DNV GL – RENEWABLES ADVISORY

UNCERTAINTY QUANTIFICATION TECHNIQUES IN WIND TURBINE DESIGN

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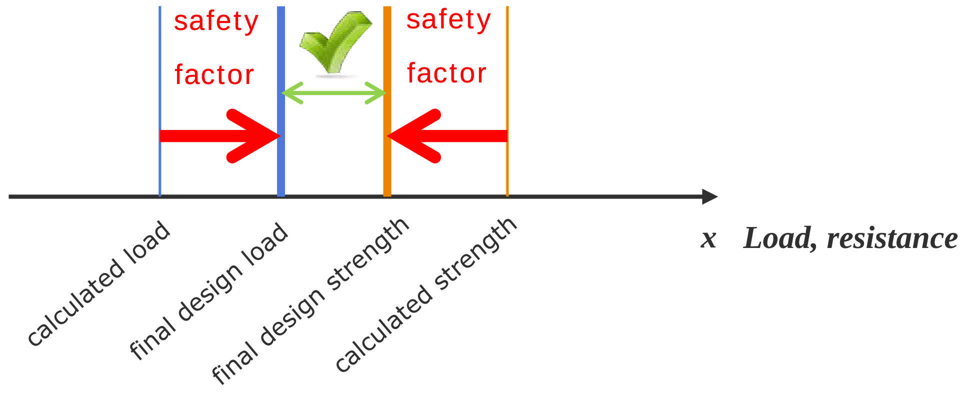
SAFER, SMARTER, GREENER

“The world is noisy and messy.
You need to deal with the uncertainty”

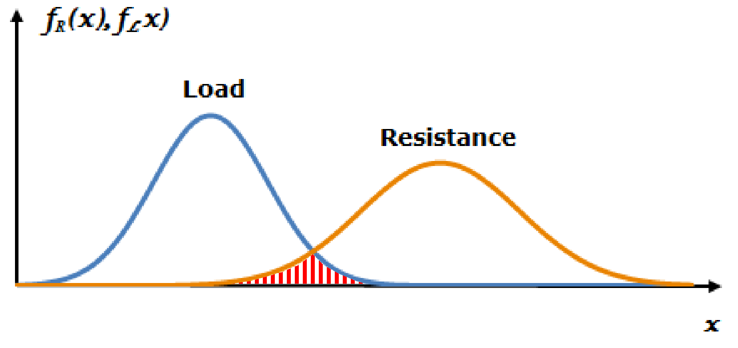
- Daphne Koller

What is probabilistic design? – the technical concept

deterministic approach



probabilistic approach



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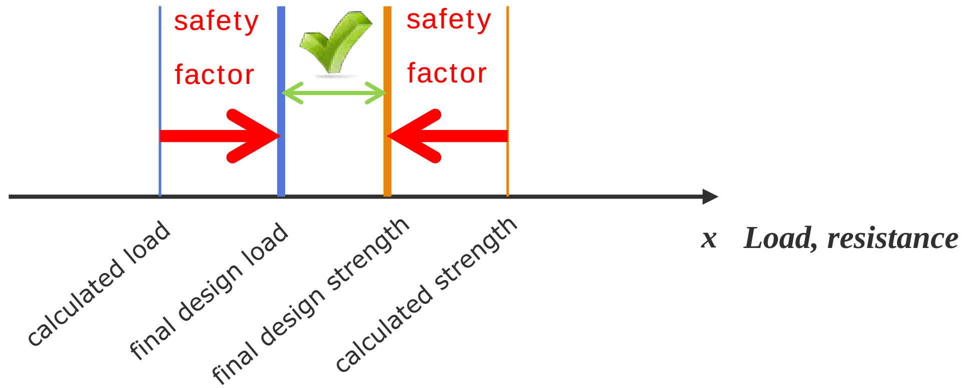
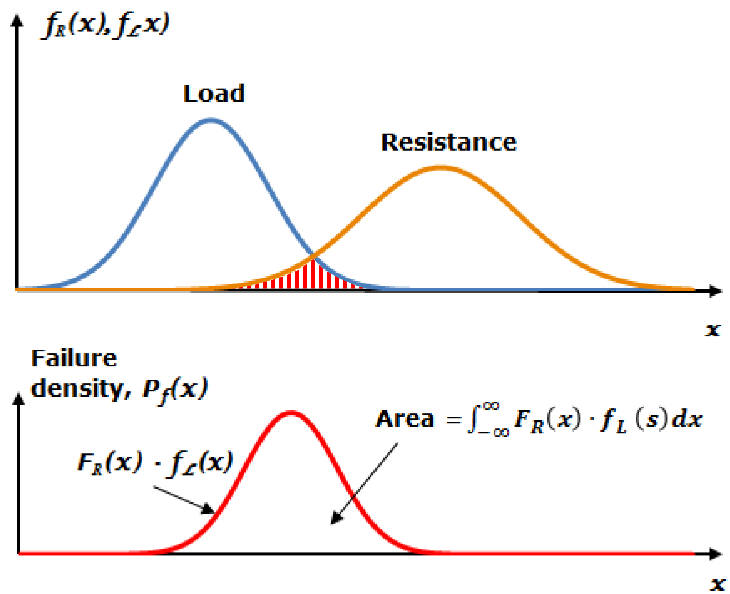
What is probabilistic design? – the technical concept

