Life cycle cost analysis on wind turbines

Master of Science Thesis in Energetic engineering

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Abstract

Wind power is considered one of the most promising renewable energy sources as increase during the last decades show. Important issues concerning the availability of wind power are its high investment and maintenance costs. The investment cost has a high price especially for offshore plans. The maintenance costs are a significant part of the total cost especially when during the life period of a wind turbine (WT) more failures than expected happen. In order to avoid unexpected failures and decrease the cost of maintenance some systems have been used to monitor the condition of specific components and control continuously the status of the turbine. Optimization of maintenance and research on new strategies to prevent the major failures it might be considered a solution to decrease costs and Life Cycle Cost (LCC) Analysis can be a fundamental tool to achieve a cost-effective maintenance for wind turbines and to obtain a more competitive electricity energy price from wind power source.

The goal of this project is to compare cost-efficient maintenance strategies for on- and off-shore wind power system using LCC analysis approach as a tool for maintenance management. The comparison has been made by application studies which were selected during the way. The first one (WT1) is an offshore turbine, Vestas 112V, 3MW; the second one (WT2), is an offshore turbine, Haliade 150, 6MW and the last turbine (WT3) is onshore, V112, 3MW. Data used for the three wind turbines have been provided by Vattenfall.
Three different strategies have been studied and the effect produced by the usage of Control Monitoring System has been analysed. The aim of this analysis is to show quantitative results that could quantify and give clear support to the value of Control Monitoring System (CMS).

A comparison between the different types of turbines has been done in order to observe when a control monitoring system is more economical profitable and then the total life cycle cost decreases more. The comparison has been analysed for offshore and onshore WTs with same rating power and two offshore WTs with a different rating power. Sensitivity analysis has also been carried out considering different values of discount rate. For any chosen value the CMS proves to be profitable.

Finally the results have been compared to those obtained in previous work from Reliability-Centred Asset Management (RCAM) research groups where the profitability of CMS has been analysed considering that part of unscheduled service is replaced by the scheduled one, and considering that part of corrective maintenance (CM) is substituted with a cheaper preventive maintenance (PM) during the usage of a CMS. Results show different values of reduction in CM and PM when a CMS is used. In this work has been shown that the 27,5% of the unscheduled service has to become scheduled to make CMS profitable while in the previous work the value was about 47%. Comparable results have been obtained in the sensitivity analysis where the value of discount rate has been changed from 0 to 10 to observe its effect on the LCC. The lower value of the discount rate the more efficient effect of CMS on LCC, the same result has been proved in the previous work. In RCAM's work an entire offshore wind farm has been observed and LCC has been performed on the entire plant while in this thesis project 3 single WTs have been analysed. The comparison between these two works can be considered suitable since the used data are similar and the LCC analysis takes into account the same type of costs. An implementation that has been done in this work is the cost of production losses. This cost varies depending on the availability of the system and then it is affected by the efficiency of the CMS.

Abbreviations

LCC	Life Cycle Cost [€/yr]
C_{inv}	Cost of investment [€]
C_{CM}	Cost for corrective maintenance [€]
C_{PM}	Cost for preventive maintenance [€]
C_{PL}	Cost for production loss [€]
C_{rem}	Remainder value [€]
PM	Preventive Maintenance
CM	Corrective Maintenance
PL	Production loss
CMS	Conditioning Monitoring System
RCM	Reliability Centered Management
RCAM	Reliability Centered Asset Management
WindAM	Wind Power Asset Management
PV	Present Value [€]
PV_LCC	Present value of LCC [€]
TPV_LCC	Total Present Value of LCC [€]
PV_f	Present Value Factor
MTTF	Mean Time to Failure [h]
MTTR	Mean Time to Repair [h]
r	Discount factor [%]
L	Invested amount of money [€]
WT	Wind Turbine
S	Initial investment [€]
n	Years of investment [yr]
FMEA	Failure mode and effects analysis
LTA	Logic decision tree analysis
$\dot{E}$	Kinetic Energy [kW]
$\dot{m}$	Air mass flow [Kg/s]
v	Wind velocity [m/s]
O&M	Operation & Maintenance
CAPEX	Capital Expenditures [€/MW]
CMPI	Commodity Metal Price Index
HAWT	Horizontal axis wind turbine
WTG	Wind turbine generator

Contents

1. Introduction

1.1.Background

Reduction of greenhouse gases emissions and independency from fossil fuels supplying countries are the main goals of a lot of states and the most common solution to reach these objectives is the production of electricity using sustainable sources.

The EU Heads of State and Government set a series of demanding climate and energy targets to be met by 2020. Indeed they are named “20/20/20 target” and they are: [1]

- A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels
- 20% of EU energy consumption to come from renewable resources
- A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

Wind power plays a central role for the development of a sustainable electric power supply system and for the achievement of the 20/20/20 targets. Indeed wind power constantly keeps growing in Europe and in the rest of the world as the picture below shows.

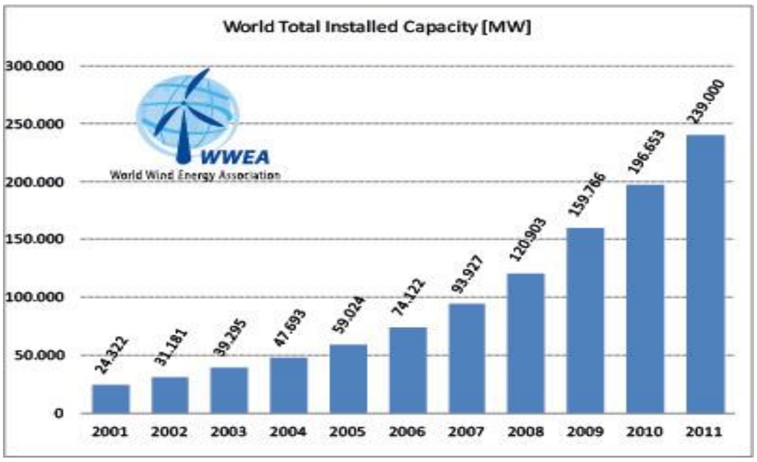

Figure 1-1: ***World total installed wind power capacity (source: Global Wind Energy Council,2011)***

However the maintenance costs for wind turbines are usually high and this impedes the increase of wind power utilization necessary to reach the desired target, furthermore up to ten faults per turbine and year causes unplanned downtimes and this imply a high cost due to extensive maintenance efforts and production losses [2].

The optimization of maintenance strategies and maintenance decision making may significantly reduce operational costs [3] and Life Cycle Cost (LCC) Analysis can be a fundamental tool to reach a cost-effective maintenance for wind turbines and to obtain a more competitive electricity energy price from wind power.

Condition monitoring systems (CMS) might be a useful tool to reach the reduction of maintenance costs. Such systems, commonly used in other industries, continuously monitor the performance of the wind turbine parts e.g. generator, gearbox and transformer, and help determine the best time for a specific maintenance work. At the moment several companies are developing and testing such systems [4] .

Techniques that are included in condition monitoring are, for example, vibrations analysis and oil analysis. Vibration analysis is the most known methodology to perform condition monitoring, especially for wind turbine wheels, bearing in the gearbox and bearings in the generator whereas oil analysis are made by the use of microprocessor-based systems that can automate most of the lubricating oil analysis. With this technique is possible to identify the most cost effective interval for oil change. [5]

The further step could be to implement Reliability Centred Maintenance (RCM) as a part of CMS. A RCM method is a structured approach that focuses on reliability aspects when determining maintenance plans. The method defines efficient maintenance plans by e.g. prioritising critical components and through the choice of maintenance tasks. [6]

LCC in off-shore and on-shore plants: comparison
In order to make the wind turbines more cost efficient they are continuously growing larger. Lately the wind farms are built in more favorable areas such as off-shore where size is not an issue and wind is more beneficial.

The main advantage of offshore over onshore wind plants is the possibility to reduce environmental impact, e.g., reduce in noise, conflict "birds ", landscape.

The main disadvantages of offshore over onshore are accessibility, stress on equipment (due to the harsh weather) and so the total cost of the plant, due to a more expensive maintenance.

Generating electricity from offshore wind turbines can cost around 2.5-3.5 times more than the wind farms built on land. For instance, even a small cheap component breakdown costs a lot to repair since the transportation to the site by vessel or helicopter is expensive and the weather can lead to a long downtime for the wind turbine.

Those contingencies complicate the prediction of the LCC for the off-shore wind turbine.

Research has shown that the present maintenance, in both on- and off-shore installations, is not optimized. It has revealed that there are large potential saving by optimizing maintenance decisions over the lifetime to reduce the total cost for maintenance activities and component failure, and cost due to production losses, especially for large off-shore wind parks. [2]

1.1 Objective

This thesis work focus on the wind turbine system function and on its most critical components since failure component may lead to system failure, lead to unavailability and loss of production.

The previous works and research have shown how preventive maintenance activities could reduce costs for the wind power plant owner and this is especially noticeable for remote site wind power plans situated offshore [7]. An important task of this project is to compare the costs associated with different maintenance method, including both PM and CM with the objective of minimizing the total cost of maintenance [8].

Maintenance is a tool to prevent failures and the main objective of this work is to compare cost-efficient maintenance strategies for on- and off-shore wind power systems using LCC analysis approach as a tool for maintenance management. The comparison has been made by application studies.

LCC is an economical calculation method to evaluate a total cost for a technical system during its life length and the goal is to minimize the total lifetime cost. The total cost involves cost from planning, purchase, operating and maintenance to liquidation. For a power plant the costs are i.e. investment cost, operation cost, maintenance cost, down time cost and remainder value. A LCC analysis where the effect of CMS is presented in different maintenance scenarios is later on presented.

Eventually this master thesis work starts from previous work within the research groups RCAM and WindAM led by Prof. Lina Bertling. The main objective is to make an update and repeat the Julia Nilsson's work [4] extending her previous work and results.

1.2 Previous work and literature review

This section gives a brief overview of some applications of RCM and recent results for electric power utilities and wind turbines.

Especially a deep literature review has been made concerning the works of the research group RCAM and WindAM.

1.2.1 RCM applied to power utilities

1.2.1.1 Example of RCM applied for hydroelectric power plants

An example of RCM applied for hydropower power plants is given by [6] where the objective of his study is to evaluate the introduction of RCM for Vattenfall Vattenkraft's hydro power plants, especially with regard to the generator.

In this work a comparative study has been conducted of three different RCM methods. Secondly factors influencing the RCM performed at Vattenfall and the resulting maintenance plan have been analysed. Finally the maintenance before RCM was introduced and the maintenance plans proposed by RCM have been analysed and compared.
The first RCM method described is the approach proposed by John Moubray in [9] (RCM II). The second method has been developed and applied by Vattenfall Vattenkraft (VVK RCM).
'The last method, developed by the RCAM group (KTH), has been applied to power distribution systems [10]. A comparison of these methods was then conducted.
VVK RCM and RCM II have a lot in common. A main difference between the methods is that RCM II has a decision diagram where certain maintenance strategies are preferred and if feasible picked. VVK RCM has a more complex way of deciding maintenance strategy. All tasks are considered and with the help of a risk and cost analysis the best maintenance strategy is picked.

The introduction of RCM for Vattenfall hydro plants in this study has resulted in changes of inspection intervals e.g. from every third to every sixth year.
The result from this study shows that this change in maintenance is economically justified if the probability to detect and prevent failures doesn't decrease with more than 2 %. The conclusion for this specific case is, under the given assumptions, if the choice is made to increase the inspection interval one should be certain that the probability to detect and prevent the failure only decreases marginally. The change in probability to detect and prevent failures is small because the cost of inspections is small compared to the cost of corrective maintenance and cost due to loss of production. [6]

1.2.1.2 Gas turbine used in power plants

A study from the University of São Paulo [11] proposes the application of RCM method to improve complex system maintenance policies aimed at the reduction of unexpected failure occurrences in critical components of a gas turbine. The method is applied to the analysis of two identical gas turbines, each with an output of 150 MW, installed in a 500 MW combined cycle power plant. The reliability and availability of the turbines are simulated based on a five-year failure database.
The method's first step consists in the elaboration of the turbine functional tree that allows the definition of the functional links between the equipment subsystems. The next step is the development of FMEA of each turbine component in order to define the most critical components for turbine operation. The method's third step involves a reliability analysis based on the 'time to failure' data recorded during the gas turbine operation. Once the critical components are defined a maintenance policy can be proposed for those components considering the RCM concepts.
This study presents a system reliability-based method used to identify the most critical components in a gas turbine. The criticality is associated with the component failure effect on the turbine operation condition. The higher the criticality of the component, the more technical and financial resources should be expended in the maintenance activities to keep the gas turbine available for operation.
The RCM concepts are used as a guideline for ranking the maintenance policy priorities for the critical components aiming at the overall gas turbine operation availability.
The results show how the maintenance policy proposed by the turbine manufacturer can be improved through the use of predictive tasks in some auxiliary systems, such as the bearings lubrication systems, since their failures can cause the gas turbine trip. That improvement is feasible once most of the auxiliary systems present some monitoring device.
Based on time to failure and time to repair data, the method allows one to carry out system reliability, maintainability and availability analyses.
The availability analysis has shown different results for each turbine, one presenting 99% and the other 96% availability, indicating differences in their systems installation and operation.
Indeed turbine 1 presented a small number of failures that were rapidly repaired having a small effect on system availability. Turbine 2 presented almost twice the number of failures of turbine 1 and had a high time to repair, reducing the equipment availability. The availability of turbine 2 was improved with the change of the maintenance policy for the lubrication oil system, mainly through the use of condition based maintenance.

The improvement of ‘time to failure’ and ‘time to repair’ databases during future operational years (with the addition of more failure and repair data) will allow more reliable estimates of the turbines reliability and availability.
Nevertheless those estimates can be used to check design and maintenance procedures in order to adapt them to the gas turbine local operational condition that may be different from the average condition considered in the equipment design. Those estimates can also be used for benchmarking in order to compare the performance of the same gas turbine model operating in different sites.

1.2.1.3 RCM applied to WTs

Rademakers et al. [12] looked at the structural breakdown of parts within a wind turbine and discussed failure detection methods such as inspection and conditioning monitoring. Via detailed analysis a flaw in the design of the studied turbine was detected and the authors suggested more sensor redundancy to cut down the risk of failure.

1.2.2 RCM applied to wind turbine by RCAM and WindAM research groups

Ribrant and Bertling [7] carried out a study which provided comprehensive failure rate and downtime data by WT subassembly. The database comprised many different WT models and manufacturers. This work also contains a study of gearbox failure modes, including repair and replacement statistics.

More studies about LCC Analysis have been applied to single wind turbine and to entire wind farm both onshore and offshore, some of these works with respective results are shown.

1.2.2.1 RCAM’s work (Julia Nilsson’s master thesis project, KTH 2005) [4]

The Julia Nilsson´s master thesis [4] deals with the comparison of the total cost analysis (LCC including additional costs for implementing CMS) for different alternative maintenance strategies. These strategies have been applied for two different studies:
A single turbine onshore: Vestas V90, 3MW, owned by Vattenfall at Näsudden, Gotland)
An average turbine offshore (Vestas V90, 30x3MW, Kentish Flats, owned by Danish Elsam, UK)
A present value of the total cost of LCC for every year has been calculated and the total sum of all present values has been calculated into the total sum of the present value of LCC. In this study six different strategies have been used. The first three, where the preventive and corrective maintenance is affected, are carried out both for the farm offshore and the single turbine onshore. The last three are carried out only for the farm offshore; in two of these strategies only the corrective maintenance is affected and in the last one only the production loss is affected. The aim of all these strategies is too demonstrate if and in which cases CMS is profitable In the first three strategies a percentage of how much the cost must be decreased to make CMS profitable is calculated The final three strategies give a direct indication of whether the price of CMS is covered within the strategy.
Results:
First three strategies:
Concerning the single turbine, the strategy 1 gave the following result when a CMS cost is added to the basic case: to compensate for the additional cost of CMS, the preventive maintenance have to be decreased by 23%. The strategy 2 shown that to compensate for the additional cost of CMS the preventive and corrective maintenance together have to be decreased by 3,5%. Lastly

the strategy 3 proved that the cost for the preventive maintenance could increase by 6,23 times to get LCC of the basic case (no CMS) when the cost of corrective maintenance is set to zero.
Concerning the wind farm offshore and the observed average turbine the results with the same strategies are 4,5%, 2,5% and 1,85 respectively.
Final three strategies:
From the final three strategies the main conclusions are that when costs for an entire farm are observed 47% of the unscheduled maintenance this has to become preventive maintenance to make a profit on CMS. Furthermore, the availability would not have to be increased with more than 0,43% to get a reduction in cost for production loss that would cover the cost for CMS.

