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# Risk-based derivation of target reliability levels for life extension of wind turbines – *preprint 2020*

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**Abstract**

The main wind turbine design standard IEC61400-1 ed. 4 includes an annual target reliability level 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 require more resources to improve the reliability. ISO2394 "General Principles on Reliability for Structures" include tables with differentiated reliability targets depending on consequences of failure and costs of improving reliability, which are derived using risk-based economic optimization. However, the assumptions behind these tables does 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 level equal to 3.1 is proposed.

## 1. Introduction

To facilitate decarbonisation, the share of wind energy needs to increase continuously. Along with new sites being commissioned, there is a large existing fleet with wind turbines gradually reaching the end of their intended life. When wind turbines reach the end of the planned life, there are four options:

- Continued operation: No major component exchanges are made, but the reliability might be updated using analyses and inspections.
- Life extension: Major component exchanges or repairs are made to extend the useful life.
- Repowering: The wind turbines are taken down and new turbines are erected on the site.
- Decommissioning: The wind turbines are taken down and the site is decommissioned.

Several factors related to economy and local constraints affects the decision.[2] For some sites, repowering with new bigger turbines is possible, which contributes to increasing the capacity. In other cases, local constraints eliminate this possibility, and the options are to decommission the site or to continue operation with the existing turbines with or without component exchanges/refurbishments.[3] Also if repowering is possible, it can be optimal to extend the life of existing turbines before going to repowering.[4]

When wind turbines are designed, they are expected to become obsolete after 20-25 years, thus they are designed with a design fatigue life of 20-25 years. For components where fatigue is the design driver, this could mean that the end of the design fatigue life is reached, and the reliability of the structure is not anymore proven sufficient. For components where extreme loads are the design driver, life extension can accepted if the normal service is continued after end of the planned lifetime.

In some countries, specific rules are made to ensure that further operation will not lead to unacceptable risk of failure. The rules in this relation differ between countries. In Denmark and Germany there are specific regulations, whereas in many other countries continued operation is allowed without any extra efforts. In both Denmark and Germany, a life extension inspection is necessary to assess the condition of turbines at the end of the planned life, and further efforts are needed to verify sufficient fatigue life. In Denmark, this is done indirectly through annual inspections of all load-transferring components. In Germany, sufficient fatigue life must be verified using updated fatigue calculations. Although not required in other countries, owners of large assets such as offshore wind farms need the assessment for negotiations with insurance companies and banks. The DNVGL standards on lifetime extension[5,6], presents various approaches for analytical assessment and allows for utilization of site specific measurements, monitoring and SCADA data, but do no present details on how. Therefore, development of efficient and accurate methods for prediction of the remaining fatigue life is a research topic with large industry interest.

Most approaches are based on semi-probabilistic (deterministic) assessment of the fatigue limit state, utilizing that the actual site conditions and operational history are different from the assumptions made in design. To this end, Ziegler et al[7] investigated which parameters are mostly affecting the fatigue life, and argue, that no generic conclusions can be made. For example, for some turbines, less availability, means less loads, but for wave dominated loading on big monopiles, the opposite might be the case. Kazemi et al[8] quantified the additional lifetime due to the wind not being unidirectional, by considering the actual wind rose for the site. Dimitrov et al[9] used SCADA data for lifetime assessment and performance optimization, and used machine learning to handle data limitations. Bouty et al[10] argue that it might not be economical to assess fatigue life for each turbine in a wind farm and propose an extrapolation method, when the conditions for several wind turbines are similar. Ziegler et al[11] compared a fracture mechanics model to the SN-Curve approach for jacket-supported offshore wind turbines, and outlined the challenges and opportunities in the fracture mechanical approach. Several studies also use strain measurements in addition to the SCADA data, for example Ziegler et al[12] developed a strain-based load extrapolation algorithm for lifetime extension of offshore wind monopiles, and Mai et al[13] predicts the remaining fatigue life of welded joints in wind turbine support structures by using strain measurement and oceanographic data. Other researchers propose ways to increase the lifetime by changing the control. Zhang et al[14] find the optimal power dispatch in a wind farm with life extension of the wind turbine blades as target. Pettas & Cheng[15] propose down-regulation and individual blade control as lifetime extension enablers, and Natarajan & Pedersen[16] propose curtailment in conditions with high loads to increase the lifetime.

Even if it can be shown to be sufficiently safe to operate for an extended life, the profitability is not guaranteed and requires analysis[17]. Often there is no debt in the wind farms, unless the wind farm is bought recently from another owner. But because there are generally no subsidies for life extension and continued operation, the electricity must be sold on the spot market, giving less income. The expenses to land rental and maintenance could be unchanged or even increasing, and with less revenue the profit margins can be narrow. Rubert et al[18] developed a tool to assist with economic assessment, and showed how the profitability would depend on the amount of required refurbishments. It was assumed that the analytical analyses would show life extension to be sufficiently safe. Nielsen et al[19] presented a method for optimal decision making for life extension for wind turbines, by including the probability that a structural analysis would not find sufficient remaining fatigue life.

While the need for and feasibility of analytical assessments are agreed upon for large assets such as offshore wind farms, the opinions are more diverse for smaller wind turbines.[20] Here, extra expenses to analytical assessments or additional inspections in the extended life could be the tipping factor making life extension infeasible. If sufficient reliability could instead be verified in a generic manner, this could reduce the economic burden on owners on smaller assets. This would facilitate sustainable decisions, and keep sites in operation for a longer time, if repowering is not possible.

A generic verification method would imply that turbines fulfilling certain requirements would not need other verifications of the reliability. An approach for setting up such requirements is to go to higher level analyses than the semi-probabilistic method used in the design standard IEC61400-1[21]. The semi-probabilistic method is the lowest level of analysis outlined in ISO2394[22]. The higher level methods of decision making are the probabilistic approach and the risk-informed approach. In the probabilistic approach, probabilistic models of loads and resistances are used to estimate the reliability using structural reliability methods, and this is compared to the target reliability. The probabilistic approach can be applied to calibrate partial safety factors for use in the semi-probabilistic approach for life extension. The target reliability can be set using the risk-informed approach, where all costs and utilities are considered directly and are combined with their probability of occurrence. Here, economic optimization is performed, so that the reliability is balanced against the consequences of failure and the relative cost of safety measures (costs of improving safety). Fatalities and indirect costs should be included here. The optimal decision is chosen as the one with highest utility. The risk-based approach can be used to find optimal target reliabilities, for direct calibration of partial safety factors[23], or for use on a case to case basis.

