# IEA Wind Task 42

## Lifetime Extension Assessment

*Deliverable Report 3+7: Recommendations on standards and regulatory frame*

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# Contents

**Executive Summary:**

This report aims to assess the fatigue life of tower and support structures based on provisions of standards, as these have been developed during the years. After presentation of turbulence models and a summary of safety factors, based on provisions of the IEC 61400-1 from its initial introduction in 1994 to its 4$^{th}$ edition of 2019, the design basis with respect to fatigue is established combining applicable safety factors. Next, a fatigue reliability assessment framework is presented to stand as the basis for different life extension scenarios to be benchmarked.

Outcomes of this work, highlight that fatigue life of components such as towers and support structures is important when considering life extension for wind turbines. The latest version of IEC 61400-1 ed. 4 is calibrated to an annual reliability level after 25 years of 3.3 based on the assumption that the 90% quantile of the turbulence intensity is used in design using safety factors, whereas the full distribution is used in the reliability assessment. The possibility of using the full Weibull distribution for deterministic design was introduced in IEC 61400-1 ed.4 without explicitly considering the influence it had on the reliability. Accepting a lower annual reliability level for fatigue can be motivated by the fact that the reliability is decreasing over time. Further, for life extension, the economic situation is different when considering life extension, compared to the situation when the wind turbine is designed.

Going beyond the recommended failure probabilities could be an option, if the expected consequence of a failure is small. It could be a possibility to include directly the risk of structural failure in the economic assessment.

# 1 Introduction

Requirements for life extension can be given in national regulations and in standards on wind turbines design and assessment, e.g. the IEC 61400 series of standards. Additionally, certification companies, e.g. DVNGL publish their own standards. A review of relevant standards can be found in (Natarajan, et al., 2020).

The focus in this deliverable is on the assessment of sufficient fatigue life of the tower and support structures. In this relation, the potential for life extension of wind turbines depends on the design, the actual wind climate at the site, and on the requirements for the reliability level for life extension. The requirements for fatigue design are generally based on IEC 61400-1, but rules have changed over time when new editions have been published. This can affect the potential for life extension, because a reassessment of the fatigue life is made based on the newest version of the standard. Other documents of relevance are the technical specifications currently under development: IEC 61400-28 “Through life management and life extension of wind power assets” and IEC 61400-9 “Probabilistic design measures for wind turbines”. Additionally, the component specific standards can be of relevance.

This document addresses how potential rules in standards and regulations affects the potential for life extension, and how it affects the reliability of operating wind turbines.

## 1.1. Turbulence models

This section describes the difference in the turbulence models used in the four versions of IEC 61400-1: (IEC 61400-1 ed. 4, 2019), (IEC 61400-1 ed. 3, 2005), (IEC 61400-1 ed. 2 , 1999), and (IEC 61400-1 ed. 1, 1994).

IEC 61400-1 ed. 4 includes four turbulence classes, A+, A, B, C, ed. 3 includes class A, B, C, ed.2 includes class A, B, whereas ed. 1 only has one class, approximately between A and B.

In ed. 4, the normal turbulence model (NTM) defines that the representative value of the turbulence standard deviation, $\sigma_1$, shall be given by the 90 % quantile for the given hub height wind speed ($V_{hub}$) :

$$\sigma_1 = I_{ref}(0.75V_{hub} + b); \quad b = 5.6\ m/s$$

In the main text it is further stated that as an alternative, *a Weibull distribution shall be assumed for $\sigma_1$ with Weibull scale and shape parameters:*

$$P_W(\sigma_1 < \sigma_0) = 1 - \exp\left[-\left(\frac{\sigma_0}{C}\right)^k\right]$$

where: $k = 0.27\, V_{hub}(\mathrm{s/m}) + 1.4$ and $C = I_{ref}(0.75V_{hub} + 3.3\ \mathrm{m/s})$

In ed. 3, the same expression is given for the 90% quantile as in ed. 4. Here, the Weibull distribution is not provided as an alternative, but in a footnote it is stated that *if other quantiles are desired for additional optional load calculations, they may be approximated for the standard classes by assuming a log-normal distribution and*

$$E\langle\sigma_1|V_{hub}\rangle = I_{ref}(0.75V_{hub} + c); \quad c = 3.8\ \mathrm{m/s}$$

$$Var\langle\sigma_1|V_{hub}\rangle = \left(I_{ref}(1.4\ \mathrm{m/s})\right)^2$$

This means that for design according to ed. 3, load calculations need to be performed using the 90% quantile, whereas in ed. 4 it is still an option to use the 90% quantile, but the designer can also choose to use the full Weibull distribution instead. However, it has been a point of discussion in the industry whether it is in fact allowed to use the full distribution without increasing the safety factor, as the reliability level is significantly lower when the full distribution is used, because part of the safety is hidden in the use of the 90% quantile.

In ed. 2 and ed. 1 only characteristic turbulence models are mentioned. The formulation of the NTM is slightly different in ed.2 compared to ed. 3 and 4, but for class A, the models in ed. 2, 3 and 4 are equivalent, whereas it is slightly different for class B. In. ed.1 there is only one turbulence class (between class A and B), and the turbulence depends on the mean wind speed. An overview of the turbulence models in ed. 1, 2, and 3 are given in Figure 1. Class A, B and C for ed. 4 are identical to those for ed. 3.

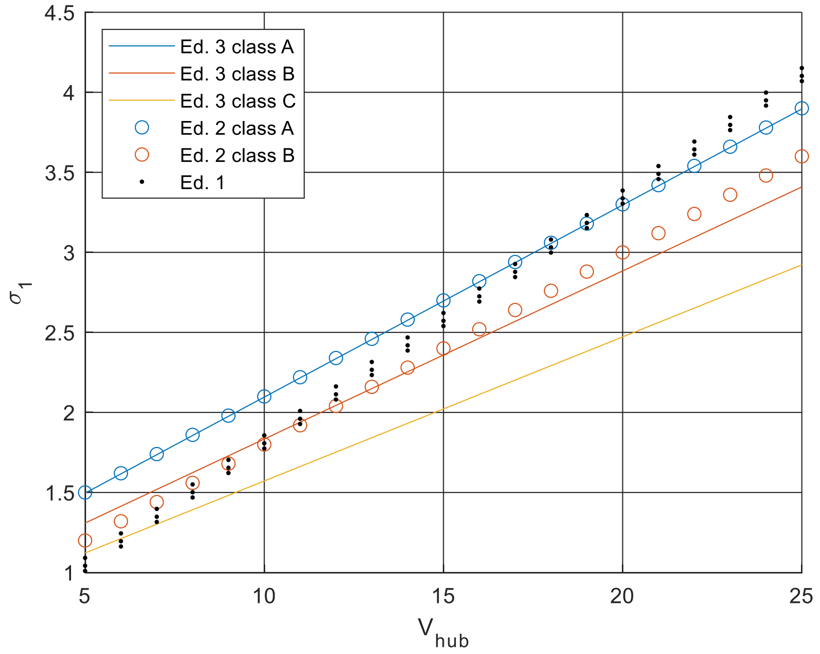



**Figure 1. NTM models in IEC 61400-1 ed. 1, 2, and 3 for the defined turbulence classes. For ed. 1 $\sigma_1$ depends on mean wind speed, thus there are different values for the three defined wind speed classes.**

