DNV·GL

DNV GL ENERGY

TURBINE ENGINEERING SUPPORT

Integrating Bladed with Reliability based design methods

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Bladed User Conference, 8th October 2015, Hamburg

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

- Daphne Koller

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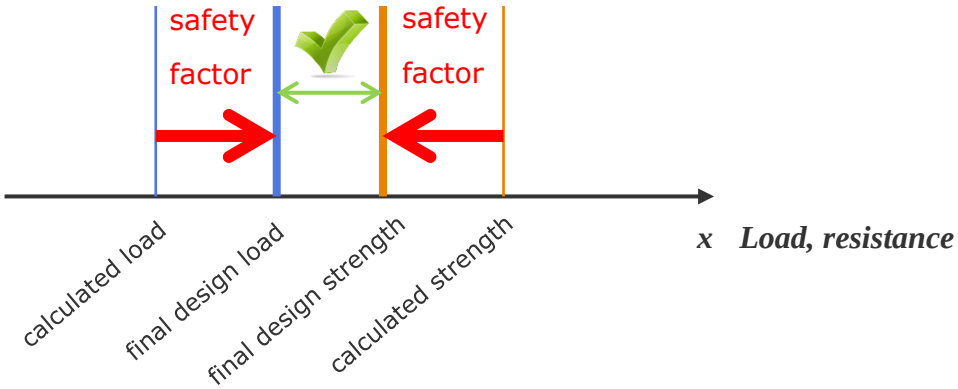
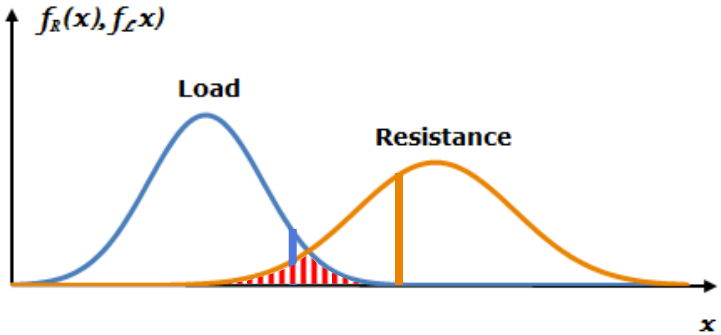
What is probabilistic design? – the technical concept

deterministic approach



probabilistic approach



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What is probabilistic design? – the technical concept

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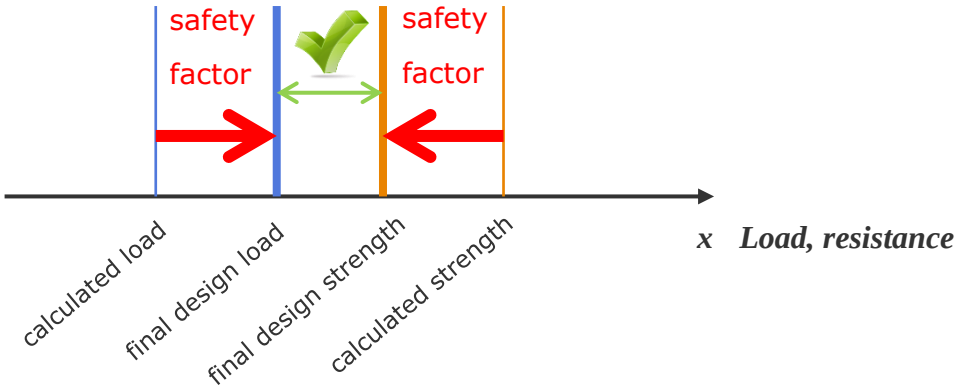
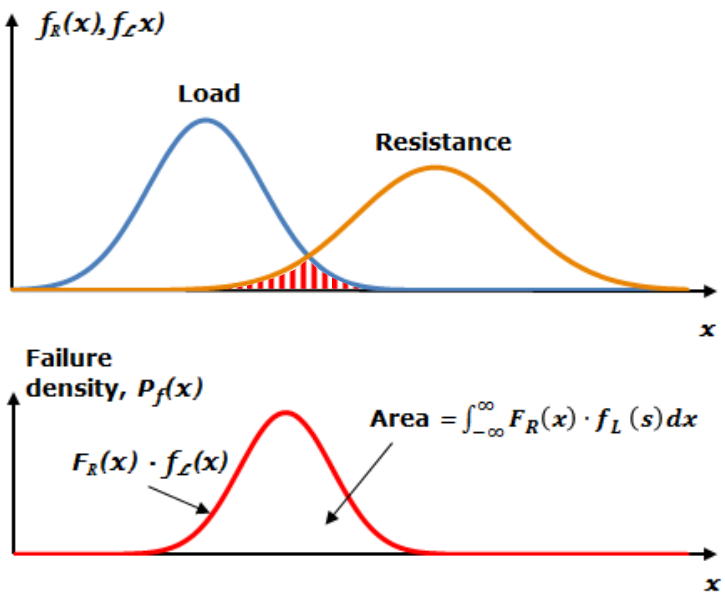


