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Optimal maintenance planning using reliability information for offshore wind turbines

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Preface

This thesis is written in order to complete the bachelor Industrial Engineering and Management at the University of Twente. The assignment is performed under supervision of Fraunhofer IEE and the University of Twente.

I would like to express my gratitude towards my supervisors of the University of Twente, Engin Topan and Ipek Seyran Topan, for the good guidance and all the valuable feedback during the execution of my bachelor thesis. My first supervisor, Engin Topan, was always available on short term if I had any questions or concerns about my research. During the meetings, we had some good and interesting discussions concerning the content and direction of the bachelor thesis. Furthermore, during the meetings and the visits to Fraunhofer IEE in Germany, we had some fun and interesting conversations on a broad variety of subjects.

Moreover, I would like to thank Fraunhofer IEE for the possibility to execute my bachelor thesis for their company. The knowledge and expertise shared by my supervisors at Fraunhofer IEE contributed greatly to a good underpinned research. Thus, I would also like to express my gratitude towards my supervisors at Fraunhofer IEE, Stefan Faulstisch and Alexander Lutz, for their valuable feedback and comments.

Finally, I would like to thank my family and friends which supported me during the execution of the bachelor thesis. They provided me with interesting thoughts and ideas which I could potentially implement in my research. If I had any struggles during my bachelor thesis, the motivational words of my family and friends would help me to continue and overcome these struggles.

With kind regards,

Mark Haring

Enschede, November 7, 2018.

Management summary

Overview

Fraunhofer IEE is conducting research for the national and international transformation of energy supply systems. They develop solutions for technical and economic challenges in order to further reduce the costs of using renewable energies, to secure the supply despite volatile generation, to ensure grid stability at the usual high level and to make the business model of the energy transition a success.

As the global operational wind turbine fleet ages and a trend towards self-operations is observed by wind farm operators, research into reducing the levelized cost of electricity continues. Operation and maintenance costs have a substantial contribution to the levelized cost of electricity and 67% of the operation and maintenance costs are caused by the high maintenance costs (IRENA, Renewable Power Generation Costs in 2017, 2018). Furthermore, offshore wind turbines operate in a harsher environment which makes it harder and costlier to execute maintenance. Therefore, high downtimes and high maintenance costs can be observed which inadvertently results in a higher levelized cost of electricity.

With reliability information provided by Fraunhofer, we have analyzed and proposed an optimal maintenance policy for a single component which minimizes maintenance cost and thereby ensures reliability. The component chosen for this research purpose is the converter system. The converter system fails frequently and has a high share on the annual downtimes. Furthermore, the optimal preventive replacement time of a rotor system in an offshore wind turbine has been analyzed and proposed.

Approach

The used optimal maintenance policy is an age-based preventive maintenance policy. This policy schedules preventive maintenance after fixed operational time which minimizes the cost per unit time. The optimum can be found at the lowest value of the objective function. The objective function is determined from the expected cost per cycle and the expected cycle length. The expected cost per cycle is calculated from the cost of preventive and corrective maintenance and the reliability information of the component.

Preventive maintenance involves the maintenance activities prior to a failure. In our study, preventive maintenance will consist of the replacement of the converter system. Corrective maintenance involves the maintenance activities after a failure has been detected. Both costs of preventive and corrective maintenance are determined from existing literature.

The provided reliability information is analyzed and modeled in excel. The reliability information consists of 7 failure categories from which the reliability of the converter system can be determined. The wind speed data of FINO1 location in the North Sea has been used to determine two of the failure categories. All failure categories are modelled hourly over a 25 year-span. Thereafter, the reliability for each quarter of a year is determined. From the reliability, the unreliability is easily calculated, and the expected cycle length can be determined.

Furthermore, the optimal fixed operational time is analyzed by means of a sensitivity analysis executed on the maintenance costs. Additionally, the work is extended to the rotor systems of offshore wind turbines.

Key findings

- The designed optimal maintenance planning model can determine the optimal preventive replacement time for numerous wind turbine components, using different cost parameters inputs and reliability information. The designed model minimizes the total downtime, maintenance and logistics costs.

- For a preventive maintenance cost of 541.213€ and corrective maintenance cost of 1.230.654€ (CM/PM cost ratio of 2,27), an effectiveness of 0,24% is found of using an age-based maintenance policy to schedule the preventive replacement of the converter system. The converter should be preventively replaced after 21,75 operational years with a cost per unit time of 56.545€.

- For the rotor system, the optimal preventive replacement time is found to be after 9,5 operational years with a cost per unit time of 189.052€. The used preventive maintenance cost is 924.691€ and corrective maintenance cost of 1.849.382€ (CM/PM cost ratio of 2). Operators can save 296.575€ in rotor system maintenance costs over the lifetime of one wind turbine. E.g. for a wind farm with 50 wind turbines, operators can save approximately €15 million in rotor system maintenance costs.

- The optimal preventive replacement time is strongly dependent on the cost ratio between preventive and corrective maintenance cost. The optimums found for the converter system range between 25 years for a CM/PM cost ratio of 2 and 13,25 years for a ratio of 6.

- Determining the optimal for all major components can yield optimums that lay close to each other and yield the possibility to perform opportunistic maintenance. Combining preventive maintenance actions can even further reduce the total maintenance cost incurred over the lifetime of a wind turbine.

Recommendations

For further research:

1. The optimal maintenance planning model should be extended with other seasonal changes such as more variability in the cost determinations, waiting times, and capacity factor.

2. Further research the possibility to use k-mean clustering to find more suitable optimums for more than one component.

3. Execute a sensitivity analysis on the influence of the reliability of a component on the optimal fixed operational time.

4. Analyze different optimums of major components to seek the opportunity to perform opportunistic maintenance.

5. Research the possibility to implement condition-based maintenance using condition monitoring systems in wind turbines.

The implementations of the above recommendations will further improve the accuracy of the optimal maintenance planning model and consequently the value derived from it. Furthermore, condition-based maintenance should be further researched as it can minimize the cost of preventive and corrective maintenance actions.

Management samenvatting

Overzicht

Fraunhofer IEE doet onderzoek voor de nationale en internationale transformatie van energievoorzieningssystemen. Ze ontwikkelen oplossingen voor technische en economische uitdagingen om zodoende de kosten van het gebruik van hernieuwbare energiebronnen verder te verlagen, het aanbod veilig te stellen ondanks volatiele opwekking, om de netstabiliteit op het gebruikelijke hoge niveau te verzekeren en om het bedrijfsmodel van de energietransitie tot een succes te maken.

Naarmate de wereldwijde operationele windturbinevloot ouder wordt en er een zelfoperatie trend wordt waargenomen door exploitanten van windparken, wordt het onderzoek naar de verlaging van de genivelleerde kosten van elektriciteit voortgezet. Exploitatie- en onderhoudskosten dragen substantieel bij aan de genivelleerde kosten van elektriciteit en 67% van de exploitatie- en onderhoudskosten worden veroorzaakt door de hoge onderhoudskosten (IRENA, hernieuwbare stroomproductiekosten in 2017, 2018). Bovendien werken offshore windturbines in een ruwere omgeving, waardoor het moeilijker en duurder wordt om onderhoud uit te voeren. Daarom kunnen hoge stilstand tijden en hoge onderhoudskosten worden waargenomen die onbedoeld leiden tot hogere genivelleerde elektriciteitskosten.

Met betrouwbaarheidsinformatie van Fraunhofer hebben we een optimaal onderhoudsbeleid voor één onderdeel geanalyseerd en ontwikkeld, waardoor de onderhoudskosten tot een minimum worden beperkt en de betrouwbaarheid wordt gegarandeerd. De gekozen component voor dit onderzoeksdoel is het elektrisch omzettersysteem. Het elektrisch omzettersysteem faalt regelmatig en heeft een hoog aandeel in de stilstand tijden.

Aanpak

Het gebruikte optimale onderhoudsbeleid is een, op leeftijd gebaseerd, preventief onderhoudsbeleid. Het beleid plant preventief onderhoud na vaste operationele tijd, waardoor de kosten per tijdseenheid tot een minimum worden beperkt. Het optimum kan worden gevonden bij de laagste waarde van de doelfunctie. De doelfunctie wordt bepaald aan de hand van de verwachte kosten per cyclus en de verwachte cycluslengte. De verwachte kosten per cyclus worden berekend op basis van de kosten van preventief en correctief onderhoud en de betrouwbaarheidsinformatie van het onderdeel.

Preventief onderhoud omvat de onderhoudswerkzaamheden voorafgaand aan het falen van een onderdeel. In onze studie zal preventief onderhoud bestaan uit het vervangen van het elektrisch omzettersysteem. Correctief onderhoud omvat de onderhoudswerkzaamheden nadat het falen van een component is gedetecteerd. Beide kosten van preventief en correctief onderhoud worden bepaald op basis van bestaande literatuur.

De verstrekte betrouwbaarheidsinformatie wordt geanalyseerd en gemodelleerd in Excel. De betrouwbaarheidsinformatie bestaat uit 7 faalcategorieën waaruit de betrouwbaarheid van het elektrisch omzettersysteem kan worden bepaald. De windsnelheid gegevens van de FINO1-locatie in de Noordzee zijn gebruikt om twee van de faalcategorieën te bepalen. Alle faalcategorieën zijn per uur gemodelleerd over een periode van 25 jaar. Daarna wordt de betrouwbaarheid voor elk kwartaal van een jaar bepaald. Van de betrouwbaarheid kan de onbetrouwbaarheid gemakkelijk worden berekend en kan de verwachte cycluslengte worden bepaald.

Verder wordt de optimale vaste operationele tijd om een component te vervangen geanalyseerd doormiddel van een gevoeligheidsanalyse uitgevoerd op de onderhoudskosten. Daarnaast is het onderzoek verder uitgebreid om de optimale vervangingstijd van het rotorsysteem te bepalen.

Belangrijkste bevindingen

- Het ontworpen optimale onderhoudsplanningsmodel kan de optimale preventieve vervangingstijd bepalen voor windturbinecomponenten, doormiddel van verschillende kostenparameters en betrouwbaarheidsinformatie. Het ontworpen model minimaliseert de totale stilstand-, onderhouds- en logistieke kosten.

- Voor een preventieve onderhoudskosten van 541.213 € en correctieve onderhoudskosten van 1.230.654 € (CM/PM-kostenratio van 2,27), is een effectiviteit van 0,24% gevonden in het gebruiken van een, op leeftijd gebaseerd, onderhoudsbeleid. Het elektrisch omzettersysteem moet preventief worden vervangen na 21,75 operationele jaren met een kosten per tijdseenheid van 56,545,77 €.

- Voor het rotorsysteem blijkt de optimale preventieve vervangingstijd na 9,5 operationele jaren te zijn met een kosten per tijdseenheid van 189.052 €. De gebruikte preventieve onderhoudskosten bedragen € 924.691 en de kosten voor correctief onderhoud bedragen 1.849.382 € (CM/PM-kostenratio van 2). Exploitanten van windparken kunnen € 296.575 besparen op onderhoudskosten van het rotorsysteem gedurende de levensduur van één windturbine. E.g. voor een windpark met 50 windturbines, kunnen de exploitanten ongeveer € 15 miljoen aan onderhoudskosten van het rotorsysteem besparen.

- De optimale preventieve vervangingstijd is sterk afhankelijk van de kostenratio tussen preventieve en correctieve onderhoudskosten. De gevonden optima voor het elektrisch omzettersysteem variëren tussen 25 jaar voor een CM/PM-kostenratio van 2 en 13,25 jaar voor een ratio van 6.

- Het bepalen van de optimale vervangingstijden voor alle belangrijke componenten kan meerdere optima opleveren die dicht bij elkaar liggen en de mogelijkheid bieden om opportunistisch onderhoud uit te voeren. Het combineren van preventieve onderhoudsacties kan de totale onderhoudskosten, die tijdens de levensduur van een windturbine worden gemaakt, nog verder verminderen.

Aanbevelingen

Voor verder onderzoek:

1. Het optimale onderhoudsplanningsmodel moet worden uitgebreid met andere seizoensgebonden veranderingen, zoals meer variabiliteit in de kostenbepalingen, wachttijden en capaciteitsfactor.

2. Meer onderzoeken moet worden uitgevoerd naar de mogelijkheid om k-mean clustering te gebruiken om meer geschikte optima voor meer dan één component te vinden.

3. Een gevoeligheidsanalyse moet worden uitgevoerd op de invloed van de betrouwbaarheidsinformatie van een component op de optimale preventieve vervangingstijd.

4. Analyseer de verschillende optima van alle belangrijke componenten om zodoende een mogelijkheid te vinden om opportunistisch onderhoud uit te voeren.

5. Onderzoek de mogelijkheid om, op toestand gebaseerd, onderhoud te implementeren met behulp van conditiebewakingssystemen in windturbines.

De implementaties van de bovenstaande aanbevelingen zullen de nauwkeurigheid van het optimale onderhoudsplanningsmodel verbeteren en daarmee de waarde die eruit wordt afgeleid. Bovendien zal, op toestand gebaseerd, onderhoud nader worden onderzocht, omdat het de kosten van preventieve en correctief onderhoudsacties tot een minimum kan beperken.

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List of abbreviations

Abbreviation	Meaning
WT	Wind turbine
O&M	Operations & Maintenance
OECD	Organization for Economic Co-operation and Development
LCOE	Levelized cost of electricity
CM	Corrective maintenance
PM	Preventive maintenance
CBM	Condition-based maintenance
TBM	Time-based maintenance
OEM	Original equipment manufacturer
SCADA	Supervisory control and data acquisition
MTBF	Mean time between failure
MTTR	Mean time to repair
MTTF	Mean time to failure
ECC	Expected cycle cost
ECL	Expected cycle length
MW	Mega watt
kW	Kilo watt
kWh	Kilo watt hour
GW	Giga watt
GWh	Giga watt hour
m/s	Meter per second
CTV	Crew transfer vessel
JU	Jack up vessel
FIT	Feed-in-tariff

1 Introduction

In the following chapter, we will give an introduction for our research. We will first give a company summary for whom the research has been executed. We will then give the problem context followed by a description of the current situation. Thereafter, the proposed research questions are formulated. We will end the chapter with the scope and demarcation set for our research.

1.1 Company summary

Fraunhofer IEE is an independent institute of Fraunhofer and is situated in Kassel, Germany. IEE stands for institute for energy economics and energy system technology. Previously it was one institute with Fraunhofer IWES which focuses on validation of wind turbine technology. Fraunhofer is the biggest research institute for applied research in Europe with around 20.000 researchers and a budget of 1,8 billion euro. Fraunhofer IEE is conducting research for the national and international transformation of energy supply systems. They develop solutions for technical and economic challenges in order to further reduce the costs of using renewable energies, to secure the supply despite volatile generation, to ensure grid stability at the usual high level and to make the business model of the energy transition a success.

Fraunhofer has been gathering and analyzing data concerning failure behaviors of wind turbines for several years. They have been working on a project named “WInD-Pool”. This is a joint database of operators in the wind energy industry. The collected data is structured using industry standards after which performance assessment and benchmarking of the industry is made. For this purpose, advice concerning the performance of wind farms can be given to the operators. Furthermore, it enables the determination of reliability characteristics and failure behavior of the wind farms, wind turbines (WTs), and its components.

The executed research will focus on the possibilities in the wind farm industry to reduce the maintenance costs of WT. Operation and maintenance costs have a big share on the total costs incurred to build and operate a power plant, such as a WT. This results in a higher price that must be obtained per kilowatt hour produced, over the lifetime of the WT. With the use of the extensive database and the failure behavior of components, maintenance of wind turbines can be optimally planned by using reliability of its components.

1.2 Problem context

Over the past few years the wind power industry has encountered a large growth. The growth is mainly focused on the development of larger WTs, maximum capacity and the size of offshore wind farms. The maximum capacity generated by a WT has grown as big as 9MW, but next generation turbines will fall between 12 and 15 MW (Merchant, 2018). Bigger turbines are mostly situated farther from shore to access higher wind speeds. However, the reliability and availability of WTs involve high level of uncertainty, which require extensive planning effort. Due to accessibility of the turbine, maintenance services are often difficult and expensive. Most operators have full-service contracts with the original equipment manufacturer. During the duration of these contracts or warranty periods, manufacturers are obliged to take on the service costs of the WT. These contracts tend to be expensive and large wind farm operators increasingly bring more service elements in-house (Global wind services market, 2017). As the trend towards self-operation by operators increases (IRENA, Renewable Power Generation Costs in 2017, 2018), an influx of researches into the reliability and maintenance management of WTs can be observed.

Whether the operator chooses for a service contract or to conduct the maintenance themselves, the maintenance costs are part of the operation and maintenance costs (O&M costs). The O&M costs consist of variable and fixed costs. The fixed O&M costs typically include insurance, administration, fixed grid access fees and service contracts for scheduled maintenance. Variable O&M costs typically include scheduled and unscheduled maintenance not covered by fixed contracts, as well as replacement parts and materials, and other labor costs (IRENA, Wind Power, renewable energy technologies: cost analysis series, 2012).

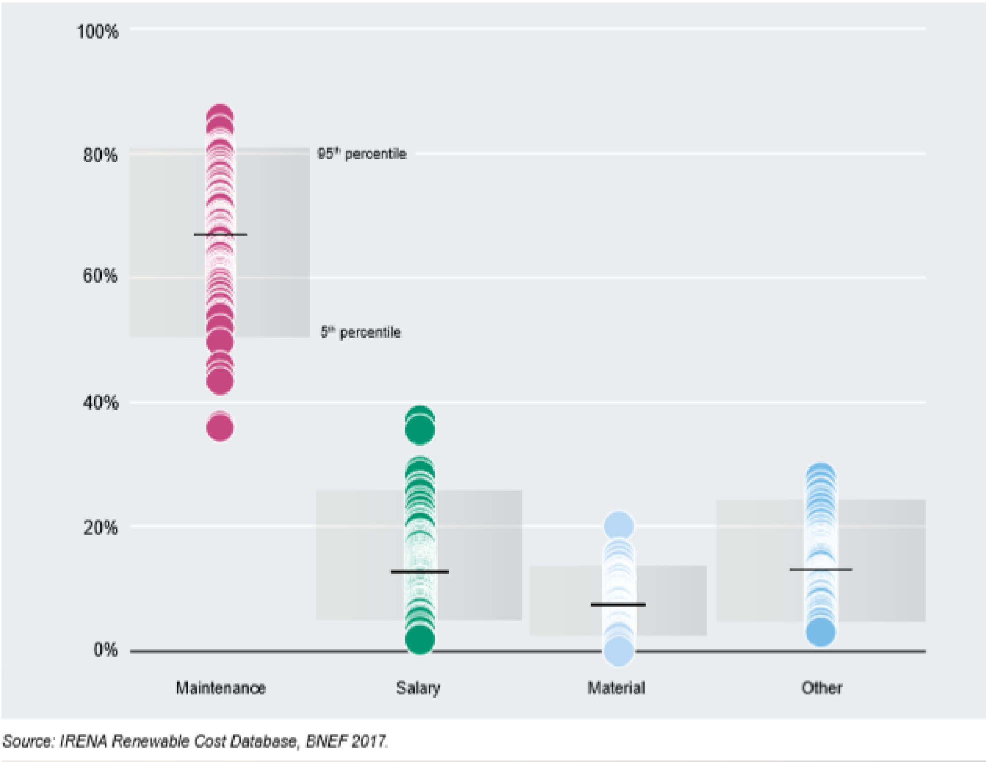

Figure 1-1: O&M cost breakdown

The costs of maintenance consist of around 67% of the total O&M costs (IRENA, Renewable Power Generation Costs in 2017, 2018). Maintenance costs are followed by labor cost, which have a share of 14% of the total O&M costs, and materials at 7%. These numbers are depicted in Figure 1-1. For OECD countries, the average O&M costs for onshore WTs tend to be between 0,02 USD/kWh and USD 0,03/kWh (approximately 30 to 47 USD/kW/year). However, O&M costs for offshore WTs are significantly higher than those of onshore WTs. This is mainly the consequence of the higher cost of accessing the site and performing maintenance actions. Crew and vessels used for these maintenance actions are expensive and tend to have high day rate, and a high mobilization cost to access the site. This is due to the marine environment which is a much harsher environment to operate in compared to dry land. In Europe the O&M costs for offshore WTs are estimated to be between 109 USD/kW/year and as high as 140 USD/kW/year (IRENA, Renewable Power Generation Costs in 2017, 2018). Therefore, our research will merely focus on offshore WTs because it is to be expected that more opportunity to decrease the high maintenance costs is to be found here.

Furthermore, the O&M costs in turn tend to have a share of 20% to 30% of the levelized cost of electricity (LCOE) (IRENA, Renewable Power Generation Costs in 2017, 2018). The levelized cost of electricity is the average price that a generating asset must receive in a market to break even over its lifetime. In this case, the generating asset is the WT and the average lifetime is between 20 and 25 years. In other words, the LCOE measures all the costs incurred during the lifetime of the WT divided by the returns obtained from the energy produced.

It is important to realize that not only the costs of maintenance actions have a big influence on the LCOE but the effects of the maintenance actions too. Implementing a good maintenance policy will prevent failures of components or subsystems which in turn will reduce the downtimes of WTs. Consequently, the WT will have a higher availability or up-time which will provide more revenue and thus achieving a lower LCOE. In conclusion, both the maintenance costs, as well as the loss in revenues play an important role in reducing the LCOE.

Different types of maintenance actions are being executed on WTs. Corrective maintenance (CM) is executed after a failure of a component or subsystem and is intended to put the item into a state in which it can perform its required function. Also, preventive maintenance (PM) is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of a failure or the degradation of the functioning item (BSI Standards Publication: Maintenance - Maintenance terminology, 2010). Additionally, preventive maintenance can sometimes avoid highly expensive corrective maintenance actions and avoid downtimes of the WT. Some maintenance may be small and frequent (e.g. replacement of small parts, periodic inspections, etc.) while other maintenance may be large and infrequent (e.g. unscheduled repair of significant damage or the replacement of principal components).

1.3 Current situation

As previously discussed, the maintenance costs have a big share in the O&M costs. This is due to the maintenance policy which is currently maintained. According to Fraunhofer a mix of PM and CM is used which can be described as an experience-based maintenance policy. Currently, maintenance actions are executed according to pre-determined time intervals based on previous failure behavior of components or specified by the manufacturer. However, the time intervals between maintenance actions can be optimized which will result in higher availability of the WT and possibly a decrease of the total maintenance costs.

There are different categories which can cause a failure. In the following referred to as failure category. Different failure categories exist e.g.: wind gusts, icing, lighting, overload, wear out, random, early or aging failure. Some failure categories are due to external modes e.g.: weather conditions, which we cannot influence. However, other failure categories can be caused by internal modes e.g.: aging failure, early failure, and wear-out failure. These can be influenced by the maintenance policy that the service provider currently maintains. By conducting PM, the WT and the components can be preserved and restored before a failure actually occurs. Not all failures can be avoided by using a PM policy and some CM actions will still take place.

When a failure occurs, maintenance actions are conducted to repair the WT. Commonly maintenance actions can be categorized in four groups: reset, minor, major and replacement (IEA wind task 26, 2016). These different categories will be explained in section 2.3.1. The total downtime with a reset is usually a few hours, while the total downtime with a replacement can take up to a few weeks. These differences should be taken into account while planning PM and determining the optimal policy. Preferably, the maintenance with long downtime of the WT is to be minimized because they are responsible for the majority of the maintenance costs.

In conclusion, the core problem is that the maintenance policy does not consider the failure behavior of components which may affect the LCOE significantly. An overview of all the problems and their relationships is described in Figure 1-2: Problem clusterFigure 1-2. The core problem is tinted in green.

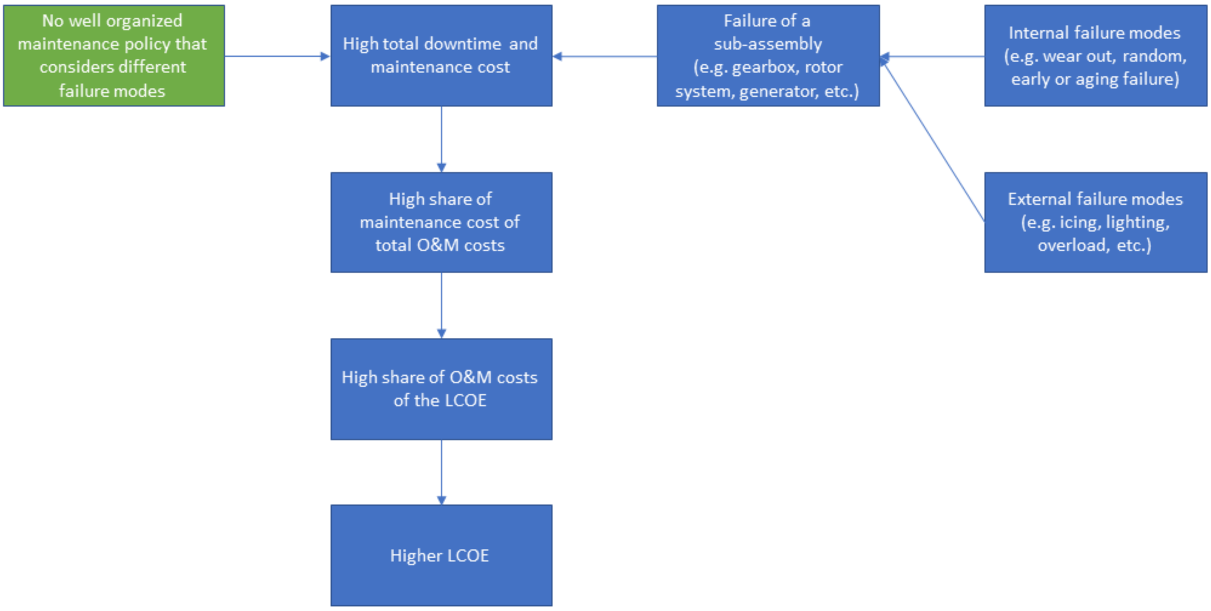

Figure 1-2: Problem cluster

1.4 Research goals

As previously discussed, the core problem is that the maintenance policy does not consider the failure behavior of components and therefore long downtimes of wind turbines with high maintenance costs are observed which inadvertently results in a higher LCOE. The main research question follows from this core problem.

How can maintenance of wind turbines be planned by using reliability information of components such that total downtime, maintenance, and logistics costs are minimized?

To be able to answer this main research question, sub questions and knowledge questions need to be formulated.

1. How can the maintenance of wind turbines be characterized? Can it be modeled by using a well-known maintenance policy? If so, how can the optimal parameters of the selected policy be calculated with the use of failure behaviors?
    a. What component of the WT should we focus on?
    b. What are the different types of maintenance actions and what are their corresponding costs?
2. What is the influence of different maintenance cost configurations on the optimal maintenance policy?

1.5 Scope and demarcations

To ensure that the research is feasible within the given time restriction, it is necessary to define the scope and the demarcations of the research. We define the scope such that the research can be done within 10 weeks. In this chapter the scope of the research and the set demarcations shall be discussed.

In our research, we will merely focus on offshore WTs. Offshore WTs can be much bigger in size compared to on-shore WTs because they are not limited by space constraints. Those WTs can generate more power thanks to the higher wind speeds measured offshore and the size of the blades. Compared to onshore WTs, offshore WTs usually tend to have a lower reliability and higher maintenance costs due to accessibility of the turbine (IRENA, Wind Power, renewable energy technologies: cost analysis series, 2012). In our research, we will analyze a 5MW offshore WT. The specification of the 5 MW WT can be found in appendix A.

