Validation of uncertainty in IEC damage calculations based on measurements from alpha ventus

DeepWind 2016

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SWE Stuttgart Wind Energy @ Institute of Aircraft Design

WindForS Wind Energy Research Cluster

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Content of presentation

„Can assumptions of environmental conditions in the design process adequately represent real loads?“

→ *IEC 61400-03 DLC 1.2, load variation*

- Research at alpha ventus, turbine, measurements & simulation model
- Applied procedure
- Measurement selection
- IEC assumptions
- Statistical evaluation
- Conclusions

Source: DOTI (www.alpha-ventus.de, 21.12.2015)

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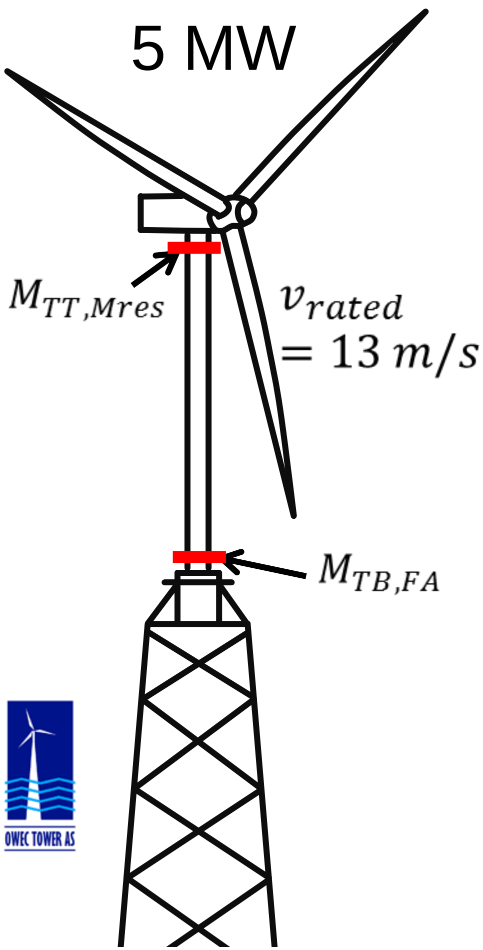
Offshore test field alpha ventus (North Sea)

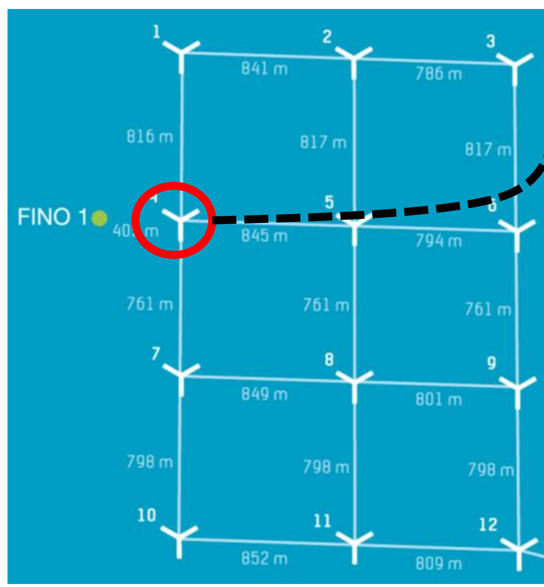
SENVION
5 MW



OWEC TOWER AS

OWEA LOADS project

- **A. Load analysis and probabilistic load description**
- **B. Load-reducing control and load monitoring**
- **C. Design conditions for future wind turbines**



> 100 sensors since 2011
- SCADA
- Loads
- Accelerations
- Environmental conditions
- Corrosion

Statistical & high resolution (50 Hz) data available online

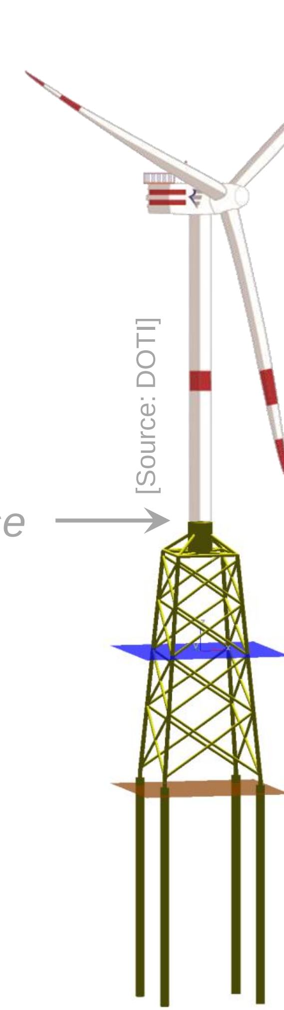
$M_{TT,Mres}$ - tower top resulting bending moment
$M_{TB,FA}$ - tower base fore-aft bending moment

SWE Applied Simulation Method

Wind turbine model:

- Tool: **Flex5** (28 DOF)
- Dynamics: nonlinear elastic multi-body system (MBS) with modal shape functions
- Aero: BEM theory with correction models
- Control: pitch and torque