1.2.2.2 WindAM's work- "A limited-scope reliability-centre maintenance analysis of wind turbines" [2]

This work has been carried out by WindAM research group at Chalmers University of Technology. The main approach applied within this work is the concept of Reliability-Centred Asset maintenance (RCAM) which combines the method of Reliability-Centred Maintenance (RCM) with quantitative maintenance optimization techniques in order to reach a better cost-effective maintenance for wind power plants. The purpose of RCAM is to reveal the components, the failure modes as well as the major underlying failure causes and to identify suitable preventive maintenance measures. This analysis has been made for two WTs : Vestas V44-600kW and Vestas V90-2MW, the owner and operator of wind turbines is Göteborg energy, the maintenance service provider is Triventus, and the provider of conditioning-monitoring services and wind turbine component supplier is SKF. A parallel analysis of the two WTs V44-600 kW and V90-2MW has been done to account the different reliability characteristic of turbines originating from different generations of technology and also the potentially different applicable preventive maintenance measures. The failures on the system which have been taken into account in this study are: the complete loss of energy conversion capability and the partial loss of energy conversion capability of the turbine.
Implemented RCM process
The implemented limited-scope RCM analysis has covered the following steps:

- System selection and definition
- Identification of system functions and functional failures
- Selection of critical items
- Data collection and analysis
- Failure modes, effect and critically analysis
- Selection of maintenance actions

The focus has been on providing an in-depth understanding of the functions, main failure modes, failure consequences, failure causes and failure mechanisms on the one hand and suitable maintenance measures to prevent these on the other hand.
Results
Based on the results of both the failure data analysis and the questionnaire assessment, the gearbox, generator, electrical system, hydraulic system and rotor were chosen for in-depth analysis in the RCM study. In this work a tabulated compilation of selected analysis results is shown, the three most critical subsystems identified are: the gearbox, the generator and the converter (V90)/ the rotor current control (V44) as the most critical parts of the electrical system. The gearbox, bearings, gearwheels and the lubrication system are identified to be the components with highest relevance for gearbox failure. Failure of shafts in the gearbox is

considered to occur only as a secondary damage and has thus not been included in the RCM analysis.
In case of complete demolition, gearbox failure can have severe consequences:
Parts of the gearbox can constitute a risk for personnel and the lubrication oil contained in the respective gearboxes can cause environmental impact. This type of failure causes the longest average downtime and thus has a strong impact on production availability. It can cause severe secondary damages, e.g. in the main bearing or the rotor shaft.
Concerning the generator failure, usually it doesn´t constitute a risk to personnel safety or the environment, it often implies significant loss of production availability and costly down-tower repair. Secondary damage to other subsystems can occur e.g. in case of excessive vibrations from damaged generator bearings or strong heat release. The consequences of rotor current control (RCC) failures in the V44 are usually limited to production losses and they are failures of the power electronics unit or the microprocessor unit still allows operation at reduced power of 300kW, and failure of the resistor unit fully prohibits turbine operation.
In case of V90 system, failure of the converter results in a full loss of the power generation capability.
Vibrations
A particularly frequent case of failure is vibration. Excessive vibration is often a result of bearing damage. In case of the gearbox, early detection of impending bearing failure can e.g. prevent severe secondary damages, enable up-tower repair instead of significantly more expensive removal and external repair. Suitable measures to detect impending bearing failure are vibration-based condition monitoring systems (CMS) and temperatures measurements. A major difference between vibration and temperature monitoring is that vibrations CMS usually provide a pre-warning time in the range of several weeks to months while the temperature CMS provides a pre-warning time in a range of hours to days. On V44 turbines CMS is not usually installed while on V90 turbines, vibration-based CMS are not part of the standard equipment provided by the wind turbine manufacturer, but they are installed in virtually all turbines of this type.
Vibration monitoring and vibration-based diagnosis of planetary stages in gearboxes is at present still challenging and an improvement of condition-monitoring technology for this purpose is subject to intensive development activities today.
Conclusions
Experience has shown that the better the schedules and plans for service maintenance are followed, the more reliable a wind turbine works. This apparently trivial statement suggests that the present service intervals of 6 months are appropriate.
Correct installation and de-installation routines as well as a proper alignment of components have a strong impact on the reliability of wind turbines. A fundamental problem revealed during this study is that maintenance decisions are at present usually made with the aim of a short-term minimization of cost per kWh, not with a focus on long-term minimization of total life cycle cost. Lastly, collection of in-depth failure and maintenance data of wind turbines are strongly needed in order to tap the full potential of quantitative maintenance optimization for cost-reduction of wind energy.

1.2.2.3 WindAM´s work (Bertrand Kerres's master thesis project) [13]

The Bertrand Kerres master thesis [14] focus on comparison of operations and maintenance costs resulting from different maintenance strategies. The model has been applied to a wind turbine V44-600 kW from the Danish company Vestas.
A RCM study of Vestas V44 wind turbine was previously performed at the Division of Electric Power Engineering at Chalmers University of Technology. Based on the results from this study, five components have been modelled in the Kerres work: the electrical system, the generator, the gearbox, the control system and the hydraulic system. Those components together are responsible for 86% of the turbine downtime [13]. This study revealed that corrective maintenance is the cost-optimal maintenance strategy for this type of turbine. The benefit from an online CMS has been found to be too low to justify the cost of such a system in case of investigated turbine with relatively low rated capacity. Also a sensitivity analysis has been applied to this turbine and it shows how a CMS becomes more beneficial when increasing power prices or turbine size. Furthermore, the turbine of this study is an onshore turbine and therefore could be reached by the service team in a short time compare to an offshore turbine. Indeed for offshore turbines the benefit of CMS is expected to be significantly higher; because of the weather conditions and availability of vessel often maintenance actions could be more complicated compared to an onshore turbine and this increases the benefits of long-term maintenance planning in offshore plants.

1.2.2.4 David McMillan and Graham W. Ault´s works

David McMillan and Graham W. Ault have recently presented two different works about application of LCC analysis on wind turbine systems:

1. “Towards Reliability Centred Maintenance of Wind Turbines” [14]
2. “Wind farm capital cost regression model for accurate life cycle cost estimation” [15]

1. Towards Reliability Centred Maintenance of Wind Turbines

This study presents a real application of RCM methods to a fleet of operational wind farms and it shows that by analysing operational maintenance data, important failure modes can be highlighted and action taken to mitigate them. The system under study is a Danish concept multi-MW onshore wind turbine. The analysis of the system has been limited to the wind turbine asset and switchgear. The RCM process follows four main steps [9]:

- System selection and information collection
- Develop understanding of system
- Define system functions and functional failures
- Task selection (feedback)

The collected data for three different sites are: electric power [MW], turbine model (A,B), *WTn*-number of wind turbine at the side n, data start, data end, months of activity, *Δtn*-time in years covering the maintenance record from that side.
By multiplying *WTn* and *Δtn* the total number of WT operational years can be deduced, the final value in this study is 255.72 WT-years equivalent.

- Failure mode number (FM) per each asset group
- Risk priority number for the most critical assets (1=low risk, 5=very high risk)
- Failure rate per year of the most frequently occurring failure modes, that is component failures which require an unscheduled maintenance visit
- Cost ranges for failures

Data processing

All the available data have been processing and categorized according to fault type, asset category, turbine model and type of maintenance performed. The main issue in the data processing section has been a lack of standardization in terms of fault reporting. The report shows the occurrence rate of maintenance entries by asset category, these include all entries: inspection (planned and reactive), fault investigation, replacements and retrofits.
The top 10 failure modes by risk level are plotted and annual cost of maintenance per wind turbine and annual cost of maintenance per MW are calculated. The top 3 high risk set of failures are further examined to establish what actions can be taken to mitigate these key failure modes.
Corrective actions
There are several practical actions that a wind farm operator can explore in order to minimize operational risk. For the cracked gearbox failure mode, 95% of the cost is tied up in component replacement actions. More accurate measures of condition will help operators to plan gearbox replacements in an improved manner. Use of borescopes for improved inspection and offline oil analysis are two tools which have been used in the aviation industry and can be used on wind turbine gearboxes, the high risk nature of gearbox failure modes justifies the cost of these outlays.
Conclusions
One of the main conclusions from this study are: gearbox failures continue to dominate operational risk in wind turbines, this brings into sharp focus the need for design robustness, and in the long term, cost effective conditioning monitoring.
Furthermore this study showed that the rate of occurrence and impact of lower risk failures will increase in the offshore environment. Finally, some of the mostly occurring failures are measurement devices, whose good function is crucial to turbine control and operation. The rate of occurrence of such failures will increase in offshore wind farms due to the most hostile maritime environment.

2. Wind farm capital cost regression model for accurate life cycle cost estimation
Study description
This study focus on an alternative method to the application of technological learning models used to capture wind turbine capital cost, indeed the authors judge inappropriate these methods for "the current level of technical development of wind, particularly offshore wind".
This paper proposes a model based on coupling capital cost with *metals commodities indexation* and *water depth*.
The choice of these two factors is due to the large amount of metal utilised in wind turbine construction (especially in offshore turbine with high metallic content of foundation and inter-array cabling) and to the important influence of water depth on costs.
Initially the study explains how in the previous work several authors have designed curves for prediction of wind turbine cost with data based on theoretical experience and how this theoretical curves don not reflect the actual cost trend of the wind energy market.
Input data
Starting with the main assumption that commodities pricing and water depth are the main drivers of wind turbine capital cost, a table with the following data are presented for several wind farm located in Denmark, Sweden, Nederland and UK: project name, country, year of commission, wind farm CAPEX [€/MW], water depth [m], and mean water depth [m].
CAPEX are expenditures creating future benefits, it is used by a company to acquire or upgrade physical assets e.g. equipment. Data of CMPI produced by the International Monetary Found are also presented for the period 1999-2011.

Regression Analysis

A linear regression from Draper and Smith [16] is presented:

$$y = \text{Wind farm CAPEX } [€/MW] \tag{1.1}$$

$$x1 = \text{Water Depth } [m] \tag{1.2}$$

$$x2 = \text{CMPI} \tag{1.3}$$

It is assumed the relationship can be explained by the linear dependency:

$$y = b0 + b1x1 + \varepsilon \tag{1.4}$$

where b0 and b1 are estimated model parameter.

After the water depth regression is completed, the CMPI is regressed on the residual (*ε).*

Results

Data are firstly modelled with the model regression on water depth only, indeed it can be seen that even a crude model based on water depth roughly captures the increasing cost seen in data.

In the next step, the CMPI data are used to fit a model to the residuals of the first model. The influence of CMPI is an order of magnitude less than the water depth nevertheless the CMPI regression is included in the model in order to observe its effect on estimating the CAPEX.

The two model results (water depth only and combined CMPI +water depth) are plotted alongside the original data. The results suggest that cost of metals is statistically significant in overall project cost but less so compared with the influence of water depth.

This model can be therefore used in predictive mode to estimate future costs.

Conclusions

The technological learning models do not explain the recent upwards cost trends seen in practice in the wind turbine systems, this is a major flaw with such models.

Nevertheless water depth and materials costs are not the only drivers in offshore wind farm capital cost, the presented model provides a highly intuitive approach which can be tested and used easily. Furthermore, non linear regression methods may be more appropriate for future estimates of capital costs.

2 Technical system description

2.1 Wind turbines

A wind turbine is a machine which converts kinetic energy from the wind into mechanical energy which is converted to electric energy. WTs can produce energy only in response to a resource that is immediately available: the wind; since is not possible to store the wind and use it a later time, the output of a WT is thus inherently fluctuating and non-dispatchable. For this reason any system to which a WT is connected must take this availability into account.

Figure 2-1: ***Horizontal axis wind turbine (Source: Public Domain)***

Main components in WTs [17]

Today, the most common design of WT is the horizontal axis wind turbine (HAWT). That is, the axis of rotation is parallel to the ground. The principal subsystem of a typical HAWT includes the rotor, drive train, generator, nascelle and yaw system, tower and foundation, and control system.

Rotor

The rotor consists of the hub and blades of the wind turbine. The blades transform the kinetic energy into rotational energy, using the same aerodynamic principles as an airplane wing. They can be rotated around their longitudinal axis, called pitch, to maximize the energy yield from the wind. The blades are mounted to the hub.

Drive Train

The drive train consists of the other rotating parts of the WT downstream of the rotor. These typically include a low-speed shaft, a gearbox, and a high-speed shaft. Other drive train components include the support bearings, one or more couplings, a brake, and the rotating parts of the generator.

The gearbox transforms the rotational energy from the hub, which is usually in a high torque with low speed format, into low torque – high speed format required by the generator.

Hydraulic system
The pitch mechanism in a WT is usually driven by oil pressure. An oil pump, control valves and actuators are needed to rotate the blades into their designated position. A mechanical rotor brake is often also hydraulically actuated.

Generator
The generator in a WT is located on the high-speed side of the gearbox, and converts rotational energy into electrical energy. It consists of a rotor creating a rotating magnetic field, which itself then induces a voltage in the stator. There are different types of generators; common types used in wind turbines are synchronous generators, as well as single or double fed asynchronous generators.

A synchronous generators produce current, which alternates with the same frequency as the rotor rotates.
Asynchronous generators rotate slightly faster than their output current oscillates.

Nascelle and yaw system
This part includes the WT housing, the machine bedplate or main frame, and the yaw orientation system, required to keep the rotor shaft properly aligned with the wind. The main frame provides for the mounting and proper alignment of the drive train components. The nascelle cover protects the contents from the weather.

Tower and foundation
The principal types of tower design currently in use are the free-standing types using steel tubes, lattice towers, and concrete towers. The stiffness of the tower is a major factor in WT system dynamics because of the possibility of coupled vibrations between the rotor and the tower.

Control system
The control system supervises operational data and supports control of the turbine operation. It can detect some abnormalities during operation, for example when a sensor detects a high temperature and triggers an alarm or shuts down the generator rotation. Furthermore, it controls the pitch system to maximize the energy production.

A WT control system includes: sensors (speed, position, temperature, current etc), controllers (mechanical mechanisms, electrical circuits), power amplifiers (electrical amplifiers, hydraulic pumps, and valves), actuators (motors, pistons, magnets, and solenoids), and intelligence (computers and microprocessors).

2.2 Electric power generation from WTs

Wind turbines convert kinetic energy of moving air masses into electric energy. The kinetic energy content of a flow is given by: [13]

$$\dot{E} = \frac{1}{2}\dot{m}v^2 \tag{2.1}$$

- v is the velocity of the wind
- $\dot{m} = A\rho v$ is the air mass flow, with ρ as the density of air and A as the cross section of the air flow.

A typical energy flow through a wind turbine rotor with 44 m diameter, at ρ = 1.25 kg/m2 and v = 10 m/s would thus be:

$$\dot{E} = \frac{1}{2}\pi \cdot \frac{(44m)^2}{4} \cdot 1,25\,\frac{kg}{m^3} \cdot \left(10\,\frac{m}{s}\right)^3 \approx 950\ kW \tag{2.2}$$

The WT generates electric power in a given wind speed range; the lower and upper bound of that range are called cut-in speed and cut-out speed, respectively. Below the cut-in speed, the energy content of the flow is not sufficient to overcome resistance from e.g. friction in the turbine drive train. Above the cut-out speed, the mechanical stress for components can become too high, and the turbine is shut down to extend its lifetime.

3 Theory

This chapter introduces the fundamental and theoretical background concerning basic definitions as reliability, availability, maintenance, Mean Time to Failure, RCM and so forth; the concept of Life Cycle Cost analysis is described and an overview a few different maintenance approaches is shown.

3.1 Definitions and terminology

Reliability

In order to describe the reliability concept the standard definition can be used [18]:

”Ability of an item to perform a required function under given conditions for a given time interval”

Availability

“Ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided” [18].

The average availability is defined by:

$$\boldsymbol{A_{av} = \frac{MTTF}{MTTF+MTTR}} \quad \textbf{[19]} \tag{3.1}$$

Where MTTF (*Mean Time to Failure, [h]*) expresses the average operating time of an item and MTTR (*Mean Time to Repair, [h]*) denotes the average of the times to restoration after failures.

Downtime

“Time interval throughout which an item is in a down state” [18]

In the following figure an example of downtimes due to replacements is described.

In the first draft, the MTTR of corrective maintenance, in case of actual failure, is shown; while in the second one the MTTR in case of preventive maintenance is illustrated where there is not an actual failure but only a preventive replacement.

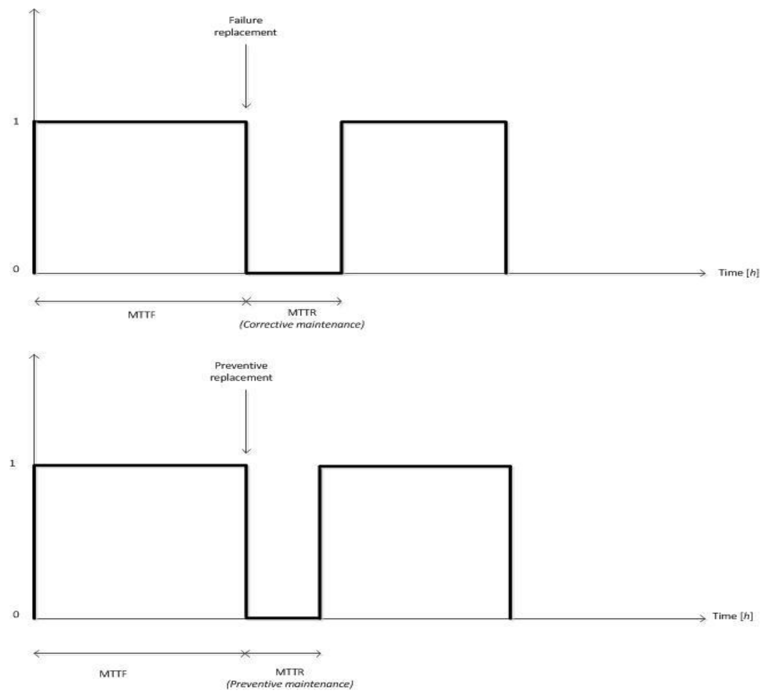

Figure 3-1: ***MTTF and downtime for different types of maintenance*** **[20]**

Operation and Maintenance cost (O&M)
Wind turbines need to be serviced and repaired during their lifetime, the costs arising from those actions are operations and maintenance costs.

