# UpWind 1A1 - Integral design approach and standardization

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# WP 1A1 - Integral design approach and standardization

A. Define and update a reference wind turbine and a reference technical-economic cost model for benchmarking
B. Development, application and evaluation of an integral design approach methodology in offshore wind turbine design.
C. Development of standards for the application of the integral design approach. Uncertainty analysis & probabilistic design.
D. Arrange workshops for integration

# WP 1A1 - progress

Task C – Standards and uncertainty / reliability

- Assessment of IEC 61400-1 and -3 standards (D1A1.C1):
    - Wind turbine classes: Inclusion of hurricane / typhoon conditions
    - Wind conditions: Specifications for wind conditions at large heights
    - Ultimate limit states: integration with structural codes, e.g. the Eurocodes and methods for adjusting safety factors
    - Assessment of wind turbines for site specific conditions

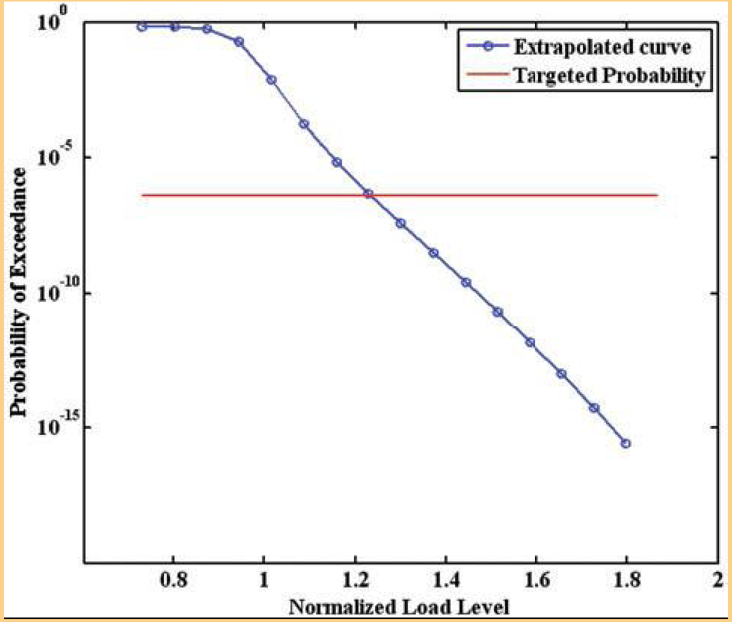
# WP 1A1 - progress

Task C

- Assessment of IEC 61400-1 and -3 …
  - Load extrapolation: recommendations on procedure(s) that give robust estimates (with few simulations) and verification of physics resulting in the loads used in the extrapolation
  - Marine conditions: more guidance on wind-wave misalignment
  - Design situations and load cases: recommendations on reduction of number of load cases
  - Assessment of soil conditions: guidance on assessment of damping
  - Relation to ISO 19900

# WP 1A1 – Load extrapolation

- Extreme loads determined in normal turbulent wind simulations need to be extrapolated to a 50 year probability level of occurrence.
- Most extreme data sets of loads obtained from simulations show high raised peaks that are not sufficiently repeated in other simulations resulting in distorted parametric fits.




- Does the designer remove these high loads from the parametric fit or include the loads in the stochastic extrapolation leading to amplified 50-year load levels?

# WP 1A1 – Load extrapolation

- Assumptions:
  - Output loads will be a stationary process and close to a Gaussian process.
  - Non-linear transformations resulting from the turbine dynamics do not strongly distort the long term extrapolation.
    - Both assumptions may not hold in all situations and thereby lead to isolated extremes in the data.