Coupled integrated approach, dynamically linked at tower base



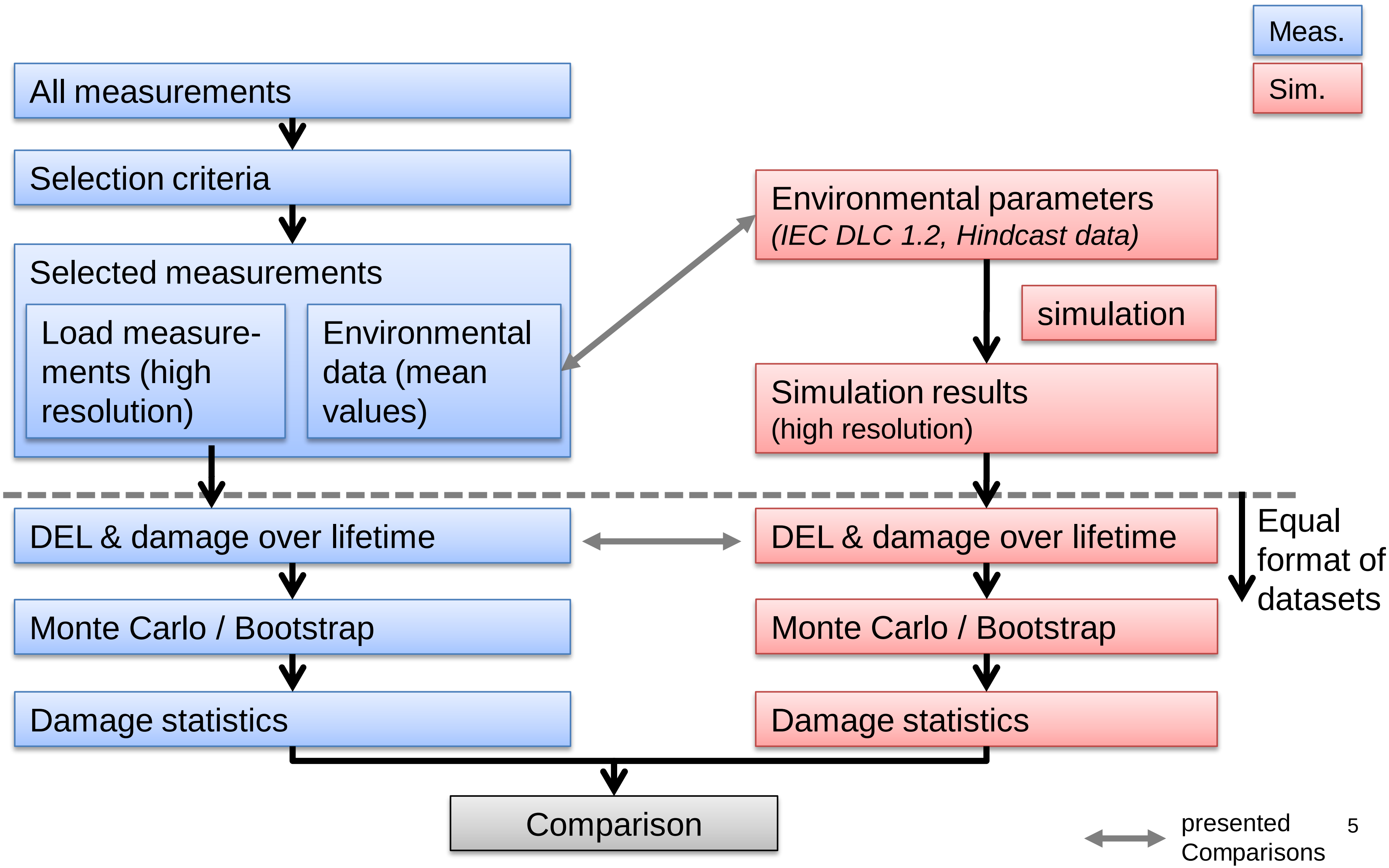
Substructure and foundation model

- Tool: **Poseidon** (n DOF)
- Dynamics: FE model
- Elements: Bernoulli beams and force elements
- Hydro: irreg. sea states, Morison equation

- Validated for equivalent environmental conditions
- Variation of measured loads can be represented with simulations

D. Kaufer et al. " **Validation of an Integrated Simulation Method with High Resolution Load Measurements of the Offshore Wind Turbine REpower 5M at Alpha Ventus** ." **Journal of Ocean and Wind Energy**, Vol. 1, No. 1

Applied procedure for validation of fatigue load variation implied in IEC design assumptions

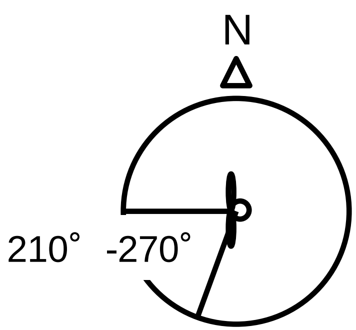


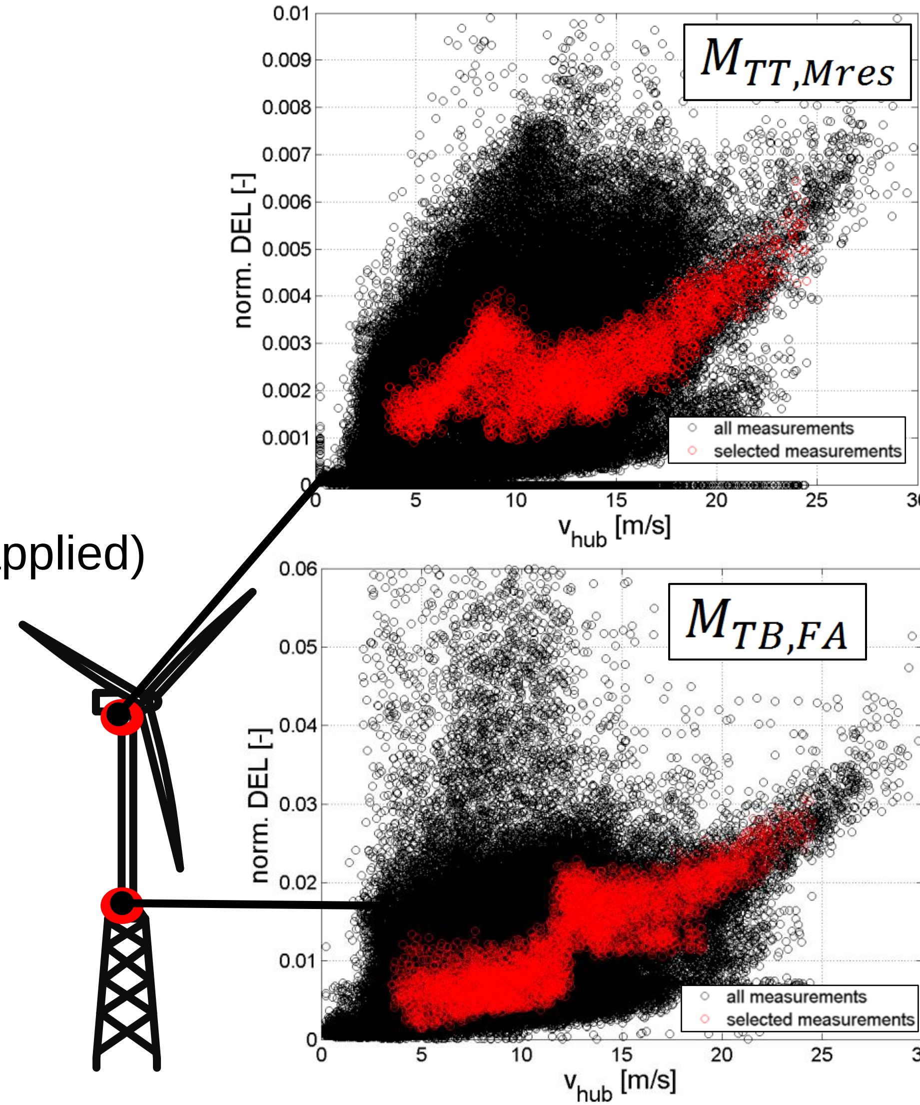
SWE Selection of measurements

Turbine status
- Only power production
- Only free flow conditions
- No curtailment periods

Quality of measurements
- High resolution data available for considered sensors
- No fault conditions of sensors
- No outliers (Palmgren Miner Rule applied)

⇒April 2011 - January 2012
(10 months of measurements)





