Optimal Decision Making for Life Extension for Wind Turbines

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ABSTRACT: This paper presents how the decisions made in relation to life extension for wind turbines can be formulated as a Bayesian decision problem with decisions on analyses and inspections before the decision on whether to extend the lifetime. The paper presents an implementation where semi-probabilistic analyses are used to verify whether the fatigue life is sufficient for life extension, and where operational data can be exploited to reduce epistemic uncertainties for a more accurate prediction of the fatigue life. The optimal decision policies depends on the expected benefit of life extension, and there is a potential for making general recommendations to support wind turbine owners.

1. INTRODUCTION

In Europe, thousands of wind turbines are reaching their intended design lifetime of 20 years within the next few years. Due to conservative design assumptions, many wind turbines could be able to operate safely beyond the 20 years. Therefore, the possibility of extending the lifetime could be considered. To make the decision to extend the lifetime, two aspects should be considered: a) Can it be verified that the structural components will function with sufficient safety for the intended lifetime extension period? and b) Is life extension an economically beneficial decision?

The integrity of wind turbine design is ensured by satisfying specific design criteria based on assumptions about the environmental conditions, loading, and material properties. These assumptions are associated with uncertainty which is taken into account by introducing partial safety factors in the design. However, after erection and after 20 years of operation, data from condition monitoring systems are available and many uncertain quantities such as material properties and loading history have attained a specific value, which is deterministic but still unknown – i.e. the aleatory uncertainties have become epistemic instead. In such situations, the use of operational data and inspection data can provide additional information about the current state of the structure, and thus lead to a reduction in the uncertainty. Operational data and measurements can be used to reduce the uncertainties on the input to the aeroelastic models used in the design, for example regarding eigenfrequencies and wind climate. In design, the turbines are typically dimensioned for a certain reference class of environmental conditions (e.g. the IEC reference classes (IEC 61400-1 ed. 4 2018)), while they are typically erected on a site with milder wind climate (lower wind speed and less turbulence) than they were designed for. Also, the frequencies of occurrence of each operational situation (start-ups, stand still, operation in the wake of another turbine) in the passed lifetime can be estimated from the operational data, and the predictions for the future can be based on this. In this way, operational data can improve the estimates of the accumulated fatigue loading.

To update the distributions for the resistances, inspections can be used. Inspections of fatigue critical details can reveal, if cracks have initialized, and if no cracks are found, a fracture mechanical approach can be applied to update the remaining fatigue life, in combination with the SN model used in design, as done in reliability- or risk-based inspection (RBI) (Faber 2002). In this paper, the decision problem will be presented and illustrated using an example.

2. RISKS ASSOCIATED WITH LIFE EXTENSION

Rational decision making should optimally be based on the associated risks, costs and benefits (ISO2394 2015). Risks can for example be related to fatalities, injuries, economic loss, pollution, or loss of reputation. For decisions, where human safety is not an issue, optimal decisions are typically done by minimizing the risks, calculated as the expected costs, or more generally, by maximizing the expected utility. The expected utility related to an event is for a risk neutral decision maker equal to the probability of the event multiplied by the net present value of a benefit, or the negative for a cost. For an event of failure, all direct and indirect consequences associated to the events of failure should be included.

Generally, the risk to human lives is low for wind turbines, as they are unmanned and located away from buildings. In the event of failure, it is unlikely that a person is injured. The largest risk is to the technicians maintaining the turbines. Usually they will not be near the turbines in conditions with extreme wind, and the turbine will be shut down and secured during maintenance, so a structural failure under those conditions is not likely. Therefore, the individual risks are likely to be acceptable. However, for the health and safety of technicians it is of high importance that the safety system of the turbine functions as intended.

2.1. Stakeholders

There are two levels of decision makers in the decision problem for life extension, the society and the owner. From a societal point of view, the safety should be acceptable, and the resources should be utilized optimally. Thus, if life extension is safe and beneficial from an economic and sustainability point of view, it should be encouraged. The owner is primarily interested in the economic feasibility of the project. In relation to life extension, it might be economically optimal to accept a lower reliability level of components, which would result in a higher expected number of failures. Technicians and their unions will be concerned with the health and safety. The wind energy industry in general would be concerned with their reputation if old turbines are allowed to run until they collapse, and future wind farm projects could meet increased resistance from the public. Insurance premiums may increase as the insurers could perceive the lower reliability as higher financial risk. So even if it would at first seem optimal from an economic point of view to run turbines until they suffer a structural collapse, multiple stakeholders are likely to oppose to the implementation of this approach or its authorization in a standard, even if the risks of fatalities are acceptable.