Failure Mode and Effects Analysis-FMEA
FMEA is an inductive failure analysis used in operations management for analysis of failure modes within a system for classification by the severity and likelihood of the failures.

A successful FMEA activity helps to identify potential failure modes based on past experience with similar products or processes or based on common failure mechanism logic, enabling the team to design those failures out of the system with the minimum of effort and resource expenditure, thereby reducing development time and costs.

Total costs of a wind farm
The total cost over a life time for a WT could e.g. be calculated by the sums of all expenses during its lifetime. These costs can be divided into three groups: total installation costs, capital costs and O&M.

The total installation costs can be estimated as the total invested money to build a wind park, divided by the actual number of wind turbines. This includes all cost up to the start of the wind turbines.

The capital costs are defined as the interest on the invested money in the wind farm.

3.2 Life Cycle Cost Analysis

LCC concept can be expressed by a standard definition [18]:

"Life cycle cost is all the costs generated during the life cycle of an item".

LCC is commonly adopted for cost saving for an investment and it implies calculation methods of total life time costs. LCC could be describes e.g. as *"A technique which enables comparative cost assessment to be made over a specified period of time, taking into account all relevant economic factors both on terms of initial capital and future operational costs"*. [21]

The use of LCC analysis is finalized to compare different investment options, calculated over a given period of time, where both initial and future costs have to be taken into account.

The fundamental idea of LCC is to estimate what an investment actually costs, where the initial investment cost has to be taken into account as well as costs related to the product's whole lifetime.

Within this work the LCC analytic definition is:

$$\text{LCC}=\boldsymbol{C_{inv}}+\boldsymbol{C_{CM}}+\boldsymbol{C_{PM}}+\boldsymbol{C_{PL}}+\boldsymbol{C_{rem}} \quad \text{[Euro]} \ \textbf{[22]} \tag{3.2}$$

The economic parameters and the input data considered within this definition are the cost of investment (C_{inv}), the cost for corrective maintenance (C_{CM}), the cost for preventive maintenance (C_{PM}), the cost for production loss (C_{PL}) and the remainder value (C_{rem}).

3.2.1 Production losses

During the lifetime of a WT, failures could occur and they cause unplanned downtimes.

It´s possible to evaluate the cost for production losses as:

$$\boldsymbol{C_{PL} = N \cdot P \cdot C_f \cdot C_{el} \cdot D} \ \text{[Euro]} \ \textbf{[23]} \tag{3.3}$$

N, number of wind turbines

P, electric power generated

C_f, capacity factor; the capacity factor of a power plant is the ratio of the actual power produced and the maximum power that could be produced. $C_f = \frac{P_{out}}{P_{max}}$

C_{el}, cost of electricity [€]

D, downtime [h], (see definition section 3.1)

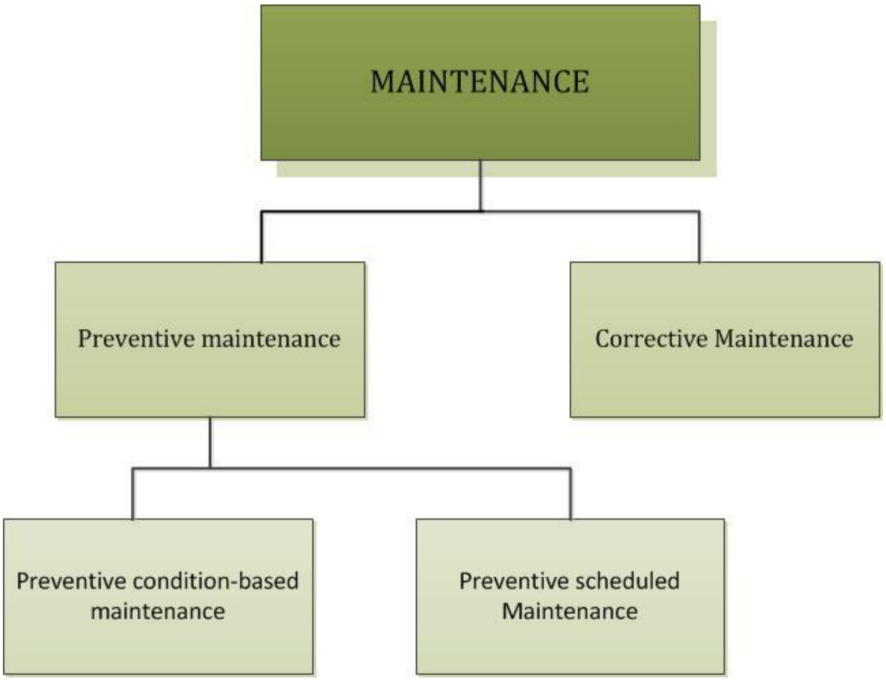

Figure 3-2: ***Maintenance strategies (adopted from*** **[24]*)***

3.2.2 Preventive maintenance

PM is the maintenance carried out before failures occur and it can be divided into:

1. *Preventive scheduled maintenance*: it is the "the preventive maintenance carried out in accordance with an established time schedule" [24]
2. *Preventive condition based maintenance*: it is based on performance and parameter monitoring and subsequent actions. In order to predict when maintenance is needed history about when, how and why the component have failed is occurring [22].

The motivation for any PM strategy is that the cost of applying the PM measure should be less than taking no action at all [8].

3.2.3 Corrective maintenance

"Corrective maintenance is the maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function" [24].

The CM implies that as long as a component is working no maintenance is carried out; when a component is not working anymore it is repaired or removed.

If little or no PM is done, then more system failures are likely to occur resulting in more repair actions being required in more corrective maintenance actions.

The PV method can be used to compare future payments over a certain time at one point in the present time.

The costs are typically evaluated on an annual basis with an assumed increase due to inflation.

Present Value Method
The Present Value (PV) means the amount of money that should be put into the bank now at a certain rate (*d*) to pay for an outlay (C) after *n* years. This means that all future payments are re-calculated to the equivalent value for the present time.

The present value of one outlay (C) to be paid after n years is gained by multiplying this with the present value factor ($PV_f(n,d)$) as follows:

$$\boldsymbol{PV = C \cdot PV_f(n,d) = C \cdot (1+d)^{-n}} \textbf{ [4]} \quad \textbf{(3.4)}$$

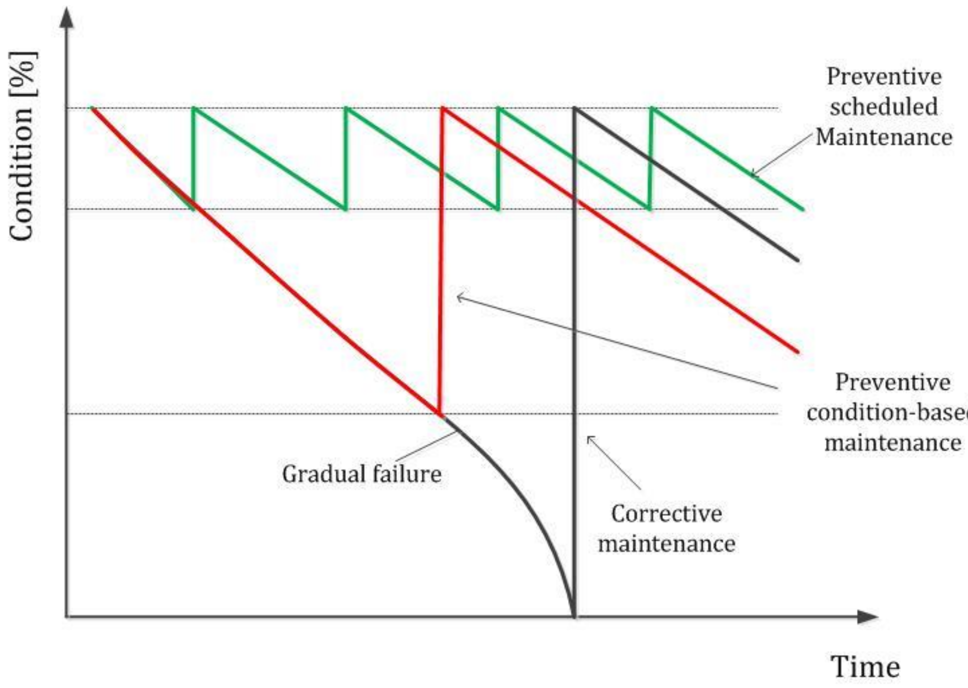

Figure 3-3: ***Component conditions based on different strategies(adopted from [20])***

3.3 Reliability centered maintenance, RCM

RCM is a structured approach that focuses on reliability aspects when determining maintenance plans. [6]. The improvement of a physical asset management is a process that can be used to give a systematic method to balance between PM and CM, and to choose right PM activities for the right component at the right time to reach the most cost efficient solution [4]. One example of available methodology to enhance reliability of physical assets is RCM. (See definition section 2.2)

3.3.1.1 How has been RCM introduced?

The RCM method was introduced in the civil aircraft industry in 1957 with the creation of the Boeing 747 series of aircraft and it was developed during the fast technical development in 1940-1960. [10]

Firstly this method identified the maintenance tasks that would have avoided the cost for not necessary maintenance actions without reducing safety and quality of the system. This method was successful and in 1975 it was applied to the all major military system of US.

In the 1980s RCM was also introduced to the nuclear power industry by the Electric Power Research Institute (EPRI).

Today RCM is applied to many electrical power utilities in order to improve the maintenance planning, for instance RCM is largely implemented to wind turbines to give a systematic method to balance between preventive and corrective maintenance.

There are several descriptions of the process to define a RCM plan, some of these are:

- RCM according to Smith
- RCM according to Nowlan
- RCM according to Mourbray
- RCM according to Jadine
- RCM according to Bertling

3.3.1.2 RCM according to Smith

This method is based on a systematic analysis and it is divided into seven steps [25]:

1. System selection and information collection
2. System boundary definition
3. System description and functional block diagrams
4. System functions and functional failures
5. Failure mode and effects analysis (FMEA)
6. Logic decision tree analysis (LTA)
7. Selection of maintenance tasks

3.3.1.3 RCM according to Nowlan

This method concerns cases in which information are limited, the RCM plan is defined as follows [26]:

- Partitioning the equipment into object categories in order to identify those items that require intensive study
- Identify significant items that require intensive study and those that have essential safety or economic consequences and hidden functions that require scheduled maintenance.
- Evaluating the maintenance requirements for each significant item and hidden function in terms of the failure consequences and selecting only thise tasks that will satisfy these requirements
- Identify items for which no applicable or effective task can be found, then either recommending design changes if safety is involved, or assigning no scheduled maintenance tasks to these items until further information becomes available
- Selecting conservative initial intervals for each of the included task and grouping the task in maintenance packages for application
- Establishing an age-exploration program to provide the factual information necessary to revise initial decisions.

3.3.1.4 RCM according to Mourbray

The RCM process presented in [9] has been formulated into seven questions for each selected item; the first step is to identify the system items and to establish which of these have to refer to the following questions:

1. *What are the functions and performances required?*
   Functions can be anything an asset has to abide by thus they are divided into primary and secondary function. The primary ones describe the main purpose of the asset while the second ones additional features.
2. *In what ways can each function fail?*
   This question deals with the ways in which the specific item cannot fulfill the demand.
3. *What causes each function failure?*
   The cause of the failure has to be analyzed on the right level; indeed too many details can make the process long and expensive but on the other hand too few details could make the process meaningless.
4. *What are the effects of each failure?*
   The events after a failure are described including physical or environmental damage and how to fix the equipment.
5. *What are the consequences of each failure?*
   The consequences of each failure are divided into three classes:
   1. *Safety and environmental consequences*; these consequences consist of event in which a person could be injured and an environmental law could be broken
   2. *Operational consequences*, this class concerns consequences that affect production and operation costs
   3. *Non-operational consequences*, those only give cost in the form of operation
6. *How can each failure be prevented?*
   Depending on the consequence classifying of the failure and what kind of maintenance is applied the best maintenance strategy is determined
7. *How does one proceed if no preventive activity is possible?*

3.3.1.5 RCM according to Jardine

This RCM method develops the maintenance tactics through several steps: [20]

Step 1: *Select and prioritize equipment:* analysis of operations, cost of downtime, and cost to repair.

Step 2*: Define functions and performance standards:* identification of the functions of the equipment, functions of each part of the system selected for RCM analysis is defined with its operating limits.

Step 3: *Define functional failures:* when the system operates outside its normal parameters, it is considered to have failed. It´s possible to study the system failings when they are high, low, on, off, open, close, unsteady, stuck, and so forth.

Step 4: *Identify failure modes/root causes:* a failure may have more than one possible cause, thus this step identifies the chain of events that happen when a failure occurs. The relevant question in this step is: "What event is necessary to trigger the failure?"

Step 5: *Determine failure effects and consequences:* in this step the severity of the failure´s impact on safety, the environmental, operation, and maintenance is studied.

Step 6: *Select maintenance tactics:* depending on the type of system and its condition monitoring an appropriate maintenance tactic is chosen.

Step 7: *Implement and redefine the maintenance plan:* the chosen maintenance plan is implemented and the results are reviewed to determine if the plan needs to be refined.

RCM determines the type of maintenance task to be applied to an asset.
Asset managers who wish to optimize the life cycle value of the organization´s human and physical asset must consider three key decision areas: [20]

1. Component replacement (best preventive replacement time, spare parts provisioning, repairable systems)
2. Inspection producers (inspection frequency for a system, condition-based maintenance)
3. Capital equipment replacement (economic life, repair versus replace)

Benefit wit using RCM
RCM aims to generate a scheduled maintenance program that logically anticipates specific failure modes. It can produce the following benefits: [20]

1. Improve understanding of the equipment: how the system fails and the consequences of failure
2. Clarify the roles that operators play in making equipment more reliable and less costly to operate.
3. Make the equipment safer, more environmentally friendly, more productive, and more economical to operate.

3.3.1.6 RCM according to Bertling

The RCM concept formulated in [10] can be divided into three main steps:

1. *System reliability analysis:* defines the systems and evaluates critical components for system reliability. *(system level analysis)*
2. *Evaluation of PM and component behavior:* analyses the component in detail and with the support of necessary input data, a quantitative relation between reliability and PM can be defined. *(component level analysis)*
3. *System reliability and cost/benefit analysis:* the effect of PM on components is analysed with respect to system reliability and benefit in cost for different PM strategies and methods. *(system level analysis)*

3.3.1.7 Developments of RCM; Reliability centered asset management, RCAM [10]

The RCAM method, developed from RCM principles, provides a quantitative relationship between preventive maintenance of assets and the total maintenance cost. The RCAM method relates more closely the impact of maintenance to the cost and reliability of the system than the RCM method. In this way one can see with quantitative methods the effect on a component level of preventive maintenance on system reliability results.

The aim of RCAM is to relate preventive maintenance to the total maintenance cost and system reliability. [10]

The main stages for the RCAM approach are [8]:

1. *System reliability analysis*, it defines the system and evaluates component affecting system reliability.
   This means:
   - Define reliability model and required input data
   - Identify critical components by reliability analysis

2. *Component reliability modelling,* it analysed the components in detail and, with the support of appropriate input data, defines the quantitative relationship between reliability and PM measures.
   This means:
   - Identify failure causes by failure mode analysis
   - Define a failure rate model
   - Model effect of PM on reliability
   - Deduce PM plants and evaluate resulting model

3. *System reliability and cost/benefit analysis,* it puts the results of the second stage into a system perspective, and evaluates the effect of component maintenance on system reliability and the impact on cost of different PM strategies.
   This means:
   - Define strategy for PM (when, what, how)
   - Estimate composite failure rate
   - Compare reliability for PM methods and strategies
   - Identify cost-effective PM strategy

These three stages emphasize a central feature of the method: that the analysis moves from system level to the component level and then back to the system level. [4]

3.4 Condition Monitoring System, CMS

The CMS can be defined as follows: "Activity performed either manually or automatically, intended to measure at predetermined intervals the characteristics and parameters of the actual state of an item. CMS is distinguished from inspection in that it is used to evaluate any changes in the parameters of the item with time. CMS may be continuous, over time interval or after a given number of operations. " [18]

Condition monitoring systems can be a tool to decrease costs by optimizing maintenance strategies, especially concerning off-shore wind farm where the maintenance is known to be difficult and expensive [27]. The crux of condition monitoring effectiveness lies in the ability of the CMS to reliably diagnose the status of the component and hence the overall system. There are many methods of achieving this, some more simple than others. [28]

Most common CMS within the wind power are vibration and oil analysis and the typical components subjected to the CMS are the most critical ones, as blades, gearbox, generator, and main shaft.

How CMS has been applied to WTS

McMillan and Ault [28] studied a CMS installed in WT generators for onshore wind farms. This work shows how via modelling a WTG and its sub-components in a Markov Chain solved via Monte Carlo simulation it is possible to evaluate the impact of a CMS on the performance of an onshore WT over its operational lifetime. The set of models being developed for this purpose aim to answer the following questions:

- What is the value of WTG CMS?
- Are WTG CMS currently cost-effective for onshore conditions?
- What are the necessary conditions for cost-effective WTG CMS?

This complex problem is divided into three modelling approach levels: physical deterioration and faults, wind farm yield modelling and weather effects, and high-level asset management decisions.

A set of models to quantify the benefits of CMS indicate that the benefit of onshore WTG CMS is marginal for the evaluated conditions. But it must to be noted however that the value of the information provided by WTG CMS may have some benefits beyond informing maintenance, such as information regarding how turbines react to specific operating conditions.

