Technische Universität München
Wind Energy Institute

Uncertainty Quantification in the Aeroservoelastic Simulation of Wind Turbines

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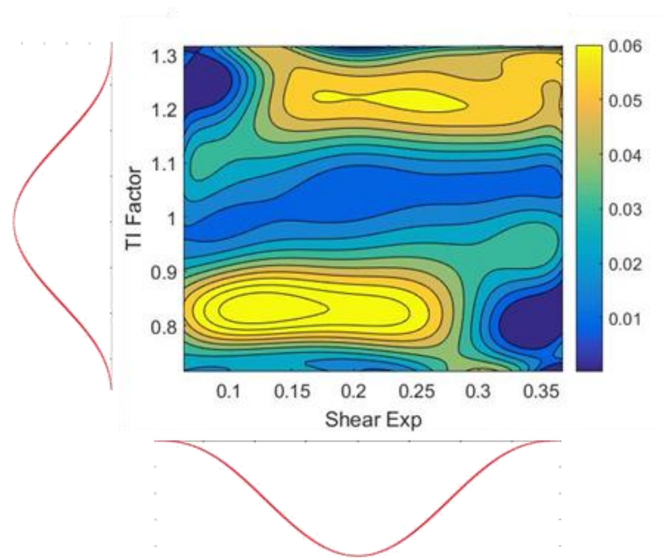

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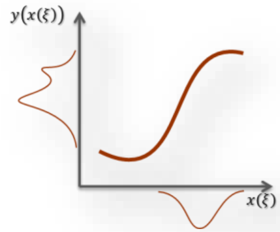
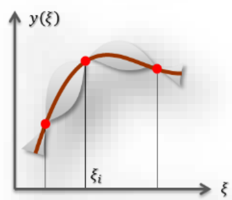
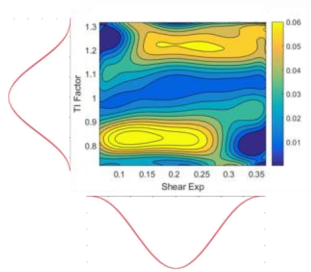
Outline



Motivation: uncertainties in wind turbine simulation and design



Uncertainty Quantification (UQ) methods



Preliminary results

Motivation: Uncertainties in Wind Turbine Modeling

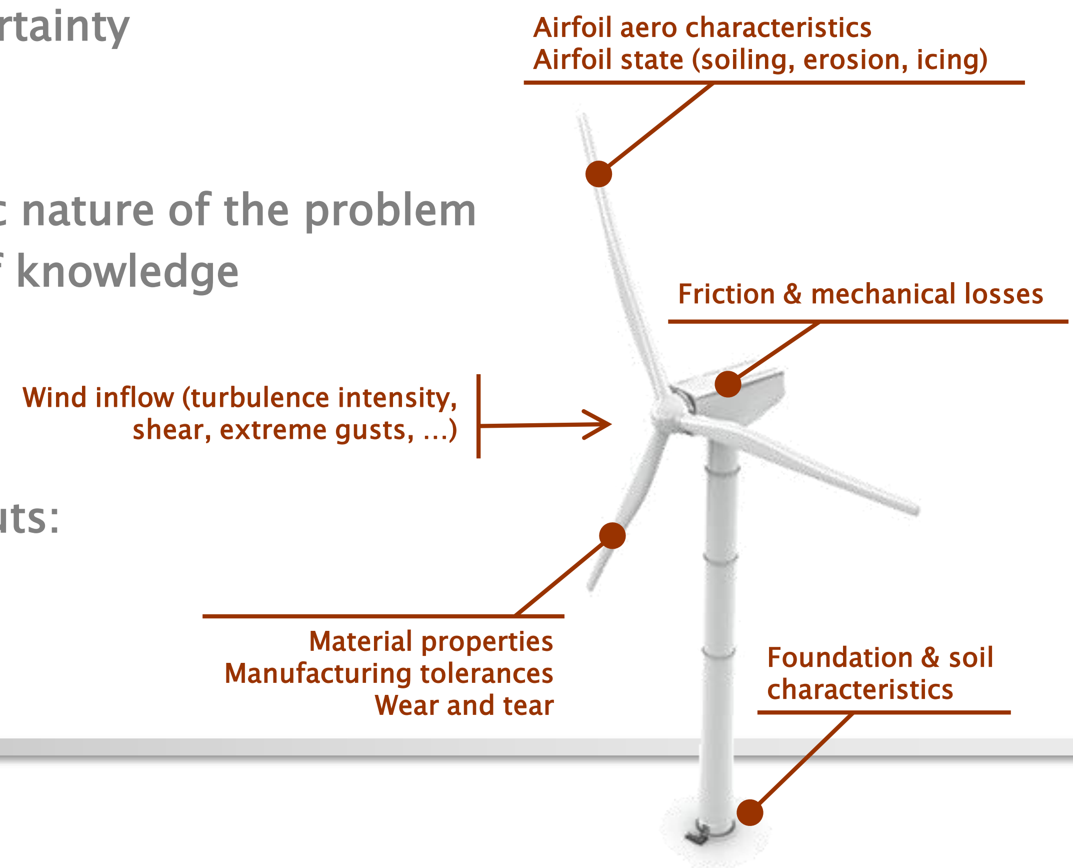
Sources of uncertainty:

