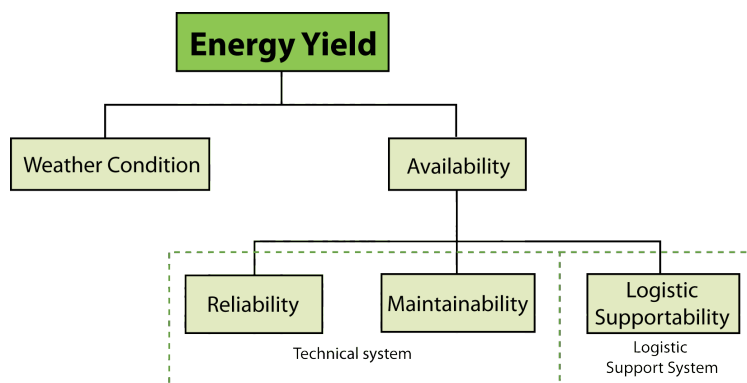
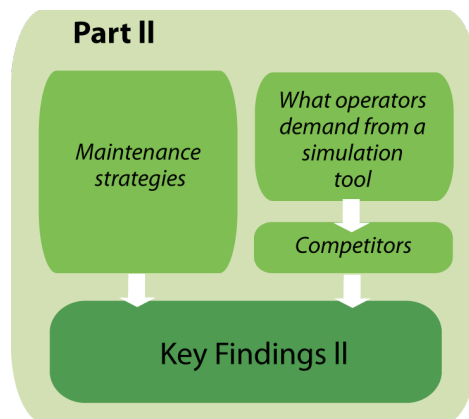


Figure 31: The yield concept

PART II



Chapter 9: Maintenance Strategies
Chapter 10: Simulation Tools for O&M of Wind Farms
Chapter 11: Experiences from O&M Simulations
Chapter 12: Key Findings Part II

9 Maintenance Strategies

This chapter describes maintenance concepts, the relationship between these, and how maintenance can be categorized.

9.1 Maintenance concepts

Swedish Standard, SS-EN 13306, has determined that maintenance is a combination of all technical and administrative actions during the life cycle of an item intended to retain or restore it to a state in which it can perform a required function¹⁸⁸. Figure 32 illustrates maintenance, where corrective and preventive maintenance constitutes the main maintenance concepts.

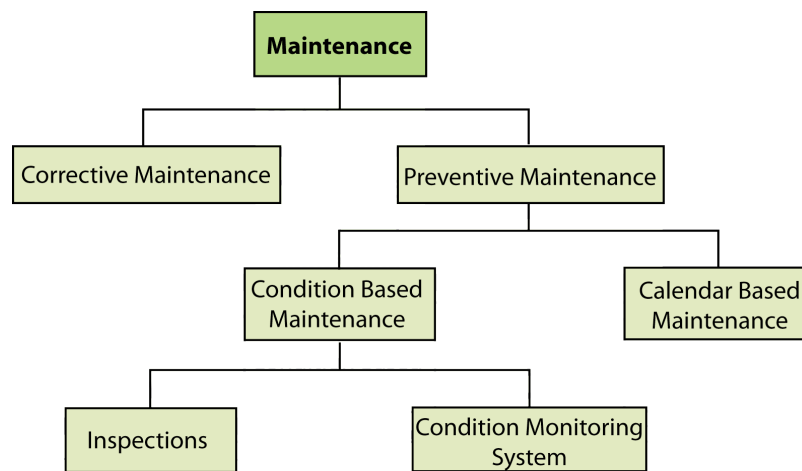


Figure 32: Types of Maintenance concepts¹⁸⁹

9.1.1 Corrective Maintenance

Corrective maintenance (CM) is performed in order to restore or repair a system's functionality¹⁹⁰. CM is unplanned maintenance, commonly associated with failures that are difficult to forecast. In a wind power context, CM is related to higher costs in the wind farms' early years.¹⁹¹ The CM cycle includes activities such as failure identification, localization, item removal, replacement or repair and condition verification¹⁹².

9.1.2 Preventive Maintenance

In order to prevent breakdowns and failures, preventive maintenance (PM) is performed. PM aims to prevent failure before it occurs and is generally carried out according to a schedule. PM can be subdivided into two main approaches: calendar based maintenance and condition based maintenance (CBM).¹⁹³ By performing PM

¹⁸⁸ Swedish Standard SS-EN 13306 (2001)

¹⁸⁹ Besnard (2009) p.24

¹⁹⁰ Marais and Saleh (2009) p.645

¹⁹¹ Obdam et al (2008) p.3

¹⁹² Blanchard (2004) p.36

¹⁹³ Rademakers et al (2008) p.4

activities, costs for unscheduled breakdowns can be reduced. Following benefits is received through PM:

- Improved system reliability
- Decreased cost of replacement
- Decreased system downtime
- Better spares inventory management

PM makes no sense if it's assumed that failure rates are constant no matter how much PM tasks that are performed. Maintenance must have an impact on the failure rate, since the aim is to increase the reliability in order to avoid CM.¹⁹⁴ An advantage with PM is that it can be scheduled during periods with low wind speeds, which result in lower impact on yield.¹⁹⁵ Figure 33 shows the relationship between the costs of PM and CM. In order to minimize total costs, one must find an appropriate balance concerning PM and CM.

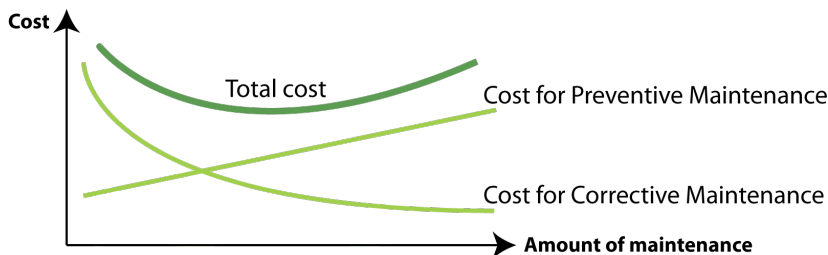


Figure 33: Total Cost for PM and CM¹⁹⁶

Calendar Based Maintenance

Calendar-based maintenance is carried out according to predefined time intervals. It's preferable for failures that are related to the age of the components. In that case the probability distribution of a failure can be set. In general calendar-based maintenance becomes more frequent over time, for example due to an increased need of oil changes in gearboxes. PM involves activities such as: equipment checks, partial or complete overhauls at specified periods, changes of consumables etc.¹⁹⁷

Condition Based Maintenance

By monitoring current status or performance of a system, CBM tries to find the right time for maintenance. Inspections as well as CMS are used in order to determine what type of maintenance that is needed. Inspections implicate tests, monitoring techniques or use of human senses i.e. noise and visual. CMS can be applied to failures that are not related to the age of the component and monitor the status continuously.¹⁹⁸

¹⁹⁴ Weibull.com

¹⁹⁵ Mc Millan, and Ault (2007)

¹⁹⁶ Modified from Johansson (1993) p.42

¹⁹⁷ Rademakers et al (2009) p.21

¹⁹⁸ Besnard (2009) p.24

9.1.3 Opportunistic Maintenance

When PM or CM is performed on a component of a system, opportunistic maintenance (OM) is the opportunity to carry out maintenance on other components¹⁹⁹. Even though the time for maintenance of this component isn't optimal it might be more cost-effective and convenient. Instead of optimizing maintenance of each component in the system it's beneficial to consider the system as a whole. This holistic view enhances OM. The main objective with OM is to benefit from resources; efforts and time already dedicated to maintenance of others parts in the system, in order to reduce total costs. OM is most beneficial if close by components must be maintained, but also when transport costs are significant.²⁰⁰ OM performance reduces downtime by avoiding CM; it also improves the system's safety and reliability. Over term, OM decreases the total maintenance costs and revenue losses. In order to decide if OM should be performed, assumed an opportunity arises, many factors, such as criticality and costs, must be considered.²⁰¹

9.1.4 Classification of Maintenance

Failure frequencies are often used in order to categorize components. This classification in itself provides limited information about maintenance actions, for instance the character and duration of repairs. In order to provide this kind of information in a classification, van Bussel and Zaaijer have developed four categories for O&M of offshore wind farms:

- Category 1: Heavy components
- Category 2: Large components
- Category 3: Small parts, 48 hours repair time
- Category 4: Small or no parts, 24 hours repair time

Different categories require diverse resources. For instance, category 1 includes the most severe repairs that require a crane and category 4 includes the least severe faults.²⁰²

¹⁹⁹ *MIRCE Academy*

²⁰⁰ *Weibull.com*

²⁰¹ *MIRCE Academy*

²⁰² Bierbooms and van Bussel (2002)

10 Simulation Tools for O&M of Wind Farms

In this chapter O&M tools for offshore wind farms are described: O2M from Garrad Hassan, O&M Tool and OMCE from ECN and CONTOFAX from University of Delft. The description mainly regards scope of use, input data and simulation output.

At present, there are few companies on the market that offers modelling tools for O&M of offshore wind farms. The energy research centre of the Netherlands (ECN) presents different existing tools that model O&M aspects of offshore wind farms:

- CONTOFAX from Delft University of Technology
- O2M from Garrad-Hassan
- BMT SLOOP from BMT²⁰³
- ECN O&M tool and OMCE from ECN

The models (except from ECN's O&M Tool) are based on Monte Carlo analysis and handles failures taking place on a stochastic basis. All of the models focus on modelling of unplanned CM aspects, but they also take PM into account.²⁰⁴

10.1 O&M Tool and OMCE from ECN

The wind energy unit at ECN, in collaboration with Delft University has been developing methods and tools to optimize O&M of wind farms for more than 15 years. Their focus has been on lowering the O&M costs for offshore wind farms since year 2000. ECN has been recognized for many years to have a leading role in the field of O&M for offshore wind farms. Many owners and operators today use ECN's knowledge and models to develop O&M strategies for their offshore wind farms. ECN has developed two tools for O&M of offshore wind farms: O&M Tool and the O&M Cost Estimator (OMCE). O&M Tool, which is a predecessor to OMCE, is available as a commercial software package. It's a cost-modelling tool, not a simulation tool that uses mean values from long-term data as input.²⁰⁵ ECN is currently developing the cost estimator tool: OMCE, which is only available as a demo- version at present. OMCE is a simulation tool programmed in Matlab, which is applied in the operational phase. It contains building blocks that use information from acquired operational data from a specific wind farm and a calculator that generates output.²⁰⁶ In the following section the modelling approach for OMCE will be described, which has a similar structure as the O&M Tool.

10.1.1 Scope of Use

OMCE estimates costs for the next coming 1-5 years for a specific wind farm. The cost estimates can be used in several different ways e.g:

²⁰³ BMT Sloop will not be discussed further due to lack of information. Information about the BMT Group can be found at: <http://www.bmtrenewables.com/>

²⁰⁴ Rademakers et al (2009) p.14

²⁰⁵ Rademakers et al (2008) p. 2

²⁰⁶ Braam et al. (2009) p.3

- Decide how to continue with O&M after expiration of the warranty period
- Make reservations for future O&M costs
- Change or improve the initial O&M strategy

10.1.2 Input Data

Input from different factors in the system is required in order to obtain useful information. Data from O&M, SCADA systems, condition monitoring and load measurements are interpreted as useful information. Data regarding failure rates, repair actions, vessel usage, spare parts and weather conditions are analysed in concern of CM. Data from condition monitoring and load measurements are analysed in concern of CBM.

OMCE includes different blocks for processing of available data from an offshore wind farm in order to obtain useful information. The result from these blocks is used as input to the OMCE-calculator, where the simulations are run. The information flow, from raw data to estimated O&M costs is illustrated in Figure 34. Five Building Blocks (BB) is specified that contains different data sets: Operation & Maintenance, Logistics, Loads & Lifetime, Health & Monitoring and Weather Conditions. The purpose of the Operation & Maintenance block is to gather information about failure behaviours to evaluate the appropriateness of maintenance strategies and rank and perform trend analysis of failures. This information is used as input to the OMCE-calculator regarding repair actions and failure frequencies. In the Logistics block, resource and spare part utilization is evaluated for maintenance and repair actions. The Logistics block generates information about accessibility, repair times, number of visits, lead times for spare parts etc. to the OMCE-calculator. The purpose of the Loads & Lifetime block is to analyse load measurements from different turbines. The Health Monitoring block provides information about the health of the components. Information from these two blocks results in input to the OMCE-calculator regarding expected time to failure of components. The development of these two blocks is not finalized and consequently they are not available in the demo-version. In the O&M Tool, CBM is interpreted as a percentage of stochastic failures that are fixed before they actually occur.