## 1.2. Safety factors

This section describes the differences in the different versions of IEC 61400-1 in relation to safety factors for fatigue design. Table 1 shows the safety factors for fatigue for component class 2 in the four versions of IEC 61400-1, when the characteristic SN curve is based on 97.7% survival probability.

The safety factors on the resistance have decreased over time, which reflects better procedures for control. Although the safety factor on the load is formally 1.0 in all versions of the standard, the uncertainties on the load estimation has decreased over time, as new methods have been developed.

The safety factors in the first versions of the IEC 61400-1 standard were mainly based on experience and standards in other fields. In the process of making ed. 4, a reliability background was developed for the safety factors (Sørensen & Toft, 2014). An annual target reliability level $\beta = 3.3$ was defined for component class 2. The target was motivated by target reliability levels given in ISO2394 (ISO 2394, 2015) dependent on the costs of improving reliability and the consequence of failure. Further, the argument was provided that not all wind turbines are utilized to the limit, as wind turbines are not designed to the specific position, where they will be erected, thus most turbines will have a larger reliability. For various representative limit states, limit state equations were formulated, and stochastic models were defined which were consistent with the safety factors. For fatigue, a simple surrogate was defined to model the relation between the wind conditions and the stress range distribution on selected components. The turbulence was modelled according to the NTM in IEC61400-1 ed.3. Therefore, in the design equation based on safety factors, the 90% quantile of the turbulence was used, and in the probabilistic limit state equation, the lognormal distribution was used, as this was the alternative provided in ed.3.

| Version | Ed. 4 (2019) | Ed. 3 (2005) | Ed. 2 (1999) | Ed. 1 (1994) |
|---|---|---|---|---|
| $\gamma_f$ | 1.0 | 1.0 | 1.0 | 1.0 |
| $\gamma_m$ | 1.25 | 1.1 | 1.1 | 1.15 |
| $\gamma_n$ | 1.0 | 1.15 | 1.15 | 1.25 |
| $\gamma_f\gamma_m\gamma_n$ | 1.25 | 1.265 | 1.265 | 1.4375 |

**Table 1. Safety factors in the four versions of IEC 61400-1 for component class 2, for welded and structural steel when the SN curve corresponds to 97.7% survival probability.**

### 1.3. Design basis

The changes in standards means that there are several options for how currently operating wind turbines are designed w.r.t. fatigue:

1) Using $\gamma_f\gamma_m\gamma_n = 1.25$ and the Weibull turbulence distribution (ed.4 W, from 2019)
2) Using $\gamma_f\gamma_m\gamma_n = 1.25$ and the 90% quantile of turbulence (ed. 4, from 2019)
3) Using $\gamma_f\gamma_m\gamma_n = 1.265$ and the 90% quantile of turbulence (ed. 3, from 2005)
4) Using $\gamma_f\gamma_m\gamma_n = 1.265$ and ed. 2 turbulence model (ed. 2, from 1999)
5) Using $\gamma_f\gamma_m\gamma_n = 1.4375$ and ed. 1 turbulence model (ed. 1, from 1994)

Further, there can be differences in the choice of SN curve, both regarding the type (linear, bilinear, bilinear with cutoff), slope(s) (3, 4, or 5), and the detail category.

Wind turbines are generally designed to IEC classes, whereas the turbines may be erected on sites with more benign conditions. For newer wind turbines in wind farms, the wind turbine towers may be designed site-specific to the harshest position within the site. Consequently, many wind turbines will therefore experience less loading than they were designed for.

After some years of operation, the loading on each position can be estimated with much larger certainty, if information from relevant sensors is available. Especially the OEM (wind turbine manufacturer), who has access to detailed design information, can make a better estimate of the utilization and potential for life extension. Third parties can only do relative assessments, and uncertainties are present regarding the design.

# 2 Probabilistic fatigue assessment benchmark

In order to study the effect of rules in standards, benchmark calculations are performed. The design is assumed performed using the deterministic/semi-probabilistic approach using safety factors. A reassessment is then made using either safety factors or a probabilistic assessment, and the reliability level is evaluated.

## 2.1. Method

The overall procedure for reliability assessment is as follows:

- **Aeroelastic simulations:** Run $n_{sim}$ aeroelastic simulations for each bin of wind speed and turbulence, and for the 90% quantile of turbulence. (FAST, NREL 5MW turbine)
- **Rainflow counting:** Perform rainflow counting on the time series of tower bottom fore-aft bending moment.
- **Short term moment Markov matrix:** For each time series, discretize the Markov matrix into bins for the bending moment range.
- **Weights:** Calculate the probability for each combination of wind speed and turbulence using the distributions in IEC61400-1 based on $\mathrm{V_{avg}}$ and $\mathrm{I_{ref}}$, and based only on the wind speed distribution, when the 90% quantile of turbulence is used.
- **Long term moment Markov Matrix:** Create the annual Markov matrix by combining short term Markov matrices with the weights, and multiplying by a factor $6 \cdot 24 \cdot 365/n_{sim}$.
- **Design parameter:** Find necessary design parameter (cross-sectional parameter) $z$ for deterministic design using the design equation (based on 90% quantile of turbulence or using the full turbulence distribution).
- **Long term stress Markov Matrix:** Using the design parameter $z$, calculate the long term stress Markov matrix (based on full turbulence distribution). $\{n_i; \Delta\sigma_i(z)\}$
- **Fatigue damage surrogate:** Create a grid-based surrogate using the long term stress Markov matrix for a grid of values of $\log K$ and $X_{load}$ for the selected SN-curve.
- **Monte Carlo simulations: Draw** $n_{MC} = 10^7$ random realizations of the stochastic variables, and evaluate the limit state equation using interpolation in the fatigue damage surrogate for realizations of $\log K$ and $X_{load}$. Calculate the cumulative failure probability for each year and the annual failure probability. Calculate the annual reliability index $\beta = -\Phi^{-1}(P_f)$