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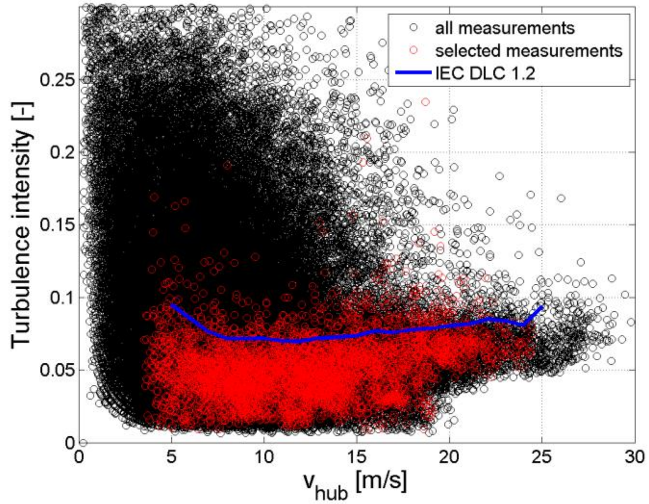
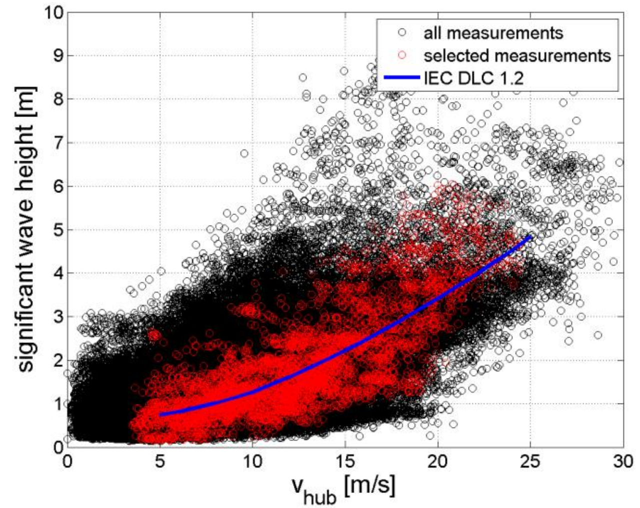
Simulation input: IEC DLC 1.2 environmental conditions

Applied IEC simplifications (DLC 1.2):

- Environmental conditions with dependence on wind speed and wind direction
  - $TI, H_s, T_P = f(v, \theta)$
  - TI = 90th percentile
  - H_s, T_P = 50th percentile
- Constant values
  - $\alpha = 0.14$
  - Azimuth error
  - Water depth
  - Marine growth
  - Wind-wave-misalignment
  - Soil conditions





TI -Turbulence intensity
H_s - wave height
T_P - wave period
v - wind speed
θ - wind direction
α - wind shear

Assumptions of IEC DLC 1.2 environmental conditions

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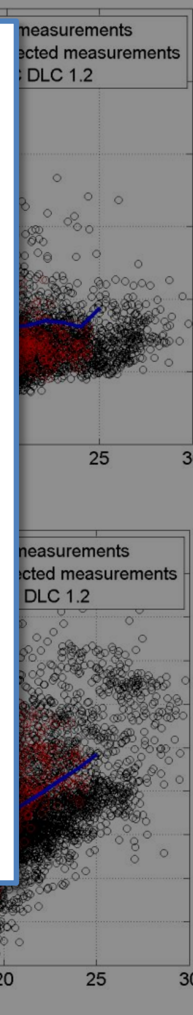

