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Authors' addresses:

Bertrand Kerres
KTH Royal Institute of Technology
School of Industrial Engineering and Management
Machine Design / Internal Combustion Engines
Brinellvägen 83, SE-100 44 Stockholm, Sweden
kerres@kth.se

Katharina Fischer
Fraunhofer-Institut für Windenergie und Energiesystemtechnik IWES
Senior Scientist
Appelstr. 9A, 30167 Hannover, Germany
E-Mail: katharina.fischer@iwes.fraunhofer.de

Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
School of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Mathieustrasse 10
52074 Aachen, Germany
E-mail: RMadlener@eonerc.rwth-aachen.de

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Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Mathieustrasse 10, 52074 Aachen, Germany
Phone: +49 (0) 241-80 49820
Fax: +49 (0) 241-80 49829
Web: www.eonerc.rwth-aachen.de/fcn
E-mail: post_fcn@eonerc.rwth-aachen.de

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Economic Evaluation of Maintenance Strategies for Wind Turbines: A Stochastic Analysis

Bertrand Kerres[1,2,*], Katharina Fischer[3,4], and Reinhard Madlener[5]

[1] *RWTH Aachen University, D-52062 Aachen, Germany* [2] *KTH Royal Institute of Technology, School of Industrial Engineering and Management, Department of Machine Design, SE-10044 Stockholm, Sweden*

[3] *Chalmers University of Technology, Department of Energy and Environment, Division of Electric Power Engineering, S-412 96 Gothenburg, Sweden*

[4] *Fraunhofer Institute for Wind Energy and Energy System Technology IWES, Hannover D-30167, Germany*

[5] *Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, D-52062 Aachen, Germany.*

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Abstract

We develop a stochastic model for assessing the life-cycle cost and availability of wind turbines resulting from different maintenance scenarios, with the objective to identify the most cost-effective maintenance strategy. Using field-data based reliability models, the wind turbine – in terms of reliability – is modeled as a serial connection of the most critical components. Both direct cost for spare parts, labor, and access to the turbine, as well as indirect cost from production losses are explicitly taken into account. The model is applied to the case of a Vestas V44–600kW wind turbine. Results of a Reliability-Centered Maintenance (RCM) analysis of this wind turbine are used to select the most critical wind turbine components and to identify possible maintenance scenarios.

Keywords: Maintenance strategy, Reliability modeling; Wind turbines, Stochastic analysis, Life-cycle cost;

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[*] Corresponding author. Phone: +46-8-790 95 07, e-mail: kerres@kth.se.

1. Introduction

Wind power is an important renewable energy source with a globally installed capacity of presently 318 GW, and a continued strong growth expected in the future [1]. Among the challenges that hinder expansion is the operation & maintenance (O&M) cost, which accounts for approx. 18–23% in European offshore wind farms and approx. 12–30% in onshore wind farms ([2], [3], [4]). Modeling O&M costs allows the selection of cost-effective maintenance strategies. In addition, it reduces the uncertainty for wind power investors and with that their financing costs. Hence it is an important step toward increasing the attractiveness of wind power.

An overview of models to compare different maintenance strategies or to optimize maintenance is given in Scarf [5]. Of special interest here is the delay-time model, first mentioned by Christer [6], and described in detail by Wang [7], which is used in this study. Specifically for the energy sector, deterministic as well as stochastic maintenance optimization approaches for wind turbines and nuclear power plants are described in Nilsson [8]. Seminal work on stochastic optimisation of wind turbines maintenance was done by Rademakers, Seebregts and associates [9], [10]. Welte, Vatn and Heggset [11] use a Markov chain deterioration model as well as a Monte Carlo simulation to optimize maintenance costs for hydro power plants. A similar approach is employed by Besnard [12] for wind turbine blades. Byon and associates ([13], [14]) use dynamic programming and a partially observed Markov process for studying stochastic deterioration, the benefits of dynamic strategies, and the influence of seasonality and weather on optimal maintenance. Andrawus et al. [15] and McMillan and Ault [16] use other stochastic approaches (based on maximum likelihood and Monte Carlo simulation). Andrawus [17] gives an extensive overview of approaches to wind power maintenance optimization and conducts a case study, in which inspection intervals are optimized using the delay-time model. However, in his analysis of maintenance strategies, the option of using online condition-monitoring, being widely applied to wind turbines today, is not taken into account.

This paper presents a model to estimate the effects of different maintenance strategies on wind turbine O&M cost as well as production losses due to turbine downtime. The work is part of a combined approach, which aims at achieving cost-effective maintenance for wind turbines using field-data based methods: Reliability-Centered Asset Maintenance (RCAM) merges the proven systematic approach of RCM, explained e.g. in [18] and [19], with quantitative maintenance optimization techniques (described, e.g., by [20] and [21]). While

RCM as a qualitative method is limited in assessing the cost effectiveness of different maintenance strategies, mathematical maintenance optimization techniques alone do not ensure that the maintenance efforts address the most relevant components and failures. By combining these two approaches, the RCAM method, which was originally developed for the application to electric power distribution systems [22], provides a promising framework also for the maintenance strategy selection of wind turbines. In this context, Fischer et al. [23], [24] conducted an initial study of predominant failures in wind turbines and how to counteract them, using the RCM method. The present work is a continuation of this and takes the next step of model development, using comprehensive data and information from the RCM study. The model introduced in this paper is highly flexible and enables the simulation of more maintenance strategies than previous models, including the use of an online Condition-Monitoring System (CMS). The model uses Monte Carlo simulation to calculate a probability density of O&M cost and production losses for each strategy. A specific strength of the work is the utilisation of comprehensive field reliability data on the considered type of wind turbine.