CMS applied to WTs- WindAM's work

Another interesting study has been implemented by the WindAM research group at Chalmers University [27]. Within this work it has been shown how LCC can be evaluated with probabilistic methods and sensitivity analysis to identify the benefit of using CMS. The cost benefit of CMS over the life of a WT has been analysed with a probabilistic LCC model and two approaches has been used to study the random behaviour of the failures and the critical parameters that influence the value of CMS.

Within the first approach an average LCC has been estimated, the randomness has been averaged by the yearly expected number of failure for each component. While in the second approach a probabilistic evaluation of LCC has been studied. The Monte Carlo simulation has been used to build a set of failure scenarios. The LCC of each scenario is then evaluated with the cost model, the statistics of the different scenarios provides information on the possible risk of operating WTs with different options.

Since the main objective of the model is to estimate the expected benefit of CMS, average logistic time and production are considered. If a CMS is used, a certain percentage of CM costs is replaced by PM costs for a specific component and the maintenance costs are lower.

The main assumptions of the model are:

- Only components monitored by the vibration CMS are included in the model
- It takes n hours to remove failure of a certain component and the component is then as good as new
- The cost for the failure of a component includes component and logistic costs
- A CMS detects a certain percentage of the failure of a component in time for preparing the maintenance
- If a failure is not detected in time, a delay of t hours is necessary to get a spar part and the logistic necessary to perform the maintenance, this parameter is also referred as logistic time
- In order to estimate the damage reduction parameters, it is assumed that the cost of a failure is 10% of the component cost for the half of the failures that are detected by CMS

This approach has been applied to a 3 MW WT, and cost data have been estimated based on data from previously studies concerning benefits of CMS.

In the following figure the total LCC is shown, with and without CMS. The investment cost for the CMS can be observed by the peak in the year 1. The total cost benefit of using CMS is 190,000€ for this case.

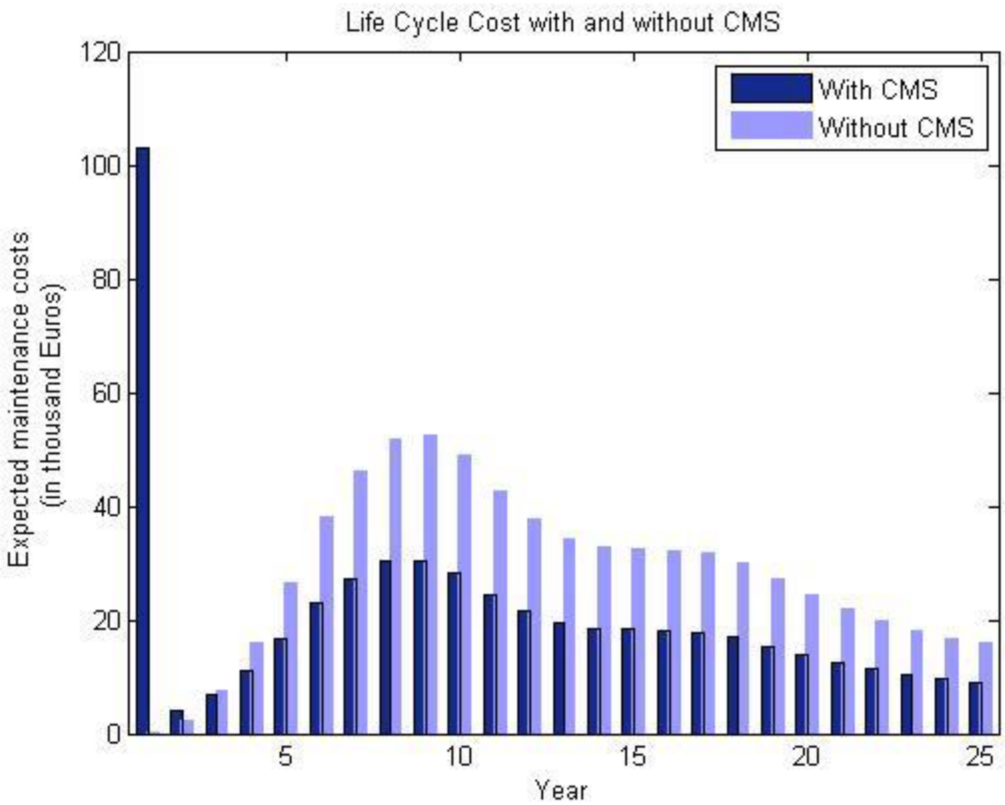

Figure 3-4: ***LCC with and without CMS*** **[27]**

Sensitivity analysis has been also carried out for the scale parameter of the gearbox. The scale parameter affects the economic benefit in two ways: it affects the expected number of failures during the life time of the WT and it shifts the happening of the failures. Therefore the higher scale parameter, the lower the number of failures. This study has shown that CMS is beneficial if the scale parameter for the gearbox is lower than 21. Even though the lower bound for maintenance costs is also higher due to the CMS installation and service costs, the stochastic analysis of the LCC showed that the risk of high cost was lowered by the use of a CMS.

CMS applied to WTs- RCAM's work

Nilsson and Bertling [22] presented a LCC analysis with different strategies where CMS improved maintenance planning for two case studies: a single WT onshore and a wind farm offshore. These two case studies are based on real data from Olsvenne2 at Näsudden (Sweden) and Kentish Flat (UK).

The description of the project has been shown in the section 1.3.2.1, where the different strategies applied to the case studies have been explained. The purpose of these strategies is to evaluate the benefit of implementing CMS.

The purpose of using a CMS is the achievement of some possible benefits:

- That maintenance could be planned better
- The right maintenance can be carried out at the right time
- Unnecessary replacements can be minimized
- Downtime could be reduced as failures are discovered more easily

The six strategies are based on the following assumptions:

1. The cost of PM is compared to the cost of PM plus cost of CMS without taking into account costs of CM and PL.
2. The costs of PM+CM are compare to the costs of PM+CM and a CMS without taking into account the cost of PL.
3. The costs of PM+CM are compared to the costs of PM and a CMS, with the cost of PL equal to zero.
4. Cost of man-days is reduced and CM becomes PM because of better planning with CMS. The point at which a certain amount of unscheduled service becomes preventive is determined in order to see when CMS is profitable.
5. Cost of man-days is reduced when the components are replaced two at a time instead of one at a time
6. Availability increases because of CMS and therefore the cost of PL decreases.

With this assumption a LCC analysis has been carried out to understand whether a CMS is profitable for the single wind turbine onshore and the wind farm offshore.

Results from the calculations of the two cases are shown in the following table, the first three strategies have been applied to the both cases and the last three only to the Kentish Flat wind farm.

Table 3-1: ***Main results RCAM's work*** **[4]**

	Olvenne2	Kentish Flat
Strategy 1 **TPV(Ccms+A1Cs)=TPV(Cs)** **A1=factor that decreases Cs**	A1=0,7	A1=0,95
Strategy 2 **TPV(Ccms+A2(Cs+Ccm))=TPV(Cs+Ccm)** **A2=factor that decreases Cs+Ccm**	A2=0,96	A2=0,97
Strategy 3 **TPV(Ccms+A3*Cs)=TPV(Cs+Ccm)** **A3=factor that increases Cs**	A3=6,3	A3=1,8
Strategy 4 ***47% of the unscheduled maintenance becomes preventive maintenance because of CMS***	-	Within this strategy the total cost for the entire farm decreases by 600000€
Strategy 5 ***Major components are replaced two at time instead of one at a time because of CMS***	-	The total cost for the entire farm decreases by *227770€*
Strategy 6 ***The availability increases from 97,5% to 98% because of CMS (Cost of production loss decreases***	-	The total cost for the entire farm decreases by 699200€

These results show that CMS can be profitable in both cases and there are many ways to cover the cost of a CMS, especially for the wind farm offshore where maintenance could be planned more efficiently with a CMS.

4 Method

In the case study presented, the LCC analysis is carried out for three different turbines, with different collocations (onshore and offshore) and different rated powers.

1. WT1 is an offshore wind turbine, 3MW rating power
2. WT2 is an offshore wind turbine, 6MW rating power
3. WT3 is an onshore wind turbine, 3 MW rating power

The analysis takes into account different types of real costs obtained from interviews, discussions and meeting with some wind turbines manufactures and sellers during the period of thesis work. The obtained data have been used to calculate two main different models: a *base model* where the frequency failure of each component is constant during the all life time of the turbine because of the applied PM and an *ageing model* where the frequency failure increases exponentially every year because of the ageing factor of the components, the older component the higher probability to fail. The main difference between these two models is that in base model the average failure rate is a result of the applied PM while in the ageing model the preventive maintenance is carried out based on the value of the failure rate.

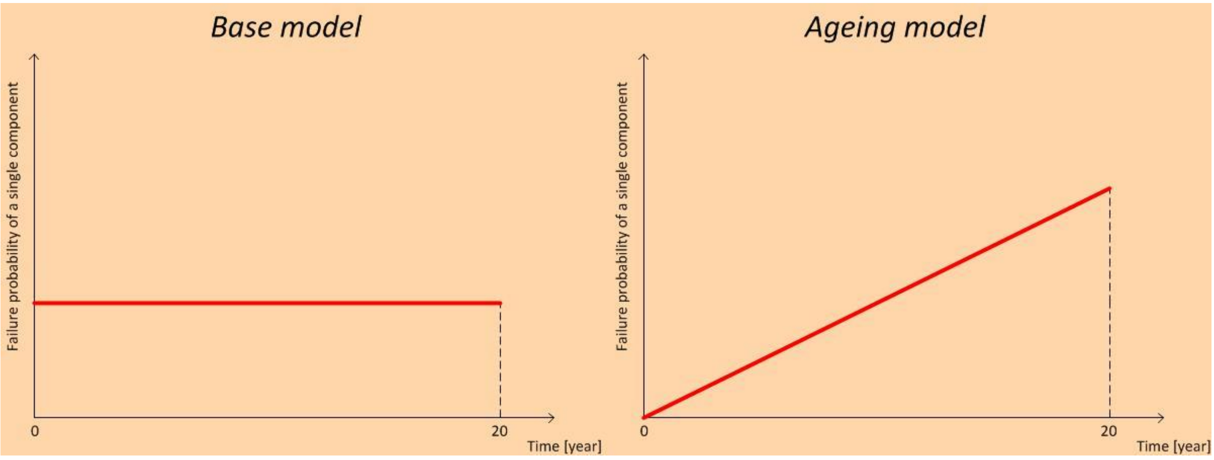

Figure 4-1: ***Base and ageing models scheme***

Within each model three different scenarios have been carried out:

1. *Scenario 1*: LCC analysis is made considering no Control Monitoring System.
   The PM is schedule preventive maintenance applied to each component.
2. *Scenario 2*: LCC analysis is carried out considering CMS with an efficiency of 80%.
   For components where CMS is installed the PM is effected at any pre warning alarm, with a preventive reparation or substitution of the failing component. The 80% of the failures of those components is treated by the usage of PM instead of CM.
3. *Scenario 3*: the CMS is supposed to be 100% efficient. LCC analysis is studied in the case where 100% of failures of the monitored parts are preventively repaired. Corrective maintenance is carried out for components of the turbine where there is not a control monitoring system.

The purpose of these three scenarios is to see if CMS is profitable, how much is economically convenient for different types of wind turbines and how the results differ between a 3MW and a 6MW WT. In the LCC analysis the cost of CMS is added to the investment cost of each turbine and this cost changes when the CMS has a different efficiency. The results show how this initial cost and the benefits of using CMS changes the total present value of LCC and the final cost is compared for the onshore and offshore WTs and for a 3MW and 6MW offshore WTs. When CMS is used the preventive maintenance is carried out instead of corrective maintenance and this affects the final cost because PM is supposed to be cheaper than the corrective one. During the PM, maintenance activities are planned and booked in advance, the CMS is able to predict a failure 3 months in advance and during this time the maintenance is planned and the necessary tools are booked. Furthermore using a PM most of the failures are fixed before a component is not able to work anymore, in this way the production loses due to the stop of the turbine for a complete part substitution decrease. Eventually the sum of the costs for each year is calculated taking into account the present value factor and the present value of LCC of each year is summed to obtain the total present value of LCC. This is the final value that will be used to compare the different types of observed WT systems.

The following image draws a schematic system of the methods:

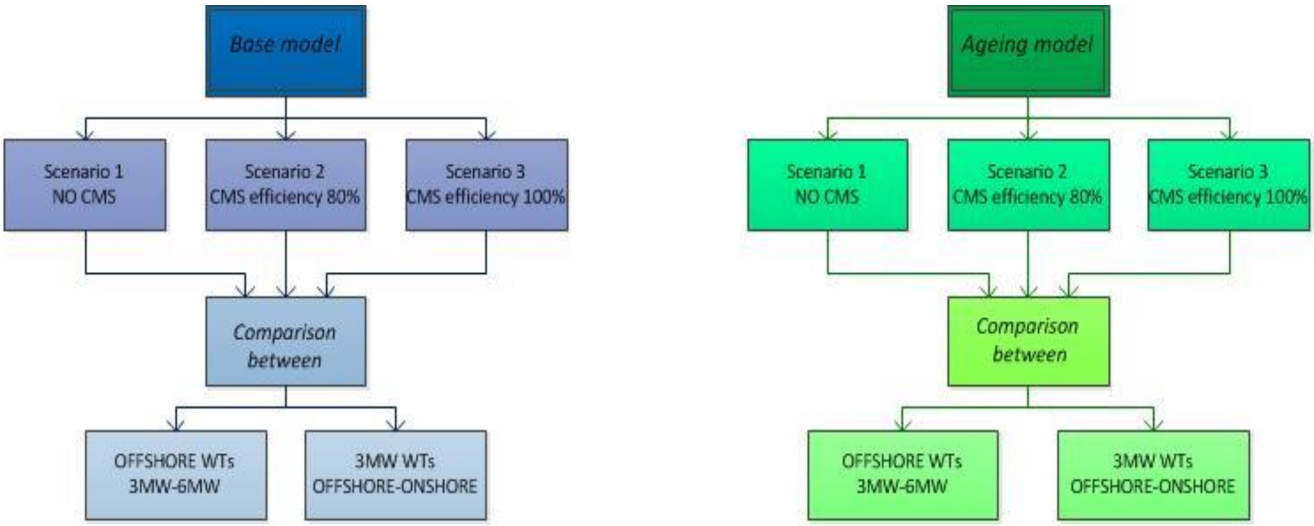

Figure 4-2: ***Applied approaches scheme***

5 Application

This chapter presents the case study on which the LCC analysis has been carried out. The system description, input data, and assumptions are so expounded.

5.1 System description

The case study system is composed of three WTs: the first one is an offshore WT with a rating power of 3MW and it is owned by Vattenfall, the second WT is an offshore WT with rating power of 6MW and it is owned by Vattenfall, the assumed model is V112-3.0MW; the third WT is an onshore WT with rating power of 3MW and it is owned by Vattenfall; the assumed model is Haliade 150-6MW the assumed model is a V112-3MW WT.

Data concerning cost of maintenance, downtime and failure probability of these systems have been obtained by communication with Pär Attermo [29], operation manager at Vattenfall and Francois Besnard [23], Phd student at Chalmers University.

Service contracts

The service contract plays an important role on the evaluation of LCC. Through these contracts the manufactures decide for how long the costs of maintenance are covered by the manufactures itself and at what time of the WT lifetime the purchaser company starts to pay the maintenance costs. Vattenfall has contract on service with different companies depending on the different types of wind turbine.

In this specific case for the offshore wind turbines (WT1 and WT2) there is a 5 year contract with the manufactures which consist of a 5 years contract with full maintenance service. This means that during the first 5 years of operation any cost due to corrective and preventive maintenance is covered by the manufacture itself.

Concerning the onshore wind turbine (WT2), Vattenfall has a contract with the manufacture which consists of a 2 year contract. Therefore the maintenance is totally covered during the first two years of operations.

Periodic maintenance

In the WT1 and WT3 the preventive scheduled maintenance consists of 50 hours of maintenance per year, it involves 3 technicians and the total cost per year is about 6000€.
In the WT2 the PM consists of 60 hours per year of maintenance, it needs 4 technicians and its total cost is 8000€ per year.
The scheduled maintenance lies manly in lubrication, exchange of filters, check security equipment, tighten up bolts and visual checking.

When a Control Monitoring System is used the PM is not scheduled anymore but it consists of Preventive Condition Based Maintenance.
This means that the PM is carried out any time the CMS observes a certain component is going to fail within a certain period of time. The component is then repaired or substituted.
The main difference between a schedule maintenance and a condition based ones is that the latest reduces the CM, indeed part of CM is replaced by PM and the higher efficiency of CMS the more CM is replaced by PM.

5.1.1 Maintenance activities and turbine components

The data obtain by Vattenfall have been studied and evaluated for each component and for each different maintenance activities. For instance the same maintenance activity (i.e. inspection) applied to two different components it might have different cost due to the different number of hours need to carried it out.

In this study four different maintenance activities and 17 different components have been considered. The maintenance activities are:

1. Inspection
2. Small repair (4 and 8 hours)
3. Major repair (12, 16 and 24 hours)
4. Major replacement (12, 24, 36, 48, 60 hours)

In addition these operations can present different operation times. A small repair, for example, can take 4 hours or 8 hours of operation depending on the type of component and turbine, the same for major repair and major replacement. Some of these maintenance activities include the usage of a crane ship when the maintenance is carried out in an offshore WT. The cost of shipping is then added to the basic cost of the maintenance.

