Wind Turbine Reliability Modeling

By Símon Einarsson

Thesis of 60 ECTS credits
Master of Science in Sustainable Energy Engineering
June 2016

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Thesis of 60 ECTS credits submitted to the School of Science and Engineering
at Reykjavík University in partial fulfillment
of the requirements for the degree of
Master of Science in Sustainable Energy Engineering

June 2016

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I. ABSTRACT

Although the technical concepts and reliability of wind turbines have improved over the years, there is still room for further advancements. Wind turbine operators and researchers have reached a consensus with respect to the need for improvements in the field of wind turbine reliability, associated with operation and maintenance (O&M). Maintainability plays an important role in the operation of wind turbines. The high maintainability requires sufficient maintenance strategies and the right stock of inventory. Service and spare parts are estimated to comprise 26% of the operational expenditure (OPEX). OPEX and availability are key factors that affect the levelized cost of energy (LCoE), whereby OPEX represents 11% - 30% of the LCoE [1].

A quantitative reliability block diagram (RBD) model was developed to use reliability data in order to evaluate wind farm availability and OPEX. The model was developed using the Blocksim software tool developed by Reliasoft Inc. The model was based on reliability data from NREL and verified through a comparison of the estimated OPEX with the OPEX of selected OECD countries.

The model's results were in many ways unexpected, as the behavior of the wind farms are challenging to predict without a simulation model. The model showed that reliability data may be used to analyze O&M strategies, to evaluate the availability, forecast service, and maintenance costs. The sensitivity analysis demonstrated how important it is to prevent the failure of expensive parts. Based on these results, it was concluded that the model is a valuable tool to evaluate and analyze wind farm operation and maintenance.

This study also makes exciting future recommendations for the optimization and reliability centered maintenance, which is specifically designed to maximize system reliability and availability at the lowest price possible.

Keywords: Wind Turbine; Reliability Block Diagram; Availability; Monte Carlo Simulation; Operation & Maintenance.

II. ÁGRIP

Tækni og áreiðanleiki vindhverfla hefur aukist á síðustu árum en þó er svigrúm fyrir enn frekari framfarir. Rekstrar- og þróunnaraðilar eru samróma um að það sé þörf á auknum áreiðanleika í tengslum við rekstur og viðhald vindhverfla. Viðhald spilar stórt hlutverk í rekstri vindherfla. Gott viðhald byggist á góðri viðhaldsáætlun og birgðahaldi. Þjónusta og varahlutir eru áætluð 26% af rekstrarkostnaði vindhverfla. Rekstrarkostnaður og uppitími eru einn af þeim helstu þáttum sem hafa áhrifa á raforkuverð. Hlutfall rekstrarkostnaðar af jöfnuðu raforkuverði er á bilinu 11% - 30%.

Sjónrænt áreiðanleika líkan var þróð til að meta og greina rekstur vindgarða. Líkanið var þróað í Blocksim, hugbúnaði frá Reliasoft Inc. Líkanið var byggt á gögnum frá NREL um tíðni bilana í vindhverflum. Líkanið var staðfest með því að bera saman áætlaðan rekstrarkostnað við rekstrarkostnað í völdum OECD löndum.

Niðurstöðurnar voru á margan hátt óvæntar og hefði verið erfitt að spá fyrir um þær án notkunar líkansinns. Líkanið sýndi að gögn um tíðni bilana má nota til að greina rekstur og viðhald ásamt því að spá fyrir um uppitíma og viðhaldskostnað.

Næmnigreining sýndi hversu mikilvægt er að beita réttu viðhaldi til að koma í veg fyrir dýrar bilanir. Útfrá niðurstöðunum var ályktað að líkanið sé gagnlegt tæki til þess að greina rekstur og viðhald vindhverfla.

Spennandi tillögur voru gerðar um bestun í rekstri með áreiðanleika miðuðu viðhaldi sem er sérstaklega hannað til að hámarka áreiðanleika og uppitíma með sem lægstum kostnaði.

Leitarorð: Vindhverfill; Sjónrænt áreiðanleika líkan; Uppitími; Monte Carlo hermun; Rekstur og viðhald.

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IV. CONTENTS

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VII. LIST OF SYMBOLS AND ACRONYMS

CP	Capacity factor [dimensionless]
MTBF	Mean time between failures [time]
MTTF	Mean time to failure [time]
MTTR	Mean time to repair [time]
NPV	Net present value
O&M	Operation and maintenance
Rpm	Rotations per minute
RS	ReliaSoft
EVI	Expected value of information
EVPI	Expected value of perfect information
EVIU	Expected value including uncertainty
FCI	Failure criticality index
DTCI	Downtime criticality index
SCADA	Supervisory control and data acquisition
TLCC	Total life cycle cost
CAPEX	All capital expenditure of a system or project
OPEX	All operational expenditure of running a system
LCOE	Levelized cost of energy [USD/MWh]
OECD	Organisation for Economic Co-operation and Development
NREL	National Renewable Energy Laboratory
IEA	International Energy Agency
LWK	Landwirtschaftskammer Schleswig-
VTT	Technical Research Centre of Finland
WMEP	Wissenschaftliches Mess- und Evaluierungsprogramm
WT	Wind turbine
WEI	Wind Energy Index
f(t)	Probability distribution function (pdf)
F(t)	Cumulative distribution function (cdf)
R(t)	Reliability at time t [dimensionless]

A(t)	Availability at time t [dimensionless]
U(t)	Unavailability at time t [dimensionless]
M(t)	Probability successful repair action at time t [dimensionless]
$\lambda(t)$	Lambda the failure rate function [time]
η	Eta the scale (life) parameter [time]
β	Beta the shape (slope) parameter [dimensionless]
γ	Gamma the location parameter [dimensionless]
σ	Sigma represent standard deviation in data set
μ	Mu represent mean (average) of a data set
π	Pi a mathematical constant

1 INTRODUCTION

This chapter provides background information about the topic of this thesis. It explains the motivation behind the research and furthermore discusses the research focuses, aims and objectives. Finally, it discusses the value of this research and introduces its structure.

1.1 BACKGROUND

Today, governments over the world set goals to reduce greenhouse gas emission and to increase electricity production from renewable energy sources [2], [3]. The European Commission's targets for 2020 are:

- 20% decrease of greenhouse gas emission from the 1990 levels
- 20% of the EU's total energy comes from renewables
- 20% increase in energy efficiency

From an examination of the renewable energy sector, hydropower, geothermal power and biogas are all considered developed solutions, whereas wind, solar and nuclear are still under development [4]. It is debatable whether nuclear can be considered a renewable energy. Nuclear fusion is exciting technology for which many have high hopes, but still this technology is considered 30 to 50 years away [5]. Today's focus is on the renewables that have demonstrated many opportunities and recent growth, namely solar and wind energy.

The Icelandic energy market is known for stable renewable energy and its favorable long-term electricity contracts, which attract power intensive industries. Through increased development and the new players that have emerged in the Icelandic market, such as solar silica producers, ferrosilicon plants and possible subsea cable, demand for electricity remains high [6],[7],[8].

Currently, hydro and geothermal power dominate Icelandic energy production [4]. The addition of wind power within the energy mix is also an interesting option. Wind energy is generally considered predictable over the long-term, whereas hydropower is more predictable over the short-term. A mix of hydro power and wind turbines is generally considered a good decision because of hydropower's ability to level out short term variability in energy production and wind power's long-term reliability [9]. Wind turbines' main power season in Iceland is through the winter, when water flow are low. This aspect leads wind power to be used to compensate for hydro power throughout the low season, when the reservoir may be used as energy storage [10].

Landsvirkjun (Icelandic biggest power producer) and Biokraft (Icelandic wind power startup company) have shown interest in wind energy as each installed two experimental wind turbines. Landsvirkjun installed two 900kW turbines (the word trubine is commonly used instead of wind turbine in this thesis) from Enercon at Hafið in the Búrfell area in January 2013. The wind projected at Hafið is considered successful, as it had a capacity factor of 40% [11] in the year 2014 in comparison to a world average of 28% [12]. Biokraft installed two 600kW V44 turbines from Vestas at Þykkvabær in Julie 2014, which have had an average capacity factor of 42% since they began to produce electricity. Biokraft is currently in the process of an environmental assessment to add 13 wind turbines with a total 45MW of installed power. With respect to the project's feasibility, the levelized cost of electricity (LCoE) must be competitive. Reliability is important to keep LCoE competitive and to increase the project's probability of success. The wind turbine industry has already recognized the importance of reliability, especially in terms of offshore wind turbines, whereby maintainability is lower [13]. According to the International Energy Agency (IEA), there are considerable opportunities to improve wind turbine reliability and to optimize operating and maintenance (O&M) strategies. Maintenance is currently being planned and executed according to statutory requirements and rough guidelines from wind turbine manufacturers. Corrective maintenance (CM) due to unexpected malfunctions of components can cause serious economic losses as a result of catastrophic failures [14]. To prevent these failures from occurring, O&M should be shifted from corrective maintenance to preventive maintenance (PM) strategies. IEA addresses this problem through wind task 33, which aims to standardize the collection of reliability data. Access to good data serves as the foundation for the effective preventive maintenance strategy [15]. Interviews with wind turbine maintenance experts have further confirmed the importance of reliability data and modeling [16].

1.2 RESEARCH FOCUS

Previous research on wind turbines in Iceland has ranged from general feasibility studies to more focused studies on how to optimize wind turbine selection. This thesis focuses on how reliability statistics may be utilized with the wind farm owner's best interest in mind, for example to evaluate and forecast maintenance costs, availability and other key metrics, as well as to lay the groundwork for the optimization of wind farms. This study employs a reliability block diagram (RBD) because of its visually-based ability to clarify overall concepts and its ability to simulate complex systems. The Monte Carlo simulation is used to obtain as realistic result from the RBD modeling as possible. The modeling uses the Blocksim and Weibull++ software packages from Reliasoft. The modeling work is based on statistics and engineering, using probability distributions, failure statistics, cost and other logistics information to build a realistic model. More specifically, the model accounts for the following:

- Failure statistics
- Cost of spare parts
- Cost of repair
- Cost of consequences of failure
- Spare part pools
- Wind turbine maintenance crews
- Repair time
- Crew delay time
- Spare part shipping time

1.3 RESEARCH AIM AND OBJECTIVES

This research's overall objective is to advance the understanding of wind turbine reliability and its connection to the O&M, availability and OPEX. This will be done utilizing RBD to model wind turbine operations with a focus on component failure and replacement.

More specifically, this research's objectives are as follows:

1. Explore the latest research on wind turbine reliability
2. Develop a wind turbine RBD simulation model
3. Discuss the value of reliability data and optimization

4. Recommend a method to estimate availability and maintenance costs

1.4 RESEARCH VALUE

This research demonstrates the importance of reliability data and the value of choosing a suitable O&M strategy to operate a complex system such as wind farm. Through the use of simulation key metrics such as reliability, availability, maintainability and maintenance cost can be analyzed. The analysis of these metrics is useful to develop an O&M strategy and to evaluate different wind farm service agreements. It is critical to execute the correct maintenance strategy for project feasibility and through the use of the simulation, it is possible to compare different strategies and optimize them. According to IRENA Wind Power Report, OPEX represents 11% - 30% of wind turbine LCoE [17]. OPEX can be decreased by optimizing wind turbines, strategizing, and reducing maintenance costs. OPEX is one of the three pillars that determine wind farm profitability, along with capital costs and revenue which are listed below. For further explanations, view Figure 30 on wind turbine economics.

- CAPX (Capital expenses)
- OPEX (Operational expenses)
- Revenue (Based on power output, which is mainly determined by wind source, rotor diameter and availability)

An adequate reliability model is based on quality data, which encompasses all the O&M factors, in such a way that decisions can be made to ensure the success of wind farm projects.

1.5 THESIS STRUCTURE

This thesis is organized into 6 chapters:

Chapter 1 provides the introduction to the thesis topic and aims to provide the reader with background information about the thesis topic.

Chapter 2 fulfills the first and third research objectives, as it provides a literature review on the following topics:

- Wind turbine subsystem and components
- Previous wind turbine reliability research
- Importance of reliability data, concepts and methods
- Main probability distributions used in reliability engineering
- Reliability and economics
- Wind turbine standards

Chapter 3 outlines the methodology used to develop the RBD model and discusses the analysis of the model's output data. The chapters aims to satisfy research objective 2.

Chapter 4 presents the results of the methods discussed in chapter 3.

Chapter 5 concludes the paper with a discussion of the methodology, model and results. The chapter aims to satisfy research objectives 3 and 4.

2 LITERATURE REVIEW

This literature review provides a summary of wind turbine components and subsystems. The chapter further outlines the basics of reliability theory. It compiles the current research on wind turbine reliability, O&M. The end of the chapter discusses wind turbine economics and its connection to reliability, along with turbine standards.

2.1 RELIABILITY DEFINITIONS AND FUNCTIONS

Reliability is defined as the probability that a system performs its duty over a defined amount of time when it is operated correctly in a defined operating environment. The definition of reliability can be broken down to four main parts [15]:

- Time
- Probability
- Operating environment
- Performance

Unreliability is the probability of a system failure over a defined amount of time when operated correctly in a defined operating environment. Unreliability is the inverse of reliability.

Maintainability is the ease at which a system is maintained and how quickly broken item are replaced or repaired after failure in order to restore the system to its functional operating state. Maintainability also includes the prevention of unexpected breakdowns, and the correction of wrong operations to maximize the system's availability [18].

Availability depends on both reliability and maintainability**.** One should not confuse availability with reliability. Several specific definitions for availability do exist, and therefore it is important to identify what definition is used. This thesis mainly uses operational availability. Operational availability is the percentage of time that a system is operational, which can best be described by the following formula:

$$Availability = \frac{Uptime}{Uptime + Downtime} \tag{2.1}$$

The sum of uptime and downtime is equal to the system's lifetime, whereby the uptime is the system's operating time and the downtime is the time that the system is not in operation [19].

Unavailability is the opposite of availability and provides information about how much time the system is not operational.

Table 1 demonstrates the relationship between reliability, maintainability and availability [29]. In the table one can see how availability is dependent on both reliability and maintainability and to increase availability either reliability, maintainability or both factors need to be increased.

Table 1: Relationship between reliability, maintainability and availability

Reliability	Maintainability	Availability
Constant	Decreases	Decreases
Constant	Increases	Increases
Increases	Constant	Increases
Decreases	Constant	Decreases

All three metrics may be analyzed at given point of time in the system's life cycle. This analysis is known as point reliability, maintainability or availability [20].

- Point reliability, R(t) = Reliability at time t
- Point maintainability, M(t) = Probability successful repair action at time t
- Point availability, A(t) = Availability at time t

The calculation of these metrics is different depending on the probability distribution that fits the underlying data set [27]. For example, for the Weibull distribution maintainability, M(t), is provided by:

$$M(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2.2}$$

Where

$t = point\ of\ time$

$\beta = shape\ parameter$

$\eta = scale\ parameter$

The exponential distribution maintainability, M(t), is provided by:

$$M(t) = 1 - e^{-\mu t} \tag{2.3}$$

Where

$t = point\ of\ time$

$\mu = repair\ time$

The other important definitions in reliability engineering are as follows:

- Failure
- Mean time to failure (MTTF)
- Mean time between failure (MTBF)
- Repair
- Mean time to repair (MTTR)
- Repairable system
- Non-Repairable system

The following sections explore these definitions.

Failure is an event in which the component or system fails to perform its duty under certain conditions. When a component or system cannot perform it duty, the curves considers that failure's occurrence [21]. Figure 1 indicates when the stress curve overlaps the strength curve probability of failure to occur in the failure area [22].

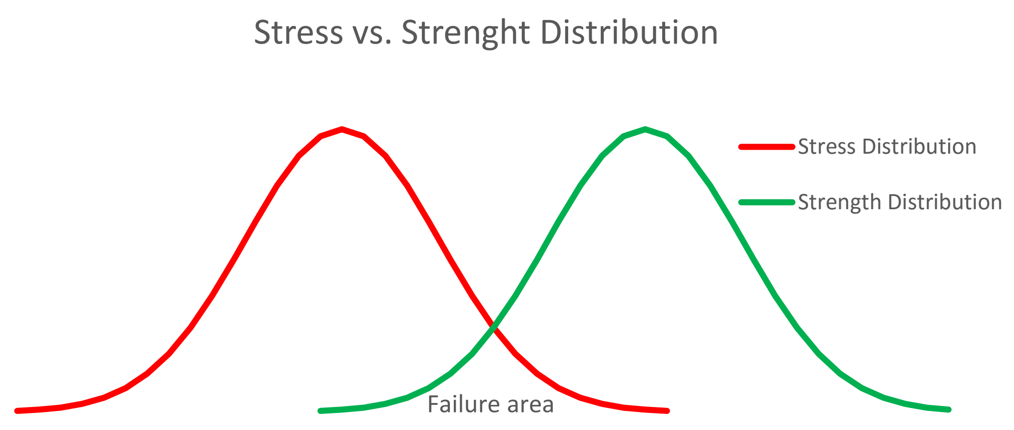

Figure 1: Stress vs. strength distribution

Mean time to failure (MTTF) is defined as the mean time to failure in a system that is normally non-repairable. If the system is non-repairable, then this time is equal to expected life time of the system [29].One should note that MTTF is not an adequate metric to measure a system's reliability because the system with the same MTTF does not need to have the same point reliability or availability. This metric can be best demonstrated with a graph. Figure 2 shows three systems that have nearly the same MTTF, but do not have the same reliability. From the figure, it is evident that the three lines have different reliabilities at the same point of time. This example indicates that the system can have the same MTTF, but still have different points of reliability R(t). Therefore, MTTF does not take failure behavior into account at specific time in the system's lifetime.

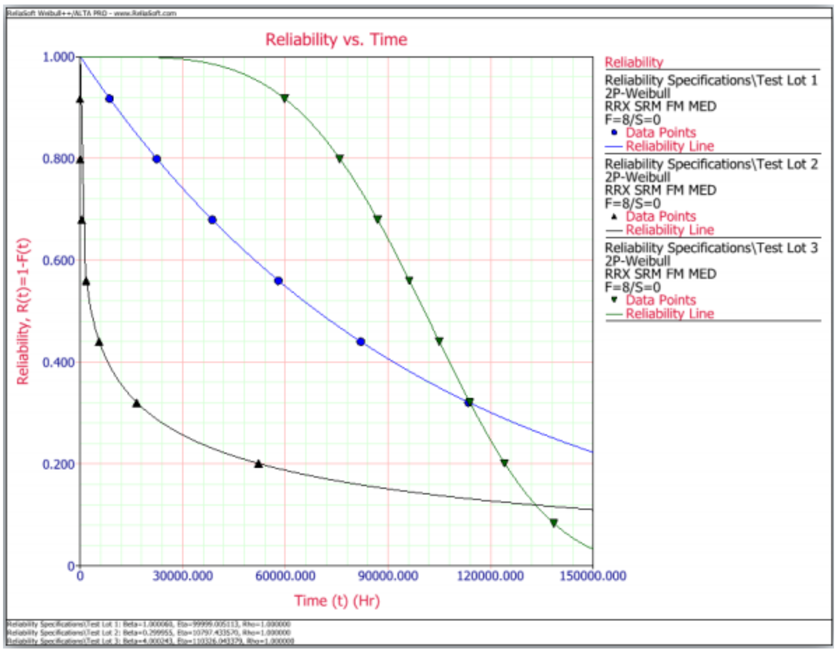

Figure 2: Reliability vs. time [23]

Mean time between failures (MTBF) describes the mean time between failures in a system during operation and can be found by dividing operating time by the number of failures [19]. MTBF is given by:

$$MTBF = \frac{operating\ hours}{number\ of\ failures} \tag{2.4}$$

MTBF is used to maintain a repairable system, and cases in which the system is non-repairable, MTBF equals MTTF.

A **Repairable System** is defined as system that can be repaired after failure and consequently restored to operation conditions. A **Non-Repairable System** is a system that cannot be repaired after failure and restored to its operable conditions. These systems need to be replaced with a new working system [20].

Repair is the process of a restoring system that has failed to operate. A **Minor Repair** is normally due to smaller failures, such as a failure from the sensors or a replacement of smaller parts within a short period of repair time. A **Major Repair** is normally a failure from the turbines' mechanical parts, in which repair time is longer [24].

Mean time to Repair (MTTR) is a term used only with repairable systems. It represents the time from the point of the failure until the system is fully operational again [15].

Along with these definitions of reliability, there are some key reliability functions that are important to identify, that is:

- f(t) Probability distribution function (pdf)
- F(t) Cumulative distribution function (cdf)

- U(t) Unavailability at time t
- λ(t) Failure rate function

The probability distribution function f(t) represents the failure distribution when working with reliability data and the cumulative distribution function F(t) represents unreliability at time t. The probability of failure has occurred at time t, which is known as unreliability, is calculated by finding the cdf, given by:

$$F(t) = \int_0^t f(t)dt \tag{2.5}$$

The relationship between the unreliability and reliability is given by:

$$R(t) + F(t) = 1 \tag{2.6}$$

The relationship between availability and unavailability is given by:

$$A(t) + U(t) = 1 \tag{2.7}$$

The hazard or failure rate function provides the number of failures over a period of time, and is given by:

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{2.8}$$

The failure rate may be increasing, decreasing, constant or increasing.

- A decreasing failure rate appears in the first stage of a product's lifecycle
- The constant failure rate is the stage in which failure accrues randomly and in the middle of the product's lifecycle.
- Increasing failure rate impels wear out and accrues at the end of the product lifecycle

Table 2 summarizes and shows the relationship between probability density function f(t), reliability R(t), unreliability F(t) and the failure rate λ(t) [25].

Table 2: Relationship between f(t), F(t), R(t) & λ(t)

	F(t)	R(t)	f(t)	λ(t)	
F(t) =	*F* (t)	1 - R(t)	$\int \; ( )$	1-exp$\left(-\int \; ( ) \;\right)$	**Pribability of failure**
R(t) =	1 - F(t)	R(t)	$\int \; ( )$	exp$\left(-\int \; ( ) \;\right)$	**Reliability**
f(t) =	*F*(t) —	R(t) —	f(t)	( )exp$\left(-\int \; ( ) \;\right)$	**Prbability density function**
λ(t) =	$\frac{F(t) —}{- F(t)}$	$(ln\ R(t))$ —	$\frac{f(t)}{( )}$	λ(t)	**Failure rate**

All reliability calculations and functions are based on the underling probability distribution function f(t) selected as the best fit for the system's failure statistic. For this reason, some of the most common distributions are introduced in chapter 2.5.

2.2 Wind Turbine Subsystems

This subchapter describes the basics of wind turbine components. Figure 3 illustrates the main subsystem and parts of wind turbines.

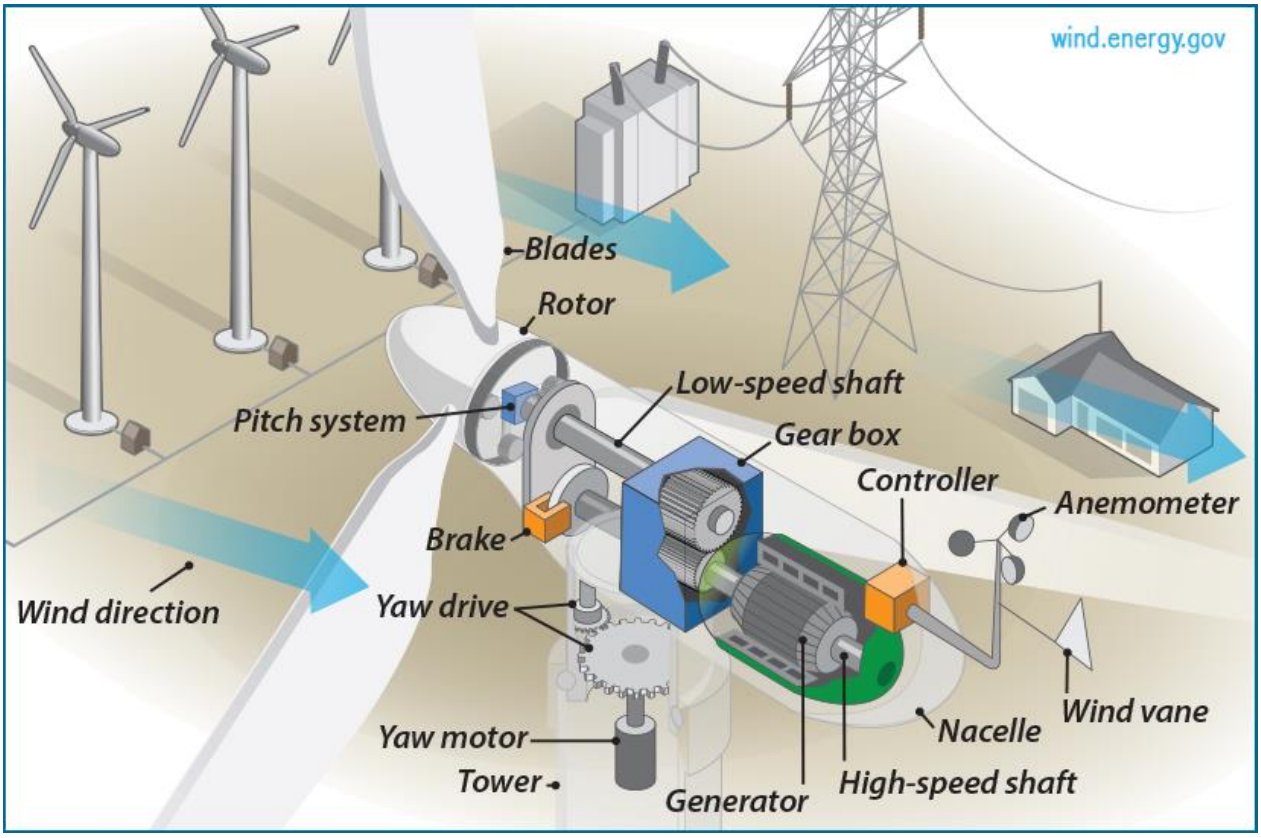

Figure 3: Inside of a wind turbine [26]

2.2.1 Rotor Blades & Hub

The rotor blades are the wind turbine's mechanism that captures the kinetic energy of the wind and transforms it into mechanical energy used to power the generator. The rotor blades are bolted to the rotor hub, which is connected to the main shaft [27].