Maintenance is defined as the combination of all technical and corresponding administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function [25]. Maintenance strategies are generally classified into corrective maintenance and preventive maintenance. Corrective maintenance denotes a strategy according to which an asset is operated until it fails. This strategy helps to avoid unnecessary repairs or inspections of the system and the resulting costs and downtimes. Preventive maintenance can be predetermined or condition-based maintenance (CBM). It is carried out in order to avoid the occurrence of failure. Predetermined preventive maintenance is performed in fixed intervals of calendar time, operational time, or another usage parameter. Preventive CBM is carried out when component deterioration exceeds a certain threshold. A prerequisite is therefore the ability to monitor the component condition. Ding and Tian [26] propose a combination of corrective and time-based maintenance called opportunistic maintenance. Preventive maintenance enables an early planning of the maintenance actions, with the benefit of reducing downtimes resulting from spare-part lead time or the unavailability of auxiliary equipment, such as cranes. Furthermore, preventive maintenance has the advantage of avoiding secondary damage or total breakdown. In contrast to predetermined maintenance, CBM avoids unnecessary maintenance and improves the utilization of the component lifetime.

This paper is structured as follows. In Section 2, the model for estimating the turbine life-cycle O&M cost depending on the maintenance strategy for different turbine components is presented and subsequently applied to the case of a Vestas V44–600kW turbine. In Section 3, the assumptions and input data used to model the wind turbine components and investigated maintenance scenarios are introduced. Section 4 presents and discusses the results. The main conclusions regarding the potential and limitations of the model in general, and of the maintenance strategy selection for the studied wind-turbine model in particular are provided in Section 5.

2. Wind Turbine Reliability and Maintenance Cost Model

The purpose of the model presented here is to allow for a comparison of different maintenance strategies with regard to O&M cost and availability from a utility's perspective. The resulting availability can be translated into cost of lost production, given the power curve of the wind turbine, wind data for the turbine site, and electricity prices. The model consists of two main parts: one for a wind turbine and one for a service team. Optionally, a CMS can be included in the model.

The wind turbine is modeled – in terms of reliability – as a serial connection of the most critical components, i.e. the turbine is available for power generation only if all of these components are functional. Each component itself can deteriorate according to two different processes: binary deterioration and delay-time deterioration. The binary process allows two possible states: a *good* state, in which the component fulfills its designated function, and a *failed* state, in which the component does not. The transition from state *good* to state *failed* is described by a random variable T; instances of T are assumed to be independent and identically distributed. After a failure and the subsequent renewal, the process begins again. An example of the deterioration state over time in the binary process is shown in Fig. 1 (top plot).

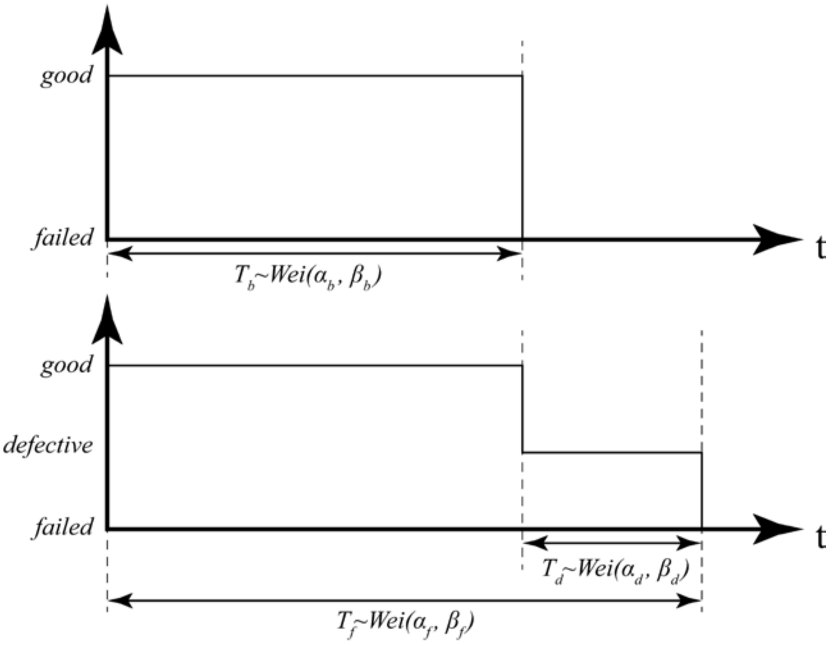

Figure 1: Binary (top plot) and delay-time (bottom plot) component deterioration

The delay-time model expands this process by adding a *defective* state between *good* and *failed*. In this state, a fault, e.g. in the form of a crack, is developing, but the component is still functional. In the *defective* state, an inspection of the component could warn the maintenance engineer of an impending failure, cf. [7]. There are different options to model the benefits of knowledge about impending failure. For instance, it may be assumed that the item can be repaired at a lower cost than replacing it as a preventive measure. Another possible benefit is the enhanced planning of a replacement for components that have to be ordered in advance, thus avoiding the long downtime resulting from unexpected breakdown.