To conduct our research, we have used existing wind speed data of an offshore location situated in the North Sea. In January 2002, the federal government of Germany decided on the construction of three research platforms (FINO1, FINO2, FINO3). These sites were potential sites for the development of wind farms. The wind speed data used are those of the FINO1 location. We will use the FINO1 location to estimate the costs of PM and CM in section 3.3.

Furthermore, while calculating the optimal maintenance policy, we will only focus on one component of the WT. The component choice is discussed in section 2.1. We will use an approximate evaluation model based on discretizing time to be able to calculate the optimal maintenance schedule of this particular part. This model can eventually be expended to other components or sub systems by adjusting the failure behaviors of the component.

Moreover, the found optimal fixed operational time to schedule PM will be compared to the benchmark policy operators currently adhere to. Currently, operators do not use PM to replace components prior to a failure. Therefore, the maintenance policy they adhere can be considered to be solely CM and thus components are only replaced upon failure. The benchmark policy will be determined using the MTTF of components and will be explained in section 3.5.

The LCOE and the total O&M costs will not be determined. There are too many unknowns to amount to a good approximation and therefore these costs indicators will be left out of the research. However, the total maintenance costs and the total downtime costs will be used to give an impression of the improvements the optimal policy yields.

2 Theoretical framework

In the following chapter, we will use existing literature to answer some of our research questions and to underpin several choices that we have made during the execution of the research. We will first discuss what component to focus on. We will then explain some basic statistical knowledge and the two most important distributions, followed by the explanation of the optimal maintenance policy. Moreover, we discuss the maintenance cost structure and make a distinction between preventive and corrective maintenance. We will end this chapter with the assumptions and limitations of the optimal maintenance planning model.

2.1 Component choice

There are different types of WTs with varying designs, advantages and disadvantages. The most common type is the horizontal axis WT as depicted in Figure 2-1. A typical WT will contain up to 8000 components. The main components are the generator system, yaw system, blade/pitch system, gearbox system, converter system, rotor system and several other systems. In Figure 2-1, the main components are indicated with numbers. We will briefly explain some components and their functions. The converter (number 13) and transformer (number 14) indicated below can also be installed in the tower instead of in the nacelle.

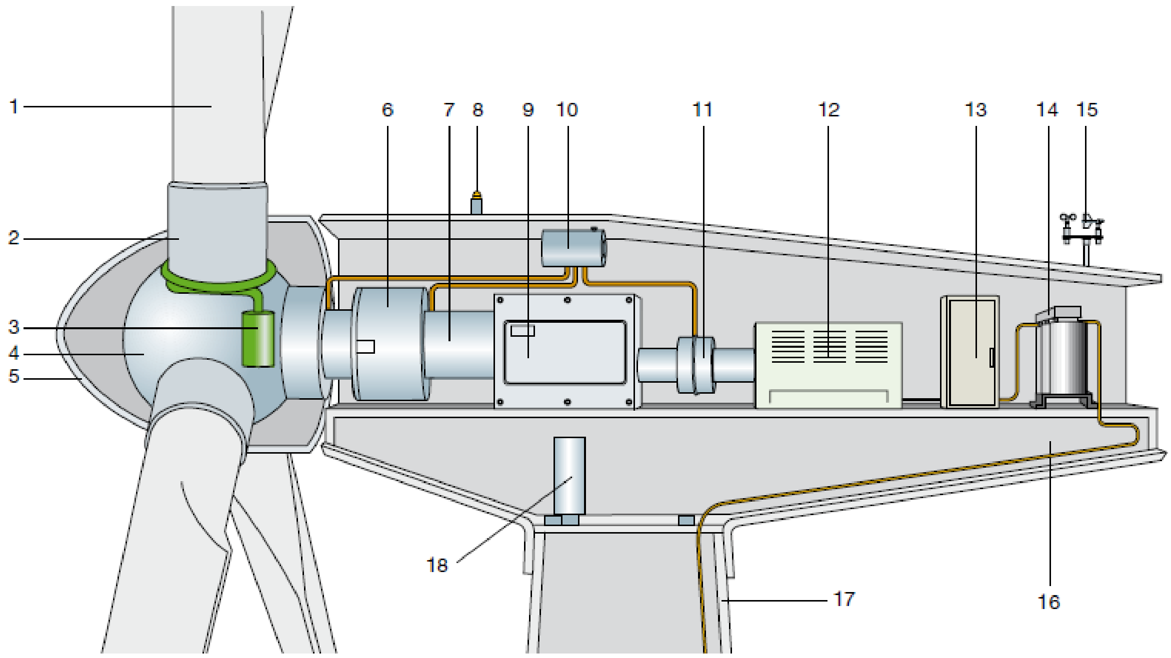

Figure 2-1: Main components of a WT

The main components of a WT are shown in Figure 2-1and their functions (EWEA, 2017) are:

1. **Blade**
2. **Blade support**
3. **Pitch angle actuator** adjusts the angle of the blades to make the best use of the prevailing wind
4. **Rotor hub** is made from cast iron and it holds the blades in position as they turn
5. **Spinner**
6. **Main support**
7. **Main shaft** transfers the rotational force of the rotor to the generator
8. **Aircraft warning lights**

9. **Gearbox**, the gears increase the low rotational speed of the rotor shaft in several stages to the high speed needed to drive the generator
10. **Mechanical brakes**, disc brakes bring the turbine to a halt when required
11. **Hydraulic cooling devices**
12. **Generator** converts mechanical energy into electrical energy. Both synchronous and asynchronous generator are used
13. **Power converter and electrical control**, protection and disconnection devices. Power converter converts direct current from the generator into alternating current to be exported to the grid network
14. **Transformer** converts the electricity from the turbine to higher voltage required by the grid
15. **Anemometers** measures the wind speeds
16. **Frame of the nacelle**
17. **Supporting tower**
18. **Yaw driving device**, mechanisms that rotates the nacelle to face the changing wind direction

A failure of the WT can be caused by one or several components. Some components cause more failures of the WT then others. According to Fraunhofer (M.Lutz, 2017), and shown in Figure 2-2, the rotor system, converter and control system have the biggest share on the failures. These components also have a high share on the mean time to repair. Perhaps the most important and interesting part is the fact that the converter and rotor system have the biggest share on the annual downtime.

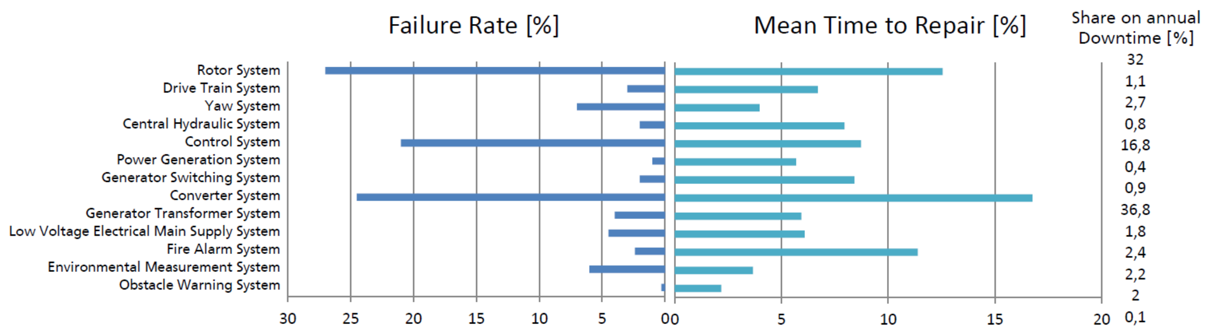

Figure 2-2: Share on annual failure rate, MTTR and downtime (M.Lutz, 2017)

According to Zhao, Li, Dong, Kang, Lv and Shang (2017), as shown in Figure 2-3, the generator and converter system have the biggest share on the annual downtime of WT. There is however a difference in the data used by Fraunhofer and Zhao which explains the discrepancy between the results. Zhao used data collected from the widely available supervisory control and data acquisition (SCADA) system of two different wind farms in China. On the contrary, Fraunhofer has a broader categorization of components compared to Zhao et al. (2017) and other researches. It can be seen that Fraunhofer makes a distinction in several generator components and systems whereas this is not the case in Zhao research. Nevertheless, we can see that the converter system has one of the biggest shares on the annual downtime of the WT.

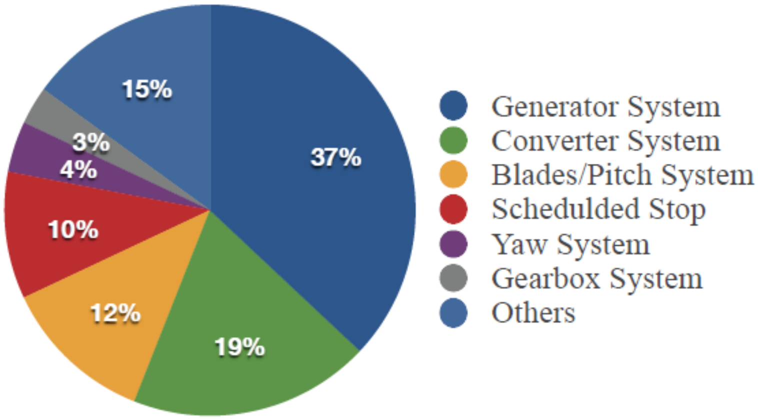

Figure 2-3: Percentage of downtime per component for two wind power plants in China (Zhao et al, 2017)

As discussed in the introduction, not only do O&M costs have an influence on the LCOE but also the observed downtime of WTs. We will make a distinction between the total PM and CM costs in section 3.3. However, for now, it is important to note that the downtime costs will be accounted for in the total PM and CM costs. Obviously, components with a big impact on the failures and long downtime of the WT are the most interesting for our research. Conducting PM activities can avoid unnecessary failures and thus decrease the downtime of the WT. Combining the above and after consultation with Fraunhofer, we have chosen to research the optimal maintenance policy for the converter system.

2.2 Maintenance policy

Maintenance is defined "as the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (BSI standards publication, 2010). Maintenance is crucial for heavy and capital-intensive industries to keep their machinery and equipment in good operating condition. Many different types of maintenance policies are available with each their own benefits and drawbacks. Some maintenance policies are better suited for some components and others for the overall system. After consultation with my supervisor and Fraunhofer, we have chosen to use the optimal aged-based replacement (type 1 policy) which will be explained in section 2.2.4.

2.2.1 Terminology

First, three important definitions frequently used in maintenance concepts and methodology are to be explained.

Availability is defined as the probability that an item will perform its required function under given conditions at a stated instant of time (Scheu, Kolios, Fischer & Brennan , 2017). Logically, positive financial turnover can only be encountered in periods of availability. It must be noted that availability rests on other important factors such as reliability, maintainability and accessibility. Availability can be expressed with an equation if the mean time between failures (MTBF) and mean time to repair (MTTR) is known. We will not use this specific equation because we do not possess actual data of the up and downtimes of WT's. We would like to refer the reader to Ostachowicz, McGugan, Hlnrichs & Luczak (2016) and Tinga (2013) for the equation of availability.

Maintainability refers to the relative ease and efficiency of performing tasks associated with machine maintenance, including both routine service and unplanned repairs (Walford, 2006). Maintainability can also be expressed with the probability of achieving an objective (repair, replacement, etc.) within a given time.

In the English vocabulary, accessibility is defined as the fact of being reached or obtained easily. As previously explained, the accessibility of offshore WTs are more difficult than onshore WTs because of the harsher marine environment, and the vessels needed to access the site.

In our study, we will not make use of the three definitions and equations above. However, these definitions are often used in maintenance practices and concepts and it is thus important to know their definitions.

2.2.2 Lifetime probability distributions and statistics

To be able to understand how our maintenance policy works, we first need to explain some distributions and statistical concepts. This will help us understand the different failure modes addressed in section 3.1.

A failure is the termination of the ability of an item to perform a required function (BSI Standards Publication: Maintenance - Maintenance terminology, 2010). With adequate data it is possible to show that, on the average, a component fails after a certain given time. This is called the failure rate and it is often used in reliability engineering. It can be expressed with the Greek letter, λ (lambda). Probability distributions are used to model the failure behavior of e.g. components. Failure rates commonly depend on time and vary during the life cycle of the component or system. Thus, the failure rates are usually not constant and are mostly shaped as the bathtub curve (Scheu et al., 2017) as depicted in Figure 2-4. This implies that in the early stage components encounter a decrease in the failure rate. However, an increase in the failure rate is observed in a later stage, which is named aging failure.

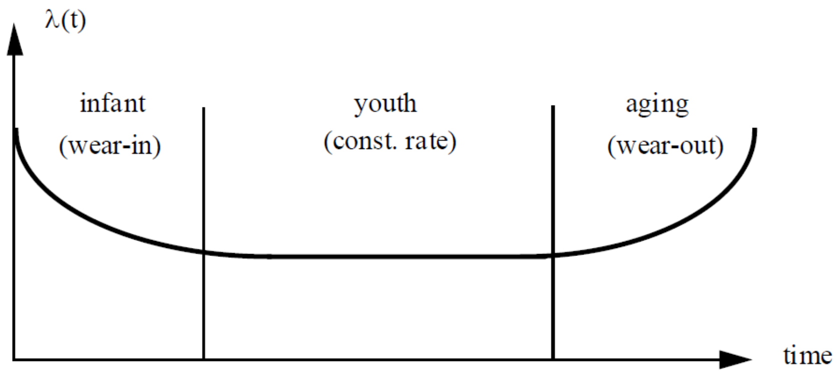

Figure 2-4: Bath-tub curve (Scheu et al., 2017)

A random variable is a numerical description of the outcome of an experiment whose value depends on chance, i.e., whose outcome is not entirely predictable (Reddy, 2011). There are mainly two types of random variables. A discrete random variable is a variable that can only take a finite or countable number of values (e.g. a coin with heads and tails). On the contrary, a continuous random variable is a variable that may take on any value in an interval (e.g. temperature).

The probability of a variable taking on different values is represented by the distribution functions of the random variable. We will discuss two examples and make a distinction between a probability density function and a cumulative distribution function (resp. PDF and CDF). Depending on whether a random variable is discrete or continuous, one will get a discrete or continuous probability distribution.

In Figure 2-5, we see the probability functions of a discrete random variable involving the outcomes of a rolling dice. The first histogram (Figure 2-5a) represents the probability of the dice taking on a certain value which is called the probability density function (PDF) and denoted with f(x). The Y-axis represents the probability and the X-axis represents the value of the dice. Thus, the probability of a dice taking on the value “3” is 1/6.

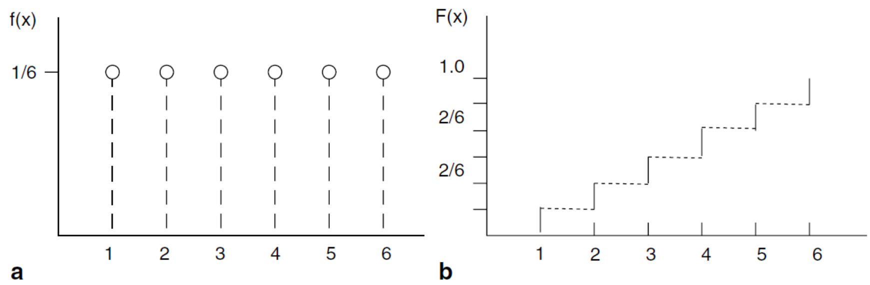

Figure 2-5: PDF and CDF of a discrete random variable (Reddy, 2011)

In Figure 2-6, we see the probability functions of a continuous random variable. However, for a continuous random variable it is implausible to determine the probability that the outcome will be a certain value e.g. 57,5°F. The probability that the value will be within a certain range, e.g. between 55°-60°F, can be determined by calculating the area under the PDF curve, as shown in Figure 2-6b. It is for the continuous random variables that the CDF becomes useful, denoted with F(x). The CDF is simply the area under the PDF curve starting from the lowest value up to the desired value. This is illustrated in Figure 2-7. With such a CDF plot, it is easily to determine the probability that the temperature will be less than 60°F.

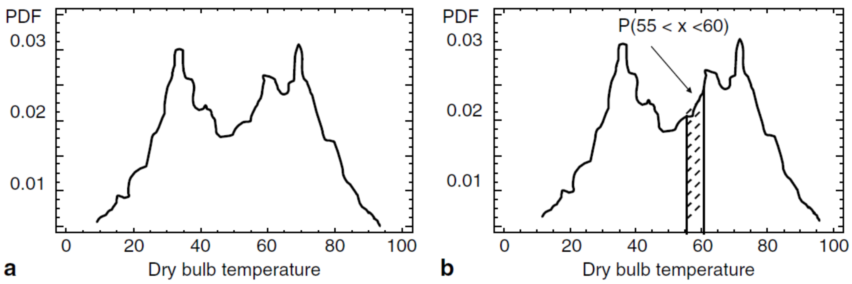

Figure 2-6: PDF of a continuous random variable (Reddy, 2011)

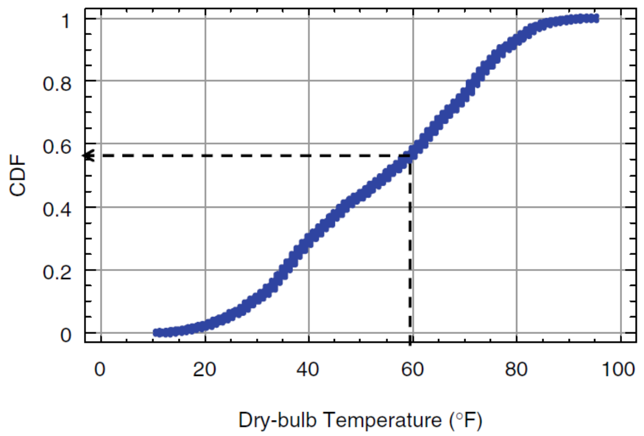

Figure 2-7: CDF of a continuous random variable (Reddy, 2011)

Provided a derivative exists, the inverse relationship between f(x) and F(x) is as followed.

$$f(x) = \frac{dF(x)}{dx} \qquad \textbf{(1)}$$

Asset reliability is defined as the “The ability of an item to perform a required function under stated conditions for a given time interval” (Igba, Alemzadeh, Durugbo & Henningsen, 2015). Reliability is expressed as a probability value (a value between 0 and 1) and is denoted with R(x) or $\bar{F}(x)$. The reliability can be calculated with the use of the PDF. The sum of all the possible outcomes of the PDF must be equal to 1 and cannot be negative.

With the use of the PDF, the probability that an item will fail within a certain time interval can easily be calculated with the knowledge above. Now, the continuous random variable is the variable time. So, calculating the probability that an item will fail up to a given point in time is the area under the PDF curve. Knowing that the sum of all possible outcomes must be equal to 1, the probability that an item will survive up to that given point in time, is simply 1 subtracted by the probability of a failure. The equation of reliability is as followed and illustrated in Figure 2-8.

$$R(t) = 1 - F(t) \qquad \textbf{(2)}$$

Note that the “x” in the equation has been replaced with “t” due to the random variable now being time, which is denoted by t. The reliability can also be calculated from the failure rates with the following equation:

$$R(t) = e^{-\int_0^t \lambda(t)dt} \qquad \textbf{(3)}$$

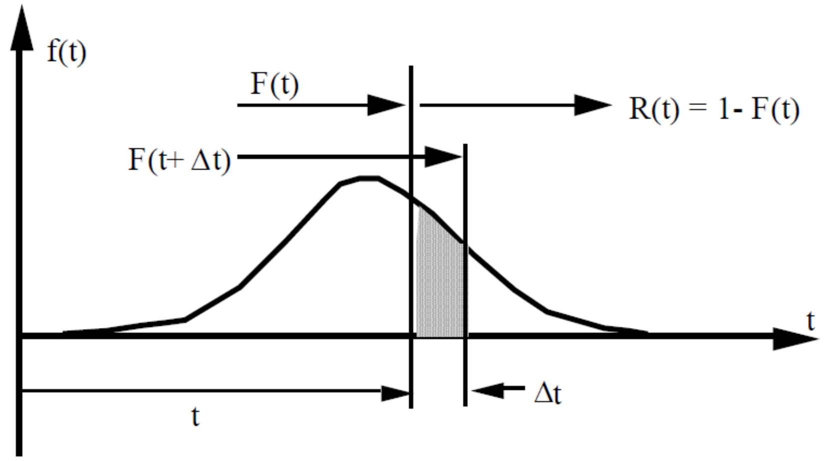

Figure 2-8: Reliability calculated from the PDF

Where R(t) represents the reliability, F(t) can also be described as the unreliability of a component. However, what is more commonly used is the failure rate function or the so-called hazard function denoted with λ(t). Given that the component has survived until time t, the hazard function represents the probability of a failure per unit time t. It can be expressed with the following equation:

$$\lambda(t) = \frac{f(t)}{R(t)} \quad \textbf{(4)}$$

Finally, the MTTF describes the mean time expected until the first failure for a non-repairable system. MTTF can be determined from the reliability using the following equation:

$$MTTF = \int_0^{\infty} R(t)dt \quad \textbf{(5)}$$

2.2.3 Exponential and Weibull distribution

Consequently, we need to discuss two types of distribution often used in reliability engineering. As discussed above, we can calculate the failure rate and the probabilities of a failure after a given time t. Depending on the failure rate, one distribution is more suitable then another.

2.2.3.1 Exponential distribution

Assuming we are dealing with a constant failure rate, we can use the exponential distributions to determine the probability of a failure. Components with a constant failure rate are simply components that do not degrade as time continues. In fact, the exponential distribution is a special case of the Weibull distribution with a shape parameter of 1 (β=1). We will discuss the Weibull distribution and its characteristics later on. The exponential distribution is useful to calculate the remaining useful life of a component. The PDF of the exponential distribution is as followed.

$$f(t) = \lambda e^{-\lambda t} \quad \text{for } 0 \leq t \leq \infty \quad \textbf{(6)}$$

In Figure 2-9, we can see the exponential probability distribution function for various values of λ.

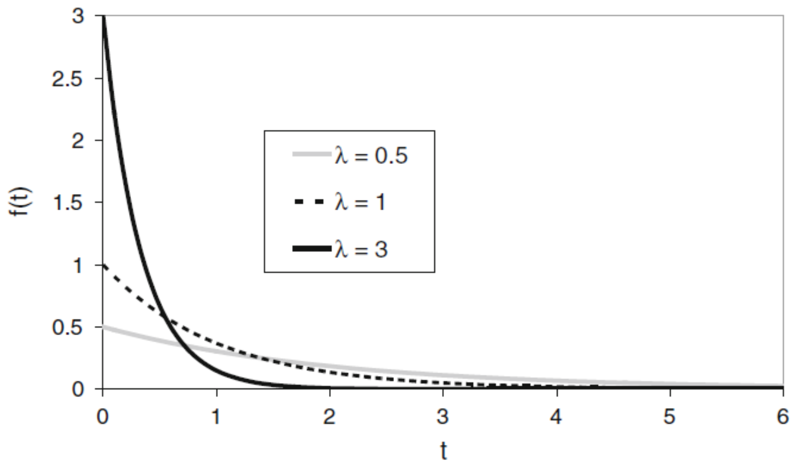

Figure 2-9: Exponential probability distribution functions

The CDF of the exponential distribution is as followed.

$$F(t) = 1 - e^{-\lambda t} \qquad (\mathbf{7})$$

The reliability can now be calculated and is as followed. The exponential reliability functions for various values of λ are depicted in Figure 2-10.

$$R(t) = 1 - F(t) = e^{-\lambda t} \qquad (\mathbf{8})$$

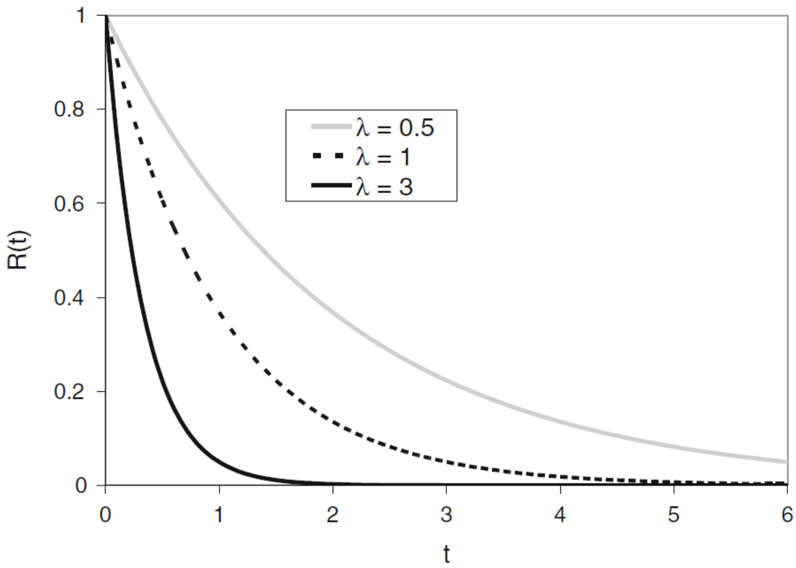

Figure 2-10: Exponential reliability functions

Combining equations (6) and (8), the Hazard function will yield the following:

$$\lambda(t) = \frac{f(t)}{R(t)} \qquad (\mathbf{9})$$

2.2.3.2 Weibull distribution

The Weibull distribution has wide range of applications in reliability calculation due to its flexibility in modeling different distribution shapes. In addition to being the most useful distribution function in reliability analysis, it is also useful in classifying failure types, trouble shooting, scheduling preventive maintenance and inspection activities (Vermat, Ajit, Karanki, 2016). The Weibull distribution has two parameters, α and β (scale and shape parameters). Thanks to the scale and shape parameters, several other distributions can be modelled. The PDF of the Weibull distribution is as followed.

$$f(t) = \frac{\beta}{\alpha}(\frac{t}{\alpha})^{\beta-1}e^{-(\frac{t}{\alpha})^{\beta}} \qquad \textbf{(10)}$$

In Figure 2-11 we can see that the Weibull PDF takes on different shapes according to the shape parameter β.