2.2.2 Pitch System

The pitch system provides the blades with the ability to change the tilt and can be used to optimize the extraction of kinetic energy from the wind or brake in the case of storms [27]. The presence of pitch control reduces stress in the mechanical parts of the drive train. However, to add a pitch system does greater the chances of failures [28].

2.2.3 Nacelle

The nacelle is the housing that protects the generator, gearbox and electrical equipment. The nacelle connects to the top of the tower through bearings, which are able to turn as the wind changes direction [27].

2.2.4 Drive Train

The drivetrain is the connection of the necessary components required to generate electricity. In many cases, it is comprised of the of following components:

- The main shaft
- Gearbox
- Brakes
- Generator

The main shaft is the connection from the rotor hub to the gearbox. In the direct drive turbines, the main shaft is connected directly to the generator. The drive train arrangement differs depending on the producer and turbine model. For example, Enercon only produces direct drive turbines that have no gearbox [29]. Figure 4 illustrates a typical utility-scale drivetrain with a gearbox.

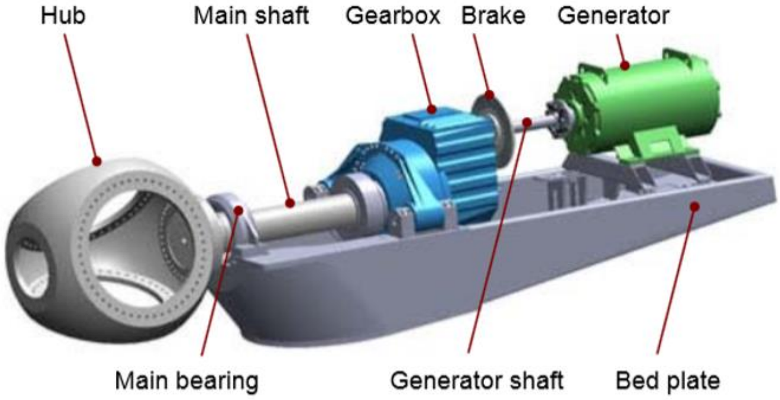

Figure 4: Typical utility-scale turbine drivetrain [29]

Figure 5 shows the drive train of Enercon E-48 direct drive turbine. Direct drive turbines are less complex, have fewer rotating parts and operate at lower speed. The generator of the direct drive turbine needs to be large enough in order to match the traditional high speed generator output. This aspects leads to a larger and heavier nacelle than is traditionally used [30].

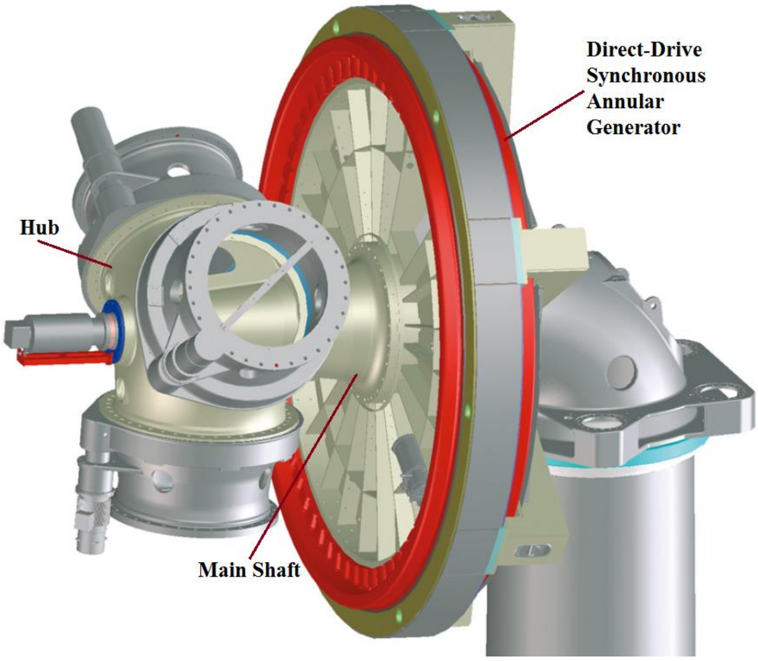

Figure 5:Direct-drive turbine drivetrain [29]

2.2.5 Gearbox

The gearbox converts the slow rotation 30-60 rpm of the main shaft to a high rotation of around 1000-1800 rpm, which fits the generator's requirements. A crane is required to replace the gearbox in cases of a failure, which consequently leads to a long down time and high costs. For this reason, some manufactures have developed direct drive turbines that have lees moving parts [26].

2.2.6 Mechanical brake

The mechanical brake is used when the turbine undergoes maintenance or is in a hazardous situation of high wind in which the aerodynamic brakes can fail. The mechanical brakes may be hydraulically or electrically driven disk brakes. The brakes need to be heavy duty in order to absorb the kinetic energy of the wind in emergencies [27].

2.2.7 Generator

The generator converts mechanical energy to electrical energy through a rotating magnetic field. Generally, there are two types of generators used in wind turbines: synchronous generators and induction generators, which are also known as asynchronous generators.

Induction generators are robust, low maintenance and produce power when the rotor rpm is higher than the synchronous speed. These generators self-starting and can be quite easily connected with the grid [31].

Synchronous generators operate in synchronization to the power system frequency, as their name indicates. They are not self-starting, but do have other positive attributes such as their higher efficiency and power quality. They can be connected to the grid through an invertor, which allows the synchronous generator to operate at variable speed [32], [33]. For example, the Enercon low speed annular generator is synchronous generator that has no direct grid coupling. Its voltage and frequency vary in relation to the rpm, and its connection to the grid is established through a DC link and inverter [34].

2.2.8 Electrical Control

The electrical control system is used to control a variety of elements in the turbine, such as the nacelle yaw angle and rotor blade pitch angle, which affects the spin of the rotor shaft and may be used to achieve a smoother power curve. Additionally, voltage, current frequency and other variables need to be controlled and monitored [27].

2.2.9 Sensors

Wind turbines have a variety of sensors to track their performance. The wind anemometer and the wind vane are two evident sensors that and send data to the control system to configure the yaw and pitch system. Other sensors, for example, may be electrical, vibration and temperature sensors [27].

2.2.10 Hydraulic System

The hydraulic system is used to change the position of the yaw system and the pitch system. Electrical motors can also be used instead of the hydraulic system [27].

2.2.11 Yaw System

The turbine yaw system is located between the nacelle and the tower and enables the turbine to turn according to the direction of the wind [27]. Above, Figure 3 demonstrates the configuration of the yaw-motor and the yaw drive that constitute the yaw system.

2.2.12 Tower & Foundation

The tower is normally made of steel and holds up the nacelle and the rotor blades. The tower must be strong enough to withstand the forces that work on the wind turbine. The tower sits on a solid foundation made of concrete and iron [27].

2.2.13 SCADA

SCADA (supervisory control and data acquisition) is a computer system that gathers and logs data from the wind turbine’s sensors and sends this data to a remote central location in order to track the wind turbines performance. SCADA system can be equipped with multiple alarms and special modifications in order to fulfill its purpose. The SCADA system is useful with respect to condition monitoring. The system is frequently used in order to inform operators about which part of the turbine requires maintenance or a replacement. In this way, it is condition-based and preventive maintenance proves to be very valuable [35].

2.3 WIND TURBINE STANDARDS

The International Electrotechnical Commission (IEC) developed the IEC 61400. Its standards are specifically designed for wind turbines and address most of the turbine design aspects [36]. The standards ensure that the turbines are produced, installed and operated in the correct manner. Iceland has generally strong winds and is often categorized in the top wind classes but that is site dependent[37]. The Ia is the harshest wind class, with an average wind speed at hub height of 10 m/s and 18% turbulence.

Table 2: Wind class standards [38]

Wind Class/Turbulence	Annual average wind speed at hub-height (m/s)	Extreme 50-year gust in meters/second (miles/hour)
Ia High wind - Higher Turbulence 18%	10.0	70 (156)
Ib High wind - Lower Turbulence 16%	10.0	70 (156)
IIa Medium wind - Higher Turbulence 18%	8.5	59.5 (133)
IIb Medium wind - Lower Turbulence 16%	8.5	59.5 (133)
IIIa Low wind - Higher Turbulence 18%	7.5	52.5 (117)
IIIb Low wind - Lower Turbulence 16%	7.5	52.5 (117)
IV	6.0	42.0 (94)

2.4 Previous Wind Turbine Reliability Research

This section explores existing research related to wind turbines and farms. It identifies the key results in terms of reliability in the wind energy sector. Research data is always necessary in reliability research. The research cited in this chapter is based on data from following the databases or institutions [39]:

- ReliaWind: Program under the European Commission that ran from March 2008 to March 2011. Its focus was on reliability and optimization of wind turbine systems, their design, operation and maintenance [40].
- Wind Stats Germany
- Wind Stats Denmark
- Landwirtschaftskammer Schleswig-Holstein (LWK)
- Wissenschaftliches Mess- und Evaluierungsprogramm (WMEP) was active in the years from 1989-2006.
- Vindstat database from Sweeden since 1988
- Technical Research Centre of Finland (VTT). Wind turbine failure and performance data from 1992

2.4.1 IEA 2014 wind report

The IEA wind report is divided into a list of tasks, including one especially relevant for this research, Task 33 [41]. Task 33 explores how wind data and failure statists are collected in participating countries. It provides a plan on how to structure databases for reliability data. It further outlines how the data should be collected. It results in an open forum database with a sufficient amount of data to analysis and optimize both reliability and O&M strategies. Reports of this topic have currently been drafted, but have not been released to the public. In short, Task 33 aims to use reliability data in order to:

- Increase wind turbine reliability and safety
- Optimize O&M strategies

2.4.2 NREL 2013

The NREL report on wind turbine subsystem reliability from 2013 is among the latest research in the field. This report is based on various databases and provides a good idea about wind turbine reliability and their subsystems.

2.4.3 Wind Turbine failure cause

It is important to understand the failure mode and its root cause. Figure 6 indicates wind turbine components and their causes of failure.

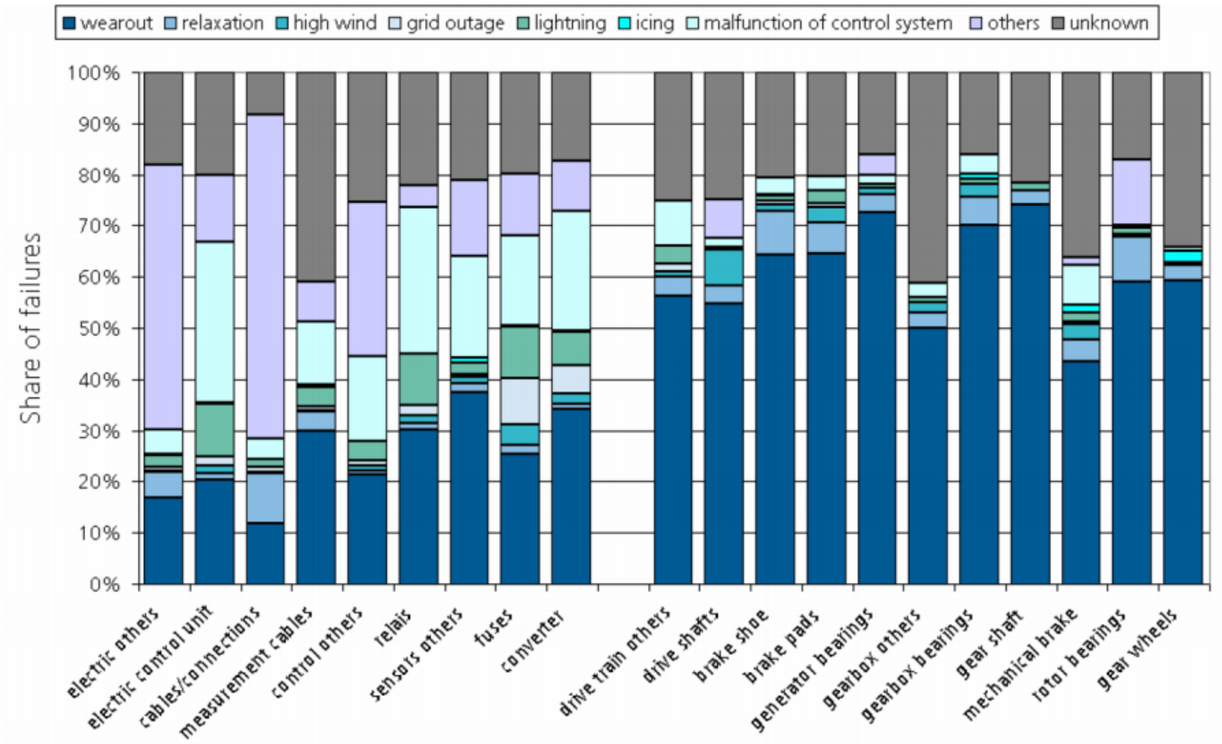

Figure 6: Wind turbine cause of failure from WMEP [42]

2.4.4 Wind Turbine Failure and Downtime

Figure 7 is noteworthy as it shows that 75% of failures cause only 5% of the downtime and 25% of the failures cause the remaining 95% of the downtime. The electric system has the highest failure rate, whereas the gearbox failure causes the longest downtime.

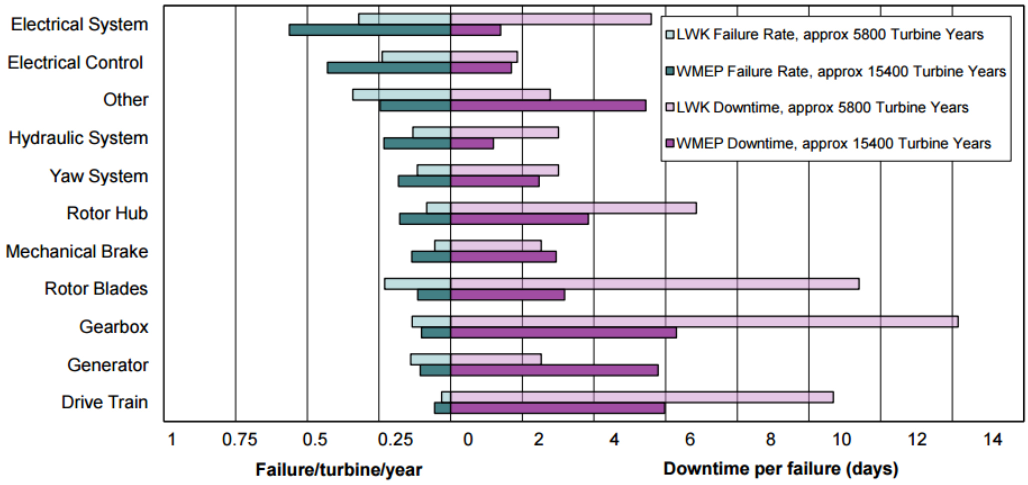

Figure 7: Failure/turbine/year and downtime from two large surveys of land-based European turbines over 13 years [43]

Figure 8 represents Reliawind normalized failure rate data from multiple manufactures. The graph shows how the subsystems contributes to the turbine’s overall failure rate. From the graph, it is evident that the power module is among the top subsystems that contributes to turbine failures. The pitch system contributes to around 20% of failures and is the greatest single factor.

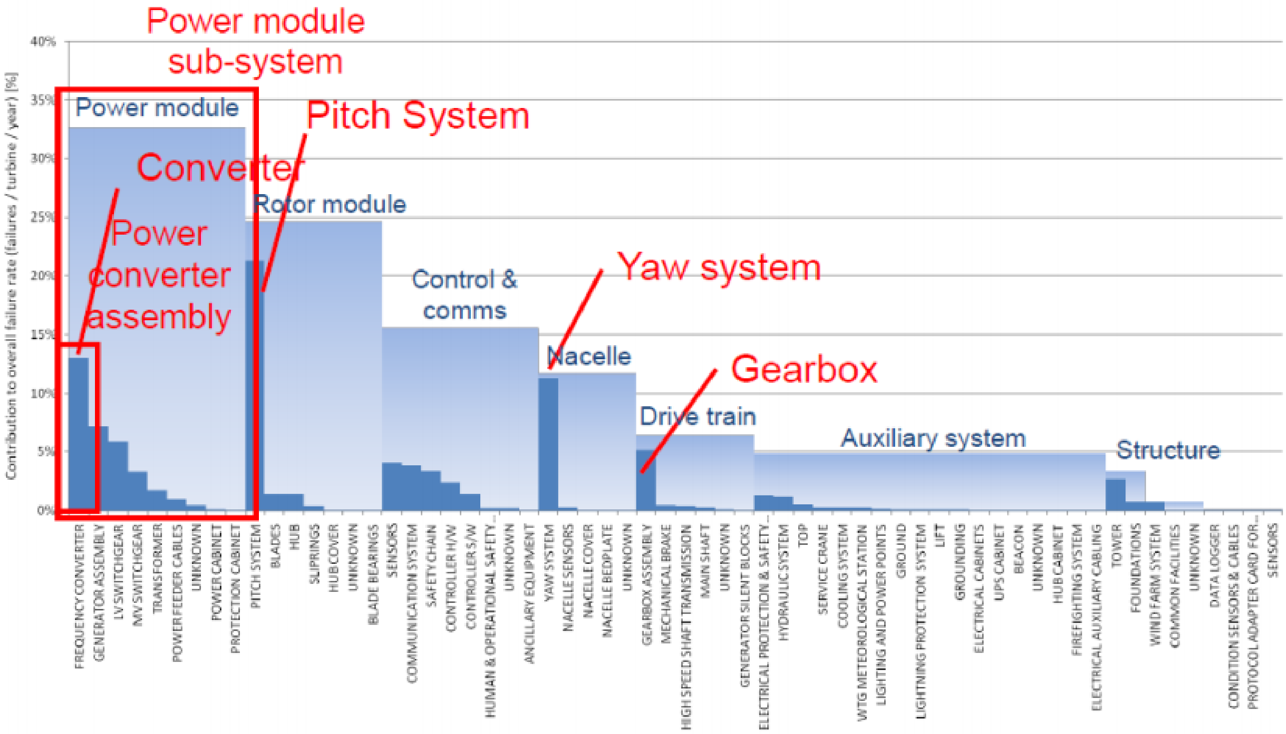

Figure 8: Reliawind, contribution to overall failure rate failure/turbine/year [43]

Figure 9 highlights Reliawind normalized down time data from multiple manufacturers. The graph depicts how each part contributes to the subsystem's downtime and how the subsystem contributes to the wind turbine's overall downtime. The top contributing subsystems to the overall downtime are the power module and the rotor module.

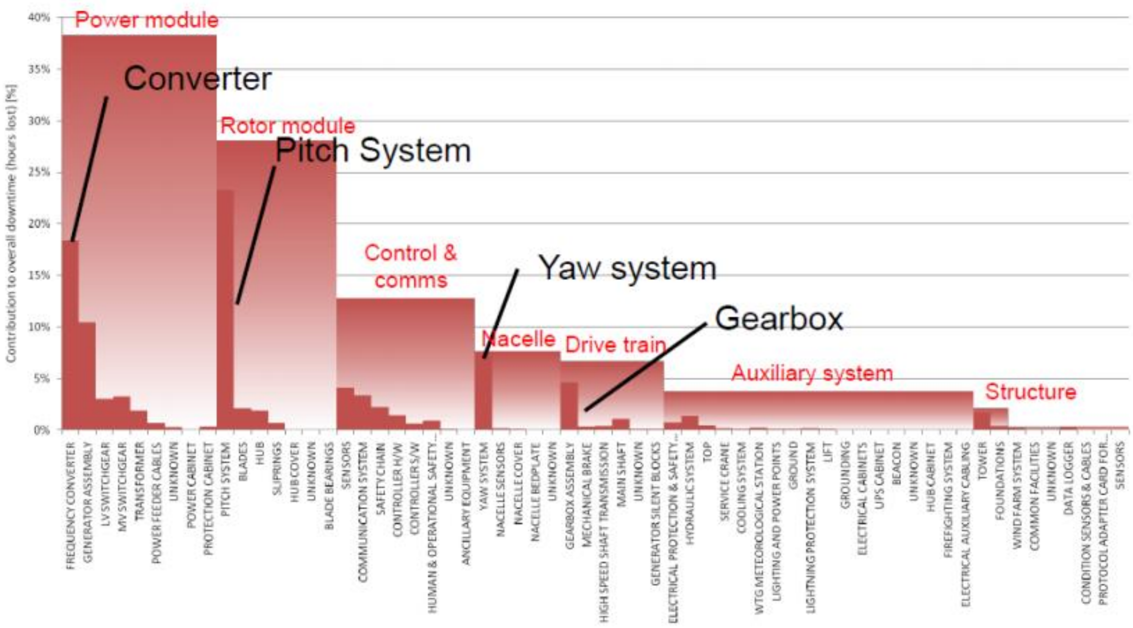

Figure 9: Reliawind, contribution to overall downtime [43]

Figures 8 and 9[44] are based on data from VTT (Technical Research Centre of Finland) and indicate the average failure rate and down time versus operational years. Figure 10 shows an increasing failure rate once wind turbines have been in use for over 15 years. The figures shows that after 13 years, the turbine count drops to 10 turbines. In year 17, five more turbines were taken offline, by year 18, all had been taken offline, which leads the quality of the data to be uncertain from the years 13 to 17.

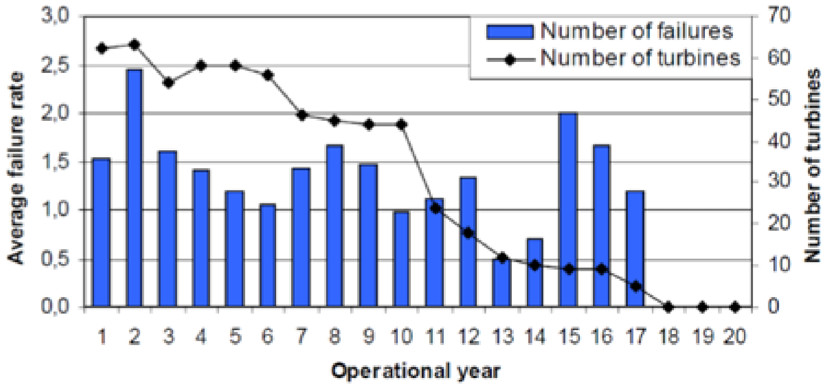

Figure 10: Wind turbine failure rate vs. operational year [44]

Figure 11 shows downtime spike in year 15.

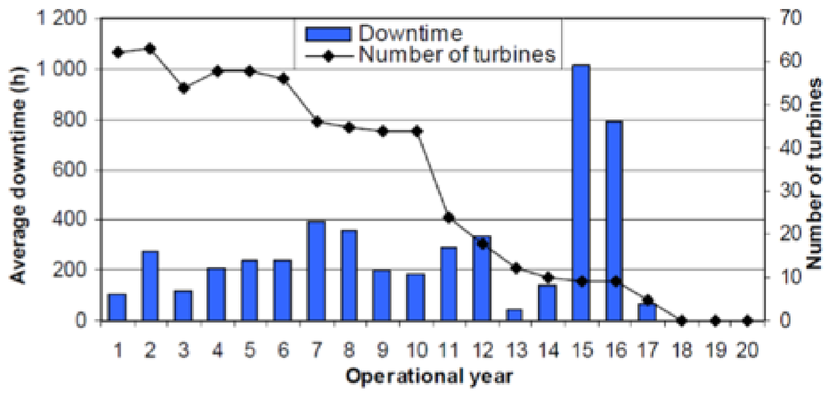

Figure 11: Wind turbine downtime vs. operational year [44]

2.4.5 Wind Turbine Reliability between technical concepts

Figure 12 illustrates the subsystem's contribution to total downtime based on multiple databases. All of the five databases show that most of the turbine downtime is a result of failures in the drive train module, power module and rotor module. The variation between the databases can be caused by differences in turbine ages, technology, the environment and the number of turbines in each database.

