PROBABILISTIC AND RISK-BASED FATIGUE REASSESSMENT FOR WIND TURBINE TOWERS

DECOM TOOLS CONFERENCE 9/2-2021

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Task 42: Lifetime Extension Assessment

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About the speaker

Jannie Sønderkær Nielsen, Associate professor, Risk & Reliability research group, Department of the Build Environment, Aalborg University, Denmark

- Participation in various national and EU projects on O&M, life extension and probabilistic design such as: REL-OWT, NORCOWE, LEANWIND, MANTIS, LIFEWIND, CORTIR, PROBWIND, COST Action TU1402, IEAWIND T42, IEAWIND T43
- IEC Committee Member: TC 88/PT 61400-9
- JCSS member (Joint Committee on Structural Safety)

Mission

Increase the sustainability and decrease risks associated with wind farm projects ensuring resilient renewable energy supply by providing risk-informed decision support through the lifecycle considering planning, design, installation, operation, and decommissioning.

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Decision scenario

- A wind farm has been operating for the planned life of 20-25 years
  - Options:
    - Continue operation
    - Life extension
    - Repowering
    - Decommision

- Does the tower and substructure have sufficient fatigue life?

Deterministic fatigue reassessment

- Application of updated data compared to design
  - Loads analysis
  - Operational analysis

- Deterministic design equation for fatigue failure (bi-linear SN curve)
  - $G(z,t) = 1 - \nu \cdot t \left(\frac{(\gamma_f \gamma_m)^{m_1}}{K_{1,C}} D_{BL1,tot}(z) + \frac{(\gamma_f \gamma_m)^{m_2}}{K_{2,C}} D_{BL2,tot}(z) \right)$
  - D_{BL}: Fatigue damage (mean of $\Delta\sigma^m$) estimated based on distribution of wind speed and 90% quantile of turbulence (hidden safety)

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Methods for decision making structures

- ISO 2394:2015 General principles for reliability of structures

Risk-informed decision making	• Used to derive optimal target reliability for reliability-based methods
Reliability-based decision making	• Used to calibrate safety factors for semi-probabilistic method
Semi-probabilistic method	• Used for design (also referred to as deterministic design)

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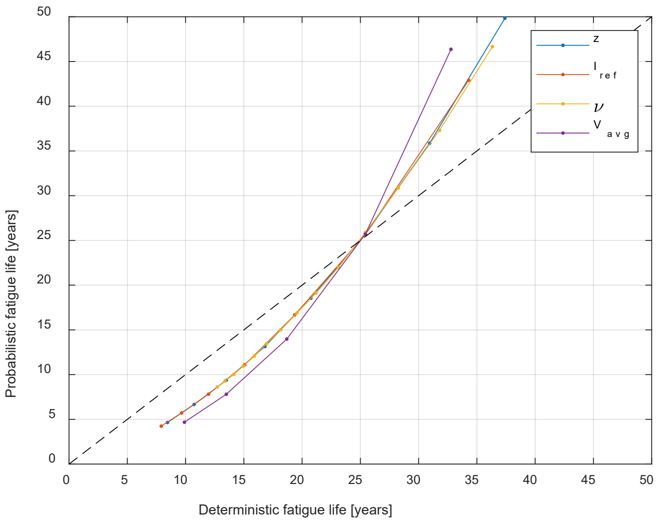
Probabilistic assessment

- Probabilistic limit state equation for fatigue failure (bi-linear SN curve)
  - $g(z,t) = \Delta - \nu \cdot t \left(\frac{(X_{load})^{m_1}}{K_1} D_{BL1,tot}(z) + \frac{(X_{load})^{m_2}}{K_2} D_{BL2,tot}(z) \right)$
- Fatigue damage calculated based on joint distribution of wind speed and turbulence
- Was used to calibrate partial safety factors for deterministic method
  - $G(z,t) = 1 - \nu \cdot t \left(\frac{(\gamma_f \gamma_m)^{m_1}}{K_{1,C}} D_{BL1,tot}(z) + \frac{(\gamma_f \gamma_m)^{m_2}}{K_{2,C}} D_{BL2,tot}(z) \right)$
- The deterministic method is a simplification of the probabilistic