The design equation is formulated as follows, based on the load input in terms of a Markov matrix $\{n_i; \Delta\sigma_i(z)\}$ of annual stress ranges:

$$G(z,t) = 1 - t \sum_{\mathrm{i}} \left( I_{1,i} \frac{n_i}{K_{1,c}} (\gamma_M \, \Delta\sigma_i(z))^{\,m_1} + I_{2,i} \frac{n_i}{K_{2,c}} (\gamma_M \, \Delta\sigma_i(z))^{\,m_2} \right)$$

Where $K_{1,c}$ and $K_{2,c}$ are the characteristic values of the SN curve intercept parameters for the first and second part of the curve; $m_1$ and $m_2$ are the slope parameters; $t$ is time in years, $\gamma_M$

is the combined safety factor $\gamma_M = \gamma_f \gamma_m \gamma_n$, and $I_{1,i}$ and $I_{2,i}$ distributes the stress ranges on the correct parts of the SN curves as follows:

- For linear SN-curve:
    - $I_{1,i} = 1$ and $I_{2,i} = 0$
- For bilinear SN-curve without cutoff:
    - For $\gamma_M \Delta\sigma_i \geq \Delta\sigma_D$: $I_{1,i} = 1$ and $I_{2,i} = 0$
    - For $\gamma_M \Delta\sigma_i < \Delta\sigma_D$: $I_{1,i} = 0$ and $I_{2,i} = 1$
- For bilinear SN-curve with cutoff:
    - For $\gamma_M \Delta\sigma_i \geq \Delta\sigma_D$: $I_{1,i} = 1$ and $I_{2,i} = 0$
    - For $\Delta\sigma_L < \gamma_M \Delta\sigma_i < \Delta\sigma_D$: $I_{1,i} = 0$ and $I_{2,i} = 1$
    - Else $I_{1,i} = 0$ and $I_{2,i} = 0$

The limit state equation for probabilistic assessment is written as follows:

$$g(z,t) = \Delta - t\, DAM(K_1, X_{load}, z)$$

$$DAM(K_1, X_{load}, z) = \sum_{\mathrm{i}} \left( I_{1,i} \frac{n_i}{K_1} (X_{load}\, \Delta\sigma_i(z))^{\,m_1} + I_{2,i} \frac{n_i}{K_2} (X_{load} \Delta\sigma_i(z))^{\,m_2} \right)$$

The following stochastic variables are included:

- $\Delta$ is the model uncertainty related to the use of Miner's rule for damage accumulation.
- $X_{load}$ is the model uncertainty of the wind load effect and stress concentration factor $K_1$ and $K_2$ are the SN curve intercept parameters, where the mean is found as the characteristic values plus two standard deviations (corresponding to that the characteristic value is a 97.7% quantile).

In the expressions for $I_{1,i}$ and $I_{2,i}$, $\gamma_M$ is replaced with $X_{load}$.

Table 2 and Table 3 shows the stochastic model and remaining input parameters for the baseline model. The model corresponds to the model used for the calibration of safety factors in (Sørensen & Toft, 2014), except that the procedure applied here uses aeroelastic simulations instead of the simple surrogate used there. The bilinear SN curve is based on (EN 1993-1-9, 2007).

| Variable | Distribution | Expected value | Standard deviation / Coefficient of variation |
|---|---|---|---|
| $\Delta$ | Lognormal | 1 | $COV_{\Delta} = 0.3$ |
| $\mathrm{X}_{\mathrm{load}}$ | Lognormal | 1 | $COV_{load} = 0.175$ |
| $\log K_1$ | Normal | Found from $\Delta\sigma_C$ | $\sigma_{\log K_1} = 0.2$ |
| $\log K_2$ | Normal | Found from $\Delta\sigma_C$ | $\sigma_{\log K_2} = 0.2$ |
| $m_1$ ; $m_2$ | Deterministic | 3; 5 | - |
| $\log K_1$ and $\log K_2$ are fully correlated. | | | |

**Table 2. Stochastic baseline model.**

| | Variable | Baseline value |
|---|---|---|
| 10 min mean wind speed | $\mathrm{V}_{\mathrm{avg}}$ | 8.5 m/s (II) |
| Reference turbulence intensity | $\mathrm{I}_{\mathrm{ref}}$ | 0.14 (B) |
| Fatigue strength | $\Delta\sigma_C$ | 71 MPa |
| Safety factor | $\gamma_M$ | 1.25 |
| SN curve type | | Bilinear without cutoff |
| Design life | $T$ | 25 years |

**Table 3. Input parameters for baseline model.**

### 2.2. Resulting reliability level

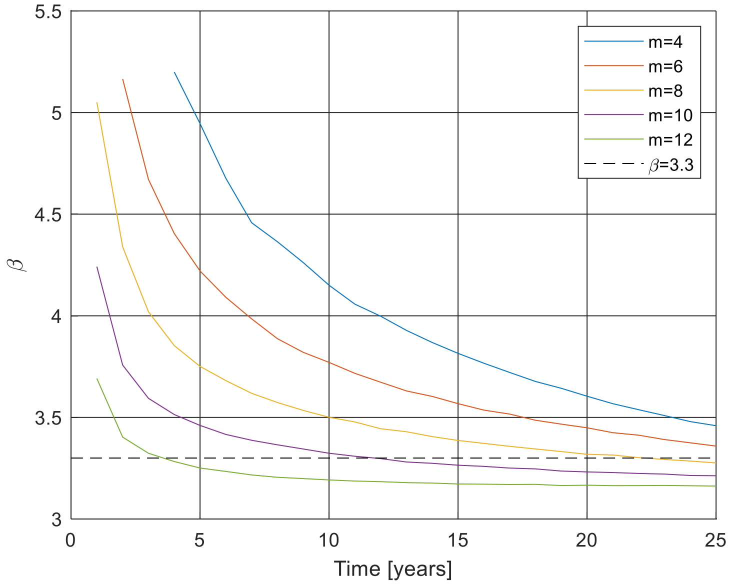
In order to assess the importance of various assumptions, the annual reliability index in the last year of the design life is assessed for the baseline model and some variations in Table 4. It is seen that changes of the SN curve type, detail category, and mean wind speed only has an insignificant influence on the reliability index. When the design life is reduced from 25 to 20 years, the reliability in the last year is reduced. When the 90% quantile of the turbulence is used for design, probabilistic assessment based on the Weibull distribution gives a larger reliability level than the lognormal distribution. When the full distribution (Weibull or lognormal) is used for the design, the reliability is substantially lower than when the 90% quantile is used. Compared to the target reliability 3.3, the reliability is insufficient when the full distribution is used according to this model.