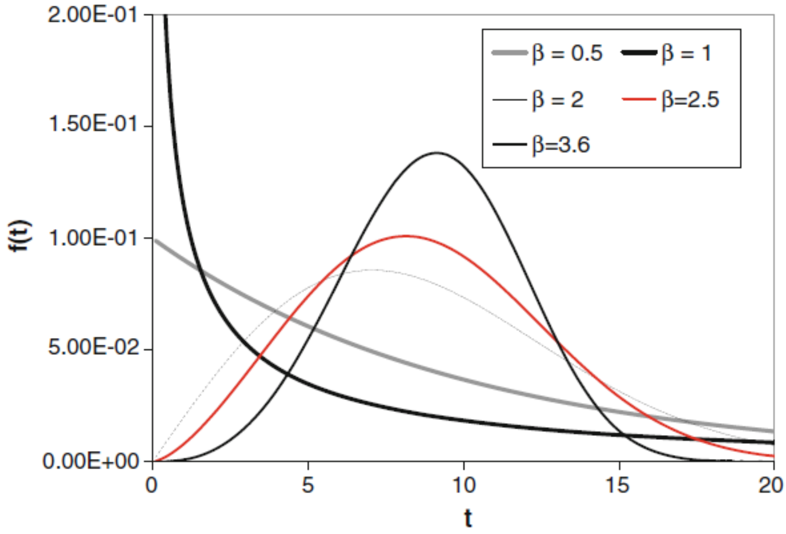

Figure 2-11: Weibull PDF

The Weibull CDF and reliability function are as followed. The Weibull reliability functions for various shape parameter β are depicted in Figure 2-12

$$F(t) = 1.0 - e^{-(\frac{t}{\alpha})^{\beta}} \qquad \textbf{(11)}$$

$$R(t) = e^{-(\frac{t}{\alpha})^{\beta}} \qquad \textbf{(12)}$$

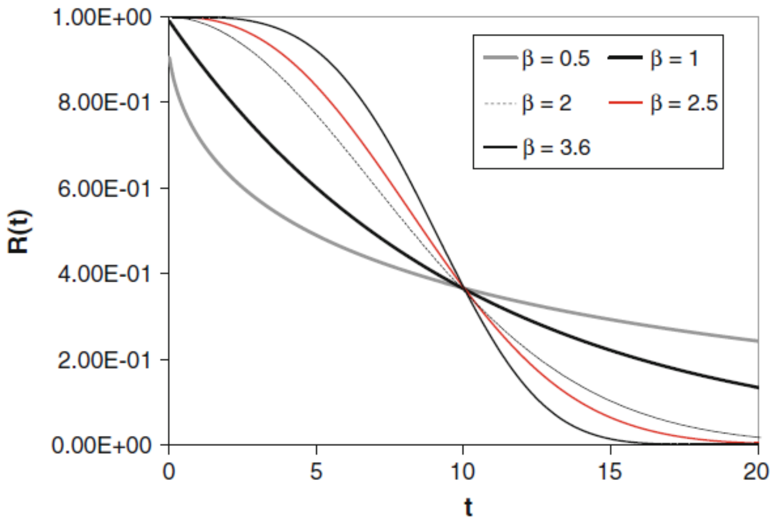

Figure 2-12: Weibull reliability

The Weibull hazard function is as followed and is shown in Figure 2-13 for various shape β parameters.

$$\lambda(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \quad \textbf{(13)}$$

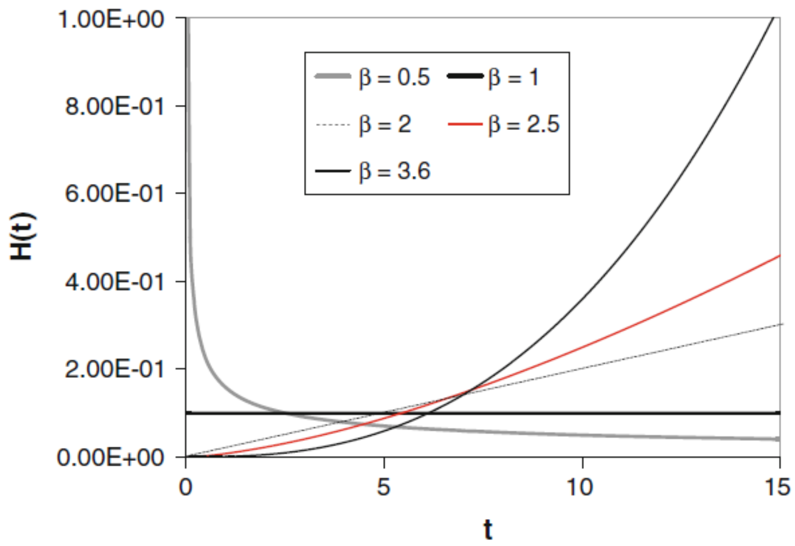

Figure 2-13: Weibull hazard function

Taking into consideration the bath-tub curve discussed at the beginning of this chapter, the three bath-tub regions can be represented with the Weibull distribution and varying β values.

β < 1 results in decreasing failure rate (burn-in period)

β = 1 results in constant failure rate (useful life period)

β > 1 results in increasing failure rate (Wear-out period)

2.2.4 Optimal age-based preventive maintenance policy

Two distinctive maintenance strategies can broadly be classified as corrective and preventive maintenance (Galambos, Galambasova, Rataj & Kavka , 2017). CM is executed only when a system or component has failed and needs replacement or repair. In some cases, systems can continue working when a failure of a component has occurred due to installed back-up components or due to the importance of the component itself. WTs are very complex systems where a failure of a component can have severe consequences such as damage to other components or subsystems. But for us the most important part is that the failure of a component can also have economic consequences such as expensive maintenance costs due to accessibility of the WT, labor hours, costs of spare parts or loss in revenue caused by the downtime.

PM involves maintenance activities prior to the failure of the system or component. However, the optimal moment of replacement is often hard to determine. One of the main objectives is to reduce the failure frequency or the downtime of the system or component. PM contributes to minimizing failure costs and machine downtime (Galambos, Galambasova, Rataj & Kavka , 2017). This strategy can be based on the Original Equipment Manufacturer (OEM) recommendations. This is suitable for some PM activities such as lubrication, oil changes, filter cleaning and so on. In our case, PM will involve the maintenance action of replacing a component prior to a failure, even though the component has not reached the end of its life cycle. However, we will first explain the different types of PM policies.

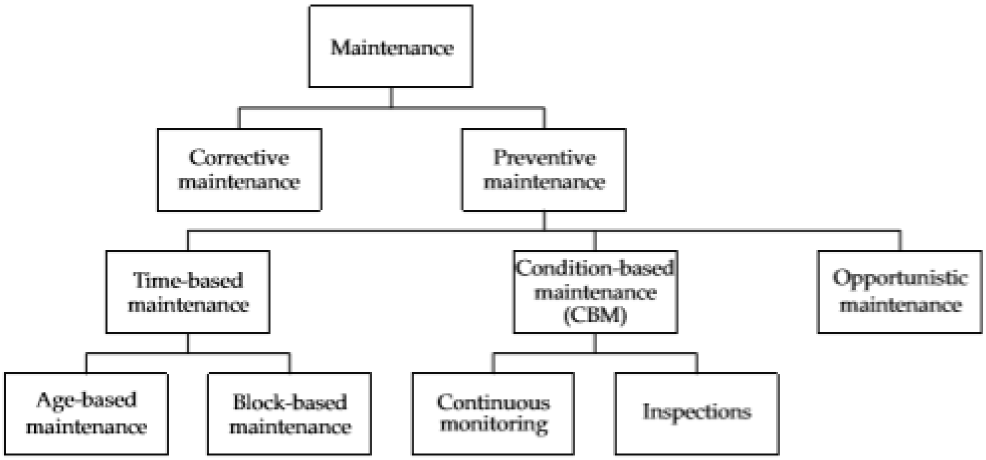

Figure 2-14: Schematic overview maintenance policies

Generally, there are three types of PM policies: time-based maintenance (TBM), condition-based maintenance (CBM), and opportunistic maintenance. These are depicted in Figure 2-14. Opportunistic maintenance is a form of PM and it is based on the opportunity to perform PM actions by taking advantage of planned or unplanned maintenance. Thus, while CM or PM is performed, and suitable maintenance resources are already at location, opportunistic maintenance can be performed on other components or systems. As opportunistic maintenance is not a maintenance policy which can be used to determine the scheduling of PM actions, we will further look into CBM and TBM policies.

CBM is typically used when there is a higher degree of uncertainty in the deterioration models, thus in the lifetime of the component or system (Wind farm data collection and reliability assessment for O&M optimization, 2017). Maintenance decisions are based on information of the actual condition or health of the component or system. This information can be obtained from health or condition monitoring systems. However, applying CBM, is only possible if there are conditions that are related to the moment of failure and if it is technically possible to monitor these conditions (Jonge, 2017). Due to time restriction and availability of data, we have decided not to focus on CBM but on TBM policies.

TBM is carried out in accordance to a pre-determined time schedule. We can make a distinction between two types of TBM policies, namely age-based and block-based maintenance. Under block-based maintenance policy, PM is scheduled after a fixed interval with length T, depicted in Figure 2-15b. If a failure occurs during this fixed interval, CM is performed. However, these failures do not influence the PM schedule thus the fixed interval will remain the same. The disadvantage of this policy is that PM is sometimes scheduled shortly after an expensive CM has been performed on the system or component. The main advantages are the easier planning of PM and the clustered maintenance actions when the same block-based maintenance is applied to multiple units (Jonge, 2017). As there is a substantial cost difference between PM and CM actions, block-based maintenance might be very costly over the lifetime of a WT. Therefore, we have decided to focus on an age-based policy.

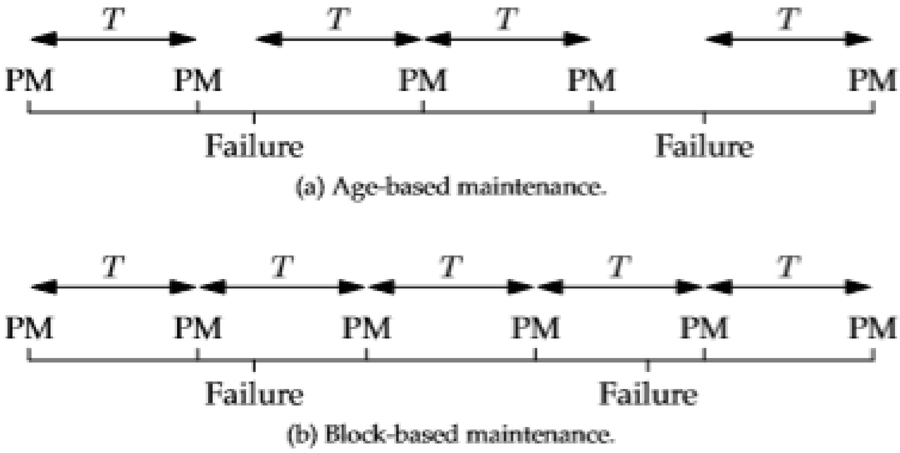

Figure 2-15: Scheme of time-based maintenance policies

As explained in section 2.1, we will only focus on one component of the WT. A commonly used PM policy to determine the optimal PM interval for a single component is the age-based preventive maintenance policy (type-1 policy). Additionally, this policy yields the possibility to be extended and to take into account several components so that an optimal PM interval can be determined for more than one component. Thus, we will use an age-based preventive maintenance policy to analyze our problem and determine the optimal maintenance policy. An age-based preventive maintenance policy is defined as a maintenance policy which performs PM after fixed operational time T (e.g. hours, days, months, years, etc.) without a failure. T can be finite or infinite. In case that T is infinite, no PM will be scheduled. If the system fails prior to operational time T, CM will take place, and the PM is rescheduled after T operational time. In this policy, the system is assumed to be "as good as new" after PM or CM (Sultana & Karim, 2015). The policy is illustrated in Figure 2-15a.

The age-based policy is useful when the failure rate function of the system or component is increasing. Additionally, the costs of PM must be (much) smaller than the costs of CM. If the costs of PM and CM would be equal or close to each other, the policy would yield to not do any PM and wait until a failure occurs.

The objective function g(T) of the age-based policy is the expected cost per unit time. It can be obtained from the ratio between the expected cycle cost (ECC) and the expected cycle length (ECL).

$$g(T) = \frac{Total\ expected\ cost\ per\ cylce\ (ECC)}{Expected\ cycle\ length\ (ECL)} \qquad \textbf{(14)}$$

The total ECC can be determined with the costs of CM and PM and the probabilities of a failure. The ECC is calculated as shown below.

$$\mathrm{ECC} = \mathrm{Co}\bar{\mathrm{F}}(\mathrm{T}) + \mathrm{C1F}(\mathrm{T}) \qquad \textbf{(15)}$$

T represents the fixed operational time as previously discussed. Furthermore, the theory stated above uses $\bar{F}(T)$ to represent the reliability. However, the reliability can also be denoted by R(T). C_0 are the costs of PM and are incurred if the system does not fail before operational time T. The probability of this happening is equal to the reliability at time T. Thus, the probability of C_0 is 1-F(T)= $\bar{F}(T)$. If the system does fail before time T, the costs of CM will be C1. The probability that the system fails prior to time T is F(T).

The ECL is calculated as followed.

$$ECL = \int_0^T tf(t) + T\bar{F}(T) \qquad \textbf{(16)}$$

The time until a failure is denoted with the random continuous variable X and distribution function F(x). PM is executed when X ≥T, thus when the time until a failure exceeds the fixed operational time T. In other words, no failure will occur before the fixed operational time T. The cycle length is then T with probability $\bar{F}$(T). CM is executed when X <T in which case a failure will occur before the fixed operational time T. The cycle length will then be X with probability density f(t). ECL can also be calculated with partial integration which yields the following formula:

$$ECL = \int_0^T \bar{F}(t)dt \qquad \textbf{(17)}$$

The ECL is actually the area under the reliability curve from 0 to time T. To ensure that we come to a good approximation of the ECL we use the trapezoidal rule to compute the area. This implies that we compute the total area by calculating small areas under the curve and finally sum these up. An example of the trapezoidal rule is depicted in Figure 2-16. The equation is as followed.

$$\int_0^T h(t)dt \approx \sum_{i=1}^{n} \frac{1}{2}\big(ti - t(i-1)\big)\{h\big(t(i-1)\big) + h(ti)\} \qquad \textbf{(18)}$$

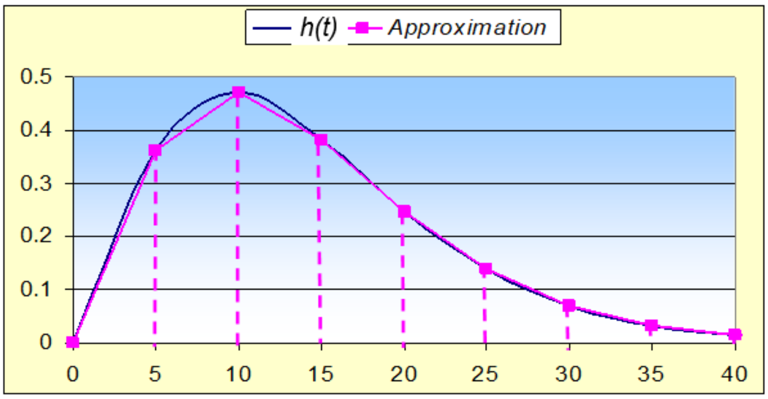

Figure 2-16: Trapezoidal rule

The typical behavior of the objective function is shown in Figure 2-17. The optimal fixed operational time to plan PM can be found at point T* where the total costs per unit time are minimal. At point g(∞), no PM is performed and the system continues working until a failure occurs. The effectiveness of using an age-based replacement policy compared to a CM policy can be determined by the following equation:

$$Effectiveness = g(\infty)/g(T*) \qquad \textbf{(19)}$$

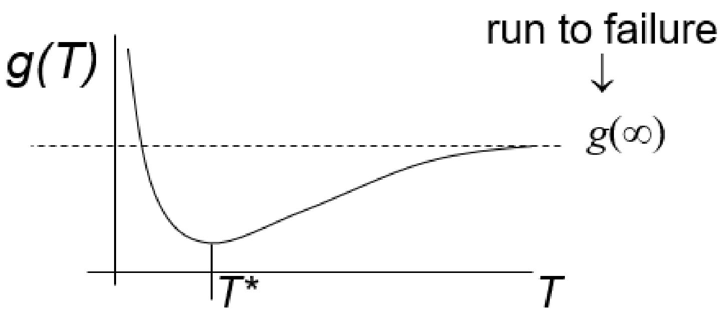

Figure 2-17: Typical behavior of the objective function g(T)

2.3 Maintenance cost

In the following section, we will determine the difference in PM and CM cost. Due to confidentiality, these costs were not provided by manufacturers or operators of WTs and assumptions have been underpinned using existing literature.

We have used wind speed data of FINO1 location situated in the North Sea to be able to calculate the wear-out and fatigue failure of a WT. We will further explain this in section 3.1. In the following sections, we will use the FINO1 location as the location of our WT where we want to perform PM and CM. The FINO1 site is located approximately 60 km of the shore of Germany, illustrated in Figure 2-18. We will use this information to determine the travel costs for different maintenance vessels in section 3.3.

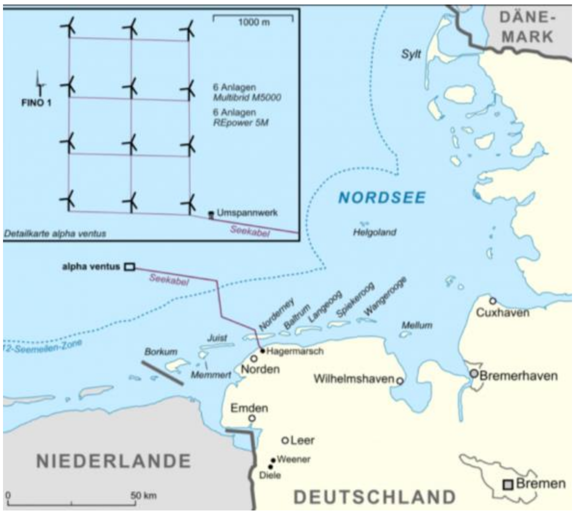

Figure 2-18: FINO1 location

2.3.1 Maintenance categorization

Maintenance of offshore WTs are more difficult and expensive due to accessibility of the site, bad weather conditions, equipment and furthermore. The costs of maintenance actions are dependent on the different vessels needed, labor costs, downtime costs, etc. In the previous section, we have made a distinction between PM and CM. CM is executed once a failure has occurred, on the contrary PM is executed before the occurrence of a failure. However, when a failure occurs different maintenance actions can be needed. The maintenance actions can commonly be categorized in four groups: reset, minor, major and replacement (IEA Wind Task 26, 2016).

- Manual resets are brief inspection or resets of the WT which sometimes involve routine replacements or some consumables. Commonly two technicians are sent to the turbine to execute these maintenance actions.
  In some cases, the maintenance action will involve a remote reset. A remote reset is where the WT is reset remotely from the control room. The consequence is only some downtime and no technicians are needed.
- Minor repairs are relatively small repairs of the WT needing small spare parts. These maintenance actions involve small crew of technicians 2 to 3 technicians.
- Major repairs are large repairs and small component replacements needing relatively small spare parts. These replacement operations take longer to execute and involve a larger crew of around 6 technicians.

- Major replacements are the replacements of large components involving a vessel with lifting capacity e.g. jack-up (JU) vessel. For these types of maintenance actions, a large crew and technicians are needed.

Reset and minor repairs usually only take a few hours. On the contrary major and replacement repairs usually take longer than a day. For the converter system, the time needed for the different maintenance actions, technicians needed, duration and vessel type are summed up in Table 2-1.

Table 2-1: Information of converter system: maintenance actions, repair duration, technicians, vessel type and material costs (Fraunhofer, 2017)

Komponente	Ausfall-konsequenz	Reparaturdauer ⌀ (h)	Techniker ⌀	Schiffs-typ	Material-kosten ⌀ (€)
Converter System (=MSE)	Reset	3	2	CTV	
	Minor Repair	7	2	CTV	240
	Major Repair	14	6	Crane	5300
	Replacement	57	6	JU	13000

On average, reset and minor maintenance are responsible for 75% of the maintenance activities but only have a share of 5% on the total downtime observed due to maintenance activities. On their turn, major and replacement repairs are responsible for 25% of the maintenance activities but have a share of 95% on the total downtime (Milborrow, 2014). Here, the same classification of maintenance actions is used as previously described. Because downtime has a big contribution to the maintenance costs, we will merely focus on the major and replacement repairs.

According to (Sperstad, McAuliffe, Kolstad & Sjormark, 2016) and (IEA Wind task 26, 2016) the vessels needed, to perform different maintenance actions are summed up in Table 2-2. This information differs from the information Fraunhofer possesses. Additionally, according to (Stalhane, Vefsnmo, Halvorsen-Weare, Hvattum & Nonas, 2016), only gearbox major repairs will require lifting capacity. Sperstad et al. state that major repair actions can be executed with the use of CTV's. Wind farm operators usually have long term agreements concerning CTV's and it can be assumed that these are always available and fairly cheap.

Table 2-2: Failure and maintenance data (Sperstad, McAuliffe, Kolstad & Sjormark, 2016)

Maintenance task	Failure rate [per turbine per year]	Active maintenance time [h]	Spare part lead time [days]	Number of technicians required	Vessel required
Manual resets	5	3	0	1	CTV
Minor repair	3	7.5	0	3	CTV
Major repair	0.3	22	10	5	CTV
Major replacement	0.11	34	60	n/a	Jack-up vessel
Annual service	n/a	70	0	3	CTV

The theory we use to determine the optimal fixed operational time to schedule PM states that the failure rate must be increasing over time, the costs of PM must be much smaller than CM, and that the system can be assumed to be "as good as new" after maintenance actions. The failure rate of the major repairs is indeed increasing over time. However, according to our calculations, the costs of CM and PM for major repairs will only differ slightly. The difference between both will consist of the cost of a pre-inspection to assess which maintenance action should take place, and the additional downtime cost of the pre-inspection. As discussed in section 2.3.2, crew transfer vessels (CTV's) have a day rate cost of 3500€ and the pre-inspection duration is approximately 8 hours. Depending on the capacity factor, which will be explained in section 2.3.4, the downtime cost due to pre-inspection will be between 1000€ and 1600€ (resp. capacity factor of 0,25 and 0,4). In case that a crane is indeed needed to undertake the major repair, a crane ship can be hired and will cost approximately 6666 €/hour (Puglia, 2013). However, the 5MW we analyze in our research has a service crane installed in its nacelle and can lift small spare parts up to 2000kg (RePower, 2004) which makes hiring a crane ship redundant.

We can use the failure rate function to determine the probability of a failure and the probability that major repairs will be needed. We could decide to schedule major repairs in advance but, in case that the failure has not yet taken place, it would be unnecessary to undertake any maintenance actions. Furthermore, the system cannot be assumed to be "as good as new" after major repairs. We could decide to aggregate the failure rates of the major repairs and major replacements. This would imply that we would always replace the component even though it could possibly be repaired with major repairs. In section 2.3.2, we show that the vessel needed for replacement is very expensive compared to a CTV or a crane ship used for major repairs.

To conclude, we have decided to focus merely on major replacements because the difference between the PM and CM costs is substantial. The difference in PM and CM for major repairs will only differ slightly and the system cannot be assumed to be "as good as new". The difference between CM and PM will consist of a pre-inspection with a CTV at a cost of 3500€, and the downtime cost during the pre-inspection which is between 1000€ and 1600€. Furthermore, the labor cost is expected to be higher during CM due to higher labor rates for unscheduled labor. All the other costs of PM and CM for major repairs will be the same. The difference between PM and CM costs for major repair and replacement are summed up in Table 2-3. The calculations of Table 2-3 can be found in section 3.3. In addition, if we decided to replace a component instead of executing major repair, the maintenance cost of replacing the component would be higher compared to performing corrective major repairs.

Table 2-3: Overview maintenance cost for major repair and replacement

	PM (€)	**CM (€)**
Major repair	67.076	73.175
Replacement	541.213	1.230.654

2.3.2 Vessel types

Depending on the maintenance action, a certain type of vessel is needed. For a reset and minor repair, CTV's are used. A standard CTV can reach speeds up to 40 km/h (22 knots). For major repairs and replacements, a CTV, crane or JU are commonly used depending on the component. JU vessels are big ships with heavy lifting equipment and enough space to transport large spare parts. However, CTVs are needed for pre-inspections, and an 8-hour pre-inspection is assumed for major repairs and major replacements (Sperstad, McAuliffe, Kolstad & Sjormark, 2016).

The costs of the different vessel types are summed up in Table 2-4. We see that the JU has a high mobilization time and costs. Mobilization time here is understood as the total length of time from when the need for the vessel is identified to the ordered vessel becoming available in the wind farm, including waiting for a vessel to become available on the market, travel time to the maintenance base of the wind farm, waiting for it to be re-equipped, etc. (IEA Wind task 26, 2016). In reality, the mobilization time has a high degree of variability and depends on location of the wind farm, vessel type, time of the year, charter strategy (buy or rent), etc. Mobilization time of 60 days is considered optimistic but not unreasonable for short-term-on-demand charters in the European market (IEA

Wind task 26, 2016). The mobilization cost are the costs incurred for the JU vessel to travel to the wind farm, being re-equipped, planning and preparing the marine operation, and the transportation method. The mobilization cost also has a high degree of variability. The travel distance may differ dependent on the previous location of the JU. Also, the JU vessel can be mobilized to the wind farm using different transportation methods e.g. being towed, heavy lift or self-propelled. A mobilization cost of 500.000€ will be incurred for CM and is based on (Dinwoodie, Enderud, Hofmann, Martin & Sperstad, 2014) and (Maples, Saur & Hand, 2013).

Furthermore, it is assumed that the JU vessel will operate 24 hours a day while at site. The labor cost of the technicians needed for major replacements and the fuel cost are included in the day rate of the JU. However, for CTV's the cost of technicians are not included in the day rate.

Table 2-4: Costs of different vessel types (IEA Wind task 26, 2016)

Maintenance type	Vessel speed [knots]	Transfer time [minutes]	Technician space	Day rate [€]	Mob. time* [days]	Mobilisation cost [€]	Significant wave height limit [m]	Wind speed limit [m/s]
Standard crew transfer vessel (CTV)	22	22	12	3,500	n/a	n/a	1.8	16
Jack-up vessel	7	n/a	n/a	140,000	60	500,000	2	11
Diving support vessel (DSV)	16	n/a	n/a	75,000	15	225,000	2	n/a
Cable laying vessel (CLV)	14	n/a	n/a	100,000	30	550,000	1	n/a

* Mobilisation time shown includes lead time waiting for a vessel to be available on the market for the sort of short-term on-demand charters assumed here.

2.3.3 Downtime cost formula

When a major component fails, the WT will stop working and will not produce any electricity. The operator occurs a loss in revenue during the standstill, which is referred to as downtime cost (Kirkeby & Mikkelsen, 2016). The cost for downtime is calculated as followed (Puglia, 2013).

$$Cost\ of\ downtime\ (€) = Number\ of\ WT * rated\ power * capacity\ factor * cost\ of\ electricity * downtime \quad \textbf{(20)}$$

In our case, the number of WT is equal to 1. The rated power is the maximum power that the WT can generate per hour. This will be equal to 5MW (5000 kW). The cost of electricity is the price obtained per kWh. The price of electricity fluctuates depending on the wind speeds and produced energy. However, in consultation with Fraunhofer, we have decided to use a feed-in tariff (FIT) of 0,10€ kWh. A FIT protects producers of renewable energy for some of the inherent risks of renewable energy production. These are typically achieved by offering long-term agreements for the pricing of the energy. The goal of a FIT is to provide price certainty and to help finance investments in renewable energy. The capacity factor will be discussed in section 2.3.4. The downtimes will be calculated in section 3.3.2. Finally, the downtime cost will be calculated in section 3.3.3.

2.3.4 Capacity factor

The capacity factor (Cf) of a WT is the ratio of the average power produced and the rated power. The equation of the capacity factor is as followed.

$$Cf\ (\%) = \frac{Average\ power}{Rated\ power} \qquad \textbf{(21)}$$

As previously stated, the maximum power that the WT can generate is 5MW. To determine the actual power output at a given point in time we need to know the measured wind speed at that point in time. Measured wind speed can be converted to average power produced using the power curve of a WT. The power curve shows the power generated by the WT at different wind speeds, see Figure 2-19.