The partial safety factors for new wind turbines in IEC61400-1 ed. 4[21] was derived using the probabilistic approach to result in a component annual probability of failure of $5 \cdot 10^{-4}$. This target reliability level was found based on economic optimization, considering the relative risk of failure and the relative costs of increasing the reliability[24]. In standards for existing structures it is often accepted to use lower target reliabilities than for new structures, because the costs of increasing the reliability is higher for existing structures, and it would lead to uneconomic and unsustainable decisions to require the same reliability level.[25–27]

The probabilistic approach for verification of sufficient reliability for life extension is included in both the Dutch standard NPR 8400[28] and the DNV GL standard[5] on lifetime extension and continued operation for wind turbines. The standards mention selection of target reliability level as the first step is the reliability analysis, but gives no guidance on selection of target reliabilities. The UL4143 standard[29] on life extension consider uncertainties, but in a semi-quantitative way without making a probabilistic analysis. Steenbergen and Vrouwenvelder[30] found lifetime reliability targets for existing structures by considering the costs in the remaining lifetime for upgrading or no upgrading, considering the remaining service life to be fixed. In decision making for continued operation or life extension for wind turbines, the remaining service life is not fixed; instead it can be considered as a decision variable constrained by the general turbine condition etc.

For new wind turbines the target reliability level used for calibrating partial safety factors is primarily obtained based on economic optimization balancing the initial material (CAPEX) costs versus the costs of failure and repairs/maintenance (OPEX) during the planned design life. The target reliability level is also important for financing and insurance of the wind turbine, i.e. the associated costs are to be included in the economic optimization.

When the life extension decision is made, the target reliability level is to be determined using a different cost profile with increased relative costs for safety measures, which often implies that a lower reliability level can be accepted.

In the present study, risk-based and probabilistic methods will be applied to derive recommendations for reliability levels for continued operation and life extension for wind turbines.

- For small wind turbines, requirements for extra inspections and computations can make continued operation infeasible. Is it feasible to accept the increased failure probability, without making requirements for any extra inspections or analyses?
- For large wind turbines there is a need for rational consideration of the risk of failure when making end-of-life decisions. Use of the semi-probabilistic methods with the target reliability level required for new wind turbines does not necessarily lead to economically optimal decisions. Thus there is a need for rules based on Risk-informed approaches, directly or via probabilistic or semi-probabilistic methods

First the economic optimization background for the reliability levels for new turbines will be presented, and using the same approach, the optimization problem will be set up for existing wind turbines. A generic cost model will be set up, and the results will be presented and discussed, and the conclusions and recommendations for standardization will be given.

## 2. Optimal reliability for new structures

For new structures, the general standard for reliability of structures ISO2394[22] recommends to use economic optimization to derive optimal target reliabilities. In case there is a risk of fatalities in case of structural failure, minimum acceptable reliabilities can be found using the marginal lifesaving cost principle. As wind turbines are generally erected in remote locations, the risk to human lives can be neglected[24]. The approach for economic optimization for new structures was considered by Rackwitz[31], and in Table 1 the derived target reliabilities are given. The background for the table was elaborated by Fischer et al[32], and will be summarized in the following to serve as background for the reader.

| Relative cost of safety measure | Consequence of failure | | |
|---|---|---|---|
| | Minor | Moderate | Large |
| Large (A) | $\beta = 3.1$ ($P_f \approx 10^{-3}$) | $\beta = 3.3$ ($P_f \approx 5 \cdot 10^{-4}$) | $\beta = 3.7$ ($P_f \approx 10^{-4}$) |
| Normal (B) | $\beta = 3.7$ ($P_f \approx 10^{-4}$) | $\beta = 4.2$ ($P_f \approx 10^{-5}$) | $\beta = 4.4$ ($P_f \approx 5 \cdot 10^{-6}$) |
| Small (C) | $\beta = 4.2$ ($P_f \approx 10^{-5}$) | $\beta = 4.4$ ($P_f \approx 5 \cdot 10^{-6}$) | $\beta = 4.7$ ($P_f \approx 10^{-6}$) |

*Table 1. Optimal annual target reliabilities, $\beta$ and annual failure probabilities, $P_f$ in [1,22] found using economic optimization.*

As decisions are made for a fleet of structures in relation to standardization, systematic reconstruction after failure and obsolescence is assumed, i.e. it is assumed that it is possible to erect new wind turbines at the site. Failure events and obsolescence events are assumed to occur randomly in time with rates $\lambda$ and $\omega$. Only costs to construction, obsolescence and failure are included, as the other costs are assumed independent of the decision variables $\boldsymbol{p}$ which determine the reliability level. For new structures, the decision variables could be variables related to the geometry of the structure, cross sectional parameters, material strengths, and for existing structures it could be related to various options for strengthening the structure. For repairable and exchangeable components, the O&M costs would depend on the reliability, but for structural components as considered here, the O&M costs are assumed independent of the decision variables. The optimal values of the decision variables $\boldsymbol{p}$ are found by maximizing the net present value of the benefit minus the costs for an infinite time horizon:

$$\boldsymbol{p}^* = \arg\max_{\boldsymbol{p}}\{Z(\boldsymbol{p})\} \tag{1}$$

$$Z(\boldsymbol{p}) = B(\boldsymbol{p}) - C(\boldsymbol{p}) - A(\boldsymbol{p}) - D(\boldsymbol{p}) \tag{2}$$

where expected present values are used for:

- $B(\boldsymbol{p})$: benefit from existence of structure
- $C(\boldsymbol{p})$: construction cost
- $A(\boldsymbol{p})$: obsolescence cost
- $D(\boldsymbol{p})$: failure cost

The benefits from the existence of the structure are assumed independent of $\boldsymbol{p}$, thus $B(\boldsymbol{p}) = B$. That is, the production of energy is not affected by the reliability level of the structural components. Therefore, the benefit needs not to be considered in the analysis, and instead the minimum of the expected net present value of the costs is found, thus the objective function becomes:

$$T(\boldsymbol{p}) = C(\boldsymbol{p}) + A(\boldsymbol{p}) + D(\boldsymbol{p}) \tag{3}$$

Costs occurring in the future should be discounted. Continuous discounting is performed by multiplication by $\exp(-\gamma t)$, where $\gamma$ is the interest rate.[31] The cost of first construction $C(\boldsymbol{p})$ occur at time zero, and should not be discounted. The expected present value of the obsolescence costs $A(\boldsymbol{p})$ is calculated from additional reconstructions occurring with constant obsolescence rate $\omega$:

$$A(\boldsymbol{p}) = \int_0^\infty \exp(-\gamma t) \cdot \omega \cdot C(\boldsymbol{p}) dt = C(\boldsymbol{p}) \frac{\omega}{\gamma} \tag{4}$$

The expected present value of the failure costs $D(\boldsymbol{p})$ is found by assuming a constant failure rate $\lambda(\boldsymbol{p})$, and by accounting for additional failure costs $H$ in addition to the reconstruction costs:

$$D(\boldsymbol{p}) = \int_0^\infty \exp(-\gamma t) \cdot \lambda(\boldsymbol{p}) \cdot (C(\boldsymbol{p}) + H)dt = (C(\boldsymbol{p}) + H)\frac{\lambda(\boldsymbol{p})}{\gamma} \tag{5}$$

The present value of the total costs are then:

$$T(\boldsymbol{p}) = C(\boldsymbol{p}) + C(\boldsymbol{p})\frac{\omega}{\gamma} + (C(\boldsymbol{p}) + H)\frac{\lambda(\boldsymbol{p})}{\gamma} \tag{6}$$