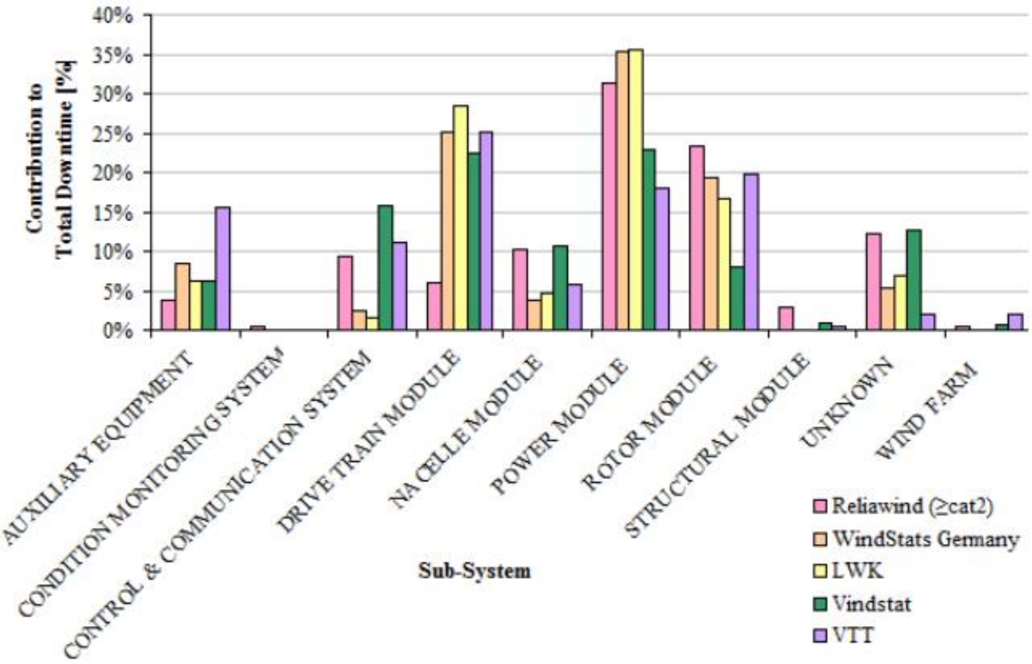

Figure 12: Subsystem contribution to total downtime from multiple database [45]

Figure 13 indicates how turbines with less mature technology have a higher subsystem failure rate. The graph shows that in many cases, direct turbines had a higher subsystem failure rate than older concept turbines. This data, however, is from 1989 to 2006, and direct drive technology is still improving [46]. It is important to note that lower reliability does not necessarily indicate lower availability.

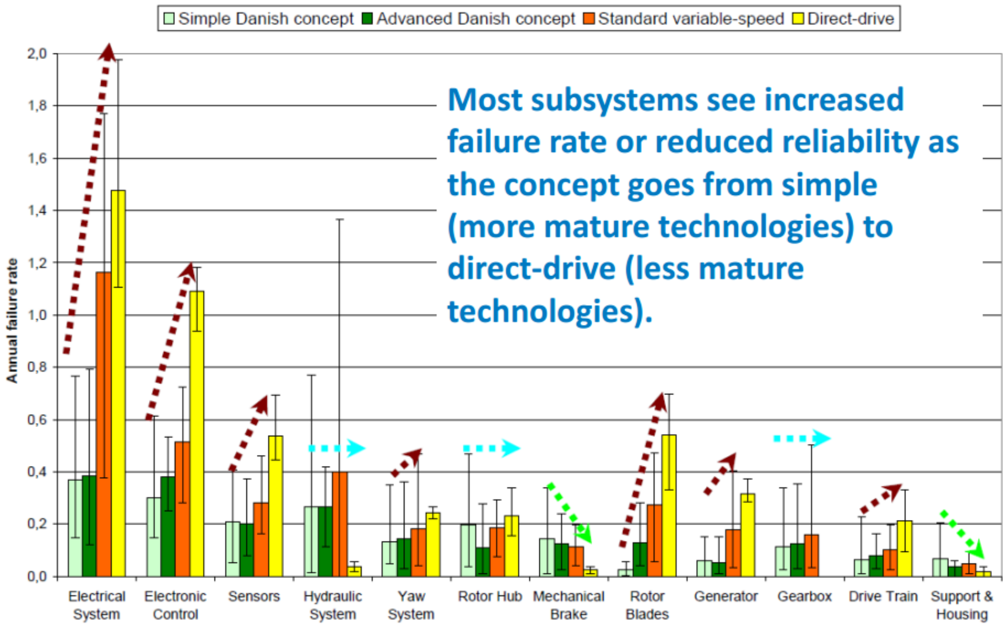

Figure 13: WMEP, failure rate vs. technical concept [46]

The reliability of direct drive turbines has not yet been proven higher than the reliability of more mature wind turbine techniques that use gearboxes. This discrepancy is a result of the higher failure rate of some electrical parts and subsystems in the direct drive turbine in comparison to the more mature technology of conventional turbines [46]. It should be noted that the development of the direct drive turbine is still taking place [39].

From these findings, the direct drive turbine appears to have an advantage with respect to availability [21] because it has no gearbox. The gearbox is the subsystem that causes most of the turbine's downtime. Today, the reliability of turbine gearboxes is similar for gearboxes in other markets, and therefore, it can be assumed that they do not lack technical improvements. The direct drive turbine has fewer moving parts that move at slower speeds. Furthermore, they have no gearbox, and instead, have a larger and heavier generator, due to their energy production at lower rotation speeds.

Figure 14 outlines the failure rate among different turbine models. It is evident that the Direct drive Enercon E40 does not have a lower failure rate than turbines in the same size category, whereas Enercon E66 has a lower failure rate in comparison. One should furthermore consider that that data is limited as a result of the low number of turbines [50].

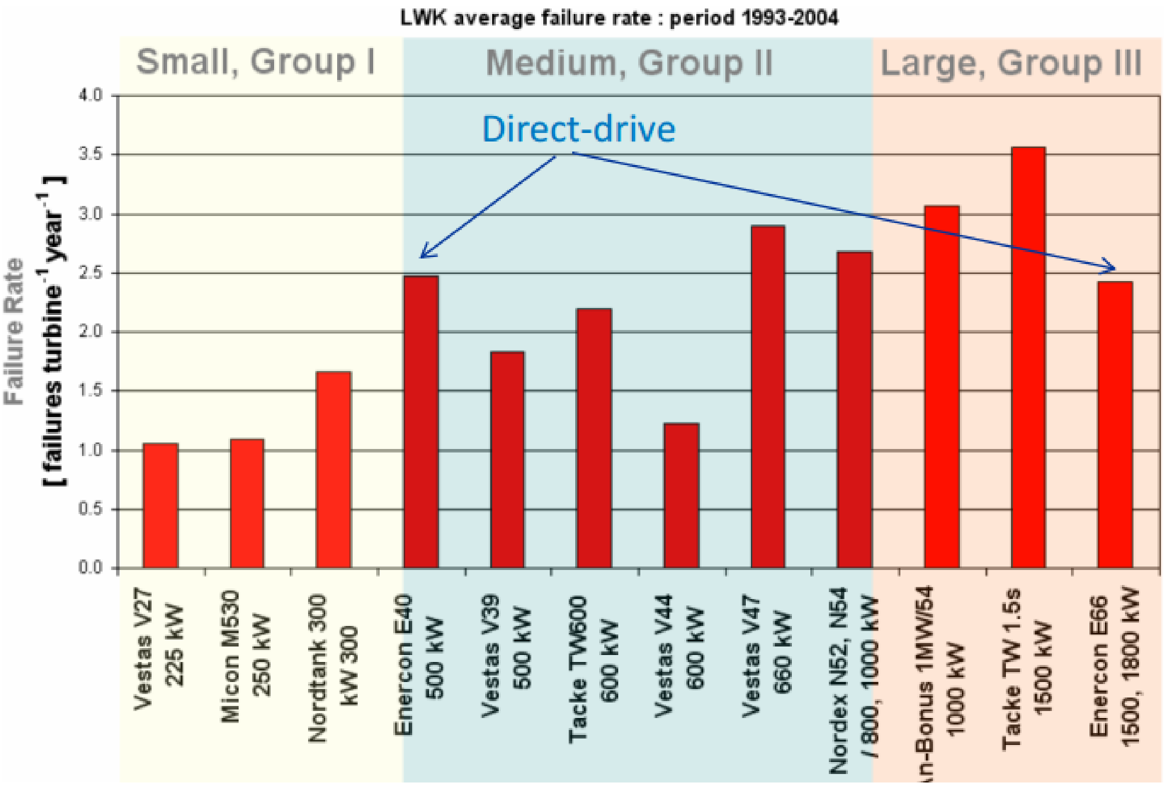

Figure 14: Failure between different turbines models, sorted by size [21]

2.4.6 Environment and Reliability

Prior research has shown how stress factors in the environment affect turbine reliability. According to a study of the effects that weather and location have on turbine failure rates, it is evident that these factors have an effect. This aspect is important to decisions about turbine design and location [47].

Figure 15 shows a comparison of average monthly failure rate and the wind energy index (WEI) over a 10 year period. The figure indicates a peak in both the WEI and failure rate in February. The graph generally shows a correlation between the WEI and the failure rate.

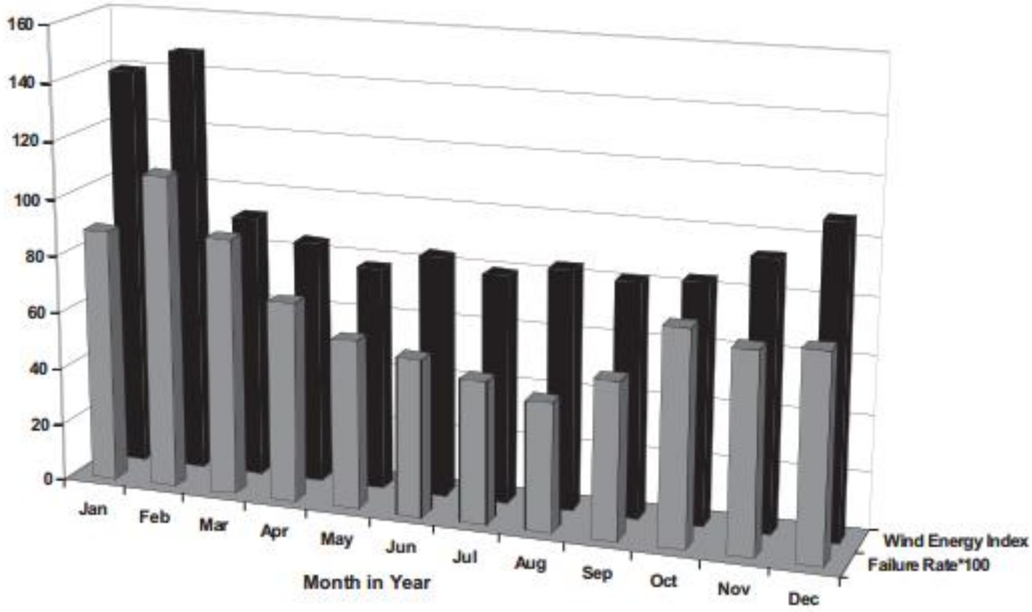

Figure 15: Average monthly failure rate and wind energy index over the years 1994-2004 [48]

Much research has indicated that there is a relationship between weather and failure rate. Some of the main findings from this research are as follows:

- There is a 55-75% cross-correlation between failure data and weather conditions (wind speed, temperature and humanity). [47]
- Wind turbulence is the root cause for pitch mechanism faults. [49]
- High wind speed increases the turbine failure rate. [50]
- Conditions of low wind speed and high gust speed or sudden change are correlated to a higher probability of failure in all sub-assemblies. [50]

A higher wind speeds leads to a greater rpm, which is deemed a life parameter, and therefore, an increase in the failure rate is natural. An increased failure rate is expected in cases in which stress is increased, as previously shown in Figure 1.

2.5 THE IMPORTANCE OF DATA

Data quality is one of the most important aspects of any model, analysis or simulation. The results from the model cannot be of higher quality than the quality of data used. Data quality is based on two important factors, confide and relevance. The two main methods to establish data are from experimental testing and the gathering of life data. Both of this methods cost money and time. Data gathering is still necessary in order to perform a reliability analysis and can have many benefits in the long-term. In many cases, companies that gather reliability data recognize its value, and wish not to share the information [15]**.** The IEA has addressed this problem in the 2014 Annual Wind report under task 33 [13]. Task 33 addresses the problem through standardized data collection. The aim of task 33 is to the stabilize the common database for all wind farms that set aside the company’s competition and work together to increase the reliability of wind farms. This progress utilizes failure data to improve the overall reliability and to optimize O&M strategies, which translates into higher availability, safety and lower OPEX. [13]

2.5.1 Accelerated Life Test

The accelerated life test is a method to gather data through experimentation and testing. It is used when access to historical operational data is not an option. For long lifetime systems such as wind turbine, this process is useful. The methodology helps to identify the system reliability without going through a test period equal to the system's lifetime. The test period is shortened through the implementation of additional stress on the system. The test results are then used to estimate the system's lifetime under normal operating conditions [51], [25].

2.5.2 Reliability Life Data Analysis

Life data analysis is a method that gathers data about components' failures and fits this data to a probability distribution that is used predict the life of all the components in the population. In simple terms, the process of life data analysis is as follows [52], [53]:

- Gather life data
- Select proper probability distribution that fits the data
- Calculate the results such as reliability, availability or mean life

The term life data is used when product life is measured. A component life can be measured in hours, kilometers, cycles or any metric component use or through any measure with which life can be measured. Life data is used to analysis important life characteristics such as reliability, availability, probability of failure and other relevant metrics. Life data can be gathered with a SCADA system and operators or service providers over the wind turbine's lifetime. Another consideration in the gathering of turbine data is that the lifetime of the wind turbine is so long that new designs may be implemented before the data gathering finishes for previous models.

2.6 PROBABILITY DISTRIBUTIONS

This section introduces the common probability distributions used in reliability engineering.

2.6.1 Weibull Distribution

The Weibull distribution is named after Waloddi Weibull, who developed the distribution in 1951 [33]. Weibull's distribution of adaptability makes it popular for the use of the statically analysis of experimental and life data. The distribution may have an increasing, decreasing or constant failure rate [23]. The Weibull distribution has three parameters: shape, scale and location parameter. The distribution is most frequently used with only the shape and scale parameter. The location parameter changes the starting point of the distribution by shifting it though the x-axis. It is almost only used when there is no possibility of failure in the system lifetime's beginning or when product damage is possible in its transportation. In these cases, the parameter has a negative value [15]. The Weibull distribution parameters and boundary are given as:

- Beta (β) is the shape parameter also known as slope ($\beta > 0$)
  - $\beta < 1$ represents a decreasing failure rate
  - $\beta = 1$ represents a constant failure rate
  - $\beta > 1$ represents an increasing failure rate

- Eta (η) is the scale parameter, also knwon as life paratmeter (η > 0)
- Gamma (γ) is the location parameter (-∞ < γ < ∞)
- t is a variable representing time

The Three-parameter Weibull pdf is given by:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{2.9}$$

The more commonly used Two-parameter Weibull pdf is given by:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2.10}$$

Figure 16 depicts how a change in the shape parameter (factor) β affects the Weibull pdf. Figure 17 indicates how a different scale parameter η affects the Weibull pdf.

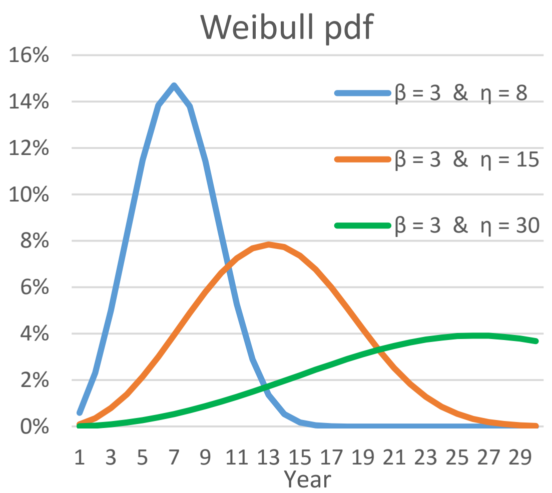

Figure 16: Changing Weibull pdf with different scale factors

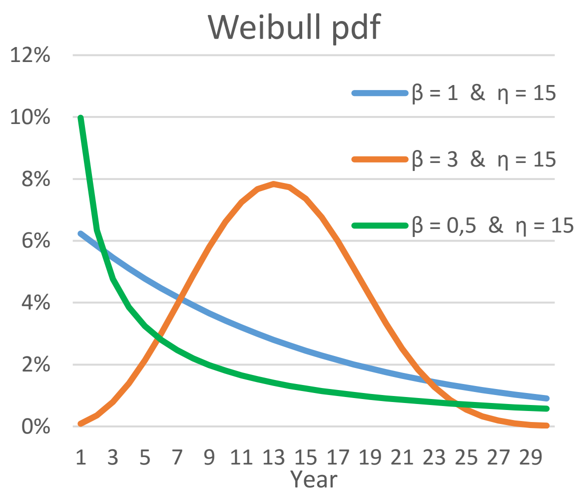

Figure 17: Changing Weibull pdf with different shape factor

When the shape parameter β is known from past experiences, it can be made a constant and the Weibull distribution can be used with only one unknown parameter, which is the scale parameter η. In these instances, it is called a One-parameter Weibull distribution. This distribution can be useful in cases in which there are few or no failures to analyze, although there accessible data available from similar or identical past experiences [33].

2.6.2 Exponential Distribution

The exponential distribution is used in cases that involve a constant failure rate. The exponential distribution is a special case of the Weibull distribution and has two parameters, and in most cases only one parameter is used. The distribution has only one shape, and therefore, no shape parameter. [15]. The distribution's parameters and boundaries are given as:

- Lambda (λ) is the scale parameter also known as life parameter (η > 0)
- Gamma (γ) is the location parameter (-∞ < γ < ∞)
- t is a variable representing time (t ≥ 0)

The two parameter exponential distribution is given by:

$$f(t) = \lambda e^{-\lambda(t-\gamma)} \quad (2.11)$$

The one parameter exponential distribution is given by:

$$f(t) = \lambda e^{-\lambda t} \quad (2.12)$$

Figure 18 indicates how a change in the lambda affects the exponential distribution. The blue top line has a lambda of 0.3 and the line under has a lambda of 0.1. The blue line has higher lambda and indicates higher probability of failure.

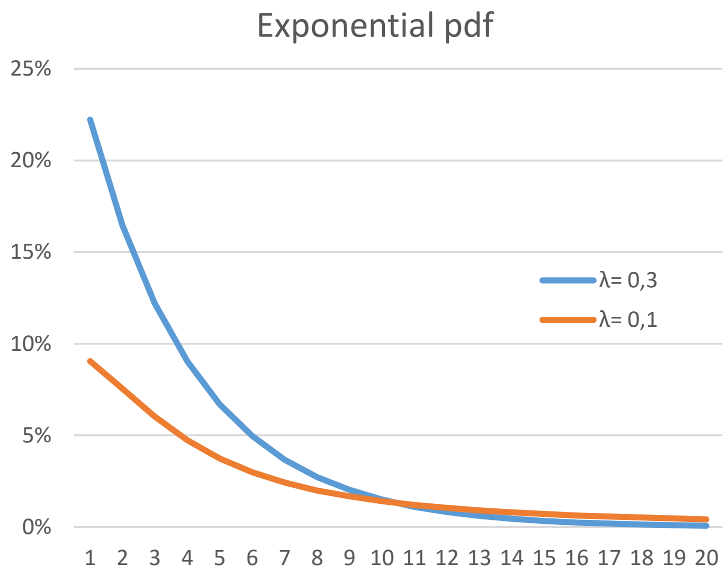

Figure 18: Exponential pdf, changing the scale factor

2.6.3 Lognormal Distribution

The lognormal distribution is normally used to analyze failures due to long term stress, as in mechanical systems. In some cases, the lognormal distribution is used in combination with the Weibull distribution. The lognormal curve differs from the normal distribution, in the way it squeezes to the right and is not symmetrical. The failure rate of the distribution increases and then decreases. The lognormal distributions parameters and boundary are given as [22], [54]:

μ´ = natural logarithms times-to-failure mean

σ´ = natural logarithms of the time-to-failure standard deviation

t´= ln(t) × t where t represents time

Lognormal Distribution pdf is given by:

$$f(t') = \frac{1}{\sigma'\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t'-\mu'}{\sigma'}\right)^2} \tag{2.13}$$

Figure 19 shows how a change in the mean affects the lognormal distribution. The lognormal distribution relationship with the time scale is in the state of natural logarithm.

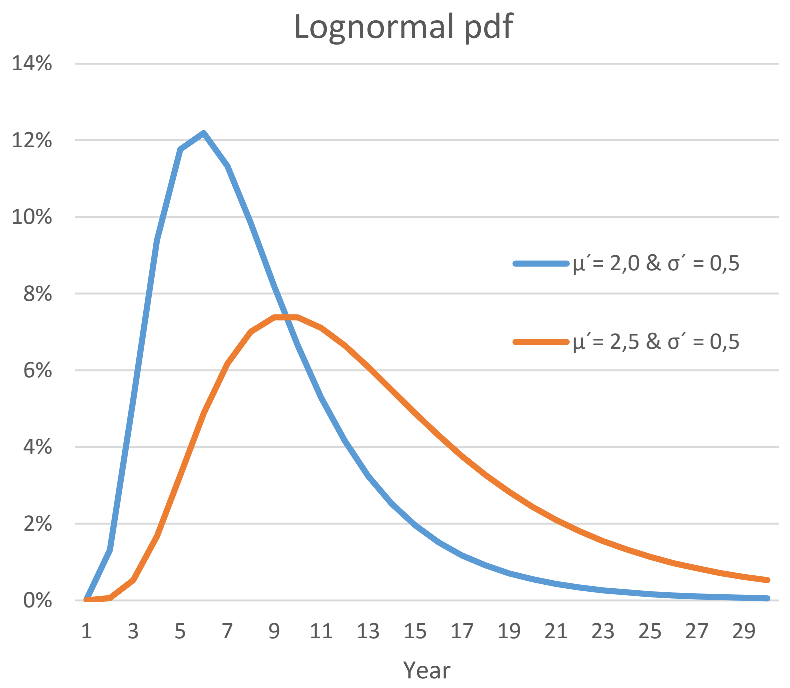

Figure 19: Lognormal pdf, chaining the mean

2.6.4 Normal Distribution

The normal distribution was introduced by the French mathematician Abraham de Moivre in 1733 [55]. The normal distribution is one of the most widely known distributions. It is defined from negative infinity to positive infinity and is symmetrical. The distribution is bell-shaped and its mean, mode and median are all equal at the middle of the distribution. The distribution has no shape factor, which means that the shape is always the same [55]. The distribution parameters and boundary are given as:

- Mu (μ) is used for the mean or location parameter ($\mu \in R$)
- Sigma (σ) is used for the standard deviation or scale parameter ($\sigma > 0$)
- t is the variable representing time

The normal distribution pdf is given by:

$$f(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(t-\mu)^2/2\sigma^2} \tag{2.14}$$

Figure 20 shows how the standard deviation affects the normal curve. A low standard deviation yields a high and narrow curve, whereas a higher standard deviation makes it flatter.

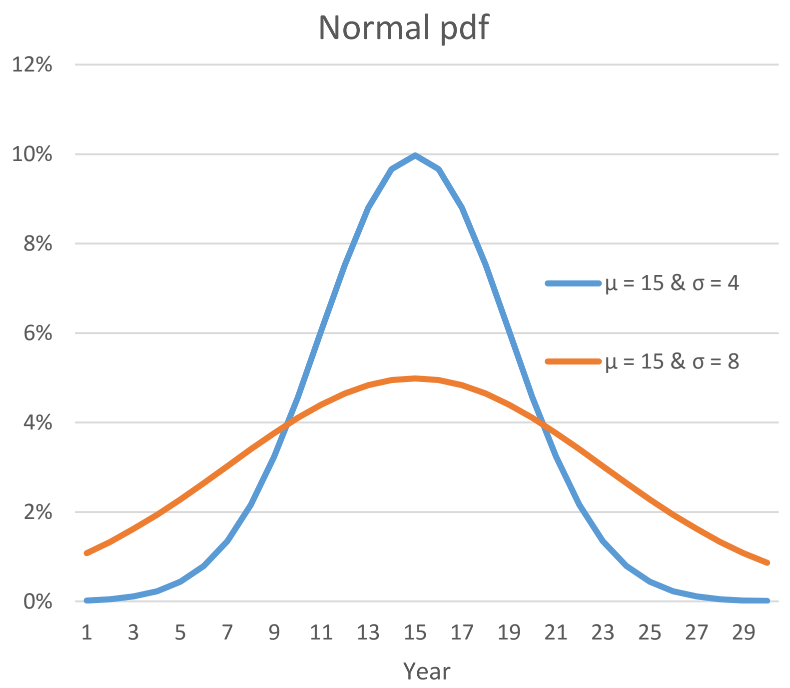

Figure 20: Normal pdf, chaining the standard deviation

2.6.5 Other Distributions

Many distributions can be used when fitting real life data. Some of these distribution may even fit better than the commonly used distribution functions mentioned above. The Gamma distribution is one of these said distributions, but it should be noted that when using complicated and rarely used distribution, it is even harder to compare results with colleagues, and by extension, to explain the results to others.