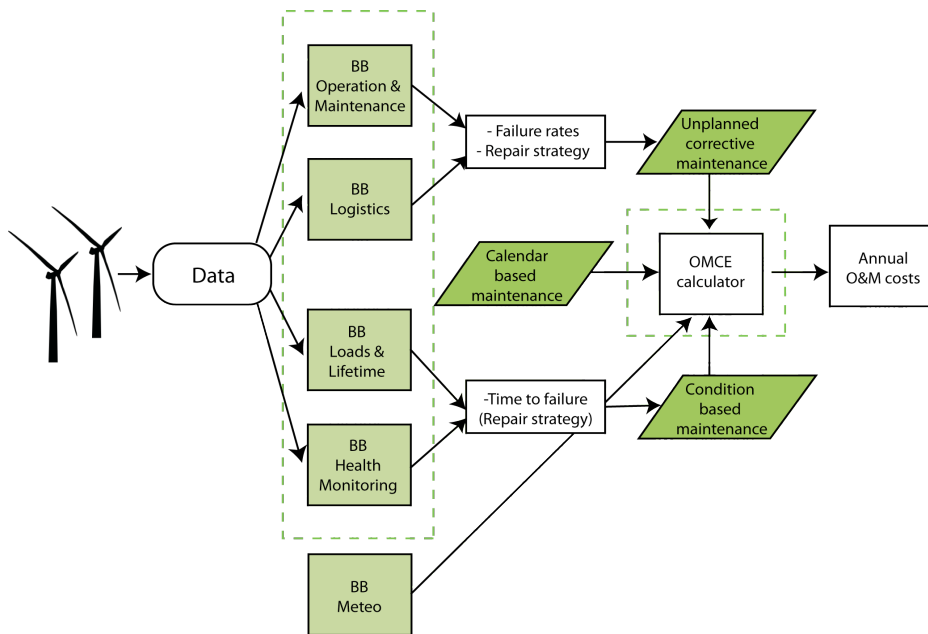


Figure 34: Shows the data flow from raw data to estimated O&M costs²⁰⁷

The Weather block contains wind and wave measurements from a specific site. In order to calculate waiting time due to bad accessibility, historical wind and wave data with three-hour intervals is used. Weather windows are created from weather data and based on this, average waiting time for suitable weather to occur after a failure is defined. Figure 35 shows how mean value waiting time depends on mission time.²⁰⁸

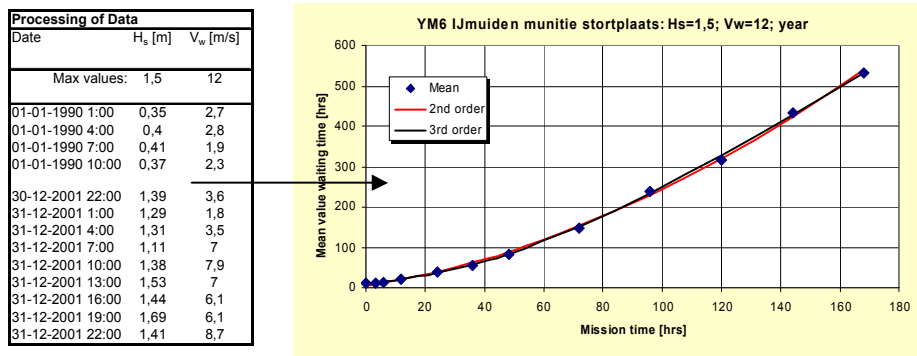


Figure 35: Mean value waiting time and mission time²⁰⁹

10.1.3 Simulation Output

The model can be applied in order to make trade-offs and optimize O&M logistics aspects regarding offshore wind farms. Following exemplifying questions can easier be answered with help from the model:

²⁰⁷ Modified from Rademakers et al (2009) p.21

²⁰⁸ Rademakers et al (2009), p.30ff.

²⁰⁹ Ibid., p.17

- Is it beneficial to buy vessels instead of renting?
- Is it beneficial to have spare parts for a certain component in stock?
- How do different maintenance strategies affect the downtime?

The simulation output consists of key parameters such as: costs, downtime, availability, cost drivers, waiting times, uncertainty analysis etc. O&M cost breakdowns make it easy to analyse different costs, but also revenue losses.²¹⁰ O&M costs are typically expressed as cost per kWh and seasonally distributed²¹¹.

10.1.4 Maintenance Concepts and Classification of Actions and Faults

OMCE separates maintenance into three types: unplanned CM, CBM and calendar based maintenance. Regarding unplanned CM, the input consists of observed failure rates of the components that belong to the block, *Operation & Maintenance* and costs associated to the repair determined by the Logistics block. Input for CBM comes from degradation of the components. The blocks Health Monitoring and Loads & Lifetime are related to this input data and the block Logistics is related to the associated repair costs. For the calendar-based maintenance, the input is expressed as number of repair days and associated costs for equipment, spare parts, labour etc.²¹² Usually PM is scheduled during summer season, when it's less windy²¹³.

To be able to keep off individual evaluation of each failure that occurs, classification of maintenance actions is done. ECN splits maintenance actions into different categories dependent on required resources and repair times. Each maintenance class is separated into different fault type classes. Repair class, spare control strategy and priority level is then defined for each fault type class.²¹⁴ The repair classes include different phases: inspection, replacement and repair. The user defines the sequence of these phases. All phases are characterized with specific: time to organize, duration, equipment needed and crew size, where each vessels type has its own weather windows.²¹⁵ The model allows the user to prioritize which maintenance that shall be carried out first²¹⁶.

10.2 O2M from GL Garrad Hassan

GL Garrad Hassan is a consultancy firm within the field of renewable energy. They have been technical experts on wind power for the past three decades.²¹⁷ GL Garrad Hassan offers a range of software, among others a dynamic module for the design of wind turbines, an O&M simulation package (O2M) and a wind farm layout optimisation tool. O2M is based on Monte Carlo simulations.²¹⁸

²¹⁰ Rademakers et al (2009) p.23

²¹¹ Ibid., p.15

²¹² Braam et al. (2009) p.3

²¹³ Rademakers et al (2009), p.8

²¹⁴ Ibid., p.25

²¹⁵ Rademakers et al (2009), p.23

²¹⁶ Ibid.

²¹⁷ *GL Garrad Hassan*

²¹⁸ GL Garrad Hassan (2010) GL Garrad Hassan, p.8ff.

10.2.1 Scope of Use

O2M considers weather windows, vessel size, availability of spare parts, wave climate and labour options among others. The model regards trade-off between revenue losses and costs related to different resource strategies.²¹⁹ It also evaluates wind farm performance and optimises O&M strategies. O2M is able to simulate several wind farms supplied from a mutual base. In summary, the model is developed to support O&M decision-making during the entire project life.²²⁰

10.2.2 Input Data

Input data and assumptions are categorised in four blocks: Environment, Project description, O&M resources and Failures (Figure 36). Time series of significant wave height constitute the input data in the Environmental block. There is also a correlation between wind speed and significant wave height that is regarded in this block. Location of stores, mobilisation and travel times and number of turbines etc. are defined in the Project description block. O&M resources require information about holding facilities for spare parts, access vessels and service crews. Limiting values for safe turbine access are also given in this block. The fourth block, Failures, needs information from appropriate failure modes. This information consists of failure frequencies, MTBF, and time to repair. Service intervals for PM must also be defined as well as essential assumptions. An essential assumption is for instance labours that cannot be utilized when limiting values are exceeded, but it also includes prioritizing of maintenance actions. When failure appears, available crew is assigned. Weather conditions must be within given limits in order to deploy the crew. If weather limits are outreached, crew must stay at base until more favourable weather occurs.

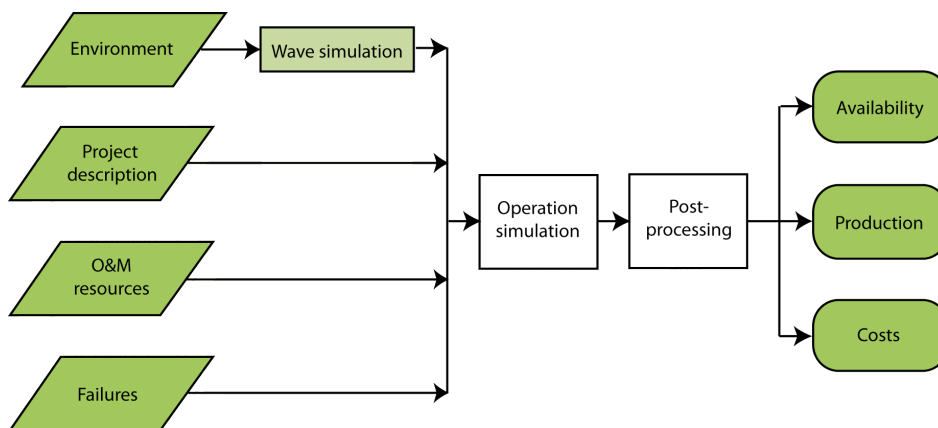


Figure 36: Simplified block diagram of the O2M model structure²²¹

Weather conditions and turbine failures are stochastic input in the O2M model while infrastructure constraints and essential assumptions are deterministic input.²²²

²¹⁹ Ibid., p.10

²²⁰ Philipps et al

²²¹ Modified from Morgan et al

²²² Philipps et al

Weather Simulation

Onsite measurements of significant wave heights commonly range shorter periods of maximum three years. Since O2M simulates over 100 years the onsite measurements are constraining. An approach based on spectral analysis is therefore used. This approach avoids repetition of time series and significant wave height becomes a completely stochastic element in the simulation. If weather condition is worsening during simulation, maintenance activities are interrupted.²²³

10.2.3 Simulation Output

Throughout the simulation, key output parameters such as availability, accessibility and lost production are recorded. Except from these parameters there are several outputs that are of interest for O&M analysis.²²⁴ Typical outputs are availability, production and costs (Figure 36). Output parameters can be presented as illustrated in Table 3.

It's also possible to compare different input data, for instance how different number of crews affects factors such as availability and total O&M costs. Different O&M strategies can be expressed in terms of costs in the simulation model. Results from the simulation are presented on seasonal basis, in order to capture the correlation between high wind speeds and low accessibility.²²⁵

Table 3: Example of output parameters in the O2M model²²⁶

Output Parameter	Long-term Mean
Availability	92,40%
Accessibility	80,60%
Ideal Production (GWh/annum) 1	955
Actual Production (GWh/annum) 2	872
Lost Production (GWh/annum) 3	83
Energy Availability 4	91,30%

1. Net production, not including turbine downtime
2. Net production, including turbine downtime
3. Production value of turbine downtime
4. Actual production as a fraction of ideal production

10.3 CONTOFAX from Delft University of Technology

Delft University of Technology has developed the CONTOFAX code. Given a maintenance strategy, the model determines needed and possible actions; CONTOFAX also deals with spare parts logistics. Input data in the model is typically information about labour, shifts, working hours per week, vessels and equipment. Simulation output is total O&M costs, produced energy and availability. The weather simulation is stochastic. Parameters from inaccessibility percentage and average wind speed, during summer and winter, constitute a two-parameter Weibull representation.

²²³ Ibid.

²²⁴ Morgan et al

²²⁵ Philipps et al

²²⁶ Philipps et al

Advantageous is that no detailed information about wind and wave condition from a specific site is needed with this method.²²⁷

²²⁷ Van Bussel and Bierbooms (2003) p.386f.

11 Experiences from O&M Simulations

This chapter consists of information from interviews with Borgström from Dong Energy and Besnard from Chalmers/Vattenfall. Experience from O&M simulations are presented, but also what Besnard and Borgström request of an O&M simulation tool.

11.1 Experience from Dong Energy

The interview with Borgström took place at Systecon in Malmö (2011-04-19). The interview guide can be found in Appendix B.

11.1.1 Dong Energy's Experience from Simulation of O&M

The Dong Energy's primary objective regarding simulations of O&M is to model logistics strategies realistically. This can be exemplified with transportation of personnel and components to wind farms in the most efficient way, given certain weather conditions. It's all about trade-offs between costs and production losses, where the aim is to achieve maximum value.

Decisions regarding O&M are generally based on practical experiences. When it comes to wind farms in new environments with unfamiliar weather conditions, there's lack of experience to lean on and consequently it's preferable to use simulation models. Most commonly, results from a simulation model are used in along with experience and engineering expertise.

Wind Speed and Significant Wave Height

Time series of wind speed and significant wave height is used as simulation input. The data is site specific and several years of historical are required for the data to be representative. Weather is an input with high uncertainties, since there are variations from year to year.

11.1.2 Key functionalities in a Simulation Tool

Dong Energy highlights that the scope of use for O&M simulations is to evaluate logistics strategies regarding access of wind farm. What the operator demand is to find the best logistics solution for a specific site based on given environment and weather conditions. Based on several years of experience from simulating offshore wind farms Dong Energy emphasizes the following key functionalities in a simulation tool:

Simulate Clustering of Sites

Sharing resources between wind farms must be looked upon and regarded in a simulation. Simulation of several wind farms in different environments with different distances to shore and different types of turbines opens up for many possibilities. Possibilities like common plant centres, shared resources and lateral transports of components.