The different maintenance activities have been selected for each component of the turbine considering the different failure probabilities and the different type of needed maintenance (mean time to failure, mean time to repair, costs, number of technicians, etc.…). The selected components are:

- Gearbox
- Generator
- Brake system
- Main sharf/bearings
- Yaw system
- Cooling system
- Composite disc coupling
- Sensors
- Crane system
- Hydraulic and oil systems
- Rotor blades/hub
- Pitch system
- Rotor structure
- HV component
- Electrical system
- Structure parts
- Accessorises

The value of PM, CM and PL of each year is the sum of the cost of the different activities for each component of the turbine. In the base model this sum it will be the same every year because of the constant value of the failure rate frequency, in the ageing model the total sum it will increases with the increasing value of the failure rate frequency.

It is important to point out that not all the components of a turbine are subjected to the "ageing effect". Indeed the electrical system has a constant value of failure rate during the all life time in both base and ageing model.

5.1.2 Installed CMS

The second and third scenarios of the base and ageing model take into account the usage of a Control Monitoring System.

In all the three WTs the CMS is applied on the following components:

- Gearbox (only WT1 and WT3)
- Generator
- Main sharf
- Yaw system
- Blades
- Pitch system
- Rotor structure
- HV component

Within the scenarios 2 and 3 part of CM is replaced with PM, the remaining parts of the turbine are not subjected to any CMS and the PM is carried out as scheduled maintenance. For those parts the cost for CM doesn't change and it is the same in every scenario.

The CMS has an initial cost that is added to the investment cost in the year zero.

The cost of a CMS with an efficiency of 80% is about 20000€ while a CMS with an efficiency of 100% costs about 26000€.

5.1.3 Technical information

In Table 5-1 technical information of the three WTs are displayed. The table shows that data are very similar for WT1 and WT3 which have same manufacture, same size (rotor diameter and blade length) and same wind speed limits. WT2 is a bigger turbine with a bigger rotor, longer blades and wider range of operating temperature.

Table 5-1: ***Techinal information of WTs*** **[29]**

	WT1	**WT2**	**WT3**
Type	V112-3.0MW-offshore	Haliade 150-6MW-offshore	V112-3.0MW-onshore
Cut-in wind speed [m/s]	3	3	3
Cut-out wind speed [m/s]	25	25	25
Operating temperature	-20°C to +35°C	-30° C to +50°C	-30°C to +40°C

range[°C]			
Rotor diameter[m]	112	150	112
Gearbox	4-stage planetary	NO GEARBOX	Multi stage
Blade length [m]	54.65	73.5	54.65

5.1.4 Power curve

In Table 5-2 the power curve of the three WTs is expounded. The minimum wind speed which gives the maximum power production is 14 m/s for the three turbines, 3300 kW for WT1 and WT3, and 5500kW for WT2. The maximum wind speed (25 m/s) is the same for all the turbines. The WT2 is able to generate power at lower wind speed compare to WT1 and WT3.

Table 5-2: ***Power curve data*** **[29]**

Wind speed [m/s]	**WT1** and **WT3**	**WT2**
3	0	95
4	147	258
5	322	532
6	573	960
7	940	1537
8	1415	2316
9	2020	3265
10	2667	4304
11	3115	5127
12	3269	5435
13	3271	5499
14	3300	5500
15	3300	5500
16	3300	5500
17	3300	5500
18	3300	5500
19	3300	5500
20	3300	5500
21	3300	5500
22	3300	5500
23	3300	5500

24	3300	5500
25	3300	5500

5.2 Assumption

Within the two models the following assumptions have been considered:

- Spare parts are booked with a certain period in advance when a condition-based maintenance is carried out and therefore their costs are 5% less compare to the case when CM is used.
- The cost of shipping and man working during the shipping activities is reduced of 10% in the condition-based maintenance compared to CM, in the first case the crane ship and shipping activities are booked in advance.

Within the models there are some costs that have been evaluated from discussions [30], [31] and previous works [28], [5]:

- One unscheduled man per hour costs 80€/hour (cost of workers during the CM)
- One scheduled man per hour costs 60€/hour (cost of workers during the PM)
- The investment cost of CMS with an efficiency of 80% is 20000€
- The investment cost of CMS with an efficiency of 100% is 26000€
- The cost of the crane ship is about 6666 €/hour
- Cost of spare part in case of scheduled maintenance is 5% less compare to the corrective maintenance due to the early booking
- Cost of shipping in case of scheduled maintenance is 10% less compare to the corrective maintenance due to the early booking
- Cost of investment includes also cost for foundations, internal cables and grid connection and its values are:
    - ~ WT1= 4500000€
    - ~ WT2=6000000€
    - ~ WT3=3000000€

- Cost of remainder value is:
    - ~ WT1=100000€
    - ~ WT2=150000€
    - ~ WT3=80000€
- The numerical value of the discount rate used in the present value method evaluation has been chosen equal to 0,07.

Preventive Maintenance

The Preventive maintenance in the second and third strategies (Condition Based maintenance) has been calculated as:

$$\boldsymbol{C_{PM} = (N_t \cdot N_{hr} \cdot C_{mh,pm} + C_{sp,pm} + C_{cs,pm} \cdot N_{hcp}) \cdot f_r(t,c) \cdot CMS_{eff}} \qquad \textbf{(5.1)}$$

N_t=number of technicians [pers]

N_{hr}=number of hours needed to repair a specific component [hr]

$C_{mh,pm}$=cost of scheduled man per hour [€/hr*pers]

$C_{sp,pm}$ = cost of spare parts when a replacement occurs in case of PM[€]

$C_{cs,pm}$ = cost of the crane ship per hour in case of PM [€/hr]

N_{hcs} = number of hours of crane ship usage [hr]

$f_{r,}(t,c)$=probability of failure of a specific component in a specific year of the lifetime

CMS_{eff}=efficiency of control monitoring system

Within the first strategy the PM maintenance is only a scheduled maintenance and the cost is fixed at 6000€ per year for WT1 and WT3 and it is fixed at 8000€ per year for WT2

Corrective mainteince

The Corrective maintenance has been calculated as:

$$C_{CM} = (N_t \cdot N_{hr} \cdot C_{mh,cm} + C_{sp,cm} + C_{cs,cm} \cdot N_{hcp}) \cdot f_r(t,c) \cdot (1 - CMS_{eff}) \quad (5.2)$$

N_t= number of technicians [pers]

N_{hr} = number of hours needed to repair a specific component [hr]

$C_{mh,cm=}$ cost of unscheduled man per hour [€/hr*pers]

$C_{sp,cm}$ = cost of spare parts when a replacement occurs in case of CM[€]

$C_{cs,cm}$ = cost of the crane ship per hour in case of CM [€/hr]

N_{hcs}= number of hours of crane ship usage [hr]

$f_r(t,c)$ = probability of failure of a specific component in a specific year of the lifetime

$1\text{-}CMS_{eff}$= inefficiency of the control monitoring system

Production Losses

When a failure occurs and a replacement is need the entire WT system has to be stopped for a certain time of period as long as the component is totally repaired. This "switched off" period causes a loss of production and consequentially a loss of money. This economic loss added in the LCC analysis through the cost of production losses.

Within this study case the cost of production losses has been evaluated with a similar equation expressed in 3.2.1:

$$C_{PL} = (f_r(t,c) \cdot (CMS_{eff} \cdot 0,85 + (1 - CMS_{eff})) \cdot N_{hr} \cdot P \cdot C_f \cdot C_{el} \quad (5.3)$$

N_{hr}=number of hours needed to repair a specific component [hours]

$(f_r(t,c) \cdot (CMS_{eff} \cdot 0,85 + (1\text{-}CMS_{eff})) \cdot N_{hr}$ equals to the total downtime [hours]

P = electric power generated [kWh]

C_f = capacity factor

C_{el} = cost of electricity [€/kW]

Within the three strategies the following assumptions have been used:

- Capacity factor =0,4

- Cost of electricity = 0,05 €/kWh

WT1: offshore, 3MW

The Table 5-3 shows the calculated values of PM, CM, and PL for each year considering a constant value of the failure probability. This means that within each strategy the values of PM, CM and PL are constant for the all WT lifetime.
Since the maintenance contract for this specific offshore WT provides the total covered payment of the maintenance during the first 5 years, the costs of PM and CM are set to zero during this period.

The year zero is considered as the year of construction of the WT where no electricity production, operations, and maintenance are carried out.

Table 5-3: ***Input data WT1 base model***

	Investment+CMS($1*10^6$) [€]			*PM [€]*			*CM [€]*			*Production Losses [€]*			*Reminder value ($1*10^4$) [€]*		
Scenario	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***
0 [yr]	4,5	4,52	4,526	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	2198,8	2062,1	2027,3	0	0	0
2	0	0	0	0	0	0	0	0	0	2198,8	2062,1	2027,3	0	0	0
3	0	0	0	0	0	0	0	0	0	2198,8	2062,1	2027,3	0	0	0
4	0	0	0	0	0	0	0	0	0	2198,8	2062,1	2027,3	0	0	0
5	0	0	0	0	0	0	0	0	0	2198,8	2062,1	2027,3	0	0	0
6	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
7	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
8	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
9	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
10	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
11	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
12	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
13	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
14	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
15	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
16	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
17	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
18	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
19	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	0	0	0
20	0	0	0	6000	65905	82480	99102	27425	9395	2198,8	2062,1	2027,3	1	1	1

The Table 5-4 points out the value of the all costs in the ageing model case for the wind turbine1. The failure rate increases with time and the costs increases in turn with time. The costs reach a maximum value at the 20th year when the failure probability is highest.

Table 5-4: ***Input data WT1 ageing model***

	Investment+CMS ($1*10^6$) [€]			*PM [€]*			*CM [€]*			*Production Losses [€]*			*Reminder value [€]*		
Scenario	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***
0[years]	4,5	4,52	4,526	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	296,0	282,3	278,9	0	0	0
2	0	0	0	0	0	0	0	0	0	507,5	480,1	473,2	0	0	0
3	0	0	0	0	0	0	0	0	0	719,1	677,9	667,6	0	0	0
4	0	0	0	0	0	0	0	0	0	930,6	875,7	862,0	0	0	0
5	0	0	0	0	0	0	0	0	0	1142,1	1073,5	1056,4	0	0	0
6	0	0	0	6000	39590	49490	59630	16570	5806	1353,6	1271,3	1250,8	0	0	0
7	0	0	0	6000	46190	57740	69500	19263	6704	1565,2	1469,2	1445,2	0	0	0
8	0	0	0	6000	52790	65980	79370	21956	7603	1776,7	1667,0	1639,5	0	0	0
9	0	0	0	6000	59390	74230	89240	24649	8501	1988,2	1864,8	1833,9	0	0	0
10	0	0	0	6000	65980	82480	99110	27341	9400	2199,7	2062,6	2028,3	0	0	0
11	0	0	0	6000	72580	90730	108980	30034	10299	2411,3	2260,4	2222,7	0	0	0
12	0	0	0	6000	79180	98980	118840	32727	11197	2622,8	2458,2	2417,1	0	0	0
13	0	0	0	6000	85780	107220	128710	35419	12096	2834,3	2656,0	2611,4	0	0	0
14	0	0	0	6000	92380	115470	138580	38112	12994	3045,8	2853,8	2805,8	0	0	0
15	0	0	0	6000	98980	123720	148450	40805	13893	3257,4	3051,6	3000,2	0	0	0
16	0	0	0	6000	105570	131970	158320	43497	14791	3468,9	3249,4	3194,6	0	0	0
17	0	0	0	6000	112170	140220	168190	46190	15690	3680,4	3447,3	3389,0	0	0	0
18	0	0	0	6000	118770	148460	178060	48883	16589	3892,0	3645,1	3583,3	0	0	0
19	0	0	0	6000	125370	156710	187930	51575	17487	4103,5	3842,9	3777,7	0	0	0
20	0	0	0	6000	131970	164960	197800	54268	18386	4315,0	4040,7	3972,1	1	1	1

WT2: offshore, 6MW

Table 5-5 displays the same types of costs of Table 5-3 concerning the WT2.
In this turbine the maintenance contract equals the one of the WT1 and the costs of maintenance during first 5 are totally covered by the manufacture.

Table 5-5: ***Input data WT2 base model***

	Investment+CMS($1*10^6$) [€]			*PM [€]*			*CM [€]*			*Production Losses [€]*			*Reminder value ($1*10^4$) [€]*		
Scenario	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***
0 [yr]	6	6,02	6,026	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	3107,6	2898,1	2845,7	0	0	0
2	0	0	0	0	0	0	0	0	0	3107,6	2898,1	2845,7	0	0	0
3	0	0	0	0	0	0	0	0	0	3107,6	2898,1	2845,7	0	0	0
4	0	0	0	0	0	0	0	0	0	3107,6	2898,1	2845,7	0	0	0
5	0	0	0	0	0	0	0	0	0	3107,6	2898,1	2845,7	0	0	0
6	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
7	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
8	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
9	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
10	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
11	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
12	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
13	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
14	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
15	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
16	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
17	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
18	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
19	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	0	0	0
20	0	0	0	8000	117490	146862	167718	41189	9557	3107,6	2898,1	2845,7	1,5	1,5	1,5

Table 5-6 shows the costs of investment, maintenance, production losses and reminder value of the WT2 within the ageing model where the failure rate increases with time.

Table 5-6: ***Input data WT2 ageing model***

	*Investment+CMS(1*10^6) [€]*			*PM [€]*			*CM [€]*			*Production Losses [€]*			*Reminder value (1*10^4) [€]*		
Scenario	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***
0 [yr]	6	6,02	6,026	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	437	416	411	0	0	0
2	0	0	0	0	0	0	0	0	0	734	692	682	0	0	0
3	0	0	0	0	0	0	0	0	0	1031	968	952	0	0	0
4	0	0	0	0	0	0	0	0	0	1625	1520	1431	0	0	0
5	0	0	0	0	0	0	0	0	0	1921	1796	1702	0	0	0
6	0	0	0	8000	82240	93580	117550	28982	6840	2218	2072	1972	0	0	0
7	0	0	0	8000	93990	108270	134280	33053	7747	2515	2347	2243	0	0	0
8	0	0	0	8000	105740	122960	151000	37124	8655	2812	2623	2514	0	0	0
9	0	0	0	8000	117490	137640	167720	41195	9563	3109	2899	2784	0	0	0
10	0	0	0	8000	129240	152330	184450	45266	10471	3406	3175	3055	0	0	0
11	0	0	0	8000	140990	167020	201170	49337	11378	3702	3451	3326	0	0	0
12	0	0	0	8000	152740	181700	217900	53408	12286	3999	3727	3596	0	0	0
13	0	0	0	8000	164490	196390	234620	57479	13194	4296	4003	3867	0	0	0
14	0	0	0	8000	176240	211070	251340	61550	14101	4593	4279	4137	0	0	0
15	0	0	0	8000	187980	225760	268070	65621	15009	4890	4555	4408	0	0	0
16	0	0	0	8000	199730	240450	284790	69692	15917	5187	4830	4679	0	0	0
17	0	0	0	8000	211480	255130	301520	73763	16824	5483	5106	4949	0	0	0
18	0	0	0	8000	223230	269820	318240	77834	17732	5780	5382	5220	0	0	0
19	0	0	0	8000	234980	284510	334960	81904	18640	6077	5658	5491	0	0	0
20	0	0	0	8000	246730	299190	351690	85975	19548	6374	5934	5761	1,5	1,5	1,5

WT3: onshore, 3MW

Table 5-7 illustrates the costs concerning the WT3. This turbine is onshore located and the maintenance contract establishes that the costs of maintenance are totally covered by the manufacture during the first two years of operation. The costs of PM and CM start from the third year of activity.

Table 5-7: ***Input data WT3 base model***

	Investment+CMS($1*10^6$) [€]			*PM [€]*			*CM [€]*			*Production Losses [€]*			*Reminder value ($1*10^4$) [€]*		
Scenario	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***
0 [yr]	3	3,02	3,026	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	1470,5	1420,9	1408,3	0	0	0
2	0	0	0	0	0	0	0	0	0	1470,5	1420,9	1408,3	0	0	0
3	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
4	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
5	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
6	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
7	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
8	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
9	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
10	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
11	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
12	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
13	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
14	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
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18	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
19	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0	0	0
20	0	0	0	6000	46406	58062	71970	21959	9395	1470,5	1420,9	1408,3	0,8	0,8	0,8

Table 5-8 expounds the values of costs obtained for the WT3 when the ageing model is carried out.