2.7 Reliability Methods and Tools (Move and switch out for 2.6)

This chapter discusses the methods and tools used for analysis and evaluate reliability as well as other related metrics.

2.7.1 The Bathtub Curve

The Bathtub Curve is a useful tool in reliability engineering. The bathtub curve describes the failure probability by dividing it into three stages.

- The first stage is in the product's early life, whereby the failure rate decreases and failures occur due to defective parts or improper use.
- The next stage is called normal life, whereby the failure rate is lower and constant.
- The final stage is called the wear out stage, whereby the failure rate increases, which occurs ordinarily due to wear out.

Figure 21 provides an example of the classical bathtub model, which shows infant mortality, followed by a constant failure rate, and finally, wear out [19].

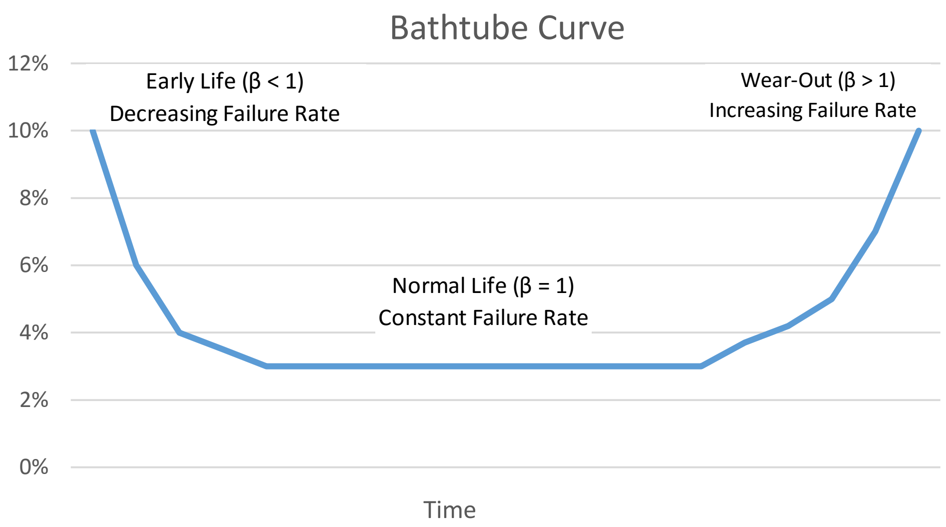

Figure 21: Bathtub model

2.7.2 Qualitative and quantitative assessment

Reliability assessment can be divided into qualitative and quantitative assessments. A qualitative assessment is more subjective and uses design criteria, and in some cases, engineering judgment to evaluate the reliability. A qualitative assessment is not scientifically accurate. Many view it as an outdated method of the past [15].

Quantitative assessments are done by collecting numerical data about failure or suspension in systems. The main purposes of the quantified assessments is to use past performance to predict the future performance of statistics.

2.7.3 Evaluating Reliability with Simulation or Analytical Approach

In the evaluation of system reliability, there are a few things that must be considered. First of all, a full understanding of a system and its functions is critical before trying to predict the system's future behavior. The engineer's knowledge and understanding of the system determines how successfully he is able to use probability theory as a tool to predict the system's future behavior. The main steps of evaluating reliability are as follows [15]:

- High system understanding
- Identify possible system failures
- Assess failure effects on the system
- Build suitable model
- Choose evaluation technique

2.7.3.1 Analytic Approach

An analytic approach models the system mathematically to evaluate the system's reliability, availability or other desired outcome. The application of an analytic approach to calculate a desired outcome leads the model to always yield the same results. The main benefits of this method are its shorter computing time and simplicity in comparison to the simulation approach. Conversely, the analytic method is limited to more simple models and is bound to equilibrium measures [15].

2.7.3.2 Monte Carlo Simulation

Simulation catches the variability of real life situations through the use of randomness in probability distribution, based on collected data. The execution of simulation involves running a random number through the probability distribution, and therefore, does generate different results every time. Simulations are done multiple times in order to reach the expected value (results). This method takes a longer time and requires more computing power than the analytic approach. The main benefits of simulation include its realistic approach to modeling real life problems as well as its wide range of possible results and outputs parameters [56]. For example, an analysis of repairable systems and proper maintenance actions would preferably be done by simulation. To summarize the main difference between the simulation and analytic approaches:

- The analytic approach is easier to compute and uses simpler models.
- Simulation requires more computing power and can be applied on more complex problems.

2.7.4 Reliability Block Diagram

A Reliability Block Diagram (RBD) is a visual tool that uses connecting blocks in series or in parallel. A RBD system is said operational if one can trace a path from the first block at the diagrams left side to the last block at the right end of the diagram without going through failed blocks. RBDs are used to calculate and analyze reliability metrics of complex systems. The RBD calculations are based on known or assumed reliability data, which in most cases, are received from accelerated life tests or by collecting life data for each component or subsystem. A RBD can be used to analyze a system’s reliability and availability before it is built. The results from the RBD provide knowledge about a system’s O&M, and can be used to minimize OPEX and maximize a system’s lifetime and profitability. Figure 13 shows an example of RBD as a series system [57].

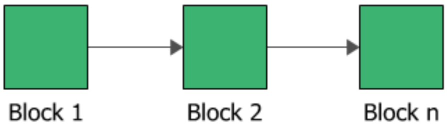

Figure 22: RBD of series system

Series system do not contain redundancy, and if one part of the system fails, the whole system fails. In most if not all cases, the RBD of a turbine at subsystem level is a series system. This fact is due to the cost of having redundancy at the subsystem level. In order to produce redundancy in a series system, backup components are required. Backup components can be expensive and are generally not used unless failure can have a critical impact. The reliability of a series system is given by [57], [19]:

$$R_s = R_1 \times R_2 \times R_3 \times \dots \times R_n \tag{2.15}$$

$$R_s = \prod_{i=1}^{n} R_i$$

Where:

$R_s = System\ Reliability$

$R_i = Reliability\ of\ Component\ i, i \in \{1, \dots, n\}$

Whether redundancy can be found in the wind turbine subsystems depends on the model [16]. Parallel block diagrams are used for systems with redundancy. A parallel system is a system in which blocks are connected in parallel. All blocks in the parallel connection need to fail in order for system failure to occur. Figure 14 show how block 1, block 2 and block n are connected in parallel to one another.

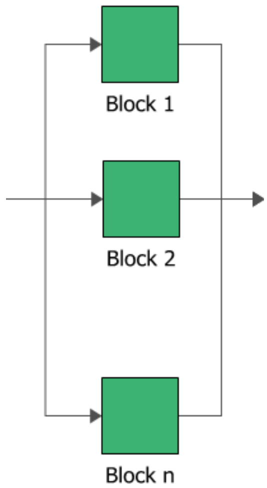

Figure 23: RBD of a parallel system

In parallel systems, only one unit must succeed in order for the system to work. This element leads the system to have redundancy. The reliability of parallel system is given by [22], [55]:

$$R_p = 1 - (1 - R_1) \times (1 - R_2) \times (1 - R_3) \times \dots \times (1 - R_n) \tag{2.16}$$

$$R_p = 1 - \prod_{i=1}^{n} (1 - R_i)$$

$$R_p = \coprod_{i=1}^{n} R_i$$

Where:

$R_s = System\ Reliability$

$R_i = Reliability\ of\ Component\ i, i \in \{1, \dots, n\}$

Even if a parallel system generally has higher reliability than a series system, one must consider whether the failure of one unit causes increased stress on the rest of the parallel units.

2.7.5 Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA), also known as Failure Mode Effect and Critical Analysis (FMECA), is an analytic technique implemented to identify potential failure modes that can occur in systems and assesses the risk of each failure [22]. The benefits of FMEA are as follows:

- It identifies the reliability and safety of critical components
- It identifies the cause of failure and develop corrective actions
- It makes it easier to choose right design of projects at all stages

The basics steps of performing a FMEA analysis are as follows:

1. Identify components and their functions
2. Identify failures
3. Assess possibilities of detecting failure in advance
4. Identify effects and causes of failures
5. Plan corrective actions
6. Recommend solution

The FMECA is one of the tools used in the preparation for reliability centered maintenance (RCM).

2.7.6 Fault Tree Analysis (FTA)

FTA analyses how system fail and further identify ways to reduce risk [22], [58]. FTA is shown graphically with a Fault Tree Diagram (FTD). FTD is built top-down in terms of events. The method identifies and quantifies possible failure events that may occur. The main difference between FTD and RBD is that FTD focuses on failure, whereas RBD focuses on success. Figure 15 provides an example of a FTD in which events 1, 2 and n need to occur in order for a failure to be triggered. Figure 23 shows an equivalent RBD is parallel RBD.

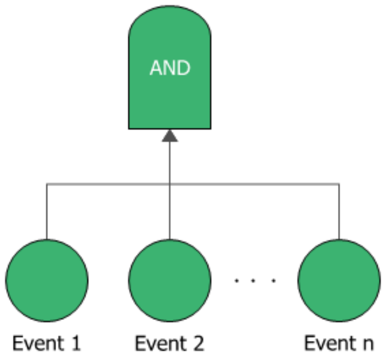

Figure 24: Fault tree analysis diagram [58]

2.7.7 Event Tree Analysis (ETA)

Event tree analysis (ETA) is a tool used to show all the possible outcomes of an event (accidental event). By listing and studying all the possible accidental events, the ETA can be used to identify all the potential outcome scenarios of accidental events in a complex system. This system can be used to identify potential weaknesses and risks [22]. Figure 16 shows an example of an event tree in which every event has the probability of occurring with a certain outcome. The information can then be used for risk analysis.

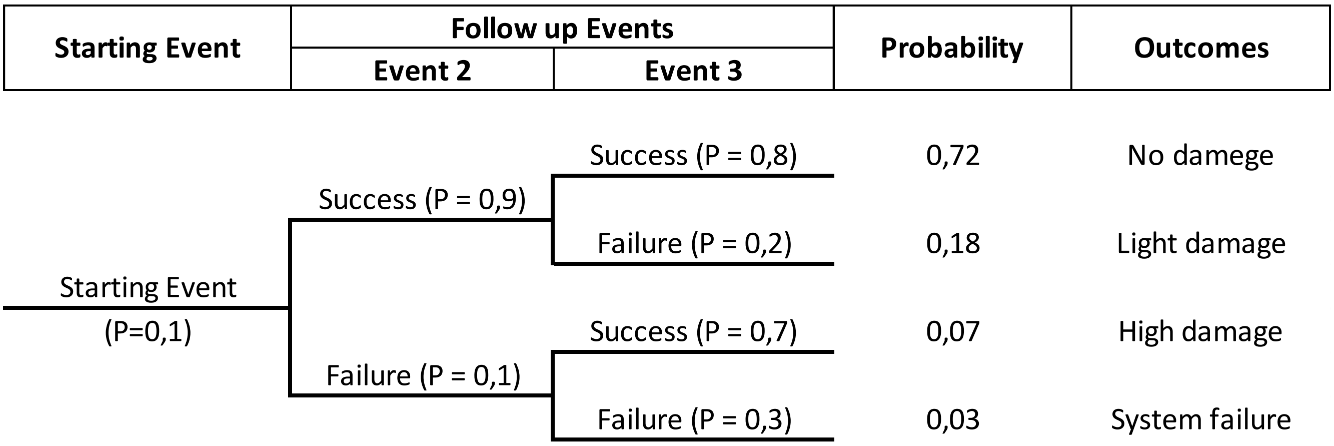

Figure 25: Example of event tree analysis

An event tree can be used to analyze failures in parallel systems, and whether these failures affect the system or its parts.

2.7.8 Sensitivity Analysis

Sensitivity analysis is used to determine how single or multiple changing factors may affect the system. For example, it can determine how key part changes in reliability would affect the systems' reliability, availability and OPEX, or alternatively, how the price of spare parts and delivery time affect these same key metrics. These determinations can be made by changing the model's input numbers, for example by lowering the reliability of key components and calculating how it affects the system. Figure 31 on page 36 shows wind turbine LCoE sensitivity to key metrics.

2.7.9 Three Point Estimation

The three-point method is a valuable tool for price estimation and other estimations where three references points are given. The methodology based one three price points for every component. The method uses a weighted triangular distribution and a certain confidence level to estimate the calculated price. The parameters used for the method are as follows:

$$Optimistic\ value = a$$

$$Most\ likely\ value = m$$

$$Pessimistic\ value = b$$

$$Weight = w$$

The weighted average is given by:

$$Weighted\ Average = (a + w * m + b)/(w + 2) \tag{2.17}$$

The standard deviation (StDev) is given by:

$$StDev = (b - a)(w + 2) \tag{2.18}$$

The variance is given by:

$$Variance = StDev^2 \tag{2.19}$$

Figure 18 shows an excel model of the Three Point Method [59]. The model provides an example of the estimated total price of three components. The model uses a weight of 4. The arrows on the figure show the steps taken to calculate the results. These steps are as follows:

- Calculate the expected value of components
- Calculated the standard deviation of components
- Calculated the variance and sum it
- Calculated the standard deviation of the summed variance
- Choose a confidence level and use the given z-factor to calculate the results.

Three Point Estimation

	Color Code					
Input	Results					
Equipment	**Optimistic**	**Most Likely**	**Pessimistic**	**Exp_Value**	**StDev**	**Variance**
	a	**m**	**b**	**t**	**s**	**V**
Part 1	218.000	223.000	227.000	**222.833**	**1.500**	**2.250.000**
Part 2	50.500	60.000	80.000	**61.750**	**4.917**	**24.173.611**
Part 3	100.000	130.000	180.000	**133.333**	**13.333**	**177.777.778**
...	0	0	0	**0**	**0**	**0**
...	0	0	0	**0**	**0**	**0**
	368.500	413.000	487.000	**417.917**	**14.290**	**204.201.389**

Weight	**4**	**Triangular Distribution**
Confidence Level	**95%**	**w = weight of m (standard 4)**
Z_factor	**1,645**	**Exp t = (a + w*m + b)/(w+2)**
		StDev s = (b-a)/(x+2)
Total Estimated Results	**441.421**	**Variance = StDev^2**
		Estimaded cost with given confidence level
		Results = Z_factor * StDev + Exp_Value

Figure 26: Three point estimations excel model

2.7.10 Maintenance strategy's

In general, maintenance schedules can be divided into two categories, preventive maintenance, which is performed before failure, and corrective maintenance, which is performed after failure. Figure 27 shows the main categories of maintenance strategies that the following text explains.

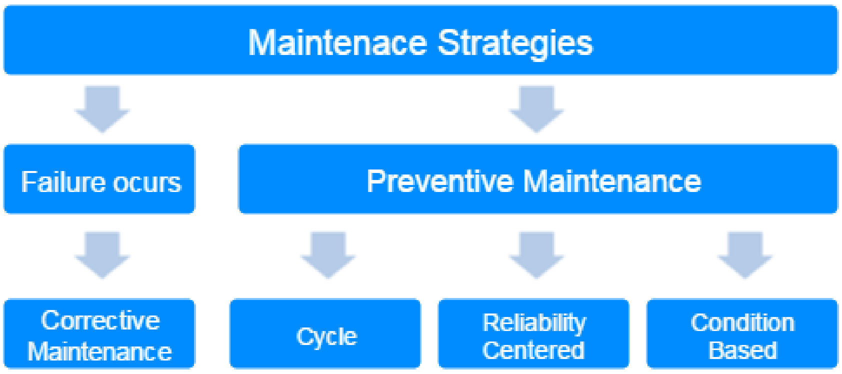

Figure 27: Maintenance strategies

Corrective maintenance (CM) is maintenance that is performed after failure takes place. In these cases, system is operated until it fails, and then, the system is repaired and begins to operate again [19].

Preventive maintenance (PM) is scheduled maintenance performed before failure takes place. It is often performed at preplanned intervals, in accordance with schedules, or other indicators that indicate that maintenance is required. Preventive maintenance should only be done when it cost less than corrective maintenance, and the system also has increasing failure rate. Preventive maintenance is a suitable option to prevent catastrophic failure or in cases when maintenance work can be done in batches. Preventive maintenance is also an appropriate option when high safety, reliability and availability is required. The main categories of preventive maintenance are as follows:

Cycle maintenance follows predetermined cycles. Often the maintenance is performed at specific time intervals or after certain cycles of usage.

Condition base maintenance is based on monitoring the product and performing maintenance only when it is necessary. SCADA monitoring system are popular in modern wind farm operations and can be used to monitor vibrations, temperature or other characteristics that may indicate that maintenance is required [19].

Reliability centered maintenance (RCM) was designed to minimize cost and maximize benefits by applying the most efficient maintenance strategy [22]. The method uses tools and statistics to eliminate more costly CM and to minimize PM, and to still obtain required reliability. These elements yield required reliability at a minimal price. The process is constant and uses a mixture of appropriate maintenance strategies [18]. The RCM method is introduced thoroughly in [22], [60] where key attributes are summarized in seven basic questions:

1. In the present operating context, what are the system's functions and standards of performance?
2. In what ways can the system fail to fulfill its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What should be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be identified?

Each maintenance strategy is used depending on the circumstance. In most cases, a mixture of different maintenance schedules is utilized. In the selection of appropriate maintenance schedules, controlling factors are often cost, reliability, availability and safety.

2.8 Reliability & Economics

Although reliability can be highly profitable, it is also costly to maintain a system at high reliability. Therefore, there is a concern whether or not to invest in higher reliability? A good practice is to ensure that the benefit of a certain reliability level is greater than the cost of providing it. Figure 28 depicts the incremental cost of reliability[15].

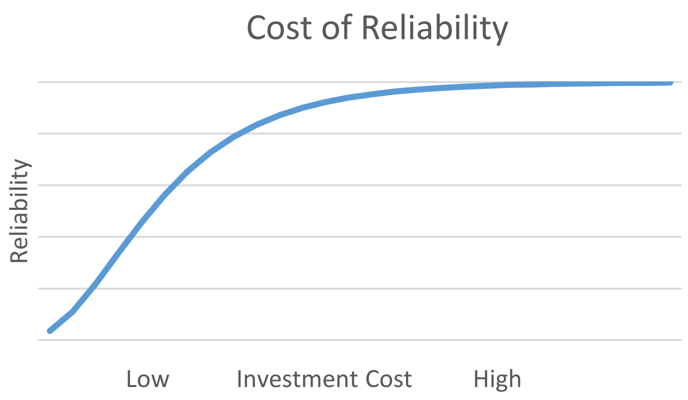

Figure 28: Cost of reliability

Figure 29 shows the financial importance of applying right amount of maintenance. The life cycle cost is minimized when the correct amount of resources is invested in reliability. An investment that is too small increases risk and the failure rate, which can result in increased lifecycle costs. A too high of an investment could lead to increases in preventive maintenance cost. Optimization helps to find the right relationships between the maintenance strategies [61]. In order to apply this methodology, two aspects must apply. First, the cost of planned replacement needs to be lower than the cost of unplanned replacement and the system needs to have an increasing failure rate.

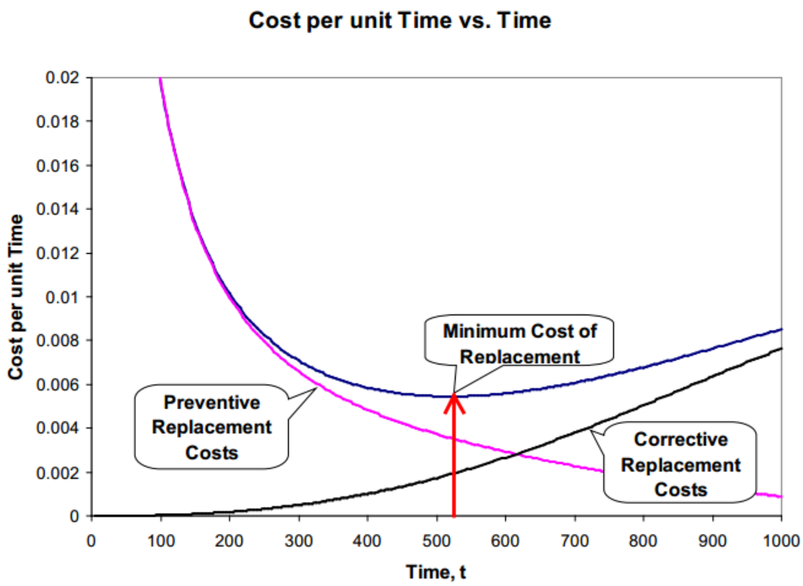

Figure 29: Minimum Cost of replacement [62]

Figure 29 shows how the minimization of the life cycle cost is a fine interaction between the right amount of preventive maintenance and corrective maintenance. Today, manufacturers compete to keep costs as low as possible, through the use of multiple sensors to detect when maintenance is required.

2.9 LEVELIZED COST OF ELECTRICITY

Levelized Cost of Electricity (LCoE) is a key metric to evaluate profitability and compare energy projects. LCoE can probably best be described with the following definition from NREL [63].

"The LCOE is the total cost of installing and operating a project expressed in dollars per kilowatt-hour of electricity generated by the system over its life."

Figure 30 explains wind turbine economics and is helpful to understand the LCoE calculations. The figure shows that the foundation of LCoE calculations are annual energy production and annual cost. In wind farm projects, annual energy is based on factors such as rotor diameter and side characteristics (specifically wind characteristic). The cost of wind farm projects can be divided into CAPEX, which covers the initial investment, and OPEX, which is the cost of the operation and maintenance.

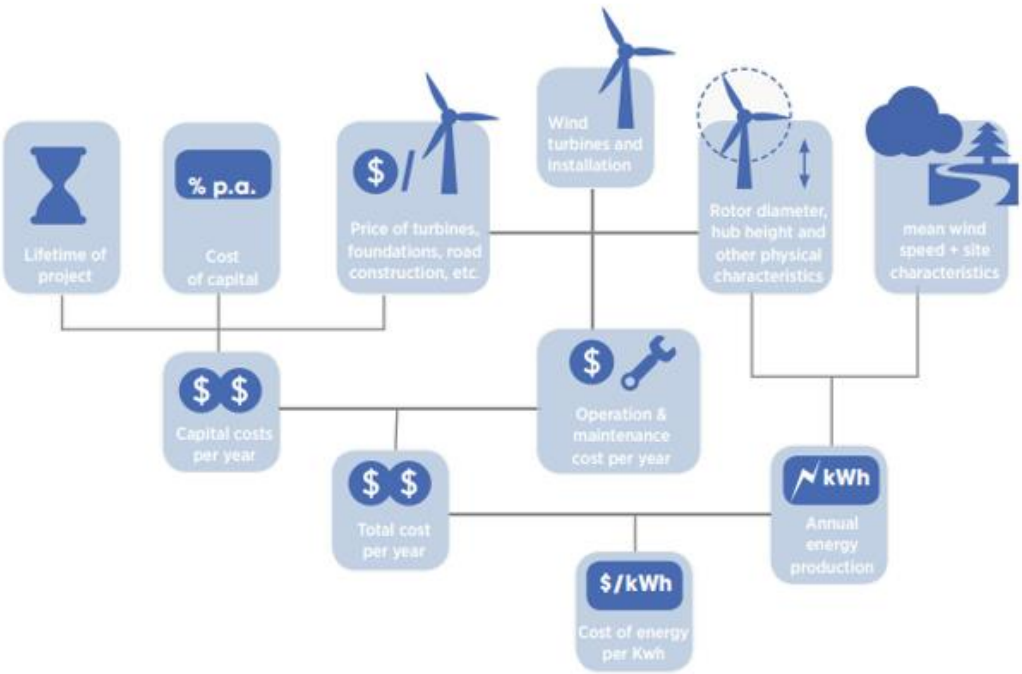

Figure 30: Economics of wind turbine [17]

From this understanding of the basis of LCoE calculations, the following formula is given:

$$\text{LCoE} = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2.20}$$

Where

n = Project lifetime

t = Point in time

C = Project cost

E = Electricity produced

r = Discount rate

One should note that the summations counter does not begin at the same time. The cost summation starts at $t = 0$, in order to include the investment cost, whereas the energy summation begins at $t = 1$, which is the time when it is assumed that the system starts to produce energy [24]. Some may find it strange to use the discount rate on energy produced, similar to the discounting of future money. Today, energy is worth more than energy in the future. In order to find the present cost of the energy, both the total life cycle cost (TLCC) and the total energy produced over the project's life time is discounted.