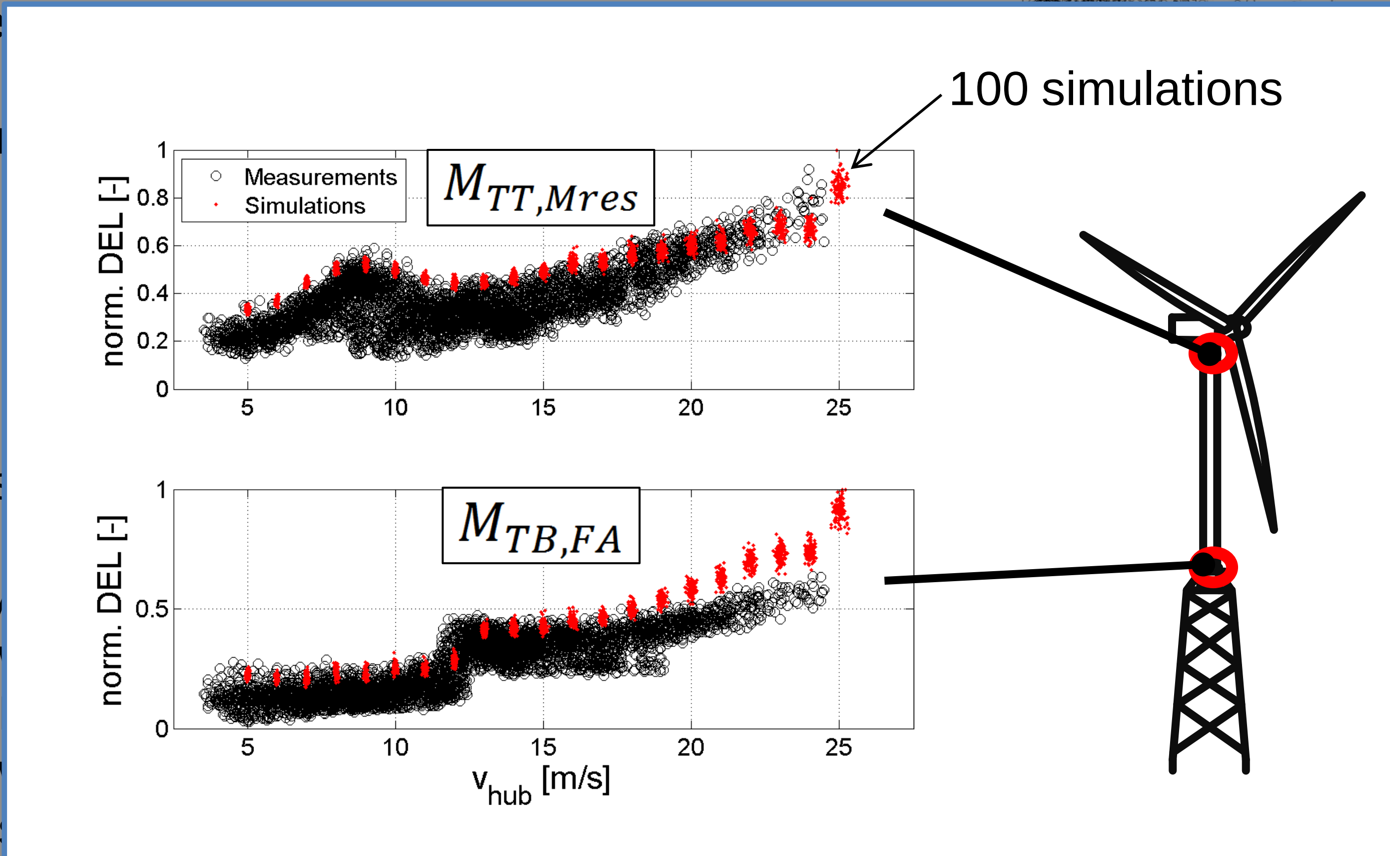

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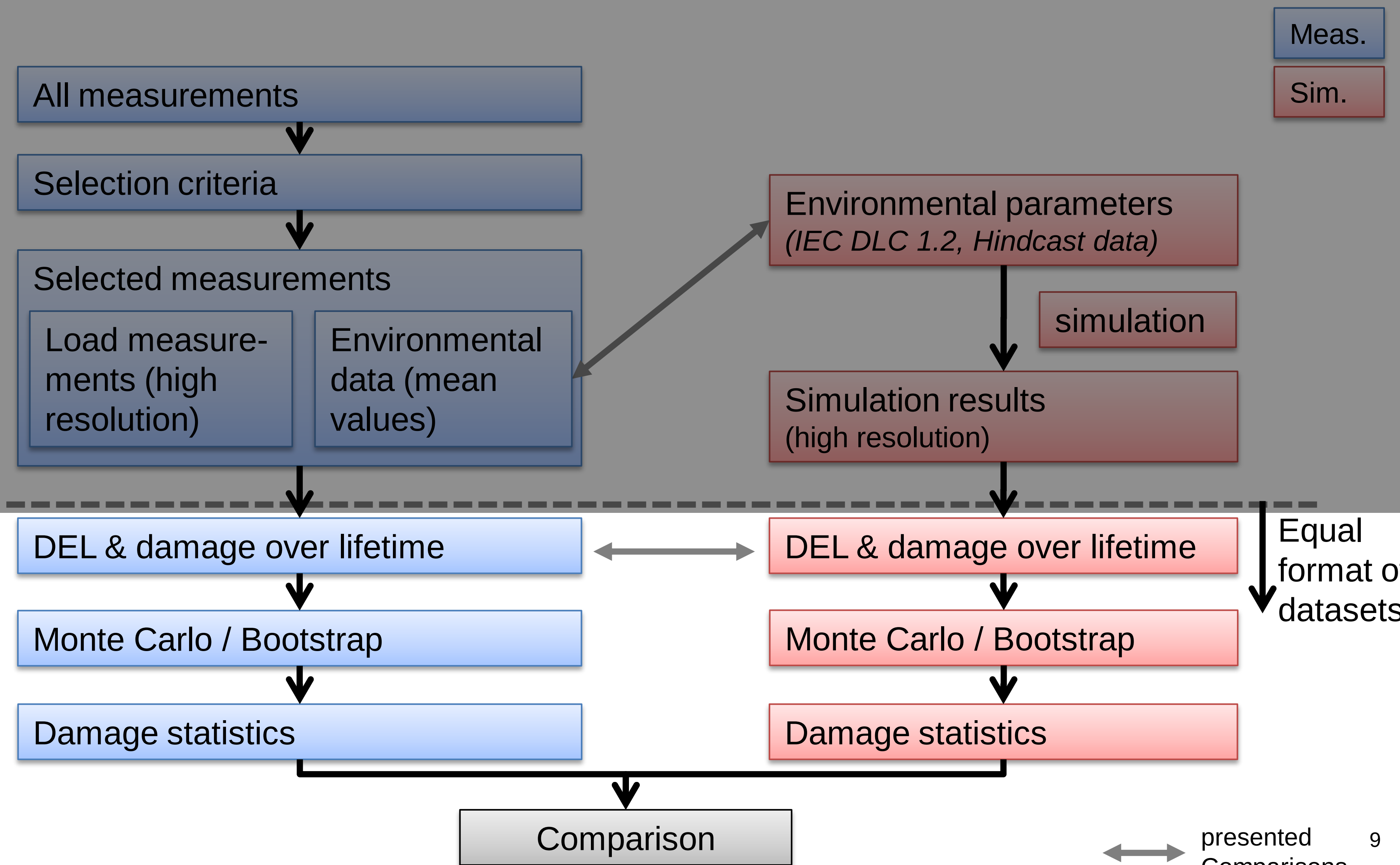
Applied procedure for validation of fatigue load variance implied in IEC design assumptions



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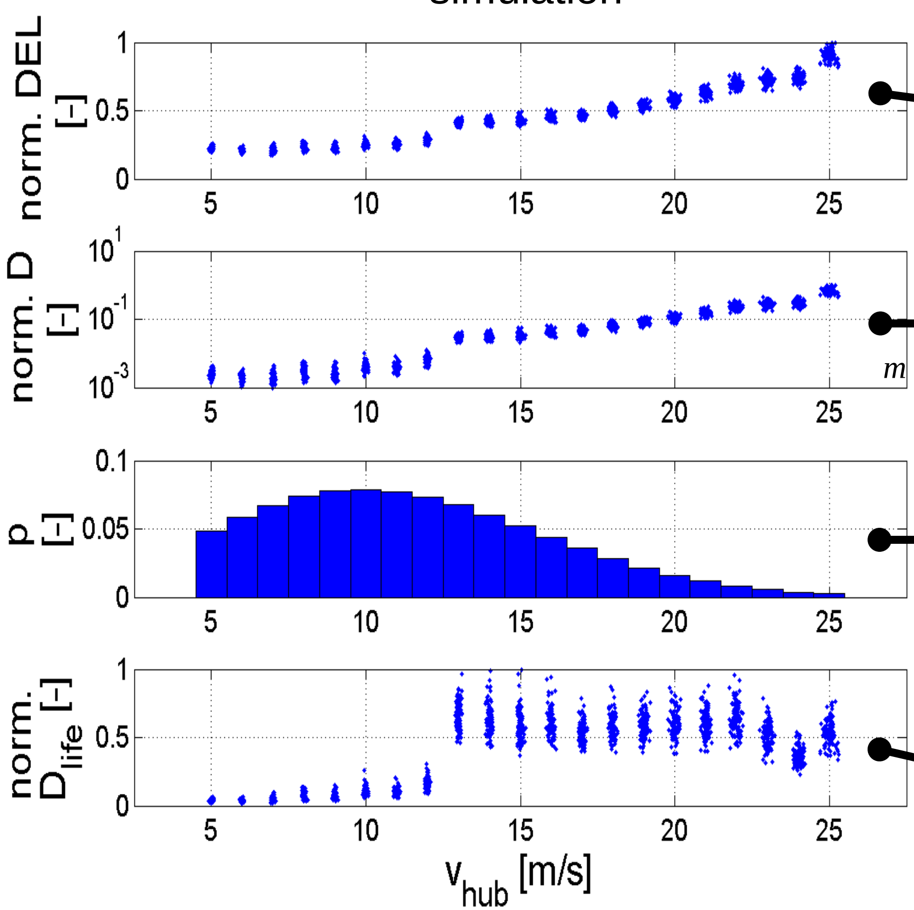
Calculation of lifetime damage



Load time series
↓
DEL of time series
↓
Damage of time series
↓
Occurence probability of wind bin
↓
Damage over lifetime

