Quantitative Approaches to Inspection and Maintenance Planning of Wind Turbine Concrete Structures

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Abstract. The present situation of energy transition processes from conventional to renewable power generating systems creates a growing need for the optimization of maintenance strategies and life cycle management of wind turbines and farms. However, any life cycle assessment of an individual wind turbine or farm still lacks the availability of well documented and structured O&M costs to choose the most effective maintenance strategies.

The poster presents a holistic approach to a sustainable wind turbine asset management by applying qualitative and quantitative reliability methods in the operation and maintenance (O&M) phase of the overall plant life cycle. The approach considers two aspects in detail; these are on the one hand a quantitative modelling and decision analysis algorithms by Bayesian updating of risk-based inspection (RBI) planning and its applicability to wind turbine concrete structures during plant operation. The RBI planning persues the objective of using probabilistic methods for an optimal allocation of deterioration control. Information gathered by the use of NDT methods during in-service inspections are seen as a quantifying measure on the risk assessment of a components condition and thus enabling a cost optimal inspection and maintenance planning. On the other hand, the approach considers analysis of cost-optimal maintenance strategies based on the mathematical model of the renewal theory. Empirical statistics for European and German wind turbines on a subsystem level are used as a preliminary assessment associated with the goal of verifying and updating an appropriate maintenance strategy during plant operation by operational data and information of in-service inspections.

Quantitative Risk-based Inspection Planning

1.1 Basic Concept

Risk-based inspection planning (RBI) in this framework has essentially the goal of using probabilistic methods for the (cost-) optimal allocation of deterioration control. The underlying probabilistic concept combines a preliminary RCAM analysis with a quantitative probabilistic optimization approach. In engineering theory there exist models to describe the specific fatigue mechanisms which cause wearing of a component. However, these models inherit implied model uncertainties. Those model uncertainties can be reduced by in-field information.

NDT methods as infield information for structural parts under this aspect can be seen as effective risk mitigation measure for existing structures. The primary goal is quantifying the effect of inspections on the risk condition of a component and thus enabling cost optimal inspection planning. Madsen [1] showed one of the first applications of the concept.

The method of uncertainty quantification has two main objectives, first the quantitative characterization of uncertainties and seconds the reduction of uncertainties.

Generally there are two different sources or categories of uncertainties, aleatoric uncertainties and epistemistic uncertainties. Aleatoric uncertainties represent statistical uncertainties or the unknowns each time an experiment is run, e.g. wind speeds, sea states or the fatigue crack growth. Epistemistic uncertainties describe systematic uncertainties including data and model uncertainties. When the modeled problem is observed, the problem turns into an epistemistic uncertainty problem and therefore enables uncertainty updating.

Inspections can reduce those uncertainties and update the incomplete knowledge of the state of nature, which can be described as an epistemistic uncertainty. In many applications in asset management of structures, inspections can be a cost effective risk reduction measure.

The concept of risk-based inspections focusses on the goal of optimal allocation of deterioration control. Existing quantitative models vary substantially dependent on the context or the industry they are applied in. Most published RBI models for structural systems are based on fully quantitative probabilistic deterioration models combined with Bayesian updating.

1.2 Development of a decision support algorithm

Generally the conditional probability of specific events is of interest, meaning the probability of occurrence of event E_2 given the occurrence of Event E_1. This classical probabilistic dependency is generally handled with Bayes' rule [2]:

$$P(E_2|E_1) = \frac{P(E_1 \cap E_2)}{P(E_1)} = \frac{P(E_1|E_2)P(E_2)}{P(E_1)} \tag{1}$$

From this basic equation one can derive basic and important definitions for the RBI framework:

- $P(E_1|E_2)$ is the likelihood measure for the amount of information on E_2 gained by knowledge of E_1. The likelihood measure is typically used to describe the quality of an inspection.
- $P(E_2|E_1)$ is known as the posterior probability of occurrence of E_2 or its updated occurrence probability.
- $P(E_2)$ is the prior probability of Event E_2, prior to the knowledge of E_1.

In the probabilistic RBI framework different inspection outcomes or results are possible. Those different inspections results will trigger different maintenance actions.
As relevant inspection outcomes in the RBI framework the following outcomes can be basically defined:

- Event of indication of a defect I
- Event of detection of a defect D
- Event of false indication FI
- Event of a defect measurement with a measured size s_{m}.