Accommodation at Sea

Offshore accommodation is important to analyse since there will be more far offshore sites in the future.

Failure Frequencies Patterns

It's unrealistic that failure frequencies are constant in a simulation model. Since component failure frequencies generally follow the bathtub curve, it would be advantageously to split the lifetime into different time periods, with different failure frequencies.

Wind Speed Related to Production

Wind data should also be related to production in a simulation model. Regarding wind and wave data for both access limits and production enables trade-offs regarding the value of performing maintenance activities under certain wind conditions.

Shifts

Simulations should have the ability to handle different type of work shifts

Application Handiness

New users must be able to learn how to use the model and understand the basics behind the model in order to use it appropriately. Consequently user-friendliness, transparent and intuitive models are important in order to gain trust in the models.

11.2 Experience from Vattenfall

The interview with Francois Besnard took place at Systecon in Stockholm (2011-05-16). The interview guide can be found in Appendix C.

11.2.1 The O&M Tool

At time being, Vattenfall uses ECN's O&M Tool. The license was bought in 2007; in 2010 Besnard developed an extended version in collaboration with Stalin at Vattenfall. The ECN O&M Tool has been used for decision basis in some projects, conversely to the extended version. Hopefully the updated version will be used with this purpose in the future. Except from Vattenfall, there are about twenty users of ECN's O&M Tool. The users are a mix of project developers, turbine manufacturers and consultants. Common is that a standard model is bought, that later can be developed from own desires.

Evaluation of the O&M Tool

Besnard believes that the O&M Tool is user friendly. Primarily because it's programmed in MS Excel, which makes it easy to use and adapt. But it's also an open model that is easy to understand. New users are provided with general input data from ECN, which Besnard consider an advantage for operators. The production is not directly calculated with the O&M Tool, it depends on the average capacity factor that is determined from historical data. It can also be defined with a Weibull distribution.

11.2.2 What Vattenfall Demands from a Simulation Tool

According to Besnard there are several aspects that preferably should be considered in a simulation model. Redundancy is one of these aspects as well as OM. Since weather has big impact on wind farms, and reliability has seasonal variations, failure frequencies that vary are desired. It's also important to split long maintenance activities in shorter activities since this captures reality performance.

It's not enough to model hourly weather windows since duration maintenance activities differ and are commonly longer than one hour. What must not be forgotten are the high costs of maintenance resources, a model should therefore contain the possibility to coordinate resources and be able to show results of resource interactions. Generally, costs and availability are of great interest at Vattenfall. A simulation model that compares different maintenance strategies and the related costs and resulting availability are therefore desirable. Besnard has in previous research considered the profit aspects of O&M of offshore wind farms and implies that this aspect is desirable.

12 Key Findings Part II

This chapter analyses information from theory and interviews from previous chapters in Part II. The key findings are used as input to Part III together with key findings from Part I. This chapter aims to answer the question: What do operators of offshore wind farms demand from simulation tools?

12.1 Comparison of Existing Models Capabilities

O&M Tool, O2M, OMCE and CONTOFAX are compared regarding weather data and categorization.

12.1.1 Weather Data

All models regard failures on stochastic basis and consider weather data as limiting values. Each model, except from O&M Tool, is based on Monte Carlo methods, but there are other dissimilarities too. The main difference is how weather is regarded in the simulations. O2M emphasizes on significant wave height, where wind speed is correlated to significant wave height in the model. Wave data is used as limiting values and wind speed in order to calculate production. By using spectral analysis wave data becomes a completely stochastic element in the O2M simulation. OMCE regards wind and wave data as limiting factors. Weather windows are calculated in the model, and based on these waiting time is defined by a polynomial function and depends on mission time. Weather data in OMCE is deterministic and not stochastic. OMCE calculate a seasonal capacity factor based on historical wind data. The capacity factor combined with the simulation output results in energy production.

The authors mean that it's complex to develop a distribution for weather since there are large variations from year to year and besides wind and waves must be correlated. Dong Energy highlights the importance of considering winds speed when calculating the production. It's according to the authors not enough to develop a distribution regarding accessibility. The wind input to accessibility parameters must be correlated to simulation output, i.e. production. CONTOFAX consists of a completely stochastic weather simulation that isn't site specific. The weather simulation is based on a two-parameter Weibull distribution, one for summer season and one for winter season.²²⁸

As mentioned, all models use weather data as limiting values. In none of the models weather data is used in the simulation in order to look at trade-off regarding value of performing maintenance during certain weather condition. The authors claim that the models don't enhance the LCP approach to a large extent.

12.1.2 Categorization

OMCE and O2M categorize maintenance and faults; faults and failures are connected to various resources. Different resources and faults are also connected to classificatory repair times. In Part I, the authors established that means of transportation are characterising for O&M of offshore wind farms. A model that connects faults and

²²⁸ CONTOFAX will not be analysed further due to lack of information.

failures to required means of transportation would therefore be appropriate. The authors further believe that categorization is preferable since it also simplifies simulation and makes it more efficient.

12.2 Key Functionalities According to Operators

To be able to evaluate different logistics strategies related to accessibility is the main requirement according to Håkan Borgström, from Dong Energy. It's in their interest to find the best logistics solution for a specific site, based on given environment and weather conditions. Francois Besnard, at Vattenfall, emphasizes the importance of regarding OM in a simulation tool. Both Borgström and Besnard believe that resource availability and utilization are important factors to consider, since the related costs are very high. In order to achieve high resource utilization factor, extremely good planning is required. Practise of OM, where PM is linked to CM, is advantageous both regarding increased resource utilization and decreased downtimes.

Borgström pinpoints key functionalities that should be included in a realistic simulation model, for example the possibility to cluster wind farms. Since a significant part of the O&M costs is related to resources, resource pooling between different wind farms will become essential in the near future.

Besnard argues that failure frequencies vary from season to season. Stress and load is much stronger during the winter season, which consequently results in higher failure rates. Accessibility is critical for O&M of offshore wind farms and it's therefore important to capture failure frequencies in a realistic way; since failures have big impact on wind farm performance. Borgström also argues that failure frequencies change over time with component age. The authors conclude that MTBF should vary both seasonally and with component age in order to create a representative model.

Besnard believe that MS Excel is easy to use and that most employees are accustomed to the application. A simulation tool must be able to simulate long periods of time with many replications. Borgström highlights, on behalf of Dong Energy, application handiness, where a user-friendly, transparent and intuitive tool is desired. According to Besnard, it's also important for Vattenfall to understand the basics behind the model.

The authors argue that trade-offs regarding the value of performing maintenance under certain weather conditions are important to regard. Besnard also reasons that it's important to cease this trade-off. Borgström as well as Besnard pinpoints that production is an essential output in a simulation model when it comes to wind power. According to key findings from Part I, production losses make a significant part of the O&M costs. The authors mean that much effort should be put on reducing these costs.

Modelling of shifts is desired from operators, as highlighted by Borgström. As wind farms become bigger, the need for modelling of several shifts becomes more relevant. The authors mean that wind speed often abates in the late afternoon in northern Europe. It might be advantageous to perform maintenance later on in the afternoon in order to reduce revenue losses. Consequently it's interesting to evaluate at what time

of the day it's preferable to perform maintenance and this reasoning can be prolonged to weeks, months and seasons.

Besnard emphasizes on behalf of Vattenfall the importance of keeping O&M costs as low as possible; it's therefore important for them to be able to evaluate different strategies from a cost perspective.

12.3 How to Regard Maintenance Concepts

All models are mainly designed to model CM, but they also take PM into account. It's important to model CM and failure frequencies realistic since they have big impact on wind farm performance. But one must not forget the importance of PM; if it's performed properly it reduces the need of CM. This is preferable since wind farms suffer from low accessibility. PM also gives the possibility to plan maintenance and thus the maintenance related costs. Another advantage with PM is that it can be performed at periods with low wind speeds, in order to to increase production. This has a positive impact on the energy yield. If PM is performed properly, it also contributes to reduced system downtime and facilitates inventory management. According to theory, maintenance must have impact on failure rate since the aim is to increase the reliability in order to avoid CM.

The main objective with OM is to benefit from resources, efforts and time already dedicated to maintenance of other parts in the system, in order to reduce total costs. OM is most beneficial if adjacent components must be maintained. OM is also valuable if high transportation costs are characterizing for the system. The authors claim that O&M of offshore wind farms are related to high transportation costs and low accessibility and would consequently benefit from OM. Operators typically want to increase resource utilization, which further strengthen that OM must be regarded for O&M of offshore wind farms. In the long term, OM reduces revenue losses and maintenance costs. As concluded in Part I, O&M of offshore wind farms are characterized by low accessibility. The wind farms are not always accessible, and when they can be accessed, the related costs are high. Besnard argues that OM can't be neglected; this further proves that OM should be considered in a simulation model. Besnard also reason that CBM should be regarded, since it has big impact on wind farm performance. Operators make large investments in CMS, so if CBM can be regarded in a simulation model it would be more realistic. The authors conclude that an appropriate combination of maintenance concepts will increase energy yield. Therefore different maintenance concepts must be considered in a simulation model.

12.4 The Yield Concept

In key findings from Part I, the authors established that O&M of offshore wind farms should be regarded with the LCP approach and that energy yield is the principal MPI to regard. Energy yield directly depends on wind speed and availability, as illustrated in Figure 37. In order to create a simulation model that reflect upon the LCP approach and energy yield, weather must be regarded appropriately.

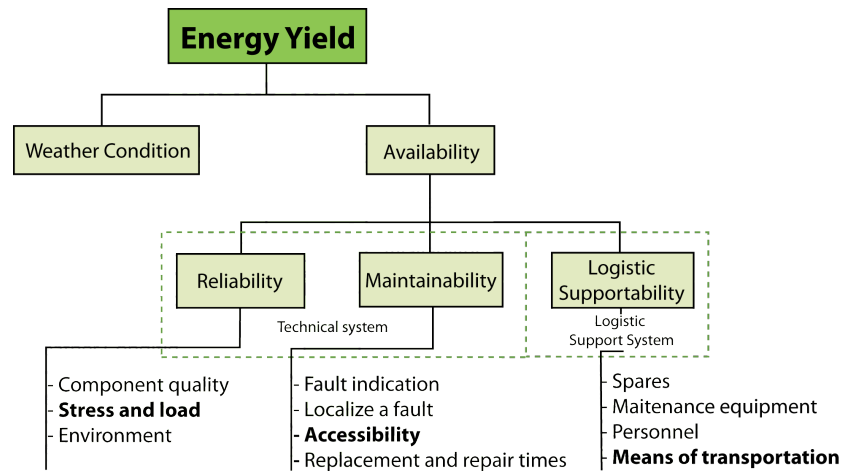


Figure 37: Extended Yield Concept

12.4.1 How to Regard Weather Conditions

Dong Energy argues that it's important to use historical weather data from several years; since yearly variations are large. Weather data can be used as deterministic or stochastic input in a simulation model. A simulation model based on Monte Carlo methods should rather use stochastic variables as input. The correlation between wind and wave data must not be forgotten; neither that wind is both a cost and a value driver. This implies that wind speed at a given time must correspond to both limiting values for maintenance but also relate to actual production according to the power curve. So, if maintenance is performed during high wind speeds, the related production loss must not be neglected. This enhances the benefits of performing maintenance during periods of low wind speeds. The authors claim that this must be emphasized in a simulation model. Maintenance activities during certain periods must be disabled in order to increase energy yield. Since PM is maintenance that can be planned, it can be scheduled at times when accessibility are high and impact on production losses are low. Therefore seasonal distributed PM must be regarded in a simulation model, according to the authors. A step further in this direction is to disable PM during periods with high wind speeds, i.e. when the energy production is extensive.

Besnard argues that weather windows should be created in a model, since it captures reality and the characteristic accessibility. It's not enough to look at weather data at hourly basis, in order to make appropriate decisions. In conformity with O2M, the authors claim that essential assumptions that regard access limits should be considered in a simulation model.

12.4.2 How to Regard Availability

In Part I, the authors claim that stress and load, accessibility and means of transportation are directly depending on weather conditions. Stress and load impact the reliability and must thus be considered. Modelling failure frequencies season by season will reflect upon this matter. Accessibility and mean of transportation regarding weather conditions must be considered in a simulation model in order to catch the

complex reality. The authors pinpoint that a model considering weather condition, availability and the complex relationship between these will help the wind farm operators to achieve maximum energy yield.

12.5 The Apple Framework

The authors have summarized key functionalities and key outputs to consider in a simulation. Key outputs, key functionalities and how they relate is illustrated in the Apple framework (Figure 38).