Figure 31 from NREL describes the key parameters that affect the LCoE. Reliability engineering can be used to optimize at least three of five of these factors. These factors are:

- Net capacity factor, which directly corresponds to the turbine's availability
- OPEX, which is determined based on the component's cost, reliability and the O&M strategy

- Operating life, which depends on proper assets management

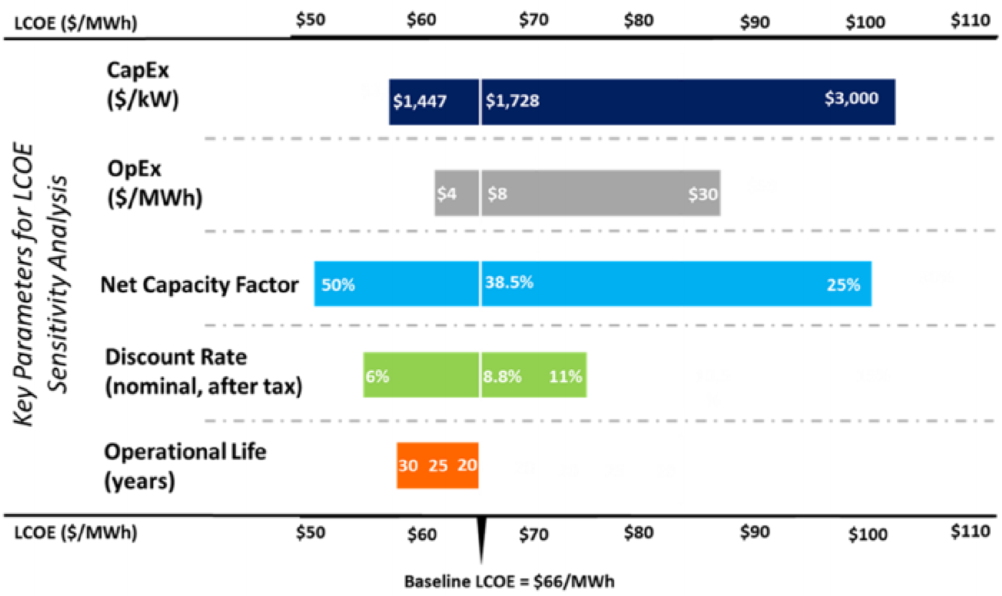

Figure 31: Sensitivity of land-based wind LCoE to key input parameters [1]

Table 3 shows the estimated OPEX of selected OECD countries [64]. The OPEX range is from 11-45 $/MWh, with an average of 28 $/MWh.

Table 3: Estimated OPEX in selected OECD countries

Country	Variable (2014 USD/MWh)
Austria	40
Denmark	15 - 19
The Netherlands	13 - 17
Norway	21 - 39
Spain	28
Sweden	11 - 35
Switzerland	45
Mean	28

Figure 32 shows the ratio between different categories of OPEX. As made evident from the figure, service and spare parts comprise of 26% of the OPEX. This percentage can vary and can easily increase after turbines get older. The service and spare parts serve as this thesis's focus.

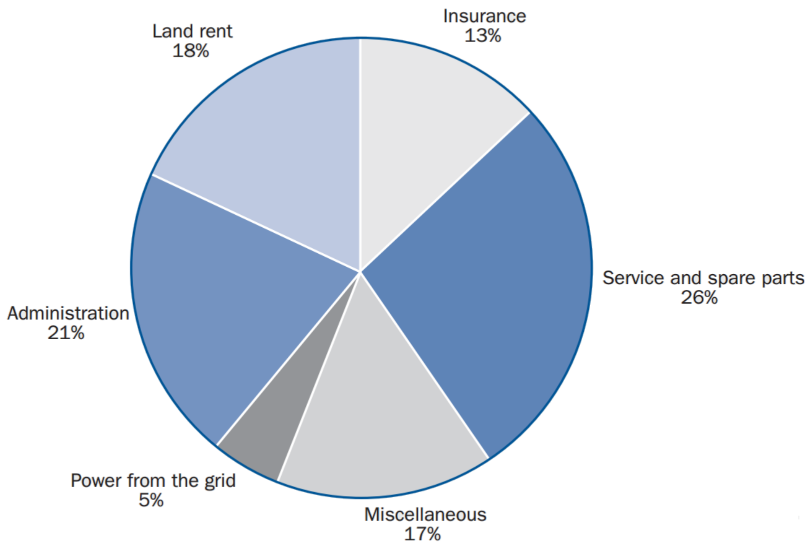

Figure 32: German turbines OPEX categories, averaged for 1997-2001 [65], [66]

2.10 Net Present Value

Net present value (NPV) is a metric used to evaluate the profitability of investments and projects. The NPV sums the project's cash flow after it has been discounted to its present value. The formula to calculate NPV is given by [67]:

$$\text{NPV} = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \tag{2.21}$$

Where

n = Project lifetime

t = Point of time

CF = Cash flow

r = Discount rate

2.11 Value of Information

Before going through the effort to gather additional information or to apply complicated mathematical methods, one should consider the value of the information. In D.W Hubbard's book, How To Measure Anything, he lists three basic reasons why information has value [68]:

1. Information reduces uncertainty about decisions that have economic consequences.
2. Information affects people's behavior, which has economic consequences.
3. Information can have its own market value.

Reasons 1 and 3 are closely related to reliability data, whereby the data is hard to obtain and can be used to evaluate uncertainty. When making decisions based on the best guess, single value uncertainty is ignored. Uncertainty is the possibility of something being wrong. To ignore uncertainty can lead to poor decision-making [69]. The cost of poor decision making is the difference between a poor choice and the best alternative. The best alternative is the decision made in cases in which one had access to perfect information. In the following text, three concepts are discussed related to the determination of the value of information.

The first concept is expected value of information (EVI), which is equal to the value of the information's reduction in risk [68].

The second concept is known in discussion theory as the expected value of perfect information (EVPI). It is maximal amount that one should be willing to pay to gain access to perfect information. This amount is equal to the economic loss that could be avoided if one had access to perfect information. When handling a range of information, for example information including confidence level, the following steps found in D.W Hubbard's book can be taken to compute EVPI [68]:

1. Slice the distribution into hundreds or thousands of small segments
2. Compute the opportunity loss for the midpoint of each segment
3. Compute the probability for each segment
4. Multiply the opportunity loss of each segment and its probability
5. Total all the products from step 4 for all segments

Finally, the expected value of including uncertainty (EVIU). EVIU is the expected difference of value between a decision that includes uncertainty and a decision that ignores it [70].

The difference between EVPI and EVIU is that EVPI has access to perfect information, and therefore, it yields no uncertainty, whereas EVIU does not have access to perfect information, and instead, uncertainty for the decisions is included. Both methods compare the expected value of the optimal decision with the decision that does not have access to perfect information and ignores uncertainty [70].

3 RESEARCH METHODS

This chapter explains the study's research methods. The RBD methodology is based on building blocks that have information about systems components. The blocks are connected together to create the RBD of the whole system. Figure 33 shows a flow chart of the general idea behind the simulation process. The input data contains the following:

- Components reliability data (Table 4)
- Corrective maintenance (CM) data (Table 5)
- For this project, preventive maintenance (PM) data was not used.

The O&M strategy and inventory settings are described in chapter 3.2 on assumptions. The model provides a wide variety of results that are presented in chapter 4.

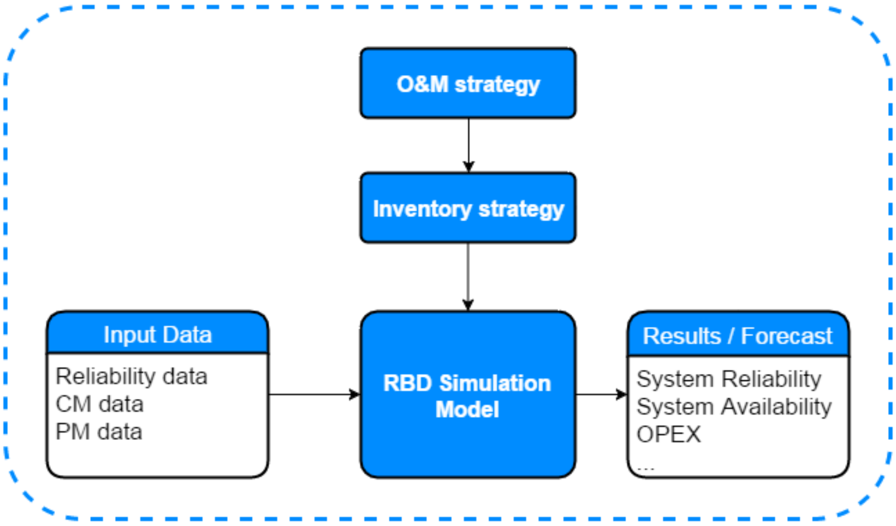

Figure 33: RBD simulation flow chart

This chapter is comprised of the following elements:

- Explanation of RBD structure of components and subsystems
- Introduction to RBD model input data
- Discussion of the model's necessary assumptions
- Introduction of the main simulation settings
- Summary of the steps of the methodology

3.1 RBD MODEL STRUCTURE

The Building of the RBD model was based on information (shown in Table 4 and Table 5 on pages 44-45) about turbine components and subsystems. This information was used to establish a series of diagrams that are linked together to represent a single wind turbine, and finally, a wind farm.

3.1.1 Wind Turbine Subsystems

In this model there are no parallel components. Parallel components could be found for example in some electrical components of the turbine. To include parallel components one would need to go deeper in to each subsystem and apply detailed modeling work.

3.1.1.1 Rotor System

Figure 34 shows the RBD of the rotor system. The stack of three boxes represents multiple components of the same type connected together in series. The first four blocks and the pitch position block all represent three components of the same type, which are connected together in the series. The entire system is connected together through the series. There are in total 18 components in the system. The rotor system has two components that require a crane to repair; the pitch bearing and the blade-structure.

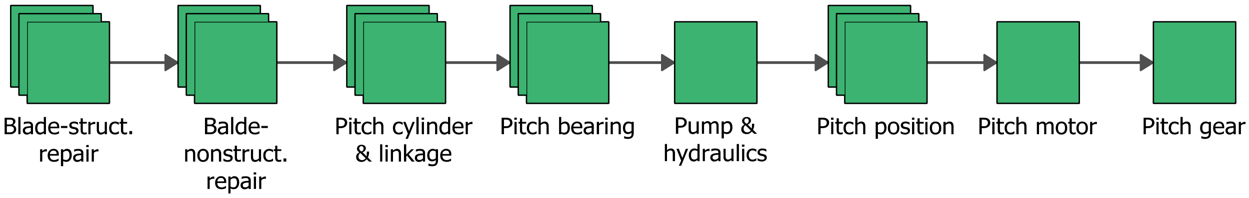

Figure 34: RBD of the rotor system

3.1.1.2 Drive Train

Figure 35 shows RBD of the drive train. The drive train includes only two blocks connected in the series, which are the main bearing and high-speed coupling. The gearbox is modeled as a separated subsystem for analytic purposes. The repair of the main bearing requires a crane.

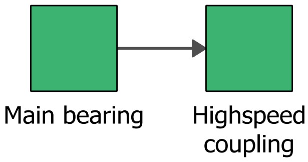

Figure 35: RBD of the drive train

3.1.1.3 Gearbox

Figure 36 shows the RBD of the gearbox. The gearbox is a seven block series system where the lube pump and cooling fan motor blocks each represent two components. The repair of the gearbox gears and bearings blocks requires a crane (the first two blocks).

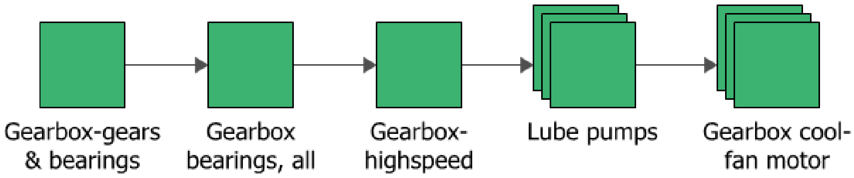

Figure 36: RBD of the gearbox

3.1.1.4 Generator and Cooling

Figure 37 shows the RBD of the generator and cooling system. The system is a nine block series system, in which the generator-bearings block represents two components and the contactor generator block represents three components. The repair of the generator-rotor & bearings block (the first block) requires a crane.

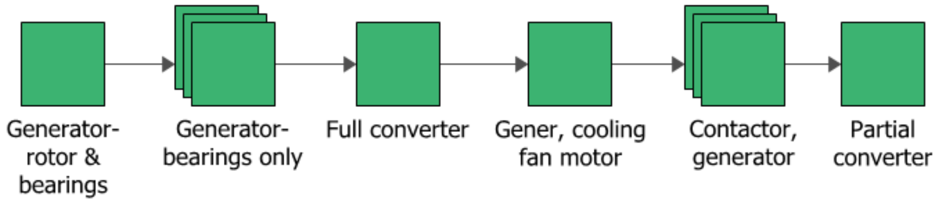

Figure 37: RBD of the generator and cooling system

3.1.1.5 Brake and Hydraulics

Figure 38 shows the RBD of the brake and hydraulics system. The system is a seven block series system in which the accumulator represents four components.

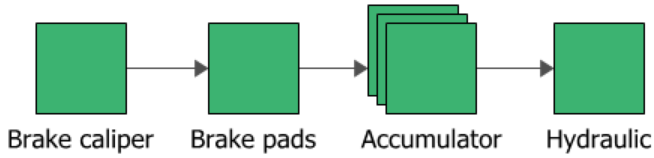

Figure 38: RBD of the brake and hydraulics system

3.1.1.6 Yaw System

Figure 39 shows the RBD of the yaw system. The system is a series system of 16 blocks where each block on the figure is representing multiple components. The Yaw gear represents four blocks, the yaw motor represents two and the yaw sliding pads represent eight.

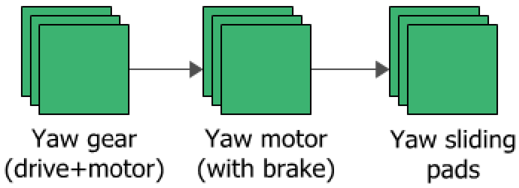

Figure 39: RBD of the yaw system

3.1.1.7 Control System

Figure 40 shows the RBD of the control system. The control system is a series system of 32 blocks. The control module represents 13 components and the sensor block represents 17 components.

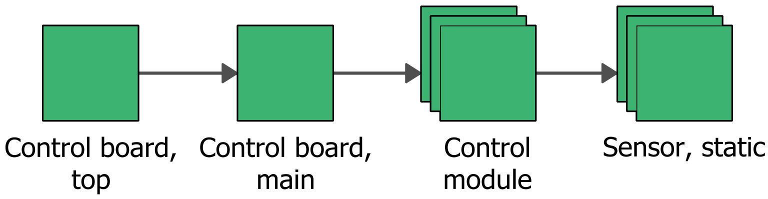

Figure 40: RBD of the control system

3.1.1.8 Electrical and Grid

Figure 41 shows RBD of the electrical and grid system. This system is a three block series system.

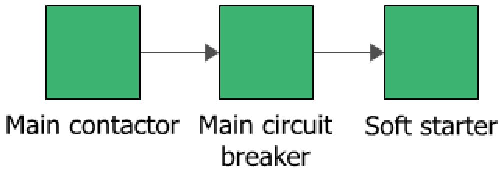

Figure 41: RBD of electrical and grid

3.1.2 Wind Turbine

Figure 42 shows the RBD of a theoretical 2MW turbine. The RBD is assembled from the subsystems above. Each folder or block in the RBD represents a corresponding subsystem. The system is a eight block repairable series system with a total of 94 components.

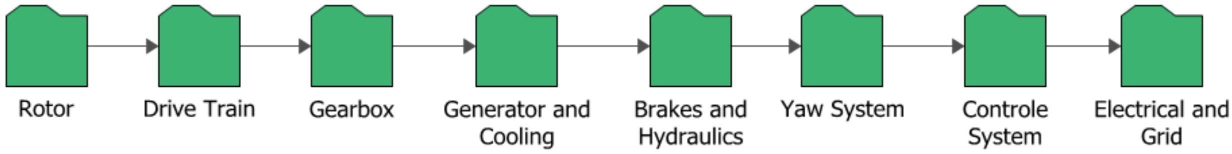

Figure 42: RBD of a wind turbine

3.1.3 Wind Farm

Figure 43 shows the RBD of a wind farm. The first block's only purpose is to connect the RBD together for the purposes of simulation. The wind farm is comprised of multiple blocks that are all based on the of 2MW turbine above. The turbine blocks are connected in parallel. The whole wind farm utilizes the same maintenance crew, which can only attend to one task at the time. For this reason, if two failures occur at the same time, the second failure cannot be attended until the repair crew is free.

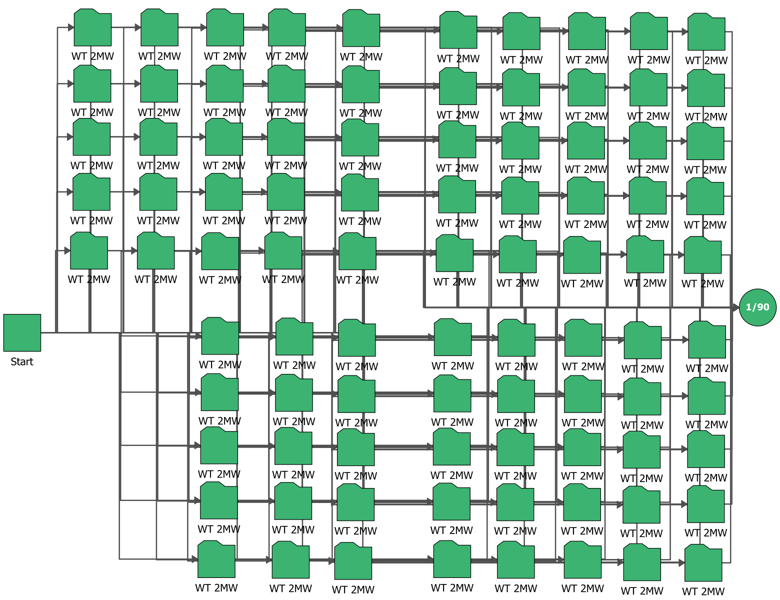

Figure 43: RBD of 90 wind turbine farm

3.1.4 Model Input Data

The input data for the model is based on two reports from NREL [24], [71]. The reports include data on the following wind turbine measures:

- Failure rates
- Repair times
- Repair costs
- Component costs

The model data was split into three main categories. The three categories including all the data required for the RBD modeling are:

- Component failure data
- Corrective maintenance (CM) data
- Preventive maintenance (PM) data

In this research, PM data was not used. Table 4 provides information on component failure distribution and parts per wind turbine.

Table 4: Wind turbine component and failure data [71]

NREL 2011 Wind Turbine Component and failure data

Wind Turbine (1,5MW - 3,0MW) components and failure data

System	Component failure mode	Failure Distribution	Exponential	Weibull paramters		Parts per WT
			λ(t) (Yr)	Scale (Yr)	Shape	
Rotor						
	Blade-struct. Repair	Exponential	400			3
	Balde-nonstruct. Repair	Exponential	100			3
	Pitch cylinder & linkage	Weibull		10	3,5	3
	Pitch bearing	Weibull		50	3,5	3
	Pump & hydraulics	Weibull		12	3,5	1
	Pitch position xder	Weibull		12	2	3
	Pitch motor	Weibull		15	1,1	1
	Pitch gear	Weibull		12	3,5	1
Drive Train						
	Main Bearing	Weibull		39	3,5	1
	High speed coupling	Weibull		25	3,5	1
Gearbox						
	Gearbox-gears & bearings	Exponential	400			1
	Gearbox bearings, all	Weibull		26	3,5	1
	Gearbox-highspeed	Weibull		26	3,5	1
	Lube pumps	Weibull		12	3	2
	Gearbox cool-fan motor	Weibull		19	1,1	2
Generator and Cooling						
	Generator-rotor & bearings	Exponential	200			1
	Generator-berainqs only	Weibull		17	3,5	2
	Full converter	Weibull		15	2	1
	Gener, cooling fan motor	Weibull		19	1,1	1
	Contactor, generator	Weibull		20	2	3
	Partial converter	Weibull		15	2	1
Brakes and Hydraulics						
	Brake caliper	Weibull		10	2	1
	Brake pads	Exponential	10	10	2	1
	Accumulator	Weibull		6	3	4
	Hydraulic	Weibull		12	3	1
Yaw System						
	Yaw gear (drive+motor)	Exponential	400			4
	Yaw motor (with brake)	Weibull		10	2	4
	Yaw sliding pads	Weibull		10	3,5	8
Controle System						
	Control board, top	Weibull		15	2	1
	Control board, main	Weibull		15	2	1
	Contorl module	Weibull		15	2	13
	Sensor, static	Weibull		14	2	17
Electrical and Grid						
	Main contactor	Weibull		20	2	1
	Main circuit breaker	Weibull		30	2	1
	Soft starter	Weibull		30	2	1

3.1.5 Corrective Maintenance (CM) data

Table 5 on CM data shows the following:

- Component Cost

- Cost of the repair (Crew cost)
- Consequential Cost of failure
- Whether a crane is required for the task
- Repair time
- Time for the crew to respond to the failure (delay time)
- The crew service needed for each component
- Restoration of the repair

Table 5: Corrective maintenance data

Wind Turbine configuration: 2,0MW and 80 Meter Tower, Cost and Maintenance Estimation

Corrective Maintainance (CM)

System	Component failure	Part Cost($)	Crew Cost($)	Consequential Cost($)	Crane	Repair Time (Hr)	Delay Time (Hr)	Crew Responsible	Restoration
Rotor									
	Blade-struct. Repair	87.500	23000	44000	Yes	40	1	Crew 1	As good as new
	Balde-nonstruct. Repair	12.700	4000			40	1	Crew 1	As good as new
	Pitch cylinder & linkage	13.000	1000			14	1	Crew 1	As good as new
	Pitch bearing	13.100	4000	44000	Yes	70	1	Crew 1	As good as new
	Pump & hydraulics	3.300	1000			10	1	Crew 1	As good as new
	Pitch position xder	1.800	500			5	1	Crew 1	As good as new
	Pitch motor	8.400	500			5	1	Crew 1	As good as new
	Pitch gear	8.300	2000			20	1	Crew 1	As good as new
Drive Train									
	Main Bearing	23.700	13000	144000	Yes	130	1	Crew 1	As good as new
	High speed coupling	7.700	1000			12	1	Crew 1	As good as new
Gearbox									As good as new
	Gearbox-gears & bearings	282.000	18000	144000	Yes	90	1	Crew 1	As good as new
	Gerbox bearings, all	196.300	8000	144000	Yes	100	1	Crew 1	As good as new
	Gerbox-highspeed	183.300	3000			30	1	Crew 1	As good as new
	Lube pumps	3.000	500			5	1	Crew 1	As good as new
	Gearbox cool-fan motor	2.300	500			5	1	Crew 1	As good as new
Generator and Cooling									
	Generator-rotor & bearing	198.300	6000	59000	Yes	60	1	Crew 1	As good as new
	Generator-beraings only	2.200	500			10	1	Crew 1	As good as new
	Full converter	36.000	500			5	1	Crew 1	As good as new
	Gener, cooling fan motor	2.300	500			5	1	Crew 1	As good as new
	Contactor, generator	11.700	500			5	1	Crew 1	As good as new
	Partial converter	17.000	1000			10	1	Crew 1	As good as new
Brakes and Hydraulics									
	Brake caliper	7.300	1000			6	1	Crew 1	As good as new
	Brake pads	5.700	500			5	1	Crew 1	As good as new
	Accumulator	2.200	500			4	1	Crew 1	As good as new
	Hydraulic	6.000	500			4	1	Crew 1	As good as new
Yaw System									
	Yaw gear (drive+motor)	9.700	800			8	1	Crew 1	As good as new
	Yaw motor (with brake)	2.200	800			8	1	Crew 1	As good as new
	Yaw sliding pads	800	800			8	1	Crew 1	As good as new
Controle System									
	Control board, top	11.700	500			5	1	Crew 1	As good as new
	Control board, main	17.700	500			5	1	Crew 1	As good as new
	Contorl module	6.300	500			5	1	Crew 1	As good as new
	Sensor, static	800	500			5	1	Crew 1	As good as new
Electrical and Grid									
	Main contactor	13.000	500			5	1	Crew 1	As good as new
	Main circuit breaker	16.300	500			5	1	Crew 1	As good as new
	Soft starter	1.000	1000			10	1	Crew 1	As good as new

The information was used to configure each block of the RBD. The price of each component was estimated using a triangular distribution and the three-point method, as the information was given as three price points. The Consequential cost did not account for the possibility of failure damaging other parts of the system, and the consequential cost is only the cost of crane. The cost varies as a result of the different weights of the parts that need to be lifted to the hub height.

3.1.6 Preventive Maintenance (PM) data

The third data table is for PM data. As a result of the lack of data, the table was not complete, even if it was ready to be used in the model. The main difference between the CM and PM table is the column for the type of PM. Additionally, there is no consequential cost of failure in the PM table. The table is shown in appendix 7.1 Preventive Maintenance Data.

3.2 ASSUMPTIONS

These thesis' assumptions are introduced in these sections. First, there are the assumptions made in the RBD model. Secondly, there are assumptions made in the analysis of the model's result.

3.2.1 RBD Model

All of the components used in the RBD can fail and are repairable. Repairs of components vary both in cost and the time they require, and are performed by repair crew 1. For the base case, it is assumed that crew 1 is always available and takes them one hour to reach the location where the repair is performed. The delay time was set to one hour in order to show the model's maximum availability. Crew 1 can only perform one task at a time. The system's spare parts are assumed to be in stock at all times and have no delay time.