- Uncertainty in the model parameters
- Uncertainty in the inputs (e.g., wind conditions)
- Structural uncertainty (model inadequacy)
- Algorithmic uncertainty (numerical errors and approximations)
- Experimental testing uncertainty

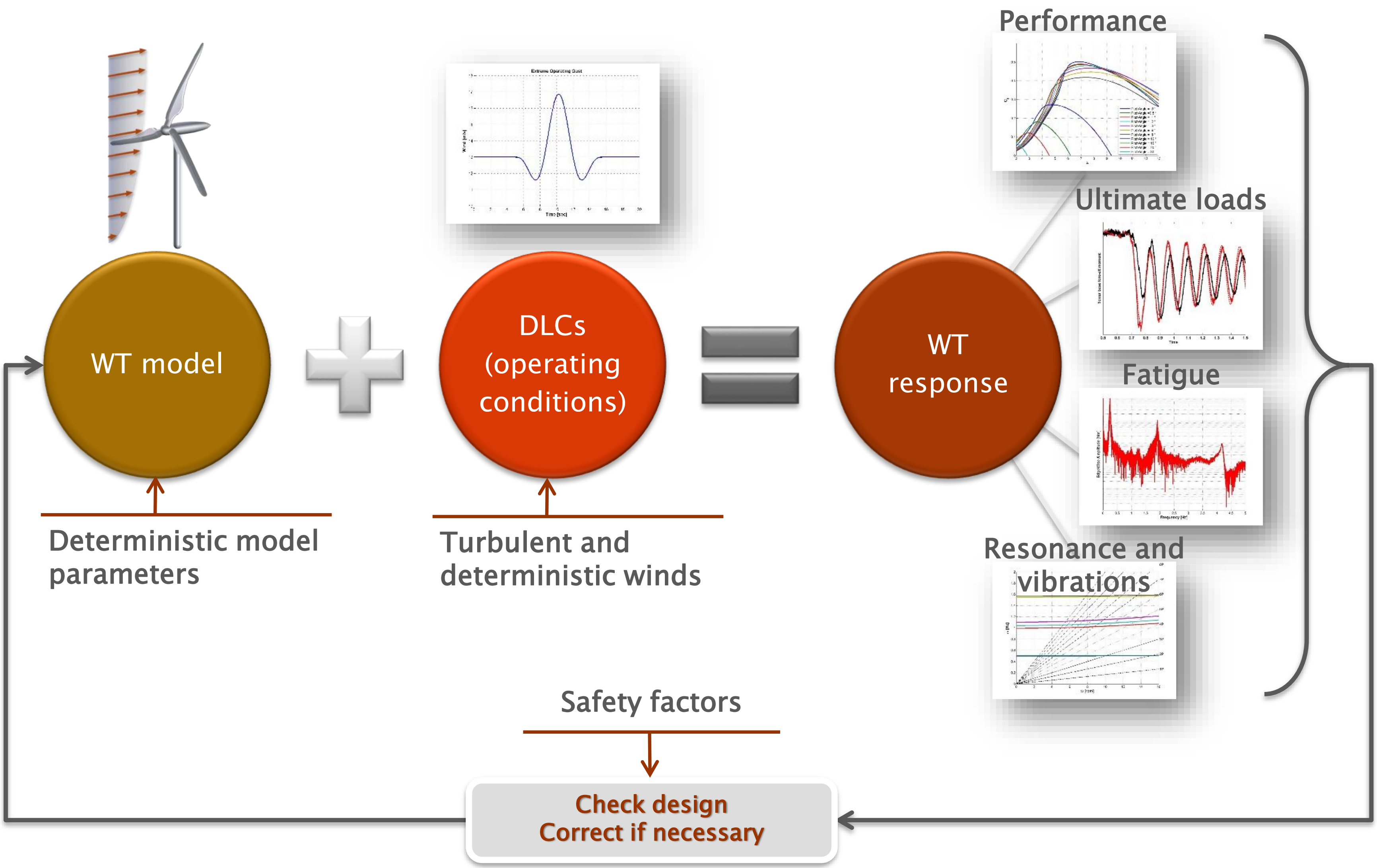
Types of uncertainty:

- Aleatory: due to stochastic nature of the problem
- Epistemic: due to a lack of knowledge

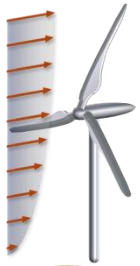
Examples of uncertainties
in model parameters and inputs:

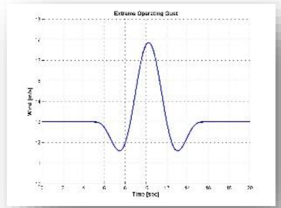


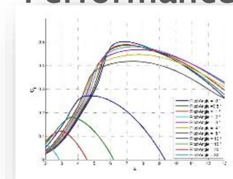
Designing According to a Standard

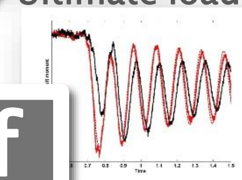


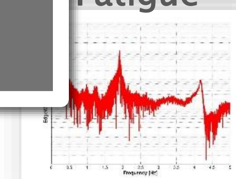
Designing According to a Standard

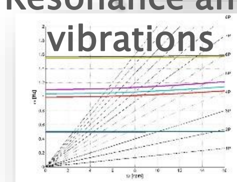












WT model

Deterministic model parameters

Turbulent and deterministic winds

Performance

Ultimate loads

Fatigue

Resonance and vibrations

No explicit treatment of uncertainties

Safety factors

Check design
Correct if necessary

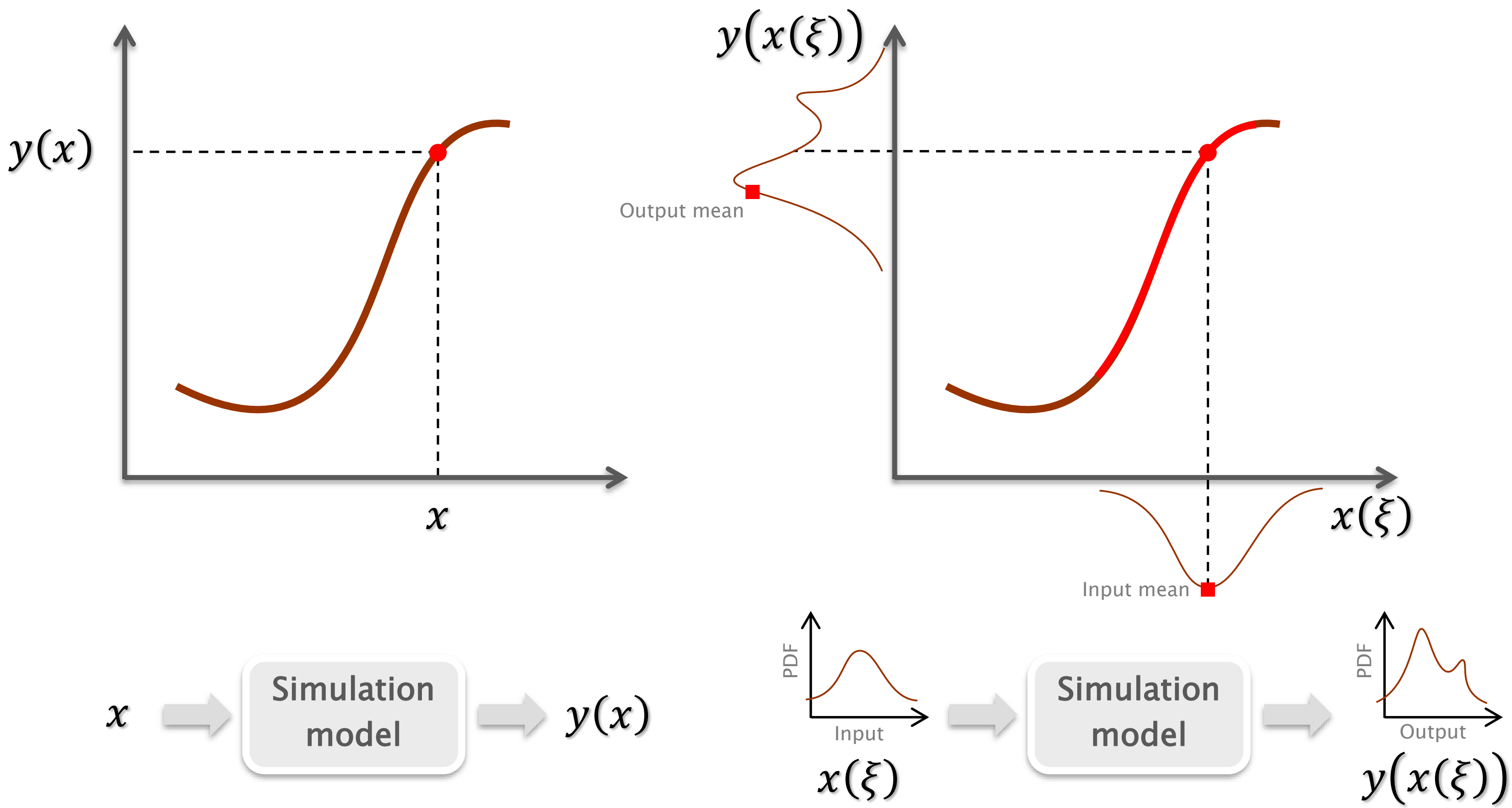
Long Term Goals

- Improved **understanding** of effects of uncertainties
- Efficient **simulation** in the presence of uncertainties (forward propagation)
- Explicit inclusion of uncertainties in the design process (**robust design**)