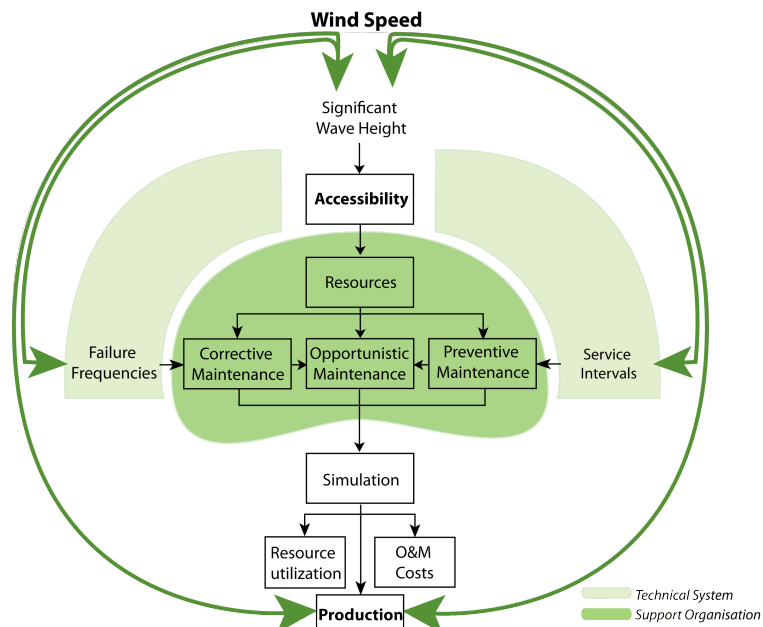


Figure 38: Apple Framework

The wind speed encompasses the entire framework, since it has impact on accessibility and production, but also how different maintenance activities are performed and distributed over time. As stress and load increases with stronger winds, the failure rates increase during windy periods and vice versa. Consequently the need of CM strongly depends on wind speed. Given service intervals in combination with preferable periods for maintenance activities, periods characterized with low wind speed, affects planning of PM. Wind speed and significant wave height are correlated factors that make up accessibility. Resources must manage changing weather conditions and the amount of maintenance to be performed. Subsequently the logistic supportability must carefully consider resource planning. Failure frequencies and service intervals symbolise the technical system, which is where the demand of maintenance arises. The support organisation must provide the technical system with resources in order to cover demand of maintenance in an efficient way. Information from the technical system, the support organization and the relationship between these, must be included in a simulation model. The authors have established that production; resource utilization and O&M costs are key outputs from a simulation. Production reflects the support organisation performance based on maintenance demand from the technical system combined with accessibility. Energy yield is the most important production output to

regard. The celadon area depicts the technical system and the bright green area illustrates the support organization in the apple framework.

12.6 Key Functionalities and Key Outputs

Accessibility

Weather windows: In order to model accessibility in a realistic way, one must find weather windows that range over a specific period of time required for performance of a maintenance task.

Resources

Modes of transportation: Different maintenance activities require classificatory vessels related to different access limits.

Offshore accommodation: As wind farms become bigger and the distance to shore increases, demand for accommodation for maintenance personnel becomes more common.

Personnel shifts: Modelling of multiple shifts would capture reality since offshore accommodation makes maintenance personnel available day and night.

Clustering of wind farms: Include several wind farms in one model would enable sharing of resources.

Corrective Maintenance

Changing failure rates: Failure rates are changing on seasonal basis, but also with component age.

Categorization: Corrective maintenance can beneficially be categorized into different classes dependent on required components and resources, but also MTTR.

Prioritization: Since the aim is to maximize production it's important to remedy the most critical failures first.

Preventive Maintenance

Seasonal distribution: Production increases during wintertime, at the same time as accessibility worsens. PM is preferably avoided during this period and to the largest possible extent performed during summertime.

Categorization: Preventive maintenance can beneficially be categorized into classes dependent on required service intervals and need of certain resources.

Disable during certain periods: Preventive maintenance is preferably avoided during periods with high wind speeds, when production is ultimate.

Condition based maintenance: Condition based maintenance can be performed both manually and automatically at present. Consequently this should be regarded in a simulation model.

Opportunistic Maintenance

Maintenance coordination: The opportunity to coordinate maintenance actions is important to regard, since accessibility and high costs of transportation characterize O&M of offshore wind farms. Opportunistic maintenance can be performed by coordination of PM and CM.

Production

The authors want to clarify that wind speeds are restrictive, but concurrently wind speeds drive energy production. This relationship must be regarded in the production outputs.

Energy yield: This is the most important MPI to consider, it regards wind as a cost and value driver.

Energy production: To be able to understand the performance of the wind farm, energy production must be considered.

Lost production: Revenue losses due to lost production make up to a significant part of the costs and should thus be regarded.

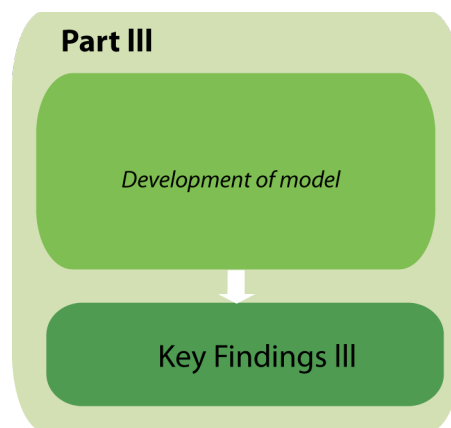
Resource Utilization

Resource utilization: Since O&M resources are very expensive, the utilization of these is important to regard.

O&M Costs

O&M costs: Since wind farms operators are focused on costs, this matter must be regarded.

PART III



Chapter 13: Simulations at Systecon
Chapter 14: Wind Farm Simulation Model in SIMLOX
Chapter 15: Outcome and Results from SIMLOX
Chapter 16: Key Findings Part III

13 Simulations at Systecon

This chapter contains information about Systecon's simulation tool SIMLOX. Since SIMLOX is the focus of this report, a description of this tool is presented. A short theory section about Monte Carlo simulations follows this.

13.1 SIMLOX

SIMLOX is a stochastic event-based simulation tool based on Monte Carlo technique. The development of SIMLOX is based on extensive experience from the development of previous simulation packages and the powerful optimization tool OPUS10. Given different maintenance prerequisites, operational profile and support structure, SIMLOX analyses system performance over time. It's commonly used to analyse the effect of limited maintenance resources on the ability to fulfil requested operational profiles. In early logistics studies SIMLOX can be used in order to translate operational need into logistics requirements and to pinpoint the most cost effective design solution. In the tendering phase it's has several functionalities to verify operational requirements, for example achieved operational hours. SIMLOX is an ideal tool in order to find bottlenecks and weak points in the support organization during the operational phase.

The main purposes of SIMLOX are²²⁹:

- Study performance of complicated logistics scenarios
- Analyse time dependent results
- Analyse efficiency measures

SIMLOX provides graphical presentations of results, confidence limits and the support organization. Examples of efficiency measures available in SIMLOX are: Mean Waiting Time for Spares, Mean Down Time for Systems and Average Operational System Availability.

13.1.1 Monte Carlo Simulation

A Monte Carlo simulation is stochastic; it randomly generates numbers to model chance or random events. The Monte Carlo method is a computational algorithm that relies on repeated random sampling to compute its results. Since the method relies on repeated computation and random numbers, Monte Carlo methods are most suited for computer calculation. The method is often applied when it's impossible to compute an exact result with a deterministic algorithm.²³⁰

²²⁹ Systecon Educational Supplies (2011)

²³⁰ Ibid.

14 Wind Farm Simulation Model in SIMLOX

This chapter first explains the developed simulation model and the weather data used. Secondly, the chapter explains how key functionalities are included in SIMLOX and how key output based on SIMLOX results should be regarded.

14.1 SIMLOX Model

In order to investigate how key functionalities can be included in SIMLOX, a simple model of an offshore wind farm was created. Note that the model is a fictitious wind farm and thus focus shall be put on key functionalities rather than specific values. All objects are defined in tables as well as the connections between the objects. The model consists of 100 wind turbines and three stations, which is illustrated in Figure 39. Each wind turbine has a capacity of 3MW and is regarded as a single system. The station on the first level is the offshore wind farm. The second level in the simulation model is a base, with all components on stock. The base is located onshore, which means that it takes a certain time to reach the wind farm. The station on the third level is a workshop, where line replacement units (LRU) are repaired. Technicians, boats, jack-ups and helicopters are the resources to use during maintenance activities. The operational profile assigned the wind farm is *fixed* and constant, which means that energy production shall be performed at all hours. The simulation period is three years and all simulations are run with ten replications.

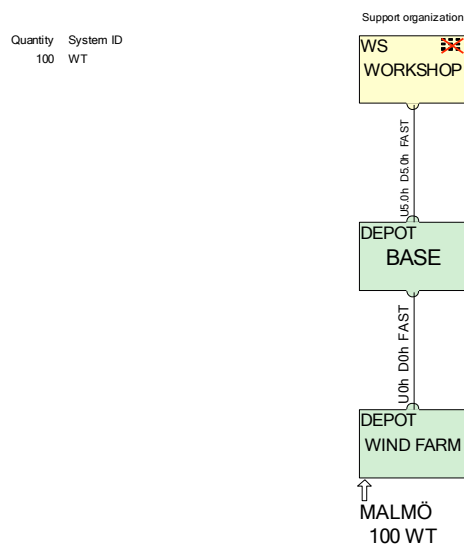


Figure 39: SIMLOX model view

14.2 Weather Data

Weather data used in the simulations originates from a specific wind farm. The weather data consists of time series of hourly-collected wind speeds and significant wave heights that covers a period of three years. Wind speed at a given hour relates to significant wave height concurrently. This correlation reflects reality. Chart 1 shows the average wind speed over three years time, calculated from weather data. The figure

typically illustrates wind speed patterns; it's less windy during summer months and conversely during winter. Consequently, the weather data comport with previous discussions in this report. Chart 1 also shows the correlation between wind speed and significant wave height.

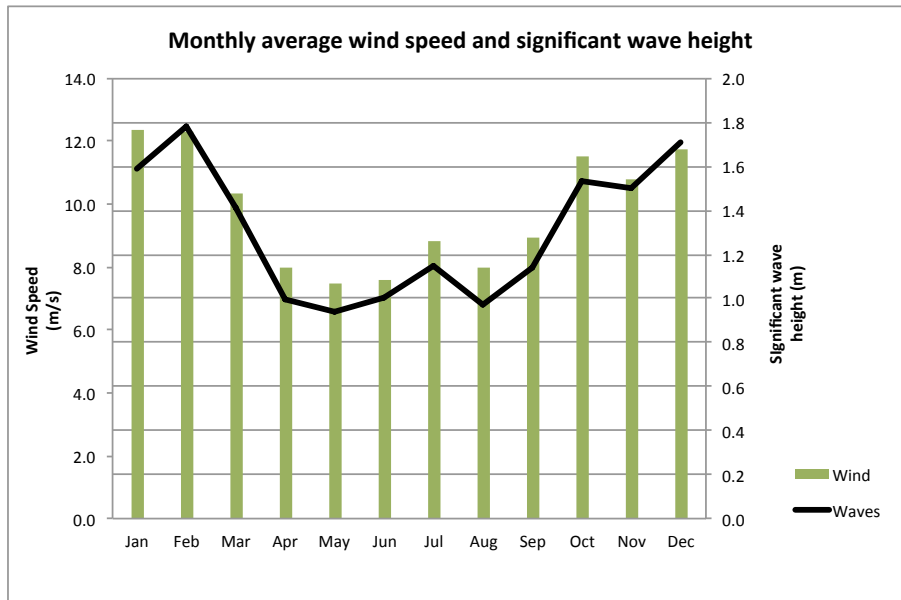


Chart 1: Monthly average wind speed and significant wave height

14.3 How to Include Key Functionalities in SIMLOX

Key functionalities are included in SIMLOX one at a time. This is done in order to evaluate how SIMLOX reacts on severally included key functionalities.

14.3.1 Accessibility

Weather conditions and choice of transport modes determines if the site is accessible. Based on historical weather data, weather windows are created. Different shifts are subsequently created for each transport mode.

Weather Windows

Weather windows are created in the MS Excel model *weather_windows_macro.xlsm*, which includes VBA script. Historical weather data series with wind speed and significant wave height are defined by year, day and hour, which are shown in Figure 40.

	A	B	C	D	E
1	Year	Day	Time	Significant wave height, m	Wind speed in hub height
2	Year 1	1	0	0.5308885	6.9
3	Year 1	1	1	0.5187575	6.0
4	Year 1	1	2	0.5050885	5.8
5	Year 1	1	3	0.487435	5.5
6	Year 1	1	4	0.4671665	5.3
7	Year 1	1	5	0.440238	5.0
8	Year 1	1	6	0.405641	4.9
9	Year 1	1	7	0.375853	4.9
10	Year 1	1	8	0.35532	5.0
11	Year 1	1	9	0.3451985	5.1
12	Year 1	1	10	0.344682	5.2
13	Year 1	1	11	0.3455745	5.3
14	Year 1	1	12	0.3470755	5.3

Figure 40: MS Excel model *weather_windows_macro.xlsm*

In order to create weather windows, input variables regarding access limits, start and end time of required time window and years of weather data are required (Figure 41). Access limits are specified for each resource, both regarding wind speed and significant wave height.