standard approach



probabilistic approach



Annual probability of failure **(P_f) < ~5e-4**

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Content Uncertainty Quantification in Wind Turbine Design

the **sources** of uncertainty

the **quantification** of uncertainty

- at the **component** level
- at the **system** level

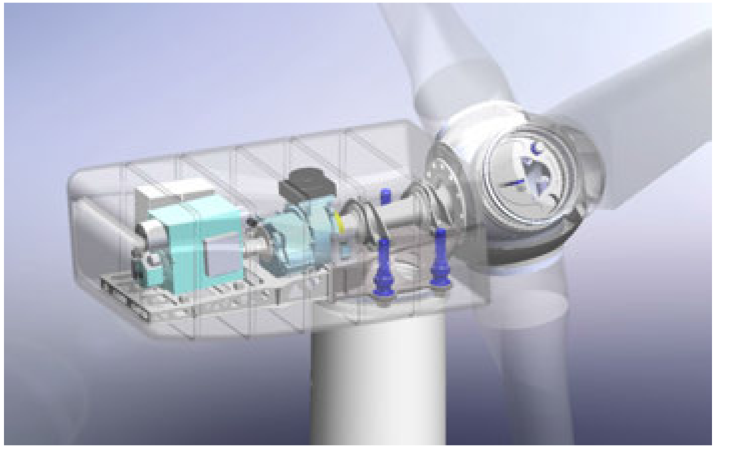
the **future** of uncertainty

The **Sources** of Uncertainty

Two fundamental types of uncertainty in a design process:

- **Aleatoric uncertainty** - physical (objective) variation

- **Epistemic uncertainty** - subjective knowledge



In principle:

Aleatoric is fixed (unless you alter the physical system)

Eg. turbulence, material yield/fatigue strength

Epistemic is reducible (if better knowledge or more information is available)

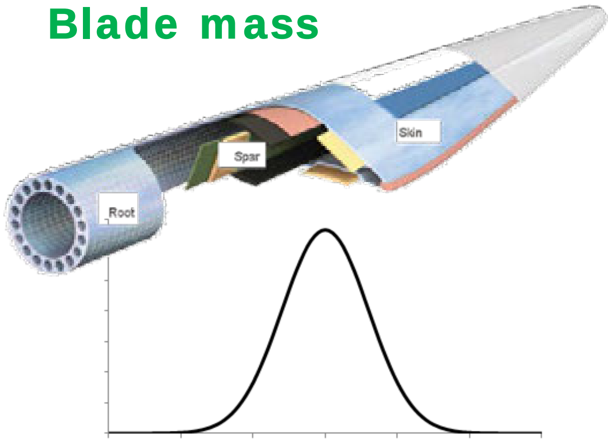
Eg. site conditions parameters (AMWS, Iref), aerodynamic models

The Sources of Uncertainty

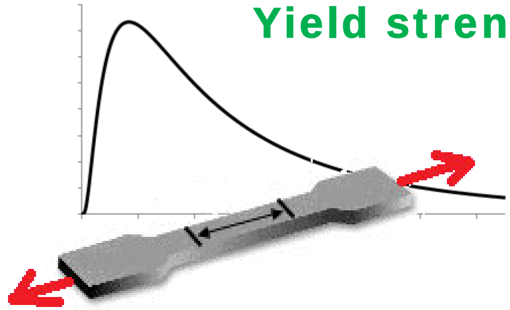
Uncertainty can reside in both the inputs to a design model, and the model itself -