Table 5-8: ***Input data WT3 ageing model***

	Investment+CMS($1*10^6$) [€]			*PM [€]*			*CM [€]*			*Production Losses [€]*			*Reminder value ($1*10^4$) [€]*		
Scenario	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***
0 [yr]	3	3,02	3,026	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	223	218	217	0	0	0
2	0	0	0	0	0	0	0	0	0	361	351	349	0	0	0
3	0	0	0	6000	13935	17420	21880	6864	3110	500	485	481	0	0	0
4	0	0	0	6000	18580	23220	29040	9015	4009	639	619	614	0	0	0
5	0	0	0	6000	23225	29030	36190	11165	4907	778	753	746	0	0	0
6	0	0	0	6000	27870	34840	43350	13315	5806	916	886	879	0	0	0
7	0	0	0	6000	32515	40640	50510	15465	6704	1055	1020	1011	0	0	0
8	0	0	0	6000	37160	46450	57660	17615	7603	1194	1154	1144	0	0	0
9	0	0	0	6000	41805	52260	64820	19765	8501	1332	1288	1276	0	0	0
10	0	0	0	6000	46450	58060	71970	21915	9400	1471	1421	1409	0	0	0
11	0	0	0	6000	51095	63870	79130	24065	10299	1610	1555	1541	0	0	0
12	0	0	0	6000	55739	69670	86290	26215	11197	1748	1689	1674	0	0	0
13	0	0	0	6000	60384	75480	93440	28365	12096	1887	1822	1806	0	0	0
14	0	0	0	6000	65029	81290	100600	30515	12994	2026	1956	1939	0	0	0
15	0	0	0	6000	69674	87090	107750	32665	13893	2165	2090	2071	0	0	0
16	0	0	0	6000	74319	92900	114910	34815	14791	2303	2224	2204	0	0	0
17	0	0	0	6000	78964	98710	122070	36965	15690	2442	2357	2336	0	0	0
18	0	0	0	6000	83609	104510	1.2922	39115	16589	2581	2491	2469	0	0	0
19	0	0	0	6000	88254	110320	1.3638	41265	17487	2719	2625	2601	0	0	0
20	0	0	0	6000	92899	116120	1.4353	43415	18386	2858	2758	2734	0,8	0,8	0,8

5.3 Results

This chapter presents results from the calculation of the two models applied to the three WTs and each model is evaluated for three different strategies.

5.3.1 Numerical results

The following tables show the Total Present Value of the Life Cycle Cost for each WT and strategy. The value of TPV_LCC decreases from the strategy1 to strategy3 in the all cases. This means that the effect of CMS is positive and efficient for the three turbines and the investment cost of a control monitoring system is lower than the benefit generated by its usage.
The WT3 has the lowest value of TPV_LCC as expected since it is an onshore turbine and shipping costs and spare parts transportations by shipping are not included in the sum of maintenance costs. WT1 has the same rating power but higher values of TPV_LCC due to the addition costs that an offshore WT has compared to an onshore one.
As expected, the highest TVP_LCC is the one of WT2 (highest rating power and offshore installation) and the lowest one is the one from WT3 (lowest rating power and onshore installation) in the both models.

Table 5-9: ***Total Present Value- Base Model***

	WT1	**WT2**	**WT3**
TPV_LCC strategy1 [€]	5’231’600	7’212’800	3’726’500
TPV_LCC strategy2 [€]	5’173’800	7’119’900	3’661’900
TPV_LCC strategy3 [€]	5’169’900	7’110’700	3’659’400

Table 5-10: ***Total Present Value- Ageing Model***

	WT1	**WT2**	**WT3**
TPV_LCC strategy1 [€]	5’340’600	7’509’400	3’687’700
TPV_LCC strategy2 [€]	5’276’300	7’400’600	3’637’400
TPV_LCC strategy3 [€]	5’271’000	7’327’000	3’635’600

5.3.2 Comparison between strategies

Table 5-11 shows the profit in euro obtained from the strategy 2 and 3 compared to the strategy 1 in the base and in the ageing model. This amount of money indicates the total saving that can be obtained with the use of CMS during the entire lifetime of the WTs.
Table 5-12 points out the percentage of profit obtained with CMS for the three WTs in the base and ageing model.

Table 5-11: ***Comparison strategy 1 vs strategies 2 and 3 [€]***

Base Model			
WTs	WT1	WT2	WT3
Strategy 1 vs strategy2	57’800	92’900	64’600
Strategy 1 vs strategy3	61’700	102’100	67’100
Ageing Model			
WTs	WT1	WT2	WT3
Strategy 1 vs strategy2	64’300	108’800	50’300
Strategy 1 vs strategy3	69’600	182’400	52’100

Table 5-12: ***Comparison stategy1 vs strategies 2 and 3[%]***

Base Model			
WTs	WT1	WT2	WT3
Strategy 1 vs strategy2	1,10%	1,29%	1,74%
Strategy 1 vs strategy3	1,18%	1,42%	1,8%
Ageing Model			
WTs	WT1	WT2	WT3
Strategy 1 vs strategy2	1,2%	1,5%	1,36%
Strategy 1 vs strategy3	1,3%	2,4%	1,41%

WT1

The following graphs illustrate how the present value cost of LCC changes during the lifetime of the WT. On the left columns a global image is shown including the high cost of the investment in the year zero, on the right columns an enlargement is shown to point out how the present value cost of LCC varies from the year 1 to the year 20.

1. The first row shows the scenario 1 where CMS is not applied
2. The second row shows the scenario 2 where a CMS with 80% efficiency is applied to the major parts
3. The third row shows the scenario 3 where a CMS with 100% efficiency is applied to the major parts

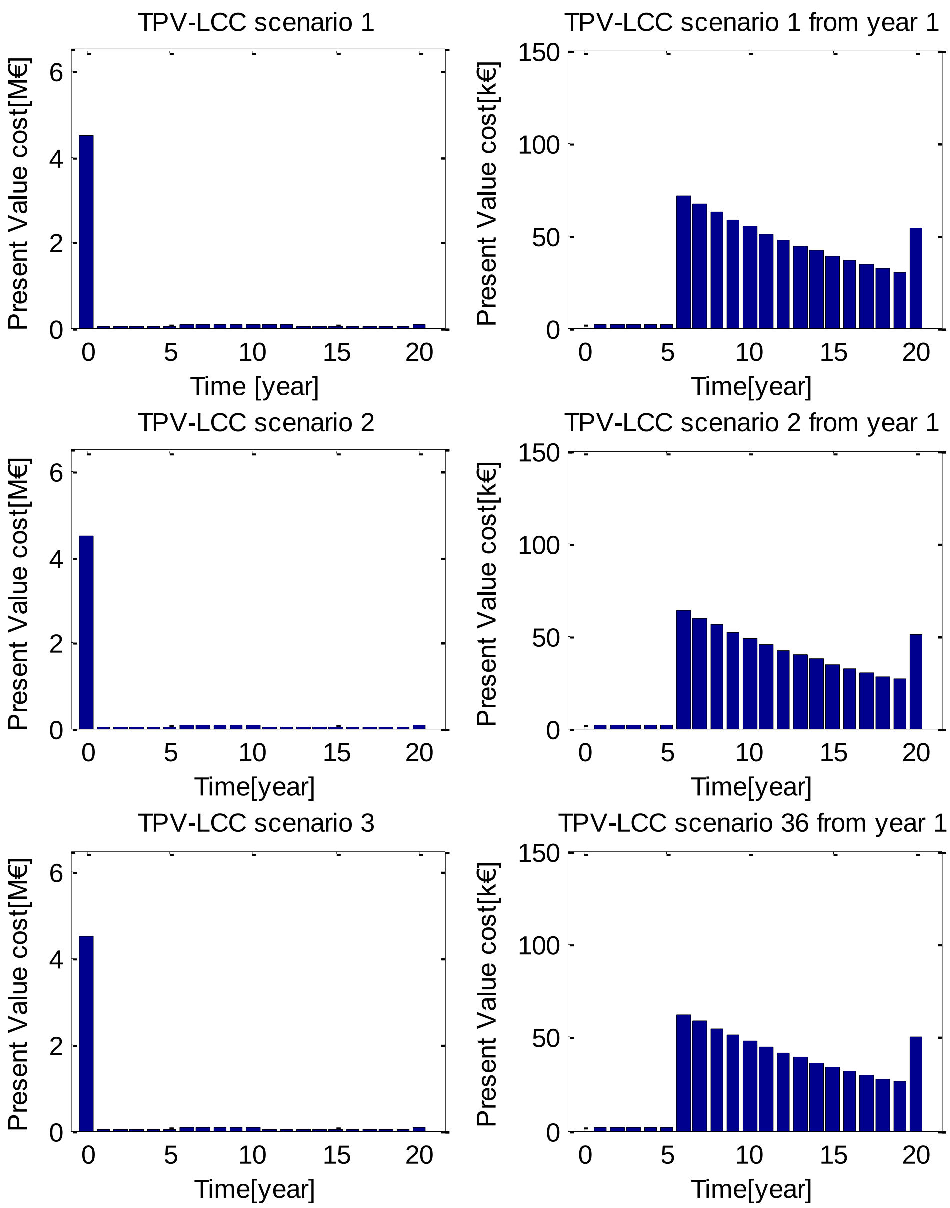

Figure 5-1: ***WT1-base model***

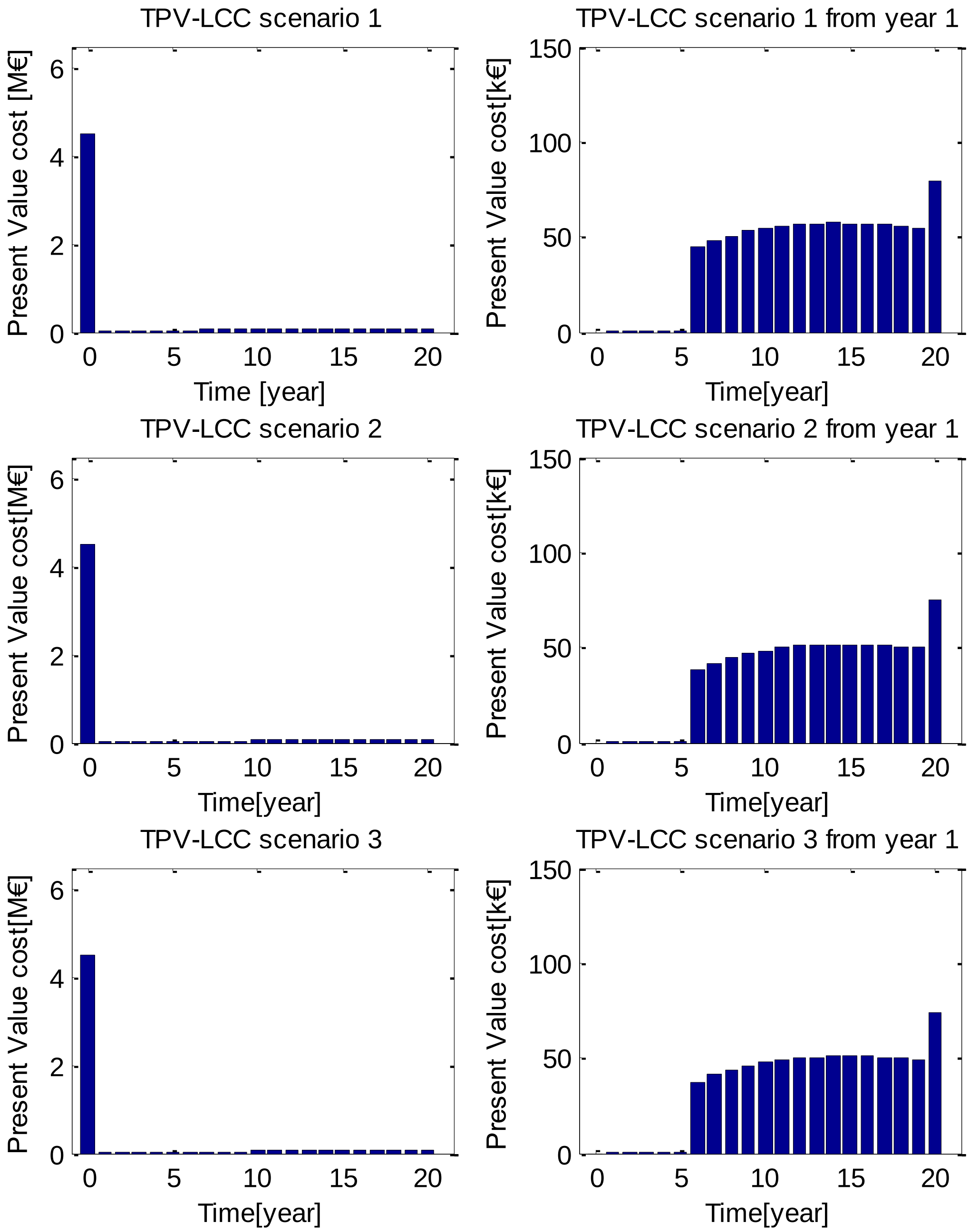

Figure 5-2: ***WT1-ageing model***

In the following page a comparison of the three strategies is shown, in Figure 5-4 the base model is compared for the three strategies. The blue lines (scenario1) are higher along the all operation life of the turbine, the green lines are lower than the blue ones because of the applied CMS and eventually the red lines have the lowest value along the all lifetime because of the applied CMS with maximum efficiency. The same is expressed in Figure 5-3 concerning the ageing model.

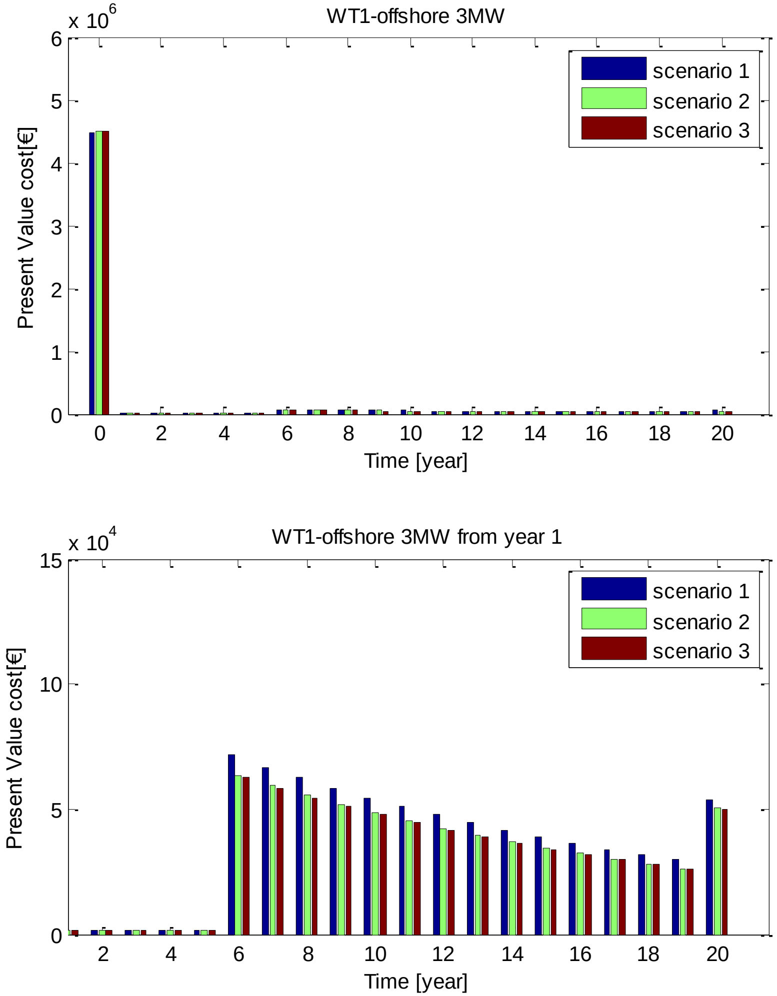

Figure 5-4: ***Comparison between strategies 1, 2, 3 applied to WT1 in the base model***

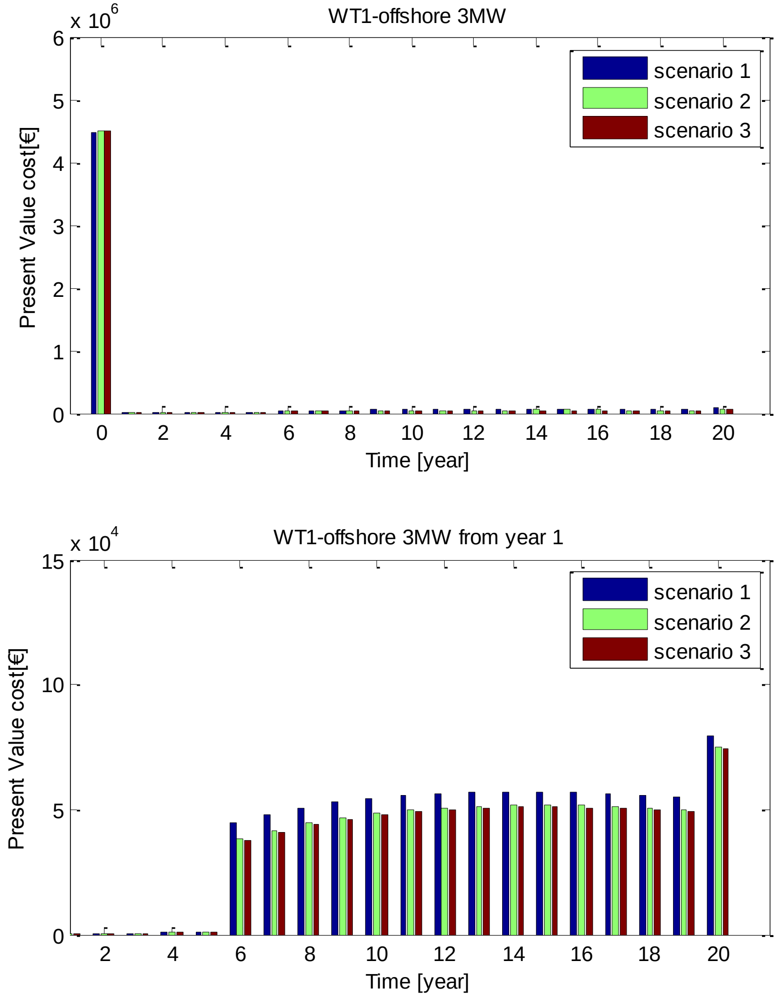

Figure 5-3: ***Comparison between strategies 1, 2, 3 applied to WT1 in the ageing model***