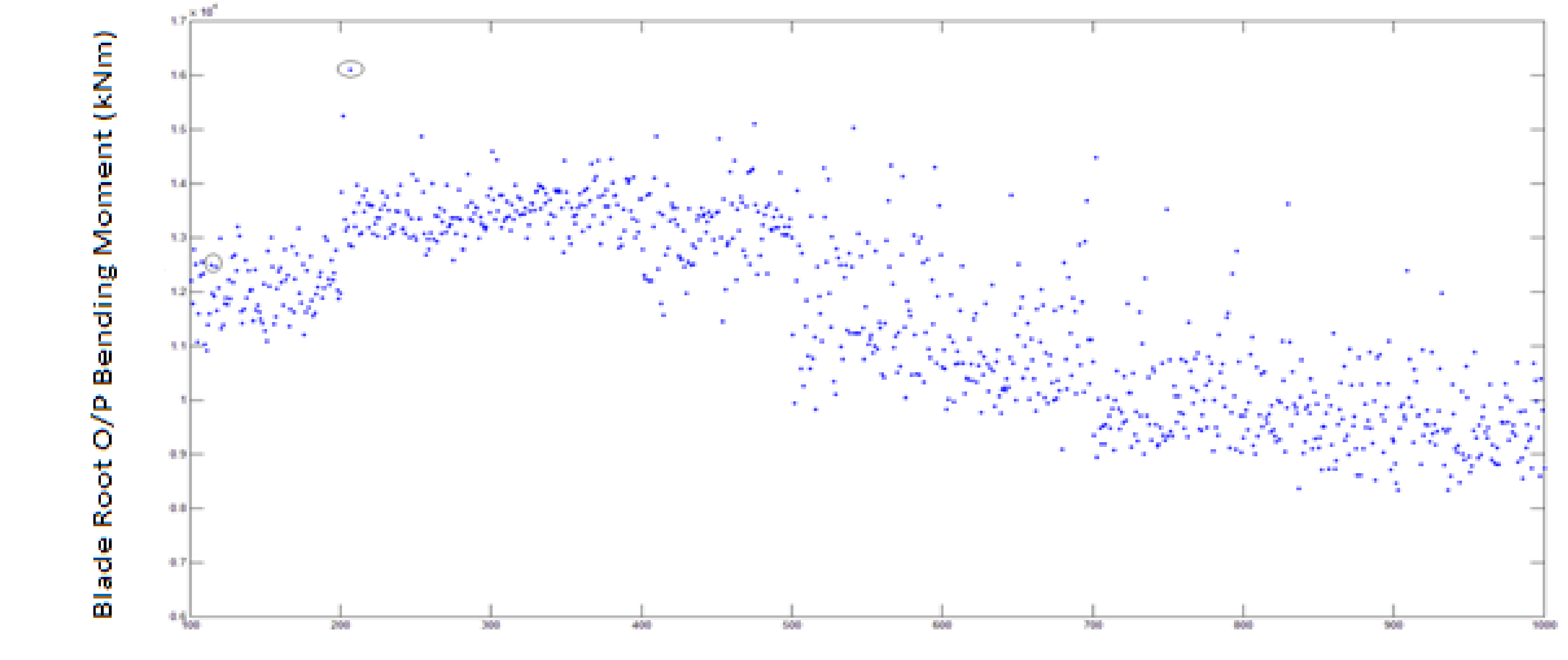
- Absence of dependence on physically correlated variables is an indicator of numerical artifacts.