Uncertainty quantification: some source examples

Blade mass

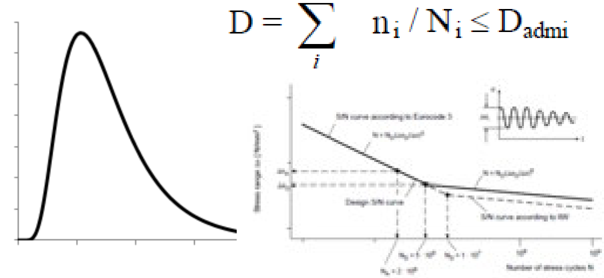


Yield strength

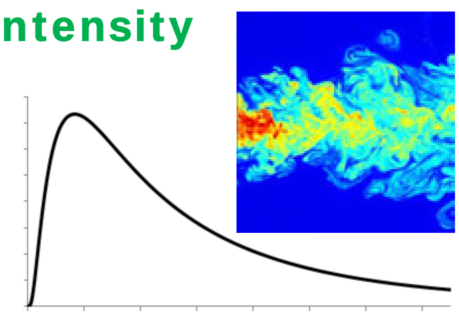


Miner's rule

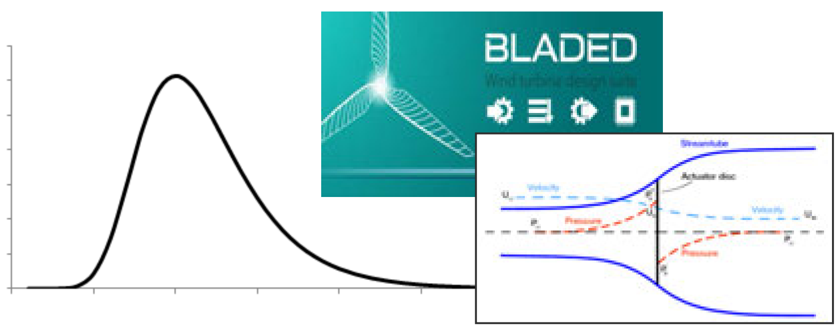
$$D = \sum_i n_i / N_i \leq D_{admi}$$



Turbulence intensity



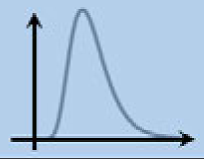
Aerodynamic model



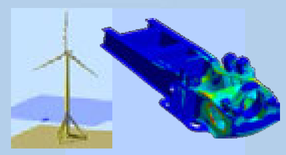
The Quantification of Uncertainty

Step B	Step A	Step C
Quantification of sources of uncertainty	Model(s) of the system Assessment criteria	Uncertainty propagation

Random variables



→ Mechanical model



→ Moments
Probability of failure
Response PDF
...

For Structural Reliability Analysis (SRA), the model is defined by:

Limit state function:

G(X,Y) = S(X) – L(Y), G < 0: failure

L: load model
S: strength model
X,Y: stochastic parameters

Probability of failure = P[G<0] ⟶ calculated using numerical methods
(FORM, SORM, Montecarlo,...)

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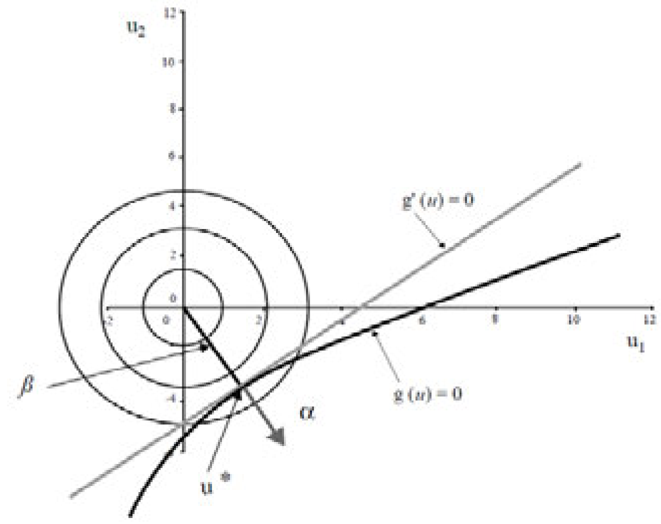
The **Quantification** of Uncertainty

Step C: Propagation Techniques



A statisticians play-ground!

Numerous methods available[1]:

- Linear perturbation
- Monte Carlo simulation
- First/Second Order Reliability Methods
- Advanced spectral methods (chaos expansions)
- Gaussian emulators
- etc, etc…

[1] e.g., Sudret. B., "Uncertainty propagation and sensitivity analysis in mechanical models – contributions to structural reliability and stochastic spectral methods", doctoral thesis, Université Blaise Pascal, 2008.

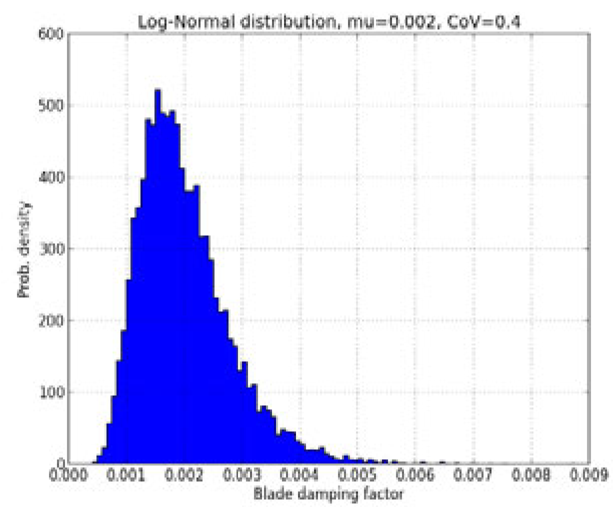
The Quantification of Uncertainty

An example…

UQ using linear perturbation: $$M(x) = M(x_0) + \sum_{i=1}^{M} \frac{\partial M}{\partial x_i}\bigg|_{x=x_0} (x_i - x_{0,i})$$