Input Variables for Conditional Limiting Values

Years of weather data

Vessel	Significant Wave Height	Wind Speed
Boat	1	10
Jack up	2	15
Helicopter	1000	20

Time window of operation

Start

End

Duration

Run Macro

Figure 41: Input variables used to create weather windows.

The MS Excel model *weather_windows_macro.xlsm* generates an output file where the outcome is binary numbers for each day and resource. If the model returns "1", there is a weather window and the site is accessible. If the site is inaccessible, the model returns "0". A weather window only exists if both wind speed and significant wave height are below access limits during the whole time window of operations.

Resource shifts are created on daily basis, when the site is accessible, i.e. days given the value "1" (Figure 42). The shifts are then inserted in SIMLOX in the tables: *ShiftResource*, *ShiftProfile* and *Shifts*.

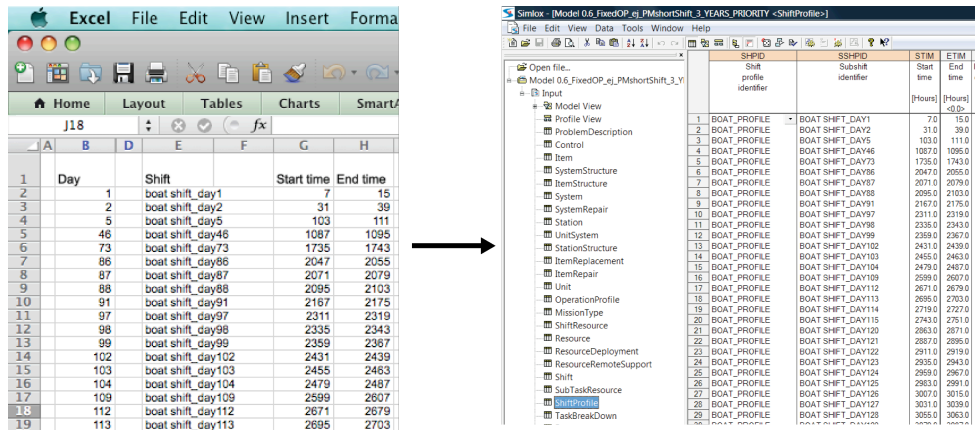


Figure 42: Boat shifts created in MS Excel and inserted in Simlox.

14.3.2 Resources

Resources are stationed at the wind farm in the simulation model. More realistic would be to place resources with spare parts at the base and send resources to the wind farm by remote support. But it's not possible to combine remote resource support with restrictions on resource availability in SIMLOX. It's however possible to combine ordinary deployed resources with remote resource support. Remote resource support is neither considered for alternative resources. Since resources are connected to shifts, resources must be placed at the wind farm. To compensate for resource placed at the wind farm, a mean transportation-time is included for each maintenance activity carried out. This transportation-time theoretically reflects the time it takes from the base to the wind farm.

Modes of Transportation

Modes of transportation are regarded as different types of resources in SIMLOX. In order to assign resource availability due to accessibility, resources are connected to shifts. This means that vessels are only available during certain periods of time, when weather isn't restrictive. Shifts are based on weather windows and limiting access values for each resource. As previously explained, this restriction on resource availability doesn't comport with remote resource support. The number of resources is defined in SIMLOX and can easily be adjusted. Resource shifts are created in the MS Excel model *resource_shifts_time7-19.xlsx*.

During periods with low accessibility use of boats and jack-ups are restricted. System down time during these periods results in large production losses. For critical component failures that result in production losses, use of alternative resources is preferable. These periods typically occur during wintertime. Consequently, helicopters are defined as alternative resources to boats in the table *SubTaskResource*.

Offshore Accommodation

Technicians are not connected to shifts in the simulation model since they are always used in combination with other resources. Consequently, this allows use of remote resource support. A share of technicians is stationed at an offshore accommodation,

and used at the wind farm if needed. It's however difficult to capture the value of offshore accommodation since it can't be modelled appropriately without remote resource support.

Personnel Shifts

Modelling of personnel shifts is a basic function in SIMLOX. In the table *ShiftProfile*, number of personnel shifts is defined.

Clustering of Wind Farms

Sharing of resources between wind farms is easily modelled with remote resource support. Since most resources are connected to shifts the resources has to be placed at the wind farm. Subsequently sharing of resources in the simulation model must be performed in a different way. Björling explains that more than one wind farm can be modelled at the same station, but resources, systems and maintenance activities must be benamed. In this way, alternative resources can be defined in the table *SubTaskResource* and thus sharing of resources between wind farms can be modelled.²³¹

14.3.3 Corrective maintenance

A CM task is performed as soon as a failure occurs and resources needed are available.

Changing Failure Rates

In order to model failure rate patterns based on varying stress on the systems, different missions for different seasons are created. The production profile is consequently split into spring, summer, autumn and winter missions. The *mission failure rate factor* makes it possible to model different stress on systems and items depending on mission type. The mission failure rate factor for winter missions is defined as greater than 1 and for summer missions the failure rate factor is less than 1.

Mission failure rate factor can also be used in order to capture failure rate patterns based on system age. This can beneficially be used for modelling of system's entire life cycle, but this function is not applied in this model since it only covers three years.

Categorization

Two types of CM are defined in the SIMLOX model, one CM for large components and one for small components. These are connected to classificatory items, but also to required resources. For example, CM for large components is required for blade failures and resources needed are six technicians and a jack-up vessel. Figure 43 shows how resources are connected to classificatory maintenance in the table *SubTaskResource*.

²³¹ Björling (2011-05-13) Systecon AB

TID	SEQ	RID	QTY
Task identifier	Subtask sequence number	Resource identifier	Resource quantity
1	CM_LARGE_REPLACEMENT	1 PERSONNEL	6
2	CM_LARGE_REPLACEMENT	2 PERSONNEL	6
3	CM_LARGE_REPLACEMENT	3 PERSONNEL	6
4	CM_LARGE_REPLACEMENT	4 PERSONNEL	6
5			
6	CM_SMALL_REPLACEMENT	1 PERSONNEL	4
7	CM_SMALL_REPLACEMENT	2 PERSONNEL	4
8	CM_SMALL_REPLACEMENT	3 PERSONNEL	4
9			
10	PM_YEARLY	1 PERSONNEL	4
11	PM_YEARLY	2 PERSONNEL	4
12			
13	PM_MONTHLY	1 PERSONNEL	2
14	PM_MONTHLY	2 PERSONNEL	2
15			
16	CM_LARGE_REPLACEMENT	1 JACK-UP	1
17	CM_LARGE_REPLACEMENT	2 JACK-UP	1
18	CM_LARGE_REPLACEMENT	3 JACK-UP	1
19	CM_LARGE_REPLACEMENT	4 JACK-UP	1
20			

Figure 43: CM categorization

Prioritization

SIMLOX handles failures and PM tasks due to criticality. The following order for criticality is defined in SIMLOX as:

- Critical failures
- Critical PM tasks
- Non critical PM
- Non critical failures

Failures require CM and planned tasks require PM. In SIMLOX, there’s a possibility to define whether a failure is critical or not. This is illustrated in Figure 44.

IID	DESCR	FRT	NSIMI	AFFRT	SGID	CRIT	TYPE	Group
Item identifier	Description	Failure rate	Number similar	Application factor	Similarity group	Criticality	Type	Group
		[1/M*hour]	<1>	<1.000>		<1.0>		
16	43_OILPUMP_SIEMENS-2300KW	Oilpump	3.00				DU	
17	44_P_ACCU15L_SIEMENS-2300KW	Piston Accu 0.15l	6.00				DU	
18	45_MOTOR4KW_SIEMENS-2300KW	Motor 4kW	16.52				DU	
19	51_SMPS1_SIEMENS-2300KW	SMPS 1	17.27				DU	
20	52_SMPS2_SIEMENS-2300KW	SMPS 2	6.00				DU	
21	53_DELTAM_SIEMENS-2300KW	Delta Module (Skill Pack)	6.00				LRU	
22	54_POWERS_SIEMENS-2300KW	Power Supply 240 V/24 V	6.00				DU	
23	55_MOTOR1.8KW_SIEMENS-2300KW	Motor 1.8kW	6.00				DU	
24	61_WINDS_SIEMENS-2300KW	Wind Sensor	12.00				LRU	
25	62_ENCODER_SIEMENS-2300KW	Encoder	6.00			0.0	DU	
26	63_IOMODUL_SIEMENS-2300KW	I/O-Modul	1.50			0.0	DU	
27	71_TRANSFO_SIEMENS-2300KW	Transformer	3.00				DU	

Figure 44: CM prioritization

In the table *Item*, item criticality is defined as a value between “0” and “1”. “1” means that if an item fails the probability that the failure becomes critical is 100%, “0” implies the opposite. Figure 44 shows that two items are connected to non-critical failures. In the *System* table, definitions of maximum number of non-critical failures can be defined. Maximum number of non-critical failures specifies at what number

non-critical failures become critical. It's also possible to define a time-interval during which non-critical maintenance activities must be carried out.

14.3.4 Preventive Maintenance

In SIMLOX, a PM task is performed within a specified interval. Within the interval, PM tasks are not critical and are only performed if the system is not on mission and resources are available. Therefore a fixed operational profile with one-hour interval is modelled. This enhances non-critical PM to be performed. When the upper limit of the interval is reached the PM task becomes critical and production is stopped until the PM task is performed, which occurs as soon as resources are available. It's important that PM is performed according to schedule; this is a fundamental assumption in the simulation model. Independent on the PM distribution over the year, the total amount of time put on PM tasks is equal in all simulations.

Seasonal Distribution

The major part of PM is planned during months with lower wind speeds. Since winter months are characterized by higher wind speeds and bad accessibility, PM is not performed during these months.

In order to model this a *PMactivation profile* is created that only activates PM tasks during the months from March to November. This PMactivation profile prevents PM tasks from being performed during winter months. A PM task that ought to be performed at a certain time, at a time when it's not activated by the PMactivation profile, does not become critical.

Categorization

PM tasks in SIMLOX are performed on regular basis and activated when a certain period of time is reached. This means that PM activities are not stochastic in contrast to CM activities. Categorization of PM is managed in the same way as categorization of CM.

Disable PM During Certain Periods

In order to maximize energy yield, PM can be disabled during periods with high wind speeds. PM activation shifts is created in MS Excel based on wind speed data and a power curve. Wind speeds on the left part of the power curve (Figure 45) don't have as much impact on production losses as wind speeds where rated power is achieved. Consequently it's preferable to perform maintenance during these periods. Shifts are built for wind speeds that generate less than a certain percentage of rated capacity. This area is illustrated by the filled area in Figure 45. Wind speeds are regarded with one-hour intervals, which result in shifts on hourly basis.

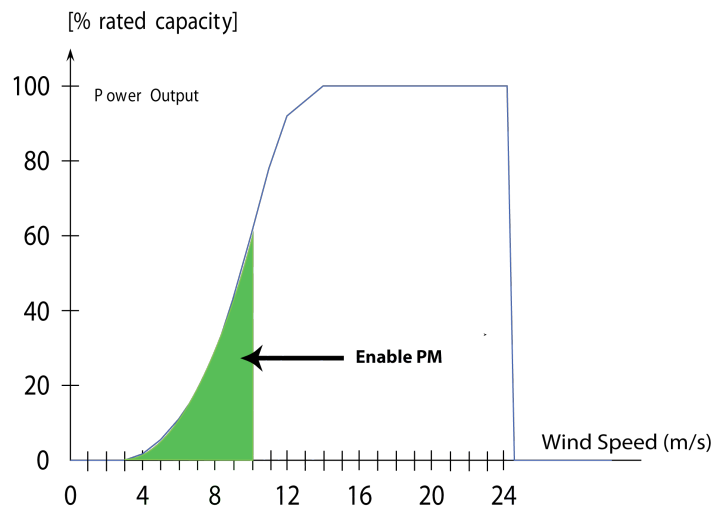


Figure 45: Disable PM during certain periods

By including this functionality as a *PMactivation profile*, PM tasks are only allowed to be activated at defined periods. PMactivation profile consists of shifts, inserted in SIMLOX in the same way as resource shifts.

Condition Based Maintenance

By using the input table *PMFailureMode* it's possible to model that failures are detected with a certain probability during a PM task. This can be classed as a type of non-online monitoring CBM. The purpose of this table is to detect a “non critical failure” during a PM task and remedy the failure before it gets critical and shuts down the system. To model online-monitoring is more complex and requires online data, for example SCADA-data.