An external observer only knows whether the component is in state *failed* or not. An inspection, with associated cost, is needed to determine the exact deterioration state. Alternatively, an online CMS can alert external observers with a given probability for each defect.

The service team can be assigned different tasks on site. An assignment consists of a set of basic actions, which can be arbitrarily combined; its total cost equals the sum of the cost of the underlying basic actions as summarized in Table 1. In this table, c_{dr} is the cost per man-hour drive, c_W is the cost per man-hour work, and C_{fix} is the fixed cost of an action that includes material and necessary auxiliary equipment like cranes. Note that all values except those for driving and regular service are component-specific. The following basic actions can be carried out by the service team:

Table 1: Basic actions of the service team

Action	Effect	Time consumption	Turbine available	Cost
Drive	--	t_{dr}	Yes	$2\,t_{dr}\,c_{dr}$
Switch on/off	Turbine changes state	0	–	0
Order	Component available after lead time	0	–	0
Regular service	–	t_{rs}	No	$2\,t_{rs}\,c_W + C_{fix,rs}$
Inspect	Technician knows component state	t_{ins}	No	$2\,t_{ins}\,c_W + C_{fix,ins}$
Replace	Component renewed	t_{repl}	No	$2\,t_{repl}\,c_W + C_{fix,repl}$

Drive: This action has no influence on the turbine, but generates costs which depend on the time needed to drive to/from the wind farm and the travel cost per time unit.

Switch on/off: No direct costs are generated by this action, but the turbine downtime will result in production losses. The turbine also shuts itself down automatically in the case of a component failure and has to be restarted manually. It is only possible to switch on the turbine if no component is in the state *failed*.

Order: Components which are not immediately available have to be ordered, which requires a certain lead time. The cost of the new component is accounted for in the basic action *Replace* (see below).

Regular service: In our model, regular service is always done the same way and in constant intervals of six months. It has no effect on component deterioration in the model, since the defect rates and failure rates were determined using data from turbines with bi-annual service. While regular service is being performed, the turbine has to be shut down. Its costs include the man-hours of work time plus a fixed charge for the consumed materials.

Inspect: Without inspection, it is only known if a component has failed or not. For that reason, it can make sense to inspect components that deteriorate according to the delay-time model. The inspections are assumed to be perfect, i.e. they always reveal the actual state. In reality, an inspection of, e.g., the gearbox would correspond to condition verification by measuring vibrations and the temperature, as well as by using an endoscope to inspect its subcomponents visually [23]. Their costs depend on the required time, the rate per man-hour and additional cost for, e.g., an oil analysis. The turbine must be stopped during inspections.

Replace: The component is replaced with a new one with deterioration state *good*. The new component has the same failure model as the old one, but starts with an age of zero. The turbine is shut down during component exchange. Expenses result from the working time of the service team, the procurement of a new component and the equipment (like cranes) needed to install it.

An assignment can originate from different sources: It can be scheduled by the service team itself, as a main service or as a planned component replacement. Alternatively, the service team is alerted by a component failure and the subsequent turbine shutdown or, if available, by a condition-monitoring system. In the latter case, the model requires that the team drives to the turbine and inspects the component in question. The detailed composition of the assignments is determined by the maintenance scenario. It is a set of rules that establishes how the service team will schedule its assignments and how it will react to component breakdowns or alerts submitted by the CMS.

The model as described so far calculates the downtime and the maintenance cost. In order to evaluate the trade-off between those two, an estimation of the downtime cost, that is, the loss in energy sales, is needed. It can be written as

$$CF_{Rev}(t) = E\big(w(t)\big) \cdot p_{el}(t) \tag{1}$$

where $w(t)$ is the wind speed in period t, $E(w)$ is the electricity production of the turbine at wind speed w, and $p_{\mathrm{el}}(t)$ is the sales price of electricity in period t. The total cost of a maintenance scenario can then be calculated as the sum of this opportunity cost and the maintenance cost and thus the most cost-effective scenario can be determined. Since the cash flows occur at different times, a present-value approach is used to make them comparable, specified as

$$PV = CF(t)/(1+i)^t \tag{2}$$

where $CF(t)$ denotes the cash flow in period t, and i the interest rate per period.

3. Model Parameterization for the Case of Wind Turbine V44–600kW

3.1. Component Selection and Input Data to the Model

The model described in the previous section is applied to a V44–600kW wind turbine. The component selection results from the previously mentioned RCM study of this turbine [23] [24]. Accordingly, the five components contributing most to the average annual downtime are considered: (1) Electrical system, (2) Generator, (3) Gearbox, (4) Control system, and (5) Hydraulic system. All components are assumed to be non-repairable, i.e., a replacement of the whole component is necessary after a failure in order to restore the wind turbine's functionality.