A single decision parameter $p$ is defined as the central safety factor between the expected values of resistance $R$ and load effect $S$:

$$p = \frac{E[R]}{E[S]} \tag{7}$$

The construction costs are assumed to be comprised by a term proportional to $p$, and a constant term:

$$C(p) = C_0 + C_1 p \tag{8}$$

The failure rate $\lambda(p)$ is estimated as the annual probability of failure, $P_f(p)$, which can be found using structural reliability methods for known distributions for resistance and annual maximum load effect:

$$\lambda(p) \approx P_f(p) = P[R - S < 0] \tag{9}$$

The total expected present value of the costs can be written as:

$$T(p) = (C_0 + C_1 p)\left(1 + \frac{\omega}{\gamma}\right) + (C_0 + C_1 p + H)\frac{P_f(p)}{\gamma} \tag{10}$$

Then, the optimal target annual reliability $\beta^*$ is found from minimizing *T(p)* wrt. *p:*

$$p^* = \arg\min_p\{T(p)\} = \arg\min_p\left\{(C_0 + C_1 p)\left(1 + \frac{\omega}{\gamma}\right) + (C_0 + C_1 p + H)\frac{P_f(p)}{\gamma}\right\} \tag{11}$$

$$\beta^* = -\Phi^{-1}\left(P_f(p^*)\right) \tag{12}$$

In Fischer et al[32], the optimal reliabilities are found for ranges of the relative marginal safety costs $C_1/C_0$ and relative failure consequences $H/C_0$:

$C_1/C_0$: relative cost of safety measure:

A. Large: $10^{-2} \le \frac{C_1}{C_0} \le 10^{-1}$
B. Normal: $10^{-3} \le \frac{C_1}{C_0} \le 10^{-2}$
C. Small: $10^{-4} \le \frac{C_1}{C_0} \le 10^{-3}$

$H/C_0 \approx \rho - 1$ : relative failure consequences

1. Minor: $\rho < 2$: $H/C_0 \leq 1$
2. Moderate: $2 \leq \rho \leq 5$: $1 \leq H/C_0 \leq 4$
3. Large: $5 \leq \rho \leq 10$: $4 \leq H/C_0 \leq 9$

Additionally, the optimal reliabilities depends on obsolescence rate $\omega$, interest rate $\gamma$, and distribution types and coefficient of variation for resistance and load effect through $P_f(p) = P[R - S < 0]$. Table 1 can be obtained using $\omega = 0.02$, $\gamma = 0.03$, and lognormal distributions for R and S with coefficient of variation equal to 0.3.

On the basis of Table 1 it can be argued that a lower reliability is sufficient for existing structures, as the relative costs of improving safety is higher. However, for decision making for life extension for wind turbines many of the conditions are different compared to the standard assumptions given here, and in the following the optimization problem is set up for this specific problem.

# 3. Economic optimization for life extension

In decision making for continued operation and life extension for wind turbines, the decision parameters would be different than for design, where the central safety factor between resistance and load is used. For end-of-life decisions, there are generally three different actions: 1) continued operation, 2) life extension (refurbishment of the structure to reach a target reliability level), or 3) decommission. Additional decisions can be made to obtain information: perform inspections or monitoring, or make analyses of existing data e.g. SCADA data. For some components, the marginal costs of improving the reliability could be very large and therefore make life extension infeasible. In this situation, the actual choices would be to accept the actual, low reliability of structural components or to decommission the turbine. The optimal decision is to decommission, if the expected profit is found insufficient, when the risks related to a structural failure is included in the assessment. The calculations are performed with a finite life corresponding to the extended life, and therefore obsolescence costs due to future reconstructions are not included here. The benefits would depend on the decision, and need to be included, and the objective function is the net present value of the profit; i.e. the net present value of the benefits minus the costs:

$$Z(\boldsymbol{p}) = B(\boldsymbol{p}) - C_{ext}(\boldsymbol{p}) - OM(\boldsymbol{p}) - D(\boldsymbol{p}) \qquad (13)$$

With the following expected present values of:

- $B(\boldsymbol{p})$: benefit (income from power production)
- $C_{ext}(\boldsymbol{p})$: life extension cost
- $OM(\boldsymbol{p})$: costs of operations, SHM, inspections, maintenance
- $D(\boldsymbol{p})$: cost of structural failure

The feasibility of life extension will typically be assessed considering only the first three terms, thus disregarding the risk of structural failure, although an insurance covering the loss could be included in the operational costs. In order to limit the risk of structural failure, a constraint on the annual probability of failure is used. In the following, we aim to find the optimal constraint, by including directly the costs related to a structural failure in the feasibility assessment. In case of a structural failure, the business case can be threatened by three contributions: the direct consequences of failure, the loss of benefit from power production after failure, and due to fixed operational costs that have to be paid also after failure in the remaining planned extended life.

The vector of decision variables $\boldsymbol{p}$ could include parameters for decisions on refurbishments, decisions on maintenance and control, and the length of the extended life. Here the focus is on the reliability of structural components. As the reliability decrease with time, the length of the life extension period $T_{ext}$ is included as decision variable. Additionally, the reliability depends on the initial design, represented by the design variable *z*.

The life extension costs $C_{ext}$ are the costs of analyses and refurbishments necessary for life extension. The costs of life extension could depend on the planned life extension period. As the life extension costs occur at the time where life extension starts (denoted time zero), this term is simply $C_{ext}(T_{ext})$. The other costs are distributed in the extended life, and should be discounted with discount factor $\gamma$.

The annual benefits are denoted $c_B(t)$. In case of failure, the benefit will discontinue, and the expected present value of the benefits is calculated as:

$$B(T_{ext};z) = \int_0^{T_{ext}} \int_0^{t} \exp(-\gamma\tau)\ c_B(\tau)\, d\tau\, f_T(t;z)\, dt + \int_0^{T_{ext}} \exp(-\gamma t)\ c_B(t)\, dt\ \big(1 - F_T(T_{ext};z)\big) \quad (14)$$

where $f_T(t;z)$ is the probability density function of the time to failure, and $F_T(t;z)$ is the cumulative distribution function for the time to failure, both conditioned on survival up until the end of the design life (time zero). The distributions depend on the design parameter *z*. The first term calculates the expected benefits in case failure happens in the extended life, and the second term calculates the expected benefits in case there is no structural failure in the extended life.

For the O&M costs that will discontinue in case of failure, the expected present value is found in a similar way, with annual O&M costs $c_{OM1}$:

$$OM_1(T_{ext};z) = \int_0^{T_{ext}} \int_0^{t} \exp(-\gamma\tau)\ c_{OM1}(\tau)\, d\tau\, f_T(t;z)\, dt + \int_0^{T_{ext}} \exp(-\gamma t)\ c_{OM1}(t)\, dt\ \big(1 - F_T(T_{ext};z)\big) \quad (15)$$

For O&M costs $c_{OM2}(t)$ that will continue for the duration of the planned extended life also in case of failure, the expected present value is found as:

$$OM_2(T_{ext}) = \int_0^{T_{ext}} \exp(-\gamma t)\ c_{OM2}(t)\, dt \quad (16)$$

The expected present value of the failure costs are:

$$D(T_{ext};z) = \int_0^{T_{ext}} \exp(-\gamma t)\, H(t)\, f_T(t;z)\, dt \quad (17)$$

where the monetary value of the failure consequences are $H$. These should include all consequences in relation to a structural failure, both economic losses and other consequences for the owner.