Full fatigue and extreme IEC load envelopes run for generic 7MW turbine with following model inputs perturbed:

Parameter	Variation	Probability Distribution
Tower Young's Modulus	+/- 5%	Normal (μ=1.0, σ=0.05)
Tower density	+/- 5%	Normal (μ=1.0, σ=0.06)
Tower damping factor	0.001, [0.005], 0.01	Lognormal (μ=0.005, σ=0.4)
Blade Young's Modulus	+/- 5%	Normal (μ=1.0, σ=0.05)
Blade mass	+/- 5%	Normal (μ=1.0, σ=0.06)
Mass imbalance	+/- 1%	Normal (μ=1.0, σ=0.05)
Blade damping factor	0.001, [0.005], 0.01	Lognormal (μ=0.002, σ=0.4)
Blade Xp stiffness	+/- 5%	Normal (μ=1.0, σ=0.05)
Blade Yp stiffness	+/- 5%	Normal (μ=1.0, σ=0.05)
Nacelle mass	+/- 10%	Normal (μ=1.0, σ=0.05)

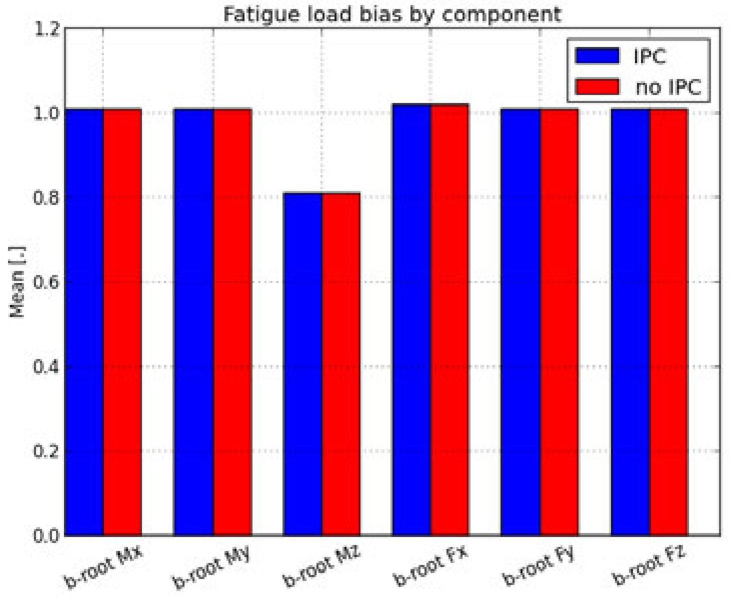


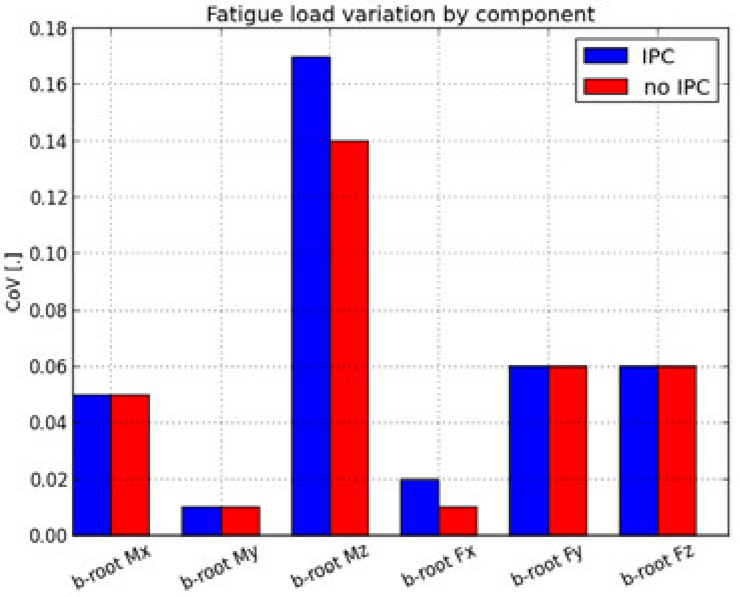
The Quantification of Uncertainty

An example…

UQ using linear perturbation: $M(x) = M(x_0) + \sum_{i=1}^{M} \frac{\partial M}{\partial x_i}\Big|_{x=x_0} \left(x_i - x_{0,i}\right)$

Stochastic response of key outputs quantified (expected and COV):





Load response COV generally < 6%, blade root Mz > 15%

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Uncertainty at the **component** level