The component-specific model input data are summarized in Table 2. The Weibull parameters describing the failure rates have been determined based on reliability data from 60 turbines of the virtually identical models V42–600kW and V44–600kW ranging from 1996-2005, provided in [27]. The parameters are estimated using maximum-likelihood estimation, taking censoring into account. Graphical evaluations of the goodness-of-fit considering different possible lifetime distributions confirm the suitability of the Weibull distribution for modeling the failure data. A limitation of the reliability data available in [27] is that they contain only the age of the wind turbine, but not the component age. In order to obtain reliability models suitable for the present maintenance-strategy assessment, the parameters are therefore based on the first reported failure per turbine and component only.

All other input data in Table 2 were collected within the scope of the above-mentioned V44-specific RCM study, i.e., it was provided by the participating industry partners. In order to estimate the delay-time Weibull parameters, the approach in [28] was followed, based on the identified failure modes in the RCM study. Four experts were asked to submit three point estimates each of the delay time for the failure modes. Those estimates were averaged and a Weibull function was then fitted. The deterioration models of the components selected above for the V44 case study are chosen as follows:

Electrical System: The Rotor Current Control (RCC) unit is the most frequently failing part in this system. Since an impending failure in the electrical system is difficult to detect during up-tower inspection, it is modeled as a component with binary deterioration. The failure rate decreases over time.

Generator: Its failure rates decrease over time, and an impending failure can be detected if the component is inspected by the service team or by means of a CMS. It is modeled using the delay-time model.

Gearbox: Gearbox defects can be detected through inspection or a CMS. Therefore, the delay-time model is chosen for this component. The failure rate increases over time.

Control System: Its physical condition cannot easily be detected. The control system is therefore modeled using a binary process. According to the available reliability data, the failure rate is slightly decreasing with the component age; a replacement is comparably quick and cheap.

Hydraulic System: The dominant failure mode is a malfunction of the proportional valve that controls the pressure for the pitch cylinders. Its deterioration is hard to observe and, therefore, assumed to be binary. The failure rate is increasing with the component age.

Table 2: Model input data for the case of V44-600kW

Component	Electrical system	Generator	Gearbox	Control system	Hydraulic system
Deterioration model	Binary	Delay-time	Delay-time	Binary	Binary
Failure α_f [a]	15.31	56.71	25.77	41.46	16.86
β_f [-]	0.6436	0.6832	1.3349	0.8782	1.7616
Defect α_d [a]	–	0.81	0.81	–	–
β_d [-]		1.300	1.300		
t_ins [h]	2	3	6	1	1
t_repl [h]	5	16	24	2	2
t_lead [h]	48	504	672	0	0
$C_\mathrm{fix,repl}$ [SEK]	270,000	330,000	990,000	10,000	13,000

The labor cost of the 2-person service team is charged on an hourly basis with different rates for work and driving. One man-hour of work is priced at c_w = SEK 900 and one man-hour of drive at c_{dr} = SEK 600. The half-yearly main service, carried out by two technicians, takes t_{rs} = 7 h and costs an additional $C_{fix,rs}$ = SEK 5, 000 for material consumption besides the man-hours [29]. It is assumed that the service team is paid for by deployment, i.e., there is no service contract with a fixed charge that includes some of these actions, and there is neither insurance nor warranty for the turbine.

In order to enable a comparison between the different maintenance scenarios, the costs of preventive maintenance have to be judged against the cost due to production losses during a turbine failure. Four data sets are required to calculate the revenue from power production of a wind turbine: the wind data, the power curve of the wind turbine, the electricity price, and the price of green certificates awarded for the production of renewable energy. The wind data used in the present study were measured by means of a met mast in the harbor of Gothenburg, provided by Göteborg Energi. The data includes the hourly mean wind speed from the period 2002 to 2010. There is a significant seasonality in the wind data: The probability of hourly wind speeds larger than 10 m/s is 23.6% in autumn and winter (Sep–Feb), but only 13.4% during spring and summer (Apr–Aug). The power curve describes the power production of the turbine as a function of the wind speed. It is provided by the wind turbine manufacturer. Power prices consist of two components: The price of the power itself, assumed to be 420 SEK/MWh, based on the average price of futures contracts for the years 2012 to 2016 in the Swedish electricity market [30], and the price of green certificates, assumed to be 250 SEK/MWh in accordance with the average prices in 2011 [31]. Certificates are only awarded for the first 15 years of operation [32]. The discount rate chosen is 9%.

3.2. Maintenance Scenarios

The maintenance scenario determines which actions the service team takes in different situations. For all scenarios considered, it is assumed that the service team reacts to non-scheduled call-outs after the elapse of a waiting time; the waiting time is a random variable with discrete uniform distribution between 1 hour and 24 hours.

The *Baseline* scenario is a pure run-to-failure strategy in which no inspections are conducted and, besides regular service, only corrective maintenance is carried out. There is no CMS installed in the turbine.

Two other scenarios are compared to this baseline. In the first alternative scenario, called *Inspections*, the gearbox and the generator are inspected yearly. If the inspection reveals a defect, it orders a new component and replaces the old one as soon as the new one arrives.