A summary of the model assumptions are as follows:

- Repair crew 1 was assumed to service the whole system. Crew 1 is on shift 24/7, which means that besides the crew 1, are actually two 12 hours shifts.
- The delay time of repairs crew 1 was assumed to be 1 hour.
- The exponential failure rate was used instead of the fixed failure rate for six components in Table 4. This was done because of problems in the use of the fixed failure rate in the simulations.
- Three point estimation was used to determine component cost (Table 11 in appendix 7.2)
- Components were assumed to always be in stock.

Other information where based on NREL reports [24], [71] . All information and data used can be found in Table 4 and Table 5.

3.2.2 Analysis of Results (LCoE)

The LCoE calculations where based on data in Table 12. Service and spare parts are assumed to constitute 26% of the OPEX [65]. From that assumption and the model's expected maintenance cost, the sum of land rent, insurance, administration, power from the grid, and other miscellaneous costs were assumed to be 19.1 $/MWh.

3.3 SIMULATION SETTINGS

The turbine and wind farm simulation settings were as follows:

- Simulated over a 20-year period
- Point results every month or every year
- Simulated between 100 and 1000 times

The simulation time of 20 years was chosen due to the fact that the data used in the model is old and the turbine life expectancy was shorter in the past than it is today. This aspect can easily be changed when the simulation is made for today's turbines, which have a life expectancy of over 20 years.

Different model settings where used to provide an idea about the model's sensitivity to key factors, which include:

- Simulate for 1 up to 90 turbines in order to understand how one crew can handle a growing wind farm.
- Simulate the wind farm with more than one crew.
- Simulate with longer crew delay time.
- Simulate with increasing failure rate of chosen components, due to potential stress factors such as high wind or icing.
- Simulate with various turbine lifespans.

The log from the simulations was then exported to Excel and used in further calculations and analyses.

3.4 Analysis of Results

The simulation log was exported to excel where analyses were done, and some of the main calculations include:

- Single turbine annual maintenance cost was fitted with lognormal distribution;
- Maintenance cost and OPEX were forecasted;
- Turbine lifespan effects on maintenance cost and LCoE;
- Reliability data was evaluated.

The main calculations can be found in appendix 7.3.

3.5 Summary

The summary improves the overall understanding of the process. Figure 44 outlines the steps taken in the chapter.

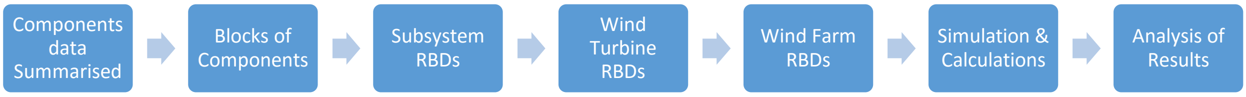

Figure 44: Methodology process diagram

The following list demonstrates the steps of the methodology:

1. Collect the components' reliability data. Examples of this data are shown in Table 4 and Table 5.
2. Design the model blocks based on the component's data and characteristic. The model should be designed for the purposes of, because of the complexity of repairable systems. In cases in which the system is not repairable, an analytic approach should be sufficient.
3. Connected blocks together to form subsystems RBD. Connect the subsystem together to create turbine RBD. Connect the turbines together to create a wind farm RBD.
4. Run a simulation with a set of preferences.
5. Analyze the results.

4 RESULTS

This chapter discusses the results from the RBD model described in previous chapter. The chapter begins with a review of single turbine results, which are more detailed than the results from a wind farm, due to long computing time and complexity involved in the wind farms simulations.

4.1 SINGLE WIND TURBINE RESULTS

The section begins on reviewing base cases results in which the turbine is serviced by 1 repair crew with a one hour response time. The chapter ends with an introduction to turbine sensitivity, maintainability and failure rate.

4.1.1 System Failures and Downtime

Figure 45 details the wind turbine point availability and reliability vs. time. From the graph, it is evident that the availability is high (over 97% at all time) over the 20-year period, whereas the reliability drops to 0 in year 2. The reliability's drops to 0 in 2 years means that the system definitely requires maintenance in the first 2 years of its life time. The high availability is a result of high maintainability.

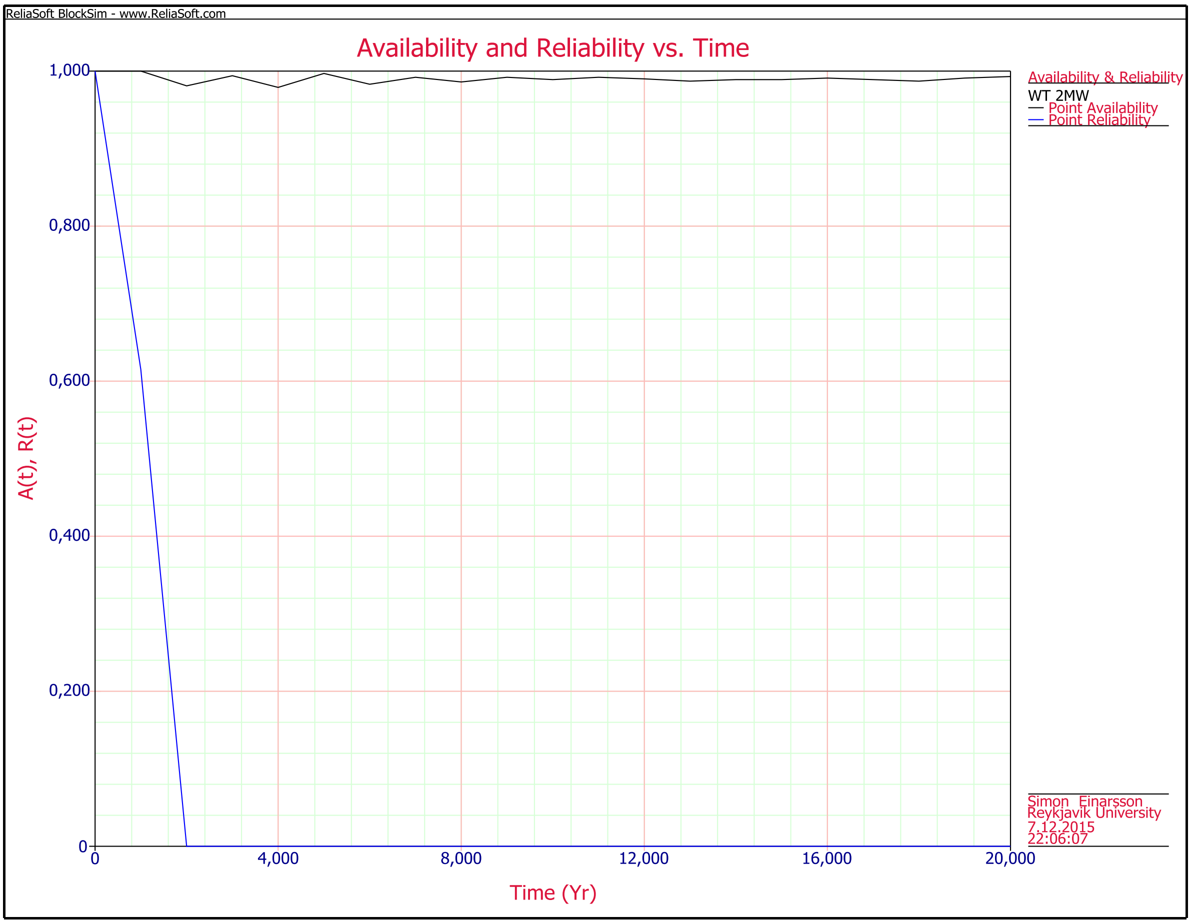

Figure 45: Availability and reliability vs. time

Figure 46 shows the turbine's system failures in 20 years. Expected failures for the system amount to 204 events over the 20-year period.

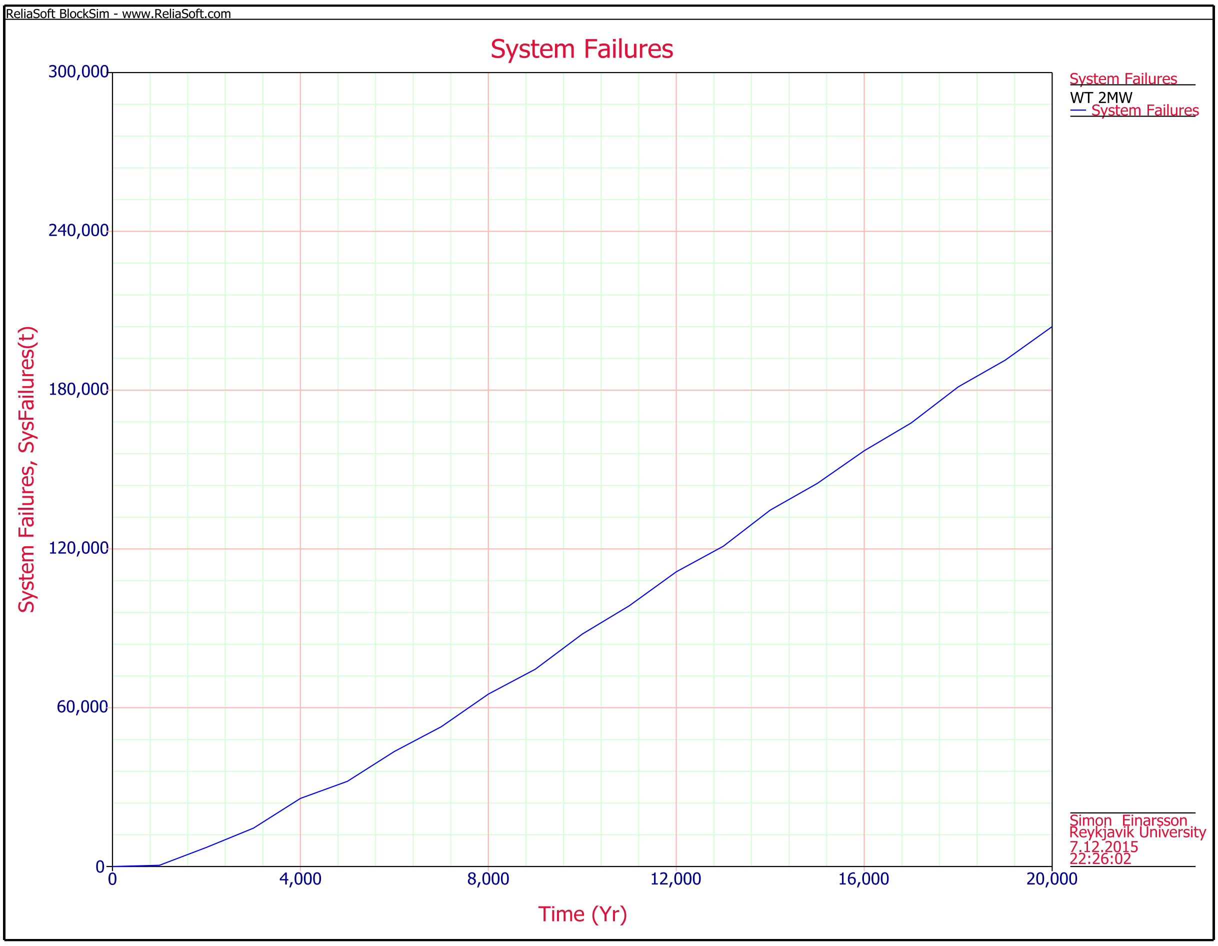

Figure 46: System cumulative failure vs. time

Figure 47 indicates when the subsystem fails. One can see when the failure occurs and in what subsystem. At the bottom of the graph, all the turbine failures are shown under the name system. The drive train only has one failure over the 20-year period.

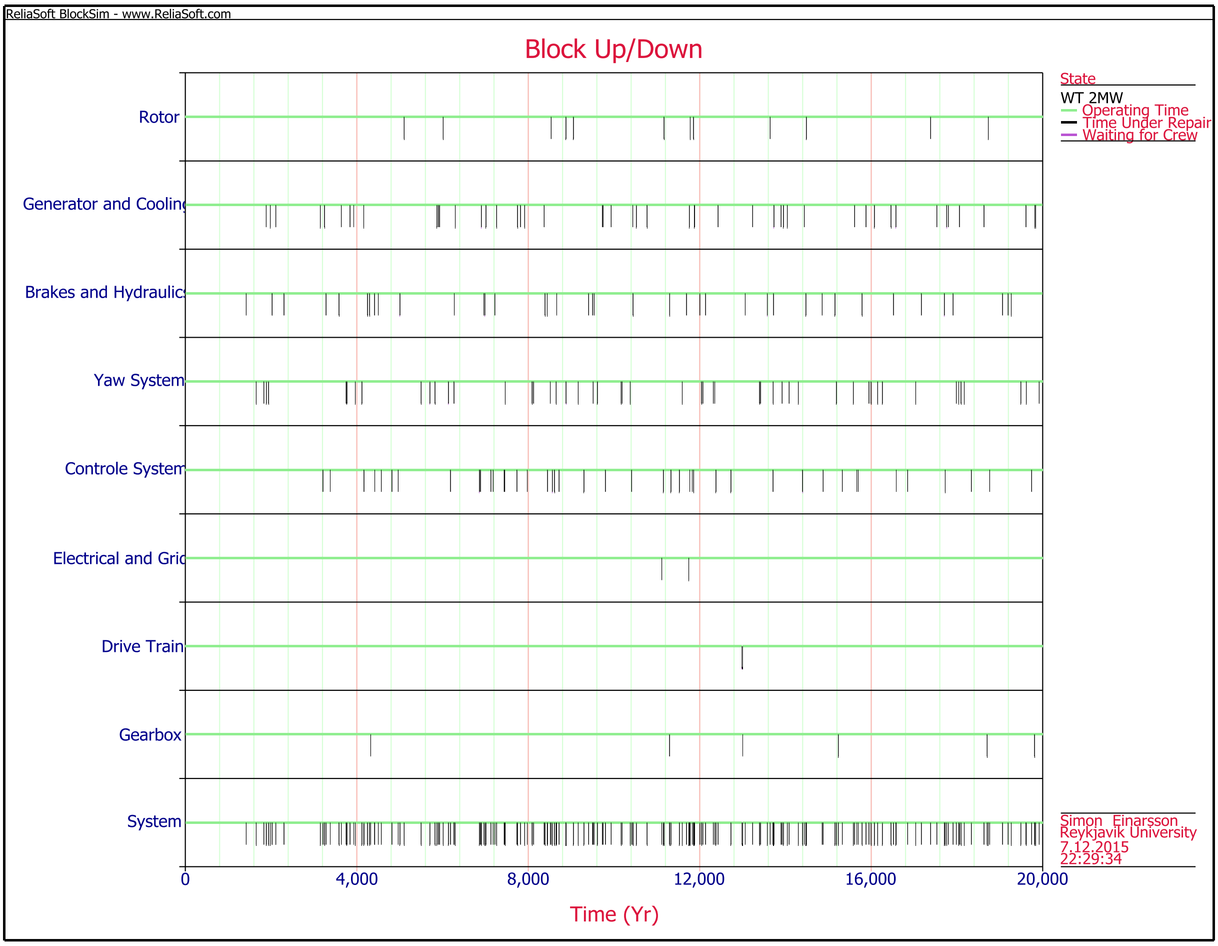

Figure 47: Subsystem up/down time

Figure 48 illustrates how many times each subsystem is expected to fail. Most of the expected failures occur in the yaw system, or in the 54 expected failure over the 20 years. ReliaSoft's color-coded failure criticality index (RS FCI) in the top right in the graph shows the percentage of the time that the component caused system failure [72].

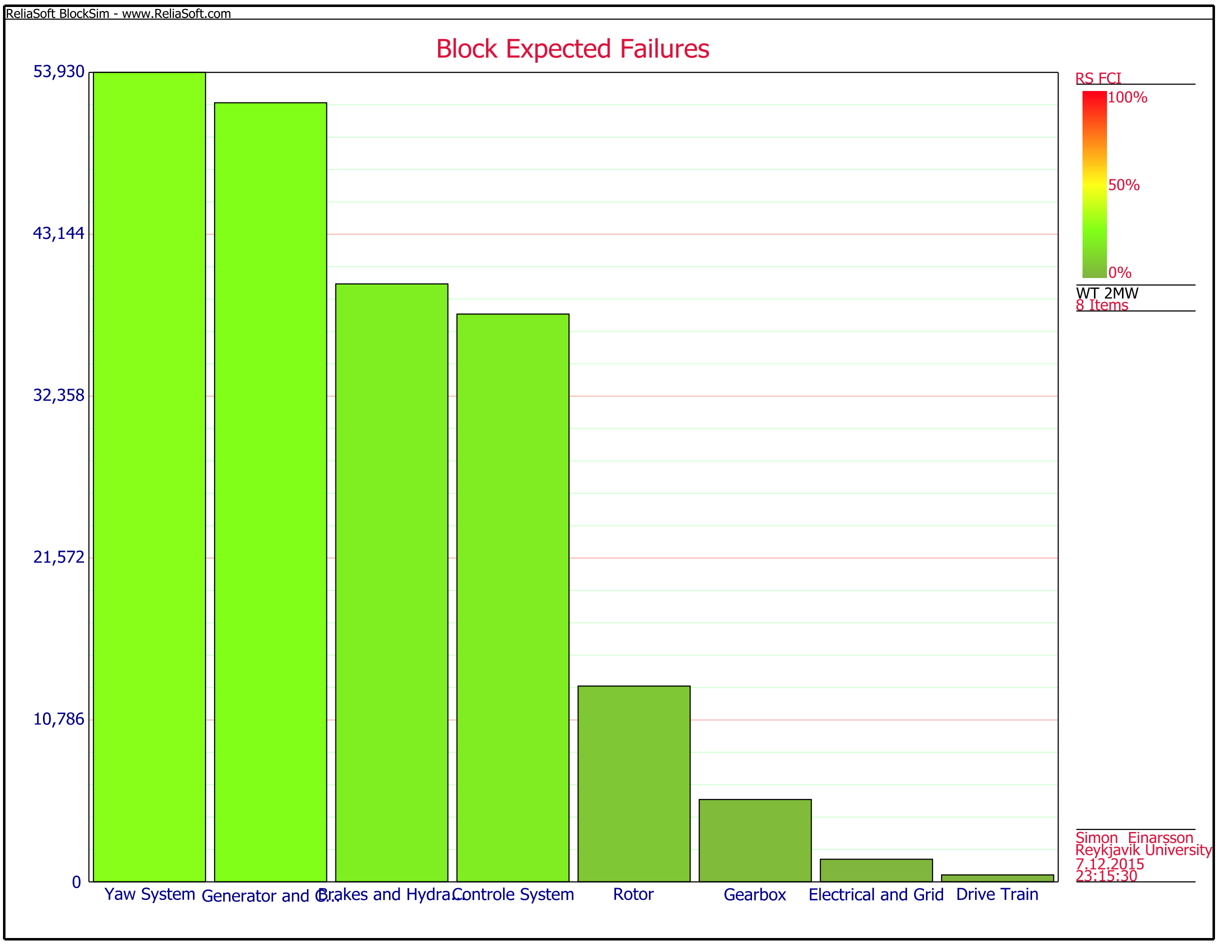

Figure 48: Block expected failures

Figure 49 shows how the failure rate can be analyzed on the component level. The Gearbox failure is shown in the top of the graph, while the components failure that causes the Gearbox failure is shown below. For example, the lube pumps caused the gearbox to fail 2 times over the course of 20 years.

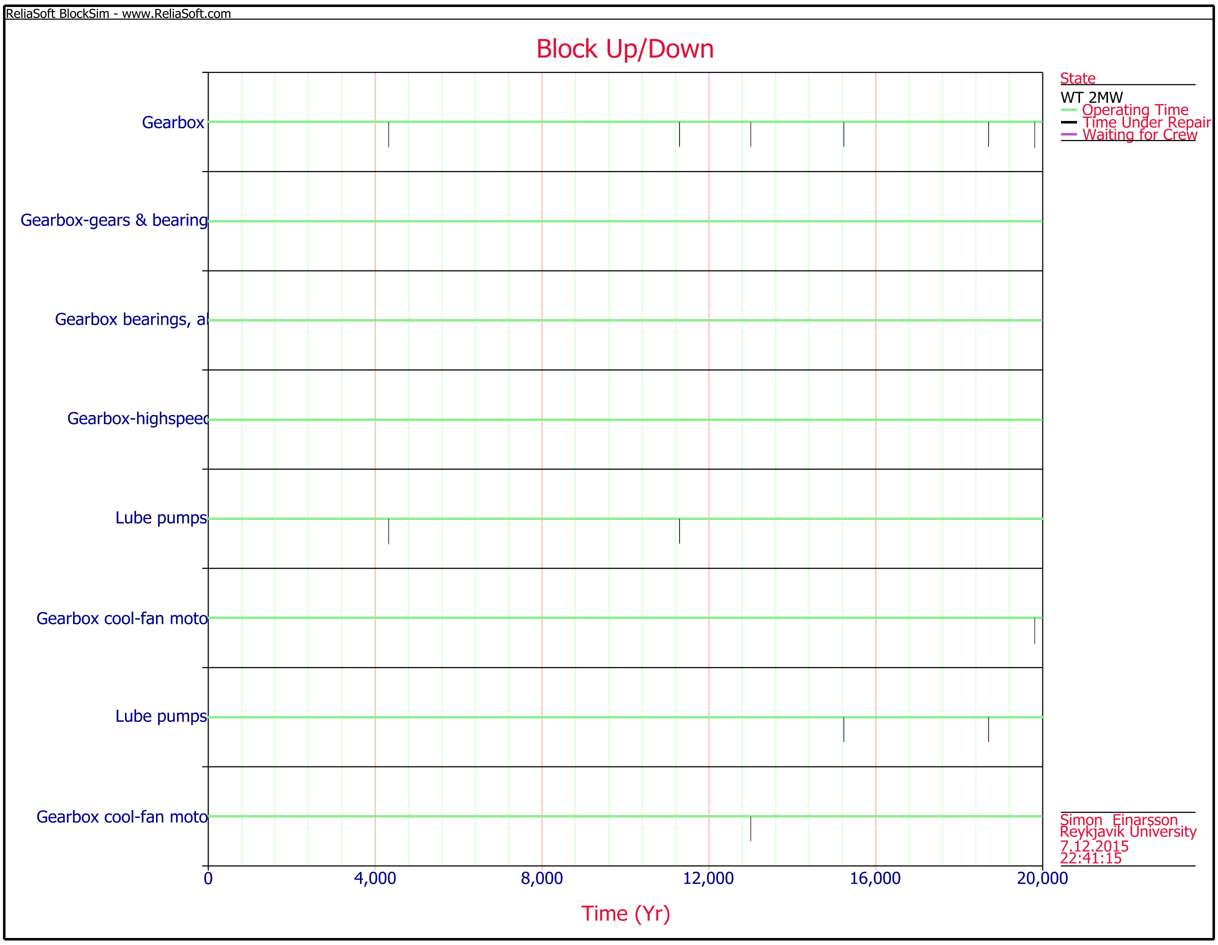

Figure 49: Gearbox up/down time

Figure 50 depicts the downtime criticality index (DTCI) table [72]. The DTCI shows the block's contribution to the system´s downtime (system downtime caused by the block divided by the total system downtime). From the figure, the biggest blocks are the five in the subsystem whereby the yaw system causes the majority of the system's downtime. The small blocks in the lower-right corner are the component's blocks.

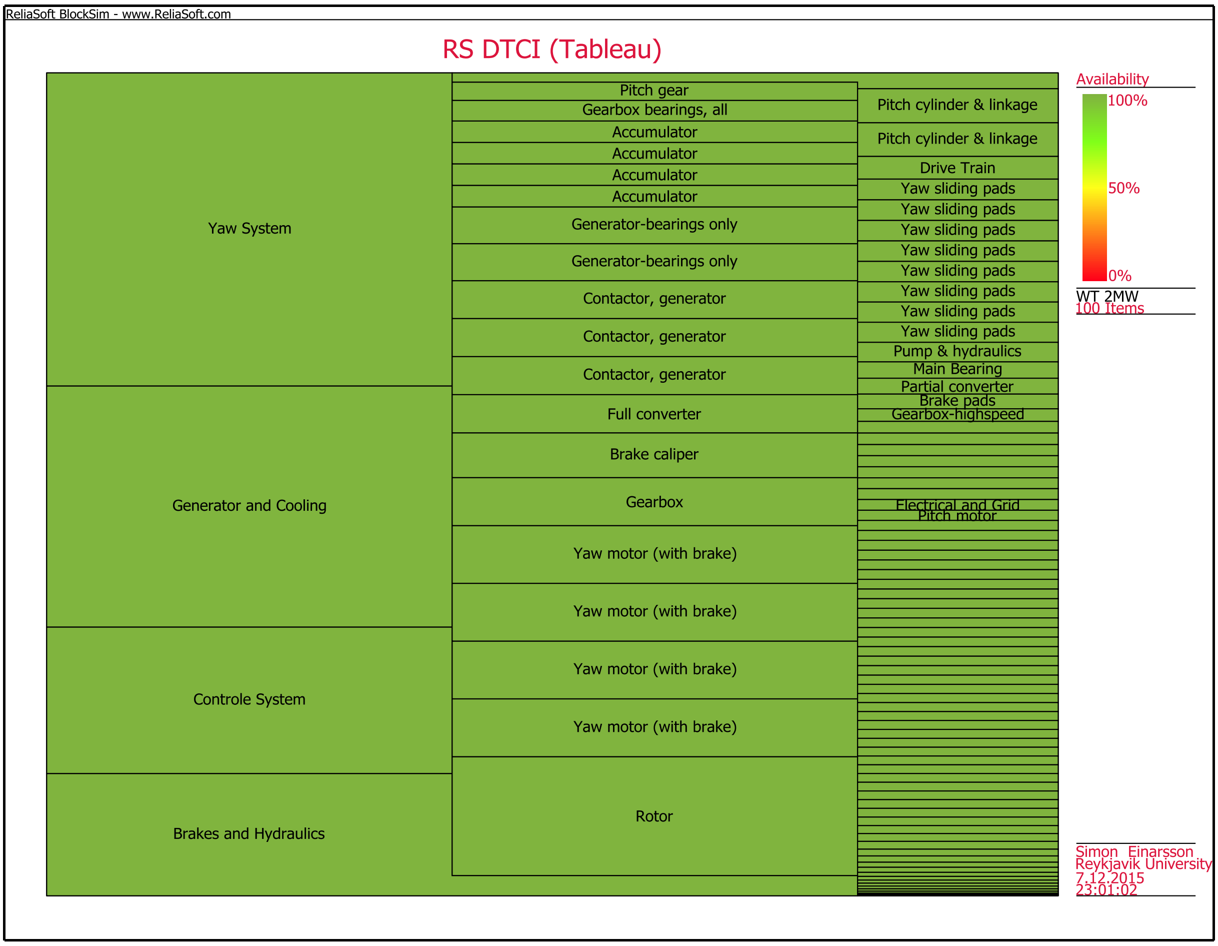

Figure 50: Downtime criticality index

Figure 51 shows the subsystem's downtime. The yaw system is the greatest contributor to the system's total downtime, with a total 485 hours out of 1587 hours. The downtime is 1587 hours for a single turbine over a 20-year period is equivalent to 80 hours per year or 2 working weeks annually.