WT2

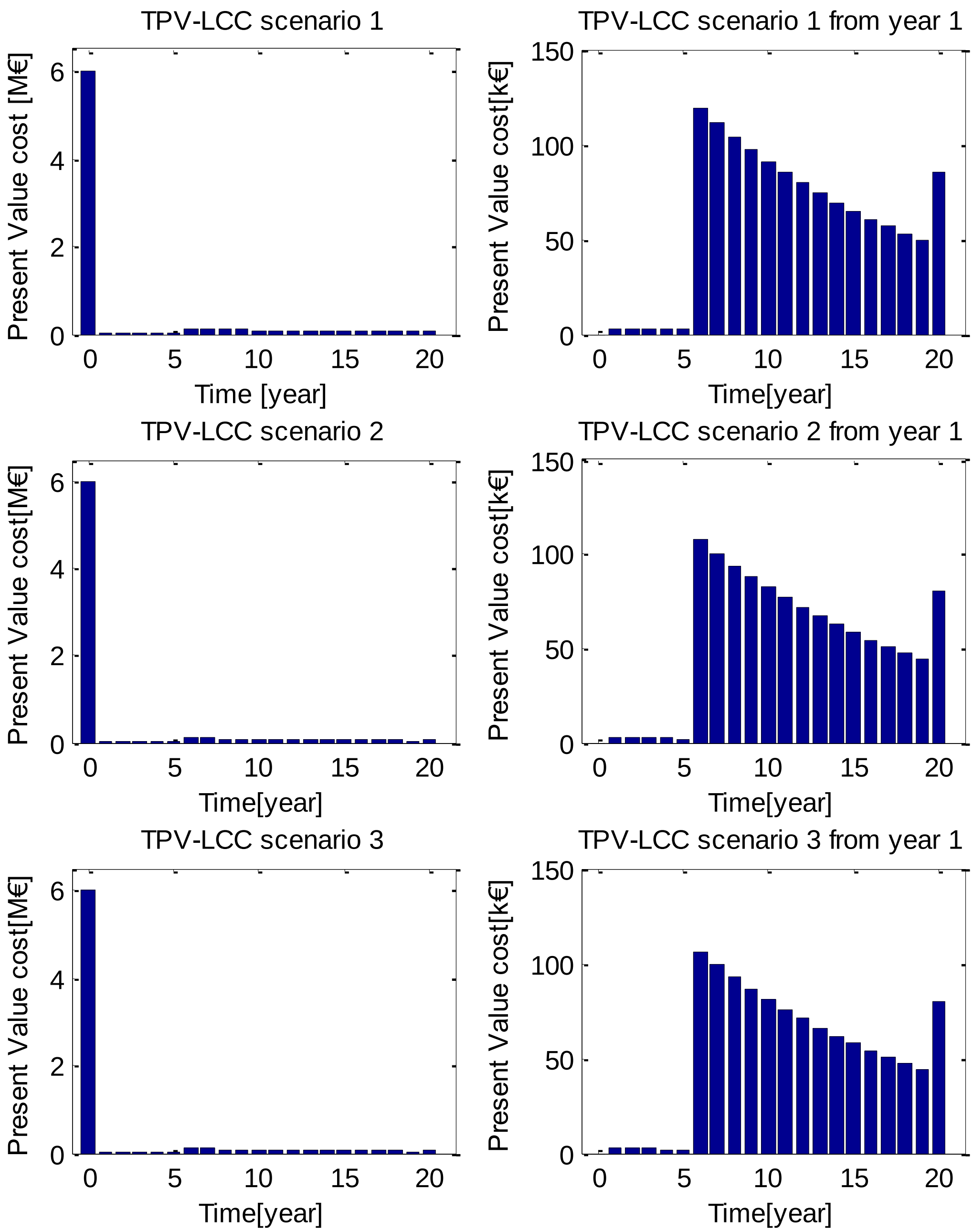

Figure 5-5: *WT2-base model*

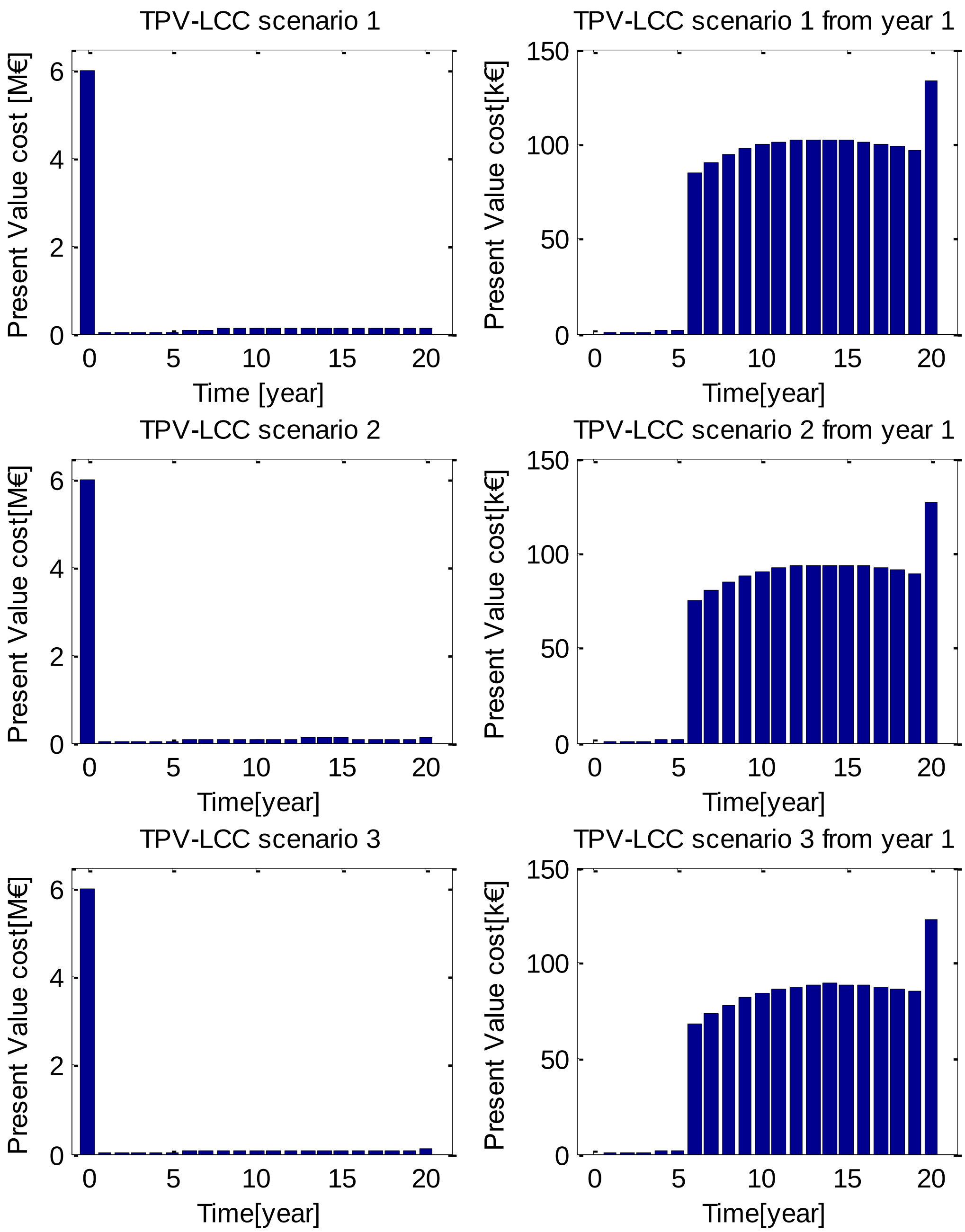

Figure 5-6: ***WT2- ageing model***

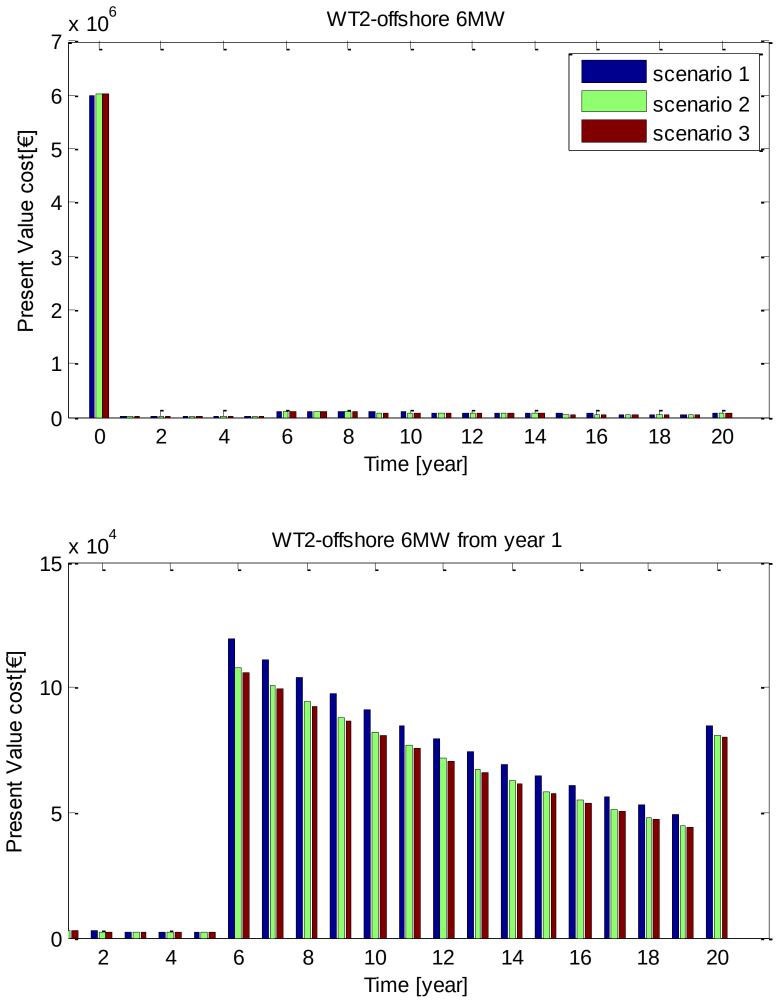

Figure 5-7: ***Comparison between strategies 1, 2, 3 applied to WT2 in the base model***

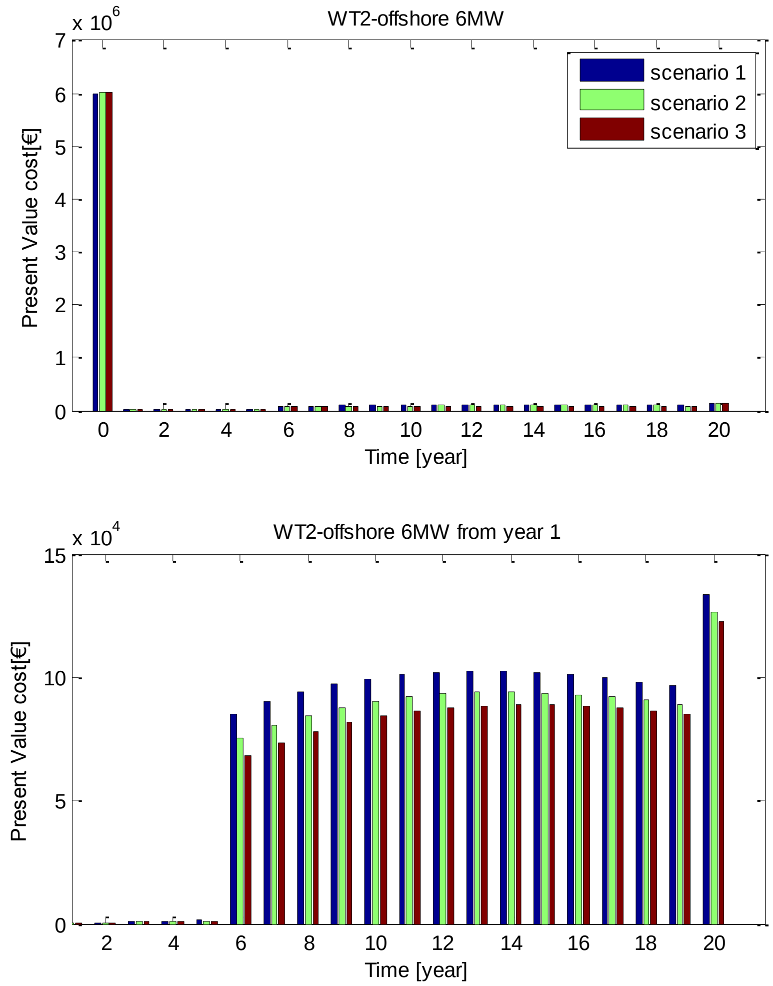

Figure 5-8: ***Comparison between strategies 1, 2, 3 applied to WT2 in the ageing model***