$$\Delta\sigma_{eq} = \sqrt[m]{\frac{\sum \Delta\sigma_i \cdot n_i}{N_{ref}}}$$

$$D(\Delta\sigma_{eq}) = \frac{N_{ref}}{a} \Delta\sigma_{eq}^{m}$$

$$D_{Life} = D \cdot w_{bin}$$

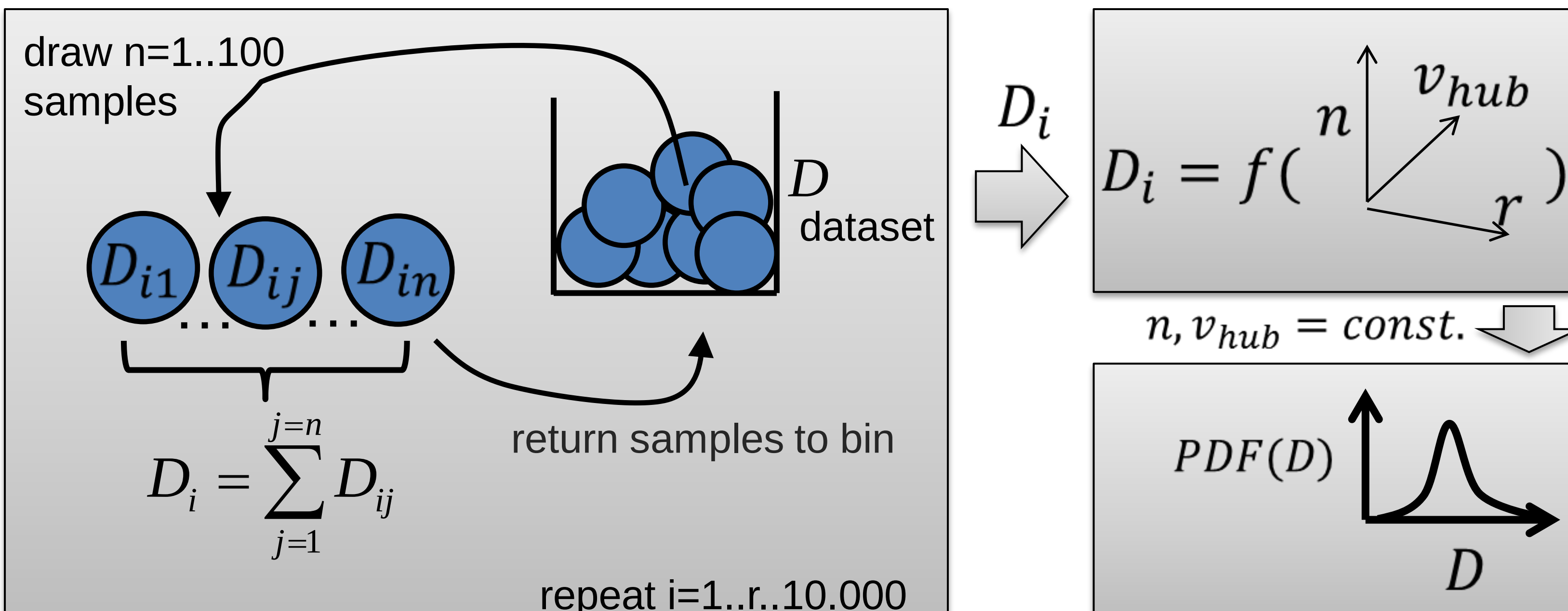
n_i - number of load cycles of i-th considered load cycle bin
$\Delta\sigma_i$- load amplitude of i-th considered load cycle bin
$\Delta\sigma_{eq}$ - damage equivalent load (DEL)
m – slope S/N-curve ***(m = 4)***

a - material coefficient (detail category: 80)
N_{ref} - stress cycle nr. endured at detail category ***(N_{ref}= 2e6)***
w_{bin}- event occurrence probability over lifetime
D – damage

Damage statistics: Monte Carlo & Bootstrap evaluation

Considered damage in design of wind turbine is calculated by summarizing results of considered seeds: $D_{res} = \Sigma_j D_j$

Statistical evaluation using Monte Carlo and Bootstrap method



Davison, Anthony Christopher, and David Victor Hinkley. *Bootstrap methods and their application*. Vol. 1. Cambridge university press, 1997.

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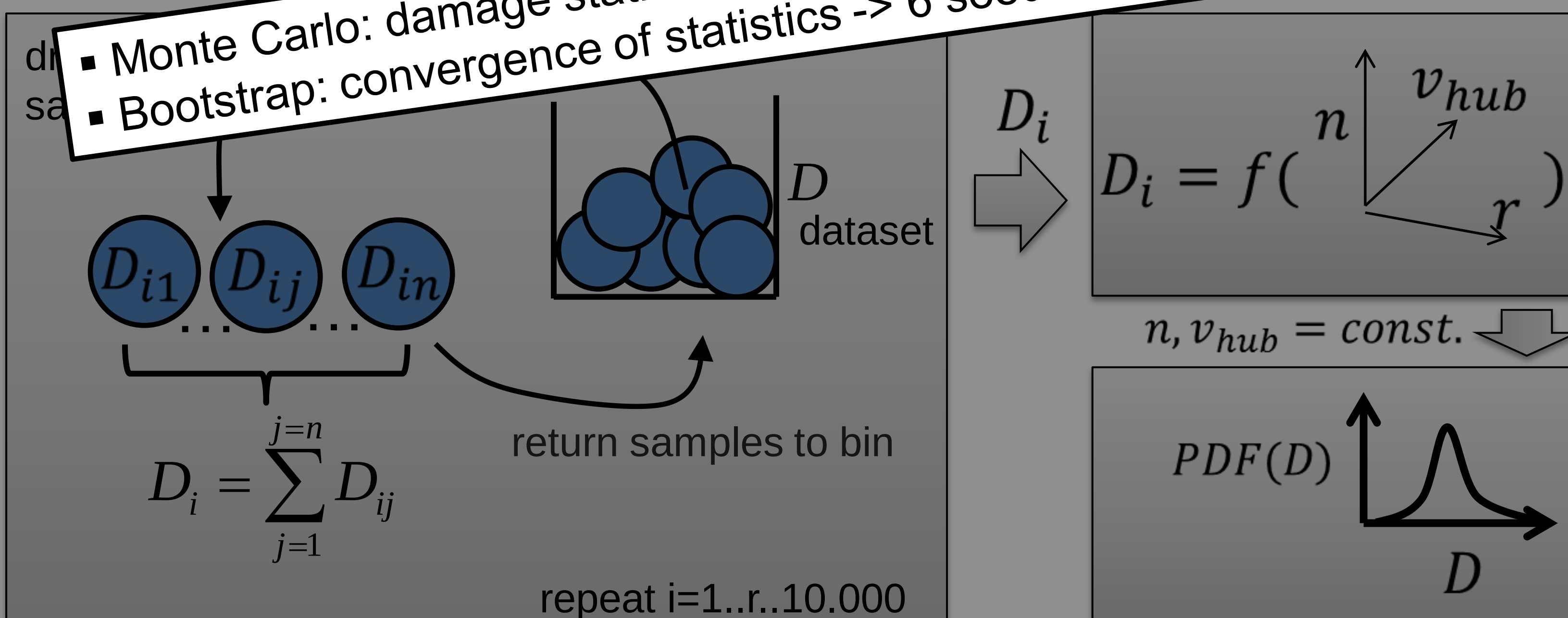
Damage statistics: Monte Carlo & Bootstrap evaluation

Considered damage in design of wind turbine is calculated by summarizing results of considered seeds: $D_{res} = \Sigma_j D_j$

Statistical evaluation using Monte Carlo and Bootstrap method

- Monte Carlo: damage statistics
- Bootstrap: convergence of statistics -> 6 seeds regarded as feasible



Davison, Anthony Christopher, and David Victor Hinkley. *Bootstrap methods and otheir application*. Vol. 1. Cambridge university press, 1997.