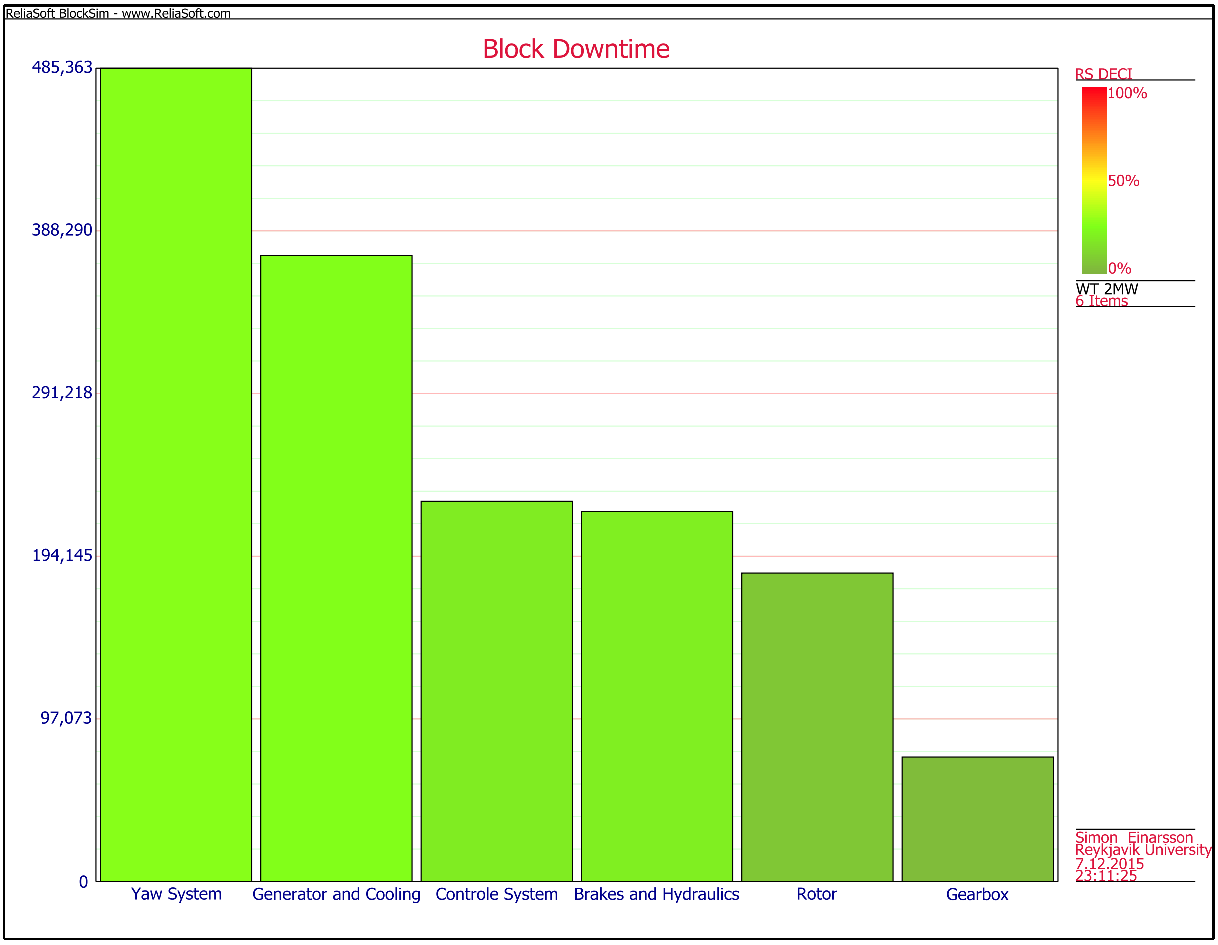

Figure 51: Block downtime

4.1.2 System Cost

Figure 52 shows the turbine maintenance cost vs. time. The top line is the total cost and the middle line is the part cost and the lowest line is the labor cost. Over a 20-year period the total cost of maintaining a 2MW turbine, is around 1.3 million dollars.

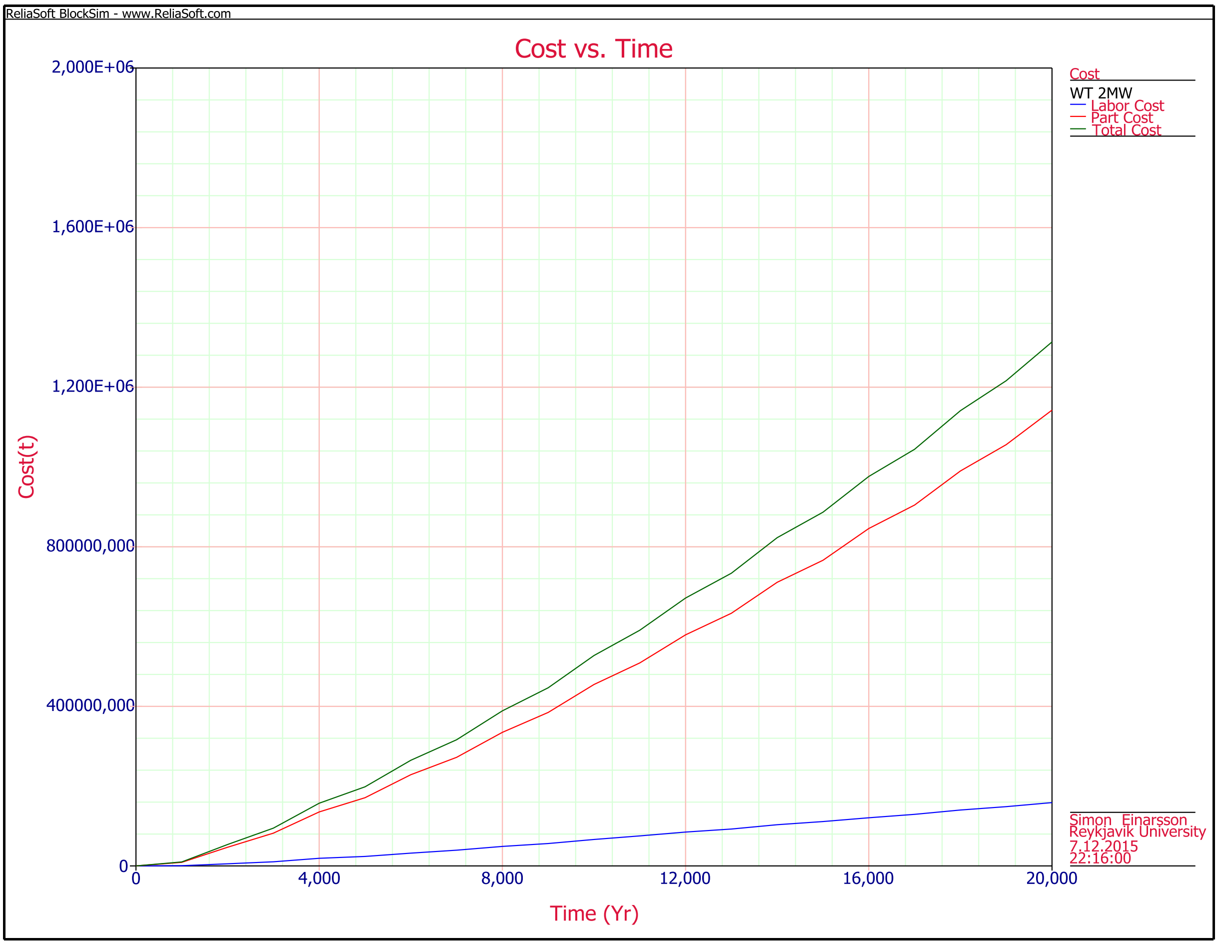

Figure 52: Wind turbine cost vs. time

Figure 53 show the cost of the subsystems, where the maintenance of the generator system costs $470 292 over 20 years.

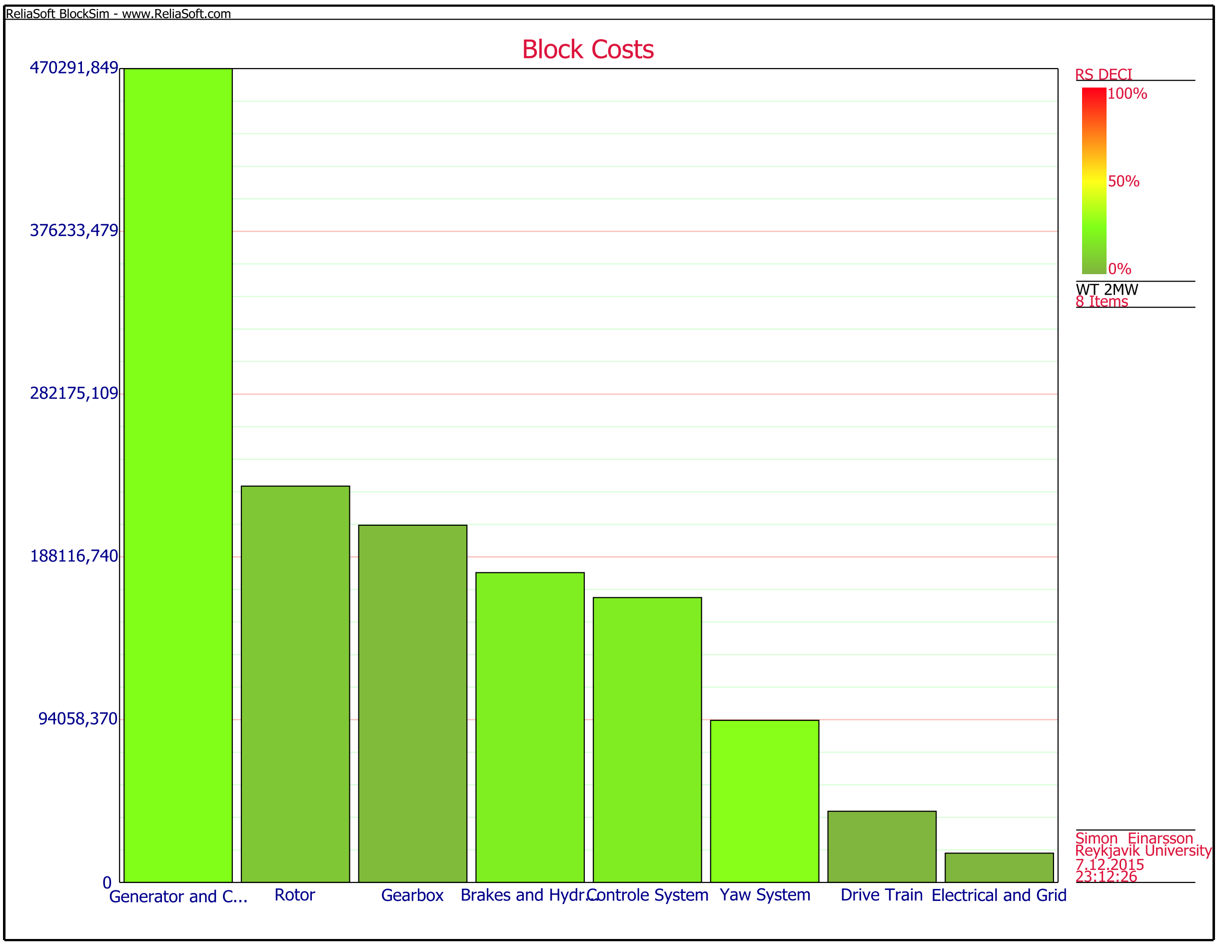

Figure 53: Subsystems cost

Figure 54 shows the monthly maintenance cost of a single 2MW wind turbine over a 20-year period. The figure is noteworthy as it shows the extent of fluctuations within the maintenance cost.

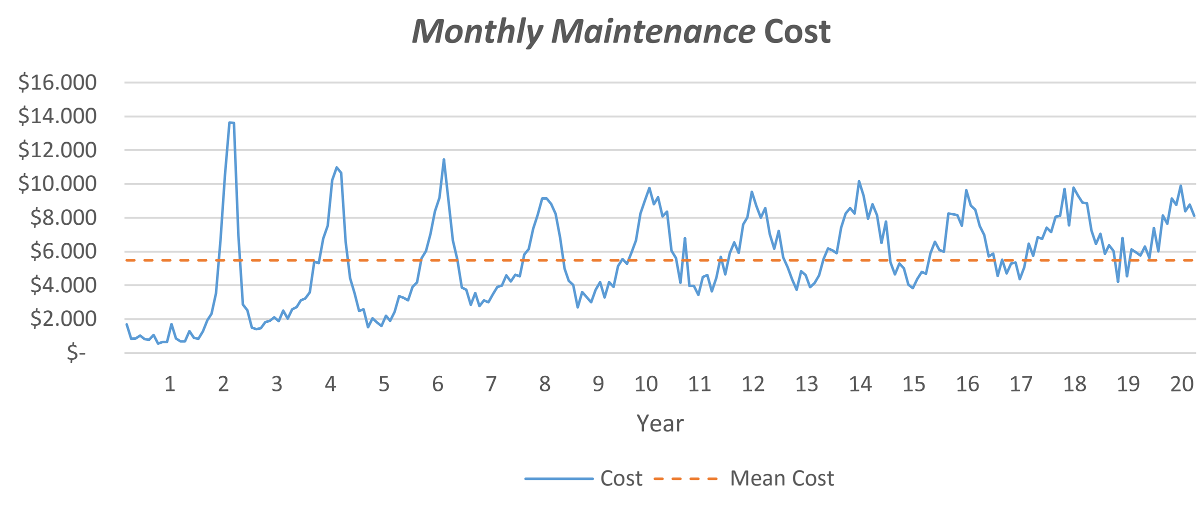

Figure 54: Monthly maintenance cost

Figure 55 shows what components caused the costs to spike around year 2 prior. The figure shows how failures over specific period of time in the generator and cooling system, brakes and hydraulic system and the yaw system caused the system maintenance costs to spike.

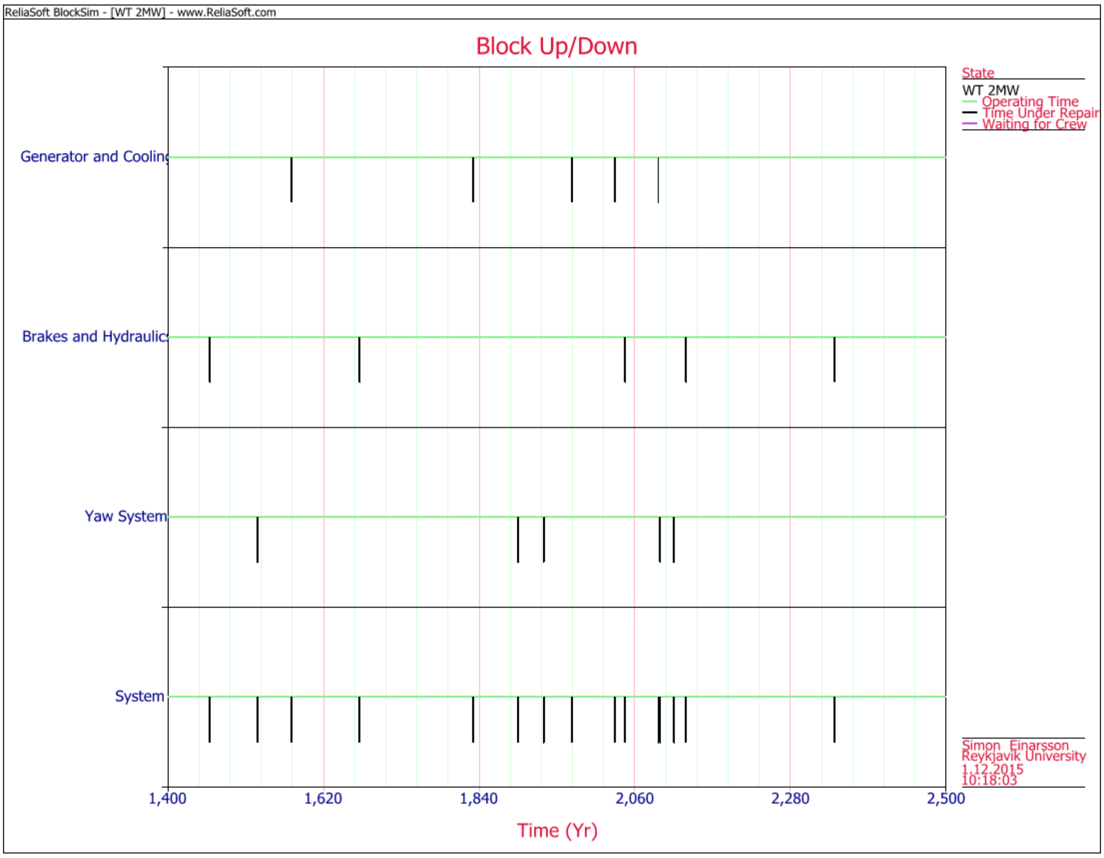

Figure 55: Block up/down time (around year 2)

4.1.3 Cost estimation

Figure 56 shows the annual maintenance cost trend line (blue) with a 95% confidence bound. The data has been smoothened through the use of a lognormal distribution to estimate the annual cost. The red dotted line is an example of the use of fixed value for the cost estimation. The red line overestimates costs in the beginning of projects and then underestimates in end of projects.

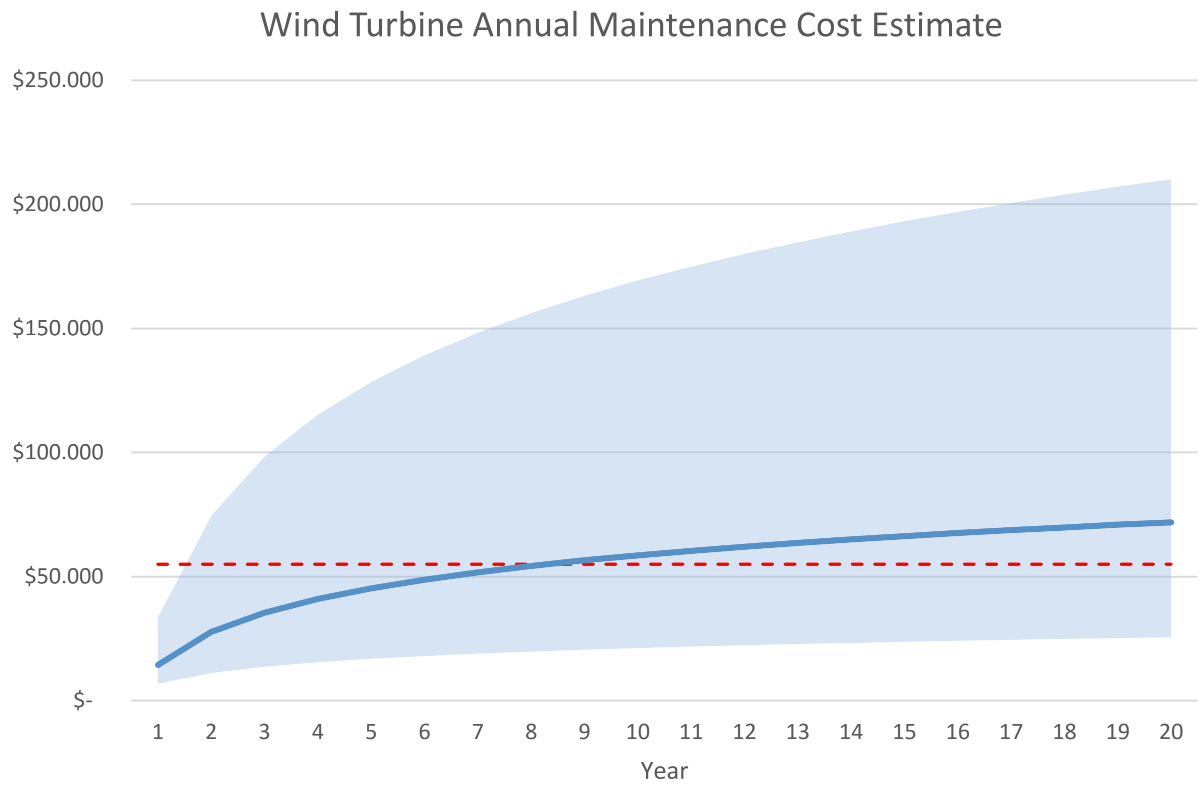

Figure 56: Estimated annual maintenance cost

Table 6 outlines the results of calculating the maintenance cost with a 95% confidence level and all other elements (land rent, insurance, administration & miscellaneous) of OPEX fixed at 19.1$/MWh (calculated by assuming maintenance cost to be 26% of OPEX [65], [66]) . The table shows minimum (Min) expected (Exp) and maximum (Max) maintenance cost calculated with 95% confidence bounds.

Table 6: Maintenance cost 95% confidence and OPEX

	Min	Exp	Max	Unit
Maintenance Cost	2,5	6,7	19,1	**$/MWh**
OPEX	21,6	25,8	38,2	**$/MWh**

The following list compiles the table's information:

- The table shows how closely expected OPEX is to the OECD countries (mean of $28/MWh, shown in Table 3) cost listed below [64].
    - Austria 40 USD/MWh
    - Denmark 15 – 19 USD/MWh
    - The Netherlands 13 – 17 USD/MWh
    - Norway 21 - 39 USD/MWh
    - Spain 28 USD/MWh
    - Sweden 11 – 35 USD/MWh
    - Switzerland 45 USD/MWh

- A comparison of the estimated OPEX range to the OECD countries range shows that it is within the OECD countries' range of $11-45/MWh.
- The calculations showed that the maintenance cost, with a 95% confidence level, contributes 11%-50% of the total OPEX.
- The table also shows that the calculation of the maintenance cost with 95% confidence results in an OPEX from 21.6 to 38.2 $/MWh.

4.1.4 RBD model Sensitivity

This chapter introduces the results on the model's sensitivity to maintainability and failure rate.

4.1.4.1 Sensitivity to less maintainability

This section analyzes the effect of lower maintainability on availability. This analysis was conducted by increasing the repairs crews delay time for every task. Figure 57 show how it seems to be a linear relationship between crew delay time and availability, which can be described with the following formula:

$$Availability = -0{,}0011t + 0{,}9939 \qquad (2.22)$$

Where

t = Crew delay time

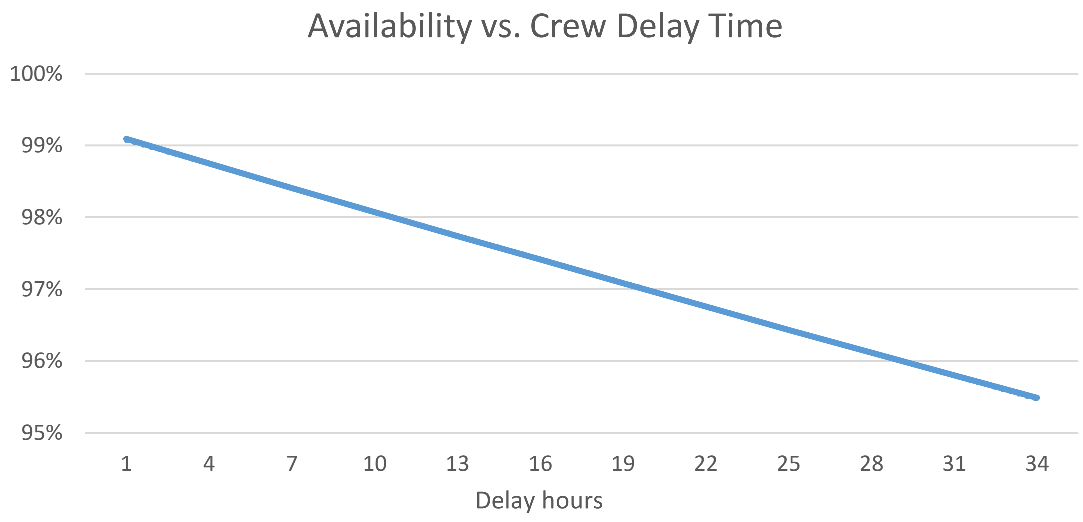

Figure 57: Availability vs. crew delay time

4.1.4.2 *Sensitivity to higher failure rate*

Prior research has shown that subsystems such as gearbox, generator and hub are more likely to fail in changeable wind conditions [50]. Higher failure rate could be expected when operating turbines in Iceland due to the harass wind class. The gearbox failure rate was increased and its effects on the system analyzed. Table 7 shows how the increased failure rate of two blocks affects the turbine's availability, downtime, number of failures and total cost. By increasing the failure rate in the gearbox, the lifecycle cost increased by about 26% due to only 2 additional failures.