In the second alternative scenario, *CMS*, a CMS monitors the vibration in the drivetrain. The CMS is assumed to detect 90% of gearbox and generator defects. The time of defect detection is a random, exponentially distributed variable. If the service team is alerted, it will inspect the component in question and inevitably find a defect, since it is assumed that there are no false positives, i.e., alerts when there is no defect. A new component is ordered and installed upon arrival. The other components are not inspected in either scenario, but maintained according to a run-to-failure strategy. This allows isolating the effects of gearbox and generator failures on maintenance costs and downtime of the scenarios.

The developed model simulates a life-cycle of 20 years. The life-cycle O&M cost depends on the random failure times of components and are hence also random variables. The probability distribution of the results is estimated using Monte Carlo simulation in which the turbine life-cycle is simulated 100,000 times. The simulations are carried out using MATLAB.

4. Results and Discussion

4.1. Availability and O&M Cost

Four key indicators are used to evaluate the outcome of each maintenance scenario: (1) unavailability, (2) opportunity cost of lost production, (3) O&M cost, and (4) total cost. Unavailability is defined as the ratio of the turbine downtime divided by its lifetime. The opportunity cost of lost production is the present value of the electricity that could not be produced due to turbine downtime. Since the turbine downtime itself is reflected in the unavailability, these two indicators are closely coupled. Their probability distributions, however, look different because additional factors, such as the discount rate and the electricity price, influence the cost of lost production. The O&M cost is the present value of all costs stemming from maintaining the turbine, i.e., the costs of the basic actions of the service team. Total cost is the sum of O&M cost and the cost of lost production. As described above, the Monte Carlo simulation results in a probability distribution for each of those indicators.

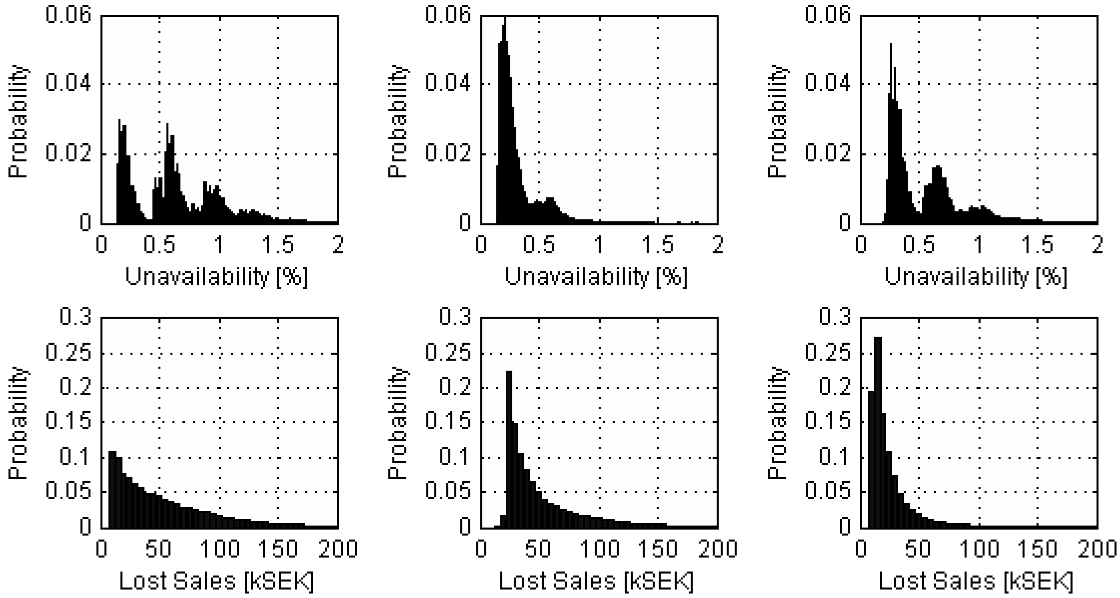

Figure 2: Unavailability and cost of lost production in the *Baseline* (left plot), *Inspections* (centre plot), and *CMS* (right plot) scenarios

The probability distribution of the unavailability is shown in Fig. 2. Using the *Baseline* scenario, peaks can be identified at unavailability values of 0.2%, 0.6%, and 0.9%, respectively. These are closely related to gearbox and generator failures, which result in a downtime of several weeks in this scenario. The peak at 0.2% is the outcome if only regular service and quick replacements of the smaller components contribute to the downtime, and neither a generator nor a gearbox failure occurs during the turbine life-cycle. The probability that neither a gearbox nor a generator failure occurs during the 20 years of turbine lifetime in the *Baseline* scenario is

$$\left[1 - F_{gen}(20a)\right]\left[1 - F_{gb}(20a)\right] \approx 0.3 \qquad (3)$$

where F is the cumulative density function of the failure time Weibull distribution of a generator and a gearbox, respectively. If one of those components fails once, the overall unavailability will be approx. 0.6%, and if two gearbox or generator failures arise, the resulting unavailability will be approx. 0.9–1.0%. The following calculation confirms this interpretation: The downtime due to an unexpected failure is

$$t_{down} = t_{ins} + t_{repl} + t_{lead} + 2t_{dr} + T_{wait}. \qquad (4)$$

Using the values from Table 2, this results in

$$(1 - A)^{gb} = \frac{6 + 24 + 672 + 4 + (0 \ldots 24)}{20 \cdot 8760} \approx 0.40\%$$

for a gearbox failure and

$$(1 - A)^{gb} = \frac{6 + 24 + 504 + 4 + (0 \ldots 24)}{20 \cdot 8760} \approx 0.30\%$$

for a generator failure. An unavailability higher than 1.0% cannot be as clearly related to single events as in the cases described above. The mean unavailability value in the *Baseline* scenario is 0.63%.