probabilistic approach



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Why probabilistic design? – the technical motivations

i) Current safety-factor based design methods are **potentially over-conservative** – don't treat structural reliability on a entirely rational basis, and

ii) Approaches to life assessment utilized in the wind industry today are **often highly simplistic**

iii) The fourth edition of the **IEC 61400-1** international design standard for wind turbines – due for publication in 2015 – is likely to contain **provision** for more probabilistic-based approaches to design

iv) **GL 2010 & 2012 guidelines** already make provision for the use of more advanced probabilistic-based design methods

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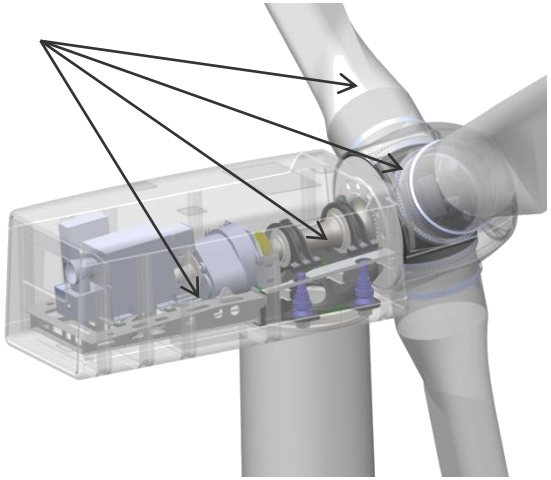
Probabilistic design – the building blocks

- Annual probability of failure calculation for each turbine component (and failure mode) → "Target Pf"~1-5e-4
- Specific probabilities of failure are well understood by year and component
- Treatment of uncertainty in a more rigorous manner
- Consistent level of safety across all turbine components

Ultimate objective: use probabilistic design approach that rationally balances reliability and costs



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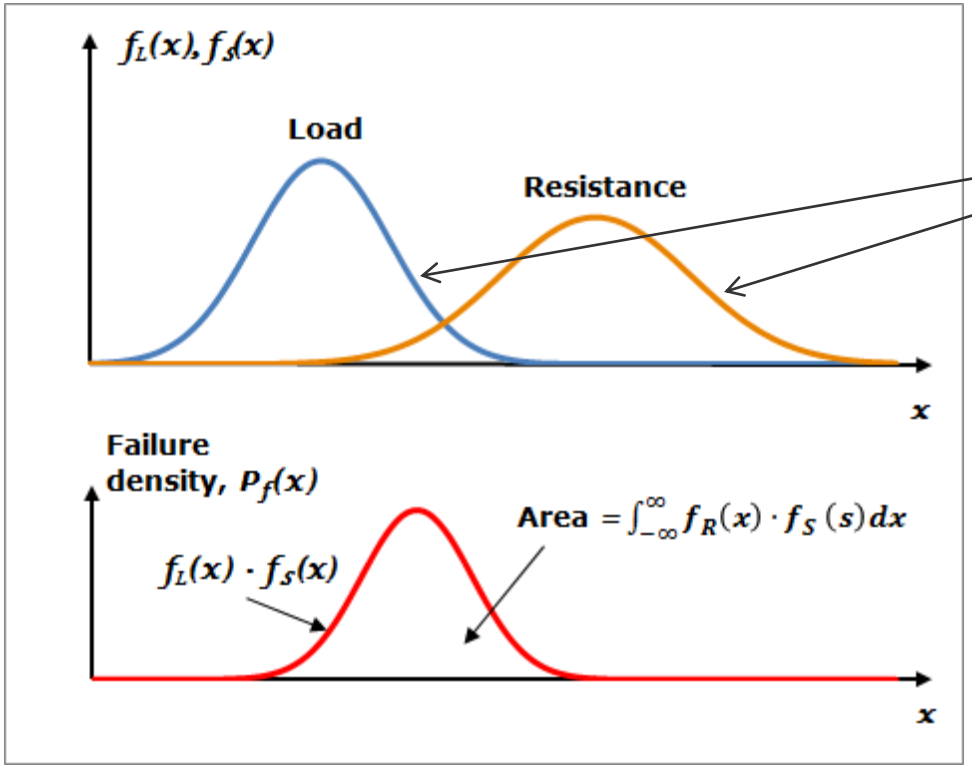
How does probabilistic design proceed? – the technical approach