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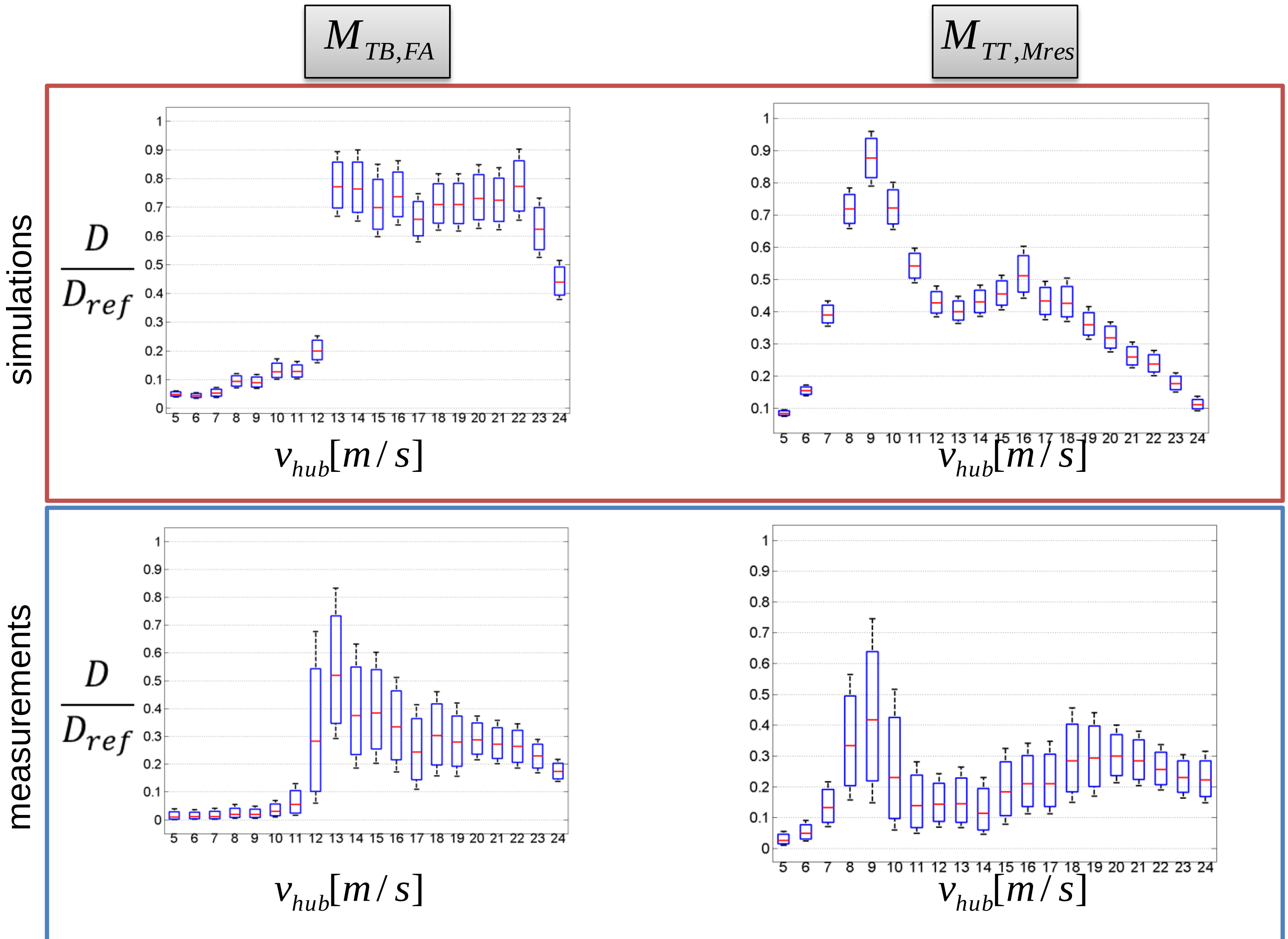
Results (1): variation of damage



Boxplots showing median, 1,5 ,95 and 99 percentiles

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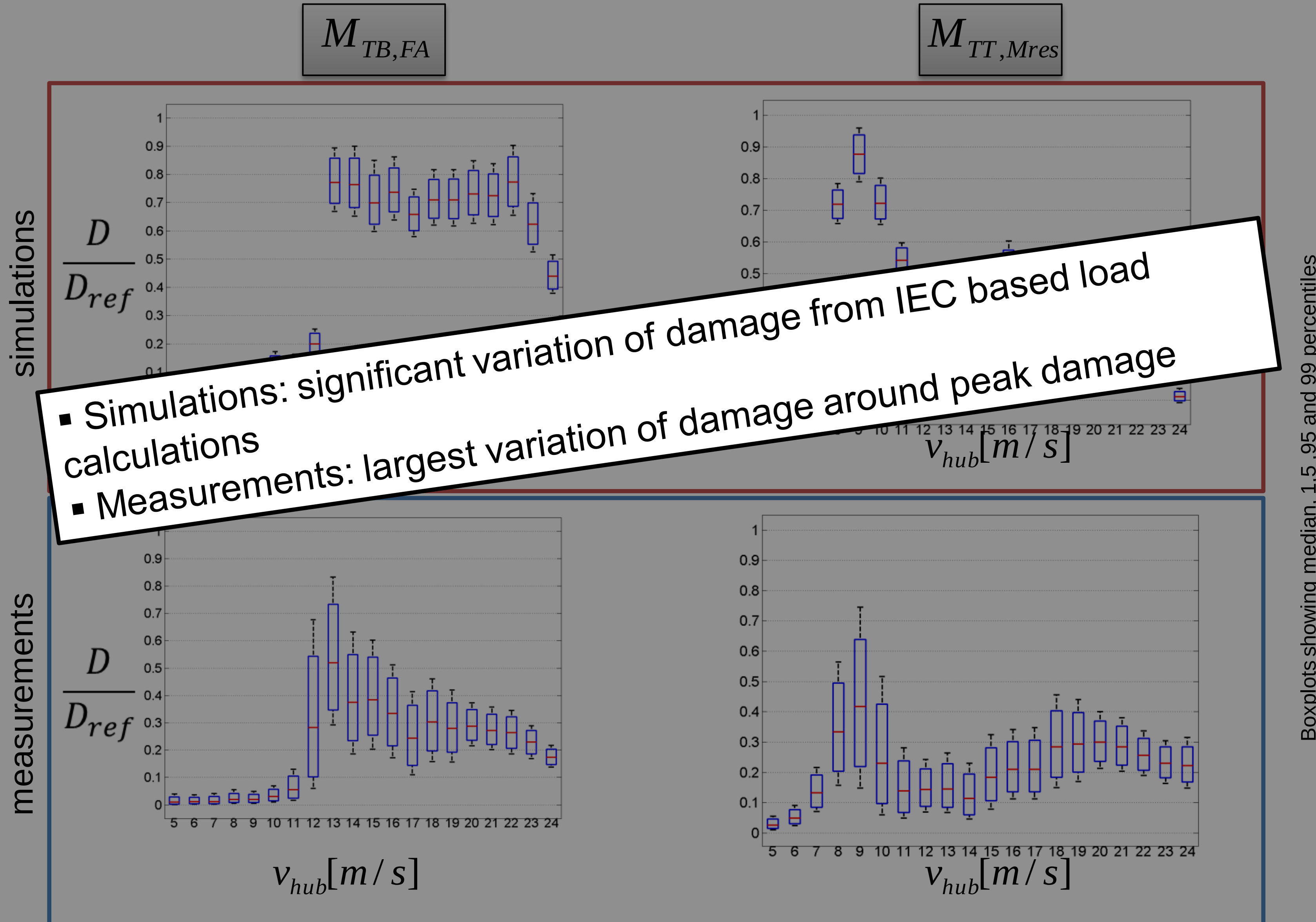
Results (1): variation of damage



- Simulations: significant variation of damage from IEC based load calculations
- Measurements: largest variation of damage around peak damage