Probabilistic assessment – Example

- Assumptions
  - Model used for calibration of partial safety factors
  - Surrogate used for loads analyses
  - Starting point – design lifetime 25 years
    - $V_{avg} = 8 \text{ m/s}$
    - $I_{ref} = 14\%$

- Result
  - Probabilistic model leads to longer fatigue lives



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Target reliability

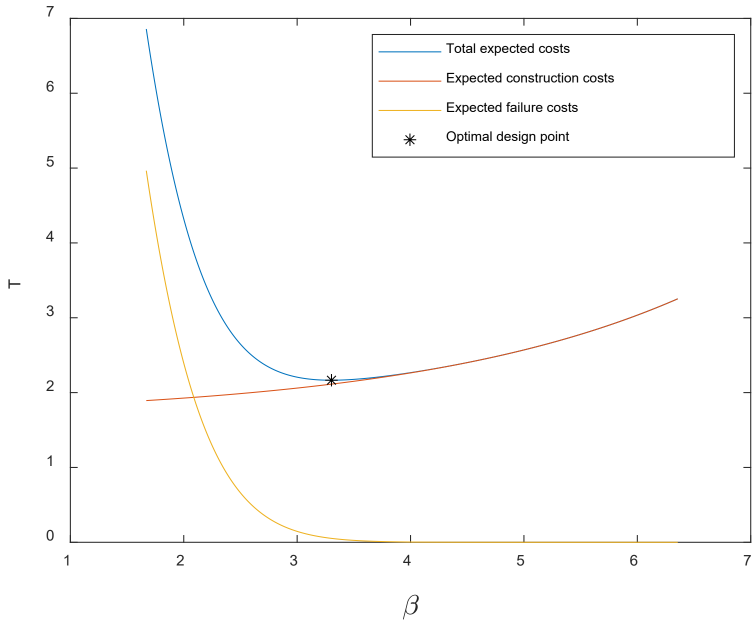
- Target reliabilities for new wind turbines
  - IEC61400-1 ed.4: $\beta = 3.3 \left(P_f = 5 \cdot 10^{-4}\right)$
- Based on table in ISO2394, derived based on risk-based method, economic optimization (maximize benefit - costs) considering:
  - Consequence of failure
  - Relative cost of safety measure

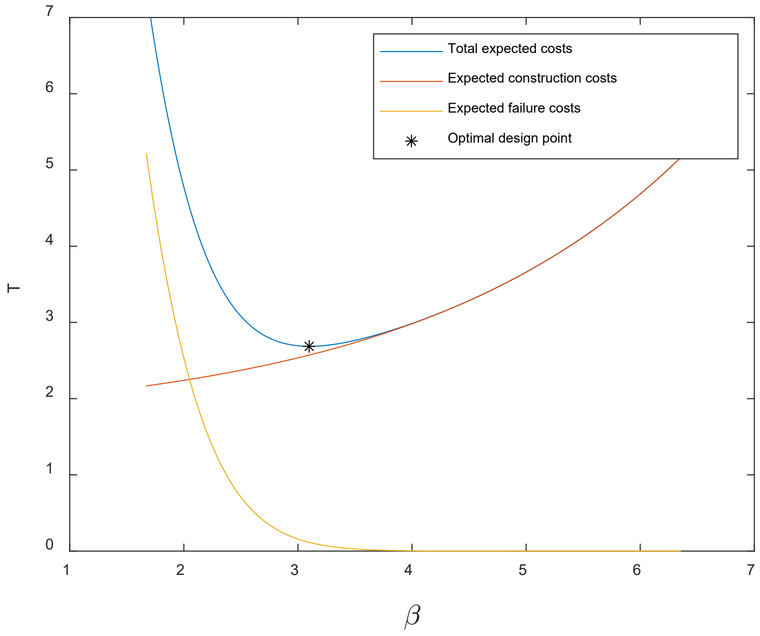
Relative cost of safety measure	Consequences of failure		
	Minor	Moderate	Large
Large (A)	$\beta = 3.1\left(P_f \approx 10^{-3}\right)$	$\beta = 3.3\left(P_f \approx 5 \cdot 10^{-4}\right)$	$\beta = 3.7\left(P_f \approx 10^{-4}\right)$
Normal (B)	$\beta = 3.7\left(P_f \approx 10^{-4}\right)$	$\beta =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