Figure 2 shows the annual reliability index as function of time for linear SN curves with various slopes *m* for (a) design based on the 90% quantile of the turbulence, and (b) design based on the full Weibull distribution, in both cases assessed using the full Weibull distribution. For larger values of SN curve slope parameter $m$, the reliability level is quite low already early in the lifetime, whereas the reliability is decreasing with time for lower values of *m*.

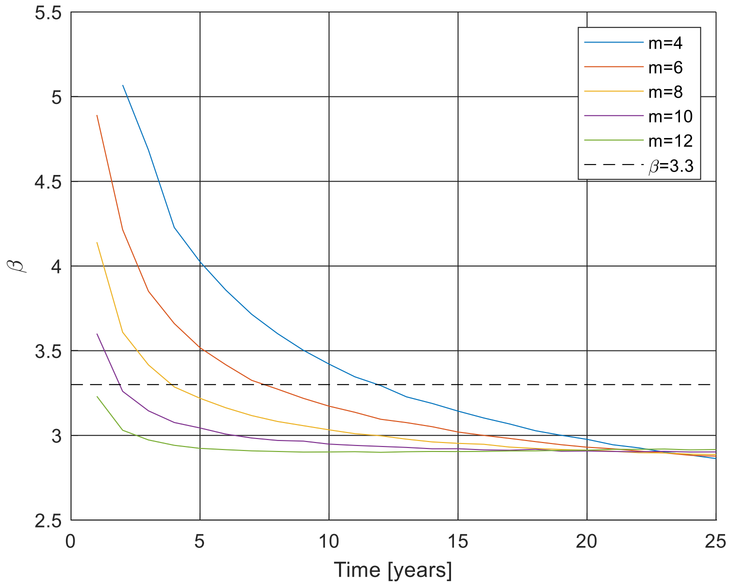
The obtained reliability levels further depend on the assumptions on the stochastic model (the uncertainties), and the safety factor. The results are similar to those obtained using the model in (Sørensen & Toft, 2014).

| $\boldsymbol{\beta_T}$ | Design 90% / Prob. Weibull | Design 90% / Prob. Logn. | Design Weibull / Prob. Weibull | Design Logn. / Prob. Logn. |
|---|---|---|---|---|
| **Baseline model** | 3.47 | 3.25 | 2.87 | 2.87 |
| Bilinear with cutoff | 3.44 | 3.24 | 2.87 | 2.87 |
| Linear SN-curve m=4 | 3.45 | 3.24 | 2.86 | 2.86 |
| $\Delta\sigma_C = 125$ MPa | 3.47 | 3.25 | 2.87 | 2.87 |
| $T = 20\ yr$ | 3.27 | 3.07 | 2.70 | 2.70 |
| $\mathrm{V_{avg}} = 10$ m/s | 3.44 | 3.22 | 2.87 | 2.87 |

**Table 4. Annual reliability level in year T for the baseline mode and for variations in the model.**




(a)




(b)

**Figure 2. Annual reliability index as function of time for linear SN curves with various slopes m for (a) design based on the 90% quantile of the turbulence, and (b) design based on the full Weibull distribution, in both cases assessed using the full Weibull distribution.**

### 2.3. Life extension scenarios

This section examines how the lifetime assessed using a relative approach is affected by the assumptions, when comparing to an absolute assessment with the same assumptions as used in the design. Here, the same aeroelastic model is used for all simulations, whereas in reality a generic model might be used instead for relative assessments.

In Figure 3 and Figure 4, it is investigated how the choice of SN curve for a relative assessment affects the assessed fatigue life when comparing to an absolute assessment with the correct SN curve. The correct SN-curve is assumed to be a bi-linear SN-curve with detail category 71 and with a cutoff limit applied. The different lifetimes are obtained by multiplying all stress ranges in the Markov matrix by the same factor. Since it is assumed that the design lifetime is 25 years, all curves go through this point, as this is the basis for the relative assessment. When using another detail category, the relative assessment is not affected. However, when using a bilinear curve without cutoff or a linear SN curve with $m$=4 through the kneepoint, the relative assessment result in slightly lower predicted lifetimes, when the assessed lifetime is above 25 years. Figure 4 further shows how the relative fatigue assessment is affected by using linear SN curves with slope $m$=3 or $m$=5. The use of a SN curve with $m$=3 overestimates the fatigue life, whereas the curve with $m$=5 underestimates fatigue life. Therefore, the use of a SN curve with slope $m$=4 results in conservative estimates of the lifetime, when the conditions are more benign than assumed in the design, but the opposite is the case for worse conditions leading to shorter fatigue lives.

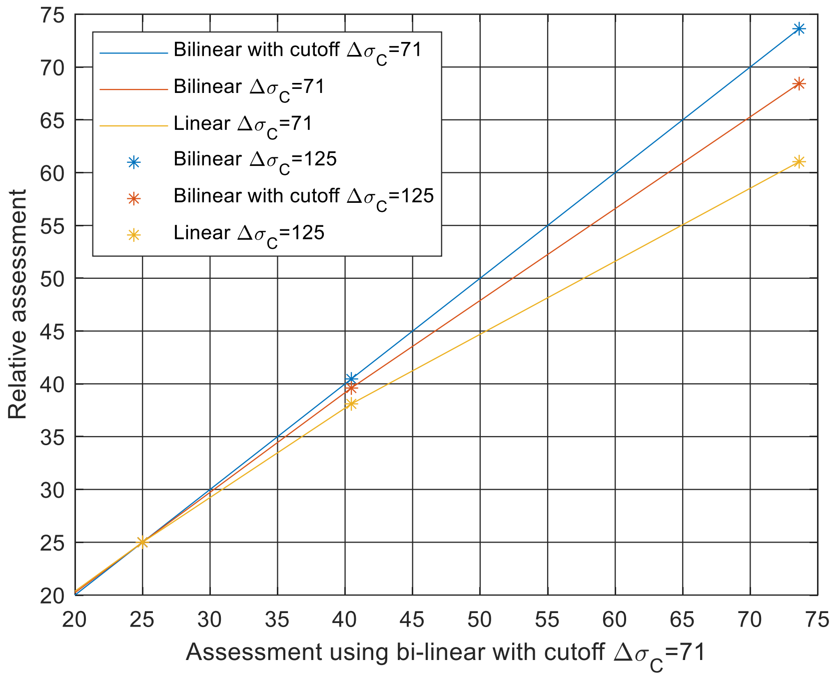



**Figure 3. Assessed deterministic fatigue life based on a relative assessment as function of an assessment based on a linear SN curve with *m*=4 going through the kneepoint of the bilinear curves.**

