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Probabilistic and risk-informed life extension assessment of wind turbines structural components

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Abstract: Reassessment of the fatigue life for wind turbines structural components is typically performed using deterministic methods with the same partial safety factors as used for the original design. However, in relation to life extension, the conditions are generally different from the assumptions used for calibration of partial safety factors; and using a deterministic assessment method with these partial safety factors might not lead to optimal decisions. In this paper, the deterministic assessment method is compared to probabilistic and risk-based approaches, and the economic feasibility is assessed for a case wind farm. Using the models also used for calibration of partial safety factors in IEC61400-1 ed. 4 it is found that the probabilistic assessment generally leads to longer additional fatigue life than the deterministic assessment method. The longer duration of the extended life can make life extension feasible in more situations. The risk-based model is applied to include the risk of failure directly in the economic feasibility assessment and it is found that the reliability can be much lower than the target for new turbines, without compromising the economic feasibility.

Keywords: life extension; wind turbines; end-of-life issues; probabilistic modelling; economic optimization; fatigue; risk; remaining useful life

1. Introduction

Wind turbine towers are typically designed for a fatigue life of 20-25 years. Upon the end of the planned life of a wind farm, wind farm owners may wish to continue the operation for several additional years. In some countries, national regulations require inspections and an updated assessment of the fatigue life to verify that life extension can be performed safely. Some components can be replaced if the condition is not sufficient for life extension, but this is too expensive for many structural components such as towers.

Methods for fatigue life assessment are described in the DNVGL standards [1,2], which reflects the German rules. Here, an inspection is required to assess the general condition of the components, and a fatigue life assessment is required for the main components based on load assessment including an operations analysis. The loads and operations analysis result in an updated assessment of fatigue life, which could be smaller or larger than the planned original life.

Fatigue life assessment based on data is a topic with large interest, and researchers search for ways to show that there is additional fatigue life remaining by exploiting differences in the design assumptions and the reality on the wind farm site. These include using the directionality [3], using measurements of environmental conditions [4–6], or using strain and other machine-specific physical measurements [7–9].

Usually a deterministic (semi-probabilistic) analysis is used with the same partial safety factors as in the original design, as given in IEC 61400-1 ed. 4 [10]. The partial safety factors were determined by Sørensen and Toft [11], who used a probabilistic model together with a design equation to calibrate partial safety factors, based on a design lifetime of 25 years. The partial safety factors were calibrated to result in a reliability target of β=3.3 for the annual reliability index in the last year of operation. This target was determined based on the generic table with reliability targets in ISO2394 [12], which was derived by Rackwitz [13] using a generic risk-based model. The probabilistic models and costs used in this generic model are not representative for the situation of life extension of wind turbines (see [14] for an elaboration of the background for the table).

An alternative to the use of deterministic assessment methods is to use reliability or risk-based approaches directly. Figure 1 illustrates how the three methods for assessment are related. The risk-based approach includes probabilistic models and costs/consequences. The approach can be used directly for risk-informed assessment [15], or it can be used to derive optimal reliability targets for probabilistic assessment. Nielsen and Sørensen [16] used this approach and propose to reduce the target to 3.1 for existing turbines, based on economic optimization and a generic cost model tailored for life extension of wind turbines.

Probabilistic assessment methods also use probabilistic models, and can be used directly for assessment against a given reliability level. It can also be used for calibration of partial safety factors for semi-probabilistic/deterministic assessment. Going down to a less advanced method means generalization, and generally results in higher variation of the reliability level and risk.

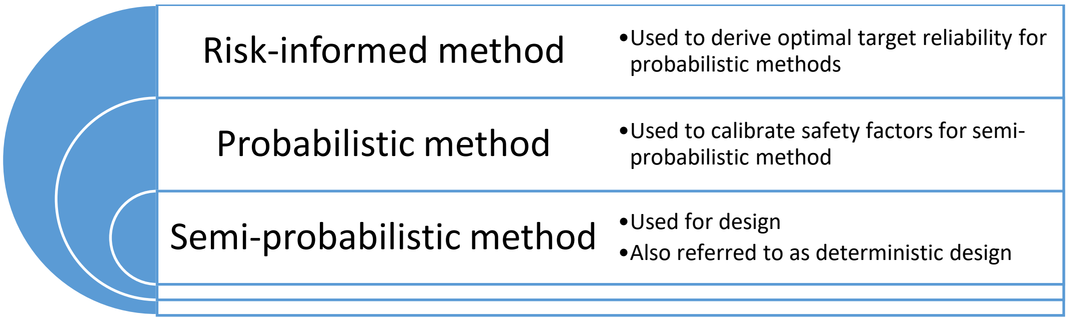


Figure 1. Overview of assessment methods.

This paper explores the benefit of using reliability and risk-informed methods, in terms of additional years of fatigue life and the increased profit of longer life extension periods. It presents how the economic optimization model presented in [16] can be applied for a specific life extension project. The paper is organized as follows: Section 2 briefly outlines the background (for details see [11] and [16]), Section 3 presents the case study input and procedures, Section 4 presents and discusses the results, and Section 5 concludes the paper with a broader discussion of the implications of the results.