The probability distribution of the unavailability for the scenarios *Inspections* and *CMS* is presented in Fig. 2 (center) and (bottom), respectively. Considering the *Inspections* scenario, it can be seen that the inspections can mitigate the appearance of a long downtime after a gearbox or generator failure. This is to be expected: perfect annual inspections detect every impending failure where the time span from defect initiation to failure is longer than a year as well as those where the time span is shorter but the inspection nevertheless takes place when the component is defective. The early fault detection reduces the downtime drastically because the new component can be ordered and delivered while the turbine is still available. The inspections also take some time, however, during which the turbine is shut down. The first peak is therefore slightly shifted towards higher unavailability. The resulting mean unavailability in this scenario is 0.56% compared to 0.63% in the *Baseline* scenario.

In the *CMS* scenario, the service team will be alerted in 90% of gearbox or generator defects before failure occurs. This reduces the probability of long turbine downtime arising from component lead times. The first unavailability probability peak is higher than in the other scenarios because more defects are detected, and not shifted towards higher unavailability (as in the *Inspections* scenario), since there are no unnecessary inspections. The mean unavailability is 0.32%, which is significantly lower than in the *Baseline* scenario.

Figure 2 also shows the cost of lost production for the three maintenance scenarios. The cost is closely coupled to turbine unavailability. As can be suspected from the unavailability curves, the risk of high opportunity cost due to turbine downtime is significantly reduced in the *Inspections* and even more in the *CMS* scenario. The reason for the different shapes of the unavailability curve and the cost of lost production curve is the influence of the discounting.

Figure 3 presents the direct O&M cost and the total cost. In the *Baseline* scenario, the service team conducts inspections only if a component has failed. There is a lower floor of SEK 350,000 due to regular maintenance and the breakdown of other components with a high probability of failure and, therefore, breakdown at least once during the turbine life-cycle. In the *Inspections* scenario, the additional inspections lead to a higher floor of the O&M cost curve distribution. The detection of a defective gearbox or generator slightly increases the probability of higher direct O&M cost, because an earlier replacement increases the chance of a second gearbox or generator failure during the turbine life-cycle. Furthermore, in the model, the service team does not take into account the remaining turbine lifetime when replacing the components. It would, therefore, buy and install a new one even if the turbine is scheduled to run only a short time. The same factors that lead to high downtime, i.e., gearbox and generator failure, also lead to high O&M cost. The first peak at around SEK 350,000 is the result if neither the generator nor the gearbox fails, while the second peak is the result if there is one failure in one of those components. For a failure in a later year, the discount factor will be higher and therefore the present value of the cost lower. Furthermore, while the downtime resulting from a gearbox or generator failure is similar, the replacement cost is much higher for the gearbox, so that a clear attribution of the peaks in the distribution to specific failures is not possible.

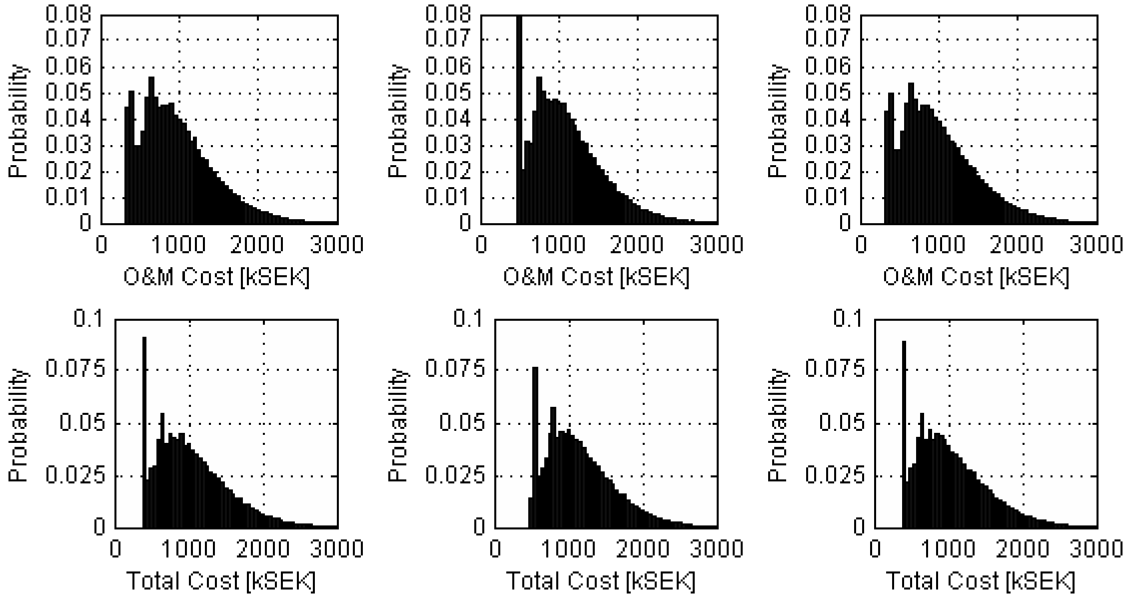

Figure 3: O&M cost and total cost over lifetime in the *Baseline* (left plot), *Inspections* (centre plot), and *CMS* (right plot) scenarios