The expected present value of the profit is a function of the life extension period and the design parameter, and can be written as:

$$Z(T_{ext};z) = B(T_{ext};z) - C_{ext}(T_{ext}) - OM_1(T_{ext};z) - OM_2(T_{ext}) - D(T_{ext};z) \quad (18)$$

It depends on the costs, the interest rate $\gamma$, and the probability density function for the time to failure $f_T(t;z)$. Assuming that failure can be modelled by a fatigue accumulation model the distribution function for the time to failure can be calculated from a probabilistic fatigue SN model using structural reliability methods, and should be conditioned on survival in the original design life.

## 3.1 Probabilistic SN model for fatigue failure

The probabilistic SN model presented here is based on the model applied for the calibration of the partial safety factors for welded steel details in IEC61400-1 ed. 4[21] as presented in Sørensen and Toft[24]. The probabilistic model is based on bilinear SN curves in combination with Miners rule for linear damage accumulation. The stress cycles for a specific mean wind speed and turbulence intensity are assumed Weibull distributed with standard deviation proportional to the wind turbulence standard deviation, and the joint distribution of wind speed and turbulence is used to find the stress range distribution.

The number of cycles *N* to failure for constant amplitude loading with stress range $\Delta\sigma$ is for a bi-linear SN curve with slope change from $m_1 = 3$ to $m_2 = 5$ at $N_D = 5 \cdot 10^6$ given by:

$$N = K_1\, \Delta\sigma^{-m_1} \text{ for } \Delta\sigma \geq \Delta\sigma_D \quad (19)$$

$$N = K_2\, \Delta\sigma^{-m_2} \text{ for } \Delta\sigma < \Delta\sigma_D \quad (20)$$

The mean value of the SN curve parameter $K_1$ can be found from the fatigue strength $\Delta\sigma_F =$ 71 MPa at $N_F = 2 \cdot 10^6$ cycles using eq. 19. Then $\Delta\sigma_D$ can be found using eq. 19, and finally the mean value of $K_2$ is found using eq. 20.

Using Miners rule, the limit state equation for fatigue failure before time *t* is written as:

$$g(z,t) = \boldsymbol{\Delta} - \nu \cdot t \left( \frac{(\boldsymbol{X_{Wind}} \boldsymbol{X_{SCF}})^{m_1}}{\boldsymbol{K_1}} D_{BL1,tot}(z) + \frac{(\boldsymbol{X_{Wind}} \boldsymbol{X_{SCF}})^{m_2}}{\boldsymbol{K_2}} D_{BL2,tot}(z) \right) \quad (21)$$

where

- $\boldsymbol{\Delta}$ is the model uncertainty related to the use of Miners rule for damage accumulation.
- $\nu = 10^7$ is the number of load cycles per year.
- $\boldsymbol{X_{Wind}}$ and $\boldsymbol{X_{SCF}}$ are the model uncertainty of the wind load and stress concentration factor respectively.
- $D_{BL1,tot}(z)$ and $D_{BL2,tot}(z)$ are the mean values of $s^m$ for each part of the SN curve divided by the proportion of cycles on the respective parts of the curve. These are calculated by:

- $D_{BL1,tot}(z) = \int_{U_{in}}^{U_{out}} \int_0^\infty D_{BL1}(U, \sigma_u, z)\, f_{\sigma_u}(\sigma_u \,|\, U) f_U(U) d\sigma_u dU$

- $D_{BL2,tot}(z) = \int_{U_{in}}^{U_{out}} \int_0^{\infty} D_{BL2}(U, \sigma_u, z)\, f_{\sigma_u}(\sigma_u \mid U) f_U(U) d\sigma_u dU$

where

- $f_U(U)$ is the Weibull probability density function for the mean wind speed with assumed shape parameter $k = 2.3$ and scale parameter $A = 9.0$ m/s. [24]
- $f_{\sigma_u}(\sigma_u \mid U)$ is the lognormal density function for the standard deviation of turbulence modelled with a standard deviation equal to $\sigma_{\sigma_u} = I_{ref} \cdot 1.4$ [m/s], with turbulence intensity $I_{ref} = 0.14$ and mean value $\mu_{\sigma_u} = I_{ref}(0.75\, U + 3.3 \text{ m/s})$. [24]
- $D_{BL1}(U, \sigma_u)$ and $D_{BL2}(U, \sigma_u)$ are found from:

$$D_{BL1}(U, \sigma_u, z) = \int_{\Delta\sigma_D}^{\infty} s^{m_1} f_{\Delta\sigma}\big(s \big| \sigma_{\Delta\sigma}(U, \sigma_u, z)\big) ds \quad (22)$$

$$D_{BL2}(U, \sigma_u, z) = \int_0^{\Delta\sigma_D} s^{m_2} f_{\Delta\sigma}\big(s \big| \sigma_{\Delta\sigma}(U, \sigma_u, z)\big) ds \quad (23)$$

where $f_{\Delta\sigma}$ is the Weibull density function for stress ranges with shape parameter assumed to be 0.8 and standard deviation $\sigma_{\Delta\sigma}(U, \sigma_u)$ proportional to the wind turbulence: [24]

$$\sigma_{\Delta\sigma}(U, \sigma_u, z) = \alpha_{\Delta\sigma}(U) \frac{\sigma_u(U)}{z} \quad (24)$$

Here, $z$ is a design parameter (proportional to a cross sectional parameter). 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[24].

Although both the mean wind speed, turbulence standard deviation, and stress ranges are modeled by their distributions, integration is performed over these to get the contributions to fatigue damage, and only the five stochastic variables given in Table 2 are to be treated as stochastic variables in the reliability analysis. The coefficient of variation of the product $\boldsymbol{X_{Wind} X_{SCF}}$ is set to the typical value $COV_{\text{load}} = \sqrt{COV_{\text{Wind}}^2 + COV_{\text{SCF}}^2} = 0.2$ in accordance with Sørensen and Toft[24].

| Variable | Distribution | Expected value | Standard deviation / Coefficient of variation |
|---|---|---|---|
| $\boldsymbol{\Delta}$ | Normal | 1 | $COV_{\Delta} = 0.3$ |
| $\mathbf{X_{Wind}}$ | Lognormal | 1 | $COV_{\text{Wind}}$ |
| $\mathbf{X_{SCF}}$ | Lognormal | 1 | $COV_{\text{SCF}}$ |
| $\boldsymbol{\log K_1}$ | Normal | Found from $\Delta\sigma_F$ | $\sigma_{\log K_1} = 0.2$ |
| $\boldsymbol{\log K_2}$ | Normal | Found from $\Delta\sigma_F$ | $\sigma_{\log K_2} = 0.2$ |
| $\log K_1$ and $\log K_2$ are fully correlated. | | | |

*Table 2. Stochastic model.*

The annual probability of failure in year *t* given survival up to time *t* is found as:

$$\Delta P_{F,t} = \frac{P(g(z,t) \leq 0) - P(g(z,t-1) \leq 0)}{P(g(z,t-1) > 0)} \tag{25}$$

In the design situation, the optimal value of *z* is found such that the annual probability of failure at the end of the design life reach the target value for new components $\Delta P_F = 5 \cdot 10^{-4}$ $(\beta = 3.3)$. Structural reliability methods can be applied to evaluate the reliability based on the limit state equation (21). Crude Monte Carlo simulations have been used with $10^8$ simulations. The annual probability of failure is shown in Figure 1 for a component designed for a lifetime of 20 years. It is noted that the probability of failure is increasing almost linearly, and will reach a value twice as high as the target value for new turbines after 35 years. Therefore, increasing the target reliability for life extension to $\Delta P_F = 10^{-3}$ $(\beta = 3.1)$ could allow for approximately 15 additional years of operation without further efforts to verify fatigue life.