2. Background

This section briefly outlines the background on deterministic, probabilistic and risk-informed assessment. The deterministic and probabilistic models are based on the models used in [11] for calibration of partial safety factors for IEC 61400-1 ed. 4 [6], and the risk-informed assessment model was first presented in [16] for derivation of a target reliability index for life extension. The models are briefly outlined for the sake of completeness, and the reader is directed to the references above for further details.

2.1. Deterministic / semi-probabilistic assessment

Fatigue assessment is based on SN curves, where the relation between the number of cycles to failure N under constant amplitude loading with stress range $\Delta\sigma$ is given as:

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

for a linear SN curve with parameters m and K. For variable amplitude loading, Miner's rule for linear damage accumulation is applied. The fatigue damage D resulting from variable loading from k stress ranges $\Delta\sigma_i$, $i = 1{:}k$, with each n_i stress cycles is given by:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \sum_{i=1}^{k} \frac{n_i}{K} \Delta\sigma_i^m, \tag{2}$$

For a bilinear SN curve, the design equation for fatigue failure can be written as:

$$G(z,t) = 1 - \nu \cdot t \left(\frac{(\gamma_f \gamma_m)^{m_1}}{K_{1,C}} D_{BL1,tot}(z) + \frac{(\gamma_f \gamma_m)^{m_2}}{K_{2,C}} D_{BL2,tot}(z) \right), \tag{3}$$

where

- $\nu = 10^7$ is the number of load cycles per year.
- t is the time in years
- $\gamma_f \gamma_m = 1.25$ is the partial safety factor on the load effect (stress cycles)
- $m_1 = 3$ and $m_2 = 5$ are SN-curve slopes
- $K_{1,C}$ and $K_{2,C}$ are the characteristic values of the SN-curve intercept parameters
- $D_{BL1,tot}(z)$ and $D_{BL2,tot}(z)$ are the mean values of $\Delta\sigma^m$ for each part of the SN curve divided by the proportion of cycles on the respective parts of the curve
- z is a design parameter (proportional to a cross sectional parameter)

For the deterministic assessment, $D_{BL1,tot}(z)$ and $D_{BL2,tot}(z)$ are calculated based on the distribution for the mean wind speed, and the distribution for the stress ranges given mean wind speed, the characteristic value (90% quantile) of the turbulence standard deviation, and design parameter z. In the design and assessment of wind turbines, this is generally evaluated using rainflow counting on time series from aeroelastic simulations for bins of the 10-minute mean wind speed. For the results presented in this paper, the aeroelastic model is represented by the same surrogate model as used in [11], which is representative for a wind turbine tower.

2.2. Probabilistic assessment

For probabilistic assessment, the limit state equation of fatigue failure for a bi-linear SN curve can be written as:

$$g(z,t) = \Delta - \nu \cdot t \left(\frac{(X_{load})^{m_1}}{K_1} D_{BL1,tot}(z) + \frac{(X_{load})^{m_2}}{K_2} D_{BL2,tot}(z) \right), \tag{4}$$

where

- Δ is the model uncertainty related to the use of Miner's rule for damage accumulation.
- X_{load} is the model uncertainty of the load effect with coefficient of variation $COV_{load} = 0.175$
- K_1 and K_2 are SN-curve intercept parameters, modelled by stochastic variables

For the probabilistic assessment, $D_{BL1,tot}(z)$ and $D_{BL2,tot}(z)$ are calculated based on the distribution for the mean wind speed, the distribution for the turbulence standard deviation, and the distribution for the stress ranges given mean wind speed, turbulence, and design parameter z (see [11] and [16] for details). In probabilistic design and assessment of wind turbines, this is generally evaluated using rainflow counting on time series from aeroelastic simulations for bins of the 10-minute mean wind speed and turbulence intensity. For the results presented in this paper, the aeroelastic model is represented by the same surrogate model as used in [11]. To evaluate the reliability, Crude Monte Carlo simulations are first used to evaluate the cumulative distribution function for the time to failure $F_T(t;z)$; then the density function for the time to failure $f_T(t;z)$ is evaluated, and the annual probability of failure given survival in all preceding years $P_F(t)$ is evaluated:

$$F_T(t;z) = P(g(z,t) \leq 0), \tag{5}$$

$$f_T(t;z) = F_T(t;z) - F_T(t-1;z), \tag{6}$$

$$P_F(t) = \frac{f_T(t;z)}{1 - F_T(t-1;z)}, \tag{7}$$

The annual reliability index is related to the annual probability of failure by the relation:

$$\beta(t) = -\Phi^{-1}(P_f(t)), \tag{8}$$

2.3 Risk-informed assessment

For the risk-informed assessment, the same probabilistic model as summarized in Section 2.2 is used to model the probability of failure. However, in the risk-informed assessment, decisions are made based on the expected present value of the profit i.e. the expected present value of the benefits minus the costs, when the risk of structural failure is included in the assessment. The risk-based model for life extension was first presented in [16], and is included here for completeness.

Figure 2 shows how the costs are distributed in time for the situation with and without a failure in the extended life. In both cases, there is an investment made in year zero; the life extension costs to inspections, analyses, and refurbishments. In the case of no failure, there will be a continuous benefit from selling power, and there will be continuous expenses to O&M until the end of the extended life. In the case of failure in the extended life, the benefits and variable O&M costs will discontinue at the time of failure, whereas the fixed O&M costs will continue. Also, the failure will be associated with a consequence/cost at the time of failure.