An example…

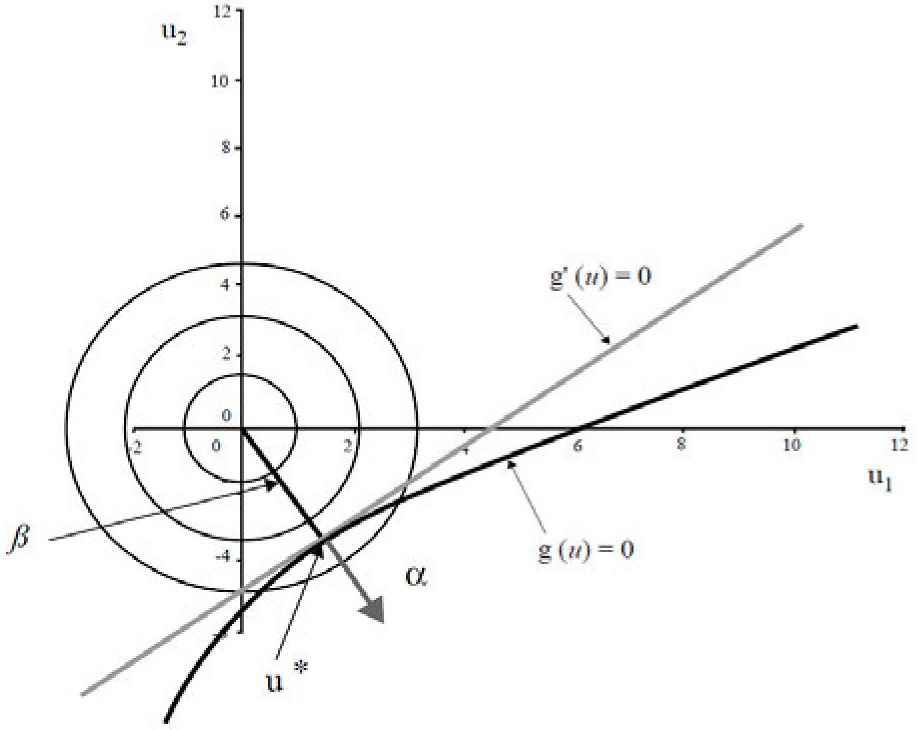
UQ using Structural Reliability methods (e.g., FORM/SORM):

First/Second Order Reliability Methods used to assess the tail behaviour of limit state G-functions.

G(X,Y) **G** < 0: failure

X: Load-related parameter
Y: strength-related parameter

Probability of failure = P[G<0]



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Uncertainty at the component level

An example…

UQ using Structural Reliability methods (e.g., FORM/SORM):

e.g., fatigue analysis of large offshore WTG cast iron mainframe:

Stochastic variables:

Variable	Distribution	Mean	COV	S.D.
m_{rotor}	Lognormal	1	0.10	0.1
X_{dyn}	Lognormal	1	0.05	0.05
X_{exp}	Lognormal	1	0.05	0.05
X_{aero}	Gumbel	1	0.10	0.10
$X_{lowcycle}$	Normal	1	0.03	0.03
X_{RFCC}	Normal	1	0.05	0.05

Variable	Distribution	Mean	COV	S.D.
$X_{Miner's}$	Lognormal	1	0.30	0.30
$X_{fatstrength}$	Lognormal	1	0.167	0.167
$X_{infcoeff}$	Normal	1	0.02	0.02

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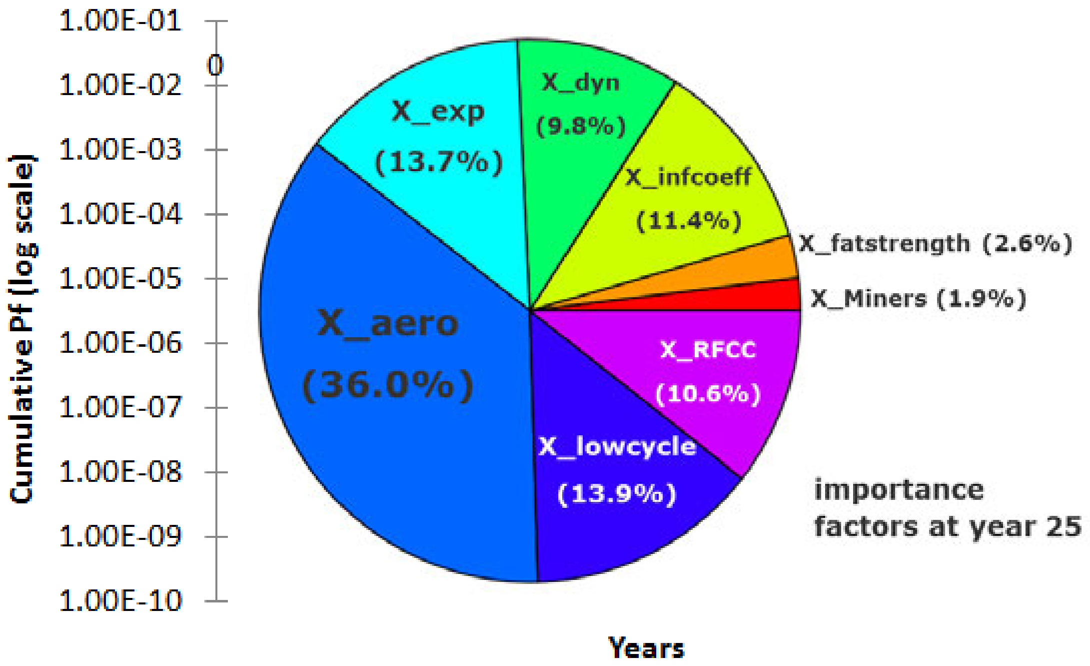
Uncertainty at the component level