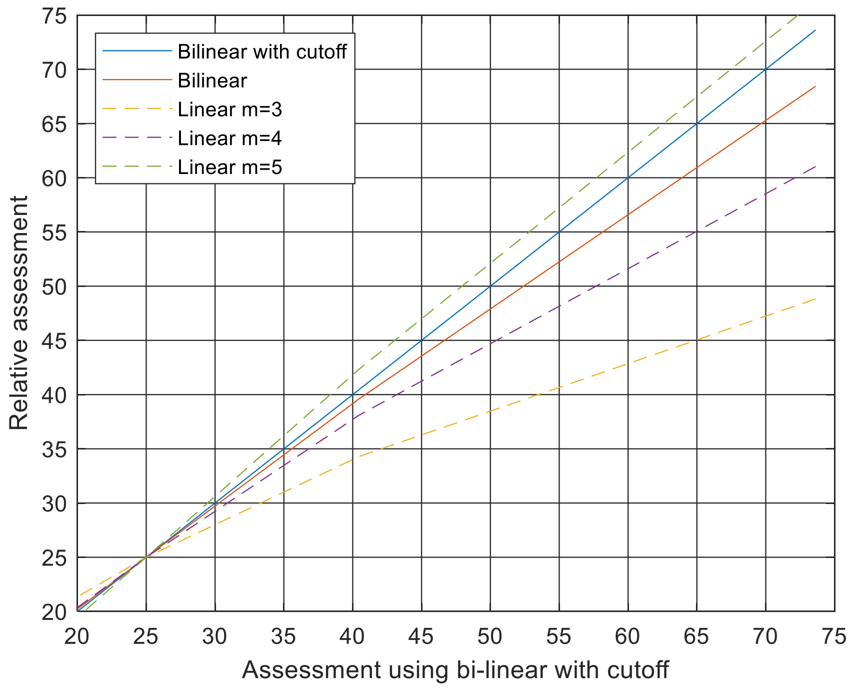



**Figure 4. Fatigue life from a relative assessment compared to the absolute assessment using a bilinear SN curve with cutoff (all based on 90% quantile).**

In Figure 5, a comparison is made between the deterministic fatigue life obtained using the full distribution of the turbulence compared to the 90% quantile. It is seen that the use of the full distribution results in a lifetime which is twice as large as the lifetime based on the 90%

quantile. For turbines designed using the 90% quantile, there is therefore the possibility to utilize this additional lifetime by making a relative assessment where the basis is established using the 90% quantile, and the full Weibull distribution (or measured distribution) is used for the updated assessment.

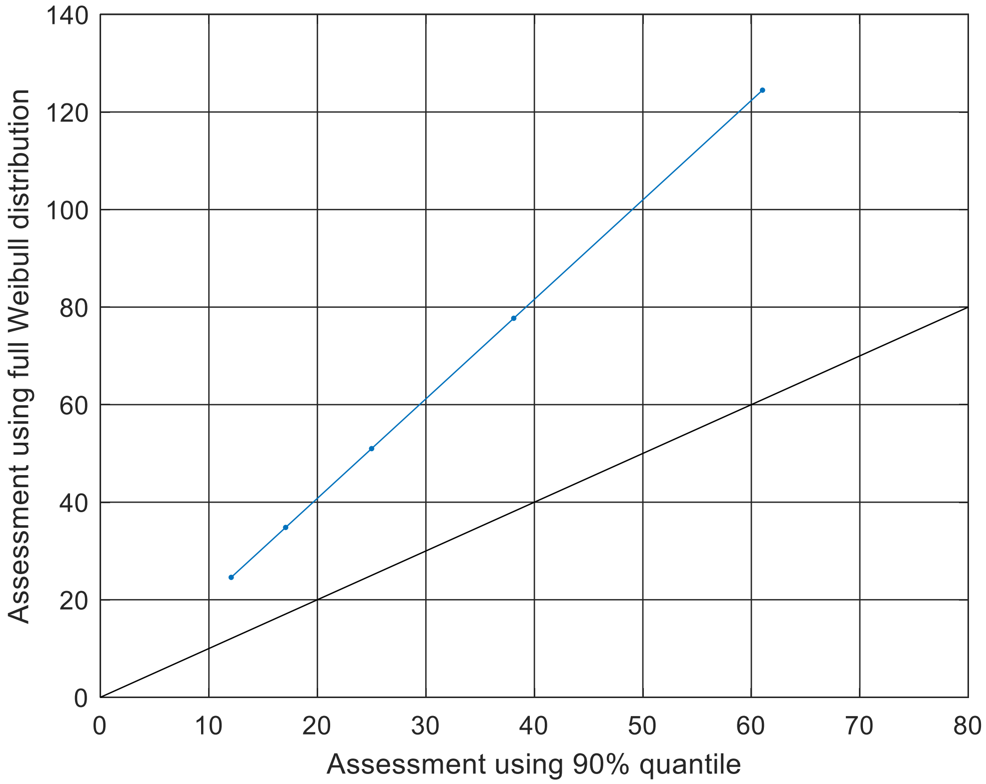



**Figure 5. Assessed deterministic fatigue life based on the full Weibull distribution as function of the assessment based on the 90% quantile of turbulence.**

Figure 6 shows the reliability index as function of time when design is made according to ed. 3 or 4 using the 90% quantile, or ed. 4 using the Weibull distribution, all with a design life of 25 years. The reliability index is shown for a coefficient of variation on the load ($COV_{load}$) on 17.5% and 8%. It is seen that when the 90% quantile is used, the reliability is sufficient until year 32-35, when $COV_{load} = 17.5\%$. However, when the Weibull distribution is used with $COV_{load} = 17.5\%$, the reliability drops below 3.3 already after 12 years. If it can be shown that $COV_{load}$ is only 8%, the reliability after 25 years is 3.3, if the Weibull distribution is used.