This presentation:

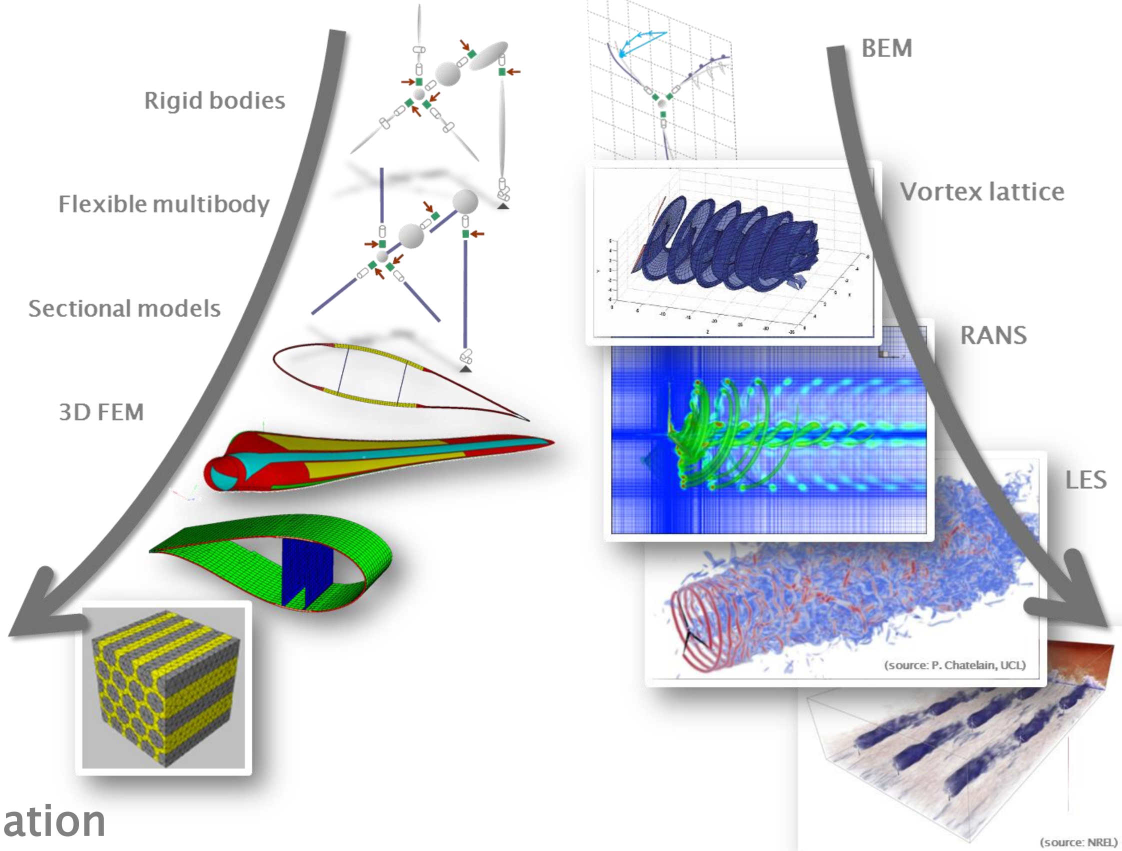
- Identification of **best algorithms (applicability to high dimensions, generality, accuracy, few samples)** for forward propagation
- Preliminary assessment of **effects of uncertainties** on design-relevant metrics

Deterministic vs. UQ-Based Simulation



UQ Forward Propagation Methods

Wind energy simulation models:

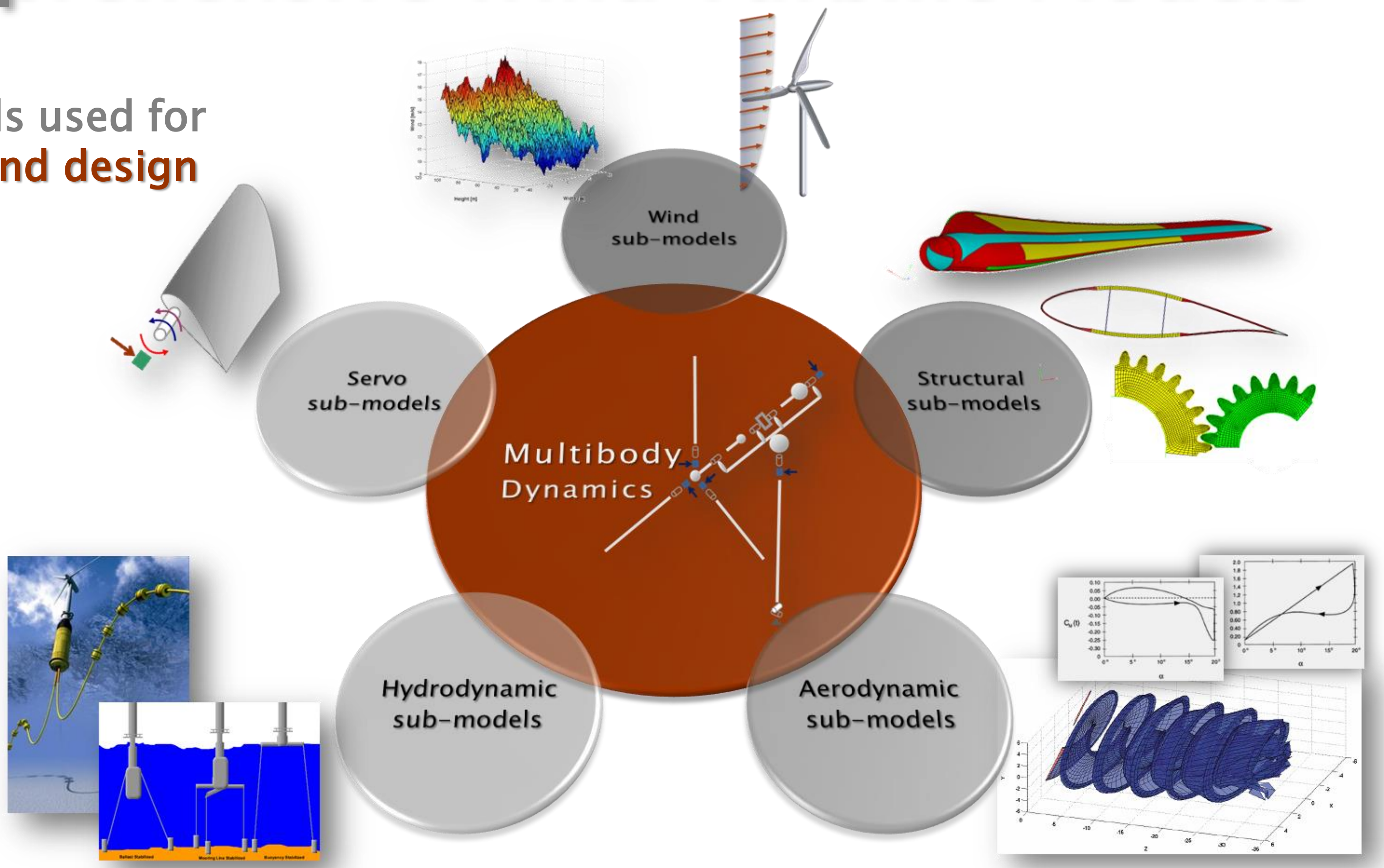


Requirements for UQ:

- Non-intrusive formulation
- Limited computational cost
- Applicable to multiple uncertain inputs (to capture couplings)

Comprehensive Wind Turbine Models

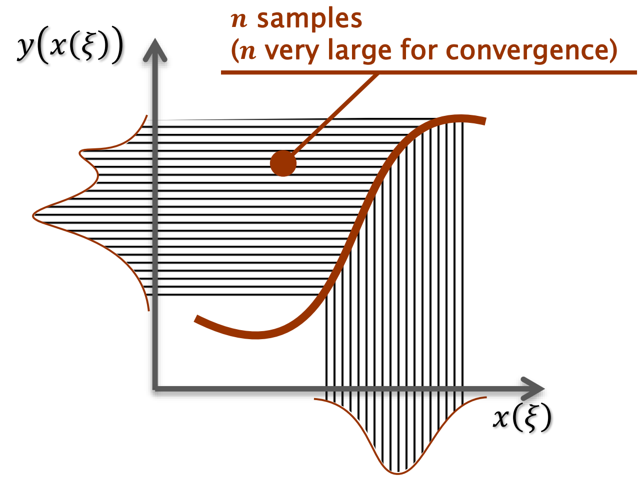
Typical models used for **certification and design**



- Medium computational complexity
- Large number of functional evaluations
- Significant computational effort for a complete load assessment

UQ Forward Propagation Methods

UQ methods:

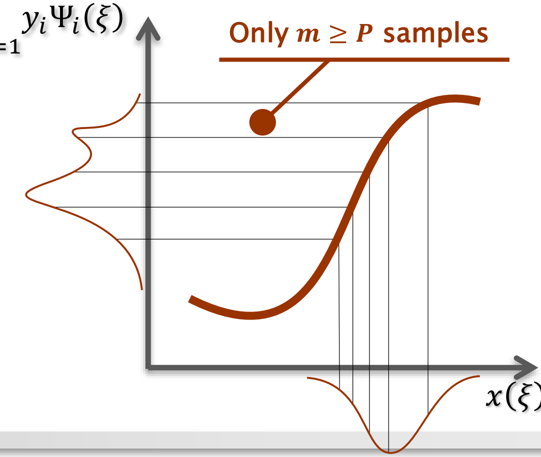


- Simulation-based methods: **Monte Carlo** (MC) (prohibitively expensive, here used for benchmarking -ground truth-)