# Extreme Loads Data Analysis

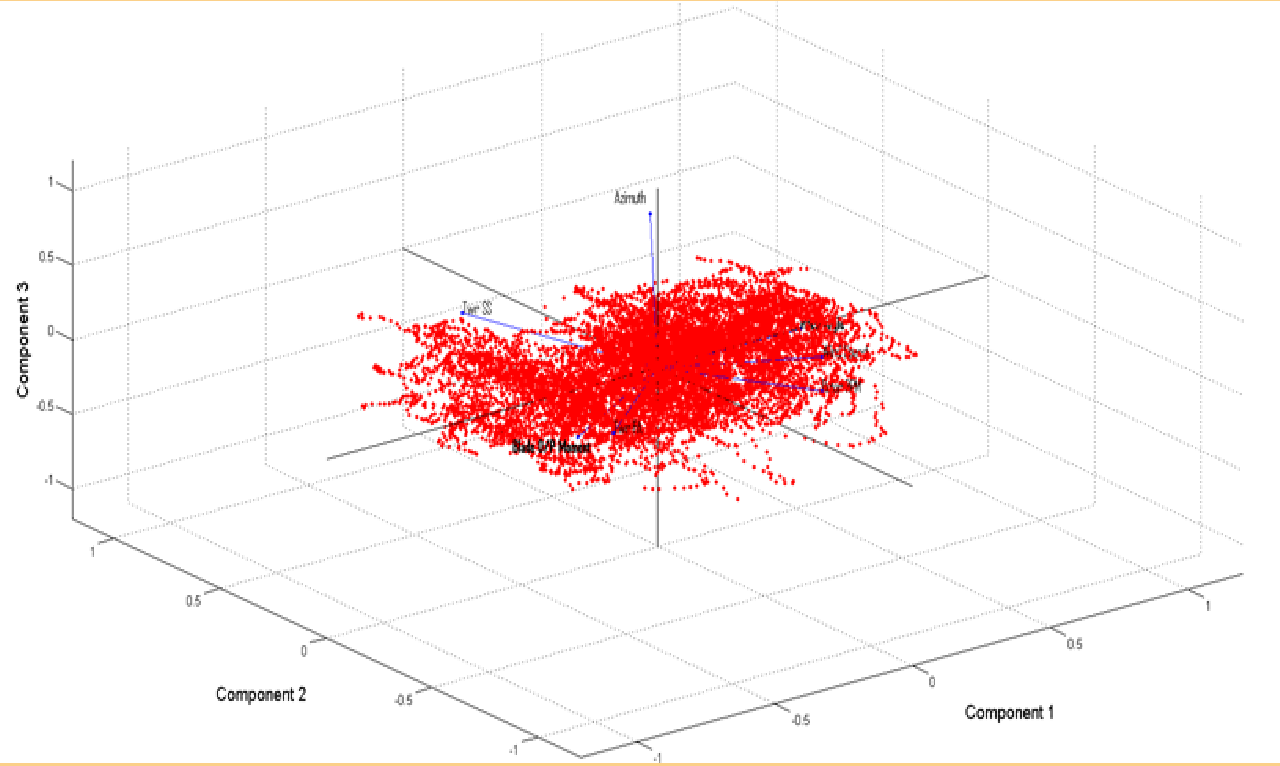
- NREL 5MW reference turbine with 400 random seeds normal turbulence wind run data chosen.
- Blade Root out of plane bending moment used as the characteristic load.
- An example data analysis is performed for the dependencies on the blade root out of plane bending with
  - Wind speed, Rotor RPM, pitch angle, azimuth, tower displacements
- The method of Principal Component Analysis (PCA) is used herein.

# Max Blade Root Bending Moment

- Consider 2 load maxima – one occurring within a cluster of other maxima, the second an isolated maxima, that maybe an “outlier”.



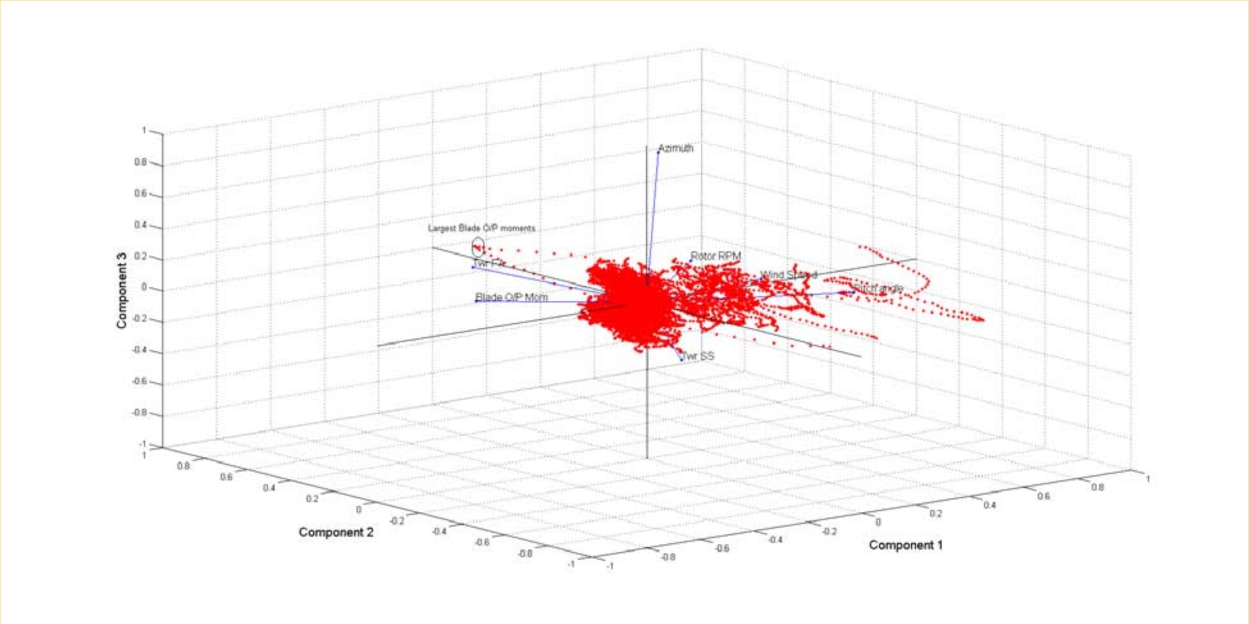
# Principal Components – Normal extreme load




Data plotted in Principal Component space should reveal similar correlated behavior between points.