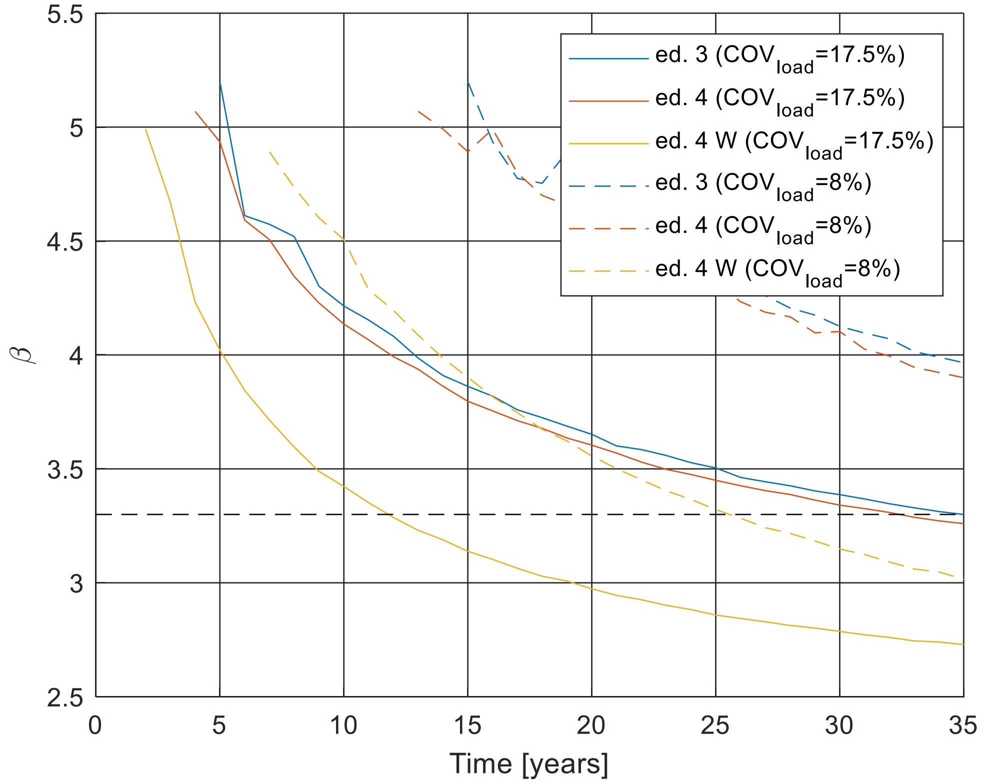
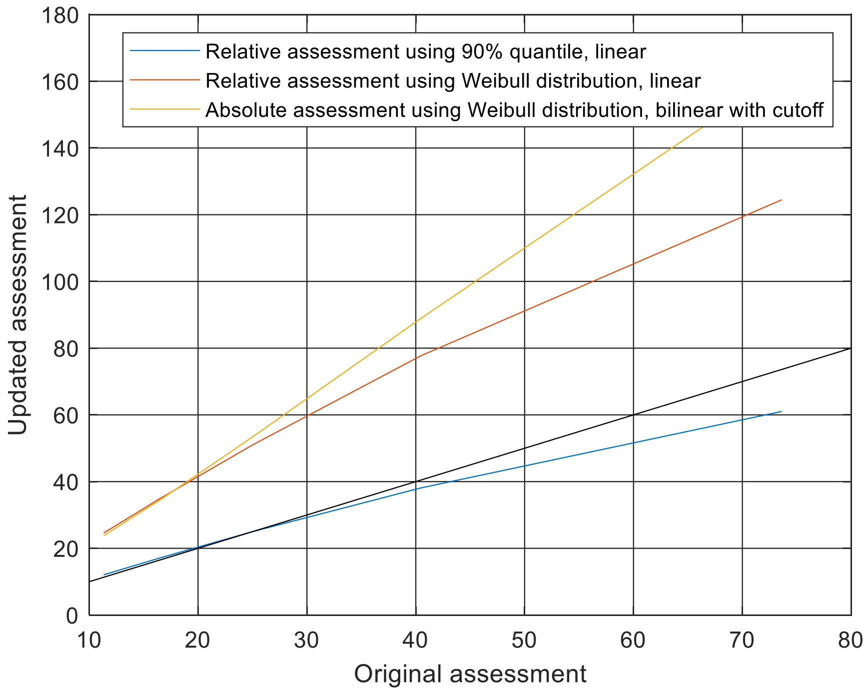


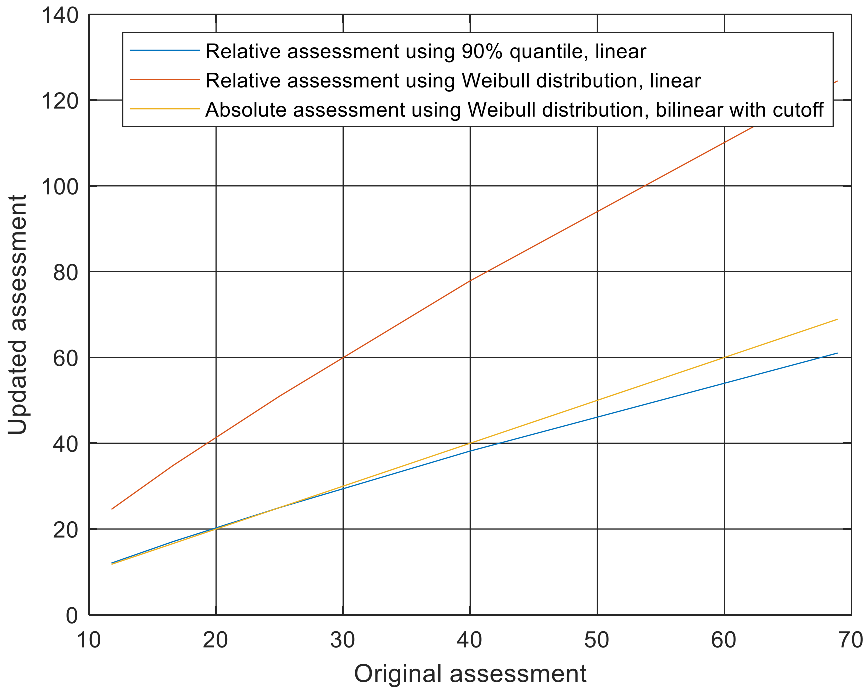

**Figure 6. Reliability index as function of time for welds designed using ed.3, ed.4, and ed. 4 W for a design life of 25 years. A linear SN curve with m=4 is used for both design and assessment.**

Figure 7a shows the additional fatigue life that can be obtained when using the Weibull distribution instead of the 90% quantile, and how the outcome of a relative assessment with a linear SN curve differs from an absolute assessment with a bilinear SN curve with cutoff. Generally, the relative assessment leads to conservative estimates.