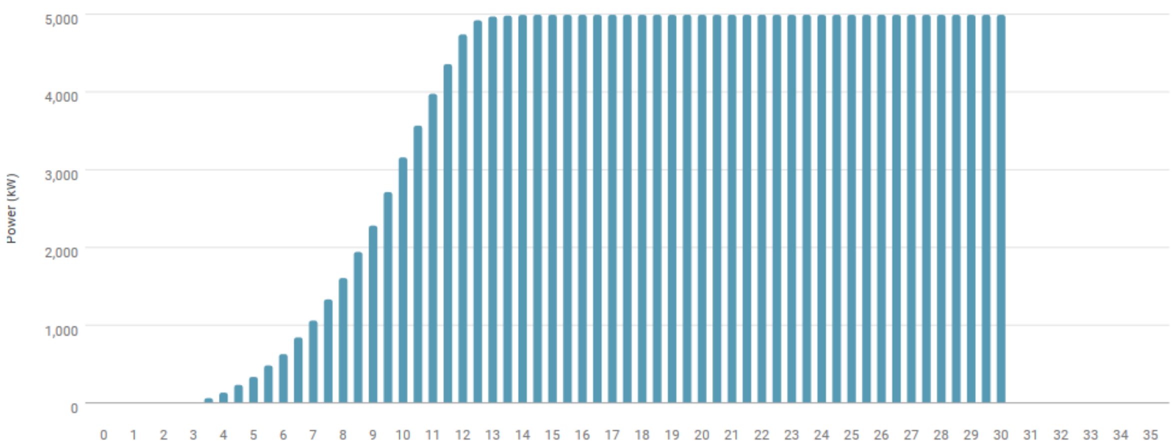

Figure 2-19: Power curve of the 5MW WT

On the x-axis we can see the different wind speeds. On the y-axis we see the generated power for the corresponding wind speed. Notice that the curve starts at a wind speed of 3,5 m/s and stops at 30 m/s. These correspond with the cut-in and cut-out speed of the WT. The turbine will not generate power at wind speeds under 3,5 m/s and above 30 m/s.

As stated at the beginning of section 2.3, we have used wind speed measurement of the FINO1 location to analyze our problem. The wind speed data of the FINO1 location is measured from 1-1-2014 until 1-1-2018 and is measured at a height of 100 meters. This is equivalent with the hub height of our WT. The wind speed is measured every 10 minutes and the date, hour, and time interval are precisely logged. The average is determined from a sequence of 6 consecutive measurements that do not overlap each other e.g. 1 to 6, 7 to 12, etc. Thus, each hour consists of 6 wind speed measurements from which the average wind speed is calculated. From the hourly average wind speeds, we can determine the hourly average power of the WT. From the data follows that for a 25 year span the average wind speed is equal to 9,2 m/s which is equivalent to an average power of somewhat near 2500 kW. This result is not exactly correct because the WT may have had some standstills due to too low or to high wind speeds (cut-in and cut-out wind speeds). Therefore, we have calculated the hourly average power for 25 years using the wind speed data of the FINO1 location. This calculation yield that the average power of the 5MW WT is equal to 2630 kW.

Even though we now have taken into account the standstill due to the cut-in and cut-out wind speeds the average generated power is higher than before. This is because the power curve of the WT isn't linear. As wind speed increases, the generated power also increases however it proportionally increases more. Thus, accessing higher wind speeds will result in substantial more power generated. The power curve and the increase in generated power compared to the wind speed are depicted in Figure 2-20.

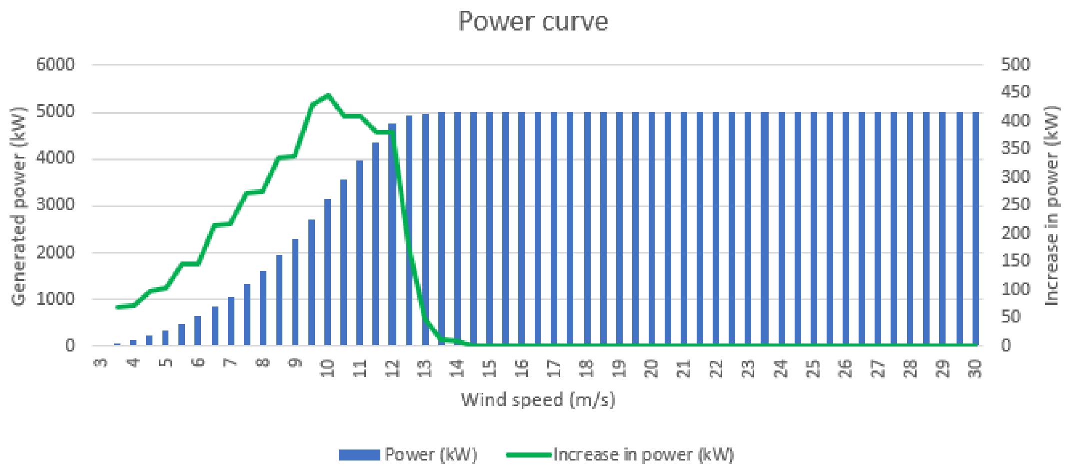

Figure 2-20: Power curve and the increase in power

According to the data and information above, the capacity factor of the WT would be equal to 52,6%. According to existing literature, baseline measurements and actual data of German wind farms, the average lifetime capacity factor is 41,1%, see Figure 2-21. We have decided to use the average capacity factor of German wind farms in our downtime cost calculation for the following reason. The data of the FINO1 location consists of wind speed measurements at 100 meters. From this the power generated by the WT can be determined. However, in addition to the standstill caused by the cut-in and cut-out wind speeds, the WT experiences standstills during maintenance actions. These maintenance actions are not included in the FINO1 data and therefore we will use the average capacity factor of 41,1%.

All numbers are to May 2018. Analysis by EnergyNumbers.info.	Latest rolling 12-month capacity factor	Lifetime capacity factor	Age (y)	Installed capacity (MW)	Total elec. gen. (GWh)	Power per unit area spanned (W/m²)
Amrumbank West	41.7%	44.1%	2.6	302	2 872	4.0
Bard Offshore 1	37.0%	37.8%	1.1	400	1 460	2.6
Borkum Riffgrund I	36.8%	40.5%	2.6	312	2 881	3.5
DanTysk	48.0%	50.0%	3.1	288	3 178	2.2
Gode Wind I		40.3%	1.0	330	1 127	
Gode Wind II		39.9%	1.0	252	852	
Nordsee One		32.0%	0.4	331	354	
Nordsee Ost 1	33.9%	36.1%	3.0	144	1 368	2.9
Nordsee Ost 2	35.8%	36.8%	3.0	144	1 402	2.9
Sandbank	46.2%	47.1%	1.3	288	1 552	2.9
Windpark Baltic 1 & 2	46.7%	46.8%	2.6	336	3 516	4.3
Total	***41.4%***	***41.1%***		***3128***	***20 563***	***3.0***

Figure 2-21: German offshore wind capacity factor (Andrew, 2018)

2.3.5 Assumptions and limitations of the maintenance planning model

It is important to note, that in the theoretical framework discussed above, we have made some important assumptions.

- **Wave and wind speed limits, as waiting times due to bad weather are not incorporated in the maintenance planning model**

The reader may have noticed in Table 2-4 that different types of vessel have different wave height limits and wind speed limits. In case of bad weather and rough sea, most vessels cannot leave port and need to wait until the weather improves to execute the maintenance actions at sea. As an example, if wave heights exceeding 2 meters or wind speeds exceeding 11 m/s are experienced, the JU cannot travel to the wind farm and must stay at port.

Weather commonly fluctuates during the year. In the winter, the weather is usually worse with higher wind speeds and wave heights. On the contrary, in the summer, the weather is usually better. Also, the weather conditions during the autumn and the spring differs. The probability of good weather and sea conditions is lower during winter months compared to e.g. the summer months, see Table 2-5. Good weather conditions refer to favorable wave and wind speed conditions which lay within the limits of the JU vessel. In addition, the waiting times of vessels in port due to weather conditions is shown in Table 2-5. This implies, that executing maintenance actions during the summer is more favorable because the probability of waiting in the port, due to bad weather, is smaller. If a vessel must wait in port, no maintenance actions can be executed on the WT. In case of CM, the WT is at a standstill and the operator will suffer additional downtime cost. For both PM and CM, if a vessel must wait in port, the vessel cost increases due to the day rate cost.

Table 2-5: Weather condition for each season and waiting time (Santos, Teixeira & Soares, 2013)

Year Seasons	Probability of having good sea conditions	Waiting time (days)
Winter	0,3	10
Autumn	0,5	7
Spring	0,6	5
Summer	0,8	2

- **Average day rate of the JU vessel is used instead of seasonal day rates**

As previously discussed, summer months are more favorable for executing maintenance action. Therefore, the demand during these months is higher and the day rate increases. During winter months, the demand is lower and thus the day rate decreases. During winter months the daily rate can be as low as 130.000 €/day and during the summer months as high as 192.000 €/day (Dalgic, Lazakis, Turan & Judah, 2015). JU vessels are commonly hired for a month from which the day rate is calculated. During the hired month, the JU is used to execute several maintenance actions on different WTs. In our research we focus on only one WT and therefore we have decided to only use the day rate in the vessel cost calculations.

- **Fluctuation in capacity factor due to seasonal weather conditions are not incorporated in the maintenance planning model**

Furthermore, the capacity factor also fluctuates during the year. As one can imagine, higher wind speed can yield more power generation. Thus, during the winter months, the capacity factor of an average WT at different locations is expected to be higher compared to the summer months, see Figure 2-22.

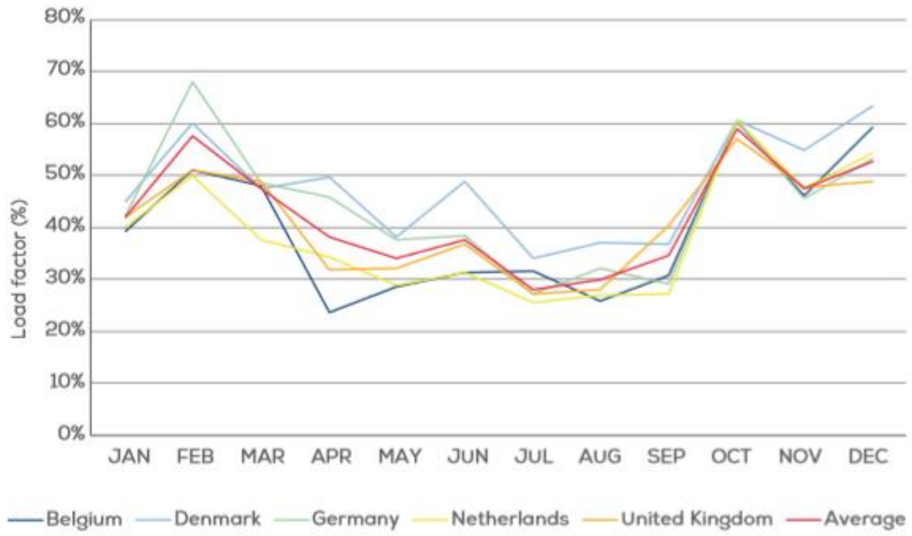

Figure 2-22: Monthly national capacity factor (load factor) of offshore wind in 2017 (Pineda, 2017)

- **Lead time of spare parts are assumed to be 0 or incorporated in the mobilization time of the JU vessel**

Finally, not all spare parts are always available on stock. The spare parts are commonly ordered once the part is needed. A lead time of a few days up to a several weeks is not uncommon. In our research we have decided to not incorporate the lead times for the following reason. In case of PM, the maintenance action is known in advance and the spare part can be ordered in time. In case of CM, the travel time of the JU is expected to be 60 days. In the meantime, it can be assumed that the spare part is ordered and delivered before the JU becomes available.

Thus, we have decided to make several assumptions concerning the literature discussed above. We will not make use of the seasonal price changes in the JU vessel day rate. This is because this information is made confidential by operators and in case it is available it is highly inconsistent. Furthermore, possible waiting times due to bad weather conditions and vessel limits will not be incorporated in our maintenance planning model. The wave heights at FINO1 location were not available be able to incorporate this into the model. The fluctuations in the capacity factor for different months of the year are also not included, as we do not incorporate the seasonal vessel pricing. Finally, the lead time for spare parts are assumed to be 0.

3 Solution methodology

In the following chapter, we will explain how we have applied the theory discussed in section 2. Furthermore, the equations presented in section 2 will be applied in the following chapter. We will first explain how we have determined the failure rates of the converter. From the failure rates, we can determine the reliability which we use as an input to calculate the optimal fixed operational time to schedule PM. Finally, the parameters used for the sensitivity analysis will be discussed.

We have made 3 different excel files. The first will be used to calculate the failure rates and the reliability of the converter system. The second will be used to calculate the objective function from which the optimal fixed operational time to schedule PM can be found. Finally, the third excel file will be used to apply the sensitivity analysis. All the details of the calculations can be found in Appendix B.

3.1 Failure behavior

The failure behavior of the converter system can be represented with the use of six failure categories determined by Fraunhofer. Some failure categories are time dependent (e.g. early failure, aging failure), however several failure categories can be assumed to be random and thus constant over time (e.g. icing, lightning). Other failure categories are dependent on external factors such as wind speeds, climatic conditions. The six different categories are explained below (Faulstich, Berkhout, Mayer & Siebenlist, 2016).

- **Early failures**: failures that occur at the beginning of the start-up phase, for example, due to installation or manufacturing errors of individual components.
- **Random failures**: failures which are constant risk based
- **Aging failures**: failures of a component that occur due to aging effects, e.g. corrosion.
- **Fatigue failures**: failures that occur because of fatigue or wear.
- **Overload failures**: failures of a component due to an overload of a component.
- **Component specific failures**: this category allows modelling additional effects. This could also comprise natural events such as lightning strikes, earthquakes and damage due to bird strike

Below, the failure rates determined by Fraunhofer of the different failure categories are shown. The early and aging failure are time dependent, but the random, icing, and lighting are constant. Furthermore, the overload failure is dependent on the wind speeds and the wear-out failure is dependent on the total energy produced until a given point in time.

$$Early\ failure: \lambda(t) = 0{,}16668 * \left(\frac{t}{1{,}7999}\right)^{-0{,}7} \quad \textbf{(22)}$$

$$Aging\ failure: \lambda(t) = 0{,}1884875 * \left(\frac{t}{13{,}2635}\right)^{1{,}5} \quad \textbf{(23)}$$

$$Random\ failure: \lambda(t) = 0{,}08 \quad \textbf{(24)}$$

$$Lightning\ failure: \lambda(t) = 0{,}05 \quad \textbf{(25)}$$

$$Icing\ failure: \lambda(t) = 0{,}05 \quad \textbf{(26)}$$

$$Overload\ failure: \lambda(Vwind) = 0{,}01171838 * (Vwind - 3{,}5) \quad \textbf{(27)}$$

$$Wear\ out\ failure: \lambda(t) = 0{,}015504753 * \left(\frac{E}{154{,}7912416}\right)^{1{,}4} \quad \textbf{(28)}$$

We have modelled the different failure categories for 25 years to be able to determine the reliability of the converter system. As stated above, some failure categories are dependent on external factors such as wind. The used wind speed data is collected from the FINO1 location. The wind speeds are measured every 10 minutes. We could determine the failure rate and probabilities for every 10 minutes over the 25-year span, however this would lead to very slow calculation times in excel. Furthermore, it will not be necessary to know exactly at which time of day the maintenance actions should be executed. Nevertheless, to come to a good approximation of the overload and wear-out failure, we have determined the hourly average wind speed. The determination of the hourly average wind speeds is discussed in section 2.3.4. This yields hourly (overload and wear-out) failure rates over the life span of the WT. This also implies that we should use the same interval (hours) to calculate the other failure rates.

As it can be seen in equations (22) and (23), the early and aging failure rates are dependent on time. The "t" in the equation represents years. Because we have decided to calculate the failure rates in hours, we need to convert hours to years. One year exists of 8760 hours, so one hour is exactly 0,000114155 years. To determine the failure rate at a certain point in time, we simply need to fill in the same number of hours (for that point in time) in the equation. Say we want to know the aging failure rate after half a year, this would imply that we fill in $0{,}000114155 * \left(\frac{8760}{2}\right) = 0{,}5$ in equations (22) and (23).

For equations (24), (25), and (26) it is fairly simple. Because the rates are not time dependent, the failure rate at any given point in time will be equal to its own failure rate. Thus, icing and lightning are equal to 0,05 and random is equal to 0,08 per year.

As previously discussed, the overload failure is dependent on the wind speed. Thus, to determine equation (27), we need to fill in the measured wind speed into the equation. The FINO1 wind speed measurements are extrapolated to simulate wind speeds for 25 years. So, to determine the overload failure at a certain point in time, we fill in the measured wind speed in equation (27). Note that 3,5 is subtracted in the equation. This is due to the cut-in wind speed of the WT, explained in section 2.3.4.

Finally, the wear-out failure is dependent on the energy produced. The order of magnitude in equation (28) is measured in GWh (1.000.000.000 Wh). Since it is a value for the produced energy it is measured in Wh. The energy produced can be determined from the wind speeds using the WT power curve. No power will be produced at wind speeds lower than 3,5 m/s or higher than 30 m/s, see section 2.3.4. Wear-out failure represents the deterioration of the turbine as time passes and more energy is produced. Therefore, to calculate the failure rate at a certain point in time, we fill in the cumulative energy produced, until that given point in time, in equation (28). The cumulative energy produced is measured in kWh, so we must divide it with 1.000.000 to convert it to GWh. This yields a failure rate per GWh. For our analysis we need to convert this to a failure rate which is time dependent. To achieve the previous, we need to multiply the failure rate (per GWh) with the energy produced per year. The energy produced per year is the summation of all the energy produced in that corresponding year. The energy produced in each year is depicted in Figure 3-1. The yearly average cumulative energy produced over a 25 year-span is 23,04 GWh.

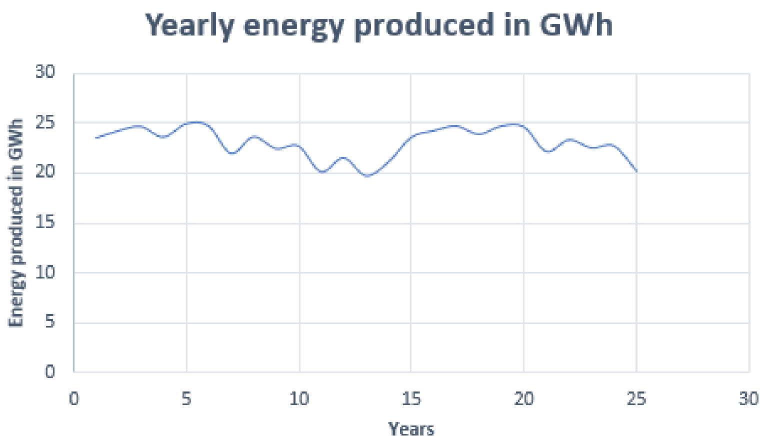

Figure 3-1: Yearly energy produced in GWh

With the calculations above, we determine the failure behavior of the converter system. As explained in the theoretical framework, not all failures will lead to a replacement of the component. Both the failure categories as well as the maintenance actions contribute to the overall failure behavior of the converter system, as depicted in Table 3-1. The failure categories are respectively: early, aging, random, lightning, icing, overload, and wear-out.

Table 3-1: Share of maintenance actions and failure categories on overall failure behavior (Fraunhofer, 2017)

	Early (22)	**Aging (23)**	**Random (24)**	**Lightning (25)**	**Icing (26)**	**Overload (27)**	**Wear-out (28)**
Reset	5	4	4.5	4	4	3.5	5
Minor	5.7	8.3	7.3	4.7	4.7	5	11.3
Major	1	4	4	1	1	3	6
Replacement	0.3	0.7	0.2	0.3	0.3	0.5	0.7

These shares must be incorporated in the failure rate calculations of the different failure categories. This implies that equation (22) is multiplied with a factor of $\frac{0,3}{12}$, equation (23) with $\frac{0,7}{17}$, equation (24) with $\frac{0,2}{16}$, equation (25) with $\frac{0,3}{10}$, equation (26) with $\frac{0,3}{10}$, equation (27) with $\frac{0,5}{12}$, and equation (28) with $\frac{0,7}{23}$.

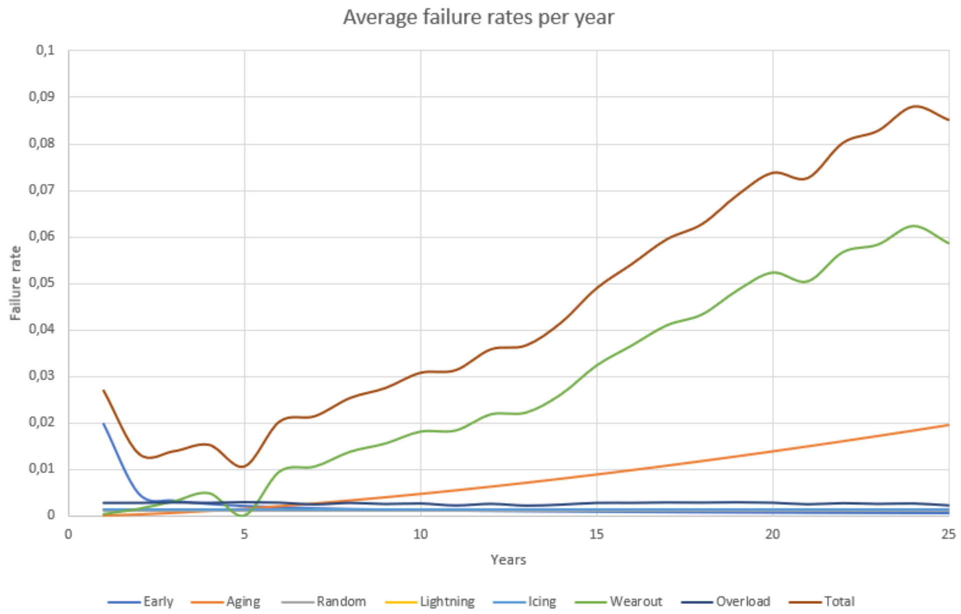

Figure 3-2: Average failure rates per year of the converter system

3.2 Reliability

We have now determined the failure rates for the different failure categories for each hour over a 25-year span. Using equation (3) and the calculated failure rates, we can determine the reliability of the converter system.

To determine the reliability at a given point in time, all the failure rates until that given point in time should be added together and filled in into equation (3). Thus, λ(t) represents all the different hourly failures rates added up until time t.

$$\lambda(t) = \lambda eary(t) + \lambda aging(t) + \lambda random(t) + \lambda icing(t) + \lambda lightning(t) + \lambda wearout(E) + \lambda overload(Vwind)$$

Subsequently the λ(t) is inserted into equation (3). The “dt” from the equation should be consistent with the time increments of the failure rates thus $dt = 0{,}000114155$. The number “e” from the equation is also called the Napier’s constant and $e = 2{,}718281828459$.

The time unit used in our maintenance planning model is years. Thus, we have determined the reliability for every 0,25 years for a 25 year-span. The reliability of the converter system is depicted in Figure 3-3.

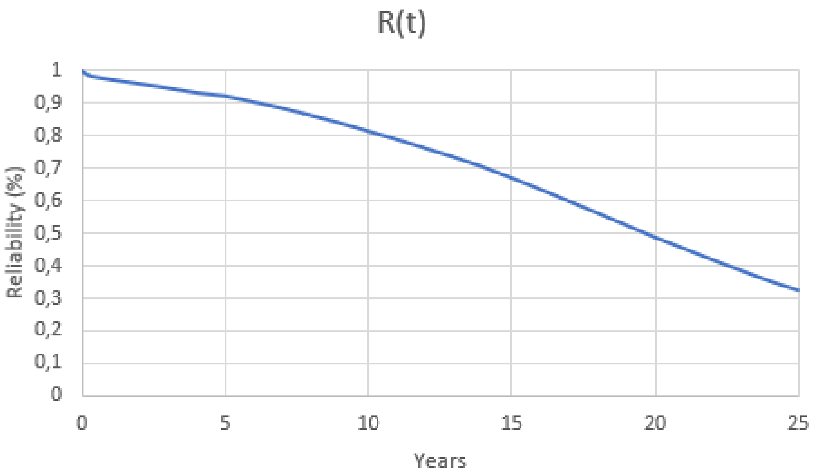

Figure 3-3: Reliability of the converter system

3.3 Preventive and corrective costs

3.3.1 Vessel cost

With the information from section 2.3.2, the vessel cost for major replacements can be determined. For PM no pre-inspections are needed because the maintenance is scheduled in advance and the maintenance action is known. In addition, the mobilization time can be assumed to be almost 0 because the JU vessel is scheduled in advance and will be available at the moment of PM.

The mobilization cost is amongst others, the cost associated with planning and preparing a marine operation before the vessel arrives at the wind farm (Dinwoodie, Enderud, Hofmann, Martin & Sperstad, 2014). In case of scheduled PM, the mobilization costs will be smaller, and it is estimated to be between 57 000€ and 114 000€ (Steenbergen, Gelder, Miraglia & Vrouwenvelder, 2014). We have used a mobilization cost of 114.000€ for PM.

In case of CM, the vessel cost will be much higher. A pre-inspection with a CTV, at a day rate of 3500€, will be needed which takes approximately 8 hours. During this time the WT is at a standstill. After the pre-inspection, the failure cause is assumed to be found and the planning and preparation of the marine operation can start. Due to the mobilization time, the WT will have a standstill for an additional 60 days until the JU arrives at the site location and starts the maintenance action. Additionally, a mobilization costs of 500 000€ will be added to the CM cost, see Table 2-4.

For both PM and CM, the day rate of the JU vessel will be estimated at 140 000€ (5833,33 € per hour). According to Fraunhofer, the average duration of the maintenance action at site location will be 57 hours. However, the JU vessel needs to travel to the site from shore and eventually travel back. The JU can travel at a speed of 7 knots. 1 knot is equal to 1,852 km/h and thus the total travel time from shore to site will be as followed.

$$Total\ travel\ time\ from\ shore\ to\ site\ (h) = \frac{60}{7 * 1{,}852} = 4{,}6\ hours$$

In the above formula, the numerator represents the distance from shore to the center of the wind farm. We will round up the travel time up to 6 hours because the WTs are not situated next to each other but have a distance of 3-10 rotor diameter (378- 1260 meter) between each other. Thus, the travel time cost (from shore to the site and back) will cost $12 * 5833{,}33\ = 70\ 000€$.

In conclusion the PM and CM vessel costs are as followed.

$$Vessel\ cost\ (€) = cost\ inspection\ vessel\ (CTV) + mobilization\ cost + (hourly\ rate\ JU * maintenance\ time) + (hourly\ rate\ JU * travel\ time)$$

$$PM\ vessel\ cost = 0 + 114000 + (5833{,}33 * 57) + (5833{,}33 * 12) = 516500€$$

$$CM\ vessel\ cost = 3500 + 500000 + (5833{,}33 * 57) + (5833{,}33 * 12) = 906000€$$

As one may have noticed, the WT does not work when CM is needed, or when maintenance actions are being executed. During this time, the wind farm operator is losing money. In section 3.3.2 we will discuss the downtimes incurred during PM and CM.

3.3.2 Downtimes

We will now determine the downtime of the WT in case of PM and CM. In case of PM, the WT will only have a standstill during the maintenance operation time. Thus, the downtime during PM will be equal to 57 hours. During the travel time to the wind farm, the WT is still operational. Once the component has been replaced, the WT is working again.

However, during the CM more downtime is observed. CM is executed once the WT has stopped working. A CTV with two technicians on board is sent to the WT to inspect and determine the failure cause. The total travel time of the CTV from shore to the wind farm and back is calculated in section 3.3.4 and is equal to 3 hours. After the inspection, the operator will contact maintenance providers and search for an available JU vessel. As described in section 3.3.1, the mobilization time of a JU vessel is approximately 60 days (1440 hours). As mentioned in section 2.3.2, the mobilization time here is understood as the total length of time from when the need for the vessel is identified to the ordered vessel becoming available in the wind farm, including waiting for a vessel to become available on the market, travel time to the maintenance base of the wind farm, waiting for it to be re-equipped, etc. (IEA Wind task 26, 2016). After the CM, the WT is assumed to be operational again.