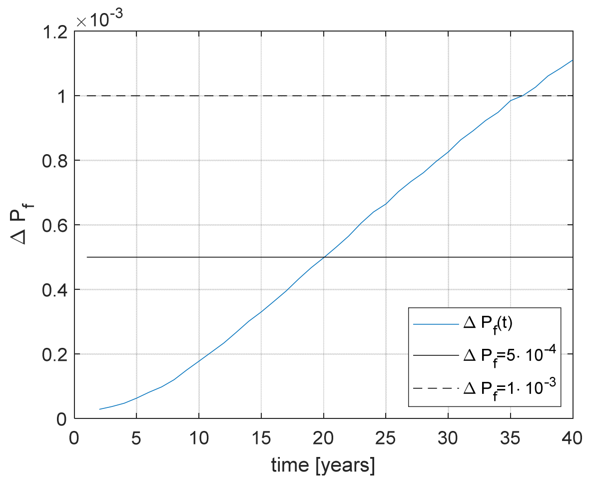



*Figure 1. Annual probability of failure as function of time for a component designed to have a probability of failure equal to the limit.*

# 4. Decision making for a generic life extension project

In this section, economic optimization will be applied on a generic life extension project, assuming that the structure is designed according to current codes to reach the target reliability at the end of the original lifetime of 20 years. The probabilistic model presented in Section 3.1 is applied in the reliability analysis, and a generic cost model is set up.

## 4.1 Cost model

For a specific case, the benefits and costs to be included in the model presented in Section 3 are:

- $c_B(t)$: Expected annual benefit – depends on expected power production and expected selling price of electricity
- $C_{ext}$: Costs of life extension (life extension CAPEX), e.g. costs of analyses, inspection and component exchanges
- $c_{OM1}(t)$: Annual OPEX in extended life that will discontinue in case of failure, e.g. direct variable maintenance costs to spare parts etc.

- $c_{OM2}(t)$: Annual OPEX in extended life that will continue in case of failure, e.g. land lease and other fixed expenses
- $H$: Consequence of failure in monetary value

For decision making, the ratio between costs are important, not the absolute value of the costs. For the purpose of generic modelling, the costs are assumed constant with time, and the number of input parameters can therefore be reduced. First, the annual profit $P_a$ (considering annual costs and benefits but excluding life extension costs) is defined by: $P_a = c_B - c_{OM1} - c_{OM2}$, and all costs are the defined relative to $P_a$. The annual profit then appears as a scaling factor, and the expected present value of the profit $Z(T_{ext}; z)$ will scale with this factor. We will require that $P_a$ is positive, as this is a requirement for life extension to be feasible. The values of $T_{ext}$ resulting in maxima and zero crossings for the net present value of the profit are invariant with respect to $P_a$ and therefore optimal values and ranges of feasible values can be determined without defining $P_a$.

The costs to be defined are the costs of life extension, the operational costs that will continue in case of failure, and the consequence of failure. The proportion of operational costs that are fixed $c_{OM2,rel}$ and the consequence of failure $H_{rel}$ are defined directly as a proportion of the annual profit:

$$c_{OM2,rel} = \frac{c_{OM2}}{P_a} \tag{25}$$

$$H_{rel} = \frac{H}{P_a} \tag{26}$$

The costs of life extension could be defined in a similar way. However, as the annual profit is distributed in time, whereas the cost of life extension is not, the annual profit should be discounted for a meaningful comparison, and thus the life extension period and discount rate should also be accounted for when defining $C_{ext}$. Most important is the profit margin or the expected internal rate of return (IRR). The internal rate of return is defined as the discount rate which cause the net present value of all costs and benefits to be equal to zero. Defining the life extension costs through the internal rate of return (not considering the probability of failure) has the advantage that the interest rate need not to be defined as an additional parameter prior to the estimation of utility. Instead, the interest rate will appear as an acceptance criteria; the minimum acceptable internal rate of return, when a reduction of utility due to the probability of failures is considered. Although profit margins for life extension projects are often narrow, the opposite could also be the case. For life extension projects with only minor investments, the IRR could in principle be very high – much higher than the interest rate.

The internal rate of return when failures are not considered is denoted $\gamma_0$, and the cost of life extension is calculated based on this value from:

$$Z_0(T_{ext}) = \int_0^{T_{ext}} P_a \exp(-\gamma_0\, t)\ dt - C_{ext}(T_{ext}) = 0 \Rightarrow \tag{27}$$

$$C_{ext}(T_{ext}) = \int_0^{T_{ext}} P_a \exp(-\gamma_0\, t)\ \ dt = P_a \frac{1}{\gamma_0}(1 - \exp(-\gamma_0\, T_{ext})) \tag{28}$$

With these definitions, the only cost values to be defined are $\gamma_0$, $c_{OM2,rel}$ and $H_{rel}$, and the reduction to these values have been made without loss of generality, if the annual costs are constant with time. Figure 2(a) shows the corresponding life extension costs $C_{ext}$ as function of $\gamma_0$ for various life extension periods. For a rate of return equal to zero, the life extension costs correspond to the sum of the annual profits ($P_a$ times the length of the life extension period). For positive rates of return, corresponding to feasible investments, the costs of life extension is less than the sum of the annual profits. A negative rate of return imply that the investment is infeasible; the costs of life extension is higher than the sum of the annual profit. Generally, a rational investor will not make investments if the internal rate of return is lower than the interest rate.

Figure 2(b) shows the life extension costs per year of life extension $C_{ext}(p)/T_{ext}$ as function of internal rate of return. It is equal to one for an internal rate of return equal to zero for all life extension periods. However, the slope is generally steeper for larger life extension periods. Thus a unit change in rate gives a higher change in cost for a longer life extension period. This relation should be kept in mind when analyzing the results.