All deterioration mechanisms are time-dependent and consequently all reliability problems in fatigue are time dependent [3]. A failure event of a deteriorating structure can be modelled as a first passage problem. Consequently the limit state function is then additionally a function of time. Failure occurs when the limit state function becomes negative for the first time, given that it was positive at t=0. In that case the probability of failure between time t=0 and time t=T can be expressed by the following equation:

$$p_F(T) = 1 - P(g(\underline{X}(t)) > 0 \tag{2}$$

For most deterioration processes the problem is simplified by the fact that damage is monotonously increasing with time. If the modelled deterioration problem has a fixed damage limit – meaning that a failure occurs when damage reaches a constant limit – the deterioration problem can be solved as time-independent problem. The time variable t is then a simple parameter of the model and deterioration is treated as a monotonously increasing process. E.g. if failure has not occurred at time t_1, failure has also not occurred at time $t < t_1$. For the definition of a failure rate of the modelled system, several definitions are possible. In this case the annual failure probability of the modelled system is best fitting. This circumstance enables to evaluate the reliability problem at fixed time intervals $t = t_1; t_2 \dots; t_n$.

Consequently the annual probability of failure in year t_i can be expressed as follows:

$$\Delta p_F(t_i) = \frac{p_F(t_i) - p_F(t_{i-1})}{1 - p_F(t_{i-1})} \tag{3}$$

Very typical for that kind of reliability problem is the SN fatigue modelling problem. Failure is defined to occur when the accumulated damage has reached Δ or commonly defined as Δ=1. In application the computation of probabilities is done with Monte-Carlo-Simulations and FORM-algorithms.

The ultimate goal in the decision analysis process is the identification of optimal decisions on maintenance actions for deteriorating structures. The decision environment is subjected to uncertainty under the following aspects:

- Uncertainty on the state of the system; state of deterioration
- Uncertainty on the performance of the inspection; probability of detection (POD)
- Uncertainty on the performance of repair actions
- Uncertainty on the consequences of failures

The specific decision problem is formulated through a decision tree. Each path of the decision tree is assigned with a utility value and its probability characteristics. The prior analysis represents a decision analysis with given information. At this state, the utility function and the probabilities of the various states of nature corresponding to the different consequences have been defined. The decision analysis is reduced to the computation of the expected utilities and finding the optimal point of the optimization problem. The posterior decision analysis represents a decision analysis problem with additional information on the state of nature. If additional information becomes available – e.g. through inspections – the probability structure in the decision problem can be updated.

The probability update is carried out using Bayes' rule. The pre-posterior analysis represents a decision analysis situation dealing with unknown information. The decision maker has the possibility to buy additional information through an experiment. If the cost of this information is small in comparison to the potential value of information, the experiment should be performed. If several experiments are potentially suitable, the decision maker has to choose the experiment yielding the overall largest utility for his decision problem.

The final optimization criterion is the expected cost criterion. Therefore the utility index u is assigned to monetary units in a linear way for the considered range of events. The indirect costs associated with the events of failure, repair and inspection are included in the probabilistic modelling. Thus, all consequences of an event have to be expressed in monetary terms.

Concerning the inspection actions is has to be determined:

- Where to inspect ➔ location of inspection
- What to inspect ➔ indicator of the system state
- How to inspect ➔ what kind of inspection technique
- When to inspect ➔ time of inspection

For future developments of the approach it is planned to validate the probabilistic model on a real wind turbine.

2. Preliminary Maintenance Planning

Reliability and availability field data for European WTs has been statistically analyzed by several research projects such as Reliawind, WMEP, LWK, EVW, Swedish and Finnish WT statistics Vinstat and VTT, and WindStats (Denmark and Germany) and the currently running Project WinD Pool; for a review see [4-8]. However, for an owner or operator, any life cycle assessment still lacks the availability of well documented and structured O&M costs to choose the most effective maintenance strategies for its wind power plants.

A qualitative assessment of required inspection and maintenance activities as deduced by failure mode and effect analysis (FMEA) can be supplemented in a quantitative manner by implementing historical failure rates, costs of failure consequences and the probability of not detecting a failure [9-11]. This type of risk-based assessment accounts for the chosen inspection or monitoring method and its possibility of failure detection. By additionally quantifying the effect of inspection on a components risk condition, a validated probabilistic model of a RBI planning will enable a cost optimal long-term maintenance planning in a future reliability-centered asset management (RCAM).