An example…

UQ using Structural Reliability methods (e.g., FORM/SORM):

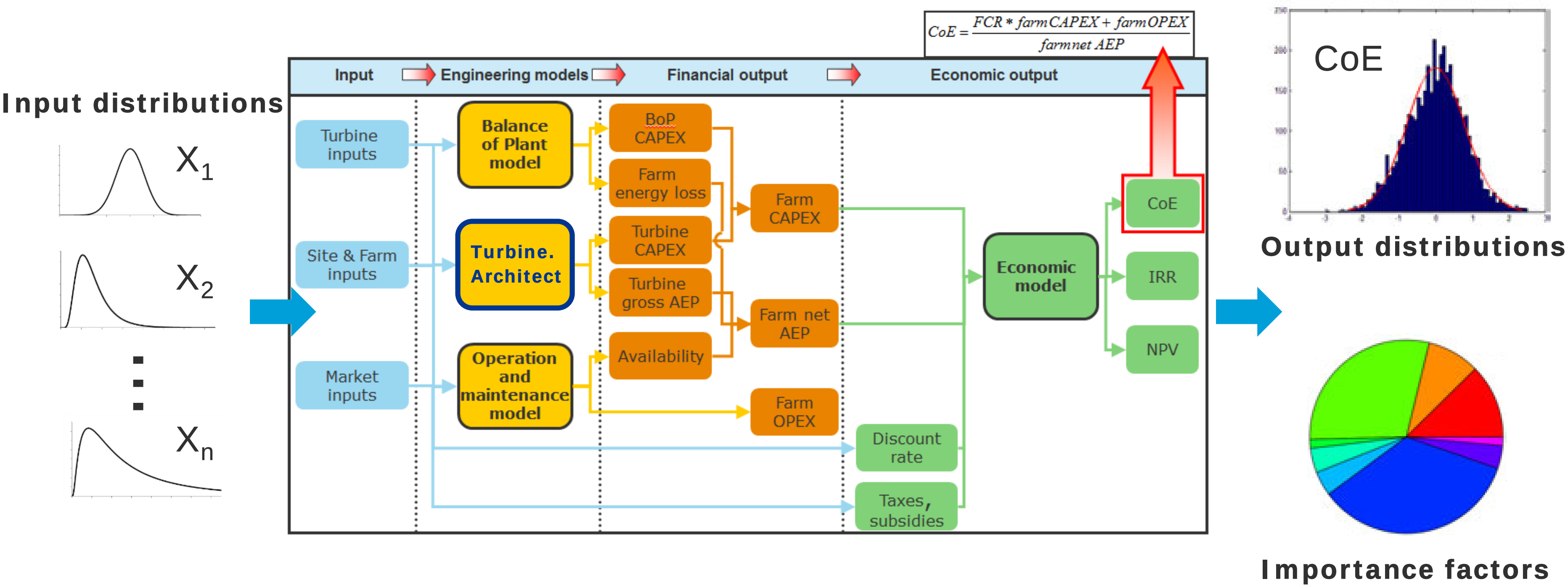
e.g., fatigue analysis of large offshore WTG cast iron mainframe:

Results:



Uncertainty at the system level – Turbine.Architect

- Any input variables relating to the turbine, its installation, and operation within the wind farm can be modelled with associated uncertainty – and sub-models!
- Assess the cumulative impact of uncertainty on output variables such as cost of energy – and understand uncertainty drivers
- Uncertainty propagation using Montecarlo techniques