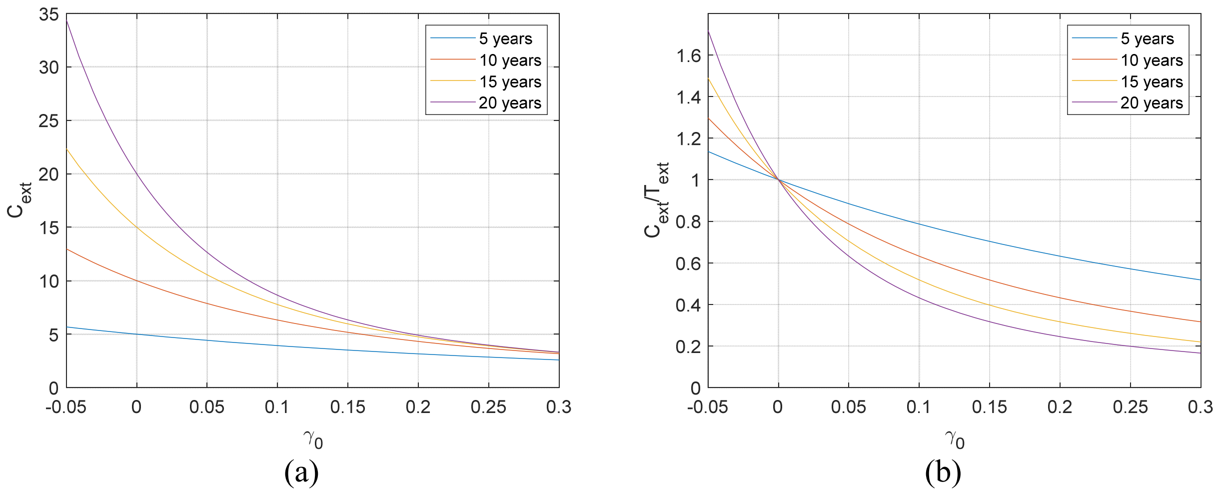



*Figure 2. Costs of life extension (total and per year) as function of internal rate of return for life extension periods $T_{ext}$=5, 10, 15, 20 years for $P_a = 1$.*

## 4.2 Results and discussion

The net present value of the profit when the risk of structural failure is considered, is calculated using equation (18) for life extension periods 5, 10, 15, and 20 years and for various values of the cost parameters. The base case values are set to $\gamma_0 = 0.05$, $c_{OM2,rel} = 1$ and $H_{rel} = 10$, and are discussed in Section 6. Each parameter is varied one at a time, while the others are fixed, and the result are shown in Figure 3(a-c). The net present value of the utility is generally negative because the internal rate of return $\gamma_0$ is applied as the discount rate. This means that the utility will be zero if there is no risk of failure, and the larger the risk, the higher is the negative value of the utility. It is seen that higher reduction of utility happen for longer life extension periods. Changes in cost parameters which give a decrease in utility, give the largest decrease for longer life extension periods. This is due to the costs generally being higher for larger life extension periods, as could be seen in Figure 2(a).

The utility is decreasing linearly with increasing relative failure costs and with increasing relative fixed O&M costs. The most important cost parameter in terms of reduced utility is the internal rate of return. A reduction in internal rate of return gives a decrease in utility, and the rate of change is higher for lower internal rate of return.

Figure 3(d-f) shows the absolute reduction of internal rate of return when failures are included. The reduction is higher for higher initial internal rate of return, but as there is also more “margin to reduce”, a life extension project with a higher initial internal rate of return, will also have a higher “adjusted” internal rate of return. For low internal rates of return (the potentially critical values), the absolute reduction is almost constant for initial internal rate of return between 0 and 0.1. The IRR reductions are generally largest for shorter life extension periods, which might be surprising, as the utility reduction is lowest. However, this can be explained by Figure 2(b): for a shorter life extension period, a larger change in IRR is resulting from the same reduction in annual profit.

The IRR reduction is increasing with increasing relative failure costs and with increasing relative fixed O&M costs. For high relative failure costs, the increase is highest for short life extension periods, whereas long life extension periods become critical for high fixed operational costs compared to the failure costs.

From a decision making perspective, the initial IRR subtracted the IRR reduction should be larger than the interest rate to be profitable. If comparing different projects, the projects with highest IRR should be chosen.

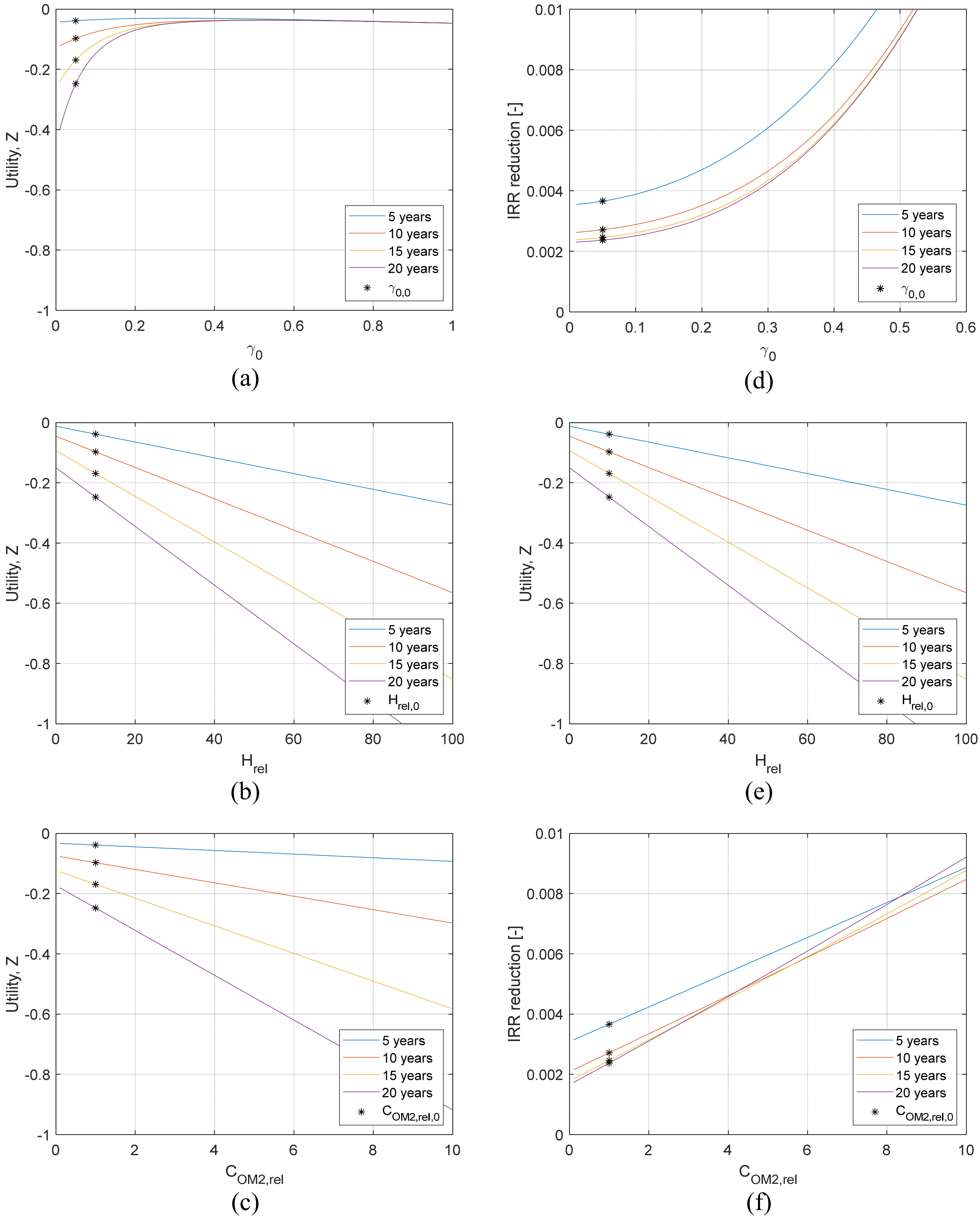



*Figure 3. The net present value of the utility calculated using the internal rate of return (not considering risk of failure) $\gamma_0$ as the discount rate (a-c), and reduction of the internal rate of return due to the risk of structural failure (d-f). Both are shown for various values of internal rate of return $\gamma_0$, proportion of operational costs that are fixed $c_{OM2,rel}$ and the consequence of failure $H_{rel}$. The base case value are marked with stars.*