14.3.5 Opportunistic Maintenance

CM and PM tasks should to the largest possible extent coincide and share resources in order to minimize transportations and increase resource utilization. To detect failures when a PM task is performed can be defined by using the input table *PMFailureMode* (as described in Section 14.3.4). This enables the opportunity to perform a CM task in coordination with a PM task.

14.4 How to regard Key Output

How key outputs, presented in the apple framework, are regarded based on SIMLOX results is further introduced.

14.4.1 Production

A power curve is used in order to calculate percentage of rated capacity at different wind speeds. The power curve is a polynomial where output, y , is percentage of rated capacity and input, x , is wind speed in meter per second. The power curve and rated capacity is presented in Chart 2.

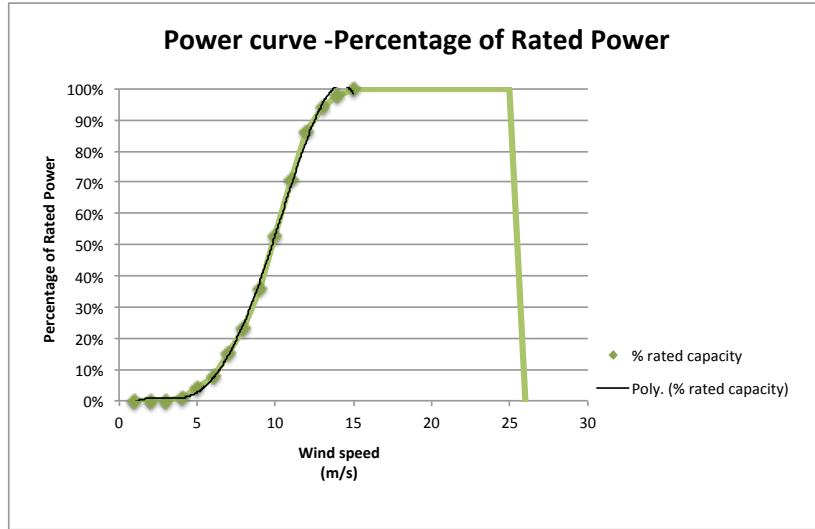


Chart 2: Power curve and percentage of rated power

Time series of wind speed data are linked together with the power curve in the MS Excel file *power_curve_rated_power.xlsx*. Percentage of rated power is subsequently calculated for each hour. This result is transferred to MS Excel file *energy_production.xlsx*, where it's used for computing of production. Percentage of rated power is linked to the wind turbine's capacity; consequently the power produced at each hour is calculated. In order to calculate possible energy production, hourly power production is multiplied with maximum number of wind turbines. Table 4 shows information needed to calculate possible power according to the denominator (Formula 6) in the energy yield formula presented in Part I.

Table 4: Possible energy production

Hour	% rated power	Max systems in operation	Possible Energy Production
32	0.87	100	260.4
33	0.81	100	243.1
34	0.75	100	224.5
35	0.68	100	205.3
36	0.62	100	186.1
37	0.56	100	167.7

$$Energy\ Yield = \frac{\sum_t Energy\ Production\ (t)}{\sum_t Possible\ Energy\ Production\ (t)} \quad (6)$$

Energy Production and Energy Yield

In order to calculate energy yield, results from SIMLOX are needed. In the report *System States*, hourly information about *Number of Systems Mission Operation* is given. These results are transferred to MS Excel chart *energy_production.xlsx* where they are multiplied with the hourly percentage of rated power. The results are summarized to

get the numerator (Formula 6) in the energy yield formula. Energy production is then divided by possible energy production in order to calculate the energy yield.

Lost Production

In order to calculate lost production, results from the report *System States* in SIMLOX are required. Hourly information from Number of Systems Mission Operation is transported to MS Excel. In *energy_production.xlsx* the information is multiplied with the hourly percentage of rated power, in the same way as calculation of energy production. The results are summarized in order to number the lost production.

14.4.2 Resource Utilization

Technicians, boats, jack-ups and helicopters are defined resources in the developed SIMLOX model, as described in 14.3.2. Resource utilization is presented in tables and graphs in SIMLOX. Due to accessibility, an infinite number of resources don't result in 100% availability or possible energy production. Therefore the relationship between number of resources, availability and energy yield is a matter of investigation.

14.4.3 O&M Costs

SIMLOX is used for dynamic calculation and includes no information about costs. This means that no results regarding O&M costs can be calculated by SIMLOX. Björling means that simulation results from SIMLOX often are transferred to programs like MS Excel, in order to calculate costs. She also clarifies that Systecon AB currently is developing their ILS toolbox so that results from SIMLOX can be transferred to their LCC analysis tool CATLOC.²³²

²³² Björling (2011-05-13) Systecon AB

15 Outcome and Results from SIMLOX

This chapter presents the outcome of including key functionalities in SIMLOX and key output based on SIMLOX results. Results from including key functionalities in SIMLOX are presented in measurements presented in key output: energy yield, energy production and lost production.

15.1 Accessibility

Figure 46 shows results from including accessibility in SIMLOX. *Active repair* is systems where CM is performed and *active PM* is systems where PM tasks are performed. *Awaiting resources* are needed resources at the wind farm, *awaiting items* are needed items to perform CM and systems *on mission* refer to on going power production. The left hand picture shows wind farms with no access limits on resources. The right hand picture shows wind farms with weather restrictions on resources. There is a significant difference between the two pictures. Awaiting resources constitute a noteworthy part of the wind farm's state where access limits are put on resources.

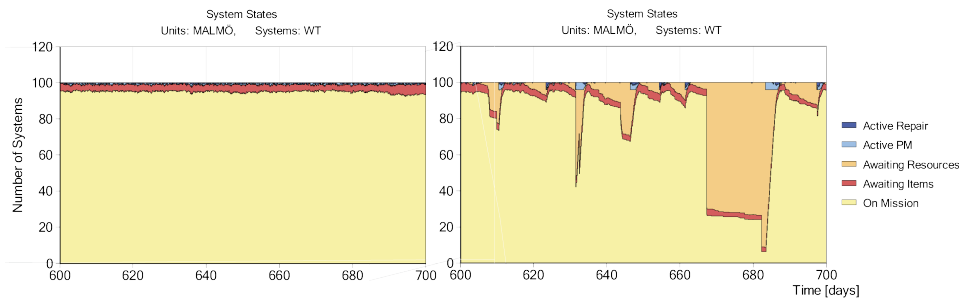


Figure 46: Accessibility in SIMLOX

15.2 Resources

Different number of resources, boats and technicians, and their impact on energy yield is investigated. Results are presented in Chart 3. The chart shows that energy yield reaches its steady state, just below 85% at about 20 boats. That steady state doesn't reach 100% depends on accessibility. Even if the number of resources available is infinite, weather conditions still have large impact on energy yield.

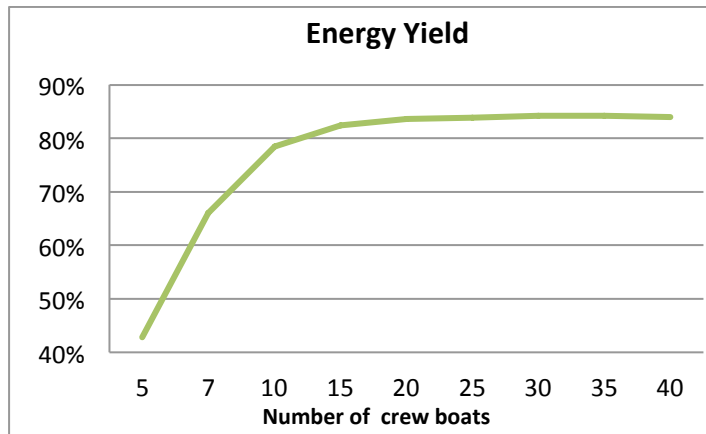


Chart 3: Energy yield for various numbers of boats

15.2.1 Modes of Transportation

Resources are connected to shifts that are related to weather windows. The connection between shifts and resources is managed by SIMLOX, but this results in difficulties with transportation times since remote resource support can't be used. Shifts are included at daily basis, which reflects reality. This results in long series of information to define in SIMLOX.

It's possible to differ between resources in SIMLOX, but also to include alternative resources. Two helicopters are defined as alternative resources to boats during winter months. Figure 47 shows the *maintenance use* of the two helicopters during winter months. *Available* refers to helicopters not in maintenance use. The interspace between the staples corresponds to periods when the helicopters are unavailable due to bad accessibility. Resource utilization can be analysed by observing the resource states.

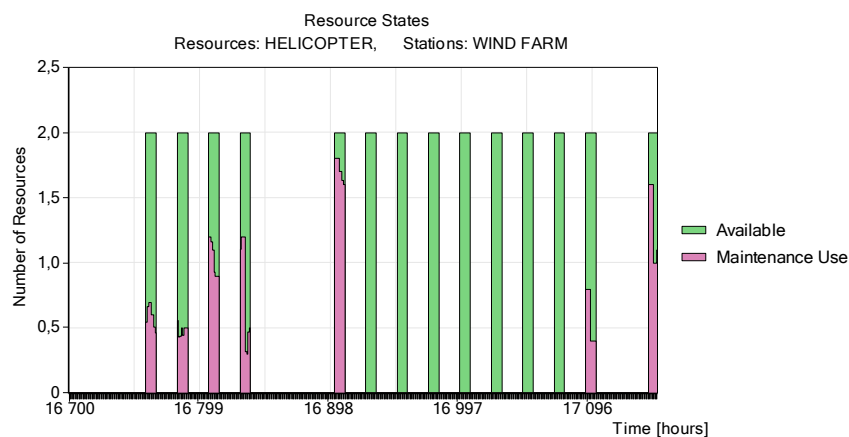


Figure 47: Helicopter as alternative resource during winter months

By looking at the energy yield for different number of helicopters, trade-offs regarding costs for different number of helicopters and profit from increased energy production can be made.

15.3 Corrective Maintenance

How modelling of changing failure rates succeeds in SIMLOX is presented below.

15.3.1 Changing Failure Rates

By using the function *mission failure rate factor* in SIMLOX it's possible to increase failure rates during winter months and decrease them during summer months. Chart 4 illustrates the average number of wind turbines in active repair over the year, i.e. the amount of CM performed. The line illustrates how failure rates are varying over the year. The columns show the reference case where the possibility for components to fail is constant over the year. Note that the failure rates in both cases are stochastic and consequently there are small variations from month to month.

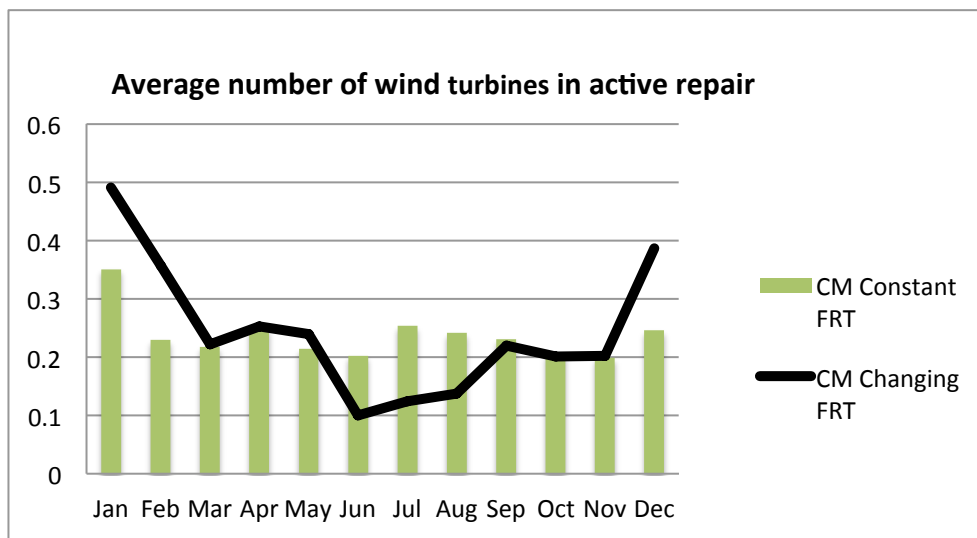


Chart 4: Corrective Maintenance distributed over the year

15.4 Preventive Maintenance

How modelling of seasonal distribution of PM and disabling of PM during certain periods succeeds in SIMLOX is presented below.

15.4.1 Seasonal Distribution

In the simulation model, PM tasks are activated during the months from March to November and subsequently SIMLOX excludes PM during winter times. No PM is performed during winter times except from: PM tasks that has been queued at earlier times and non-critical PM tasks that are coordinated with CM. Chart 5 presents how the production is affected by PM activation throughout the year in the reference case and PM activation only during certain periods. Note that the total amount of PM is the same in all cases; it's only how it's distributed over the year that differs.