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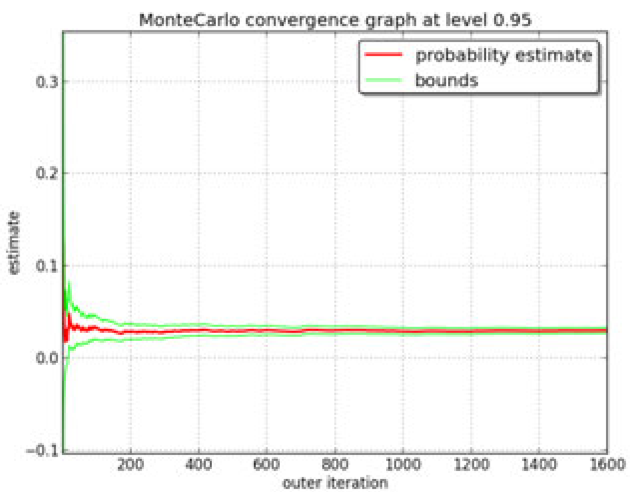
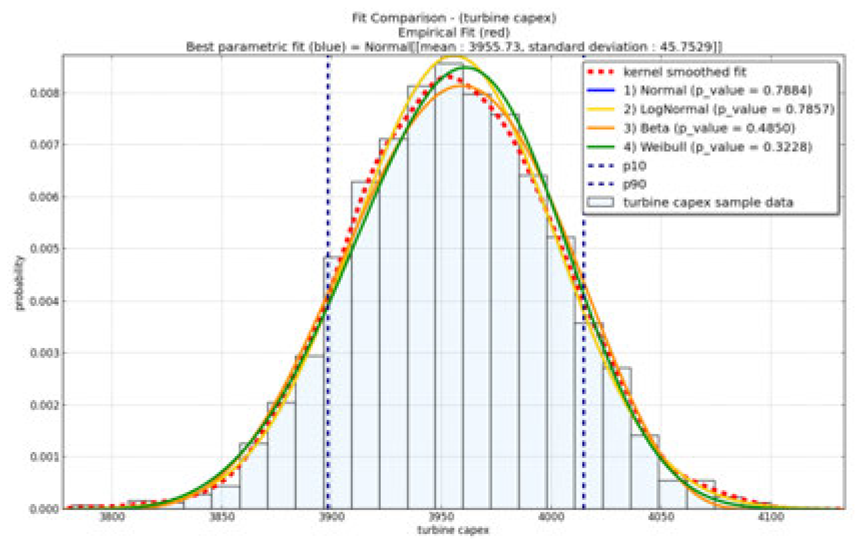
Application to a 7MW offshore turbine design

Uncertainties used in this study:

- Power curve: Normal distribution, as a function of each wind speed
- Turbine availability: Weibull distribution
- OPEX: LogNormal distribution
- Loads (inputs to turbine & sub-structure CAPEX): Truncated Normal, for each load component

Input distributions are then sampled using Monte-carlo algorithm and a distribution fitted to the results





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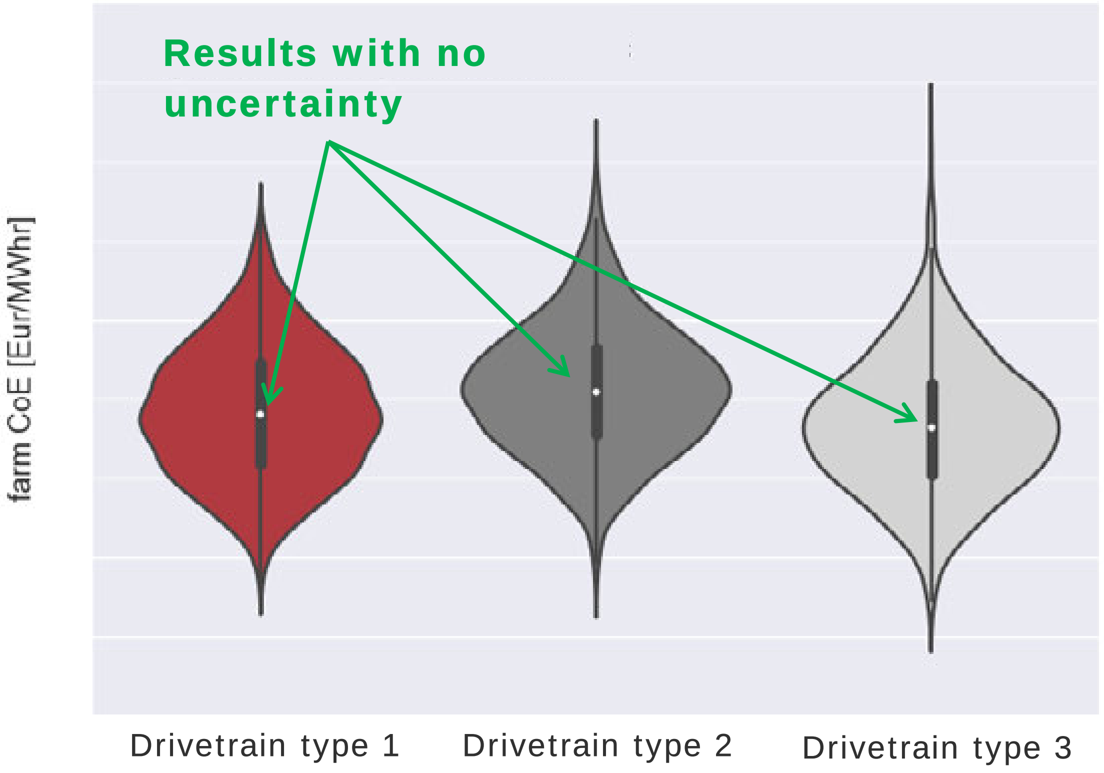
Application to 7MW offshore turbine design : results

- Combined, the CoE central estimates are very close
- Spread shows difference in *robustness* options – decision maker?