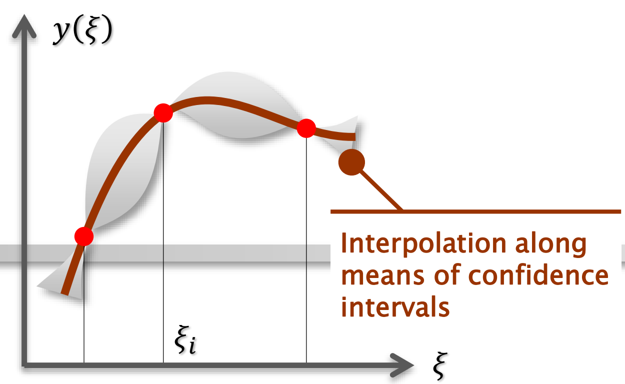
Not suitable

- ~~Local expansion-based methods (only linear models and few uncertain inputs)~~

$$y(\xi) = \sum_{i=1}^{P} y_i \Psi_i(\xi)$$



- Functional expansion-based methods:
  - **Non-Intrusive Polynomial Chaos** (NIPC) ▶
  - **Kriging** ▶



Results

Wind turbine:

Data	Value	Data	Value
Wind class	IEC 3A	Rated electrical power	2 MW
Hub height	80 m	Rotor diameter	92 m
Cut-in	4 m/sec	Cut-out	25 m/sec
Solidity	4.6%	Max V_{tip}	72 m/sec

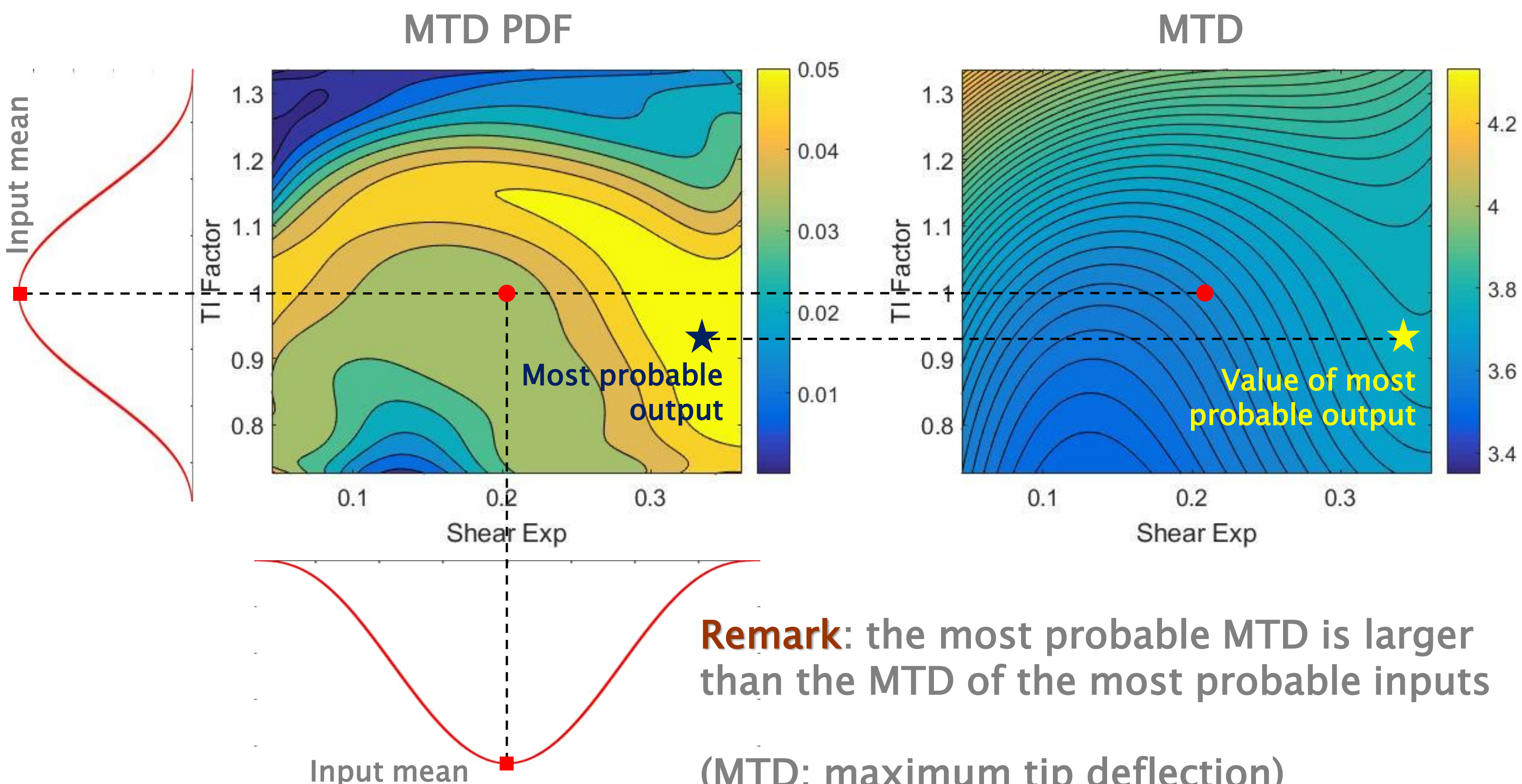
Model: Cp-Lambda aeroservoelastic multibody model (GEB + BEM)