# 5. Derivation of minimum target reliabilities

The results derived in Section 4 were based on a component designed to the have the required annual reliability level of 3.3 after 20 years of operation, without reliability updating based on inspections. In this section, minimum target reliabilities are derived by requiring that life extension should be feasible; the adjusted internal rate of return should be larger than the interest rate.

The target reliability levels are derived using the following procedure:

1. For a range of values of the design parameter $z$:
    a. The cumulative probability of failure is found as function of time.
    b. The annual reliability index $\beta$ is found as function of time.
    c. The density function and cumulative distribution function for the time to failure given survival in the original design life (20 years) is found.
2. For a range of cost parameters, the net present value of the profit $Z(T_{ext})$ if found using Eq. (18) for life extension period $T_{ext}$.
3. Interpolation is performed to find the value of $z$ resulting in $Z(T_{ext}) = 0$ and the corresponding annual reliability index in the last year of the extended life is found.

## 5.1 Results and discussion

Using the same cost model and base case values as in Section 4, the minimum target reliability levels are calculated and are shown in Figure 4(a-c) for cost parameters varied around the base case value, for interest rate equal to 3%. For increasing failure costs and the fixed operational costs, the minimum reliability index is seen to increase steadily. For failure consequences less than 100 times the annual profit, a minimum reliability of 3.3 is sufficient, and for failure consequences less that 50 time the annual profit, 3.1 is sufficient. The fixed O&M costs can be ten times the annual profit, and still a reliability index of 3.1 is sufficient. For changes in the internal rate of return, an aggressive increase is seen when it gets close to the interest rate. The reason for this is that life extension is always infeasible, when the internal rate of return is smaller than the interest rate. A more generic result can be obtained by plotting the minimum target reliability as function of the difference between the initial internal rate of return and interest rate: $\Delta\gamma = \gamma_0 - \gamma$, which is done in Figure 4(d), for values of $\Delta\gamma$ less than 0.1. If the same figure is made with other values of the interest rate, only very small changes to the figure is seen, and it can be considered valid regardless of the interest rate. This is in line with the observations in Figure 3(d) that the IRR reduction was almost constant for changes in IRR for small values.

It can be concluded that the target reliability depends mainly on the difference between the internal rate of return and interest rate, on the failure costs and on the fixed operational costs. Figure 5 shows the variation with $\Delta\gamma$ for other values of relative failure costs and relative fixed operational costs. It is seen that for a given $\Delta\gamma$, the minimum reliability will increase for increasing relative failure costs and relative fixed operational costs; for the base case values, an annual reliability level of 3.1 is sufficient if the $\Delta\gamma$ is larger than 0.5%. If both costs are twice as high, an annual reliability level of 3.1 is sufficient if the $\Delta\gamma$ is larger than 1%, and a reliability level of 3.3 is needed if $\Delta\gamma$ is between 0.5% and 1%. If the costs are five times as high, an annual reliability level of 3.1 is sufficient if the $\Delta\gamma$ is larger than 2.5%, and a reliability level of 3.3 is needed if $\Delta\gamma$ is between 1.2% and 2.4%.

Regardless of the relative failure costs and relative fixed operational costs, the required reliability becomes very low for $\Delta\gamma$ higher that 5%. For continued operation without any component exchanges, the life extension costs are comprised of costs of analyses and inspections alone, and high internal return rates could be seen. However, even if an economic assessment concludes that very low reliabilities are acceptable, this might still be unacceptable for other reasons.

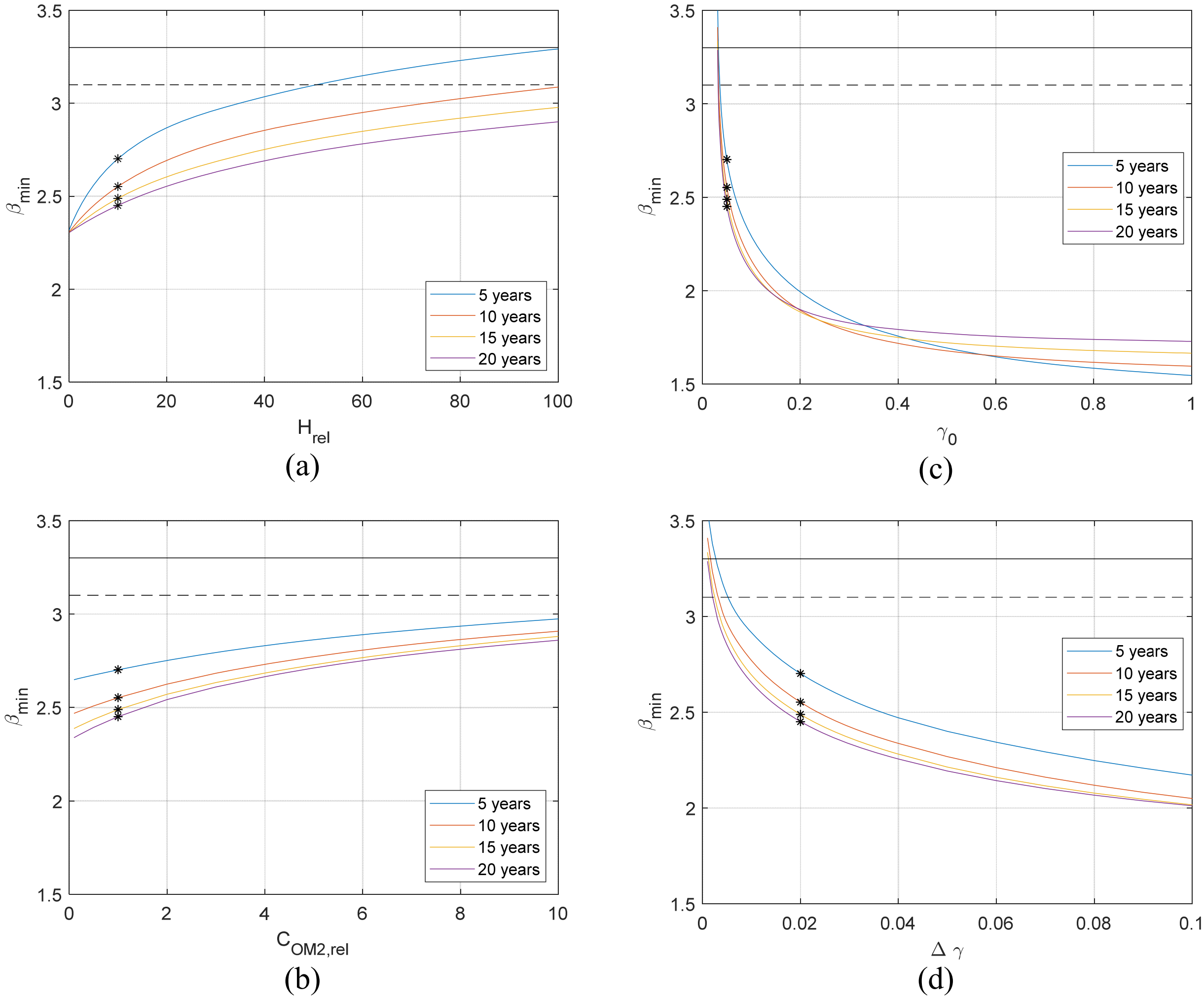
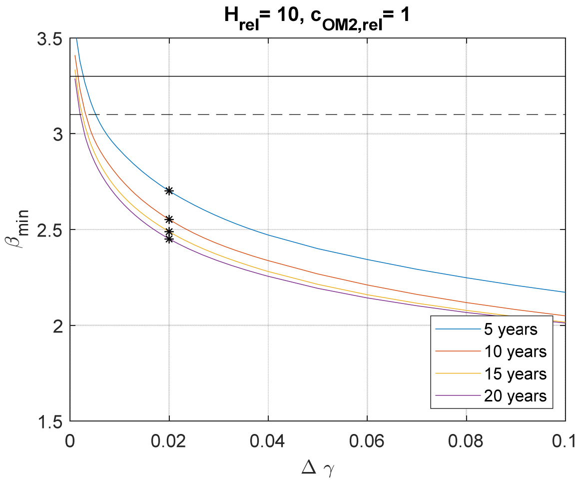
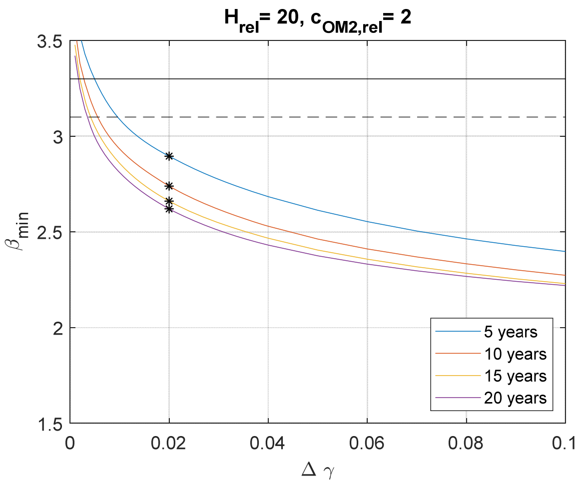