We need to define these…

… to calculate Annual probability of failure (P_f)

P_f < ~1-5e4

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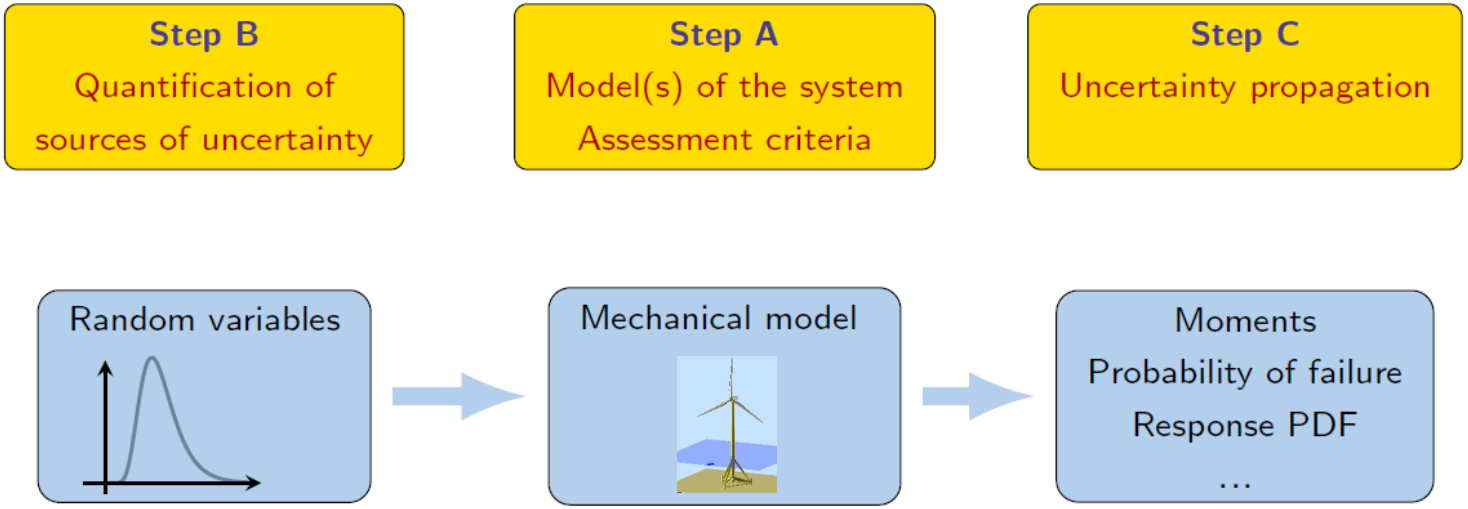
How does probabilistic design proceed? – the technical approach

Three main steps:

- **STEP A:** Define numerical model (eg. Bladed, FEA, etc)
- **STEP B:** Define uncertainties in i) inputs and ii) sub-models
- **STEP C:** Propagate uncertainties through the model



- **STEP C':** Sensitivity analysis

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Step A: Stochastic model set-up

If we are interested in a component '**limit state**', then the model needs to combine load and strength elements:
→ **G – function**

$$G(X,Y) = S(X) - L(Y),\ G < 0\text{: failure}$$

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

Probability of failure = P[G<0]