Therefore, it will likely continue to be a requirement from the society that, to allow for life extension, it should be verified that the reliability of structural components is above the acceptable level. As a result, we consider that attaining a target reliability level is a key criterion for the feasibility of a lifetime extension project.

2.2. Standards and regulations on life extension

Although there are presently no international standards (e.g. IEC) on life extension on wind turbines, there are national regulations in some countries. In Denmark, it is required (in addition to normal service inspections) to perform annual inspections of machine frame, tower, foundation, main shaft, yaw bearing and bolts in the extended life, as well as blade inspections every three years according to the Executive Order No. 73 (Danish Energy Agency 2013). In Germany, a life extension inspection and an analytical assessment is required to extend the life (Ziegler et al. 2018). The DNVGL standard (DNVGL-ST-0262 2016) concerns the German approach. The standard focus on verification of the structural integrity, and analytical verification of the fatigue limit state. As long as the structure shows no sign of deteriorated resistance in a life extension inspection, the other limit states do not need to be reassessed.

For the analytical part, three methods are presented; a probabilistic and two deterministic (semi-probabilistic) approaches: the ‘simplified’ and the ‘detailed’ approach. The simplified approach can be used without having access to an aeroelastic model for the specific turbine model. Instead a generic model is used, and the loads are estimated for: 1) the IEC reference class, the turbine was designed for, and for 2) the actual site conditions. The fatigue life is then estimated for both sets of weather conditions, and based on a comparison, the remaining fatigue life is estimated.

In the detailed approach, a type specific aeroelastic model should be used for estimation of fatigue loads, based on site specific data for each turbine (or for representative turbines). The fatigue damage is estimated for a range of representative loading conditions, and by examination of the conditions for the turbines in the wind farm, the fatigue life is estimated for all turbines.

The probabilistic part is a continuation of the practical part, but here parameters are instead represented by their probability distributions, and the uncertainties are considered directly in the analysis.

2.3. The economic perspective

Verification of acceptable reliability of the load transferring components is the part considered in existing standards on life extension. However, the owner is interested in the economic feasibility of a life extension. The expected utility of life extension can be estimated as the extra utility of operating the wind turbine for the life extension period, including all costs and benefits.

If the life of a wind turbine could be extended without any additional costs, it would be beneficial compared to decommissioning as long as the income from selling the electricity exceeds the O&M costs. The selling price of electricity might be lower in the extended life, if subsidies are only guarantied in the planned lifetime. Further, the failure rate for mechanical and electrical components might be increasing due to deterioration, leading to increased O&M costs and increased downtime.

Rubert et al (2018) presented a ‘decision support tool’ for life extension of onshore wind turbines, where the levelized cost of energy (LCOE) in the life extension period was estimated. This LCOE estimate included the costs of making the analyses necessary for life extension and assumed the annual O&M costs to be unchanged in the life extension period, but also analyzed the effect of major component exchanges. However, it is assumed that life extension is in fact possible, which is not known until after the analyses, and no information gained during the analyses are used to support the decision. In the following section, the decision problem for life extension is formulated as a Bayesian decision problem.

3. DECISIONS RELATED TO LIFE EXTENSION

A wind farm owner facing the decision of extending the life of one or more wind turbines must realize that the decision will be made under uncertainty. The first decision is whether or not to collect the information and do the analyses necessary for life extension. The costs of doing this will be incurred whether or not life extension turns out to be possible / feasible. Thus, once a life extension analysis has been made, these costs are not affected by the decision on whether or not to actually extend the lifetime.

In fact, there are several methods for making the life time extension (LTE) analysis, and it could be conducted in several steps. Here, we propose a formulation of the decision problem, with the following order of possible analyses/actions:

- Preliminary LTE analysis: generic aeroelastic model, site specific environmental conditions

- LTE inspection: inspection to ensure acceptable conditions for fulfilment of ultimate limit statess of all load transferring components
- Detailed LTE analysis: type specific model calibrated to operational data, turbine specific data on time spent in each operational state and detailed wake model.
- Probabilistic LTE analysis: including RBI strategy for fatigue critical details, where sufficient reliability cannot be verified based on data alone, and inspection information must be included also

Neither the preliminary or the detailed analysis consider information from the inspection in the estimation of fatigue life. The LTE inspection will reveal, whether a) the condition of the turbine is acceptable for life extension, or if b) major overhauls are needed for life extension to become possible, or c) if the condition is too bad for life extension.