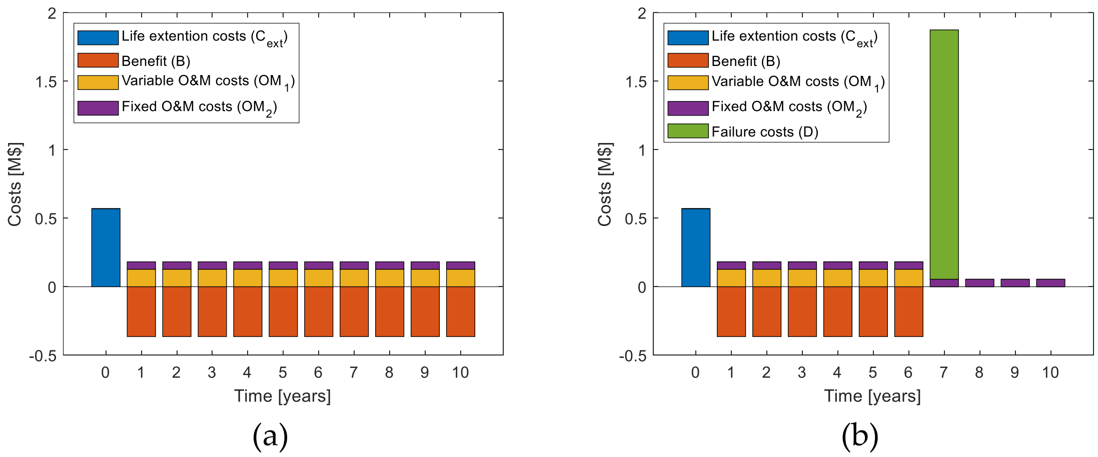


Figure 2. Illustration of how the benefits and costs are distributed in time in the extended life: (a) when there is no failure in the extended life; (b) when there is a failure in year seven.

The expected value of the profit $Z(T_{ext}; z)$ as function of life extension period T_{ext} and design parameter z is calculated from:

$$Z(T_{ext}; z) = B(T_{ext}; z) - C_{ext}(T_{ext}) - OM_1(T_{ext}; z) - OM_2(T_{ext}) - D(T_{ext}; z), \tag{9}$$

with the following expected present values of:

- $B(T_{ext}; z)$: benefit (income from power production)
- $C_{ext}(T_{ext})$: life extension cost
- $OM_1(T_{ext}; z)$: variable O&M costs
- $OM_2(T_{ext})$: fixed O&M costs
- $D(T_{ext}; z)$: cost of structural failure

Expressions of the expected present values of the benefits and costs are given below. They are calculated based on a shifted time scale t' starting at the time of life extension. Continuous discounting is performed using the discount rate γ. The expected present value of the benefit is calculated considering the risk of failure in the extended life as:

$$\begin{gathered} B(T_{ext}; z) = \int_0^{T_{ext}} \int_0^{t'} \exp(-\gamma\tau')\ c_B(\tau')\, d\tau'\, f_{T'}(t'; z)\, dt' + \\ \int_0^{T_{ext}} \exp(-\gamma t')\ c_B(t')\, dt'\ \left(1 - F_{T'}(T_{ext}; z)\right) \end{gathered}, \tag{10}$$

where $c_B(t')$ are the annual benefits, and τ' is an integration substitute for t'. Similarly, the expected present value of the variable O&M costs are calculated as:

$$OM_1(T_{ext};z) = \int_0^{T_{ext}} \int_0^{t'} \exp(-\gamma\tau')\ c_{OM1}(\tau')\,d\tau' f_{T'}(t';z)\,dt' + \int_0^{T_{ext}} \exp(-\gamma t')\ c_{OM1}(t')\,dt'\ \left(1 - F_{T'}(T_{ext};z)\right) , \tag{11}$$

where c_{OM1} are the annual variable O&M costs. The expected present value of the fixed O&M costs are simply calculated as:

$$OM_2(T_{ext}) = \int_0^{T_{ext}} \exp(-\gamma t')\ c_{OM2}(t')\,dt' , \tag{12}$$

where c_{OM2} are the annual fixed O&M costs. The expected present value of the costs of structural failure are calculated as:

$$D(T_{ext};z) = \int_0^{T_{ext}} \exp(-\gamma t')\,H(t')\,f_{T'}(t';z)\,dt', \tag{13}$$

where $H(t')$ is the consequence of failure. The integrals are evaluated numerically with one year intervals using the time to failure distribution evaluated using the probabilistic model, Equations (5)-(6).

3. Case study

The aim of this paper is to compare the deterministic, probabilistic and risk-informed method for life extension assessment. We will consider a representative wind farm, and assume that the wind turbine towers are designed according to the site conditions using the deterministic approach. We assume that the tower is the critical structural component in terms of fatigue loads. At the end of the original design lifetime of 25 years, the owner wishes to extend the life of the wind farm. The need for refurbishments of mechanical components and blades is assessed using an inspection. The structural integrity of the tower with respect to fatigue is to be verified using updated environmental and operational conditions based on measurements. The baseline assessment is made using the deterministic method, and the economic feasibility is estimated without considering the risk of structural failure, by calculation of the expected present value of the profit $Z_0(T_{ext})$:

$$Z_0(T_{ext}) = \int_0^{T_{ext}} \exp(-\gamma t')\ \left(c_B(t') - c_{OM1}(t') - c_{OM2}(t')\right) dt' - C_{ext}(T_{ext}) , \tag{14}$$

As an alternative to the deterministic assessment, the probabilistic or risk-informed approach can be applied. In the probabilistic approach it is required that the annual reliability index in the last year of the extended life is below the target value of 3.3 (or 3.1, if a reduced target is allowed, as suggested in [16]). In the risk-informed approach, it is required that that the expected present value of the profit (Z) is positive, when the interest rate is used as discount rate, and the risk of structural failure is included.