Wind turbines 3.3 (5 10^{-4})

Target reliability for existing structures

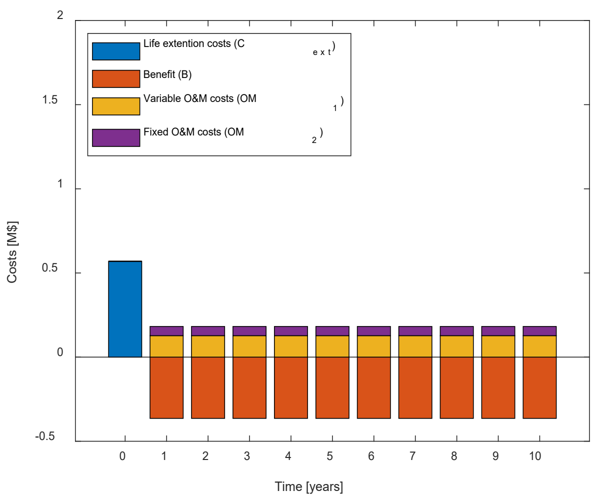
- More expensive to increase reliability of existing structures
- The cost of conservatism is so much larger in assessment than in design

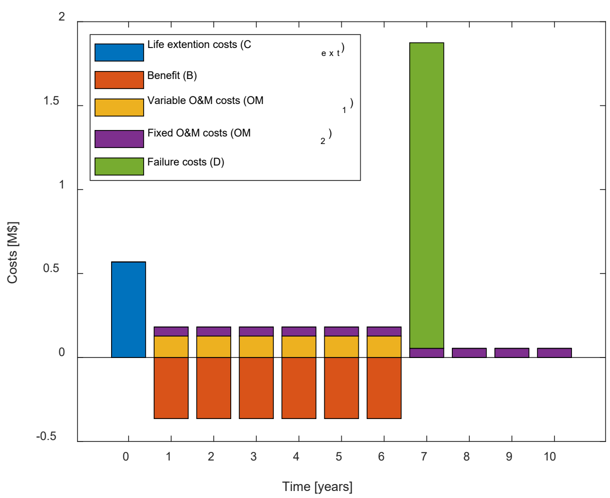




Target reliability for life extension

- Optimization for life extension – The objective function is the expected present value of the profit; i.e. the expected present value of the benefits minus the costs.





Nielsen JS, Sørensen JD. Risk-based derivation of target reliability levels for life extension of wind turbine structural components. Wind Energy. 2021;1–18. https://doi.org/10.1002/we.2610 (Open Access)

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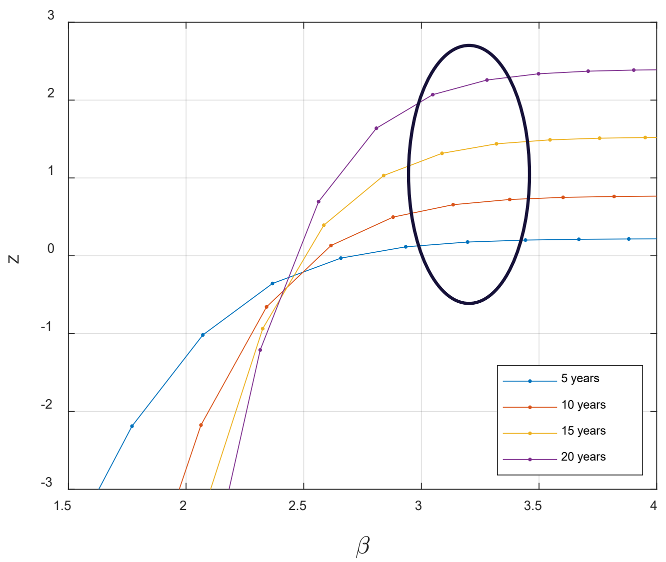
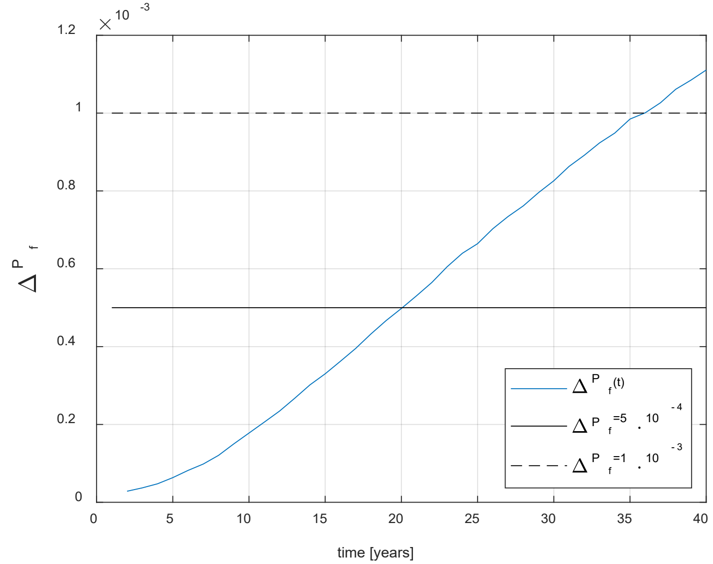
Target reliability for life extension