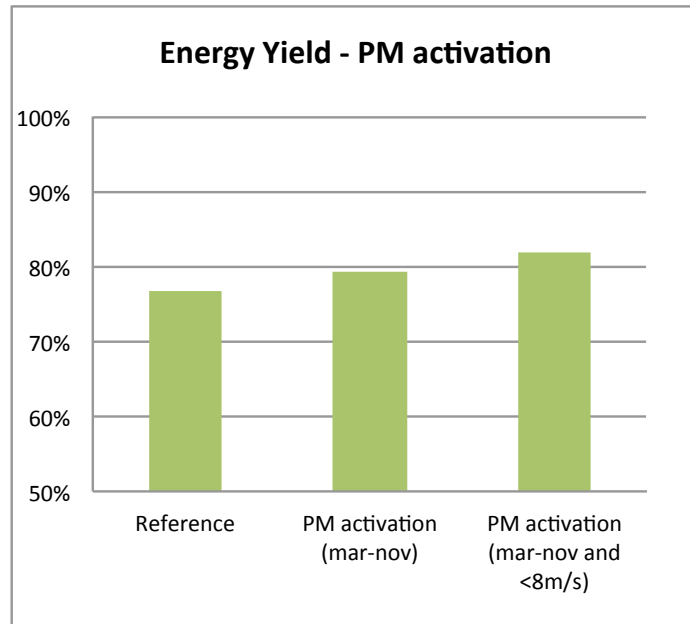


Chart 5: Energy production

15.4.2 Disable PM During Certain Periods

By disabling PM tasks during periods with high wind speeds energy production losses decrease which is shown in Chart 7. The left column illustrates the reference case, where PM tasks are allowed at all wind speeds. In the right column PM tasks are only activated when wind speeds are less than 8 meters per second.

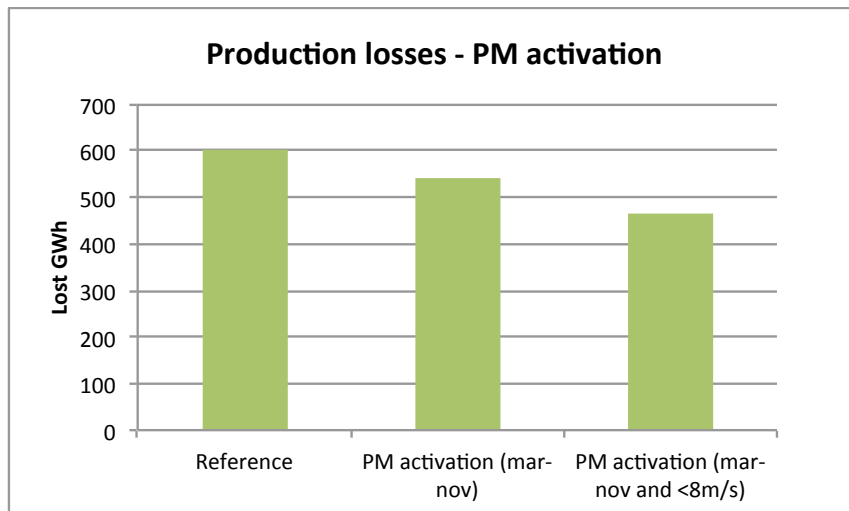


Chart 6: Production losses

The PM activation shifts are inserted in SIMLOX at hourly basis for three years time, which results in thousands of lines with data. This amount of information makes the simulation very time consuming.

15.5 Opportunistic Maintenance

If a system under active CM is completed and resources are available, PM tasks are performed on the system. Figure 48 illustrates that CM (active repair) is followed by active PM, which exemplifies that OM is performed in the model.

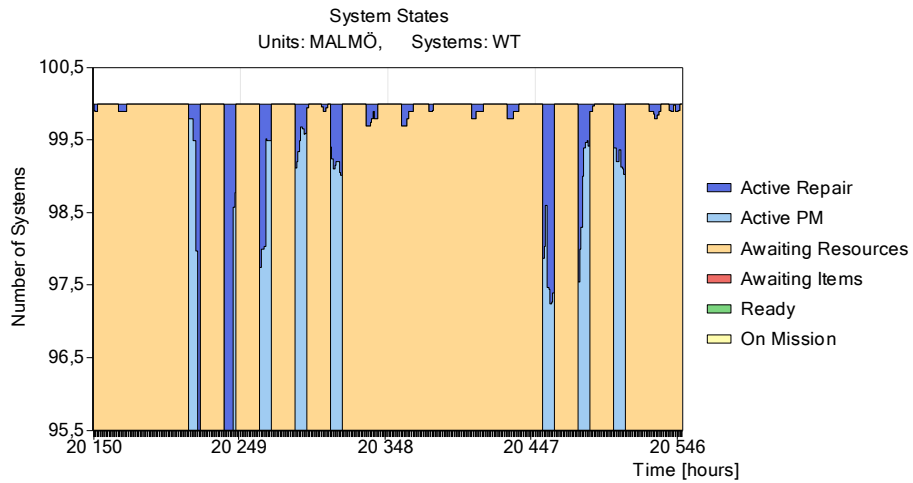


Figure 48: Opportunistic maintenance

16 Key Findings Part III

This chapter analyses information from previous chapters in Part III. This chapter aims to answer the question: How can O&M of offshore wind farms be modelled appropriately with Sysstecon's simulation tool?

The authors have used SIMLOX for dynamic computations. MS Excel has been used for arrangement of input data and calculations of output data from SIMLOX results. The developed simulation model is a simplified version of a fictitious wind farm. The model can easily be developed more realistically by defining more detailed information in SIMLOX.

16.1 Wind –A Cost and Value Driver in SIMLOX

The apple framework, developed and presented by the authors in Part II, clearly emphasizes wind speeds. The framework stresses wind as both a cost and a value driver. The authors previously clarified that wind speeds are restrictive, but concurrently wind speeds drive energy production. According to the authors, this is the most important relationship to regard. This relationship hasn't been ceased in any of the investigated simulation tools in this report. The investigated simulation tools merely captures wind speeds in a restrictive manner.

In Part I the authors presented that a LCP approach will clarify benefits from maintenance at low wind speeds, benefits that will increase both internal and external efficiency. By disabling PM tasks during periods with high wind speeds, the authors showed that energy production losses decreased. This indicates that embracing the LCP approach has positive impact on energy yield, but above all that SIMLOX has the capability to capture wind as a cost and value driver.

16.2 Key Functionalities and Key Outputs in SIMLOX

A large amount of defined information in the developed SIMLOX model is constituted by deterministic data. Commonly, SIMLOX generates stochastic variables. Operators claim that historical data must be used in simulations since there are many correlations to regard. Hence, deterministic data is regarded in reality. Wind speeds and significant wave heights correlates and there are also yearly variations in wind speed. There is also a correlation between restricting wind speeds and producing wind speeds that must be regarded. These correlations make it very complex to generate stochastic variables in SIMLOX. Advantageous is that SIMLOX handles deterministic weather data properly and uses wind speeds as both a cost and value driver. Performed simulations range over a three years period, in order to prolong the simulation period simulations must be more efficient and less time-consuming. It's in the authors' belief that simulations can be run more efficiently by decreasing the amount of defined information in SIMLOX. One method to do this would be daily, not hourly, defined information of wind speeds and significant wave heights.

16.2.1 Accessibility

Weather windows can applicably be built in the created MS Excel based on historical weather data. The model handles different resources with different requirements in an

appropriate manner. In the MS Excel model all maintenance tasks require equal time windows for operation. What could be further developed is the ability to specify a specific length of the time windows for each type of resource. The resource shifts can easily be inserted in SIMLOX and simulation results are realistic regarding wind farm accessibility. Based on resource shifts built from weather data and access limits, SIMLOX captures restrictions on times when maintenance can be performed successfully. Weather window should be generated on daily basis, since this result in less information to insert in SIMLOX compared to shift on hourly basis. This is further strengthened by the fact that site access is handled on daily basis in reality.

16.2.2 Resources

Resources are connected to shifts and maintenance activities, which allows different types of resources for different task and varying conditions. Alternative resources are a resource feature to emphasize in SIMLOX. As described, this enables modelling of transportation to the wind farm by helicopter for critical breakdowns, when other vessel must stay onshore. There are significant trade-offs to regard concerning number of vessels, technicians and energy yield. Revenues from increased energy production must be weighted against the costs for number of vessels and personnel.

Since it's not possible to combine resource shifts with the functionality remote resource support, resources are not managed fully as desired. Resources that handle maintenance and services are generally not based at the wind farm. An exception is when offshore accommodation is provided. Restrictions regarding accessibility can be applied in the current model since resources are connected to shifts. On the other hand, transport times are more complex to capture realistically with resources placed at the wind farm. In order to model transport times for resources from shore to the wind farm, a transportation subtask has been added to each maintenance task. By solving transportation of resources in this manner some realistic aspects will lose out. To benefit from coordinating several maintenance activities in order to minimize transportation of resources is difficult to capture in this model. Generally, SIMLOX is used within the defence and rail industry where maintenance resources are stationed at the same station where maintenance activities are performed. It's characterising for offshore wind farms that maintenance resources are stationed at a distance from the site. Even though the wind farm includes offshore accommodation, the critical docking phase during a maintenance activity still remains. The authors mean that if remote support shall be combined properly with essential resource shifts it would facilitate the application of several key functionalities: clustering of wind farms, offshore accommodation and maintenance coordination.

If operators require technicians to work in shifts, day and night, at the wind farm, this function can successfully be performed. Modelling of several shifts is a basic function in SIMLOX, which can be solved without any complications. Consequently the authors have not further investigated this functionality in the model.

16.2.3 Corrective Maintenance

Stress and load is one of the emphasized factors in the extended yield concept. In reality, there are large seasonal variations on failure frequencies. The authors have proved that these variations are possible to model in SIMLOX. Similarly, failure

frequencies related to component age can be modelled. Prioritizations are preferable predetermined in SIMLOX since they comport with reality. SIMLOX gives priority to CM, which is most critical, since critical failures abort missions. SIMLOX permits categorizations of CM tasks to be as detailed as desired. The authors claim that modelling of CM includes no difficulties regarding O&M of offshore wind farms.

16.2.4 Preventive Maintenance

Seasonal dependent PM distribution is a good feature that reflects reality. That's how it's carried out today: with time-consuming PM tasks scheduled during summer months and few PM tasks during winter months. Previous presented results show that energy yield increases with this PM distribution. PM activation is a commonly used function in SIMLOX. The authors have detected two situations when PM is carried out during periods when it's not enabled by PM activation. The first case is PM tasks that have been activated earlier but queued due to lack of resources. The second case is when non-critical PM tasks are coordinated with CM. These situations are beneficial since reality is reflected, but disadvantageous since they can't be controlled.

PM activation shifts that were built in MS Excel based on weather data and a power curve, resulted in desirable results in SIMLOX. Chart 7 clearly shows how production losses can be decreased performing PM at low wind speeds. In this specific case the production losses are reduced by 14%. One must not forget that periodic restrictions on PM require a more flexible support organization.

A disadvantage with PM activation shifts is the large amount of information that must be defined in the model. Therefore, it might be preferable to build activation shifts on daily basis instead of hourly. This would significantly decrease the amount of information to be inserted in the SIMLOX model and consequently speed up simulations. This is essential in order to simulate more than three years.

16.2.5 Opportunistic Maintenance

When a system under active CM is completed and resources are available, PM tasks are performed on the system. Further required is that the system is not on mission. It's excellent that OM actually is performed in SIMLOX, since it increases resource utilization.

16.2.6 Condition Based Maintenance

To take the opportunity to perform CM when a maintenance task is carried out also represents OM. This opportunity has many similarities to non-online CBM and is therefore handled similarly in SIMLOX. Detection of "non critical failures" during PM tasks can be modelled in SIMLOX. Further, the authors stipulate that this functionality have high potential for use within the field of O&M of offshore wind farms.

16.2.7 Key Outputs

The production related MPIs (energy yield, energy production and lost production) are easy to use and the authors have showed that simulation results can be presented in these terms. No results regarding O&M costs can be calculated by SIMLOX. The authors believe that there are many trade-offs to regard, e.g. resource utilization, that

require comparison of costs and profits. Results can be transferred from SIMLOX and calculations can be performed in other applications. Since many O&M decisions depends on these trade-offs it would be desirable if calculations related to costs and profits were performed by SIMLOX.

16.2.8 Summary of Key Functionalities and Key Outputs

Based on interviews with operators and previous findings, key functionalities and key outputs have been clarified. Key functionalities and key outputs aim to reflect what operators demand from a simulation model concerning O&M of offshore wind farms. Key functionalities and key outputs are presented in Table 5. The table includes comments on how well key functionalities were included in SIMLOX. The table also comments on how well key output based on SIMLOX results were calculated. The success factors are further explained in Table 6.