Thus, the downtime during CM can be calculated as followed.

$CM\ downtime = travel\ time\ CTV + inspection\ downtime + mobilization\ downtime +$ maintenance downtime

$$CM\ downtime = 3 + 8 + 1440 + 57 = 1508\ hours$$

3.3.3 Downtime cost

With the information of section 2.3.3 and 2.3.4, and the information gathered above, we can now determine the downtime cost for PM and CM using equation (20).

In both CM and PM, the number of WT is equal to 1, the maximum power generated is 5000kW, the capacity factor is equal to 41,1% and the cost of electricity is 0,10€ kW/h. Downtime of PM is equal to 57 hours and downtime due to CM is equal to 1508 hours.

This yields the following.

$$PM\ downtime\ cost(€) = 1 * 5000 * 0{,}414 * 0{,}10 * 57 = 11799€$$

$$CM\ downtime\ cost(€) = 1 * 5000 * 0414 * 0{,}10 * 1508 = 312156€$$

It is important to note that downtime cost estimations can substantially deviate in the real world. As we have explained in section 2.3.4, the capacity factor is dependent on the average power produced, which in turn is determined from the measured wind speeds. As one may imagine, it is possible that lower wind speeds are measured during the downtime of the WT. Consequently, the average power produced will be lower which will result in a lower capacity factor and thus yield a lower downtime cost. On the contrary, it is also possible that higher wind speeds are measured during the downtime which will result in a higher capacity factor and thus yield a higher downtime cost.

3.3.4 Labor cost

For the JU vessel, all the labor cost of technicians is included in the day rate. This is not the case for the CTV day rate. For a pre-inspection, a CTV is hired, and 2 technicians are sent to the WT to determine the failure cause. The duration of a pre-inspection takes approximately 8 hours, see Table 3-2. These technicians are not scheduled in advance and they are more expensive than scheduled man hours. One unscheduled man hour cost 80€/h (Puglia, 2013). Additionally, the technicians need to travel to the WT and back to shore. A CTV can travel at a speed of 22 knots (41 km/h). The travel time from shore to the site will then be $\frac{60}{22*1{,}852} = 1{,}47\ hours$. Thus, traveling from shore to the site and back will take around 2,94 hours. We will round this up to 3 hours as we did in estimating the travel time of the JU in section Vessel cost3.3.1. We have multiplied the distance to the wind farm by two because the CTV must head back to shore after the inspection.

These costs are only incurred during CM because no inspection is needed with PM. Thus, the labor cost for a pre-inspection will be as followed

$$Labor\ cost\ (€) = number\ of\ technicians * (travel\ time + duration\ of\ inspection) * labor\ cost\ per\ hour$$

$$Labor\ cost = 2 * (6 + 8) * 80 = 2240€$$

Table 3-2: Data of pre-inspection (IEA Wind task 26, 2016)

Maintenance type	Expected number of annual events	Repair time [h]	Number of technicians required	Cost (€)	Vessel requirement
Pre-inspection for major repair	0.3	7.5	2	-	CTV
Pre-inspection for major replacement	0.11	7.5	2	-	CTV

3.3.5 Overview PM and CM costs

Previously, we have determined all the costs incurred during PM and CM replacement of the converter system. The only cost which must be added to both PM and CM cost is the spare part cost which is 13.000€. Below is an overview of all the costs for each maintenance strategy, depicted in Figure 3-4. The total cost of PM is 541.213€ and CM is 1.230.654€. This is also consistent with reports that state that the costs of CM are a factor of two higher than for PM costs (Rademakers, Braam, Zaaijer & Bussel, 2003). We see that the vessel cost is responsible for 95% of the total PM cost. In case of CM, the vessel cost is responsible for 74% and the downtime cost is responsible for 25% of the total CM cost.

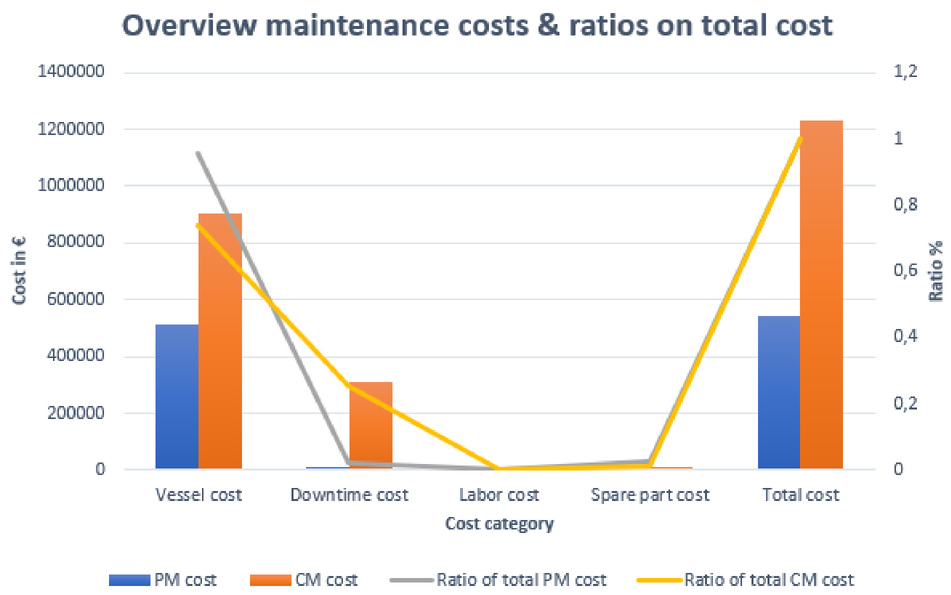

Figure 3-4: Overview maintenance costs and ratios of total PM or CM cost

3.4 Optimal time interval calculation

We have almost all the necessary data to determine the optimal fixed operational time to schedule PM. The PM and CM cost are determined in section 3.3, the reliability is calculated in section 3.2. To determine the optimal fixed operational time t to schedule PM, we first need to determine the unreliability. Once the unreliability is known, we can determine the ECC using equation (15). Furthermore, we will use equations (16) or (17) to compute the ECL.

The unreliability F(T) is simply 1 minus the reliability $\bar{F}(T)$ as explained in section 2.2.2.

To determine the ECL we use equation (17). Here we have an integral form 0 to T (wanted point in time) over the reliability function, which we have previously determined. Our used time unit is years. Using equation (18), the trapezoidal rule, we determine small areas under the reliability curve. Each area is a quarter of a year which implies that "dt" must also be equal to 0,25.

Now we have all the needed variables to compute the objective function g(t). C_0 is the corrective cost, C1 the corrective cost, $\bar{F}(T)$ is the reliability, F(t) the unreliability, and ECL the expected cycle length. Inserting these values into the equation, the objective function is determined using equation (14).

3.5 Benchmark policy

Currently operators perform PM for some maintenance actions, but they do not use PM to replace components prior to a failure. However, CM is used to replace components upon failure. As stated in section 2.2.2, MTTF describes the mean time expected until the first failure for a non-repairable system. In our case, we can consider the components as non-repairable systems because the components are replaced and not repaired. Thus, determining the MTTF of the converter system will provide us with a benchmark policy which solely performs CM to replace a component.

Using equation (5), the MTTF can be determined by calculating the area under the reliability curve from 0 to infinity. When time reaches infinity, the reliability of a component should be equal to 0. As can be seen in Figure 3-3, the reliability of the converter system is expected to be 32,37% after 25 years. Since we have not calculated the reliability of the converter system after 25 years, it is not possible to determine the MTTF using equation (5) in this specific case.

3.6 Sensitivity analysis approach

The optimal age interval to replace a component is strongly dependent on the costs of PM and CM. Therefore, we have executed a sensitivity analysis for different cost parameters and analyzed what the influence is on the optimal fixed operational time to schedule a replacement of the converter system. The costs inputs with the most variability and influence on the total cost are the most interesting to analyze. Thus, we have analyzed different cost inputs for the mobilization time and mobilization cost.

The used inputs for the CM mobilization times are 30, 45 and 60 days. As explained in the theoretical framework, 60 days is considered optimistic but not unreasonable for short-term-on-demand charters in the European market (IEA Wind task 26, 2016). Therefore, we will use a mobilization time of 60 days as the upper limit in our sensitivity analysis. This value may be lower, and 30 to 45 days is also considered reasonable for the European market. We will not use any other mobilization time inputs for PM because these maintenance actions are planned in advance and it can be assumed that the mobilization time negligible. Note that decreasing the mobilization time will have a big influence on the total CM cost, namely the downtime cost will simultaneous decrease.

We used three different inputs for the CM mobilization cost, 250.000€, 500.000€, 750.000€. The mobilization cost is dependent on the planning and preparation of the marine operation, travel distance to the wind farm and transport method. It has a high degree of variability and therefore we have used 3 different inputs categories and named them: optimistic, baseline, and pessimistic. For PM the mobilization cost inputs are respectively: 57.000€, 114.000€, and 171.000€. All the different inputs used are summed up in Table 3-3 and Table 3-4.

Table 3-3: CM and PM mobilization cost inputs for each category (optimistic, baseline and pessimistic)

Inputs (€)	**Optimistic**	**Baseline**	**Pessimistic**
CM mobilization cost	250.000	500.000	750.000
PM mobilization cost	54.000	114.000	171.000

Table 3-4: CM mobilization time inputs

Inputs (days)			
CM mobilization time	30	45	60

In conclusion, we use three different mobilization times in combination with the three different mobilization cost categories. This yields 9 configurations to determine the optimal fixed operational times to schedule PM. The inputs are inserted in the excel file and the output of the objective function is plotted in a graph. The 9 different configurations are summed up in Table 3-5.

Table 3-5: Configuration inputs for the sensitivity analysis

Configuration	**CM mobilization time (days)**	**CM mobilization cost (€)**	**PM mobilization cost (€)**
30 Optimistic	30	250.000	54.000
45 Optimistic	45	250.000	54.000
60 Optimistic	60	250.000	54.000
30 Baseline	30	500.000	114.000
45 Baseline	45	500.000	114.000
60 Baseline	60	500.000	114.000
30 Pessimistic	30	750.000	171.000
45 Pessimistic	45	750.000	171.000
60 Pessimistic	60	750.000	171.000

We have decided not to analyze the day rate of the JU vessel for the following reason. The same day rate is used for PM as for CM. When changing the day rates, it should be done for both maintenance actions. Dependent on the day rates they will simultaneous increase or decrease but the ratio between PM cost and CM cost will stay the same. The influence on the objective function is that it will shift to the right if the day rates are increased and shift to the left if they are decreased. However, the curve of the objective function will be the same but respectively with higher or lower costs.

In addition to a cost sensitivity analysis, we have analyzed one of the assumptions we have made in section 2.3.5. We decided not to include major repairs in the planning maintenance model. However, JU vessels are usually hired for a month and used to execute several other maintenance actions on the same or different WTs. JU vessels are hired several times during the lifetime of the WT. Therefore, it is interesting to analyze what the optimal fixed operational time to replace the converter system would be if we include major repair into our maintenance planning model. This optimum can possibly align with other moments when a JU vessel is hired, and (other) components are needed to be replaced. This yields the possibility to perform opportunistic maintenance on the converter system as suitable maintenance resources are already located at site.

Thus, we have added the contribution of the major repairs to the failure rates after which the new overall reliability of the converter system is determined. From Table 3-1 we can determine the new shares with which the failure rates are multiplied. This implies that equation (22) is multiplied with a factor of $\frac{1,3}{12}$, equation (23) with $\frac{4,7}{17}$, equation (24) with $\frac{4,2}{16}$, equation (25) with $\frac{1,3}{10}$,equation (26) with $\frac{1,3}{10}$, equation (27) with $\frac{3,5}{12}$, and equation (28) with $\frac{6,7}{23}$. The new average failure rates per year for each failure categories are depicted in Figure 3-5 and the new reliability of the converter system is depicted in Figure 3-6.

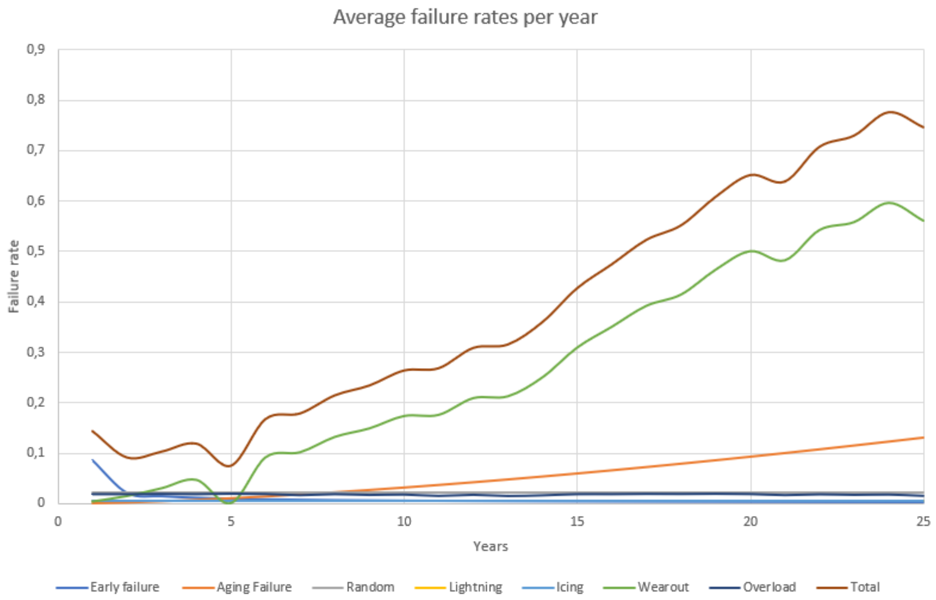

Figure 3-5: Average failure rates per year of the converter system (major repair & replacement)

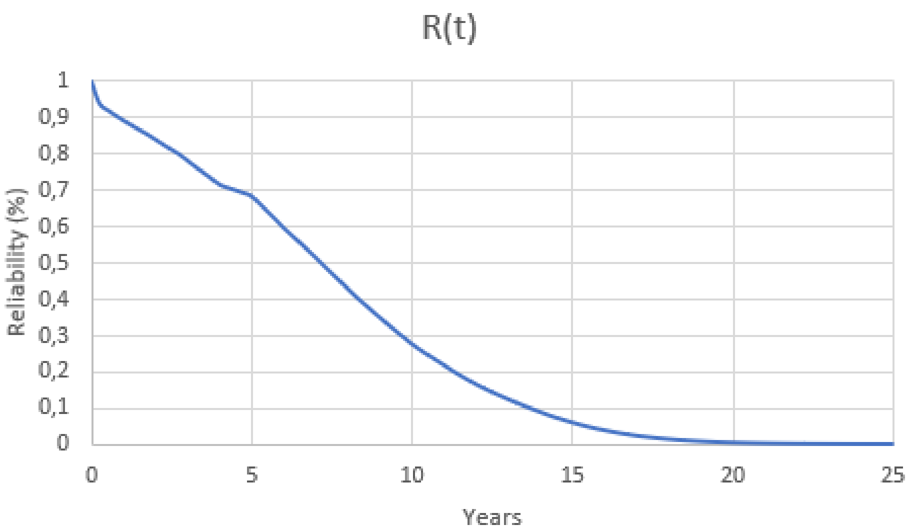

Figure 3-6: Reliability of the converter system (repair & replacement)

4 Research results

In the following chapter, the results of the optimal maintenance planning model are discussed. First, the optimal fixed operational time to schedule PM for the converter system is presented and based on the reliability and maintenance cost determined in section 3.2 & 3.3. Thereafter, we will analyze the results from the sensitivity analysis. We will end this chapter with another case study which is executed on the rotor system of a WT.

4.1 Optimal fixed operational time interval

With the parameters determined in section 3, the objective function is calculated and plotted in excel, as depicted in Figure 4-1. The parameters used are a PM cost of 541.213,5€ and CM cost of 1.230.654€, combined with the reliability and the ECL of the converter system.

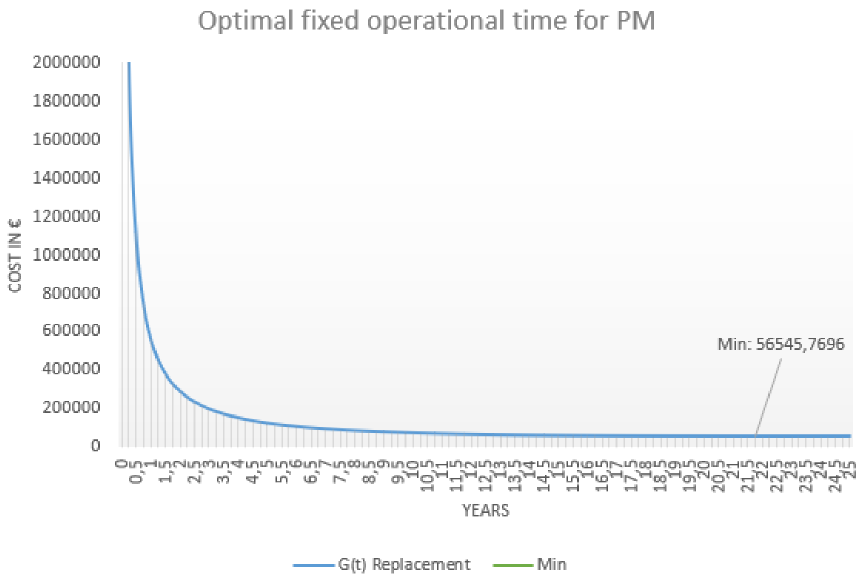

Figure 4-1: Optimal fixed operational time to schedule PM for a converter system

As shown in Figure 4-1, the optimal fixed operational time to schedule PM is found at 21,75 years with a cost per unit time of 56.545,77€. At this point in time, the costs are minimized after which the cost function starts to increase again. If the converter system has not failed prior to 21,75 years, PM actions are executed, and the converter system is to be replaced. If the converter system breaks before the found optimum (21,75), CM actions are executed, and the next PM is scheduled in 21,75 years. We expect that WTs have a lifetime of 20-25 years, thus the PM action will probably only be scheduled once during the WT lifetime. This is due to the high reliability of the converter system. The reliability of the converter system at 21,75 years is 42,69%.

Moreover, we see from Figure 4-1 that the objective function is relatively flat while we would expect a bigger increase at the end of the objective function. This is because the ECC has not yet reached its maximum. When the objective function reaches infinity, we expect the ECC to be equal to the CM cost and the ECL to be equal the MTTF. The reasoning behind this is that while time progresses, reliability decreases and eventually will become 0. By then, we expect a failure of the component and CM actions will take place.

Using equation (19), the effectiveness of using an age-based maintenance policy can be determined. However, to be able to compute equation (19), the g (∞) must be known. As stated previously, when the objective function reaches infinity, the ECC must be equal to the CM cost and the ECL must be equal to the MTTF. The ECC after 25 years is 1.007.499€ and thus not equal to the CM cost (1.230.654€). Furthermore, the ECL at 25 years is also not equal to the MTTF. Nevertheless, we will use the cost per unit time at 25 years to estimate the effectiveness of using an age-based maintenance policy. However, this estimation is an underestimation of the effectiveness of using an age-based maintenance policy. Equation (19) yields us an effectiveness of 1,0024 (equivalent of 0,24%). The low effectiveness of using an age-based maintenance policy is due to the high expected lifetime of the converter system.

4.2 Sensitivity analysis

4.2.1 Different configurations of maintenance costs

For our sensitivity analysis we have inserted 9 different configurations into our optimal maintenance planning model and plotted the results in a graph. The total PM and CM costs for the 9 different configurations are summed up in Table 4-1.

Table 4-1: PM & CM cost for the different configurations

Configuration	**PM cost (€)**	**CM cost (€)**
30 Optimistic	481.213,5	832.694
45 Optimistic	481.213,5	906.674
60 Optimistic	481.213,5	980.654
30 Baseline	541.213,5	1.082.694
45 Baseline	541.213,5	1.156.674
60 Baseline	541.213,5	1.230.654
30 Pessimistic	595.213,5	1.332.694
45 Pessimistic	595.213,5	1.406.674
60 Pessimistic	595.213,5	1.480.654

The objective functions for the 9 different configurations are depicted in Figure 4-2. However, it is hard to see where exactly the minimum is found and therefore we have summed them up in Table 4-2.

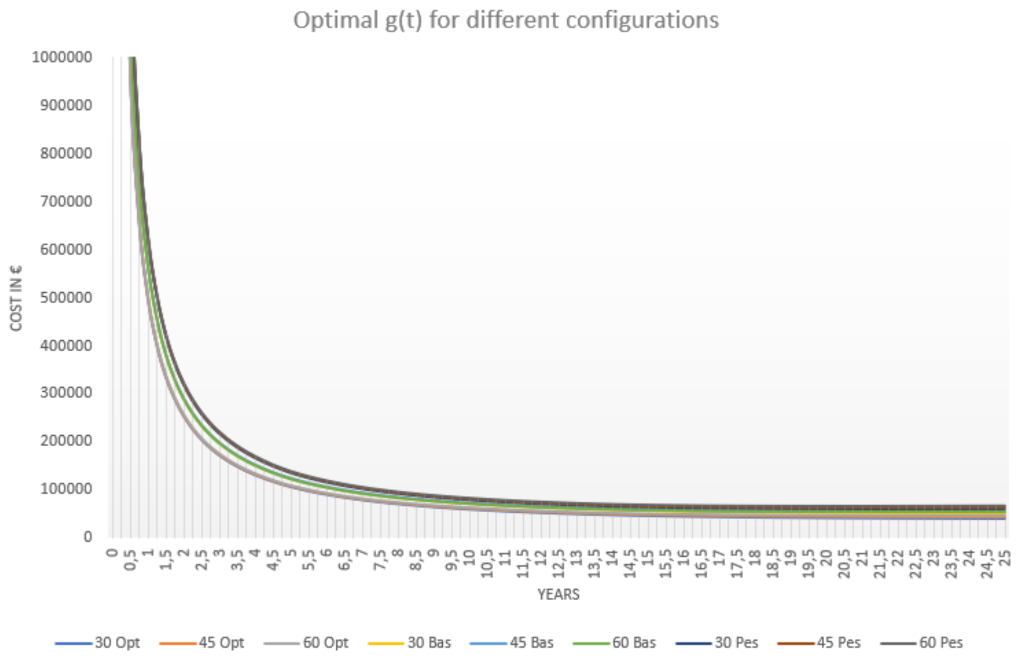

Figure 4-2: Optimal objective function g(t) for different configurations

Table 4-2: Optimal operational time t & cost per unit time for each configuration

Configuration	**Optimal fixed operational time t**	**Cost per time unit (€)**
30 Optimistic	25	40.449,60
45 Optimistic	25	43.264,72
60 Optimistic	25	46.079,86
30 Baseline	25	51055,41
45 Baseline	25	53.870,54
60 Baseline	21,75	56.545,77
30 Pessimistic	22,75	61.450,17
45 Pessimistic	21,25	64.020,10
60 Pessimistic	21	66.514,55

For the first five configurations, we see that the optimal fixed operational time to schedule PM is found at 25 years. However, their objective functions are still decreasing which implies that the optimum will be more than 25 years. As WTs are expected to have a lifetime of 20-25 years, it would be unnecessary to schedule PM for the converter system.

The last four configurations (60 Baseline, 30/45/60 Pessimistic) are the most interesting to analyze. From Table 4-2, we see that the cost per unit time increases and that the optimal fixed operational time t decreases, with the exception of one outlier. For the 60 Baseline, the optimum is found at 21,75 years at a cost per unit time of 56.545,77€. However, for the 30 Pessimistic we see an increase of the optimal fixed operational time namely at 22,75 years. Hereafter, the optimal fixed operational time decreases again.

To be able to understand why the previous happens, we must look at the difference between PM and CM costs and the ratio between them, summed up in Table 4-3. The ratio between PM and CM cost is further referred to as CM/PM cost ratio.

Table 4-3: Difference in maintenance cost & ratio between PM and CM cost for each configuration

Configuration	**Difference in maintenance cost (€)**	**CM/PM cost ratio**
30 Optimistic	351480,5	1,730404488
45 Optimistic	425460,5	1,884140823
60 Optimistic	499440,5	2,037877158
30 Baseline	541480,5	2,000493336
45 Baseline	615460,5	2,137186157
60 Baseline	689440,5	2,273878978
30 Pessimistic	737480,5	2,239018436
45 Pessimistic	811460,5	2,363309972
60 Pessimistic	885440,5	2,487601508

As it can be seen in Table 4-3, there is a bigger difference in maintenance cost between the 60 Baseline configuration and the 30 Pessimistic configuration. However, the CM/PM cost ratio is lower for the 30 Pessimistic compared to the 60 Baseline. The lower the ratio is, the longer we should wait to schedule PM. On the contrary, when the ratio is higher, it is more beneficial to schedule PM earlier to avoid an expensive CM. Thus, we see that the objective function is not dependent on the difference between PM and CM cost, but on the CM/PM cost ratio. We have run the optimal maintenance planning model several times for the 60 Baseline configuration with a CM cost of 1.230.654€ and adjusted the PM cost according to different CM/PM cost ratios. The results are shown in Table 4-4.

Additionally, using equation (19) and the information at the end of section 4.1, we can determine the effectiveness of using an age-based maintenance policy for each CM/PM cost ratio. The results have been converted to percentages and are depicted in Table 4-4 as well. As the CM/PM cost ratio increase, so does the effectiveness of using an age-based maintenance policy.

Table 4-4: Optimal fixed operation time t & cost per unit time for different CM/PM cost ratios

Ratio	**2**	**2,5**	**3**	**3,5**	**4**	**4,5**	**5**	**5,5**	**6**
CM €	1.230.654								
PM €	615.327	492.261	410.218	351.615	307.663	273.478	246.130	223.755	205.109
Optimal T* (years)	25	21	17,75	16	15	14	14	13,75	13,25
Cost/ time (€)	58.035	55.215	52.315	49.764	47.585	45.747	44.166	42.856	41.740
Effectiveness %	0	1	3,8	7	10,2	13,2	16,2	18,8	21,1

4.2.2 Optimal fixed operational time interval (major repair & replacement)

The parameters used for our model are the failure rates and reliability determined in section 3.6. Furthermore, we have used the 60 Baseline configuration to determine the optimal fixed operational time to schedule PM. We have a PM cost of 541.213,5€ and CM cost of 1.230.654€ (CM/PM cost ratio of 2,27). This yields the following objective function, depicted in Figure 4-3.