A possible representation of the decision problem is shown in Figure 1, and it can be solved as a Bayesian pre-posterior decision analysis (Raiffa and Schlaifer 1961). Similar decision trees can in principle be used whether risk of structural failure is considered in the decision analysis using a risk-informed approach, a probabilistic, or a semi-probabilistic approach (ISO2394 2015). To use the risk-informed approach, the results from the analyses should be connected to an assessment of the probability of failure in the extended life, and the consequences of failure should be included directly. For the probabilistic and semi-probabilistic approach, the probability that each analysis will result in a fatigue lifetime sufficient for life extension is of interest. Here, the consequence of structural failure is not considered directly, as this is considered through fulfillment of an acceptable reliability level.

4. EXAMPLE

Here, we will consider a simplified version of the decision problem for life extension from 20 to 25 years, where it is based on semi-probabilistic verification of the fatigue limit state. It is assumed that the turbine was originally designed for IEC site IIB with average wind speed at hub height V_{avg} equal to 8.5 m/s and a reference turbulence intensity I_{ref} equal to 0.14. However, typically the actual site could have conditions somewhere between the IIB conditions and IIIC, where V_{avg} is equal to 7.5 m/s and I_{ref} is 0.12. The prior for the analysis will be based on the assumption that all combinations of wind speeds and turbulence intensities in the range between the IIB site and the IIIC site will be equally likely for a class IIB turbine.

4.1. The decision problem

A sequence of four decisions is considered:

- Make a preliminary LTE analysis?
- Make an LTE inspection?
- Make a detailed LTE analysis?
- Extend the life?

In a preliminary analysis, the decision maker uses the knowledge of the site conditions to make an assessment of the fatigue life of the most fatigue critical component. Based on the outcome (the estimated fatigue life) a decision will be made on whether to make the inspection, necessary to extend the life. The inspection will reveal, which (if any) refurbishments are necessary in order to extend the life, and this will directly affect the benefit of life extension.

For the decision on whether to make a detailed analysis, the outcome of the preliminary analysis and the inspection is available for the decision maker. If sufficient fatigue life was verified with enough confidence already with the preliminary analysis, it is not necessary to make

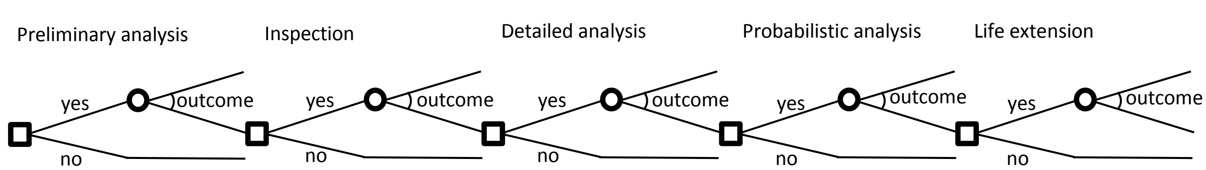

Figure 1: Decision tree for the decisions related to life extension.

the detailed analysis. Else, sufficient reliability can possibly be verified using a detailed analysis.

Solving the problem directly as a Bayesian pre-posterior decision analysis would lead to a decision policy for each decision, which is function of all previous observations and decisions. In reality, when making the last decision on whether to actually extend the life, much less information is actually relevant for the decision: the only information that is relevant are whether the fatigue life can be verified for the extended life (T_{ok}), and what will be the expected costs of repairs necessary for life extension (which is assumed to be estimated based on the outcome of the inspection Ins). Similar considerations can be made for the other decisions.

To show the conditional dependencies clearly, the decision tree can be represented by the influence diagram in Figure 2 (see (Jensen and Nielsen 2007) for an introduction to influence diagrams). The nodes that influence each decision is shown explicitly using links as is the standard for a limited memory influence diagram (LIMID). However, in this case all the relevant information is contained in the nodes pointing to each decision, so the 'limited memory' does not result in an approximation; it just results in a more compact representation of the exact solution.

The optimal decision policies are found for each outcome of the 'child' nodes. As all chance nodes are fully observed, the optimal policies can be found exactly by starting from the last decision. First, the utility contribution U_4^* from U_{ext} for the optimal decision $D_{ext}^*(T_{ok}, Ins)$ is found as:

$$U_4^*(D_{ext}^*, T_{ok}, Ins) = \max_{D_{ext}} U_{ext}(D_{ext}, T_{ok}, Ins)$$

The optimal policies for the other decisions are found recursively in a similar way, using the conditional independencies in the network. The outcome of these computations are now the decision policies and the expected (remaining) utility for each decision alternative.