3.1. Case wind farm

The case study considers a wind farm with 44 2.3 MW turbines. The wind turbine tower is designed for a reference turbulence intensity of 14% and a 10-minute mean wind speed at hub height of 8 m/s. The economic data below are adapted from Carriveau and Miller [17].

The annual energy production (AEP) is 7280 MWh per turbine. The power purchase agreement (PPA) price is \$50/MWh and the annual O&M costs (C_{OM}) are \$25/MWh. The proportion of the O&M costs that are variable (OM_{var}) are 0.7 of the total O&M cost. This yields an annual profit (P_a) per turbine equal to:

$$P_a = PPA \cdot AEP - C_{OM} \cdot AEP = \$182{,}000 , \tag{15}$$

If the PPA price was only \$30/MWh, the annual profit would be \$36,400 per turbine.

However, in order to extend the life it is necessary to do a visual inspection, a loads analysis and an operations analysis with the following costs per turbine (adapted from [18]):

- Visual inspection: $C_{VI} = \$3740$

- Loads analysis: $C_{LA} = \$7000$
- Operations analysis: $C_{OA} = \$3000$

Also, depending on the outcomes of the inspections, it may be necessary to do repairs and retrofits of various components. Four representative levels of retrofits are considered, with the following costs:

- No repairs: $C_{RR,no} = 0$
- Low level: $C_{RR,low} = \$10{,}000{,}000$ (50% of gearboxes)
- Medium level: $C_{RR,med} = \$17{,}500{,}000$ (50% of the blades)
- High level: $C_{RR,high} = \$25{,}000{,}000$ (40% each of blades, gearboxes, and generators)

The average costs per turbine for the four levels are then: \$0, \$227,000, \$398,000, and \$568,000 respectively. The life extension costs are then calculated as the sum of the costs to visual inspection, loads analysis, operations analysis, and repairs and retrofits. These costs occur at the start of the life extension period. All other costs are distributed in the extended life, and are discounted to net present values using an interest rate of $\gamma = 0.04$.

In case of a structural failure, the costs/consequences are assumed to be 10 times the annual O&M costs (\$1,820,000 per turbine).

3.2. Procedure

The procedure for deterministic, probabilistic and risk-based assessment in the case study is described in the following.

3.2.1 Deterministic assessment

The fatigue life resulting from the deterministic assessment can be different from the design fatigue life due to differences in the environmental or operational conditions compared to the design assumptions, e.g. differences in the turbulence intensity, the number of load cycles, or the mean wind speed. The conditions on the site could be more benign, similar to, or harsher than assumed in the design, leading to longer, the same, or shorter fatigue life. For the analysis, various outcomes of the fatigue life from the deterministic analysis are assumed, and the economic feasibility is assessed using Equation (14) for life extension periods corresponding to each assumed outcome, for the four different retrofit levels.

3.2.2 Probabilistic assessment

To compare the probabilistic assessment with the deterministic assessment, the models in Sections 2.1 and 2.2 are applied. First, the required design parameter z is found using the deterministic method with the initial design assumptions such that the design life is equal to 25 years (Equation (3) is set equal to zero, and is then solved for t). Then, updated deterministic fatigue lives are modelled by changing, one at a time, the design parameter z, the turbulence intensity, the annual number of load cycles, and the mean wind speed.

For each combination, the probabilistic fatigue life is also estimated. The annual reliability index is found as function of time using the procedure in Section 2.2 with 10^7 Monte Carlo simulations. To filter out year-to-year fluctuations from the overall trend caused by the limited number of simulations, a cubic smoothing spline algorithm was applied. The probabilistic fatigue life was derived as the point in time where the annual reliability index dropped below the target, which was found using interpolation in the filtered results. The probabilistic fatigue life was found for a target equal to 3.3 (the target for new wind turbines) and 3.1 (the target proposed by [16] for life extension of wind turbines).

For the deterministic fatigue lives assumed in Section 3.2.1, the corresponding probabilistic fatigue lives are found, and the economic feasibility is assessed using Equation (14) for an extended life corresponding to the additional fatigue life beyond 25 years.

3.2.3 Risk-informed assessment

In the risk-informed assessment, the procedure in Sections 2.2 and 2.3 is applied to assess the feasibility, when the risk of structural failure is included directly in the assessment.

4. Results

This section presents the results of the analyses based on deterministic, probabilistic and risk-based assessment methods. The expected present value of the profits are compared for the three analysis methods.