Importance factors

% contribution to overall variation

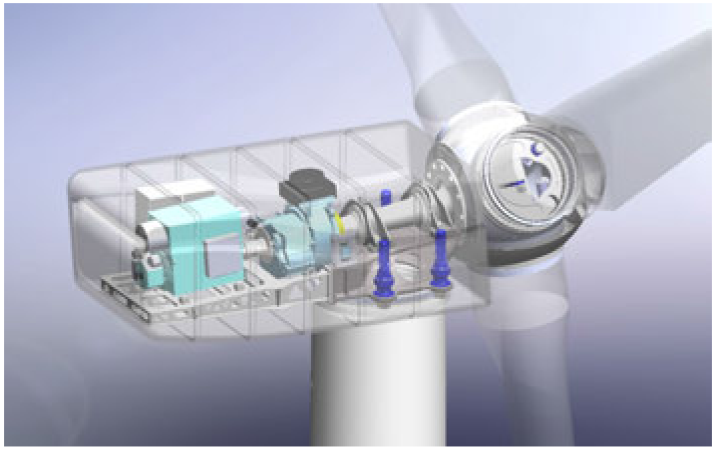
How do we (typically) deal with uncertainty in WTG design today?

i) Improve accuracy of design models (e.g., Bladed, FAST) to reduce bias

ii) Characteristic levels for key design parameters to mitigate under-conservatism

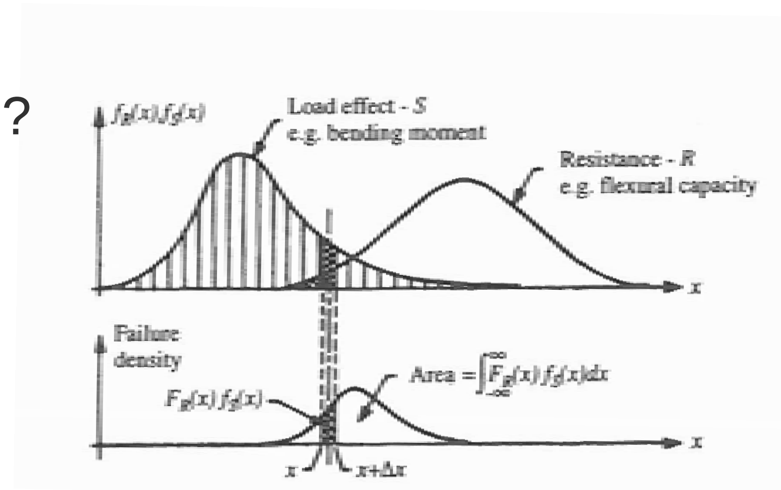
iii) Safety factors for both load and resistance side of design equation

iv) Verify design assumptions with field measurements



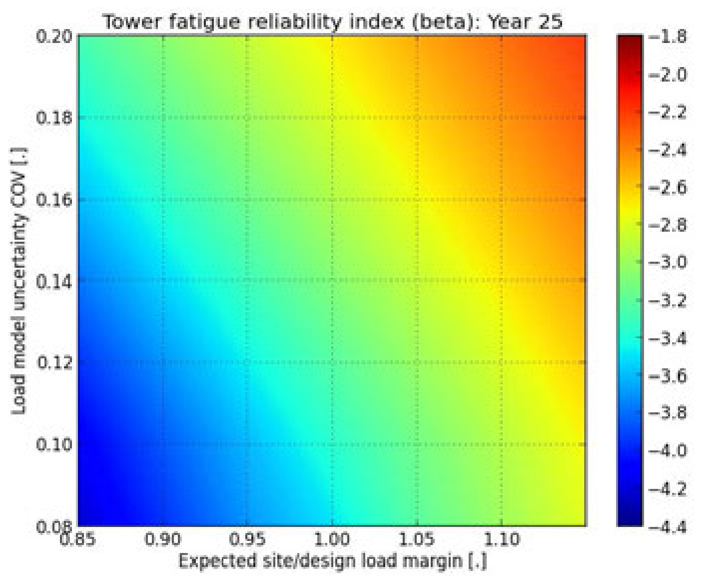
The Future of Uncertainty

A more probabilistic approach to design...?



Pros:

- a more rational basis for design and siting
- a facility to reward 'better' methods, models & monitoring
- a natural vehicle for life-cycle assessment (SIM, life extension etc)



Cons:

- difficulty of implementation
- challenge to standardize
- What about the uncertainties we don't know about?

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Thanks for your attention