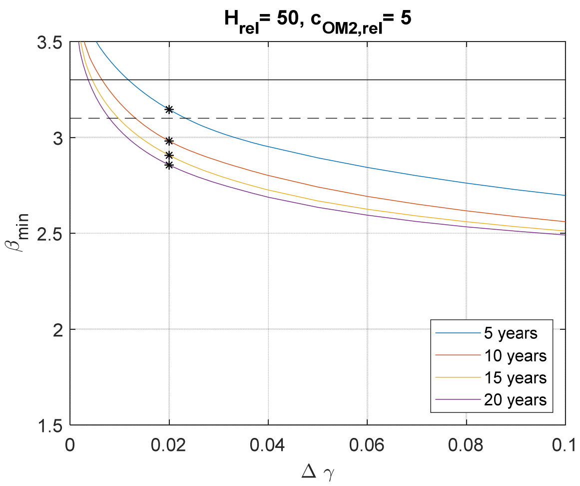

*Figure 4. Minimum target reliabilities for life extension. The horizontal black lines correspond to reliability indices 3.3 (full) and 3.1 (dashed). The base case value are marked with stars.*




(a)




(b)




(c)

*Figure 5. Minimum target reliabilities for life extension as function of $\Delta\gamma$ for values of relative failure costs $H_{rel} = 10, 20, 50$ and relative fixed operational costs $c_{OM2,rel} = 1, 2, 5$. The horizontal black lines correspond to reliability indices 3.3 (full) and 3.1 (dashed). The reliability indices for the base case value of $\Delta\gamma$ are marked with stars.*

## 6. Discussion and conclusions

The aim of this paper was to evaluate if the target reliability levels for existing wind turbines could be reduced compared to the target for new wind turbines. The analysis only considers wind turbines located in remote areas, where the probability of personal injury or fatality in case of a structural failure is negligible. This is in line with the assumptions behind the reliability target for new wind turbines in the design standard IEC61400-1 ed. 4[21]. For wind turbines located close to buildings or infrastructural facilities, a separate risk assessment should be performed.

The risks to be considered are the economic consequences for the owner, and also consequences for the society such as loss of reputation, pollution, and lack of energy production capacity. For collapse of wind turbines, there can be a lack of reputation for the owner, if is it a large developer, but also for the wind industry in general. The societal consequences should set a lower level for the acceptable reliability. If the reliability level is decreased from $\beta = 3.3$ ($\Delta P_F = 5 \cdot 10^{-4}$) to $\beta = 3.1$ ($\Delta P_F = 10^{-3}$), this alone could increase the fatigue life by around 75% (from 20 years to 35 years), as shown in Figure 1. As the probability of failure is increasing approximately linearly with time, it would lead to a factor two increase in the number of collapses seen over the fleet of wind turbines, which is within the same order of magnitude and should not lead to a loss of reputation.

While the economic consequences in case of failure are large for new assets where the expected revenue is relied on to pay back the investment, they can be much smaller in decisions on life extension or continued operation, where the alternative is to decommission the wind turbines. The risk of structural failure could be critical for the feasibility of a life extension project if the direct relative consequence of failure are high, if the relative fixed operational costs are high, or if the life extension costs are so high that the internal rate of return is close to the interest rate. The value of these could be evaluated on a project to project basis. Rubert et. al[18] showed that the feasibility (and thereby internal rate of return) of life extension heavily depends on the amount of refurbishments necessary. From their data a value of the relative fixed operational costs of around one can be derived for the base case and around two for the most pessimistic case. Thus these values are in line with the range of values used here. For the direct costs of failure, a base case value of ten times the annual benefit was used. These costs should reflect the additional costs of decommissioning a failed turbine compared to a normal decommissioning. Reasons for higher expenses are the difficulties in dismantling components, when it is not safe to access the turbine.

In addition to the economic benefit for owners, a main reason for reducing the minimum reliability level to $\beta = 3.1$ ($\Delta P_F = 10^{-3}$) would be the positive consequences for the society in terms of avoidance of unnecessary decommissioning of wind turbines which supports sustainability and sustain energy production capacity. It will become possible to extend the life of more wind turbines, and for smaller wind turbines, where the costs of an analytical assessment will make life extension infeasible, it could even be allowed to extend the life without updated analytical assessments. Larger operators could include the risk of structural failure directly in their economic assessment.

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