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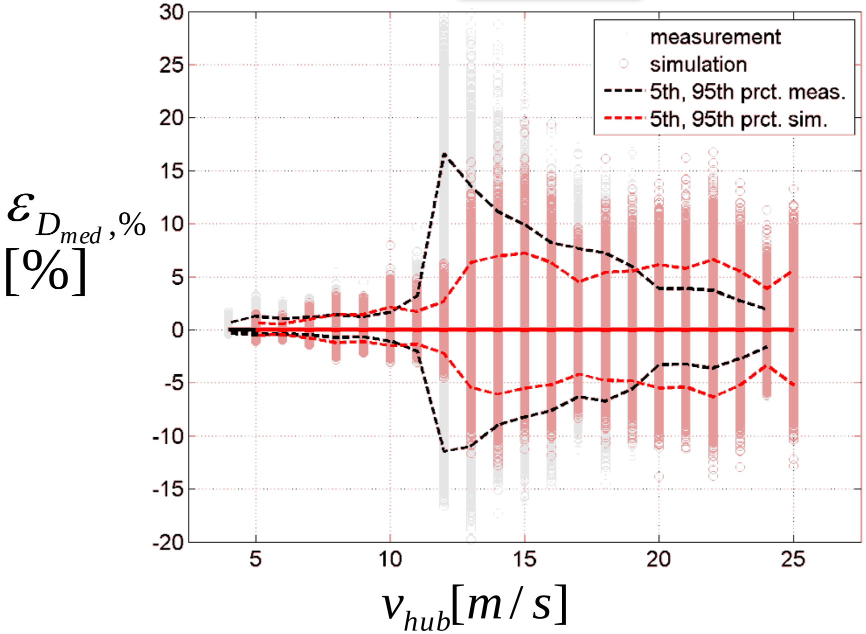
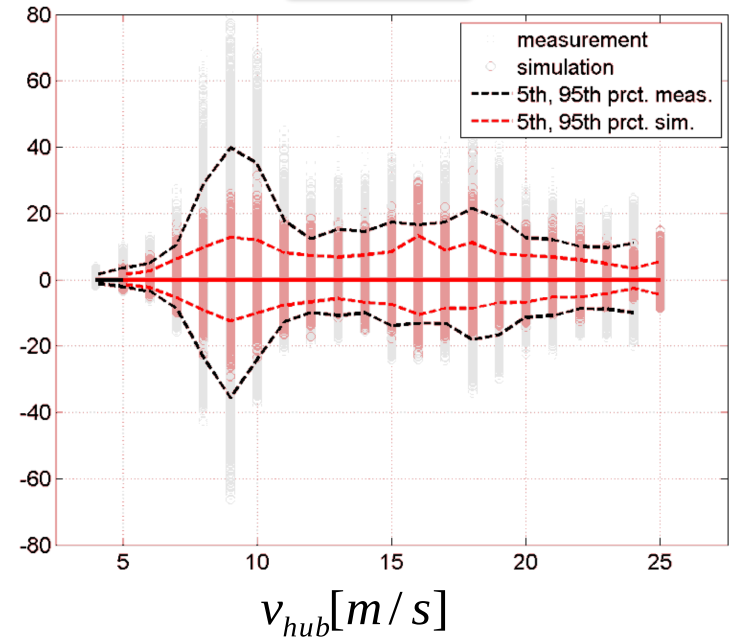
Results (2): validation of variation of damage

Normalized damage variation from bin median damage

$M_{TB,FA}$



$M_{TT,Mres}$



- no clear consistency of difference observable
- largest differences observable for regions around peak damage

$$\varepsilon_{D_{med},\%} = \frac{D(v_{hub}) - D_{med}(v_{hub})}{D_{ref}} [\%]$$

D_{med} - median damage
$\varepsilon_{D_{med},\%}$ - % deviation of damage from median damage
D_{ref} - reference damage

Conclusion & outlook

Methodology for validation of variation of damage by design assumptions

- Measurement selection
- Monte Carlo and Bootstrap methods
- Comparison of percentiles

→ Significant variation of loads from simulations observable

→ Difference between measurements and simulation varies

→ Calculation of probability of exceedence possible and could be relevant

Variation of damage cannot be captured by IEC design assumptions

-> Goals of the IEC fatigue evaluation regarding load variation?

a) Strictly conservative

b) Match variation of loads experienced in real environment

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Acknowledgement

Thank you for your attention

This research is part of the RAVE projects OWEA - "Verification of offshore wind turbines" and OWEA Loads.

It is funded by the Federal Ministry for the Economic Affairs and Energy (BMWi).

[wikipedia.org/wiki/Windmessmast]

RAVE
RESEARCH AT ALPHA VENTUS
Eine Forschungsinitiative des Bundesumweltministeriums

Federal Ministry
for Economic Affairs
and Energy

WINDFORS
Wind Energy
Research Alliance

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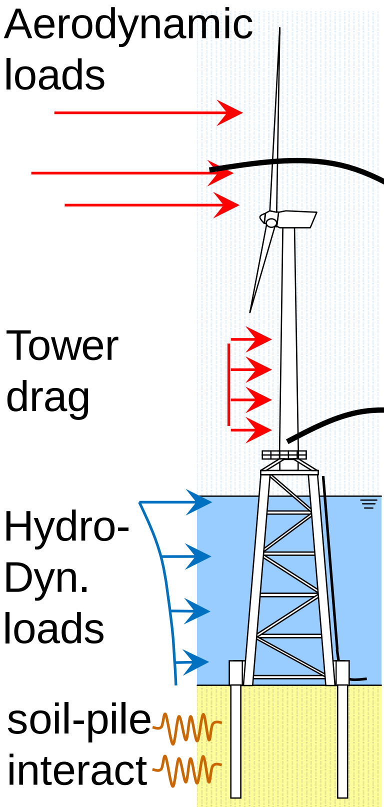
Full scale validation of numerical models

D. Kaufer et al., **ISOPE 2013**



1. Obtain measurements	**2. Obtain results**	**3. Compare results**
Selected events		
Environmental measurements →	Simulation	
Load measurements →	plausibility checks & calibration	

Comparison
1. *Time domain (rotor-/nacelle rotation)*
2. *Frequency domain (natural frequencies)*
3. *Statistics (min, mean, max, stddev)*

↓

Validated simulation model (equivalent environmental conditions)

Measurements

Simulation

→ Variation of measured loads can be represented with simulations when considering variance of environmental conditions

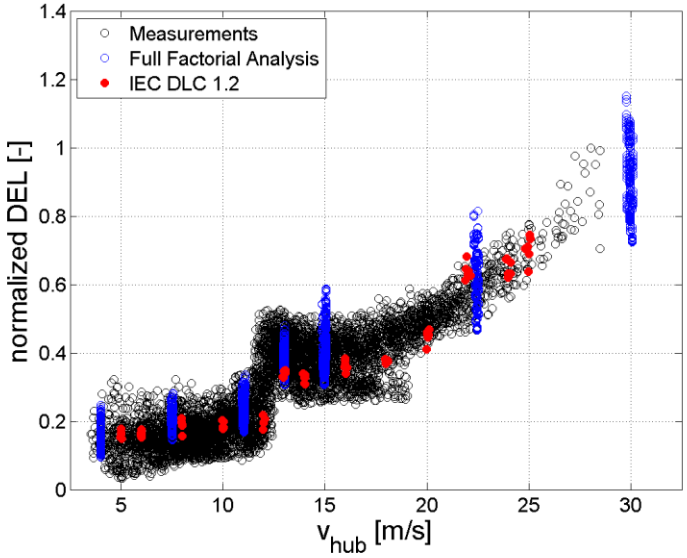
SWE Validation of load variation

Can variance of loads be represented by simulations?