- A reduction from 3.3 to 3.1 will generally not make life extension infeasible
  - But will result in many additional years of operation





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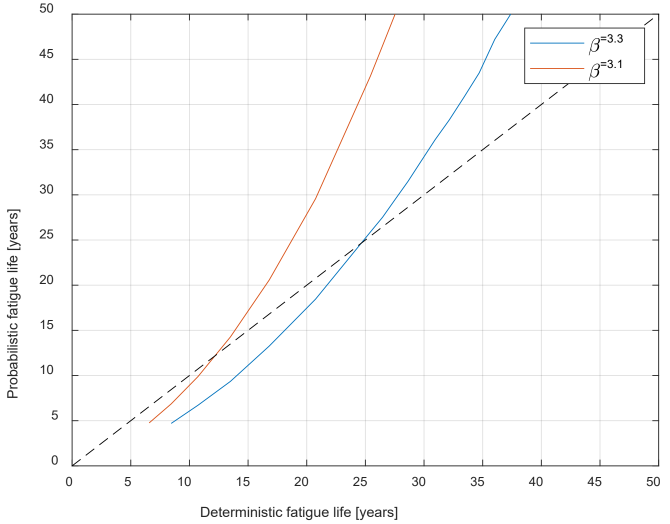
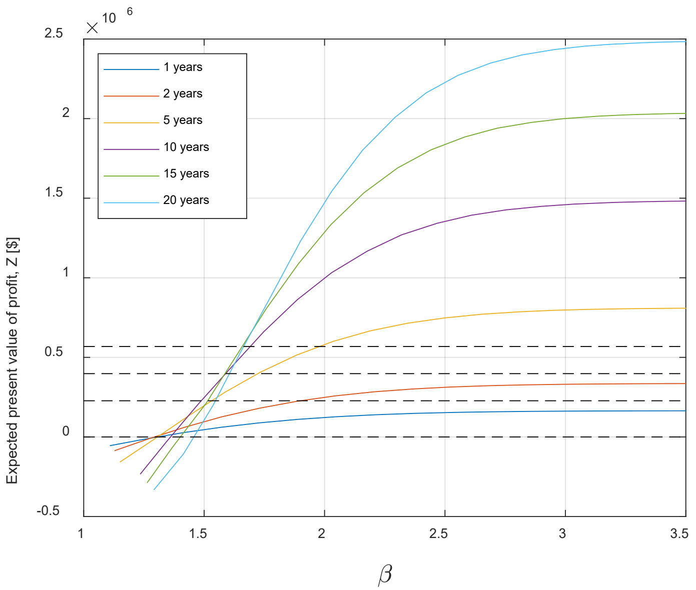
Risk-based assessment for case study

- Assessment for life extension

Based on reduced target



Direct risk-based assessment



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https://www.preprints.org/manuscript/202101.0353/v1

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Repowering

- Reliability based assessment
  - Additional capacity might be found using the probabilistic method compared to the deterministic

- Risk-based assessment
  - Much cheaper to reuse the substructure, thus the costs of increasing safety is high – could allow for a lower reliability level.

Conclusions

- Reiliability and risk-based assessment could be used for assessment of existing structures
  - Clear economic benefit
  - Clear sustainability benefit

Thank you for your attention!

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