The max values of root bending moment are in a direction that is densely populated –showing that the system is well repetitive in its physics – A valid extreme load.

# Test Case : Principal Components – Extreme Load Outlier




Data plotted in Principal Component space should reveal similar correlated behavior between points.

The max values of root bending moment are in a direction that is sparsely populated –indicating that the loads may not be physical.

In fact, the loads time series reveal that the maxima are located in the initial transience which extended beyond the first 30s.

# Modeling of uncertainties

| | |
|---|---|
| Physical uncertainty | Aleatory uncertainty |

- Strength parameters: Yield strength of steel
- Annual maximum wind speed
- Turbulence intensity

| | |
|---|---|
| Measurement uncertainty | Epistemic uncertainty |

- Wind measurement
- Strain gauge

| | |
|---|---|
| Statistical uncertainty | Epistemic uncertainty |

- Limited number of data

| | |
|---|---|
| Model uncertainty | Epistemic uncertainty |

- Mathematical model as an approximation of failure mode

# System aspects

**Damage tolerant design (fail safe):**

The structure is able to withstand damage at 'critical' locations – and a maintenance program is implemented that will result in detection and repair of the damage before the damage degrades the structural strength below an acceptable limit.

**Robustness :**

'A structure shall be designed and executed in such a way that it will not be damaged by events such as

- accidental actions and
- consequences of human errors

to an extent disproportionate to the original cause'

# Modeling of uncertainties

Modeling of failure

Assumption: Limit state equation can be formulated for each structural failure mode:

$$g(\mathbf{x}) = 0$$

Probability of failure $P_F = P(g(\mathbf{X}) \leq 0) \approx \Phi(-\beta)$

reliability index (annual) $\beta$

| Reliability index $\beta$ (annual) | Probability of failure (annual) |
|---|---|
| 3,1 | $10^{-3}$ |
| 3,7 | $10^{-4}$ |
| 4,3 | $10^{-5}$ |

# Probabilistic design basis for WT

Building codes: e.g. Eurocode EN1990:2002:

- annual $P_F = 10^{-6}$ or $\beta = 4.7$
  depend on consequences and cost of safety measures

IEC 61400-1: land-based wind turbines

- annual $P_F \sim 10^{-3}$ or $\beta = 3.1$

IEC 61400-3: offshore wind turbines

- annual $P_F \sim 10^{-4}$ or $\beta = 3.7$

Observation of failure rates for wind turbines

- Failure of blades: approx. $10^{-4}$ - $10^{-3}$ per year
- Wind turbine collapse: approx. $10^{-5}$ - $10^{-4}$ per year

# Calibration of partial safety factors

For given failure modes partial safety factors for loads and strength parameters can be calibrated to e.g. the reliability level $\beta = 3.1$ taking into account:

- Uncertainty on loads
- Uncertainty on strength parameters
- Model uncertainty for computational model
- Statistical uncertainty (number of tests)

such that less uncertainty → less partial safety factors → **cost reduction**

Uniform reliability → **cost reduction**

# Example – stochastic modeling using test results

Data – Fatigue test data of Composite blades Optimat Data base (WMC)

Linear SN-curve:

$$\log N = \log K - m \log \Delta\sigma + \varepsilon$$

*Physical uncertainty:*

$\varepsilon$ 'lack of fit': Normal $(0, \sigma_\varepsilon)$

$m$ estimated by 'least squares method

$\log K$, $\sigma_\varepsilon$ estimated by Maximum Likelihood Method

*Statistical uncertainty*:

$\log K$ asymptotic Normal distributed

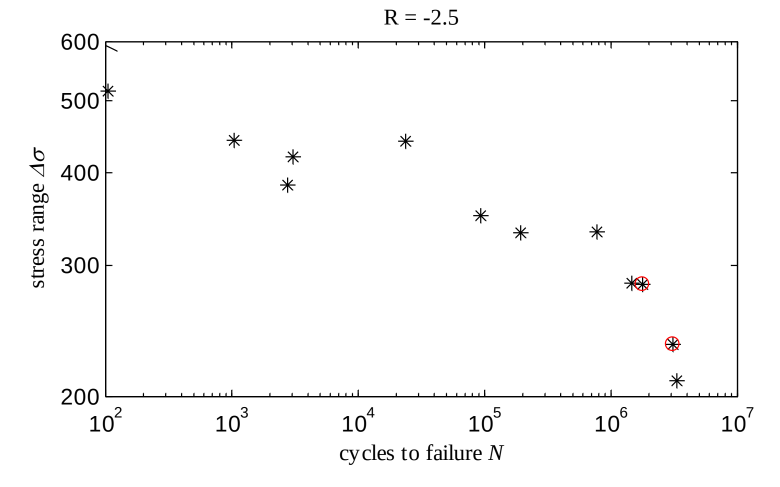
$\sigma_\varepsilon$ asymptotic Normal distributed

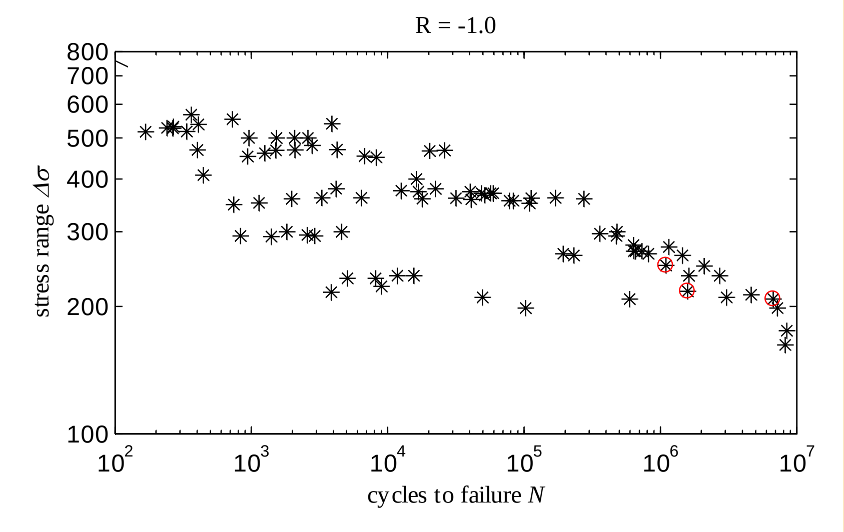
# Physical and Statistical Uncertainty

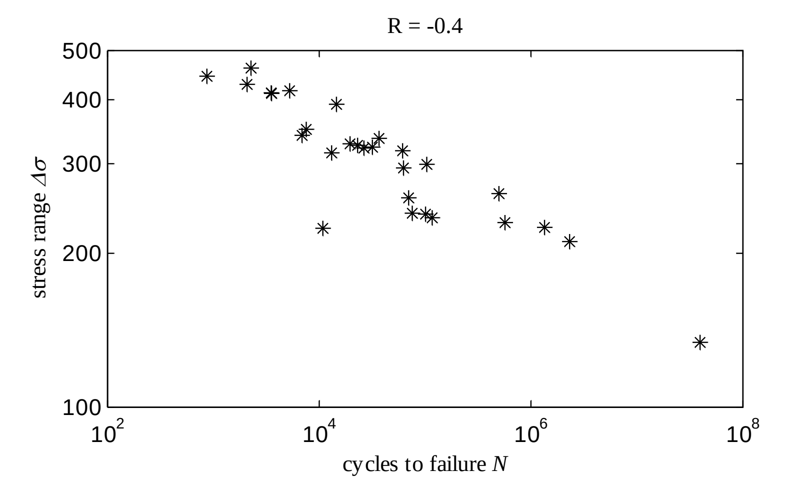
Results: OPTIDAT database: geometry R04 MD