In order to determine the best maintenance scenario, the probability distributions of the total cost are evaluated using two indicators, the mean value and the total cost upper bound that can be expected with 95% confidence (UB_{95}), analogously to the Value-at-Risk concept in investment evaluations. Lower mean total costs are obviously preferable to higher ones. Furthermore, a risk-averse turbine operator prefers a lower total cost upper bound, since it indicates a lower risk of catastrophic losses. The respective indicators for the evaluated maintenance scenarios are presented in Table 3. If Scenario A results in either lower mean values without a higher total cost upper bound than Scenario B or in a lower total cost upper bound without a higher mean value than Scenario B, Scenario A is said to dominate Scenario B. Using the metrics described, the *Baseline* scenario and the *CMS* scenario dominate the *Inspections* scenario. Choosing the *Inspections* strategy would therefore not be cost-effective. The difference between the *Baseline* and the *CMS* scenarios is very small. However, note that the total costs in the *CMS* scenario do not include the cost of the CMS hardware and the condition-monitoring service, which are in the range of € 8,000 and approx. 1,300 €/year, respectively [33]. The scenario would have to perform better at least by these costs in order to justify installation, which it does not in the case studied here. Corrective maintenance is therefore found to be the most cost-effective maintenance strategy for the gearbox and the generator of the V44. In contrast, Andrawus [9] recommends CBM with inspection intervals of 30 days to be optimal for the gearbox and the generator of a 600 kW wind turbine. This discrepancy becomes plausible in light of the much higher component lead times assumed by Andrawus. The different result is also related to the assumption in [9] that CBM would fully avoid the replacement of entire gearboxes and generators.

Table 3: Comparison of total cost by scenario

Scenario	Mean [kSEK]	UB_{95} [kSEK]
Baseline	1,060	1,988
Inspections	1,180	2,069
CMS	1,057	1,983

4.2. Sensitivity Analysis

In order to assess the influence of important input parameters, a sensitivity analysis is performed for the power price. Furthermore, the failure rate of the gearbox is varied by changing the Weibull distribution determining the times of failure. The power prices are an important component of the indirect costs of power production losses: The higher the power prices, the more important it is to avoid downtime. Avoiding downtime generally becomes more important with increasing opportunity cost per downtime; besides power prices, the wind speed and the size of the turbine influence production losses. The gearbox failure rate was chosen since it is the most expensive component in the turbine, and a gearbox failure causes the longest downtime. Lower α_f values result in a higher failure rate, and, therefore, in more maintenance. Note that only mean values and total cost upper bounds are compared in the sensitivity analysis.

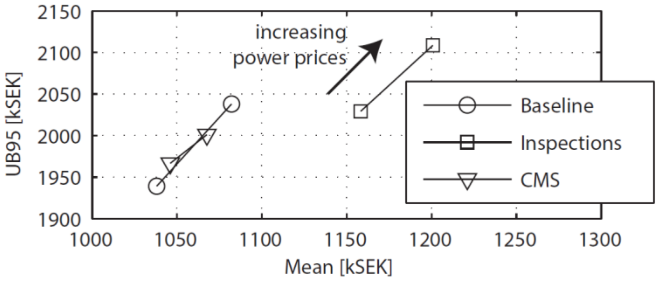

Figure 4: Change in mean total cost for different power prices

The power prices are varied in 20% steps from 60% to 160% of the original prices. The results are shown in Fig. 4; since the results scale linearly with the power price, only the symbols for the lowest and the highest price are displayed. Higher power prices increase the average total cost and total cost UB_{95}, because the cost of lost production increases and, therefore, also the difference between life-cycles with low downtimes and high downtimes. A comparison between the *Baseline* scenario and the *Inspections* scenario yields the same outcome as with standard power prices $p_{el} = p_{0,el}$. The *Inspections* scenario total cost is characterized by a higher average and a higher UB_{95}; with increasing power prices, however, the differences in both indicators decrease. This increases the attractiveness of the *Inspections* scenario, but it is still dominated by the other two scenarios. Particularly the *CMS* scenario becomes more attractive with increasing power prices. Increases in average total cost and total cost UB95 are much smaller than in the other two scenarios. For power prices of $p_{el} > p_{0,el}$ and above, the *CMS* scenario results in both lower total cost average and UB95. However, note that in the present case of a relatively small wind turbine with a rated capacity of only 600 kW, the difference is still not high enough to justify the cost of online condition-monitoring.