4.2. Fatigue life assessment

The procedure for estimating the fatigue life for decision making is based on the method used for

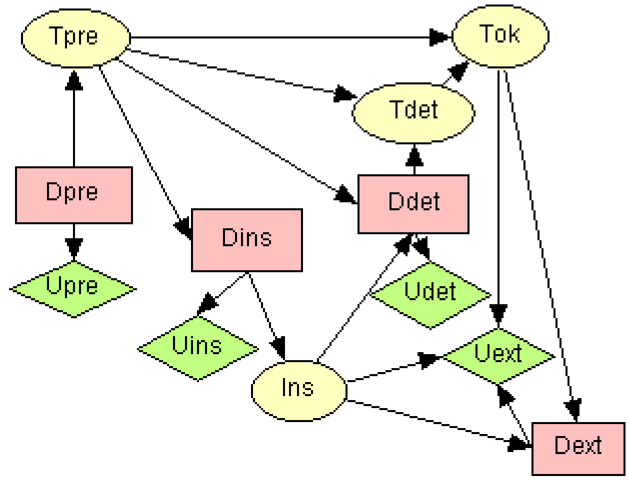

Figure 2: Influence diagram. Decision nodes Dpre, Dins, Ddet, Dext for the decisions on making a preliminary analysis, inspection, detailed analysis and for extending the life respectively, and utility nodes Upre, Uins, Udet, Uext for the associated utilities. Chance nodes: Tpre; outcome of preliminary analysis, Ins; outcome of inspection, Tdet; outcome of detailed analysis and Tok; binary node for whether the fatigue life is sufficient for life extension.

calibration of the partial safety factors in IEC61400-1 ed. 4 (2018) as given in (Sørensen and Toft 2014). The procedure is here shown for the linear case but can easily be extended to a bilinear SN curve. The number of cycles N to failure for constant amplitude loading with stress range $\Delta\sigma$ is:

$$N = K\,\Delta\sigma^{-m} \tag{1}$$

The SN slope parameter m is set to 5, and the mean of the intersection parameter K is found from the fatigue strength $\Delta\sigma_D = 71$ MPa at $N_D = 5 \cdot 10^6$ cycles. The characteristic value, K_C, is found from $\log K_c$ defined as the mean of the normally distributed $\log K$ minus two standard deviations ($\sigma_{\log K} = 0.2$).

The design equation for deterministic design is given by:

$$G(z) = 1 - \int_{U_{in}}^{U_{out}} \frac{\nu \cdot FDF \cdot T_L}{K_c} D_L(U)\, f_U(U) dU \tag{2}$$

where $\nu = 10^7$ is the number of load cycles per year, FDF is the fatigue design factor, T_L is the fatigue design life time, and $f_U(U)$ is the Weibull density function for the mean wind speed with shape parameter $k = 2$ and scale parameter A found from V_{avg}. $D_L(U)$ is the mean value of $\Delta\sigma^m$ for wind speed U, and is found from:

$$D_L(U) = \int_0^{\infty} s^m f_{\Delta\sigma}\big(s \big| \sigma_{\Delta\sigma}(U)\big) ds \tag{3}$$

where $f_{\Delta\sigma}$ is the Weibull density function for stress ranges with shape parameter 0.8 and standard deviation $\sigma_{\Delta\sigma}(U)$ proportional to the wind turbulence:

$$\sigma_{\Delta\sigma}(U) = \alpha_{\Delta\sigma}(U)\left(\frac{\hat{\sigma}_u(U)}{z}\right) \tag{4}$$

Here, z is a design parameter (a cross sectional parameter such as a cross section area or a cross section modulus), and $\hat{\sigma}_u(U)$ is the characteristic value of the standard deviation of turbulence is given by:

$$\hat{\sigma}_u(U) = I_{ref}(0.75U + 5.6\ \text{m/s}) \tag{5}$$

The factor $\alpha_{\Delta\sigma}(U)$ relates the standard deviation of the turbulence to the standard deviation of the response. Due to the control system, the ratio has a nonlinear relation with wind speed. For the example, $\alpha_{\Delta\sigma}(U)$ for the mudline bending moment is taken from (Sørensen and Toft 2014).