For a cost optimal long-term maintenance strategy, both failure distribution and cost effect of failure removal determine the criticality of a failed WT system. The failure behavior of WT subsystems is fittingly described with Weibull distribution functions. An optimal maintenance strategy for each subsystem is obtained by applying the renewal theory and determine the maintenance interval τ for which the maintenance cost rate shows a minimum [12]. The cost rate counts for the probability of costs for an unplanned corrective action within the maintenance interval τ as well as for the probability of costs of a preventive action in case of non-failure of the considered subsystem within its considered optimal maintenance interval τ.

Surely, the parameters of the Weibull distribution function depend on the individual WT conditions as e.g. design, manufacturing, operating, inspection, maintenance and local conditions. Furthermore, any cost-optimal maintenance strategy requires a rather precise knowledge of the subsystems individual preventive and corrective maintenance costs or at least a limitation of the latter. A single WT or farm usually cannot provide sufficient statistical data to specify the failure and maintenance costs characteristics. Thus, for a preliminary maintenance planning, the operator or owner of an individual WT may use the overall asset management goals as well as available literature data on WT statistics. During

WT operation these data then can be up-dated by operational data, inspections and maintenance results.

The optimal maintenance intervals τ for a preventive maintenance strategy were calculated using [13] and taking into account reliability characteristics and maintenance cost ranges for German WT [7,14,15] as well as a plausible range of Weibull shape parameters so far documented. On a subsystem level, the results allow a quantitative estimation of an optimal maintenance interval and its related annual cost rate. This information is combined with the planning of operation time slots for RBI prior to in any maintenance activity. RBI results in turn support a subsequent and more accurate planning of maintenance costs and intervals. The currently poor quality of statistical data for large WT structures such as tower and foundation illustrates the need for an improved and quantitative assessment as introduced by the RBI planning.

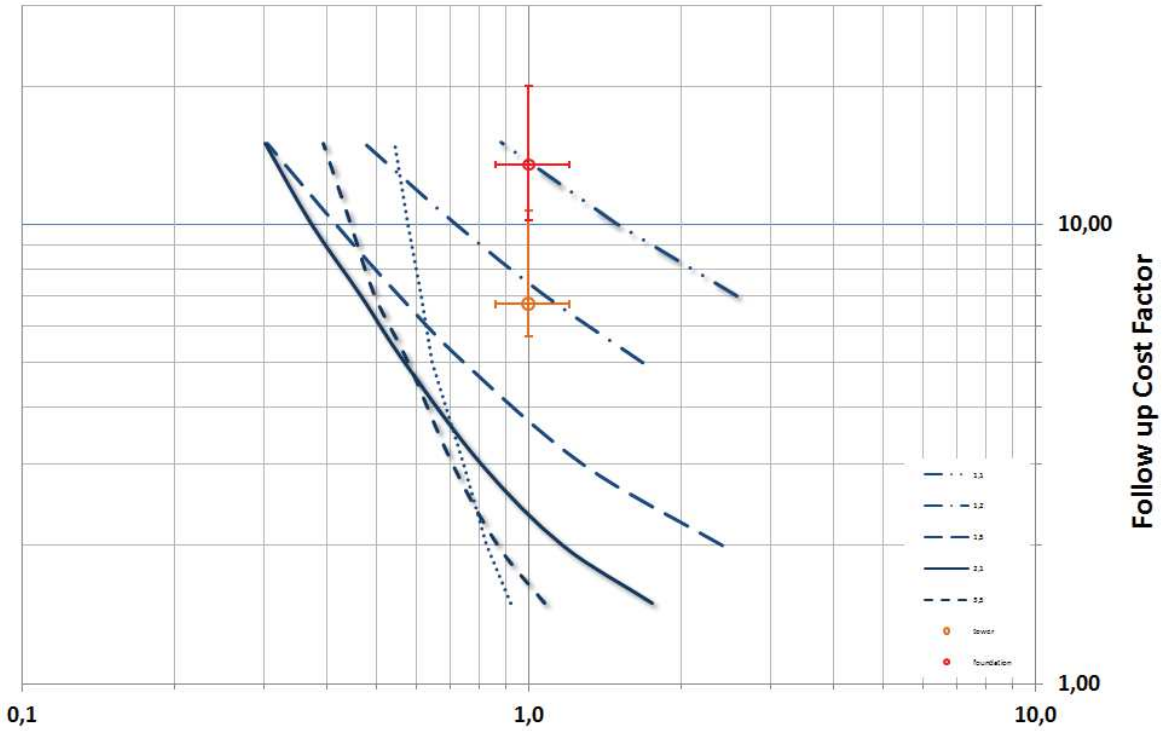

Figure 1: Optimal maintenance interval / MTTF

3 Summary and Conclusion

Operational wind turbines are highly loaded structures. Especially the high amount of load cycles – up to 10^9 – within their service life leads to the conclusion that these renewable energy structures are in need of a suitable structural health monitoring and management strategy. In times of energy transition from conventional power plants to renewable power plants a safe and reliable operation of these assets is a premise.