4.1 Deterministic assessment

The starting point for the analyses are outcomes of fatigue lives from the deterministic method. Figure 3 shows the expected present value of the profit, Z_0, calculated using Equation (14) for life extension periods 1, 2, 5, 10, 15, and 20 years for the four levels of retrofits. In Figure 3(a), the economic input presented in Section 3.1 is used, and in Figure 3(b) the power price is reduced from \$50/MWh to \$30/MWh. For the case of no repairs, all life extension periods lead to positive expected present value of the profit, but for the low power price, the margin is narrow. Increasing the costs of retrofits translates the graph downwards, and higher life extension periods are required to get a positive expected present value of the profit. For the high power price, all life extension periods above 5 years, will lead to positive profit, but for the low power price, a 5 years life extension period is only feasible, if no retrofits are necessary. For a 10 year life extension period, the low retrofit level is also feasible, whereas higher life extension periods are required for the medium retrofit level, and 20 years of life extension is not even sufficient for the high level of repairs.

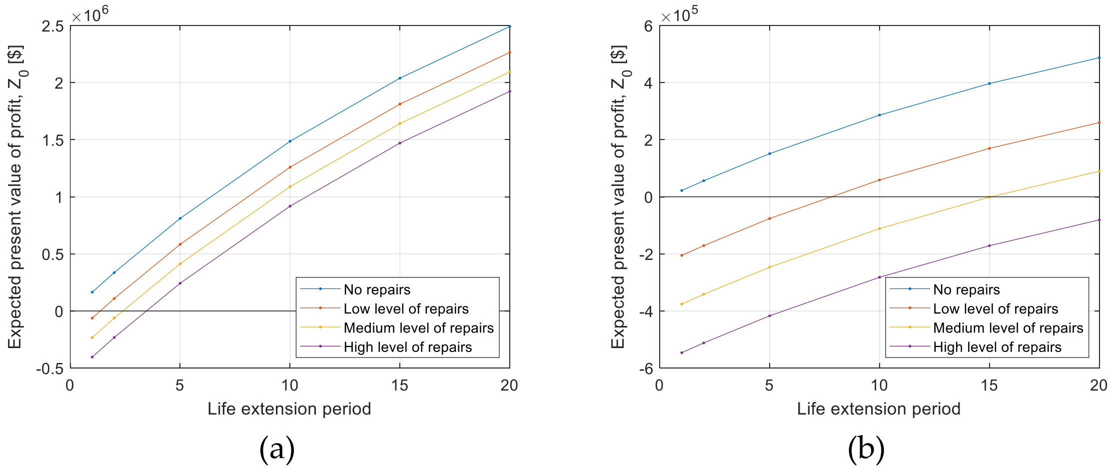


Figure 3. Expected present value of the profit Z_0 as function of life extension period (when the risk of failure is not included) for various levels of retrofits for: (**a**) PPA=50; (**b**) PPA=30.

4.2 Probabilistic assessment

The outcome of the probabilistic assessment can be related to the outcomes of the deterministic assessment using the models in Section 2.1 and 2.2 with the same assumptions on input. The probabilistic fatigue life is here understood as the point in time where the annual reliability index drops below the target value for structural components in new wind turbines, $\beta = 3.3$. In Figure 4, the probabilistic fatigue life is shown as function of deterministic fatigue life for variations of design parameter z, reference turbulence intensity I_{ref}, annual number of load cycles ν, and 10-minute mean wind speed at hub height V_{avg}. The design assumptions correspond to a deterministic fatigue life of 25 years, as the design parameter was determined to fulfill this. Here, the probabilistic model also gives a fatigue life of 25 years. However, for smaller or larger deterministic fatigue lives than 25 years, the probabilistic model resulst in a different result; for deterministic fatigue lives larger than 25 years, the probabilistic analysis gives larger fatigue lives than the deterministic model, and for deterministic fatigue lives below 25 years, the opposite is the case. Changes in design parameter, turbulence intensity or annual number of load cycles have a similar effect. A change that increase the deterministic fatigue life by 5 years to 30 years (e.g. lower turbulence intensity or less load cycles than expected in design), result in almost 10 years of additional lifetime beyond the 25 years for the probabilistic model. Changes in the mean wind speed result in even larger deviations of the fatigue life found by the deterministic and probabilistic model.

In Figure 5(a), the relation between deterministic and probabilistic fatigue life is shown for reliability index $\beta = 3.3$ and $\beta = 3.1$, for variations of design parameter z (which gives same result as variations in turbulence intensity and number of load cycles). It is seen, that acceptance of a reliability index of $\beta = 3.1$ will generally result in more than 15 additional years of operation than $\beta = 3.3$ for deterministic fatigue lives higher larger than 25 years. The same can be seen in Figure 5(b), where the reliability index in the last years of the extended life is shown as function of deterministic assessed fatigue life for life extension periods 1, 2, 5, 10, 15, and 20 years. This figure more clearly shows the relation between assessed deterministic fatigue life and reliability index.