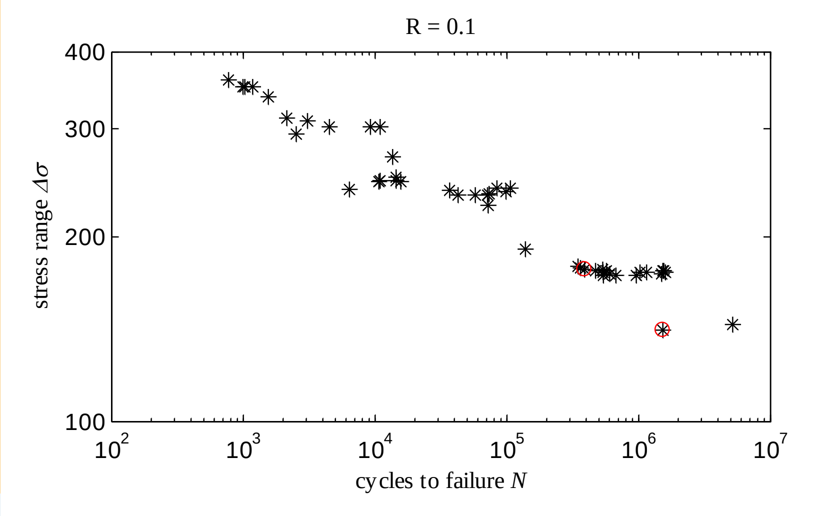
| $R$-ratio | Number of tests | Number of run-outs | $m$ | $\log K$ | $\sigma_\varepsilon$ | $\sigma_{\log K}$ | $\sigma_{\sigma_\varepsilon}$ |
|---|---|---|---|---|---|---|---|
| 0.5 | 15 | 0 | 10.5 | 27.8 | 0.36 | 0.09 | 0.06 |
| 0.1 | 45 | 2 | 9.5 | 27.2 | 0.26 | 0.04 | 0.03 |
| -0.4 | 28 | 0 | 7.6 | 23.4 | 0.44 | 0.08 | 0.06 |
| -1.0 | 84 | 3 | 6.7 | 21.4 | 0.88 | 0.09 | 0.07 |
| -2.5 | 10 | 2 | 12.0 | 35.2 | 0.63 | 0.20 | 0.14 |
| 10.0 | 34 | 0 | 22.2 | 58.7 | 0.64 | 0.11 | 0.08 |
| 2.0 | 6 | 3 | 29.7 | 73.8 | 0.35 | 0.14 | 0.10 |

# Physical and Statistical Uncertainty



# Model Uncertainity – Miners Rule

**Variable amplitude fatigue tests**

Load spectrum: Wisper and Wisperx

Miners rule for linear damage accumulation:

$$D = \sum_{i=1}^{n} \frac{1}{N(\Delta\sigma_i)}$$

Limit state equation:

$$g = \Delta - \sum_{i=1}^{n} \frac{1}{N(\Delta\sigma_i)}$$

$\Delta$ *model uncertainty*: $\mathrm{LN}(\mu_\Delta, \sigma_\Delta)$

# Calibration of partial safety factor for fatigue - example

| Case | Stochastic Model | Partial Safety Factor $\gamma_m$ |
|---|---|---|
| **1** | **Reference** | **1.37** |
| | Uncertainty Miners rule | |
| 2 | $\Delta \sim LN(0.90;0.54)$ | 1.24 |
| 3 | $\Delta \sim LN(0.28;0.20)$ | 1.40 |
| 4 | $\Delta \sim LN(0.32;0.16)$ | 1.36 |
| 5 | $\Delta \sim LN(0.46;0.42)$ | 1.36 |
| 6 | $\Delta \sim LN(1.00;0.30)$ | 1.20 |
| | Model uncertainty exposure | |
| 7 | $X_{exp} \sim LN(1.00;0.02)$ | 1.35 |
| 8 | $X_{exp} \sim LN(1.00;0.10)$ | 1.42 |
| 9 | $X_{exp} \sim LN(0.95;0.05)$ | 1.30 |
| 10 | $X_{exp} \sim LN(1.05;0.05)$ | 1.43 |

# WP 1A1 – future work

- Continuation of review of IEC 61400-1 and -3 standards, incl. assessment of design load computations and in particular needs related to very large wind turbines (D1A1.C1)
- Identification of methods, topics and results from other WPs for revision or development of the international standards (D1A1C1)
- Examples for uncertainty analysis (D1A1.C2+3):
  - External conditions: turbulence and wakes
  - Power performance