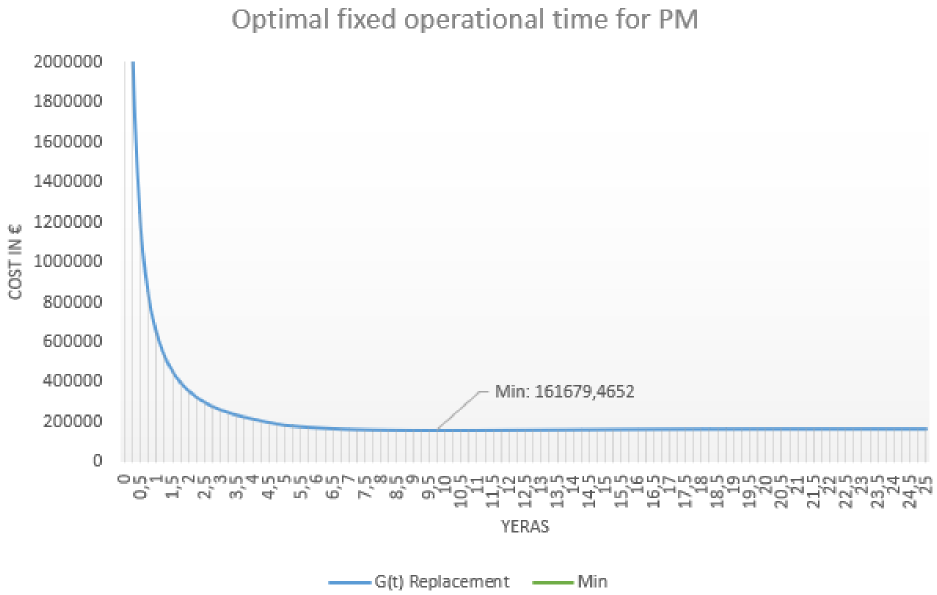

Figure 4-3: Optimal fixed operational time to schedule PM of a converter system (repair & replacement)

We find an optimum at 9,5 years with a cost per unit time of 161.679,47€. Thus, after 9,5 operational years we should schedule PM and replace the converter system. However, the reliability used in this model represents the major repair and replacement failures. Thus, the component can still be in good working condition or in need of major repair when it is replaced.

If the system fails prior to 9,5 years a CTV should be sent to the WT to assess the failure cause and to determine what type of maintenance actions are needed. As explained in section 2.3.1, major repairs can be executed with the use of a CTV, which is cheaper compared to a replacement with a JU vessel. This is due to high mobilization time, mobilization cost, and day rate of the JU vessel. Thus, if the component can be repaired, a CTV with 4-6 technicians should be sent to the WT to repair the component

Nevertheless, it is useful to model the combined reliability of major repairs and replacement for the following reason. WTs consist of many different components with each having their own reliability and maintenance cost. Running the optimal maintenance planning model for these other components can yield an optimum which is also approximately 9,5 years. Consequently, if both components are to be found operational for 9,5 years, PM actions can be performed simultaneously on both components. Thus, the converter system can possibly be replaced and reconditioned offsite using opportunistic maintenance. The reconditioned component can be considered to be “as good as new” and can eventually be used for PM on another WT.

We have run the optimal maintenance planning model for different CM/PM cost ratios and used the 60 Baseline configuration to determine the CM cost. The PM cost is calculated from the different CM/PM cost ratios. The results are summed up in Table 4-5. From Figure 4-4, we can see that the objective functions resemble the cost function more than we would expect. This is due to the higher CM/PM cost ratio but especially because of the lower reliability of the converter system. At 9,5 years the reliability is expected to be 29,47% and we expect a reliability of 0,01% after 25 years.

As the ECC is approximately equal to the CM cost (1.230.541€ versus 1.230.654€) and the reliability approaches 0 at 25 years, we can assume that objective function has reached infinity. Therefore, using equation (5), we can determine the MTTF which is estimated to be 7,3 years. Thus, when the objective function reaches infinity, the cost per unit time is estimated to be 168.356€. Using equation

(19), and the information above, we can determine the effectiveness of using an age-based maintenance policy. The effectiveness in % of the CM/PM cost ratios are summed up in Table 4-5.

Table 4-5: Optimal fixed operation time t & cost per unit time for different CM/PM cost ratios (repair & replacement)

Ratio	**2**	**2,5**	**3**	**3,5**	**4**	**4,5**	**5**	**5,5**	**6**
CM €	1.230.654								
PM €	615.327	492.261	410.218	351.615	307.663	273.478	246.130	223.755	205.109
Optimal T* (years)	11	9	7,75	7	6,75	6,5	5,75	5,5	5
Cost/time (€)	164.295	159.077	153.375	148.087	143.677	140.058	136.459	133.210	130.269
Effectiveness %	2,5	5,8	9,8	13,7	17,2	20,2	23,7	26,4	29,2

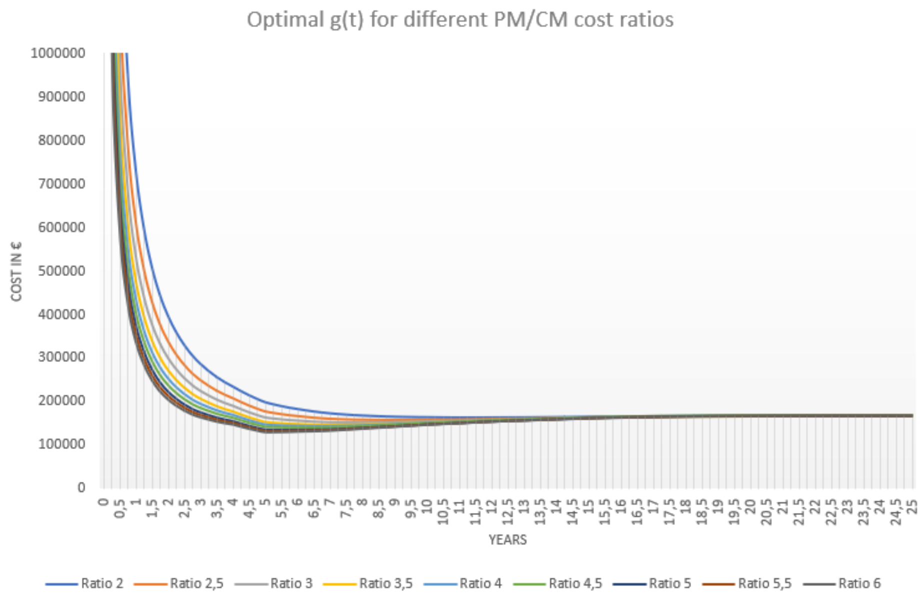

Figure 4-4: Optimal objective function g(t) for different CM/PM cost ratios (repair & replacement)

From Figure 4-4, we see an abrupt change in the objective function at around 5 years. This same abrupt change can be noted in the reliability curve of the converter system, depicted in Figure 3-6. As reliability is determined from the different failure rates categories, the abrupt change in the reliability curve can be traced back to fluctuations in failure rates, depicted in Figure 3-5. We see these fluctuations especially with the wear-out as well as the overload failure rate. Since wind speed fluctuates over time, so will the failure rates which are dependent on wind speeds. Furthermore, the wear-out failure rate is also dependent on the energy produced each year, depicted in Figure 3-1. Thus, if less energy is produced compared to a previous year, a slight decrease in the failure rate can be seen.

To conclude, assuming the reliability is unchanged, the objective function is strongly dependent on the CM/PM cost ratios. As CM/PM cost ratio increases, the optimal fixed operational time to schedule PM decreases. Thus, the lower the ratio is, the longer we should wait to schedule PM. On the contrary, when the ratio is higher, it is more beneficial to schedule PM earlier to avoid expensive CM. Using the reliability information based on solely replacement actions, PM should be scheduled to replace the converter system. Depending on the CM/PM cost ratios, the found optimums range in between 25 and 13,25 operational years. Furthermore, the usage of an age-based maintenance policy becomes more favorable as the CM/PM cost ratios increases.

However, when we determine the optimums based on the reliability information which considers major repairs and replacements, we find optimums in between 11 and 5 operational years. It is important to note that replacing the converter system based on the reliability information considering major repair and replacement, the converter system may still be in good working condition. Thus, the found optimums should be used to perform opportunistic maintenance when maintenance resources are already allocated at site.

4.3 Case study: rotor system

With the use of our model, we have analyzed the optimal fixed operational time to schedule PM for a rotor system of a WT. Only the most important steps and calculations will be discussed. We have determined the optimum for two different cases of the rotor system. First, the optimum is determined using the reliability information based on replacement maintenance actions only. Thereafter, the optimum is determined using the reliability information based on major repairs and replacement.

4.3.1 Optimal fixed operational time interval of the rotor system (replacement)

We first need to determine the reliability of the component to be able to compute the ECC and ECL from which the objective function is calculated. The reliability can be determined from the failure rates of the rotor system. Below, the failure rates determined by Fraunhofer of the different failure categories are shown.

$$Early\ failure: \lambda(t) = 0{,}29169 * \left(\frac{t}{1{,}028459149}\right)^{-0{,}7} \quad \textbf{(33)}$$

$$Aging\ failure: \lambda(t) = 0{,}4545875 * \left(\frac{t}{5{,}499491297}\right)^{1{,}5} \quad \textbf{(34)}$$

$$Random\ failure: \lambda(t) = 0{,}105 \quad \textbf{(35)}$$

$$Lightning\ failure: \lambda(t) = 0{,}05 \quad \textbf{(36)}$$

$$Icing\ failure: \lambda(t) = 0{,}05 \quad \textbf{(37)}$$

$$Overload\ failure: \lambda(Vwind) = 0{,}015624506 * (Vwind - 3{,}5) \quad \textbf{(38)}$$

$$Wear\ out\ failure: \lambda(t) = 0{,}054603696 * \left(\frac{E}{43{,}95306859}\right)^{1{,}4} \quad \textbf{(39)}$$

Just like the converter system, the failure rates must be multiplied with a certain share. These shares represent the probability that one of the maintenance actions are needed when a failure occurs, depicted in Table 4-6. We are only interested in replacing the rotor system for the same reasons as the converter system. Therefore we must multiply equation (33) with a factor of $\frac{0{,}1}{10{,}5}$, equation (34) with $\frac{0{,}5}{20{,}5}$, equation (35) with $\frac{0{,}1}{10{,}5}$, equation (36) with $\frac{0{,}1}{5}$, and equation (37) with $\frac{0{,}1}{5}$, equation (38) with $\frac{0{,}1}{8}$, and equation (39) with $\frac{2}{40{,}5}$.

Table 4-6: Share of maintenance actions and failure categories on overall failure behavior rotor system (Fraunhofer, 2017)

	Early (33)	**Aging (34)**	**Random (35)**	**Lightning (36)**	**Icing (37)**	**Overload (38)**	**Wear-out (39)**
Reset	2	5,5	2	1.4	1.4	2.9	8.8
Minor	5.9	11	5.9	2	2.5	4.5	23.3
Major	2.5	3.5	2.5	1.5	1	0.5	6.5
Replacement	0.1	0.5	0.1	0.1	0.1	0.1	2

Using equation (14), the model calculates the reliability for time t over a 25 year-span. The reliability of the rotor system is depicted in Figure 4-5.

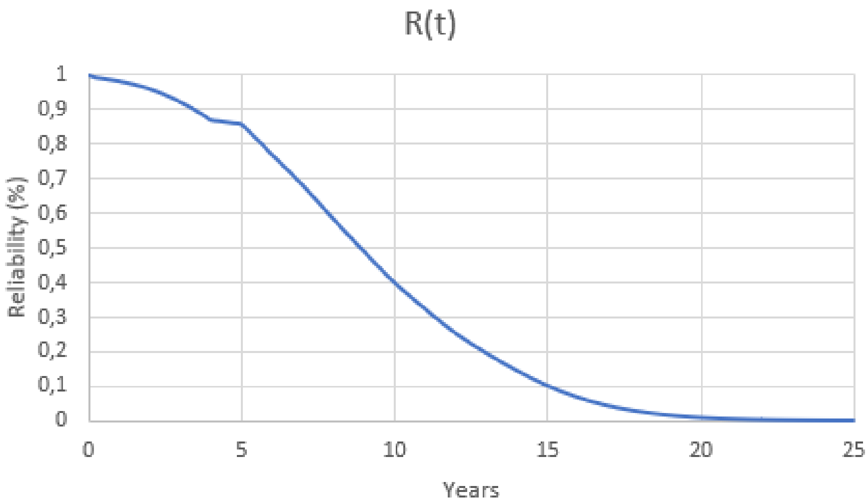

Figure 4-5: Reliability of the rotor system (only considering replacement)

We now also know the unreliability of the component, which is 1 minus the reliability. Using equations (17) and (18), the ECL is calculated. The last two unknowns to be able to compute the objective function are the PM and CM costs. Similarly to the converter system, the rotor system uses a JU vessel to replace the component. Thus, the day rate, mobilization time, and mobilization cost are unchanged. However, we need to adjust several other inputs. From Table 4-7 we see that we must change the reparation duration, which currently is 153 hours. This will also change the downtime cost for PM and CM. Furthermore, we must adjust the spare part cost to 52.000€. This yields a PM cost of 1.159.941,5€ and CM cost of 1.849.382€ (CM/PM cost ratio of 1,594375). Note that the CM/PM cost ratio is lower compared to the converter system.

Table 4-7: Information of rotor system: maintenance actions, repair duration, technicians, vessel type and material costs (Fraunhofer, 2017)

Rotor System (=MDA)	Reset	3	2	CTV	
	Minor Repair	9	2	CTV	196
	Major Repair	19	3	Crane	1879
	Replacement	153	12	JU	52000

The objective function is now calculated in the optimal maintenance planning model and is depicted in Figure 4-6. With a PM cost of 1.159.941,5€ and CM cost of 1.849.382€ (CM/PM cost ratio of

1,594375), we find the optimal fixed operational time to schedule PM at 13 years. The cost per unit time is equal to 197.198€. Thus, if the system is still operational after 13 years, the rotor system should be replaced with PM. If the system does fail prior to 13 years, CM will take place and the next PM is scheduled in 13 years.

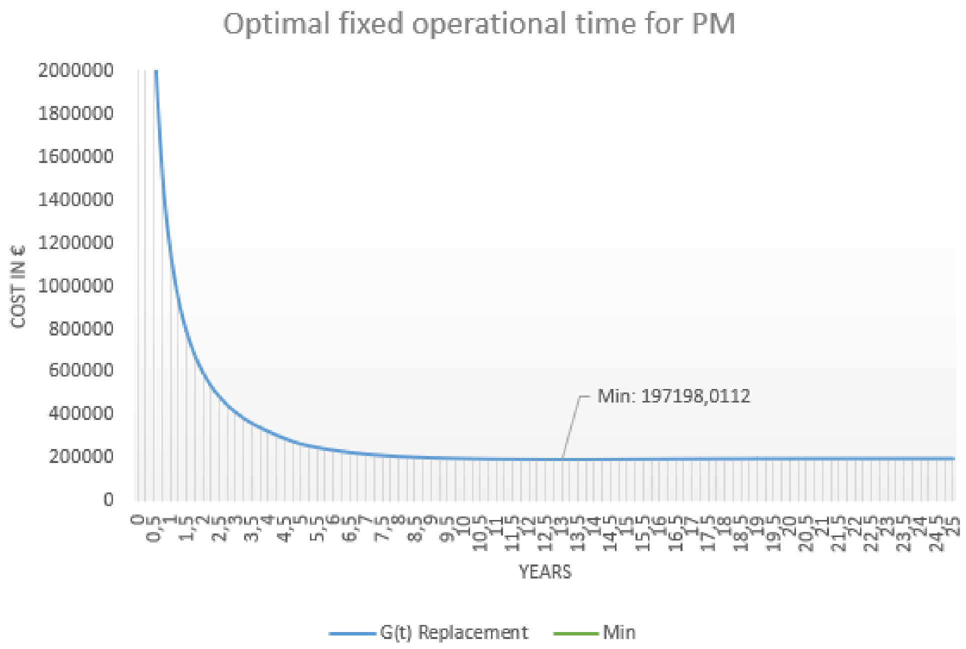

Figure 4-6: Optimal fixed operational time to schedule PM of the rotor system (replacement)

According to the parameters used, the optimum we found is correct. However, according to Rademakers et al. the CM/PM cost ratio for offshore WTs is estimated to be 2 or higher. The CM/PM cost ratio from the above found optimum is 1,594375. We have run the model several times for the same CM cost and a PM which is determined from different CM/PM cost ratios. The results are summed up in Table 4-8 and depicted in Figure 4-7. In Figure 4-7, we see an abrupt change in the objective functions. This is caused by the abrupt change in the reliability curve at around 5 years, which can be traced back to fluctuations in the failure rates, as explained in section 4.2.2.

Additionally, as the reliability approaches 0 at 25 years, we can assume that the reliability has reached infinity. Thus, we can use equation (5) to determine the MTTF of the rotor system. The MTTF of the rotor system is estimated to be 9,2 years. As explained in section 4.1, as time reaches infinity, the ECC should be equal to the CM cost and the ECL equal to the MTTF. The ECC at 25 years is 1.849.066€ and the ECL is equal to 9,2 years, which indicates the objective function has reached infinity. The cost per unit time is estimated to be 200.915€. Consequently, using equation (19), we can determine the effectiveness of using an age-based maintenance policy. The effectiveness in % of the CM/PM cost ratios are summed up in Table 4-8.

Table 4-8: Optimal fixed operation time t & cost per unit time for different CM/PM cost ratios (replacement rotor system)

Ratio	**2**	**2,5**	**3**	**3,5**	**4**	**4,5**	**5**	**5,5**	**6**
CM €	1.849.382								
PM €	924.691	739.752	616.460	528.394	462.345	410.973	369.876	336.876	308.230
Optimal T* (years)	9,5	7,75	7	5,75	5,25	5	5	5	5
Cost/time (€)	189.052	175.440	162.458	151.683	141.133	131.890	124.336	118.154	113.004
Effectiveness %	6,3	14,5	23,7	32,4	42,3	52,3	61,6	70	77,8

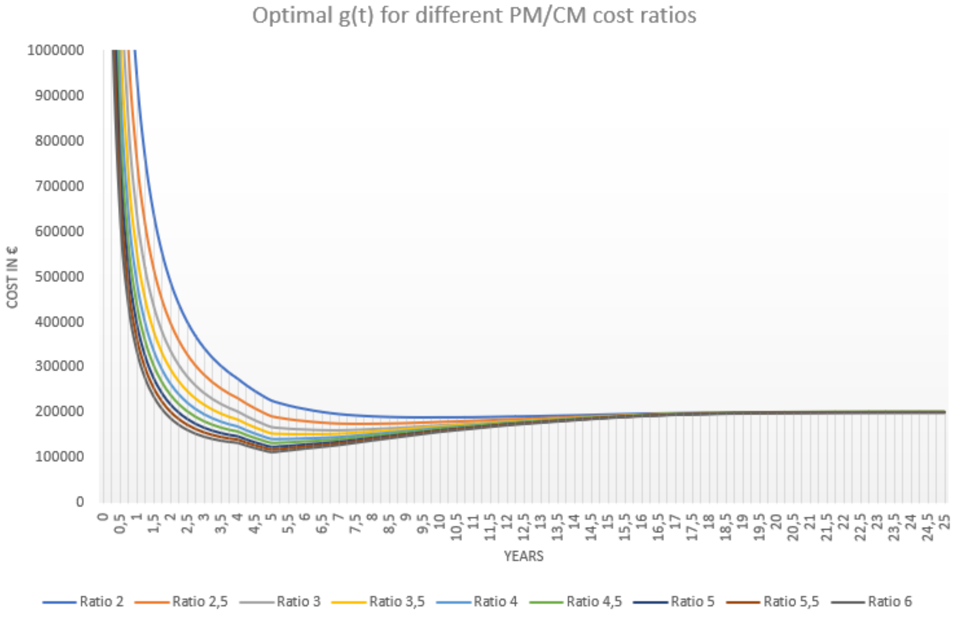

Figure 4-7: Optimal objective function g(t) for different CM/PM cost ratios (replacement of rotor system)

To conclude, using a CM/PM cost ratio of 2 which is underpinned by literature, we find the optimal fixed operational time to schedule PM at 9,5 year with a cost per unit time of 189.052€. If operators would adhere the current maintenance policy, which is a CM policy, the cost per unit time would be estimated to be 200.915€. The effectiveness of using an age-based maintenance policy compared to a CM policy is 6,3%. Moreover, using an age-based maintenance policy instead of a CM policy, 296.575€ in maintenance cost can be saved over the lifetime of one WT. Thus, e.g. for a wind farm with 50 WTs, approximately € 15 million can be saved in rotor system maintenance cost.

Therefore, we can conclude to schedule the PM replacement of the rotor system after 9,5 operational years. Moreover, from section 4.2.2, we also find an optimum at 9,5 years. If PM actions are undertaken for a rotor system and another converter system is found to be operational for 9,5 years, it would be economically sound to replace the converter system as well and recondition it offsite. Combining these two maintenance actions decreases the total logistic cost incurred over the lifetime of the WT and consequently decreases the total maintenance costs. In conclusion, while performing PM replacement on a rotor system, opportunistic maintenance can be used to replace a converter system which has also been operational for 9,5 years.

4.3.2 Optimal fixed operational time interval of the rotor system (repair & replacement)

As explained in section 4.3.1, the failure rates must be multiplied with a certain share. These shares represent the probability that one of the maintenance actions are needed when a failure occurs, depicted in Table 4-6. We are now interested in major repair and replacement of the rotor system. Therefore we must multiply equation (33) with a factor of $\frac{2,6}{10,5}$, equation (34) with $\frac{4}{20,5}$, equation (35) with $\frac{2,6}{10,5}$, equation (36) with $\frac{1,6}{5}$, and equation (37) with $\frac{1,1}{5}$, equation (38) with $\frac{0,6}{8}$, and equation (39) with $\frac{8,5}{40,5}$.

Using equation (14), the model calculates the reliability for time t over a 25 year-span. The reliability of the rotor system is depicted in Figure 4-8.

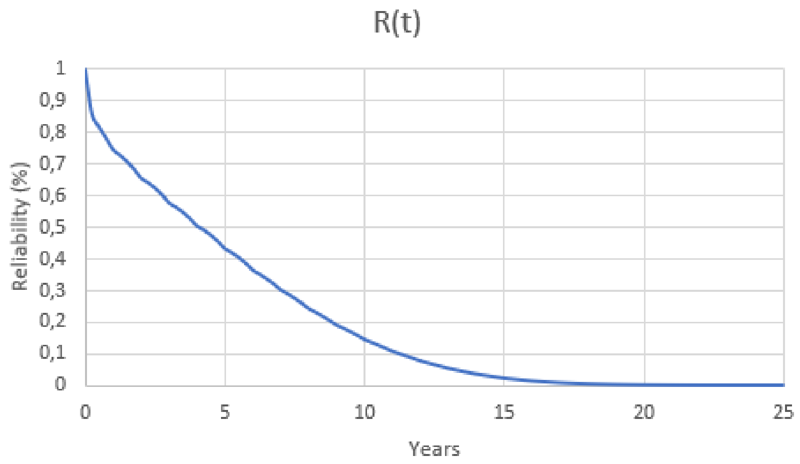

Figure 4-8: Reliability of the rotor system (considering major repair & replacement)

We now also know the unreliability of the component, which is 1 minus the reliability. Using equations (17) and (18), the ECL is calculated. In section 4.3.1, we have determined the PM cost to be 1.159.941,5€ and a CM cost of 1.849.382€ (CM/PM cost ratio of 1,594375).

The objective function is now calculated in the optimal maintenance planning model and depicted in Figure 4-9. With the PM and CM cost stated above, we find the optimal fixed operational time to schedule PM at 16,5 years. The cost per unit time is equal to 371.406€. The effectiveness of using an age-based maintenance policy is 1,0004 (0,04%). As it has been done in previous sections, the optimal fixed operational time to schedule PM is determined for several CM/PM cost ratios. The results are summed up in Table 4-9 and depicted in Figure 4-10.

Additionally, as the reliability approaches 0 at 25 years, we can assume that the reliability has reached infinity. Thus, we can use equation (5) to determine the MTTF of the rotor system. The MTTF of the rotor system is estimated to be 4,97 years. As explained in section 4.1, as time reaches infinity, the ECC should be equal to the CM cost and the ECL equal to the MTTF. The ECC at 25 years is 1.849.360€ and the ECL equal to 4,97 years, which indicates the objective function has reached infinity. The cost per unit time is estimated to be 371.555€. Consequently, using equation (19), we can determine the effectiveness of using an age-based maintenance policy. The effectiveness in % of the CM/PM cost ratios are summed up in Table 4-9 as well.

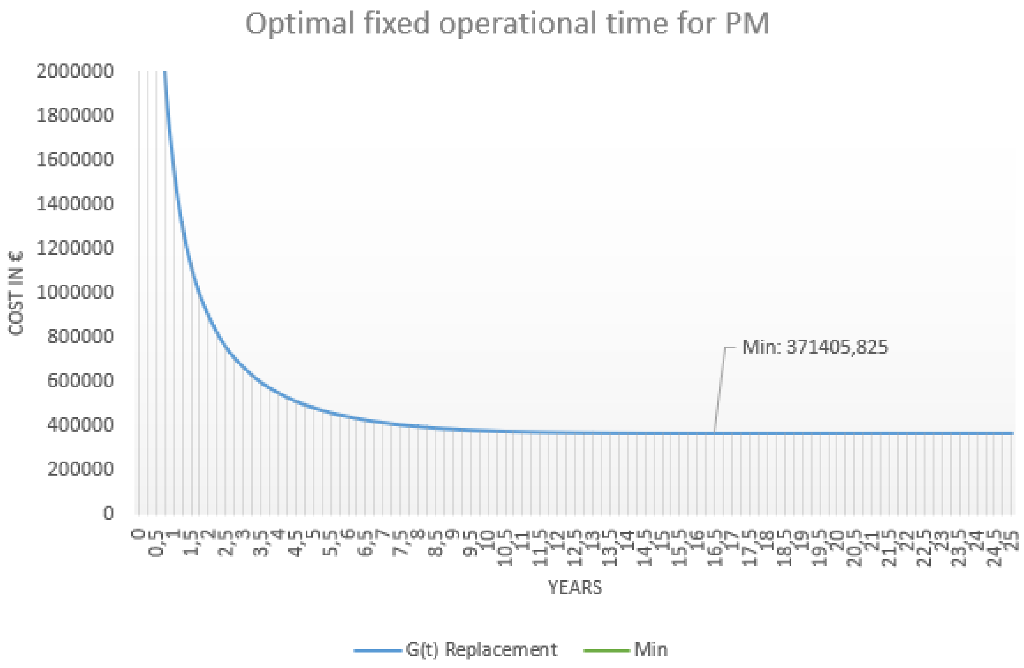

Figure 4-9: Optimal fixed operational time to schedule PM of the rotor system (major repair & replacement)

Table 4-9: Optimal fixed operation time t & cost per unit time for different CM/PM cost ratios (major repair & replacement rotor system)

Ratio	**2**	**2,5**	**3**	**3,5**	**4**	**4,5**	**5**	**5,5**	**6**
CM €	1.849.382								
PM €	924.691	739.752	616.460	528.394	462.345	410.973	369.876	336.876	308.230
Optimal T* (years)	13,5	11,5	10,5	9,5	8,75	8,5	8,5	7,75	7,5
Cost/time (€)	370.125	367.416	364.454	361.444	358.945	356.432	354.344	352.667	350.900
Effectiveness %	0,4	1,1	1,9	2,8	3,5	4,2	4,9	5,4	5,9

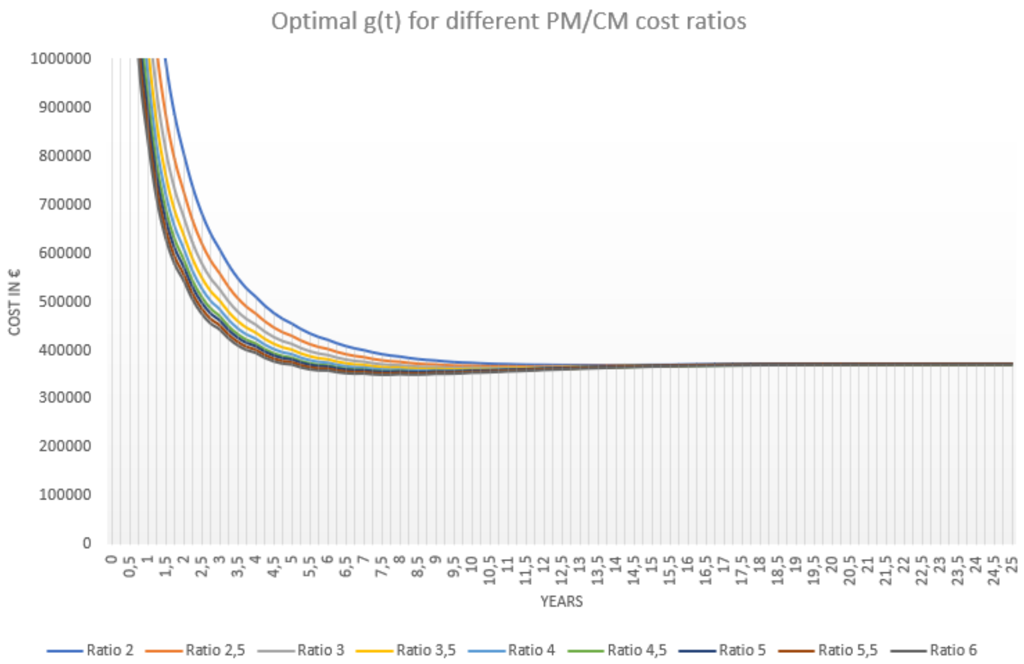

Figure 4-10:Optimal objective function g(t) for different CM/PM cost ratios (major repair & replacement of rotor system)

To conclude, for the cost parameter used (CM/PM cost ratio 1,594375) we find an optimum at 16,5 years with a cost per unit time of 371.406€. However, the effectiveness of using an age-based maintenance policy is low, namely 0,04%. Using a more reasonable CM/PM cost ratio of 2, we find the optimum at 13,5 years with an effectiveness of 0,4%. As the CM/PM cost ratios increases, so does the effectiveness of using an age-based maintenance policy.