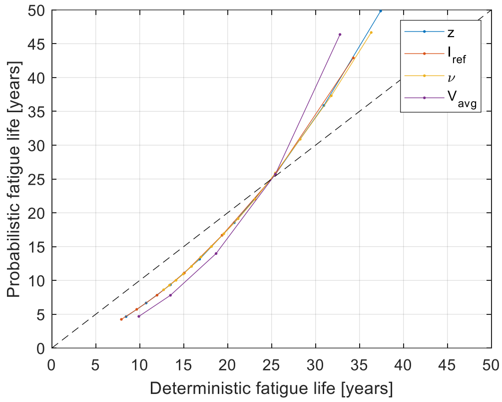


Figure 4. Fatigue life from probabilistic assessment for $\beta = 3.3$ as function of the fatigue life from the deterministic assessment for variations of input parameters: z: design parameter, I_{ref}: reference turbulence intensity, ν: annual number of load cycles, and V_{avg}: 10-minute mean wind speed at hub height.

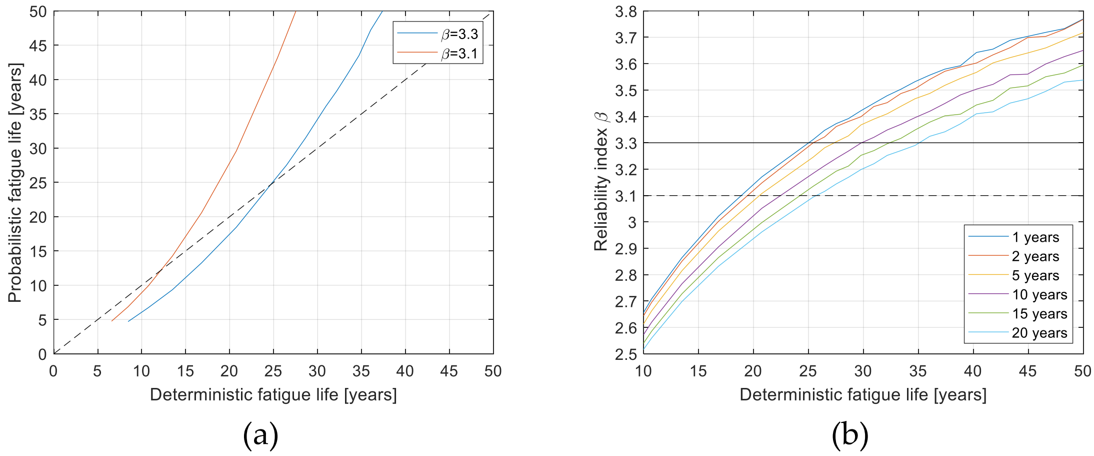


Figure 5. Effect of deterministic fatigue life on: (**a**) fatigue life from probabilistic assessment for $\beta = 3.3$ and $\beta = 3.1$ found by variation of the design parameter z; (**b**) reliability index β in last year of the extended life for life extension periods: 1, 2, 5, 10, 15, 20 years. The scatter for high reliability indices reflects the uncertainty related to the use of Monte Carlo simulations.

We will now see how the expected present value of the profit Z_0 increase due to longer life extension periods made possible by the use of a probabilistic model. Table 1 shows the remaining fatigue life estimated by probabilistic model with $\beta = 3.3$ and $\beta = 3.1$ as target for deterministic fatigue lives 1, 2, 5, 10, 15, and 20 years, and shows the expected present value of the profit for life extension periods corresponding to the remaining fatigue life for the four retrofit levels. In case the remaining fatigue life is more than 20 years, a life extension period of 20 years is used. When the deterministic assessment method predicts low fatigue lives (1, 2, or 5 years), the use of probabilistic models will lead to longer life extension periods with higher profit, and where higher levels of retrofits does not make life extension infeasible.

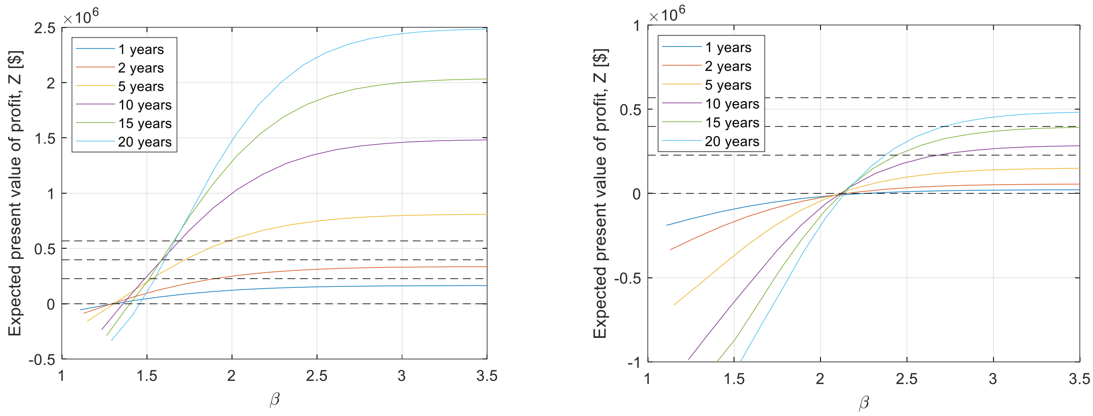
Table 1. Expected present value of the profit for four levels of retrofits: no repairs, low level, medium level and high level for life extension periods equal to the assessed remaining fatigue life using the deterministic analysis method, and for the probabilistic analysis method for target reliability levels $\beta = 3.3$ and $\beta = 3.1$.