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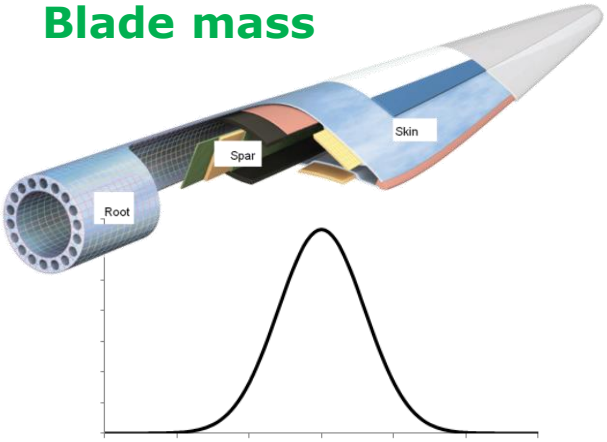
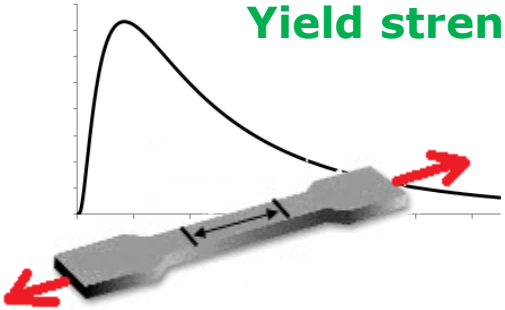
Step B: Uncertainty quantification: some input examples