The paper presented here introduced an approach on determining holistic risk-based operation and maintenance strategies for wind turbines. The concept combines qualitative and quantitative risk analysis methods and designs a framework for determining risk- and cost-optimal maintenance strategies based on the concept of reliability-centered asset management (RCAM) and risk-based inspection planning (RBI). Deterioration processes of structures are of highly stochastic nature, thus models describing structural fatigue incorporate high variations and uncertainties. Information from sensors can be used in probabilistic models to update the incomplete knowledge of the state of nature. They are a cost-effective risk-reduction measure and can be used for uncertainty quantification and reduction of uncertainties.

At present, more and more OEM manufactures implement the reference system RDS-PP. This information will allow future statistical analyses on a much more detailed level for both, failure events and maintenance costs. By means of this the RCAM models can be specified more precisely to an individual WT or farm.

The combination of the described methods is able to optimize maintenance and inspections activities according to the associated costs. The final goal is the identification of optimal decisions on operation and maintenance actions for a deteriorating wind turbine structure.

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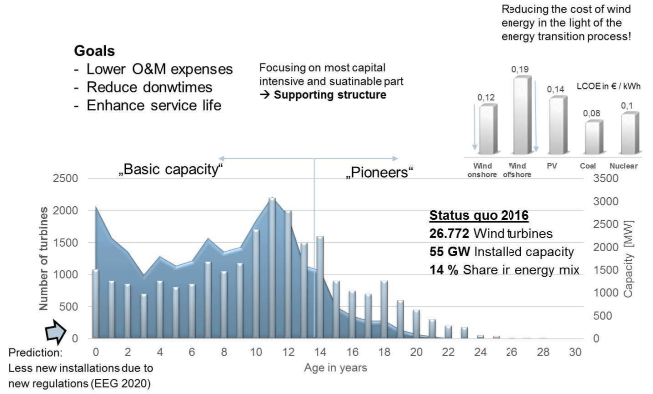
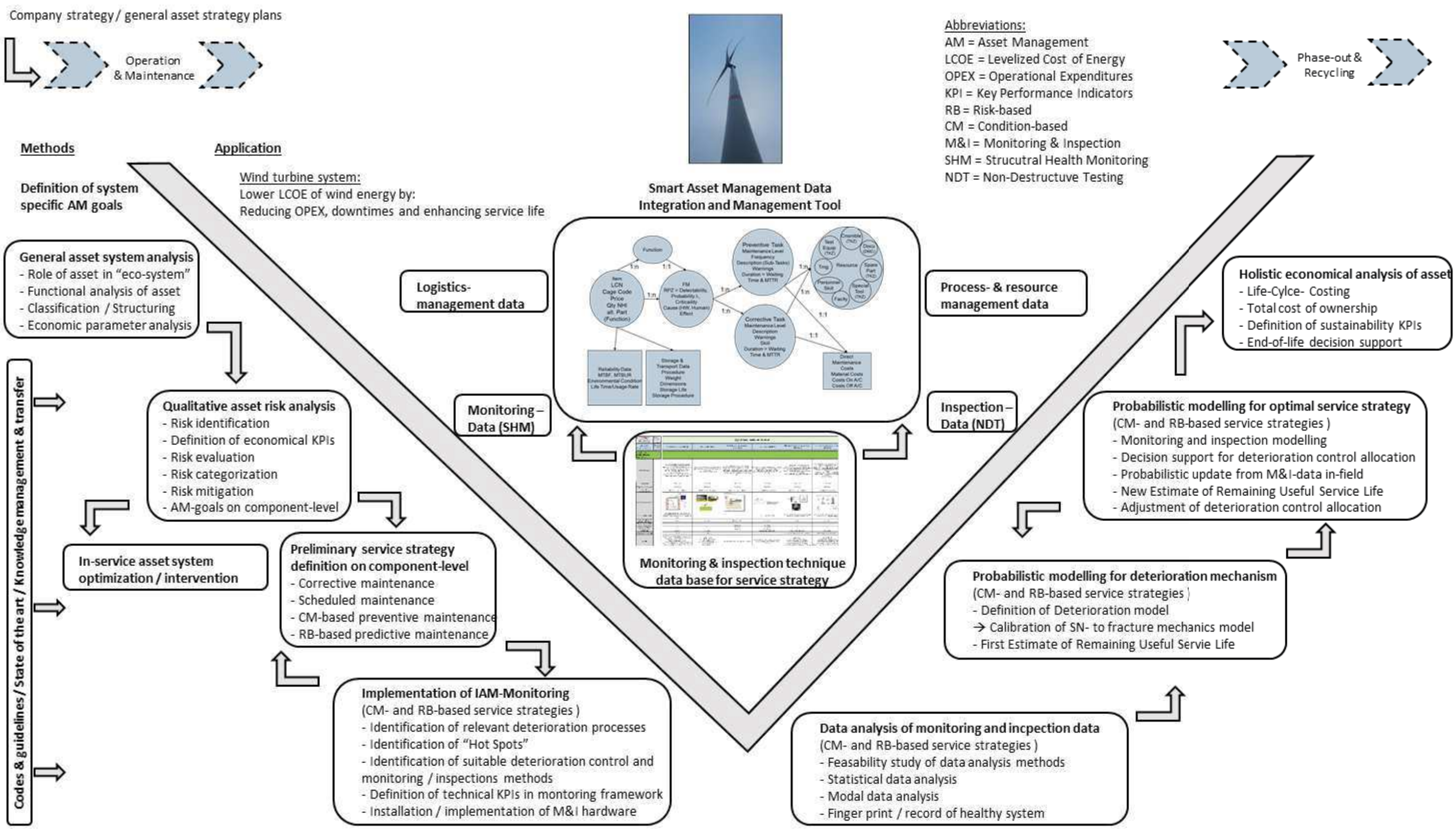
Holistic Asset Management of Wind Turbines