However, the reliability used in this model represents the major repair and replacement failures. Thus, the component can still be in good working condition or in need of major repair when it is replaced. Nevertheless, it is useful to model the combined reliability of major repairs and replacement. As explained, WTs consist of many different components. Other components might have an optimum which is close to 13,5 years and which gives the opportunity for operators to replace the rotor system using opportunistic maintenance.

5 Conclusion

In the final chapter, we will conclude the research and answer the research questions set at the beginning of the report. We will first answer the sub questions before answering the main research question.

How can the maintenance of wind turbines be characterized? Can it be modeled by using a well-known maintenance policy? If so, how can the optimal parameters of the selected policy be calculated with the use of failure behaviors?

The maintenance of wind turbines can mainly be characterized by preventive and corrective maintenance. Corrective maintenance involves the activities undertaken after a failure of the system or component. In some cases, the system can continue working even though a failure has occurred. This is due to installed back-up components or the importance of the component itself. Nevertheless, for the majority of components the system will stop working once a failure has occurred. A failure has economic consequences such as expensive maintenance cost due to difficult accessibility of the wind turbine, labor hours, logistic cost, cost of spare parts or loss in revenue caused by the downtime.

On the other hand, preventive maintenance involves the maintenance activities prior to the failure of the system or component. This strategy can be based on the Original Equipment Manufacturer recommendations. This is suitable for some preventive maintenance activities such as lubrication, oil changes, filter cleaning and so on. However, the focus of the research is on preventive maintenance activities which involve replacing a component prior to a failure even though it hasn't reached the end of its useful life cycle. One of the main objectives of preventive maintenance is to reduce the failure frequency of the system or component. Therefore, it contributes to minimizing failure costs and machine downtime.

The maintenance activities can mainly be classified as: reset, minor repair, major repair, and replacement. A manual reset is a brief inspection or reset of the wind turbine which sometimes involve routine replacements or some consumables. A minor repair is a relatively small repair of the wind turbine needing small spare parts. Reset and minor repairs take less than a day to execute. Major repairs are large repairs and small component replacements needing relatively small spare parts. As the name suggests, replacements are the replacements of large components involving a large crew and a vessel with lifting capacity. These maintenance activities can take up to a few days or weeks to execute. During this time high downtime cost is incurred by the operators of wind turbines.

Therefore, our component of choice is the converter system of an offshore wind turbine. Converter systems converts direct current from the generator into alternating current to be exported to the grid network. It has a high share on the annual downtime of wind turbines which results in high downtime costs. The preventive maintenance cost to replace a converter system on an offshore wind turbine is 541.213,5€. Corrective maintenance cost of the converter system is estimated at 1.230.654€. Furthermore, we have analyzed a second wind turbine component, namely the rotor system, to check the usage of our designed optimal maintenance planning model. The preventive maintenance cost to replace a rotor system on an offshore wind turbine is 1.159.941,5€. Corrective maintenance cost of the rotor system is estimated to be 1.849.382€.

Thus, to avoid unnecessary failures and high costs, preventive maintenance should be scheduled prior to a failure. This can be accomplished by modeling the planning of preventive maintenance with an age-based policy, also known as type-1 policy. This policy is especially useful to model the preventive maintenance of one or multiple components. To be able to use this policy to model the preventive maintenance, the failure rate function of the component must be increasing over time. Furthermore, the difference between preventive and corrective maintenance cost should be substantial for the policy to be useful. An age-based policy is defined as a maintenance policy which performs preventive maintenance after an optimal fixed operational time (hours, days, months, years). If a failure occurs prior to the optimal fixed operational time, corrective maintenance will be executed, and the next preventive maintenance will again be scheduled after the optimal fixed operational time. The age-based policy considers the system to be “as good as new” after the maintenance activities.

The optimal fixed operational time to replace a component can be derived from the objective function, which is a function over time. The objective function minimizes the maintenance cost and is found from the expected cost per cycle and the expected cycle length. As the name suggests, the expected cost per cycle is the maintenance cost expected during the life cycle of the component. It is determined from the preventive and corrective maintenance cost and the reliability and unreliability of the component. The reliability and unreliability can be determined from the failure behaviors of a component. Failure behaviors are commonly expressed with failure rate functions from which the reliability can easily be calculated. Finally, the expected cycle length is the cycle length of the component until it is expected to fail. It can be determined from the reliability and unreliability of the component.

What is the influence of different maintenance cost configurations on the optimal maintenance policy?

Using different cost configurations has a big influence on the optimal fixed operational time to schedule preventive maintenance. The optimal fixed operational time in our research is found at 21,75 years at a cost per unit time of 56.545,77€. Using different cost configurations, the optimal shifts between an optimal time of 25 years and 13,25 years. The optimal strongly depends on the reliability of the component, and the ratio between preventive and corrective maintenance cost (CM/PM cost ratio). E.g. a CM/PM cost ratio of 2 implies that corrective maintenance cost are two times bigger than the preventive maintenance cost. Assuming the reliability is unchanged, a CM/PM cost ratio of 2 will yield an optimal at 25 years which will make the scheduling of preventive maintenance redundant. On average, the expected lifetime of a wind turbine is estimated to be 20-25 years. A slight increase of the CM/PM cost ratio to 2,5 already has a significant impact on the optimal which shifts to 21 years. Increasing the CM/PM cost ratio even further to 3 yields an optimal at 17,75 years. At a CM/PM cost ratio of 6, we find an optimal fixed operational time to schedule preventive maintenance of the converter system at 13,25 years. Furthermore, the usage of an age-based maintenance policy becomes more effective as the CM/PM cost ratios increases. The effectiveness is estimated to be 1 (0%) for a CM/PM cost ratio of 2 and estimated to be 1,211 (21,1%) for a CM/PM cost ratio of 6.

Finally, our main research question will be answered:

How can maintenance of wind turbines be planned by using reliability information of components such that total downtime, maintenance, and logistics costs are minimized?

Thus, to conclude, the maintenance of wind turbines can be planned using an age-based maintenance policy. This policy schedules preventive maintenance of one or multiple components after fixed operational time (hours, days, months, years). The objective function of the age-based maintenance policy finds an optimal time which minimizes the total maintenance costs and ensures enough reliability of the system or component. The total maintenance cost includes all the downtime, maintenance, and logistics costs incurred during execution of preventive or corrective maintenance.

Furthermore, we have designed an optimal maintenance planning model which can determine the optimal preventive replacement time for numerous wind turbine components, using different cost parameters inputs and reliability information. The designed model minimizes the total downtime, maintenance and logistics costs

6 Recommendations

In the following chapter, we will discuss the final recommendations for the proceedings of future research. From the research and section 2.3.5 a few recommendations arise.

The optimal maintenance planning model should be extended with other seasonal changes such as more variability in the cost determinations, waiting times, and capacity factor.

As previously explained, the day rates of the used JU vessels fluctuate per season. This is due to the more favorable weather conditions during certain months of the year to execute maintenance on offshore wind turbines. During the more favorable months, a higher demand for jack-up vessels can be observed. Consequently, a higher day rate must be paid compared to lower demand months such as during the winter.

The higher demand during the more favorable weather conditions is a direct impact of the wave and wind speeds limits of the JU vessel. Long waiting times in port are not uncommon during the winter months compared to e.g. the summer months. Waiting times in port have a big influence on the total vessel cost and the downtime cost. Consequently, the preventive or corrective maintenance cost can dramatically increase.

Furthermore, adding other seasonal changes to the model would also imply to implement this for the capacity factor. An average capacity factor has been used to determine the downtime cost. However, seasonal capacity factor would be more suitable once the model is adjusted.

Further research the possibility to use k-mean clustering to find more suitable optimums for more than one component.

The model currently determines the optimal fixed operational time to schedule preventive maintenance for one single component. First, the model should be used to analyze the optimal of all other major components. Hereafter, the age-based maintenance policy can be extended with e.g. k-mean clustering. K-mean clustering is where different optimums of several components are grouped together in clusters and a new optimum is determined for the newly defined clusters (Teknomo, 2018). In fact, k-mean clustering is an optimization of the found optimums of each component in a cluster. Due to time restriction and insufficient available data, we were not able to determine the optimums of all major components in an offshore wind turbine.

Execute a sensitivity analysis on the influence of the reliability of a component on the optimal fixed operational time to schedule preventive maintenance.

In the research a sensitivity analysis on the maintenance costs has been carried out. However, the optimal fixed operational time is also strongly dependent on the reliability of a component. Therefore, it would be useful to analyze the influence of a change in reliability and the influence of variability on the optimal time to schedule preventive maintenance. As explained in the report, reliability is dependent on different failure categories which can be caused by internal or external factors. External factors can be factors such as wind speeds which influence the wear-out and overload failure rates. Moreover, failure categories which are dependent on internal factors can change due to e.g. improved manufactured components. Therefore, the overall reliability of the component can possibly increase or decrease which in terms has an influence on the objective function. For example, it would be useful to analyze and determine when to schedule preventive maintenance if the operators have experienced one or several years with higher measured wind speeds. As information about the parameter's limits of the of the different failure categories were not available to us, we were not able to determine the possible changes in reliability of the converter or rotor system.

Analyze different optimums of major components to seek the opportunity to perform opportunistic maintenance.

Using the optimal maintenance planning model, optimums for all major components should be determined based on reliability information which solely considers major repair and replacement. Replacing components requires expensive equipment with high logistic costs. Thus, while performing corrective or preventive replacement actions, needed maintenance resources are already allocated at site. This yields the opportunity to use the maintenance resources to replace other components which are expected to fail with a short period of time after the allocation of maintenance resources. Thus, using the determined optimums, components can possibly be replaced preventively using opportunistic maintenance.

Research the possibility to implement condition-based maintenance using condition monitoring systems in wind turbines.

As wind turbines increases in size, operation and maintenance procedures need to be optimized to increase reliability, safety and maximize cost effectiveness (A. May & D. McMilan, 2018). The installation of condition monitoring systems into wind turbines becomes more widely spread adopted by operators. This allows operators to possibly adopt condition-based maintenance and to reduce the cost of preventive as well as corrective maintenance actions. Maintenance decisions are based on information of the actual condition or health of the component or system. This information can be obtained from health or condition monitoring systems. Most wind turbines have an installed condition monitoring system, called SCADA system. The SCADA system measures temperatures, pitch angle, electrical parameters, rotor speed, etc. However, applying CBM, is only possible if there are conditions that are related to the moment of failure and if it is technically possible to monitor these conditions. Therefore, further research must be done into the possibility to adopt condition-based maintenance with the use of condition monitoring systems.

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8 Appendix

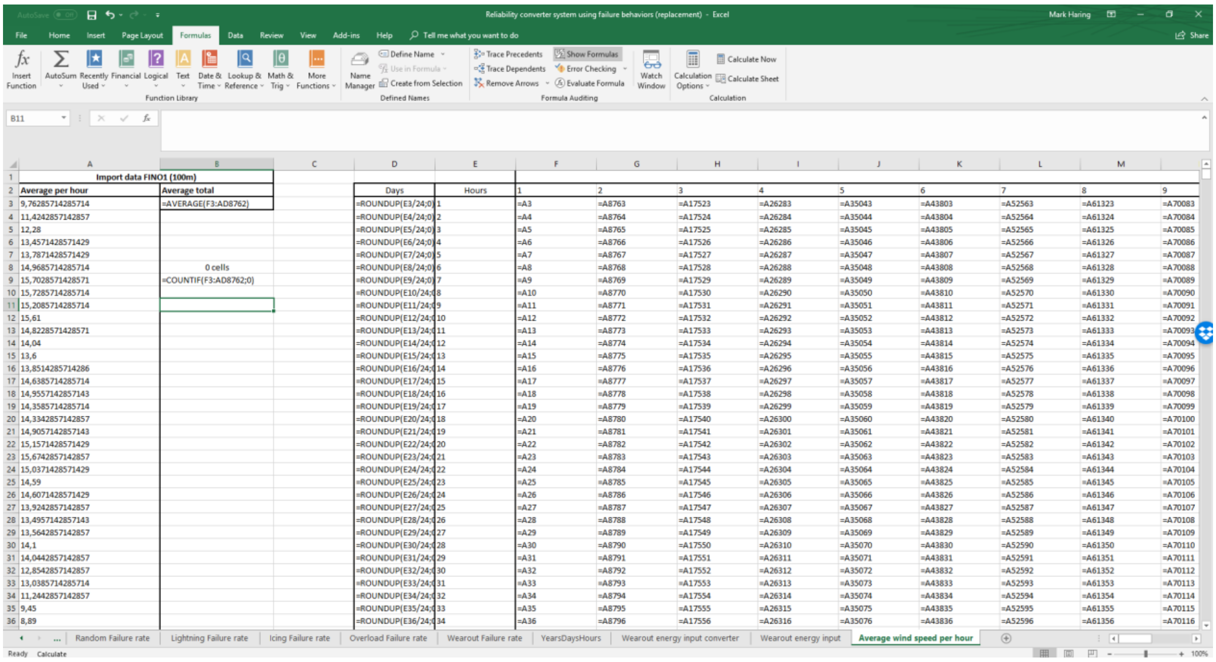
A: Technical data 5MW WT

Design	
Rated Power	5,000 kW
Cut-In Wind Speed	3.5 m/s
Rated Wind Speed	13 m/s
Cut-Out Wind Speed	
Offshore Version	30 m/s
Onshore Version	25 m/s
Certification acc. to	TK I, GL Offshore (extended with design for 10.5 m/s annual average wind speed)
Rotor	
Diameter	126 m
Speed Range, normal operation	approx. 6.9 – 12.1 rpm
Control	
Principle	Blade Angle and Speed Control, Electrical Pitch
Safety Systems	
3 Individual Fail-Safe Blade Pitch Systems	
Rotor Locking Brake	
Fully integrated lightning protection system with multiple receptor principle in the rotor blades	
Gearbox	
Design	Combined Planetary/Spur Wheel Gears
Transmission Ratio	i = approx. 97
Generator	
Design	Doubly Fed Asynchronous Generator, 6 Pole
Speed Range	approx. 670 – 1,170 rpm
Masses	
Rotor	approx. 120 t
Nacelle (without rotor)	approx. 290 t

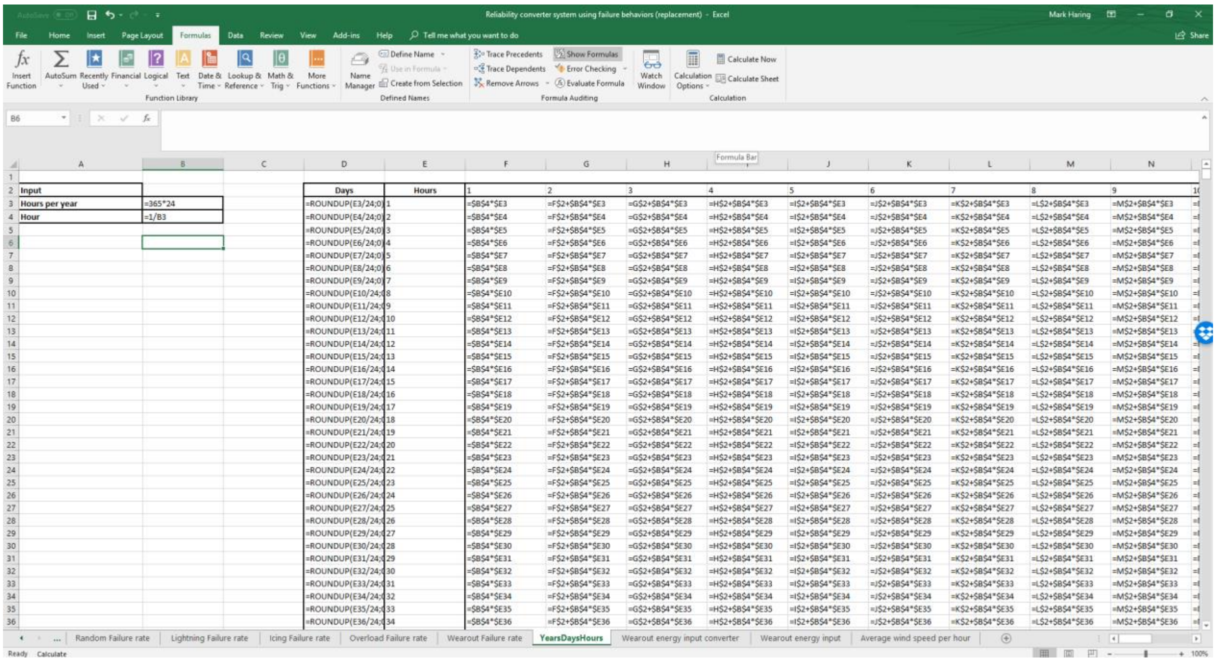
Status October 2004
Subject to technical changes