Table 5: Success factors




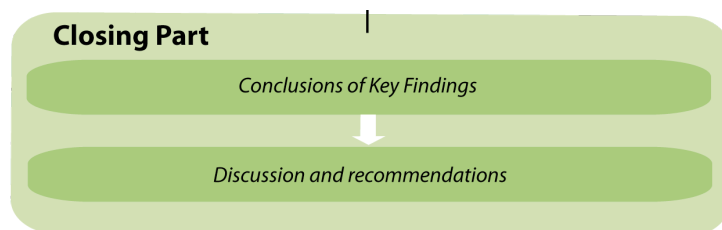
	Success Factors
	Merit
	Pass
	Fail

Table 6: Summary of key functionalities and key outputs

KEY FUNCTIONALITIES	Comments	Success
Accessibility		
Weather windows	SIMLOX successfully handles weather windows based on resource shifts.	✓
Resources		
Modes of transportation	Different modes of transportation can easily be combined with different attributes.	✓
Offshore Accommodation	Can be performed but it's difficult to capture the value without use of remote resource support.	✓
Personnel shifts	A basic function I SIMLOX.	✓
Clustering of wind farms	Can be performed but it's difficult to capture the value without use of remote resource support.	✓
Corrective Maintenance		
Changing failure rates	Works well with a varying failure rate factor for different seasons.	✓
Categorization	A basic function in SIMLOX.	✓
Prioritization	A basic function in SIMLOX.	✓
Preventive Maintenance		
Seasonal distribution	Works well with PM activation profiles.	✓
Categorization	A basic function in SIMLOX.	✓
Disable PM during certain periods	Successfully implemented in SIMLOX by PM activation shifts, but makes simulations very time consuming.	✓
Condition based maintenance	Non-online monitoring can be successfully modelled with PM failure mode. However, online monitoring needs further investigation.	✓
Opportunistic Maintenance		
Maintenance coordination	Successfully performed in SIMLOX, but needs further investigation in order to control it to larger extent.	✓
KEY OUTPUTS		
Production		
Energy Yield	Results from SIMLOX in combination with weather data and power curve are sufficient to realistically calculate energy yield.	✓
Energy Production	Results from SIMLOX in combination with weather data and power curve are sufficient to realistically calculate production.	✓
Production Losses	Results from SIMLOX in combination with weather data and power curve are sufficient to realistically calculate production losses.	✓
Resource Utilization		
Resource Utilization	Basic simulation output found in resource results in SIMLOX.	✓
O&M costs		
O&M costs	It's not possible to include costs in SIMLOX.	✗

CLOSING PART



Chapter 17: Closure

Closure

This chapter contains a summary of key findings from Part I, Part II and Part III, but it also answers the research questions. Suggestions to further studies and a recommendation to Systecon AB is also presented.

17.1 Conclusions

In Part I characterising features for O&M of offshore wind farms were investigated. The authors stated that accessibility is the most significant feature. Wind speed and significant wave height are the major causes affecting accessibility. Accessibility also depends on the distance between mainland and the wind farm. Vessels used for access of wind turbines strongly depend on wind speed and significant wave height, if waves are too high and wind is too strong, vessels are restricted from performing O&M tasks. Harsh weather conditions and harsh wind further influence wind turbine reliability. Since wind speed follow seasonal variations, wind turbine reliability do too. Hence, seasonal changing failure frequencies are characterising for offshore wind farms. In brief, wind speed has impact on wind turbine reliability, choice of transportation mode and wind farm accessibility. Decreased reliability, vessels restricted from performing O&M tasks and low accessibility are factors that drive O&M costs. Furthermore wind enables energy production and thus wind is a value driver too.

In Part II the most suitable approach for O&M of offshore wind farms was investigated. The authors found out that a LCP approach is the most suitable approach. Embracing a LCP approach enhances the support organisation to support business and focus on revenue. Sub-optimization of O&M costs will consequently be eluded. Focus on revenue will clearly highlight benefits from performing O&M tasks at low wind speed. This will additionally decrease revenue losses and thus increase profitability. In order to realise benefits from the LCP approach energy yield shall be calculated. Energy yield increases if O&M tasks are performed at low wind speed; hence it's a MPI that captures the embracement of a LCP approach.

In Part II, the authors summarized what operators demand from a simulation tool. The summary was presented in the apple framework that consists of key functionalities and key outputs. Key functionalities are features that are desirable to model in a simulation tool. Key outputs are desired results that simulations shall bring. Figure 49 further presents key functionalities and key outputs.

Key Functionalities	Key Outputs
Accessibility <i>Weather windows</i>	Production <i>Energy yield</i> <i>Energy production</i> <i>Lost production</i>
Resources <i>Modes of transportation</i> <i>Offshore accommodation</i> <i>Personnel shifts</i> <i>Clustering if wind farms</i>	Resource utilization <i>Resource utilization</i>
Preventive maintenance <i>Seasonal distribution</i> <i>Categorization</i> <i>Disable during certain periods</i> <i>Condition based maintenance</i>	O&M costs <i>O&M costs</i>
Corrective maintenance <i>Changing failure rates</i> <i>Categorization</i> <i>Prioritization</i>	
Opportunistic maintenance <i>Maintenance coordination</i>	

Figure 49: Summary of key functionalities and key outputs

In Part III the authors investigated the ability of modelling key functionalities, presented in the apple framework, in Systecon's simulation tool SIMLOX. Results from simulations were also compared to key outputs displayed in the framework. In summary a majority of the key functionalities could be modelled successfully in SIMLOX. Some key functionalities could be modelled, but some improvements were detected. For instance, modelling of resources met some difficulties regarding clustering of wind farms. At present it's not possible to combine remote support of resources with resource shifts in SIMLOX. Since resource shifts are strongly related to the possibility to model wind farm accessibility, this feature ought to be developed in SIMLOX. Further, no information about costs can be defined in SIMLOX, which results in simulations that bring no results in monetary terms.

Above all the investigation of key functionalities and key outputs showed that SIMLOX has the capability to model wind as both a cost and value driver. This relationship is important to regard since it's characteristic for O&M of offshore wind farms. Further, this is something that hasn't been ceased in any of the investigated simulation tools in this report, that merely captures wind speed in a restrictive manner.

17.2 Recommendations

Simulations have been run over a period of three years. A simulation period covering at least 10-15 years is desired in order to achieve results over the wind turbines' lifetime. Since information regarding PM activation has been defined for each hour during three years time, simulations have slowed up. Therefore the PM activation information must be defined more efficiently in order to simulate over a longer period of time.

Modelling of key functionalities meet difficulties since remote resource support can't be used in connection with resource shifts. It's important to consider that resources must be transported to the wind farm. Regarding rail traffic, maintenance is

performed the other way around: trains are transported to the resources. In order to be able to make a more realistic model, SIMLOX should be able to combine remote resource support with resource shifts.

Since costs can't be defined in SIMLOX, transportation of simulation results to CATLOC is desirable. In this way cost analysis can be performed within the suite of the ILS toolbox.

17.3 Further Studies

The authors suggest that Systecon AB should apply the apple framework in a real case study. By doing so the scope of use for SIMLOX can be further investigated. It would also be interesting to compare results from modelling of offshore wind farms in SIMLOX with results from other simulation tools. This would further clarify disadvantages and advantages with SIMLOX.

Accessibility is based on deterministic data in SIMLOX. Since stochastic variables are preferable to use in the simulations, further studies could regard development of site-specific weather distributions.

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Appendix A

Interview with Jörgen Svensson (2011-03-16)

1. What factors do you consider the most distinguishing for maintenance of offshore wind farms?
2. Which are the cost and value drivers for an offshore wind farm?
3. Which are the cost and value drivers for maintenance of offshore wind farms?
4. Based on Systecon's model of availability, can you describe reliability, maintainability and logistic supportability in context of maintenance of an offshore wind farm?
5. How is maintenance of offshore wind farms affected by accessibility?
6. Is the capacity factor a ratio used within the field of wind power?
7. How is maintenance planned in relation to forecasts, seasonal and diurnal variations?
8. Is there any documentation of performed maintenance?
9. How is condition monitoring systems practised?
10. There are numbers from ECN that indicate that approximately 50% of costs related to maintenance are revenue losses, is this your experience?
11. Is the focus on minimizing costs or maximizing profit (or both) for the maintenance organisation?
12. Is the maintenance strategies affected by the electricity demand?
13. Are there limits of values that affect decisions regarding maintenance actions?
14. Is there any categorisation of maintenance or is all maintenance activities treated in the same way?

Appendix B

Interview with Håkan Borgström (2011-04-19)

1. Does Dong Energy consider the market price of electricity?
2. Which are the main O&M cost drivers?
3. What potential have reduction of direct costs and revenue losses?
4. What is the yield concept?
5. Should LCC or LCP be considered for O&M of offshore wind farms?
6. Can you explain what internal and external efficiency is for an offshore wind farm?
7. What input is required and what output is generated in the simulation?
8. Which are the most significant uncertainties in the simulation?
9. How does the model handle wind and wave data?
10. Which are the model's advantages and disadvantages?
11. Does Dong Energy use any optimization tool for spare parts logistics?
12. Are failures and maintenance activities classified?
13. What are the costs related to the operation and maintenance?
14. What characterize Garrad Hassan's simulation tool?

Appendix C

Interview with Francois Besnard (2011-05-16)

1. Which simulation models have you tried? Which are commercial, except from Garrad Hassan and ECN? How does simulation model handle:
 - Clustering (sharing resources)
 - Changing failure frequencies
 - Wind speed related to production, not only restrictive
 - Application handiness
 - Opportunistic maintenance
2. Which are the main differences between the OMCE and the O&M tool?
3. You have evaluated ECN's O&M tool, main advantages and disadvantages?
4. How does condition based maintenance work in the O&M tool?
5. Output: what do operators (Vattenfall) require as output in a simulation model?
 - Yield concept (baseras på capacity factor och availability. HUR?)
 - Availability
 - KPI/MPI
6. Which are the most significant uncertainties in the OMCE simulation?
7. How does the model handle wind and wave data?

Appendix D

Weather windows, Visual Basic code:

```
Sub WD()  
  
Dim DayStart, DayEnd As Long  
Dim tBoat, tHeli, tJackup As Integer  
Dim intData, intPara, intOut As Excel.Worksheet  
Dim wlBoat, wlHeli, wlJackup, slBoat, slHeli, slJackup As Long  
Dim t As Double  
  
Set intData = Worksheets("Data series")  
Set intPara = Worksheets("Parameters")  
Worksheets("Outputdata").Delete  
  
DayStart = intPara.Cells(14, 3).Value  
DayEnd = intPara.Cells(15, 3).Value  
  
MsgBox ("Start " & DayStart & " End " & DayEnd)  
  
wlBoat = intPara.Cells(8, 3).Value  
slBoat = intPara.Cells(8, 4).Value  
wlHeli = intPara.Cells(10, 3).Value  
slHeli = intPara.Cells(10, 4).Value  
wlJackup = intPara.Cells(9, 3).Value  
slJackup = intPara.Cells(9, 4).Value  
  
MsgBox ("Boat " & wlBoat & " " & slBoat & "Jackup " & wlJackup & " " & slJackup)  
  
Dim oSheet As Worksheet  
  
    'creating a new excel worksheet called RawData >  
  
    Set oSheet = Worksheets.Add  
    oSheet.Name = "Outputdata"  
  
    Set intOut = Worksheets("Outputdata")  
    intOut.Cells(1, 1).Value = "Day"  
    intOut.Cells(1, 2).Value = "Boat"  
    intOut.Cells(1, 3).Value = "Jackup"  
    intOut.Cells(1, 4).Value = "Heli"  
  
    For d = 1 To 1095  
  
        tBoat = 0  
        tHeli = 0  
        tJackup = 0  
  
        For h = DayStart + 2 To DayEnd + 1  
  
            intData.Cells((d - 1) * 24 + h, 3).Font.Bold = True  
  
            If intData.Cells((d - 1) * 24 + h, 4).Value > wlBoat Or intData.Cells((d - 1) * 24 + h,  
5).Value > slBoat Then  
                tBoat = tBoat + 1  
            End If
```

```

If intData.Cells((d - 1) * 24 + h, 4).Value >= wlHeli Or intData.Cells((d - 1) * 24 + h,
5).Value >= slHeli Then
    tHeli = tHeli + 1
End If

If intData.Cells((d - 1) * 24 + h, 4).Value >= wlJackup Or intData.Cells((d - 1) * 24 + h,
5).Value >= slJackup Then
    tJackup = tJackup + 1
End If

Next h

intOut.Cells(d + 1, 1).Value = d

If tBoat > 0 Then
intOut.Cells(d + 1, 2).Value = 1
Else
intOut.Cells(d + 1, 2).Value = 0
End If

If tJackup > 0 Then
intOut.Cells(d + 1, 3).Value = 1
Else
intOut.Cells(d + 1, 3).Value = 0
End If

If tHeli > 0 Then
intOut.Cells(d + 1, 4).Value = 1
Else
intOut.Cells(d + 1, 4).Value = 0
End If

Next d

End Sub

```