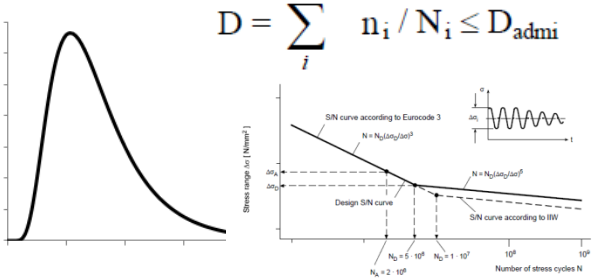
Blade mass



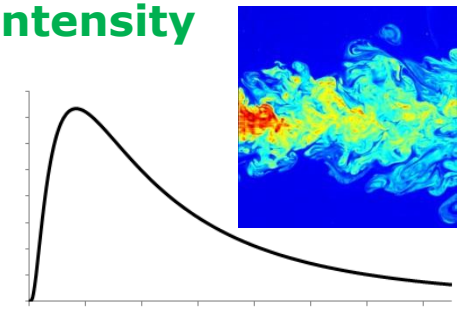
Yield strength



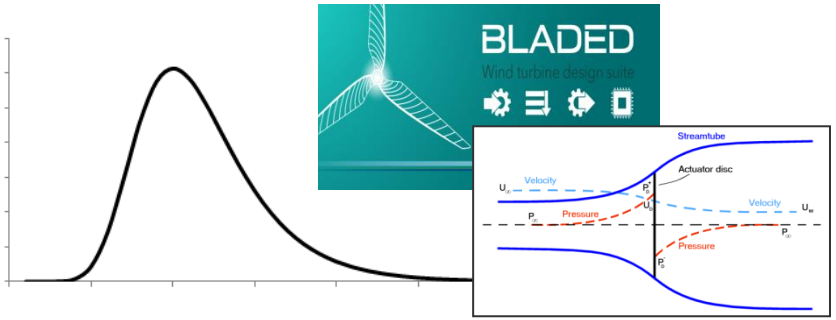
Miner's rule



Turbulence intensity



Aerodynamic model



Step C: Structural reliability analysis, uncertainties propagation

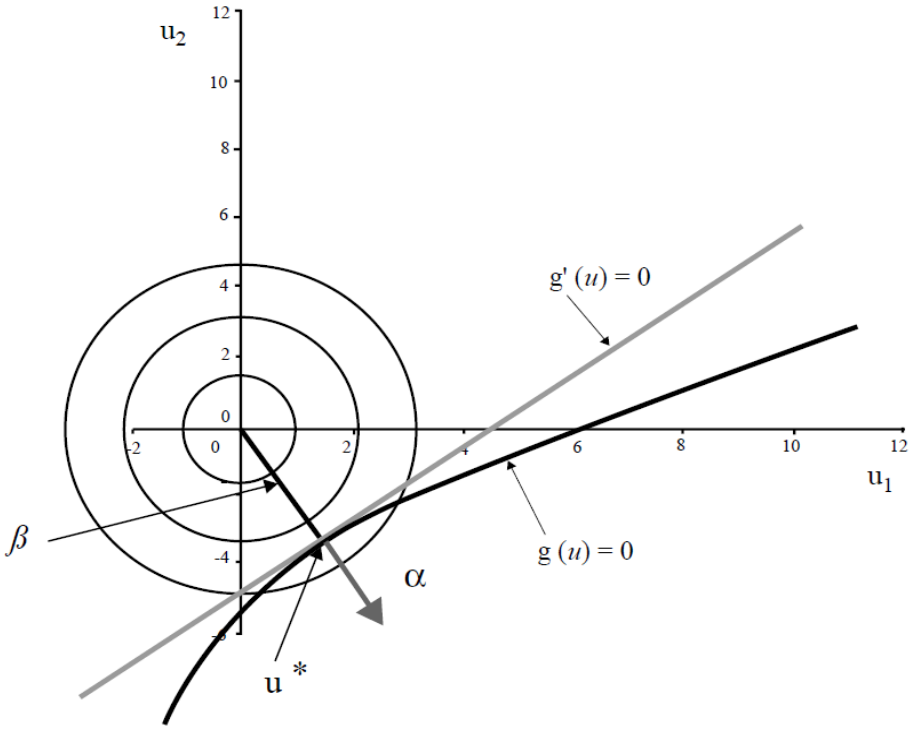
G(X,Y) = S(X) – L(Y), $P_f = P[\mathbf{G} < 0]$

FORM: **F**irst **O**rder **R**eliability **M**ethod, ***SORM***: Second Order…

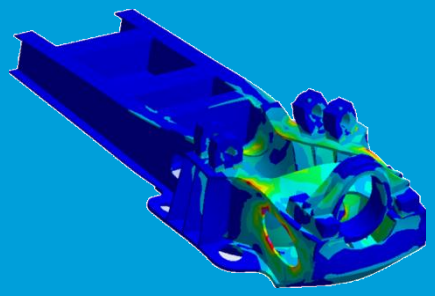
Iso-probabilistic transformation:

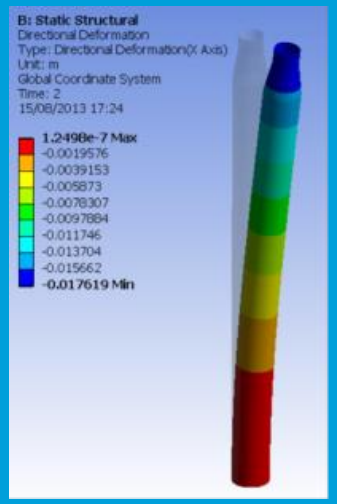
$U_{Xi} = X_i - \mu_{xi} / \sigma_{xi}$

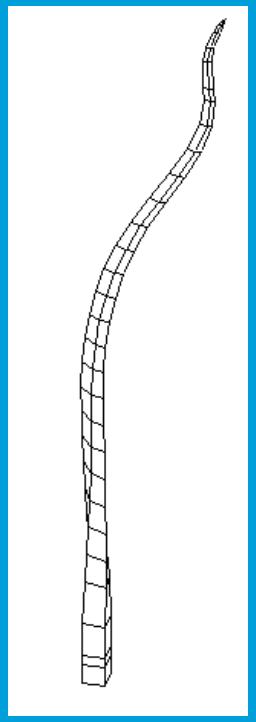
$U_{Yi} = X_i - \mu_{Yi} / \sigma_{Yi}$

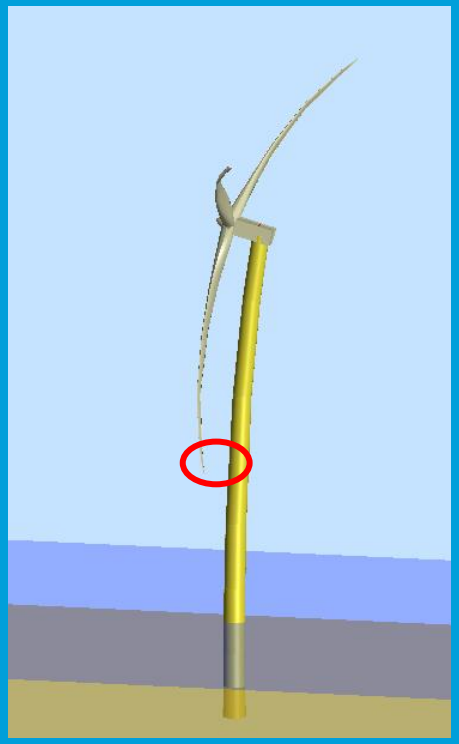


Examples of Structural Reliability Analysis (SRA)