To estimate the fatigue life for a given design parameter z, average wind speed V_{avg} and turbulence intensity I_{ref}, the design equation Eq. (2) is set to zero and solved for T_L:

$$T_L = \frac{K_c}{\nu \cdot FDF \int_{U_{in}}^{U_{out}} D_L(U)\, f_U(U) dU} \tag{6}$$

In the example, this equation is used for design, and for assessing the fatigue life in both the preliminary and detailed assessment. The aim is to model, how the additional information used in the detailed assessment gives a more reliable estimate. Therefore, the randomness in the model due to model uncertainties related to the loading X_{wind}, is introduced as a parameter in Eq. (6), in the same way as it appears in the limit state equation for probabilistic assessment in (Sørensen and Toft 2014):

$$T_L = \frac{K_c}{\nu \cdot FDF \cdot X_{wind}^m \int_{U_{in}}^{U_{out}} D_L(U)\, f_U(U) dU} \tag{7}$$

The model uncertainty X_{wind} is assumed lognormally distributed with mean 1 and coefficient of variation COV_{wind}. The fatigue design factor, *FDF*, is chosen based on COV_{wind} according to (Sørensen and Toft 2014). For the design and preliminary analysis, COV_{wind} is 0.15, and *FDF* is 3. For the detailed analysis, COV_{wind} is 0.10 and *FDF* is 2.

The computations are now performed in three steps: Design, preliminary analysis, and detailed analysis to find the distribution for the outcome of the preliminary analysis, and the conditional probability distribution for the outcome of the detailed analysis given the outcome of the preliminary analysis.

First, the design is established for the IEC class, for a range of realizations of the model uncertainty in the design $X_{wind,0}$. For each realization, the resulting design parameter $z(X_{wind,0})$ is determined using Eq. (3) to give exactly a design fatigue life of 20 years.

The preliminary analysis is assumed to be made by calibration of a generic aeroelastic model to give the fatigue life used in the design, and therefore the same realization of the model uncertainty is assumed to be used in the preliminary analysis as in design. The difference compared to the design situation is that now the actual site conditions in terms of wind speed V_{avg} and reference effective turbulence I_{ref} is used. For realizations of V_{avg} and I_{ref}, outcomes of the preliminary site-specific fatigue life are obtained using Eq. (7):

$$T_{LTE,pre}\big(z(X_{wind,0}), V_{avg}, I_{ref}\big) \tag{8}$$

For the detailed analysis, the model uncertainty $X_{wind,det}$ is assumed uncorrelated with the realization in the design model, and outcomes of the detailed assessment of the fatigue life is found using Eq. (7):

$$T_{LTE,det}\big(z(X_{wind,0}), V_{avg}, I_{ref}, X_{wind,det}\big) \tag{9}$$

For each set of realizations of the possible input parameters, an estimate of the lifetime is now available for the preliminary and detailed analysis. The outcomes of the analyses are now discretized into one-year intervals, and the number of intervals is selected to span the range of the outcomes. A discrete distribution for the outcome of the preliminary analysis $P(T_{pre})$ is found as the relative frequency of outcomes in each interval from $T_{LTE,pre}$. The conditional distribution for the outcome of the detailed analysis given the outcome of the preliminary analysis, $P(T_{det}|T_{pre})$ is found from the joint relative frequencies of $T_{LTE,pre}$ and $T_{LTE,det}$.

4.3. Condition probability distributions

The influence diagram is fully specified by the conditional probability distributions for all chance nodes conditioned on the parent nodes, and the utility nodes defined conditioned on their child nodes. The range for outcomes of T_{pre} and T_{det} is extended with the outcome 'no analysis'. The possible outcomes of the inspection node Ins range from a good condition where no refurbishments are needed to the bad condition where the costs of the necessary refurbishments exceeds the expected income from extending the life. Here, a uniform distribution is assumed for the possible outcomes.

The utility nodes $U_{pre}(D_{pre})$, $U_{ins}(D_{ins})$ and $U_{det}(D_{det})$ will all have the value zero for the decision alternative 'no', and will have the negative cost of preliminary analysis (C_{pre}), inspection (C_{ins}) and detailed analysis (C_{det}) respectively, for the decision alternatives 'yes'. For the last utility node $U_{ext}(D_{ext}, T_{ok}, Ins)$, the utility will be zero in case of no life extension, no matter if it is caused by the outcome of the decision, the analysis or the inspection. If the decision is 'yes' and the outcome of the analysis is ok ($T_{ok} = yes$), then the utility depends on the costs of the necessary refurbishments C_{refurb} and the benefit of life extension C_{ext} found as the expected income from selling power in the extended life minus the expected O&M costs in the extended life. The cost of refurbishments necessary for life extension depends on the outcome of the LTE inspection.