Analysis method	Remaining fatigue life / Life extension period [years]	Expected present value of profit [M$]			
		No repairs	Low level	Medium level	High level
Deterministic	**1**	0.165	-0.063	-0.233	-0.404
Prob. $\beta = 3.3$	1.8	0.300	0.072	-0.098	-0.268
Prob. $\beta = 3.1$	>20.0	2.492	2.264	2.094	1.923
Deterministic	**2**	0.336	0.109	-0.062	-0.232
Prob. $\beta = 3.3$	3.5	0.574	0.347	0.177	0.006
Prob. $\beta = 3.1$	>20.0	2.492	2.264	2.094	1.923
Deterministic	**5**	0.811	0.584	0.413	0.243
Prob. $\beta = 3.3$	9.2	1.381	1.154	0.984	0.813
Prob. $\beta = 3.1$	>20.0	2.492	2.264	2.094	1.923
Deterministic	**10**	1.486	1.259	1.088	0.918
Prob. $\beta = 3.3$	19.3	2.431	2.204	2.034	1.863
Prob. $\beta = 3.1$	>20.0	2.492	2.264	2.094	1.923
Deterministic	**15**	2.039	1.812	1.641	1.471
Prob. $\beta = 3.3$	>20.0	2.492	2.264	2.094	1.923
Prob. $\beta = 3.1$	>20.0	2.492	2.264	2.094	1.923
Deterministic	**20**	2.492	2.264	2.094	1.923
Prob. $\beta = 3.3$	>20.0	2.492	2.264	2.094	1.923
Prob. $\beta = 3.1$	>20.0	2.492	2.264	2.094	1.923

4.3. Risk-based assessment

In the risk-based assessment, the probabilistic model is used, but no target for the reliability is applied. Instead, the expected present value of the profit Z is calculated by including directly the risk of structural failure. Figure 6(a) shows the expected present value of the profit Z as function of the reliability index in the last year of the extended life for life extension periods 1, 2, 5, 10, 15, and 20 years for the base case economic input. Figure 6(b) shows the same for a power price reduced from $50/MWh to $30/MWh. The expected present value of the profit is shown for the case with no repairs. Curves for other retrofit level can be obtained by vertical translation of the curves (as seen in Figure 3). To give a more compact representation, the costs for each of the four retrofit levels are indicated with dashed lines in Figure 6, the highest line corresponding to the high retrofit level. If the expected present value of the profit is less than the retrofit costs, that combination of life extension period, retrofit level and reliability index is infeasible. For high reliability levels, the curves converge towards the values of Z_0 in Figure 3; the expected present value of the costs when the risk of failure is not considered.

Figure 6 shows that the decrease in Z for a reliability index in the last year of the extended life being reduced from $\beta = 3.3$ to $\beta = 3.1$ is very minor, also for long life extension periods. For the high power price, the reliability index can be as low as 2.0 before an else feasible retrofit level becomes infeasible. The profit is reduced fastest for long life extension periods, but as the initial margin is large, it generally leads to higher expected value of the profit than the lower life extension periods, unless the reliability is very low. For the low power price, the profit margins are narrow, and for reliability indices less the 3.0, the risk of structural failure can be the tipping factor, making life extension for a given period and retrofit level infeasible.



(a) (b)

Figure 6. Expected present value of the profit Z as function of the reliability index β in the last year of the extended life, for life extension periods: 1, 2, 5, 10, 15, 20 years for: (**a**) PPA=50; (**b**) PPA=30. The dashed lines correspond to the costs of retrofits for (from the bottom): no repairs, low level, medium level, and high level.

In Figure 7, each of the five economic input values are varied one at the time, while the other remain at their initial value. The varied economic input values are: (a) life extension costs C_{ext}, (b) failure costs H, (c) annual operation and maintenance costs C_{OM}, (d) power price PPA, (e) operation and maintenance costs variable proportion OM_{var}. The figures show the expected present value of the profit when the risk of failure is not considered Z_0 (full lines), and when it is considered Z (dashed lines), for a turbine with a deterministic design fatigue life of 25 years.

The life extension costs (a), annual operation and maintenance costs (c), and power price (d) affect both Z_0 and Z. The difference between Z_0 and Z is generally small, but it is highest for long life extension periods. The failure costs H (b), and the operation and maintenance costs variable proportion OM_{var} (e) only affects Z (not Z_0).

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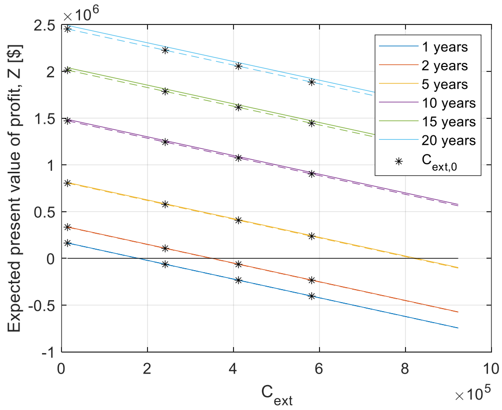
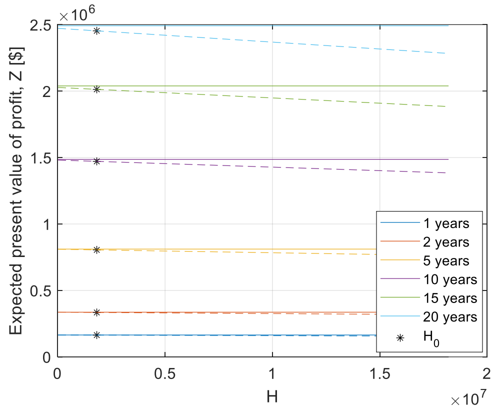
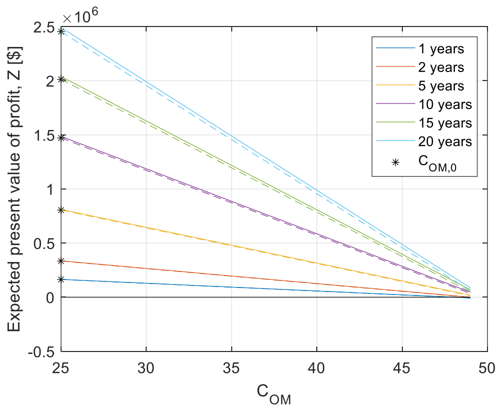