WT3

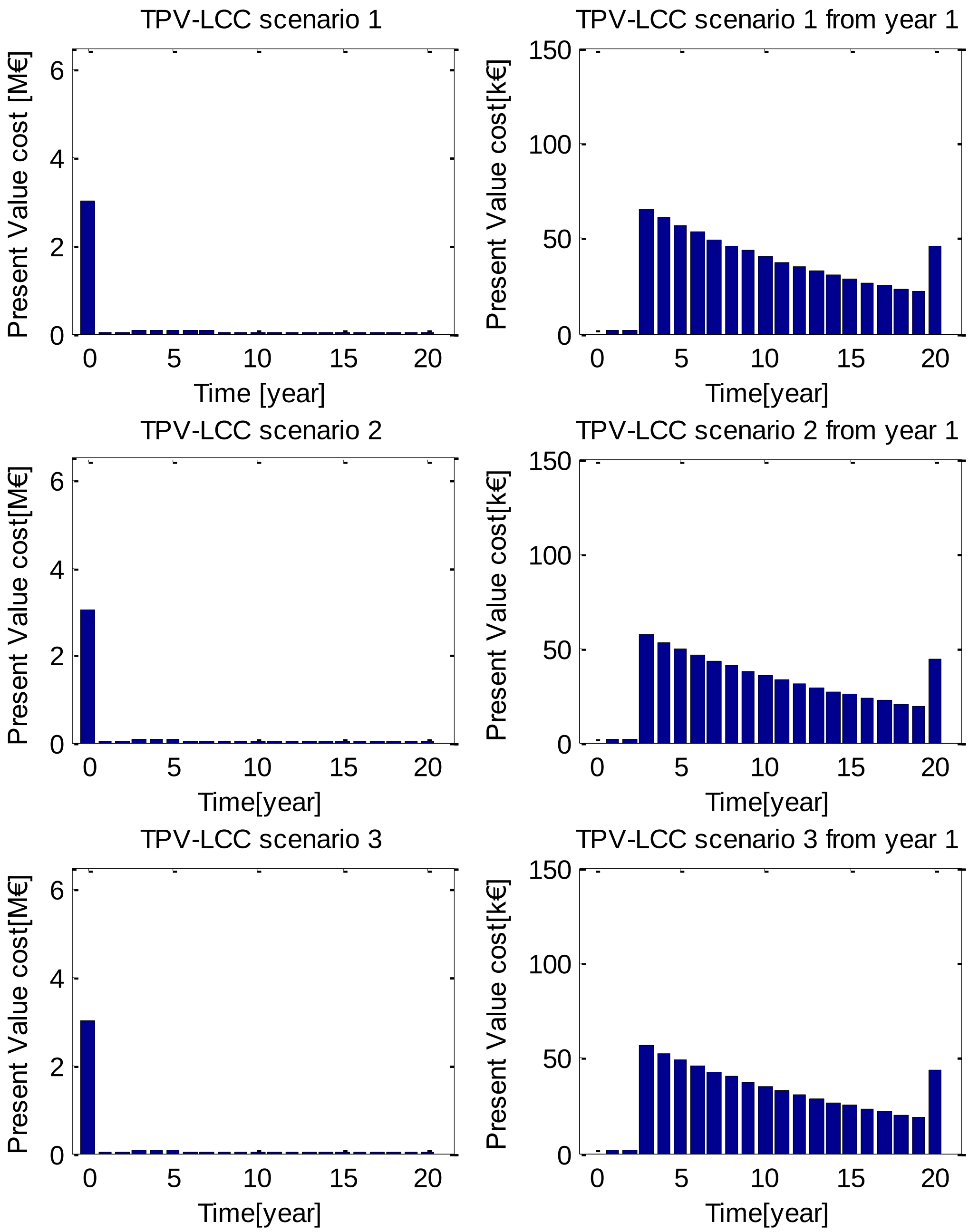

Figure 5-9: ***WT3-base model***

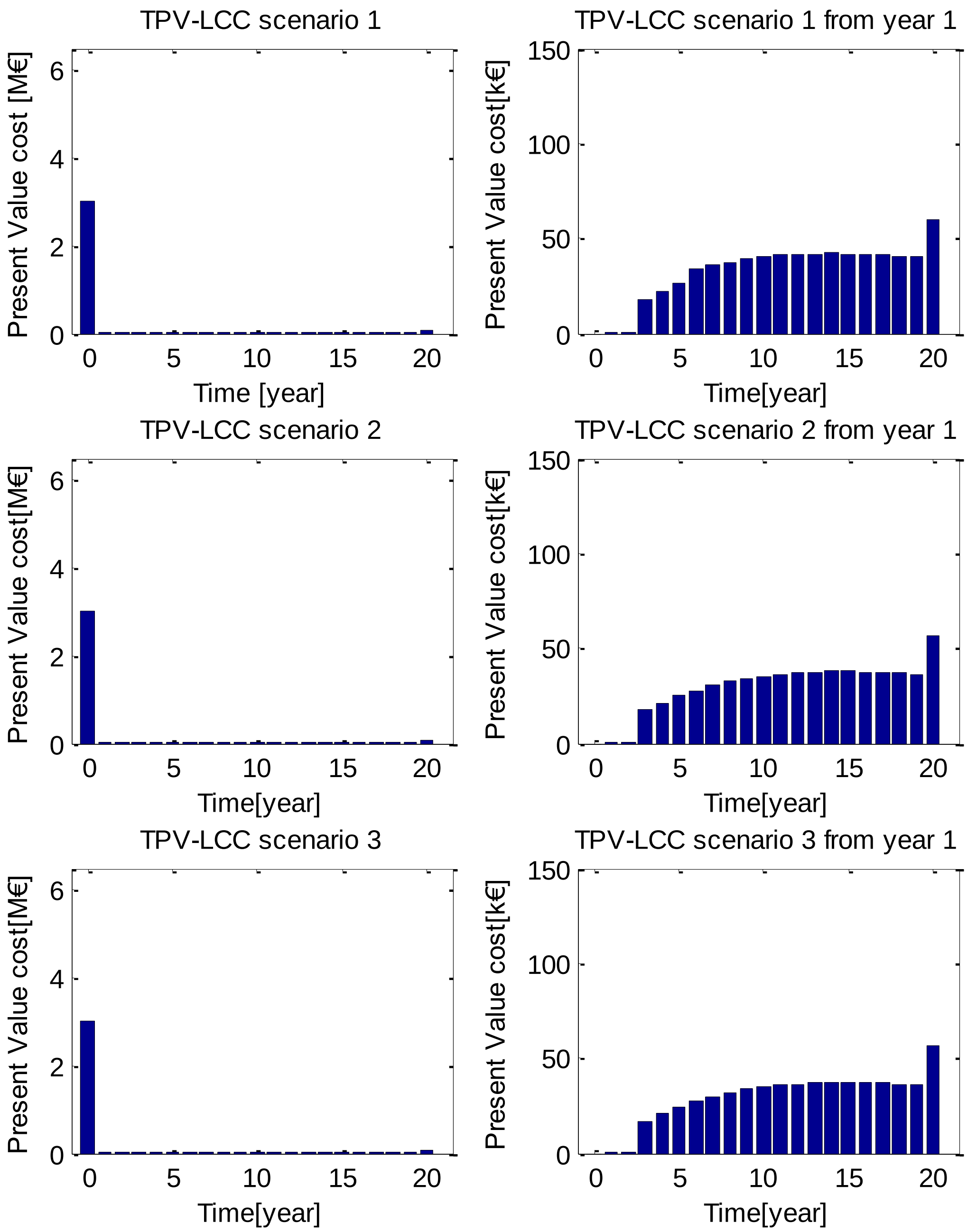

Figure 5-10: ***WT3- ageing model***

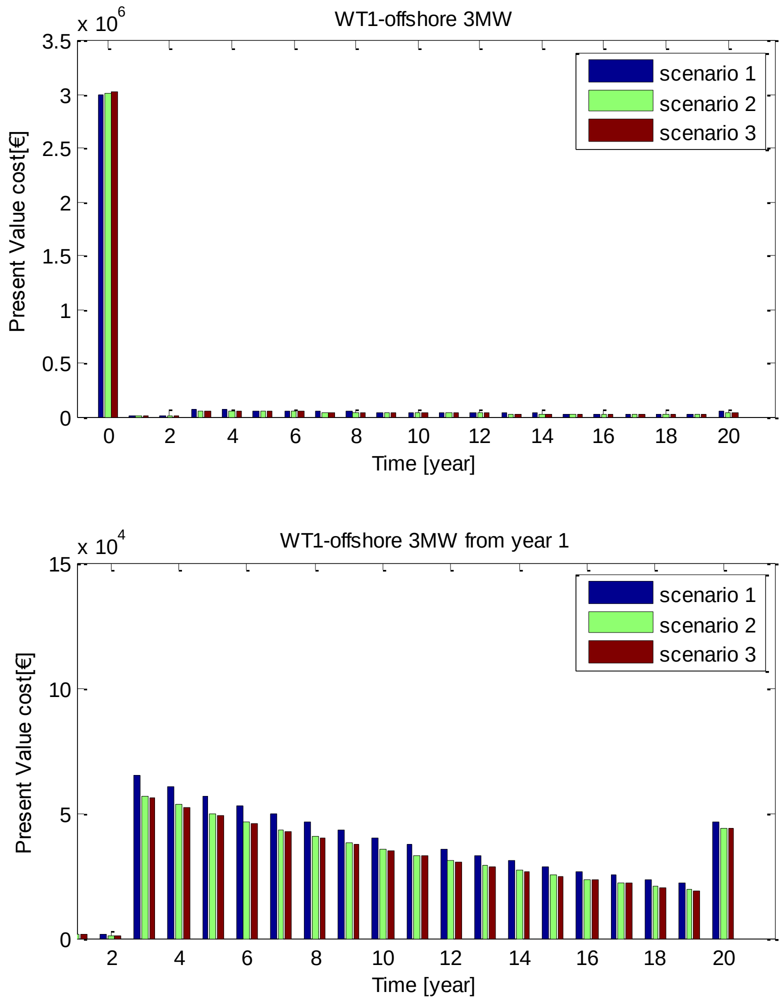

Figure 5-11: ***Comparison between strategies 1, 2, 3 applied to WT3 in the base model***

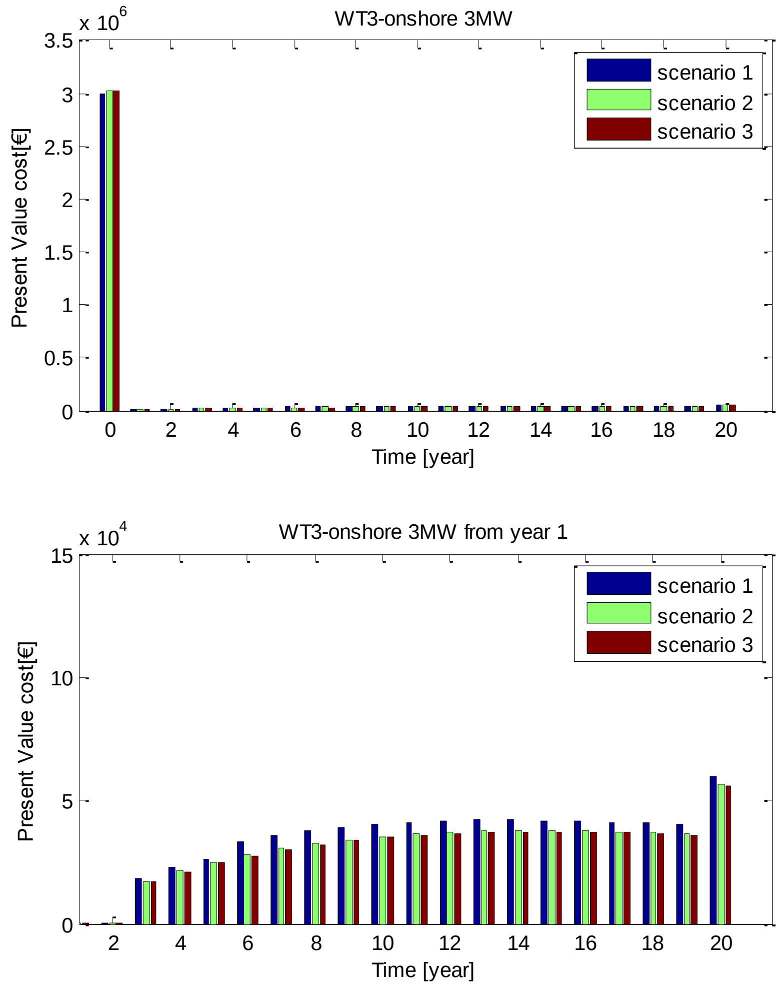

Figure 5-12: ***Comparison between strategies 1, 2, 3 applied to WT3 in the ageing model***

5.4 Sensitivity analysis

The sensitivity analysis has been carried out for different values of discount rate in order to observe how this value affects the results.
The total sum of TPV(LCC) has been evaluated with three different discount rates: 0%, 7%, 10% for each single case study and for each WT considering the ageing model.

Without CMS

The discount rate is given with three different values, as expected the TPV(LCC) decreases when the discount rate increases.

Table 5-13: TPV(LCC) with different discount rates on WT1, WT2 and WT3 without CMS.

	Total sum of the present value of LCC [€]		
Discount rate [%]	WT1	WT2	WT3
0	6’666’800	9’859’500	4’689’600
7	5’340’600	7’509’400	3’687’700
10	5’085’100	7’054’200	3’491’700

CMS efficiency 80%

Table 5-14: TPV(LCC) analysis with different discount rates on WT1, 2, and 3 with CMS 80% efficiency.

	Total sum of the present value of LCC [€]		
Discount rate [%]	WT1	WT2	WT3
0	6’481’200	9’564’900	4’543’800
7	5’276’300	7’400’600	3’637’400
10	5’045’100	6’982’500	3’461’300

CMS efficiency 100%

Table 5-15: TPV(LCC) analysis with different discount rates on WT1, 2, and 3 with CMS 100% efficiency

	Total sum of the present value of LCC [€]		
Discount rate [%]	WT1	WT2	WT3
0	6’458’300	9’382’900	4’530’900
7	5’271’000	7’327’000	3’635’600
10	5’043’200	6’931’100	3’460’900

The discount rate is given with three different values, as expected the TPV(LCC) decreases when the discount rate increases. The three different tables show the effect of the discount rate on the CMS profitability. For every strategy, every turbine and every discount rate the investment of a CMS is profitable. The profitability of CMS increases with decrease of the discount rate as Table 5-16 shows:

Table 5-16: Profitability of use of CMS for different values of discount rate

	WT1-discount rate 0%	*WT2-discount rate 0%*	*WT3-discount rate 0%*
Strategy 1 vs strategy2	2,78%	2,98%	3,1%
Strategy 1 vs strategy3	3,12%	4,8%	3,38%
	WT1-discount rate 7%	*WT2-discount rate 7%*	*WT3-discount rate 7%*
Strategy 1 vs strategy2	1,2%	1,5%	1,36%
Strategy 1 vs strategy3	1,3%	2,4%	1,41%
	WT1-discount rate 10%	*WT2-discount rate 10%*	*WT3-discount rate 10%*
Strategy 1 vs strategy2	0,78%	1,02%	0,87%
Strategy 1 vs strategy3	0,82%	1,74%	0,88%

6 Closure

6.1 Conclusions

The Life cycle cost analysis is a fundamental tool to evaluate a total cost for a technical system during its life span. In this thesis it has been shown that operations and maintenance are an important part of the wind turbine life cycle cost.
Two failure rate models have been investigated; the base model with a constant failure rate and the ageing model with linearly increasing failure rate over the life time of wind turbine. The effect of CMS on the maintenance and on the LCC has been studied for the two failure rate models.
The use of CMS provides an opportunity to plan maintenance ahead in time and carry out PM instead of CM. Consequently a saving can be achieved in spare parts, crane ships and man hours leading to a reduction of the total maintenance costs.

The benefit from a CMS has been analysed considering two different CMS efficiencies: 80% in the scenario2 and 100% in the scenario3. The results show that the installation of a CMS reduces the LCC for the three different turbines under consideration.
Condition monitoring system shows a higher benefit with the ageing model where failure rate linearly increases over time compare to the base model.
A reduction of 64’300€ was achieved in the TPV_LCC for WT1 with CMS efficiency of 80% considering the ageing model. This value increased to 69’600€ with a CMS efficiency of 100%. These results correspond to a profit of 1,2% and 1,3% respectively compared to the case without CMS.

For WT2 the reduction of costs is 108800€ and 182400€ respectively for CMS with an efficiency of 80% and 100%, with the ageing model. This translates into a profit of 1,5% and 2,4% respectively compared to the case without CMS. These results show that the profit of CMS increases with the rating of the turbine.

The profit of using CMS for the onshore wind turbine (WT3) is 1,36% and 1,41% with an efficiency of 80% and 100% respectively compared to the case without CMS. These values are higher compared to the offshore WT of same rating; this leads to the conclusion that maintenance contracts have an impact on the life cycle cost.

The reduced costs of maintenance obtained with the installation of CMS will be considerable when considered for a wind farm of standard size. Furthermore the control monitoring system might be coordinated in order to repair more than one turbine per time saving the high costs of shipping and reduce further the life cycle cost.

6.2 Comparison with previous work

The results from this work can be compared to some of those obtained in the past from RCAM's work. It is interesting to compare the same results obtained for the case study of this work and the results obtained in previous works [4], [27], and [13].

In [4] a study of the total cost analysis for different alternative maintenance strategies has been made (see section 1.2.2.1) to understand if CMS is profitable or not.

Table 6-1: Results comparison with previous work [4]

	RCAM's work –"Maintenance managment of wind power systems-Cost effect analysis of conditioning monitoring system,"-2006 [4]	*"Life cycle cost analysis on wind turbines"-2013*
How much the cost of PM+CM has to decreases to make CMS profitable	2,5%	1%
How much the cost of PM has to increase to make CMS profitable	85%	63,7%
How much unscheduled service has to become scheduled to make CMS profitable	47%	27,5%

In [4] the cost of PM and CM is compared to the cost for PM and CM when a CMS is installed and the cost of production is set to zero. The results show that the sum of CM and PM decreases by 2,5% when CMS starts to be profitable. In this work the sum of PM and CM has to decrease by 1% to make CMS profitable.

The cost of PM increases when CMS is used since part of CM is substituted by a cheaper PM. In [4] the cost of PM has to increase by 85% per year while in this work the same study shows an needed increase in the cost of PM equal to 63,7% in order to make CMS profitable.

When the CM is partially replaced by PM a change from unscheduled service to schedule service occurs. In [4] a change from unscheduled to scheduled maintenance of 47% would be enough to make CMS profitable. In this study a change from unscheduled to scheduled maintenance has been considered depended on the CMS efficiency and failure rate. In order to make CMS profitable the unscheduled service has to decrease of 27,5% and become scheduled. The results from this study show that the use CMS provides a profit and the unscheduled service is replaced more than 27,5% by scheduled service for the three WTs for any studied case.

The sensitivity analysis performed in this master thesis is the same analysis that has been made in [4]. The results show that in this study the CMS is always profitable, for every chosen value of the discount rate while in the previous work there are cases, when the discount rate is too high, where the investment cost of CMS is not covered.

In the Julia Nilsson's master thesis project an entire offshore wind farm has been observed and LCC has been performed on the entire plant while in this thesis project a single offshore WT has been analysed. The comparison between these two works can be considered suitable since data used are very similar and the LCC analysis takes into account the similar type of costs. An implementation that has been done in this work compared to [4] is the cost of production losses. This cost varies depending on the availability of the system and it is affected by the efficiency of the CMS.

In [27] results from LCC have been evaluated with probabilistic methods and sensitivity analysis to identify the benefit of using CMS installed in a 3MW WT. These results highlight that there is a high economic benefit of using CMS. Figure 3-4 shows the cost benefit of using CMS where the two cases with and without CMS are illustrated over a time scale of 25 years. The total cost benefit of using CMS is 190’000€. Sensitivity analysis has been performed to observe the influence of the scale parameter of the gearbox on the economic benefit of the CMS.
In this work the total cost benefit is about 64’300€ for a 3 MW WT and 108’800€ for a 6 MW WT and the sensitivity analysis for the scale parameter of the gearbox have not been carried out.

In [13] a comparison of operation and maintenance costs resulting from different maintenance strategies has been applied to a wind turbine V44-600kW (see section 1.2.2.3). This study revealed that CM is the cost-optimal maintenance strategy for this type of turbine. The cost of a CMS has been found to be too low to justify the cost of the system for a turbine with relatively low rated capacity. Furthermore the sensitivity analysis has shown how the CMS becomes more beneficial when increasing turbine size. The turbine of this study is an onshore WT and for offshore WTs the benefit of CMS is expected to be significantly higher.
The results of this master thesis project have proved numerically the conclusion that has been made in [13] with sensitivity analysis: the higher rating power he better profit of CMS.

6.3 Future work

Within this case study the two offshore WTs (WT1 and WT2) have been considered as single turbines.

An interesting further step might be to consider LCC of an entire wind farm where CMS can be coordinated in order to repair more than one turbine per time saving the high costs of shipping operations and reduce further the life cycle cost.

This project takes into account a base and an ageing model to predict the failure probability of each component. Another way to evaluate the LCC analysis is to carry out a probabilistic model where failures are considered having a random behaviour and a Weibull distribution function is used to evaluate the failure probability.

Eventually within this study the failure rate of each component has been considered independent from any other component. In the real case a deterioration interconnected process exists where the failure probability of some components depends on the failure probability of others components; for instance, a defect in the gearbox causes vibrations on the high speed shaft, which in turn can damage the generator bearing or windings. This approach considers the so called "secondary failures" and it offers a more realistic model for the wind turbines analysis.

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