The costs are defined relative to the cost of a preliminary analysis $C_{pre} = -1$, and it is assumed that $C_{det} = -3$. The optimal decisions are found for C_{ins} in the range from -2 to -10, and for C_{ext} in the range 10 to 50. The costs of necessary refurbishment are set to:

$$C_{refurb}(Ins) = -C_{ext}[0\ 0.2\ 0.4\ 0.6\ 0.8\ 1.1] \tag{10}$$

4.4. Results

The optimal policies are shown in Figure 3 for $C_{ins} = 4$ and $C_{ext} = 20$. It appears from the policies that a preliminary analysis should be made, and an inspection should only be made, if the lifetime found in the preliminary analysis is larger than 24 years. If one of the first four outcomes for Ins is obtained, a detailed analysis should be made if the outcome of the preliminary analysis was below 25 years. If the fatigue life is found acceptable and an inspection was made, the life should be extended if the costs of refurbishments are less that the income from extending the life.

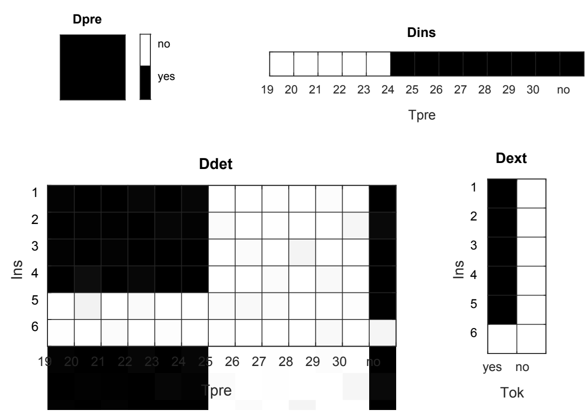

Figure 3: Decision policies.

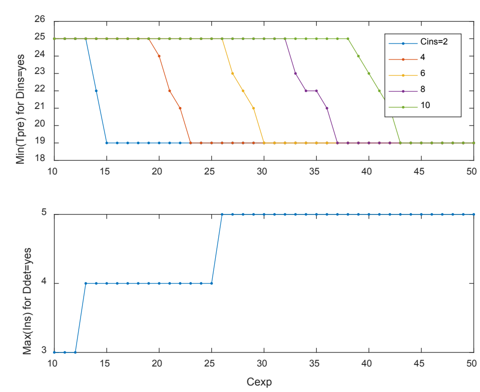

Figure 4: Variation of decision policies with costs.

Examination of Figure 4 reveals that if the benefit of life extension increases:

- A lower outcome of the preliminary analysis is enough to make it feasible to inspect.
- A more severe outcome of the inspection would still lead to detailed analysis being feasible.

If the cost of inspecting increase:

- A higher outcome of the preliminary analysis is needed to make it feasible to inspect.

5. DISCUSSION AND CONCLUSIONS

The example considered the situation where a semi-probabilistic analysis was applied for verification of sufficient fatigue life. Therefore, the inspection was only used to verify that the overall condition was adequate to fulfill the ultimate limit states and health and safety conditions, or if not, to estimate the costs of necessary refurbishments. The approach can be extended to include the possibility of using a probabilistic fatigue assessment in combination reliability updating based on inspections. This is more difficult/expensive as a probabilistic fracture mechanics model needs to be formulated, but this approach will make it possible to extend the life for even more turbines.

In the analysis, it was assumed that the power production and maintenance costs in the extended life could be estimated accurately. The decision problem can be extended to include that these estimates will be uncertain at first and ccan be improved after inspecting, although they will still be uncertain. Smaller owners will not necessarily be risk-neutral, as they might not accept a too high probability of a life extension becoming economically unfeasible. Therefore, the distribution for the utility can be relevant in addition to the expected value. The decision problem can be extended to include the possibility of repeated life extensions, and several critical components/failure modes can be included.

The decision analysis can be applied at two levels: through standardization and directly by wind turbines owners. Through standardization, guidelines can be defined for in which situations it is generally feasible to make which analyses to extend the life. The direct benefit of life extension will highly depend on the turbine size, but the cost of inspecting and especially the costs of analyses will be much less sensitive to turbine size. For direct use, big wind energy companies and consultants can have their own inhouse tools for optimal decision making for life extension.

6. ACKNOWLEDGEMENTS

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