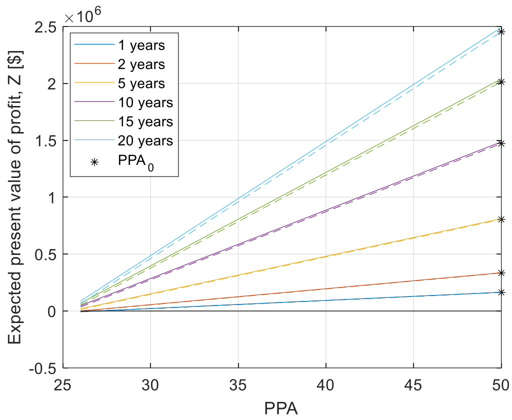
(a)



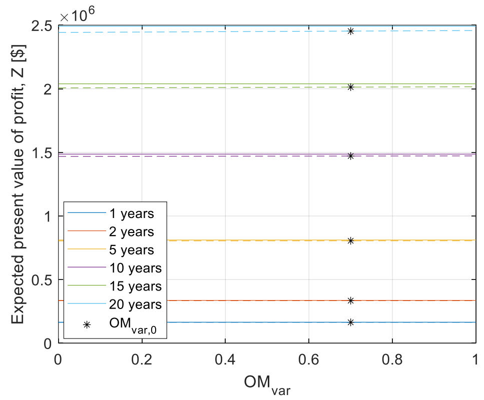
(b)



(c)



(d)



(e)

Figure 7. Expected present value of profit Z as function of: (**a**) life extension costs C_{ext}; (**b**) failure costs H; (**c**) annual operation and maintenance costs C_{OM}; (**d**) power price PPA; (**e**) operation and maintenance costs variable proportion OM_{var}. The stars indicate the base case values. For (**a**), the stars indicate C_{ext} for the four retrofit levels.

5. Discussion

This paper investigates how probabilistic and risk-based methods can be applied for life extension assessment; and examines how the use of these alternatives to deterministic assessment can enhance the economic feasibility of life extension by allowing for longer life extension periods.

A comparison of the outcome of the deterministic and probabilistic assessment methods showed that they were consistent, when the fatigue life was 25 years. This was expected, as the partial safety factor used in the deterministic model was calibrated in [11] using the same deterministic and probabilistic models as used in this study under similar assumptions. However, the comparison in this paper shows that the deterministic model leads to non-conservative results for fatigue lives smaller than 25 years, and conservative for larger lives. This means that use of the probabilistic assessment method will generally lead to longer predicted fatigue lives than the deterministic analysis, when the deterministic analysis results in additional fatigue life beyond the 25 years. If the target reliability is reduced from 3.3 to 3.1 as suggested in [7], it would lead to at least 15 additional years of fatigue life, if the deterministic assessment result in a lifetime of 25 years or more. The longer fatigue life gave a larger potential for profit generation.

The analyses assumed the same level of uncertainties for the original assessment and for the updated life extension assessment. For real projects, the updated assessment would often be based on operational data and possibly load monitoring. Here it is important to remember that the 90% quantile of the turbulence intensity is to be used in deterministic assessment, in order to be consistent with the model used for calibration of partial safety factors. If load simulations are made for the measured wind speeds and turbulence intensities based on SCADA or met-mast data, or measured strains are used, this corresponds to using the full distribution of the turbulence standard deviation, as done in the probabilistic assessment. However, using this in a deterministic assessment could lead to lower reliability levels.

The risk-informed model was applied to include the risk of structural failure in the feasibility assessment for a case wind farm. The risk of structural failure did not challenge the economic feasibility for life extension, unless the expected present value of the profit was already low; high life extension costs, high O&M costs, and low power price can challenge the business case, and including the risk of structural failure can at most be the tipping factor.

This analysis confirms the conclusions in [16] that a reduced target reliability index of 3.1 generally does not affect the economic feasibility, and such a target could be included in standards on life extension to make life extension possible for more wind turbines for longer life extension periods. In reality, factors other than the fatigue life of structural components affect whether a wind turbine is fit for life extension. The required amount of retrofits will typically be larger for longer life extension periods, and even if the fatigue life was sufficient for, for example 15 years of life extension, is could be better to extend the life for only 10 years, if large additional retrofits were required for the last 5 years of life extension.

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