DLCs: IEC 1.1 (Weibull weighting for AEP)

Reference solution: Monte Carlo (>10K samples for convergence of Mean and Std)

Results

Uncertainties: TI & shear; **Method**: NIPC

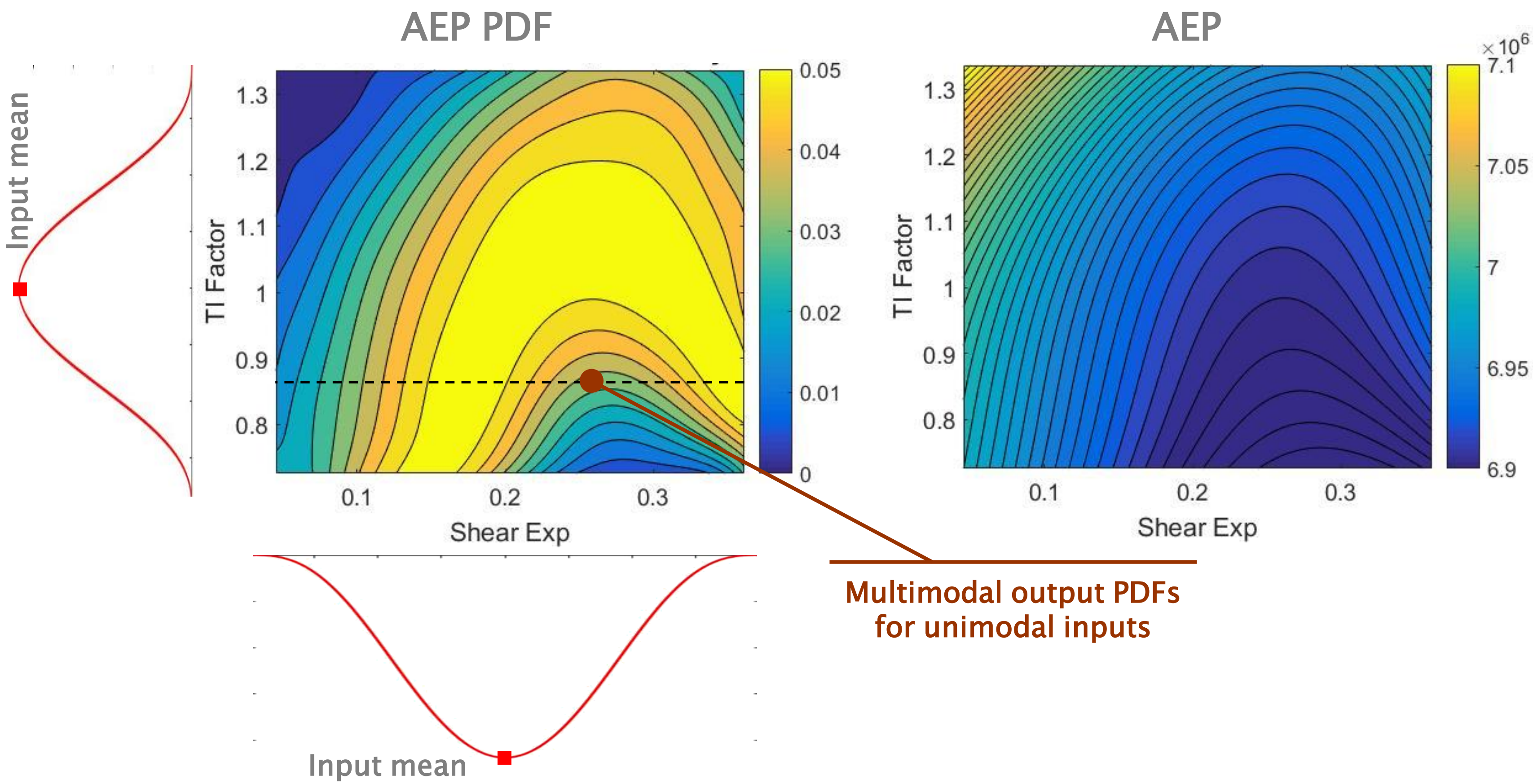


Remark: the most probable MTD is larger than the MTD of the most probable inputs

(MTD: maximum tip deflection)