Simulation study considering variation of
- Wind speed
- Turbulence intensity
- Wind shear
- Wave height
- Wave period

based on 5 year Fino1 data

Tower base fore aft bending moment



➔ Variation of measured loads can be represented with simulations when considering variance of environmental conditions

DEL – damage equivalent load

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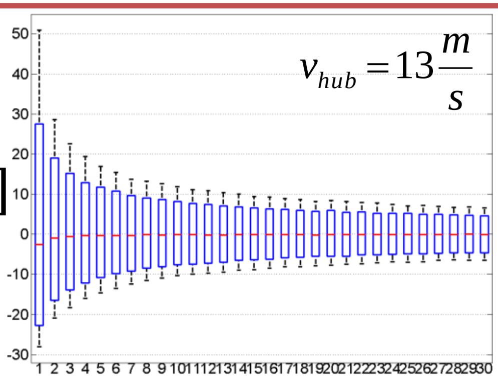
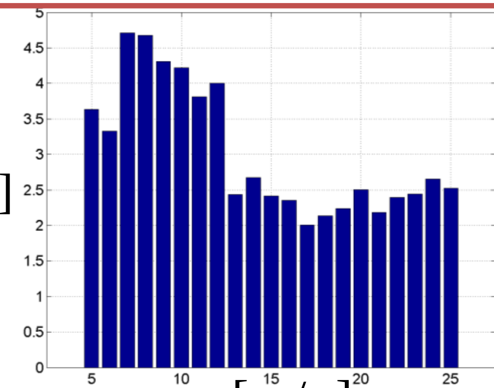
Damage bootstrap evaluation (tower bottom)

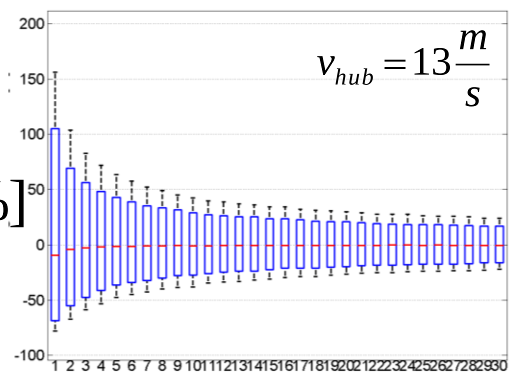
Bootstrap | **Rate of change**

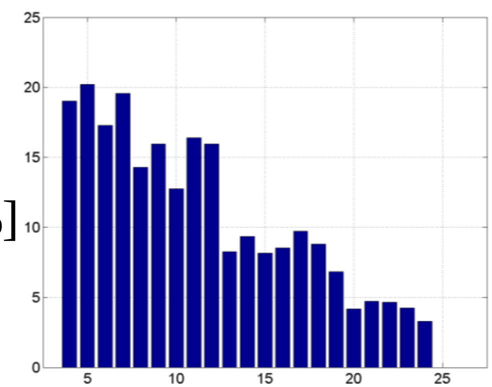
simulations





measurements





Boxplots showing median, 1,5 ,95 and 99 percentiles

$$\varepsilon_{\%}(n) = \frac{(D_n - D_{n=100})}{D_{n=100}}\,[\%]$$

$$\overline{\Delta\varepsilon_{\%}}(n_1, n_2) = \frac{1}{2}\cdot\Big(\big(|\varepsilon_{\%,5}(n_1)| - |\varepsilon_{\%,5}(n_2)|\big) + \big(\varepsilon_{\%,95}(n_1) - \varepsilon_{\%,95}(n_2)\big)\Big)[\%]$$

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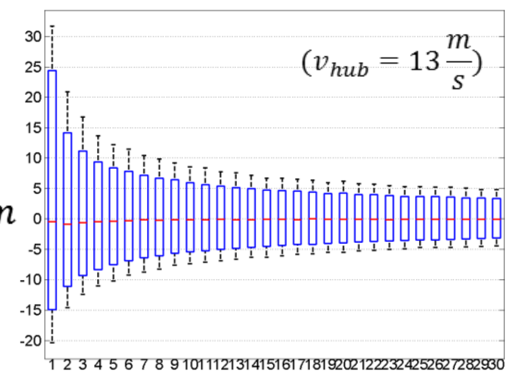
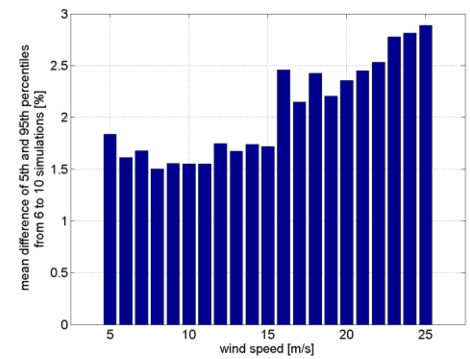
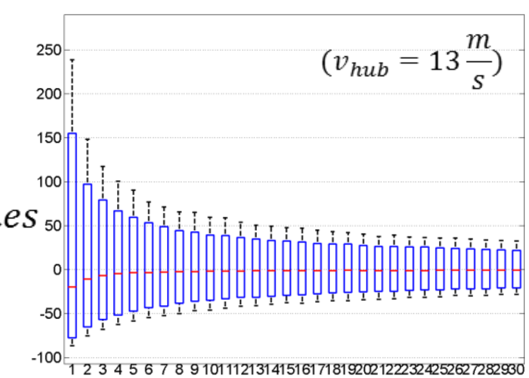
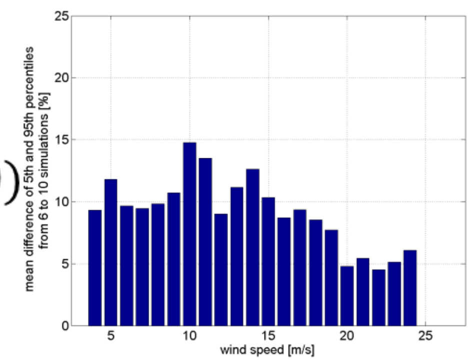
Bootstrap evaluation (tower top)

	Bootstrap	Rate of change
simulations	$\varepsilon_{\%,sim}$  n	$\overline{\Delta\varepsilon_{\%}}(6,10)$  $v_{hub}[m/s]$
measurements	$\varepsilon_{\%,mes}$  n	$\overline{\Delta\varepsilon_{\%}}(6,10)$  $v_{hub}\ [m/s]$

$$\varepsilon_{\%}(n) = \frac{(D_n - D_{n=100})}{D_{n=100}}\ [\%]$$

$$\overline{\Delta\varepsilon_{\%}}(n_1, n_2) = \frac{1}{2} \cdot \Big(\big(|\varepsilon_{\%,5}(n_1)| - |\varepsilon_{\%,5}(n_2)| \big) + \big(\varepsilon_{\%,95}(n_1) - \varepsilon_{\%,95}(n_2) \big) \Big) [\%]$$