Figure 7b shows how wrong assumptions on the design assumptions can affect estimates on the fatigue life. Again, it is assumed in the relative assessment that the 90% quantile was used, but in reality, the Weibull distribution was used for the design. Therefore, this wrong assumption will overestimate the deterministic fatigue life with a factor of two.




(a)




(b)

**Figure 7. Comparison of absolute and relative assessments using the 90% quantile and the Weibull distribution. (a) design using 90% quantile, (b) design using Weibull distribution.**

# 3 Risk-based assessment

In the previous section, the potential for life extension was assessed using a deterministic assessment, or based on the requirement that the annual reliability index in the last year of operation should be at least 3.3. Basically, there are two main reasons for having requirements regarding the reliability of wind turbines:

- Considerations on human safety
- Economic considerations

For civil engineering structures such as buildings and bridges, there is a large probability that a structural failure will result in fatalities and injuries. Wind turbines are not manned, except during maintenance, where the operation is shut down, and in most cases, they are not located close to buildings or roads. Therefore, the risk of fatalities and injuries is much smaller for wind turbines compared to other structures. However, it can be dangerous for the technicians who will need to tear down a failed wind turbine.

The design of wind turbines is driven by the economic considerations, as the economic consequence of a wind turbine failure is large, while the expected number of fatalities is very low. If a wind turbine in a wind farm designed for 25 years of operation fails completely after only 2 years, there is a direct cost associated with cleaning up the site. But more importantly, there is an indirect cost due to the loss of expected revenue in the remaining 23 years of operation. In principle, a new wind turbine could be erected on the site, but due to the large installation costs per turbine, if only one turbine is installed, this is often not done.

For life extension, the economic considerations are completely different. Here, the wind turbine has already been producing power in the planned 25 years, and the expected gain from the original investment has been obtained. Additional investments will typically be made in relation to life extension, e.g. inspections and analyzes to assess the remaining life, and exchange of major components. Additionally, the renewed contracts imply commitments in relation to land lease, inspections, and service. Nevertheless, the decision problem is completely different at this point, because the design cannot be changed. At the design stage the decision problem could be formulated: “What design will result in the optimal balance between risk of failure and costs of the structure?”. However, in relation to life extension we could ask: “Is it feasible to keep operating? (Or is there another option, e.g. repowering, which is better?)” This means that we do not need to have the most optimal design, in order to keep operating – we just need a feasible design.

From an economic perspective, it could in many cases be feasible to let wind turbines run until fatigue failure, as long as the safety systems still work satisfactory. However, there are several reasons that could be problematic. First, the aspect of human safety can be a significant factor, when the reliability level becomes very low, as the locations may not be completely deserted.

Secondly, although the risk of fatalities may still be very low, failing wind turbines will make people anxious, and will lead to an increased “not in my backyard” mentality. Thus this negatively affect the reputation of the industry, and this may lead to indirect costs.

Therefore, it may be feasible to accept lower reliability levels, but not too low. From an economic perspective, the lowest feasible target reliability can be calculated based on a risk-assessment. This analysis was presented in (Nielsen & Sørensen, Risk-based derivation of target reliability levels for life extension of wind turbine structural components, 2021), and the abstract of the paper is as follows:

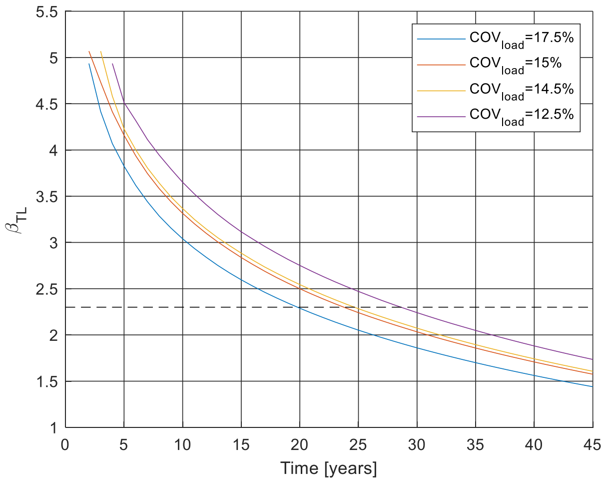
*The main wind turbine design standard IEC61400-1 ed. 4 includes an annual target reliability index for structural components of 3.3. Presently, no standards specify specific reliability requirements for existing wind turbines, to be used in relation to verification of structural integrity for life extension or continued operation. For existing structures in general, both economic and sustainability considerations support differentiation in reliability targets, as it is generally more expensive and requires more resources to improve the reliability. ISO2394 “General Principles on Reliability for Structures” includes tables with differentiated reliability targets depending on the consequences of failure and costs of improving reliability, which are derived using risk-based economic optimization. However, the assumptions behind these tables do not match the specific problem of life extension of wind turbines. In this paper, the risk-based approach is applied to derive specific target reliability levels for life extension of wind turbines, and a target annual reliability index around 3.1 is proposed.*

Further, the paper (Nielsen, Miller-Branovacki, & Carriveau, Probabilistic and Risk-Informed Life Extension Assessment of Wind Turbine Structural Components, 2021) presents how the use of reliability analysis with or without a reduced target reliability, and the use of direct risk-informed decision making can affect the potential for life extension. The abstract is as follows:

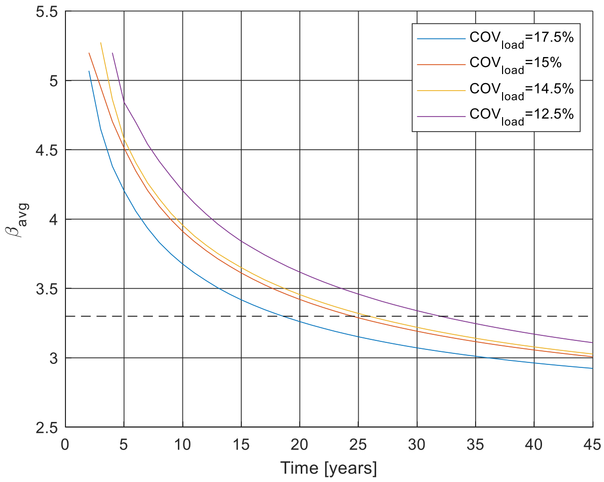
*Reassessment of the fatigue life for wind turbine structural components is typically performed using deterministic methods with the same partial safety factors as used for the original design. However, in relation to life extension, the conditions are generally different from the assumptions used for 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.*

The economic feasibility was in these papers assessed using a model, which took into consideration, that the reliability is decreasing with time in fatigue. This means, that even if the annual reliability index drops below 3.3 in the last year of operation, it will be larger in the beginning of the operational life, and the cumulative reliability may still be comparable to the level for load cases where the reliability level is constantly 3.3 in all years (e.g. extreme wind). For constant annual reliability index $\beta = 3.3$, the lifetime reliability index can be estimated as $\beta_{TL} = \Phi\left(\left(1 - \Phi^{-1}(-3.3)\right)^{25}\right) \approx 2.3$ (assuming independence from year to year, i.e. the load variability dominates the uncertainties). Accepting this lifetime reliability level also for fatigue would imply accepting an 'average' annual reliability index (based on average annual failure probability) of 3.3. Figure 8 shows the (a) lifetime reliability $\beta_{TL}$, (b) average annual reliability $\beta_{avg}$, and (c) annual reliability $\beta$ for different values of $COV_{load}$ as function of time (with deterministic design for 25 years).

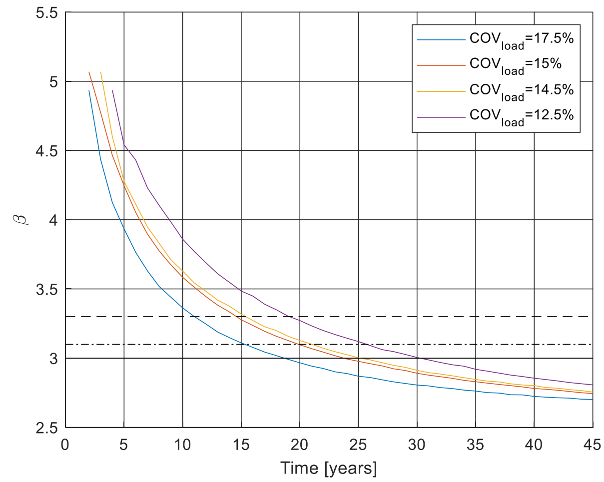
It is seen that an assumption on $COV_{load} = 14.5\%$ would satisfy a requirement for the lifetime reliability to be $\beta_{TL} = 2.3$ and the average annual reliability to be $\beta_{avg} = 3.3$. Then, the annual reliability index in the last year of operation would be $\beta = 3.0$. If accepting $\beta = 3.1$ for fatigue, the load uncertainty should be $COV_{load} = 12.5\%$, in order for the current design rules in IEC61400-1 ed. 4 to be sufficient to obtain this.




(a) Cumulative/lifetime reliability index. Vertical line for $\beta_{TL} = 2.3$.




(b) Average annual reliability index. Vertical line for $\beta_{avg} = 3.3$.




(c) Annual reliability index. Vertical lines for $\beta = 3.0, 3.1, 3.3$.

**Figure 8. The (a) lifetime reliability $\beta_{TL}$, (b) average annual reliability $\beta_{avg}$, and (c) annual reliability $\beta$ for different values of $COV_{load}$ as function of time (with deterministic design for 25 years).**

# 4 Summary and recommendation

When considering life extension for wind turbines, the fatigue life of the components is of interest, especially for the tower and support structure. The rules regarding both design and assessment in standards and regulations affects the possibilities for life extension.

The safety factors in IEC 61400-1 ed. 4 are calibrated to an annual reliability level after 25 years of 3.3 based on the assumption that the 90% quantile of the turbulence intensity is used in design using safety factors, whereas the full distribution is used in the reliability assessment. The possibility of using the full Weibull distribution for deterministic design was introduced in IEC61400-1 ed.4 without explicitly considering the influence it had on the reliability. It was known that the design was less conservative, but it was also considered a more accurate method, thus the reduced uncertainty was considered to justify the reduced conservatism. However, recent studies have shown that a reduction from 17.5% to 8% on the load uncertainty is needed to result in adequate reliability, when the target for the annual reliability index is 3.3. Accepting a lower annual reliability level for fatigue can be motivated by the fact that the reliability is decreasing over time. Further, for life extension the economic situation is different when considering life extension, compared to the situation when the wind turbine is designed. This can motivate acceptance of a lower reliability level in relation to life extension. Going beyond the recommended failure probabilities could be an option, if the expected consequence of a failure is small. It could be a possibility to include directly the risk of structural failure in the economic assessment.

While the OEM has the best basis for making an updated assessment of the remaining life, third parties have the possibility of doing relative assessments. In order to do a relative assessment, it is necessary to know some information on the original design, at least the wind turbine class. Knowing the year of certification also gives information on the version of the standard valid at that time. For wind turbines designed according to ed. 3, it is known that a 90% quantile was used for the design.

However, with the introduction of two options for the turbulence in IEC61400-1 ed. 4, it is beneficial to know whether the 90% quantile or full Weibull distribution was used, as the difference can be exploited in relation to life extension, if the 90% quantile was used. For example, if strain measurements are used directly for fatigue assessment, this corresponds to using the correct full distribution.

For wind turbines designed according to ed. 4, if it is not known whether the 90% quantile or full distribution is used, the relative assessment should assume that the full distribution is used. For relative assessments: if the full distributions (e.g. strain measurements) are used for relative fatigue assessment, the design parameters should be determined using the full Weibull distribution, if the design is according to ed.4. Else the fatigue life will be overestimated.

It was found here that relative assessments are not too sensitive to the selection of SN curve, and using a linear curve with $m$=4 leads to conservative assessments when bi-linear curves have been used for the design.

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