Table 7: Comparison of different failure rate in the gearbox

		Base Case		Increased failure rate	
Gearbox-gears & bearings	Exponential	400	-	200	-
Gearbox bearings, all	Weibull	26	3,5	13	3,5
Availability		99,1%		99,0%	
Downtime (Hr)		1577		1689	
Number of Failures		203		205	
Total Cost (USD)		1.375.733		1.735.946	

4.1.4.3 *Sensitivity to wind turbine lifespan*

Figure 58 shows how the turbine lifespan effects the service and maintenance cost per the amount of electricity produced (electricity produced was assumed constant). From the figure, it is evident that the maintenance cost increases with turbine lifespan, which finally starts to stabilize after 30 years. This figure indicates that it should not be expected for the maintenance cost to exceed 9 $/MWh in the same time it is unlikely for wind turbine to last 100 years.

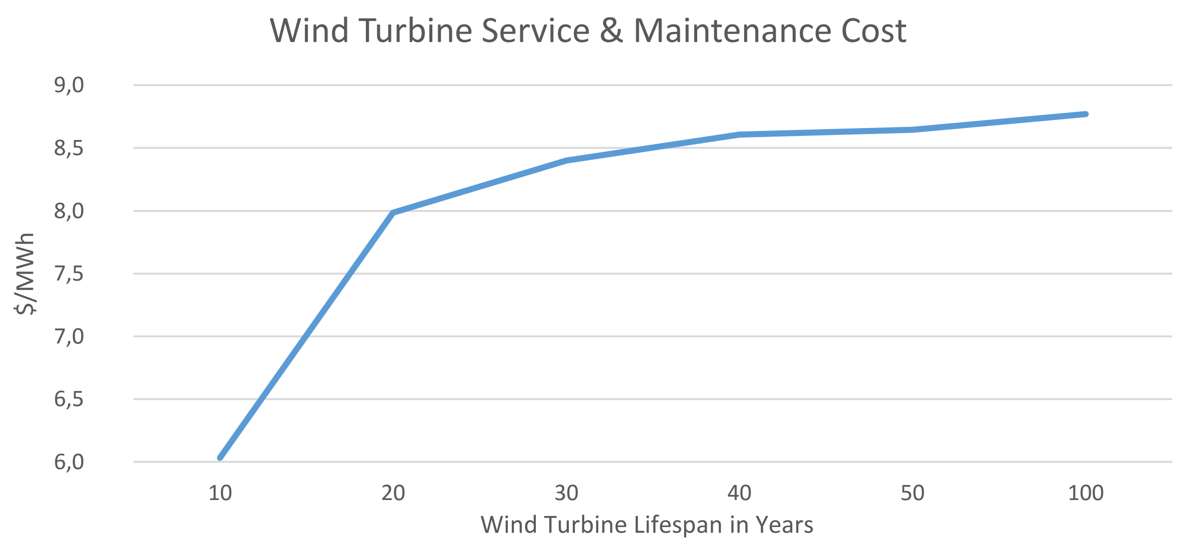

Figure 58: Wind turbine maintenance cost / lifespan

Figure 59 demonstrates how the turbine lifespan effects the LCoE. The figure highlights how increased maintenance cost is not significant enough to actually increase the LCoE, which is affected more by the turbine lifespan, due to high CAPEX.

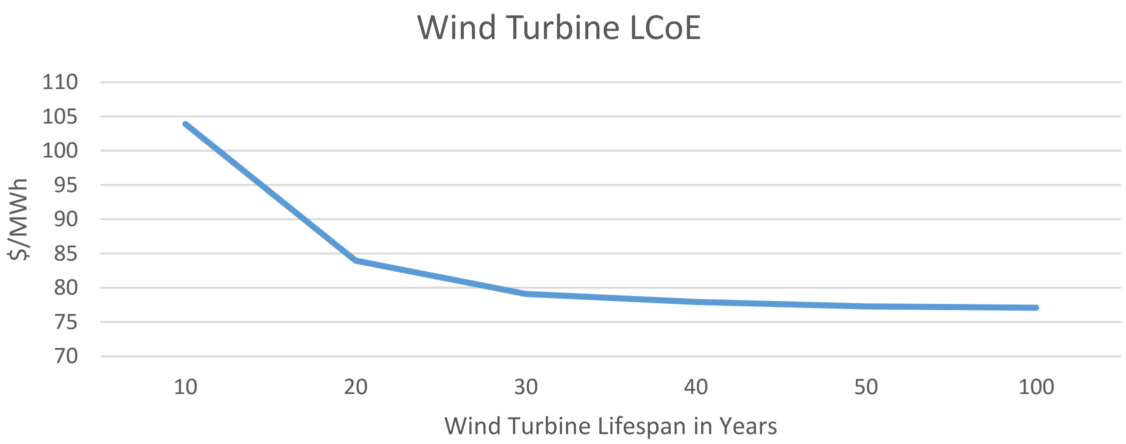

Figure 59: Wind turbine LCoE / lifespan

4.2 Wind Farm Results

Figure 60 illustrates how various wind farm sizes serviced by 1 repair crew affect the average availability of the turbines in the wind farm. The repair crew was assumed to have a one hour response time and it could only attend to one repair at a time. The wind farm was simulated by 1 to 90 turbines, which were serviced by 1 crew. The results show that availability decreases exponentially after the turbines amount over 40. The turbine availability is 99% in 40 turbine farm and drops to 77% in 90 turbine farms.

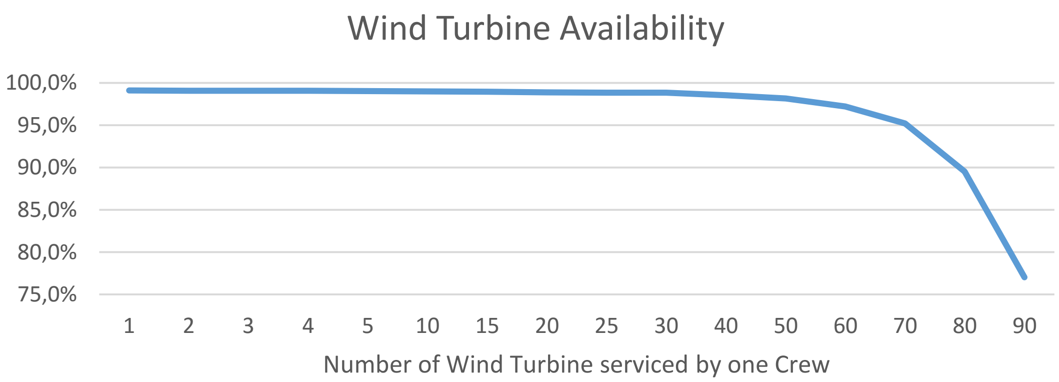

Figure 60: Wind turbine availability

4.2.1 90 Wind Turbine Farm Sensitivity

The base case, which includes a 90 turbine farm, has 1 crew that services the farm with a one hour response time, similar to the prior example. Through the addition of 1 crew servicing the wind farm, the mean turbine availability of the 90 turbine farm went from 77.0% to 98.8%. Through the use of two repair crews and the increased delay time to 10 hours resulted in 57% average turbine availability in the wind farm.

5 CONCLUSION & DISCUSSION

The chapter is divided into four sections.

- First, it concludes the main findings and results from the research;
- Secondly, the value of reliability data is discussed;
- The third section provides a critique of the model and methodology;
- Finally, this chapter discusses future research topics and potential improvements as well as this research's potential usefulness in other fields.

5.1 KEY FINDINGS

Studies shows that wind turbine's technical concepts and reliability have improved over the years, although there is still room for further advancements[39]. It is clear that weather affects turbines' reliability [48] and operators and researchers are in harmony when it comes to the need for improvements in the field of reliability and O&M of the turbines [16],[29]. Maintainability plays big role in the operation of the turbine. The maintenance strategy and the correct inventory of spare parts are both aspects of high maintainability. Service and spare parts constitute up to 50% of the OPEX [65], and it is therefore important to apply right amount of maintenance to prevent the risk of expensive failures and to keep costs at a minimum. OPEX and availability are two key factors that affect the LCoE. OPEX accounts for 11 – 30% of the LCoE [1].

A quantitative RBD model was developed for the purpose of using reliability data to evaluate wind farm availability and OPEX. The model was developed from the Blocksim software tool produced by Reliasoft Inc. The model was based on reliability data from NREL [24], [71]. The data included the following information, as each building block represent a component in the turbine.

- Failure statistic
- Repair time
- Repair cost
- Component cost

The data was used to determine each block properties. The blocks were connected together to form a subsystems, and eventually, a wind turbine. The turbines were used to form a wind farm and simulations were made for multiple cases. The simulation process required a few days, and the time of each simulation ranged from a couple seconds in cases of a single turbine to 20+ hours for the wind farm. The main results are listed in the following:

- Crew delay time had a linear effect on the availability in the service of a single turbine. This finding did not seem to be the case in the analysis of crew delay times for wind farms.
- One Crew with a 1-hour delay time was able to service 50 turbines and maintained a 98% mean availability with every added turbine after that the availability began to exponentially drop. The number of turbines that can be maintained by a single crew is expected to decrease if the crew delay time were to be longer.

- A sensitivity analysis showed that increased failure of key parts dramatically increased the turbine life cycle cost dramatically, whereby two additional gearbox failures increased the lifetime maintenance costs by 26%.
- The sensitivity analysis on turbine lifespan showed that the service and maintenance costs per amount of electricity produced stabilized for turbines around 30 years old.
- OPEX was calculated whereby maintenance costs had a 95% confidence level. The results showed that maintenance accounted for 11-50% of the OPEX.

The model was verified through a comparison of the estimated OPEX to the OPEX of selected OECD countries [64]. The verification showed that the model was accurate and within the range of the OECD countries OPEX. The models' expected value was $26/Mwh in comparison to the mean value of the OECD countries, which was $28/Mwh.

5.2 VALUE OF RELIABILITY DATA

The value of the reliability data lies in the additional information about the system, which can be used to prevent economic loss due to a lack of information and poor decision-making. The model provided results that would be hard or impossible to predict without access to data. The main benefits are as follows:

- The models provides clear results for key metrics such as reliability, availability and maintenance costs associated with the chosen O&M strategy.
    - Wind farm O&M can be optimized, which results in better asset management, lower OPEX and higher availability.
- The value of preventing economic loss by making the wrong decision
    - It is important to prevent expensive failure by applying the right maintenance strategy without spending too much on preventive maintenance.
    - The model can be used to compare and evaluate the value of service from turbine manufactures or independent service providers.
- The method can be used to evaluate uncertainty and risk factors.

The method derives the possibility of lowering maintenance cost and maintaining a higher availability by choosing the right maintenance strategy and avoiding bad decisions. In a modest example with 0.1% increased availability and 1% saving in maintenance cost, the annual economic benefits would be $63.144 for a 180MW wind farm. Therefore, one can predict that the economic benefits of the method may be much greater over the project's life time.

Table 8 shows that a 1% saving in maintenance cost of a 180MW wind farm is equal to $42,286.

Table 8: Annual maintenance cost saving

Annual Maintence Cost Saving				
Hours in Year	**Wind Farm**	**Capacity Factor**	**Maintenance Cost**	**Saving**
h	MW	[ ]	$/MWh	1%
8.765,8	180,0	0,4	6,7	**$ 42.286**

Table 9 shows that a 0.1% increased availability of a 180Mw wind farm would annually yield 631MWh of electricity, which is worth $20,828.

Table 9: Increased annual electricity production

Increased Annual Electricity Production						
Hours in Year	**Wind Farm**	**Capacity Factor**	**Increased Availability**	**Yield**	**Price of Electricity**	**Profit**
h	MW	[ ]	[ ]	MWh	$/MWh	$
8.766	180	0,4	0,1%	**631**	33	**$ 20.828**

The model enables the optimization of the maintenance budget for wind turbine O&M and is able to forecast maintenance cost. This aspect will minimize possible opportunity loss of not having the right budget or spare parts available when they are required.

In a competitive market in which the price of electricity is $33/MWh, factors such as OPEX and availability can make or break a wind farm project [73]. It is essential to have a tool that can be used to assess and analyze these factors in deeper depth than before. By building a quantitative reliability model, OPEX and availability are analyzed in parallel through the use of a visually-based tool to perform complex research in a simple way. In order to conduct this research, developers need reliability data, preferably from turbine manufactures. The reliability data is valuable and should be used to influence a projects' success rate.

5.3 Model and Method Critique

The RBD model assumes that the environment has a constant stress level. Improvements could be made by assuming a higher stress over the winter time or by associating the stress level with the long term wind forecast (to counter changing operation environment). These improvements could be made by using a phase diagram in Blocksim. When using a model such as this one, one must be cautious about the quality of input data, in order to receive trustworthy results.

One of the greatest shortcomings of the Blocksim RBD model is its lack of flexibility to changes of inputs, after it has been built for the purpose of sensitivity analyses.

The RBD model employed spare part pools with unlimited spare parts and no deliver time. It would be more realistic to have certain amount of spare parts and a certain delivery time for new parts. These aspects would provide the possibility of adding inventory stock costs to the total cost.

Improvements could also be made in the field of using probability distributions for repair time and time delays, rather than fixed numbers.

Due to the difficulty to obtain useful information, the model was based on data from NREL. The results where compared to data from the OECD countries. It would have been more ideal to compare the results to the same data bank from which the input data originated. Of course, there are probably many other aspects that could be handled differently or better. Still, the model is theoretical and the goal was to explore and find the value of the methodology, and this research may be a stepping stone to implement more accurate asset management and forecasting system for complex systems.

5.4 FUTURE RESEARCH

As the model critique concluded, there are improvements that could be made to the model to improve the accuracy of the results.

Figure 61 summarizes the whole model idea and how it could be used in wind farm operation to optimize O&M. The blue box represents the flow chart of the RBD simulation model. In order to generate the maintenance strategy, the RBD could be combined with RCM, which is specifically designed to maximize system reliability and availability at the lowest price possible. After power production has begun, the yellow box would be added in places where sensors would be used to trigger maintenance. Weather forecast would be used determine the suitable maintenance dates and to predict the additional stress to the system as well as the collection of life data. After choosing to apply these methodologies, developers are better informed about the system performance, potential risks and are more likely to maximize profits.

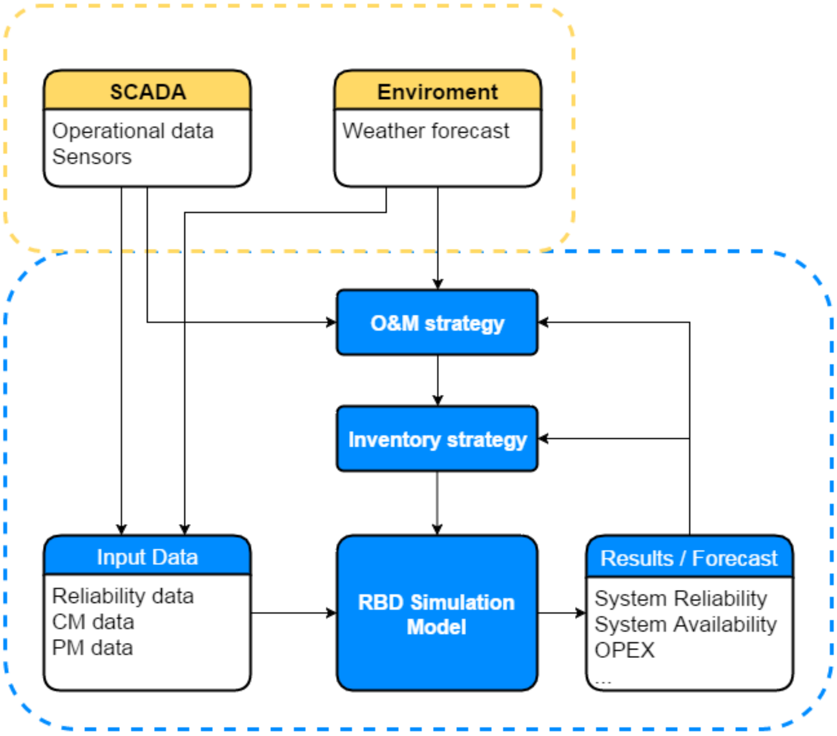

Figure 61: O&M simulation flow chart

The following list summarizes the potential improvements and future possibilities for further research:

- Improve data quality. This includes:
  - Going deeper into the subsystem and components data

    - Use statistical distributions to describe repair time, delay time and the shipping time of components.
- Add inventory system with holding costs, shipping time and etc.
- OPEX could be estimated with much greater accuracy by having values for land rent, insurance, administration, power from the grid, and other miscellaneous costs.
- Add phase diagram to distinguish between probability of failure in winter and summer
- Model effects of weather and environment on turbines (could be used to designate the phase diagram) [50], see chapter on environment and reliability.
- A good model should include both sensitivity and uncertainty analysis. An uncertainty analysis on the models input data is recommended and advised.
- Develop RBD model using programing langue such as Python, C++ or matlab. The programs could offer more flexibility for sensitivity analysis and the possibility of reading life SCADA data and optimizing RCM and inventory strategies.
- The method is strongly recommended to be used and researched on complex systems in other fields, especially those with stable operation environments such as manufacturing lines and factories.

6 REFERENCES

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7 APPENDICES

7.1 PREVENTIVE MAINTENANCE DATA

Table 1 shows how preventive maintenance data could be organized.

Table 10: Preventive maintenance data table example

Wind Turbine configuration: 2,0MW and 80 Meter Tower, Cost and Maintenance Estimation							
			Preventive Maintainance (PM)				
System	**Component failure**	**Type**	**Part Cost($)**	**Crew Cost($)**	**Repair Time (Hr)**	**Crew**	**Restoration**
Rotor							
	Blade-struct. Repair	Cycle					As good as new
	Balde-nonstruct. Repair	Condition based					As bad as old
	Pitch cylinder & linkage	Reliability based					...
	Pitch bearing	...					
	Pump & hydraulics						
	Pitch position xder						
	Pitch motor						
	Pitch gear						
Drive Train							
	Main Bearing						
	High speed coupling						
Gerbox							
	Gearbox-gears & bearings						
	Gerbox bearings, all						
	Gerbox-highspeed						
	Lube pumps						
	Gearbox cool-fan motor						
Generator and Cooling							
	Generator-rotor & bearings						
	Generator-beraings only						
	Full converter						
	Gener, cooling fan motor						
	Contactor, generator						
	Partial converter						
Brakes and Hydraulics							
	Brake caliper						
	Brake pads						
	Accumulator						
	Hydraulic						
Yaw System							
	Yaw gear (drive+motor)						
	Yaw motor (with brake)						
	Yaw sliding pads						
Controle System							
	Control board, top						
	Control board, main						
	Contorl module						
	Sensor, static						
Electrical and Grid							
	Main contactor						
	Main circuit breaker						
	Soft starter						

7.2 THREE POINT COST DATA

Table 11 shows the data used for the three point cost estimation.

Table 11: Three point cost data

Wind Turbine configuration: 1,5 - 2,0MW, 80 Meter Tower				
System	Component	Low	Average	High
Rotor				
	Blade-struct. Repair	$ 57.000	$ 88.000	$ 109.000
	Balde-nonstruct. Repair	$ 6.000	$ 13.000	$ 19.000
	Pitch cylinder & linkage	$ 3.000	$ 13.000	$ 23.000
	Pitch bearing	$ 11.000	$ 13.000	$ 15.000
	Pump & hydraulics	$ 3.000	$ 3.000	$ 4.000
	Pitch position xder	$ 100	$ 2.000	$ 3.000
	Pitch motor	$ 2.000	$ 8.000	$ 14.000
	Pitch gear	$ 3.000	$ 7.000	$ 15.000
	Pitch controler	$ 8.000	$ 9.000	$ 10.000
Drive Train				
	Main Bearing	$ 9.000	$ 24.000	$ 38.000
	High speed coupling	$ 5.000	$ 7.000	$ 11.000
Gerbox				
	Gearbox-gears & bearings	$ 180.000	$ 221.000	$ 445.000
	Gerbox bearings, all	$ 180.000	$ 194.000	$ 215.000
	Gerbox-highspeed	$ 180.000	$ 183.000	$ 187.000
	Lube pumps	$ 1.000	$ 2.000	$ 6.000
	Gearbox cool-fan motor	$ 1.000	$ 2.000	$ 4.000
Generator and Cooling				
	Generator--rot. & brgs.	$ 52.000	$ 131.000	$ 412.000
	Generator--brgs. only	$ 500	$ 2.000	$ 4.000
	Full converter	$ 25.000	$ 36.000	$ 47.000
	Motor, generator coolant fan	$ 1.000	$ 2.000	$ 4.000
	Contractor, generator	$ 2.000	$ 13.000	$ 20.000
	Partial converter (rotor side)	$ 16.000	$ 17.000	$ 18.000
Brakes & Hydraulics				
	Brake caliper	$ 6.000	$ 7.000	$ 9.000
	Brake Pads set	$ 2.000	$ 6.000	$ 9.000
	Accumulator	$ 500	$ 2.000	$ 4.000
	Hydraulic pump	$ 1.000	$ 5.000	$ 12.000
	Hydraulic valve	$ 500	$ 500	$ 1.000
Yaw System				
	Yaw gear (drive+motor)	$ 3.000	$ 9.000	$ 17.000
	Yaw motor (with brake)	$ 500	$ 2.000	$ 4.000
	Yaw sliding pads	$ 500	$ 1.000	$ 1.000
	Yaw bearing (with gear)	$ 22.000	$ 31.000	$ 40.000
	Yaw slew ring	$ 169.000	$ 199.000	$ 229.000
Control System				
	Control board, top	$ 6.000	$ 11.000	$ 18.000
	Control board, main	$ 16.000	$ 17.000	$ 20.000
	Control module	$ 5.000	$ 6.000	$ 8.000
	Sensor, static	$ 500	$ 1.000	$ 1.000
	Sensor dynamic	$ 3.000	$ 3.000	$ 5.000
Electrical and Grid				
	Main contactor	$ 13.000	$ 13.000	$ 13.000
	Main circuit breaker	$ 10.000	$ 15.000	$ 24.000
	Soft starter	$ 1.000	$ 1.000	$ 1.000

7.3 LEVELIZED COST OF ENERGY (LCOE)

Table 12 shows assumptions used in calculations.

Table 12: Assumptions in LCoE calculations

Discount Rate	10%	[66]
Capacity Factor	40%	[10]
Hours in Year	8766	
Maintenance % of OPEX	26%	[65]
CAPX [$/MWh]	1700	[1]

Table 13 show how the foundation for calculating the LCoE.

Table 13: LCoE calculations based on lognormal distribution with 95% confidence level

Year	Maintenance				Electricity	
	Cost	PV min	PV exp	PV max	MWh	Discounted MWh
1	14.455	6.218	13.141	30.547	7.013	6.375
2	27.738	9.228	22.924	61.527	7.013	5.796
3	35.508	10.290	26.677	73.885	7.013	5.269
4	41.021	10.581	28.018	78.747	7.013	4.790
5	45.297	10.484	28.126	79.753	7.013	4.354
6	48.790	10.173	27.541	78.567	7.013	3.959
7	51.744	9.742	26.553	76.086	7.013	3.599
8	54.303	9.245	25.333	72.840	7.013	3.272
9	56.560	8.716	23.987	69.162	7.013	2.974
10	58.579	8.177	22.585	65.268	7.013	2.704
11	60.406	7.642	21.172	61.303	7.013	2.458
12	62.073	7.121	19.778	57.364	7.013	2.234
13	63.607	6.618	18.425	53.515	7.013	2.031
14	65.027	6.138	17.124	49.800	7.013	1.847
15	66.349	5.683	15.884	46.246	7.013	1.679
16	67.586	5.254	14.709	42.870	7.013	1.526
17	68.748	4.851	13.601	39.679	7.013	1.387
18	69.843	4.475	12.562	36.678	7.013	1.261
19	70.879	4.123	11.589	33.864	7.013	1.147
20	71.862	3.796	10.682	31.235	7.013	1.042
Sum	1.100.377	148.555	400.410	1.138.935		59.704