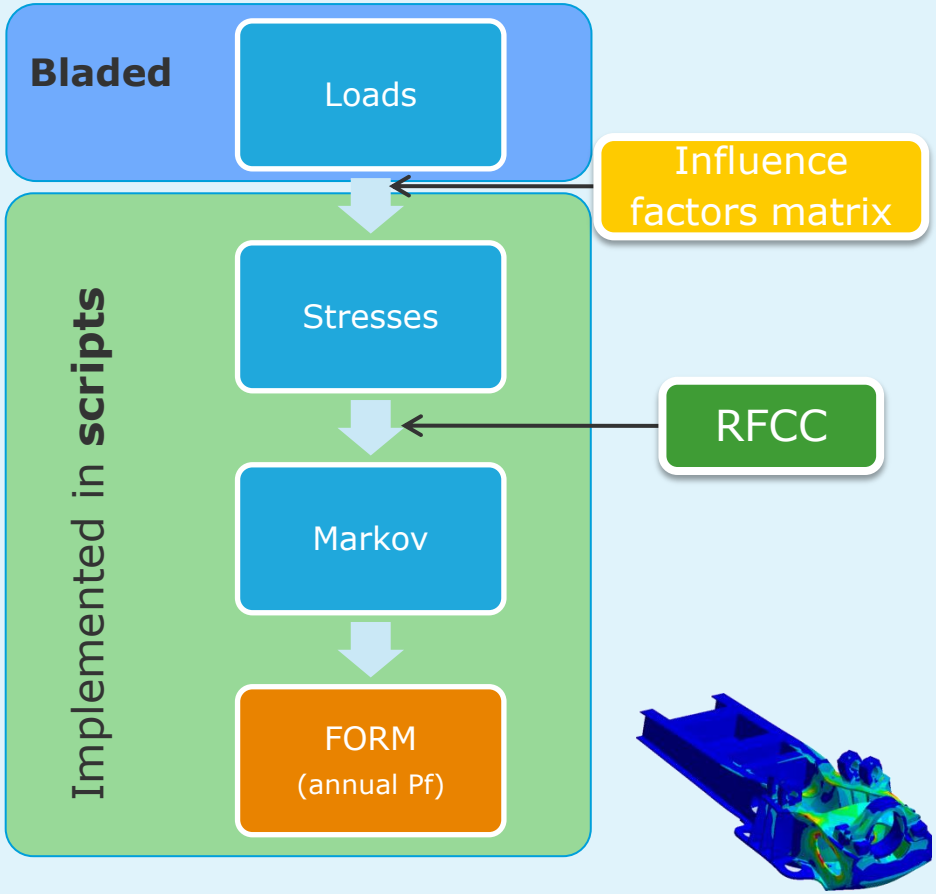




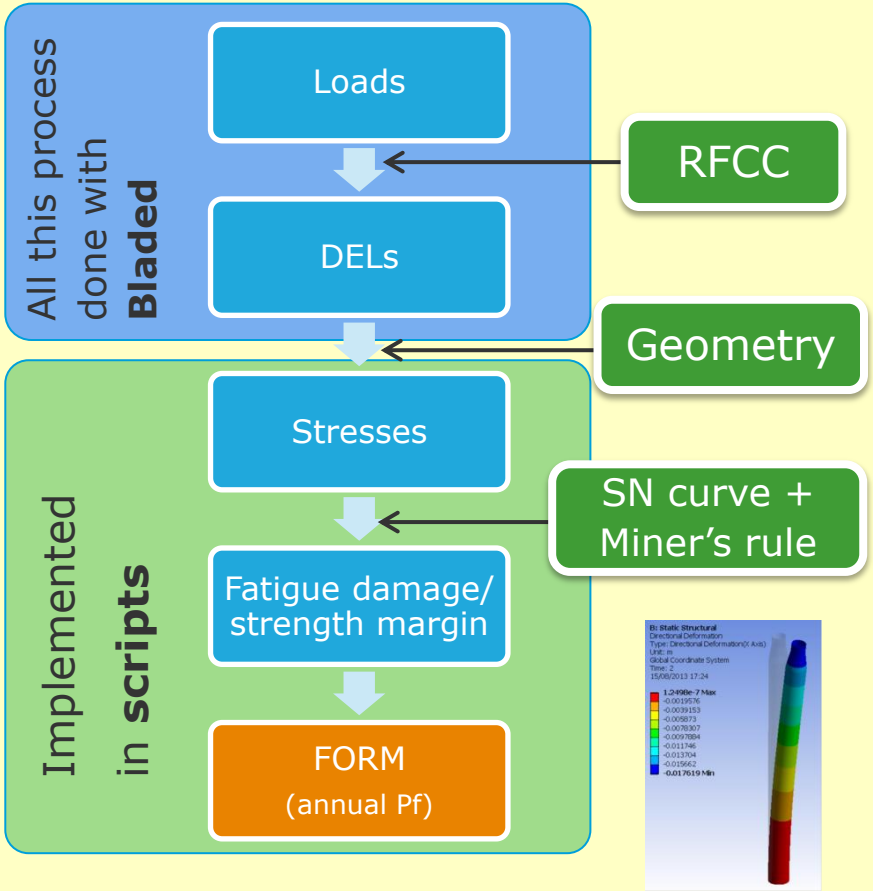


Probabilistic design methods for fatigue limit states

Generalized method for geometrically