RISK-BASED SUSTAINABLE MAINTENANCE STRATEGIES

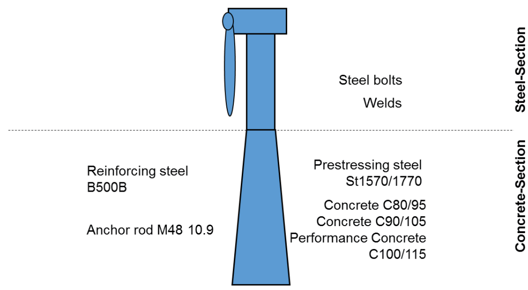
MISTRALWIND – Monitoring and Inspection of Structures At Large Wind Turbines

Wind turbines are probably the most dynamically stressed constructions we know in the art of engineering. Besides, in times of energy transition from conventional power to renewable power technologies, we rely on the operation of wind turbines on a macro economical level. Therefore, all parts of a wind turbine system have to be subjected to quality management including design, manufacturing and especially operation and maintenance. On the system level this includes all main systems of a wind turbine plant – rotor blades, power train and especially the supporting structure, because it is one of the most capital-intensive and worth retaining parts of a wind turbine.
Non-destructive testing and structural health monitoring techniques can be applied to establish new efficient and sustainable maintenance strategies for wind turbine systems. The research focus in the framework of the thesis is on the development of new maintenance strategies for wind turbines using combinations of inspections and monitoring techniques.

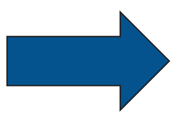




Structural Composition of Turbine Tower



Calibration of Fatigue design law with deterioration control

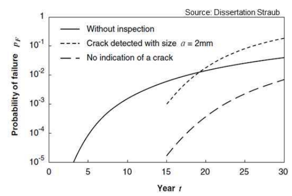


Bayesian Updating for Risk-based Inspection Strategy

- **Conditional probability is of interest**
  - **Probability of occurrence of Event E_2 given the occurrence of Event E_1**
  - Classical Bayes' Rule
  - $P(E_2|E_1) = \frac{P(E_1 \cap E_2)}{P(E_1)} = \frac{P(E_1|E_2)P(E_2)}{P(E_1)}$
  - = **updated occurrence probability**
- $P(E_1|E_2)$ = **likelihood measure** for the amount of information on E_2 gained by knowledge of E_1 → used to describe the quality of an inspection

Non-destructive testing
- Uncertainty reduction
- Risk mitigation measure

Especially for existing structures!



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