The gearbox failure rate parameter α_f was varied from 50,000 h to 350,000 h in steps of 50,000 h (the original value is 225,777 h). The mean time from renewal to failure (*MTTF*) for Weibull distributions is given by

$$MTTF = \alpha_f \cdot \Gamma(1 + \frac{1}{\beta_f}) \qquad (5)$$

where Γ is the gamma function. *MTTF* is therefore proportional to α_f; a lower value results in a lower mean time between defects, and hence more failures and higher downtime. Figure 5 (top plot) shows the mean unavailability in the three maintenance scenarios for different values of *MTTF*. The influence of very low values of *MTTF* on the unavailability is strong in the scenarios where defects always or often lead to failure, e.g., in the *Baseline* and the *Inspections* scenarios. In the *CMS* scenario, in contrast, where most defects are detected before failure and thus the component can be pre-ordered, the effect of varying *MTTF* is smaller.

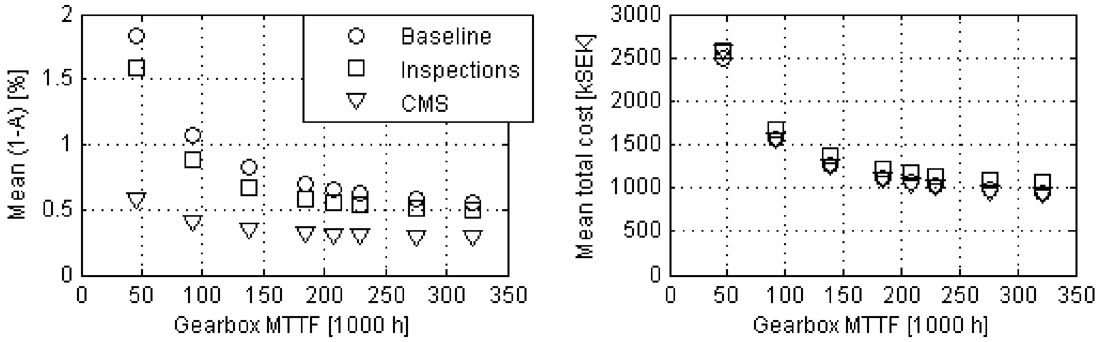

Figure 5: Change in mean unavailability (left plot) and mean total cost (right plot) for different gearbox MTTF

The average total cost curves in Fig. 5 (bottom plot) show similar characteristics. Average total cost declines steeply at low *MTTF* values but flattens as *MTTF* increases. The *Inspections* scenario leads to consistently higher average cost than the *Baseline* scenario, but for higher *MTTF* the difference becomes more significant because the expected benefit of an inspection decreases if the probability of a defect decreases. Unlike the unavailability, the mean total costs in the *CMS* scenario increase sharply for very low *MTTF*. This can be attributed to the earlier gearbox replacements in this scenario. Earlier replacements, on average, lead to more gearbox replacements over the turbine life-cycle, and these replacements are very costly. For high *MTTF*, the mean values of the *CMS* scenario are almost identical to those of the *Baseline* scenario.

5. Conclusions

O&M cost are a significant part of the wind turbine life-cycle costs. The model developed in this study is a flexible tool to estimate O&M cost for different maintenance strategies over the wind turbine life-cycle. Using field-data based reliability models and a basic binary or delay-time deterioration model for the most relevant wind turbine components, no detailed technical knowledge regarding the turbine components is needed. The case study performed for a Vestas V44–600kW is based on input data and information from a previously published RCM study of this turbine. While the gearbox and the generator are modeled using a delay-time deterioration model, the electrical system, the control system, and the hydraulic system are described using a binary deterioration model. The maintenance scenarios simulated are (1) Run-to-failure as a baseline scenario, (2) Annual inspections of the gearbox and generator, and (3) Installation of a vibration condition-monitoring system that detects 90% of the gearbox and generator defects. Using these assumptions, the case study revealed that corrective maintenance is the most cost-effective maintenance strategy for the gearbox and the generator of the V44. The benefit of a CMS was found to be too low to justify the cost of such a system in the case of the investigated turbine with a relatively low rated capacity. As the sensitivity analysis showed, however, a CMS becomes more beneficial for higher power prices, as the opportunity cost of lost production increases. Similar results can be expected for a turbine with a higher capacity, except that this relationship is non-linear, since (a) electricity production over all wind speeds is not proportional to the turbine capacity, and (b) O&M cost would also increase. The turbine in the case study was located onshore and, therefore, could be reached by the service team within two hours. Offshore, the benefit of a CMS is expected to be significantly higher: Weather conditions and the availability of vessels often constrain maintenance actions at short notice and thus increase the benefits of long-term maintenance planning.

The possibility to repair components is ignored in the model. Therefore, the benefit of defect detection is enhanced planning of replacements as well as reduced downtime, while the positive effect of avoiding secondary damage is neglected. The model could be extended with a basic action “Repair”, which would imply a state-change from *defective* or *failed* to *good*. Another way of implementing repairs could be a more detailed turbine model, in which, e.g., the gearbox could be modeled as a combination of gears, bearings, shafts, and lubrication system, with their respective different failure rates and inspection times and cost.

However, the above-described model extensions as well as the application of the model to contemporary wind turbine generations are restricted by the availability and accessibility of suitable reliability data. The standardized and automated collection of in-depth failure and maintenance data from a large number of wind turbines is therefore considered a key prerequisite for the utilization of quantitative methods in wind-turbine maintenance management.

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