B: Calculations Excel

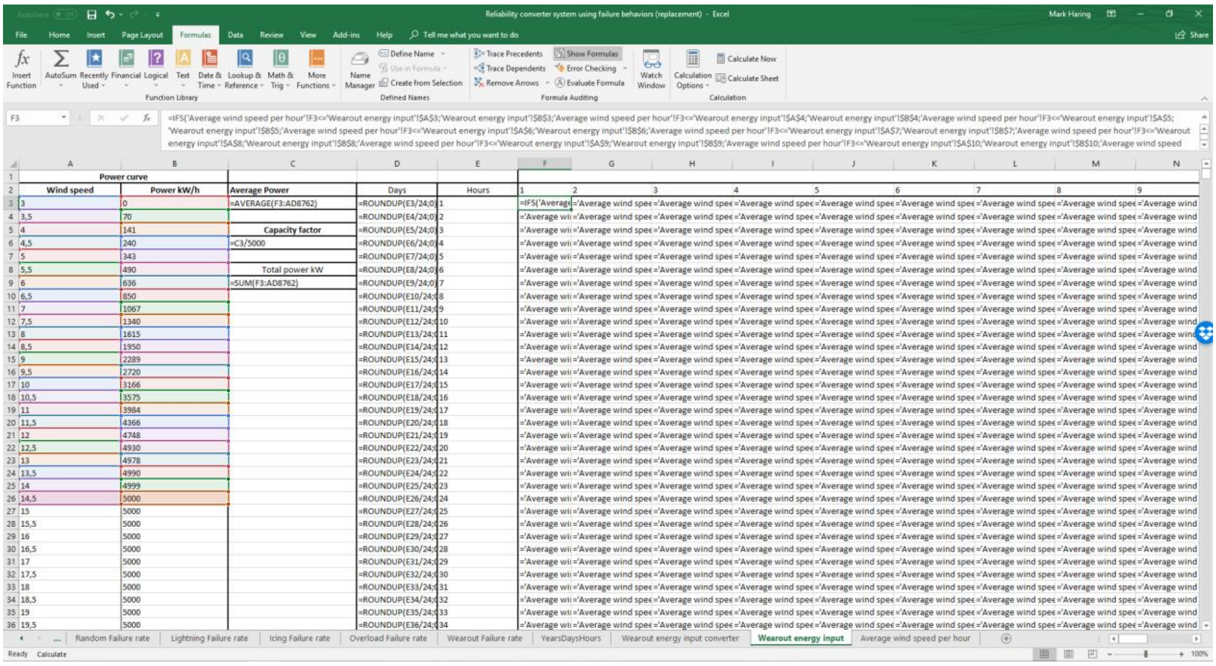
Hourly wind speeds



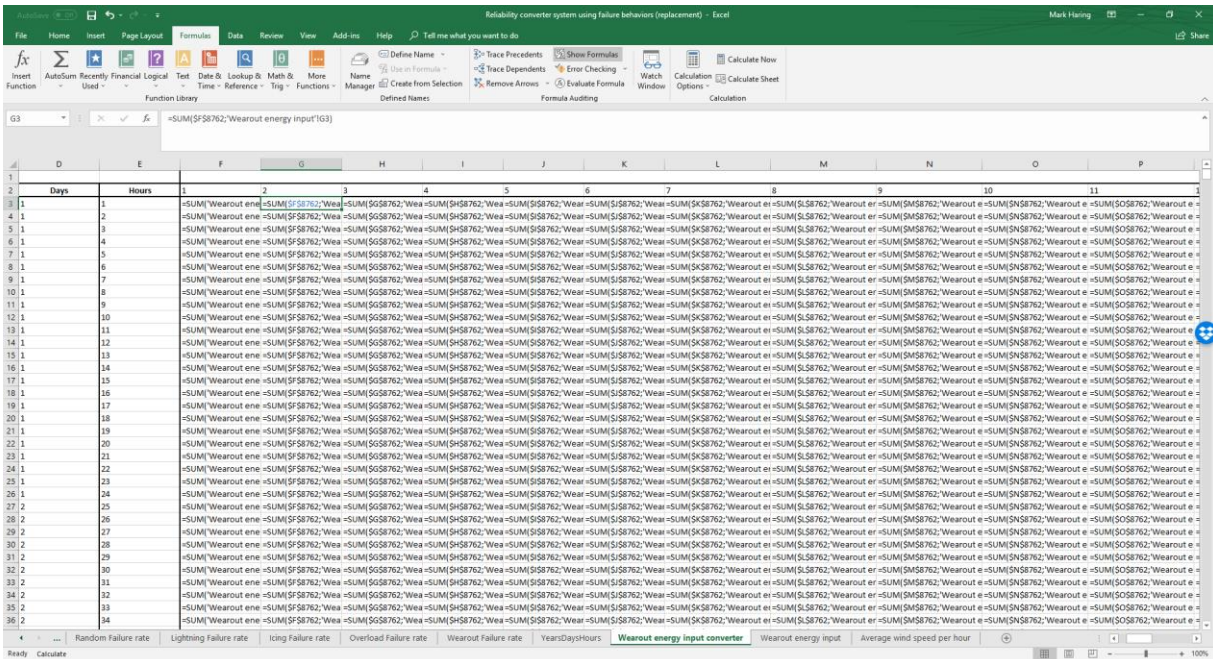
Hours in a year



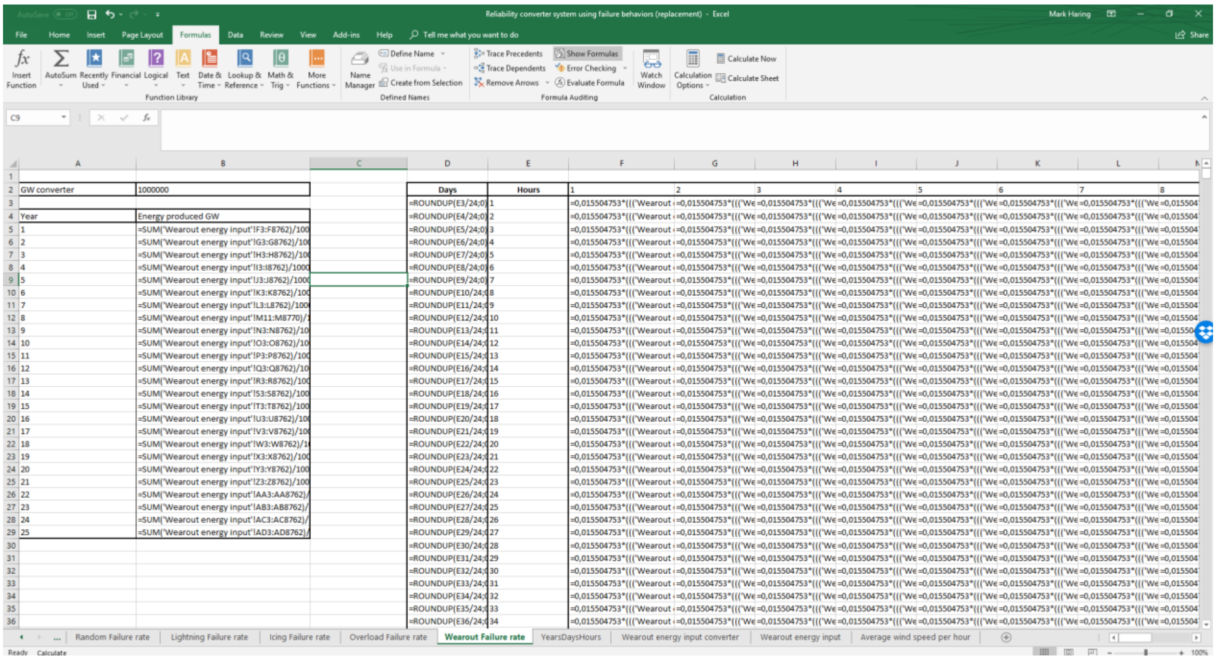
Wearout energy input



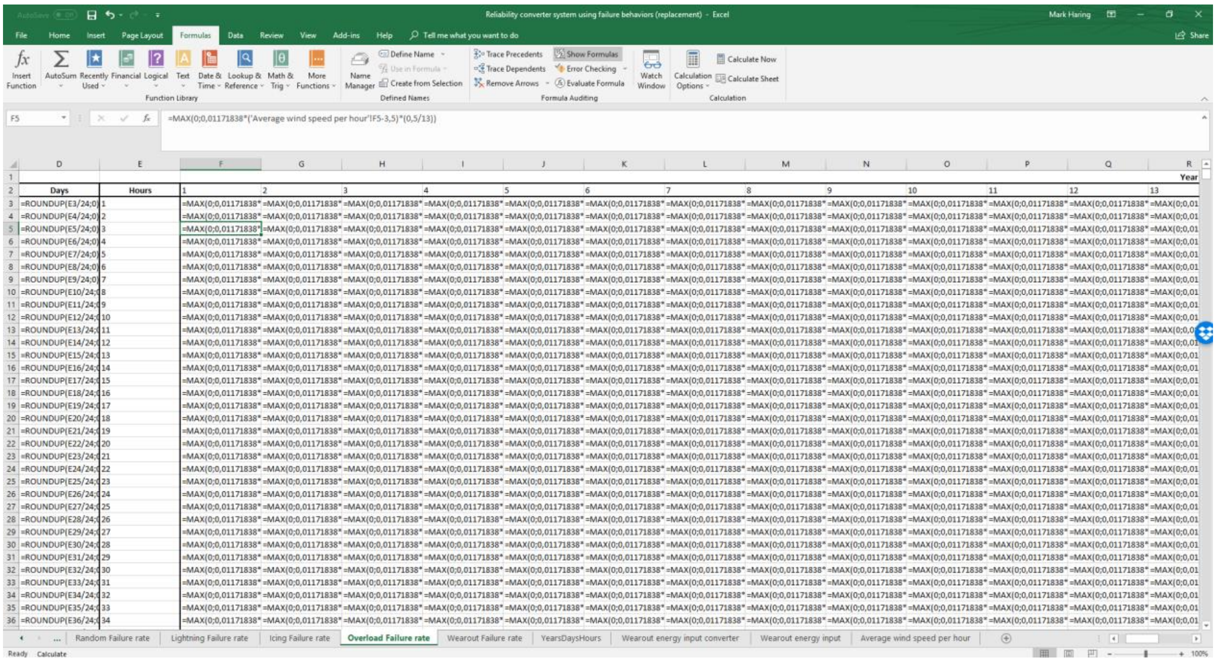
Wearout energy input converter



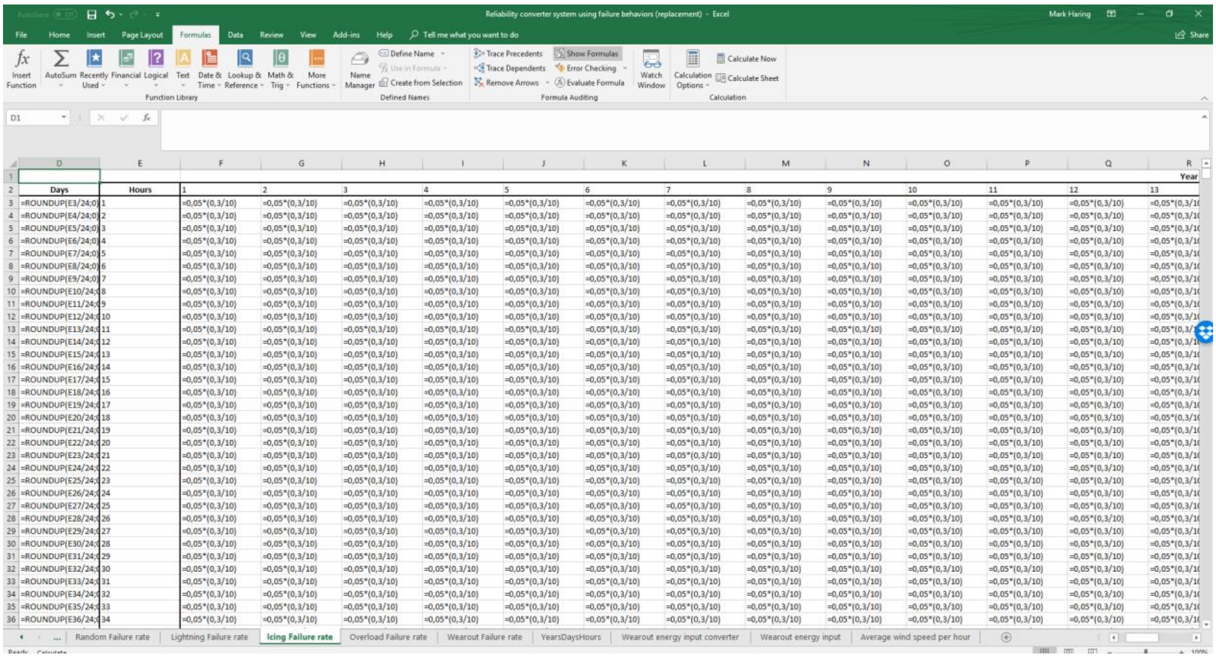
Wearout failure rate



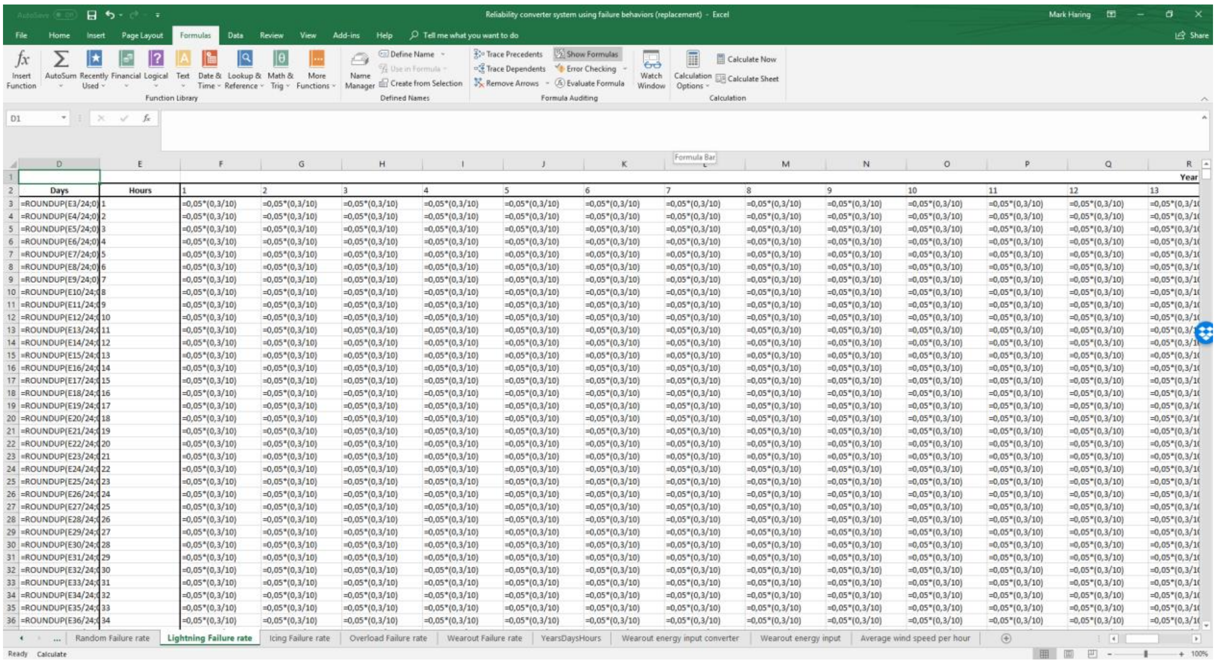
Overload failure rate



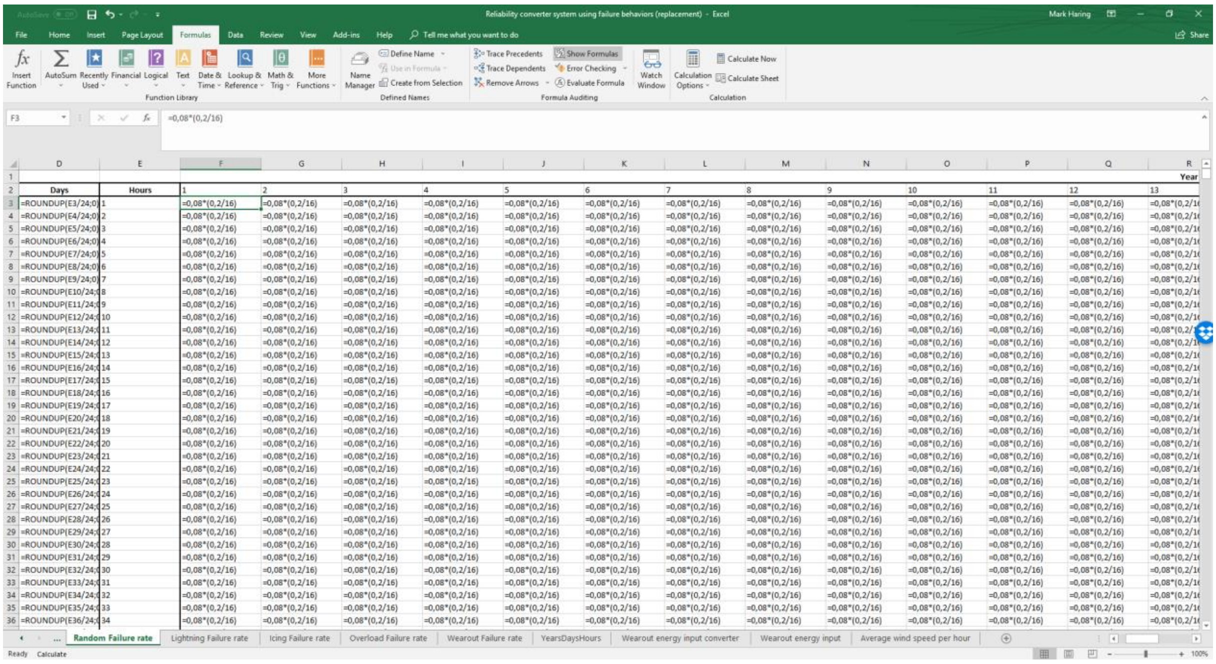
Icing failure rate



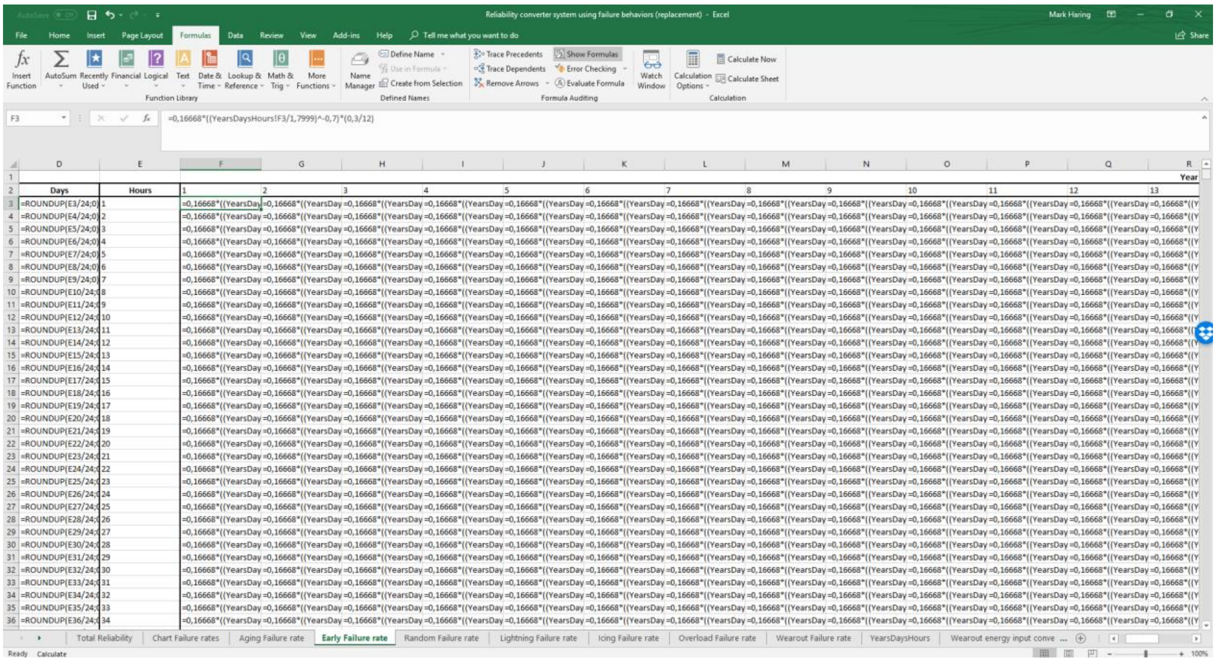
Lightning failure rate



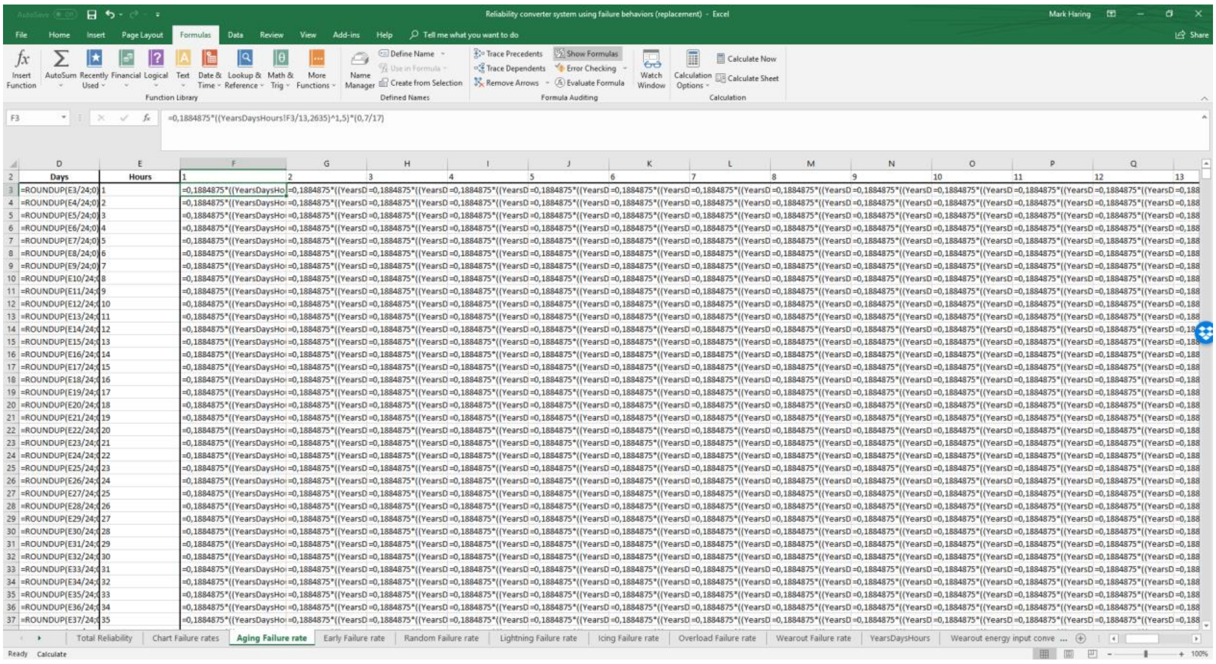
Random failure rate



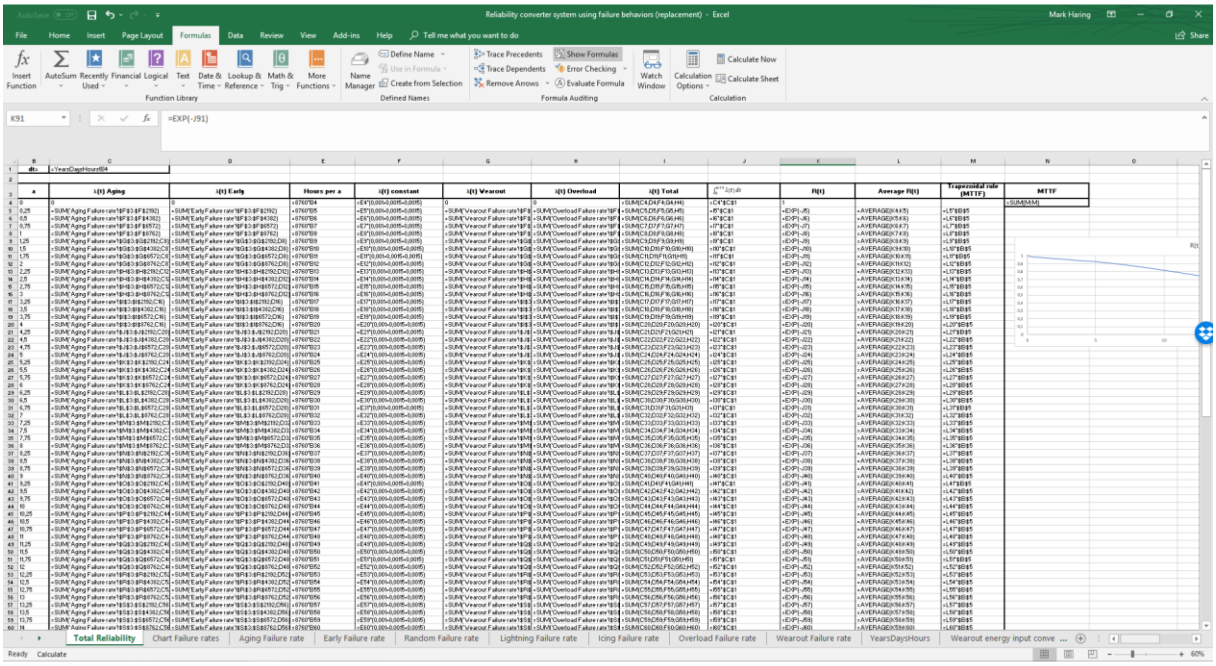
Early failure rate



Aging failure rate



Reliability converter system



Overview PM and CM costs

CM (C1)	Vessel cost									
	Maintenance action	Pre-inspections CTV [€]	Vessel type	Mobilization time (h)	Mobilization costs [€]	Day rate [€]	Hourly rate [€]	Maintenance time (h)	Travel time (h)	Total vessel cost [€]
	Replacement	3500	JU	1440	500000	140000	5833,333333	57	12	906000

Downtime cost								
Number of WT	Feed-in price (€ kW/h)	Turbine size (kW)	Capacity factor (%)	Downtime travel time CTV (h)	Downtime pre-inspection (h)	Downtime mobilization time (h)	Duration maintenance (h)	Total downtime cost [€]
1	0,1	5000	0,411	3	8	1440	57	309894

Labor cost				
Number of technicians	Travel time (h)	Inspection time (h)	Hourly rate (€/h)	Total labor cost [€]
2	3	8	80	1760

Spare part cost [€]	
Component	Cost
converter system	13000

Total PM cost				
Total vessel cost [€]	Total downtime cost [€]	Total labor cost [€]	Total spare-part cost [€]	Total PM cost [€]
906000	309894	1760	13000	1230654

PM (C0)	Vessel cost									
	Maintenance action	Pre-inspections CTV [€]	Vessel type	Mobilization time (h)	Mobilization costs [€]	Day rate [€]	Hourly rate [€]	Maintenance time (h)	Travel time (h)	Total vessel cost [€]
	Replacement	0	JU	0	114000	140000	5833,33333	57	12	516500

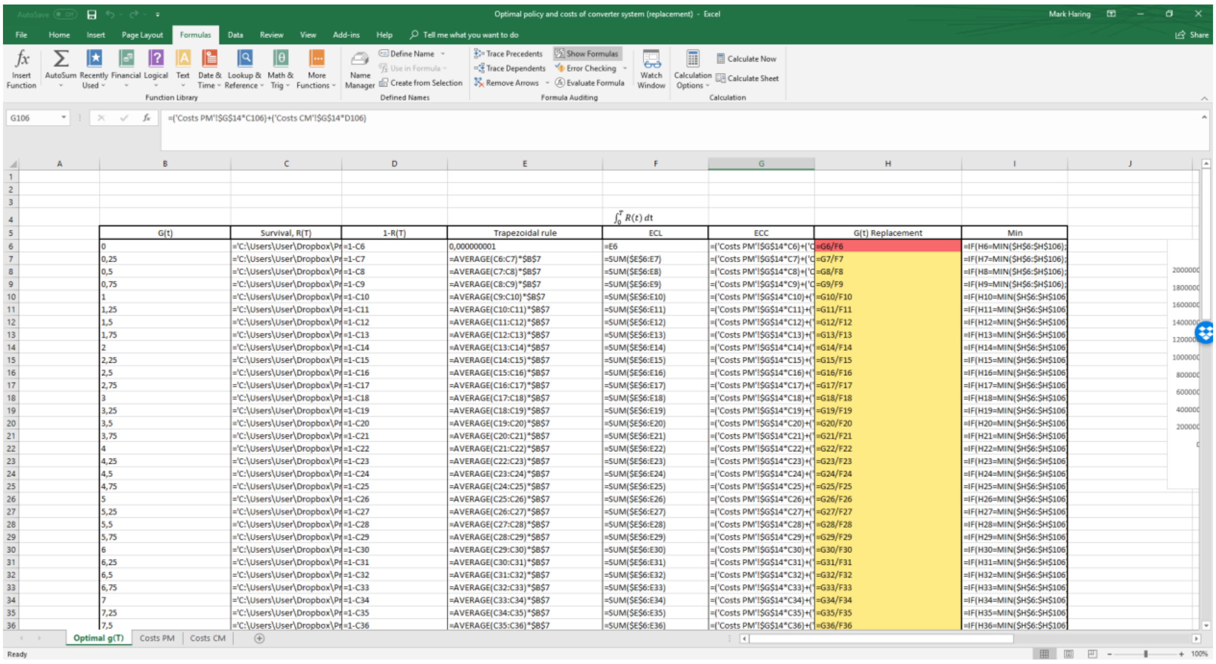
Downtime cost								
Number of WT	Feed-in price (€ kW/h)	Turbine size (kW)	Capacity factor (%)	Downtime travel time CTV (h)	Downtime pre-inspection (h)	Downtime mobilization time (h)	Duration maintenance (h)	Total downtime cost [€]
1	0,1	5000	0,411	0	0	0	57	11713,5

Labor cost				
Number of technicians	Travel time (h)	Inspection time (h)	Hourly rate (€/h)	Total labor cost [€]
0	0	0	80	0

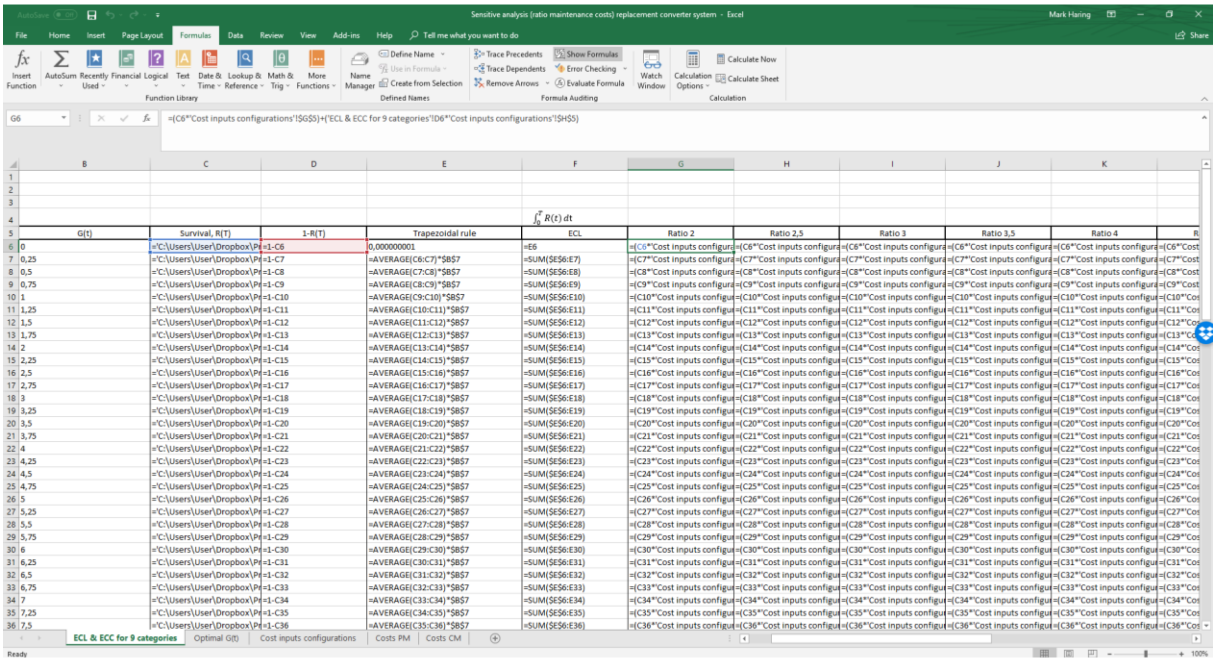
Spare-part cost	
Component	Cost [€]
converter system	13000

Total PM cost				
Total vessel cost [€]	Total downtime cost [€]	Total labor cost [€]	Total spare-part cost [€]	Total PM cost [€]
516500	11713,5	0	13000	541213,5

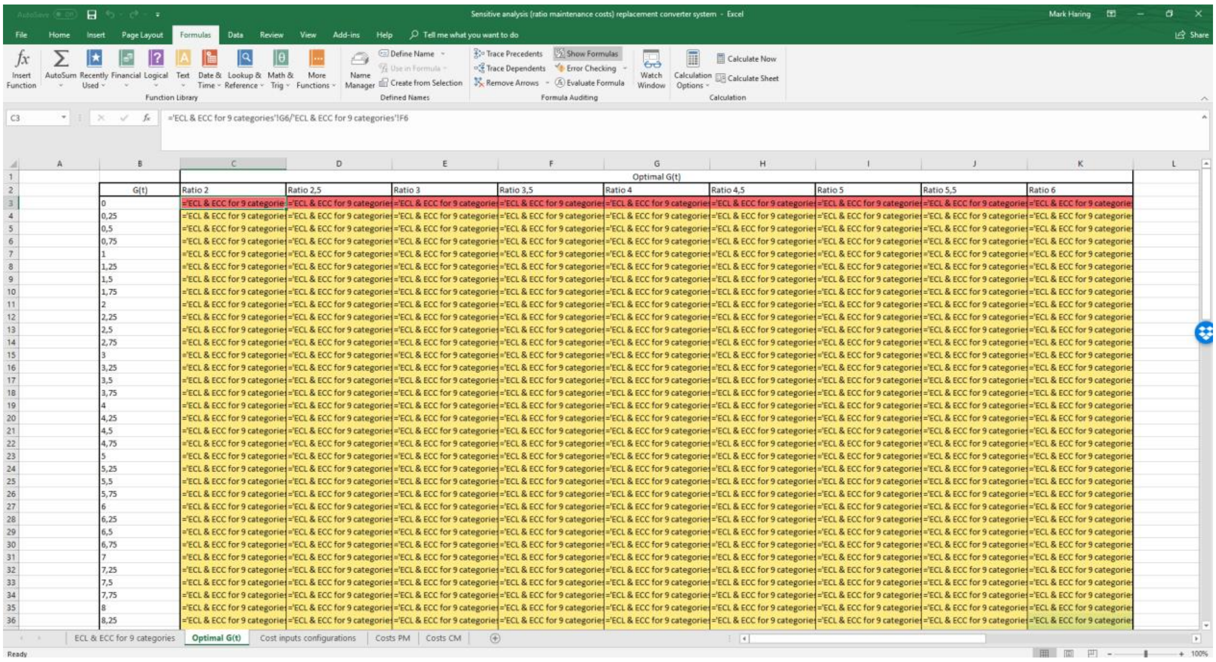
Optimal fixed operational time



ECC different CM/PM cost ratios



Optimal G(t) different CM/PM cost ratios



C3: ='ECL & ECC for 9 categories'!G6/'ECL & ECC for 9 categories'!F6

	Optimal G(t)								
G(t)	Ratio 2	Ratio 2,5	Ratio 3	Ratio 3,5	Ratio 4	Ratio 4,5	Ratio 5	Ratio 5,5	Ratio 6
0	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
0,25	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
0,5	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
0,75	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
1	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
1,25	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
1,5	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
1,75	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
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2,25	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
2,5	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
2,75	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
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3,25	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
3,5	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
3,75	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
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4,25	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
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4,75	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
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6,25	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie	='ECL & ECC for 9 categorie
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