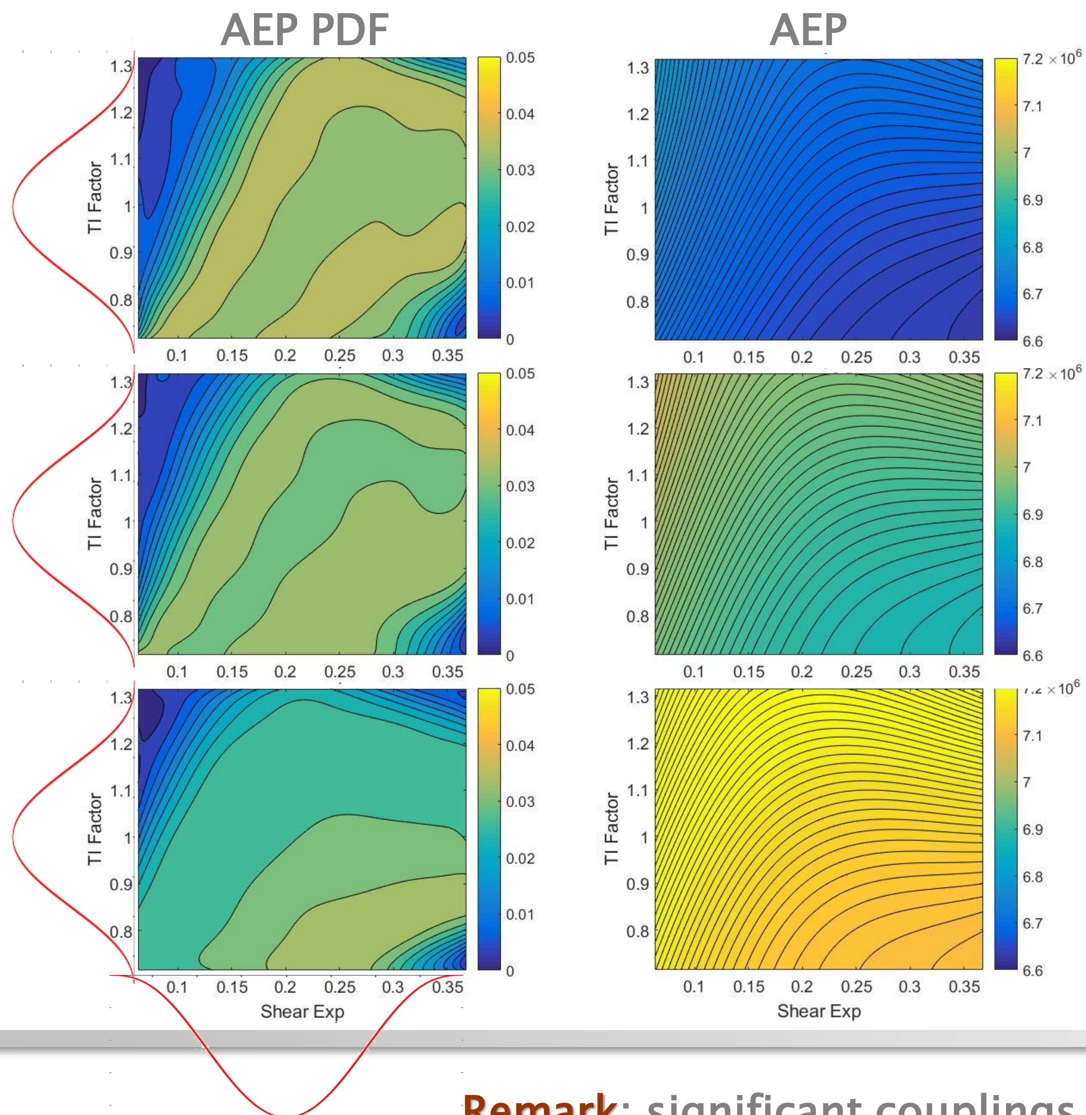
Results

Uncertainties: TI & shear; **Method**: NIPC



Results

Uncertainties: TI, shear & roughness; **Method**: NIPC



Polar factor = 0.25 (almost fully rough)

Polar factor = 0.50

Polar factor = 0.75 (almost clean)

Remark: significant couplings among uncertainties

Conclusions

- **Strong non-linearities**: rigorous uncertainty forward propagation methods are necessary
- **Strong couplings** among uncertainties: individual analysis of uncertainties can be misleading
- **Methods**:
  - Both NIPC and Kriging work well at similar costs, small preference for the latter
  - $\mathcal{O}(10^{1 \div 2})$ samples, Std convergence slower than Mean

Outlook:

- Use UQ for **extreme load calculation** (avoiding extrapolation)
- **Robust design:**
  - How to include uncertainties in the design process?
  - Would the results be significantly different?