complex components (**hub, mainframe**)



Simplified method for the **tower**



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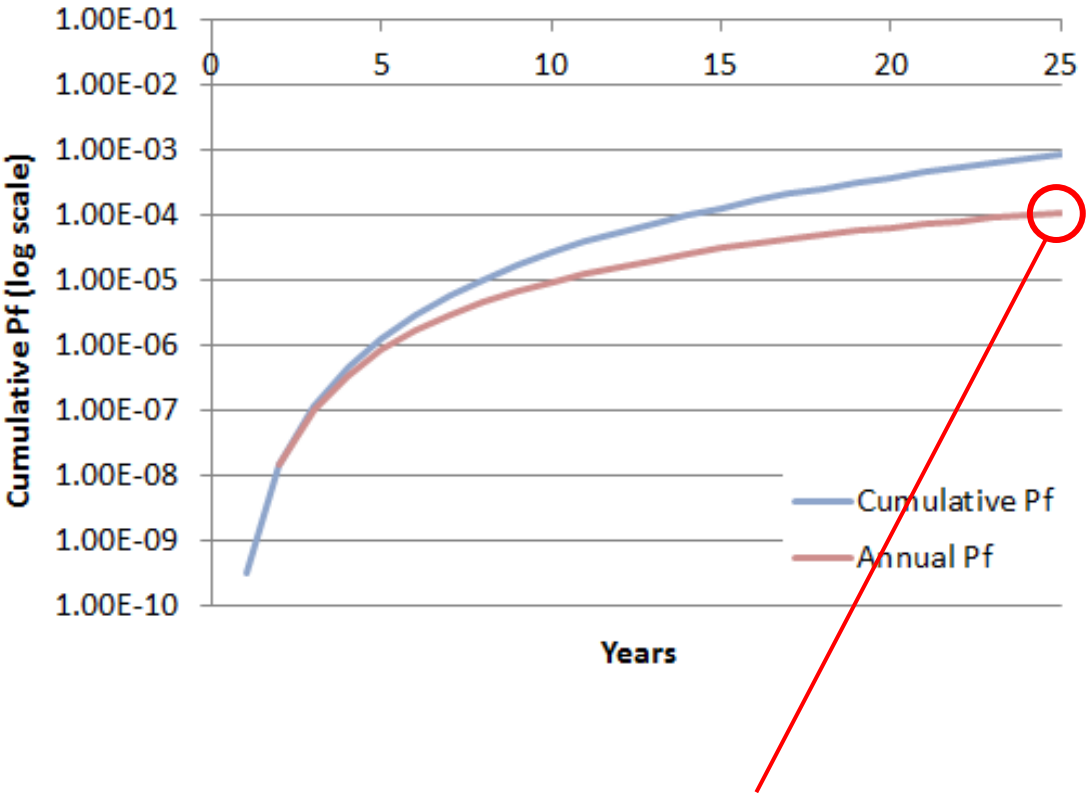
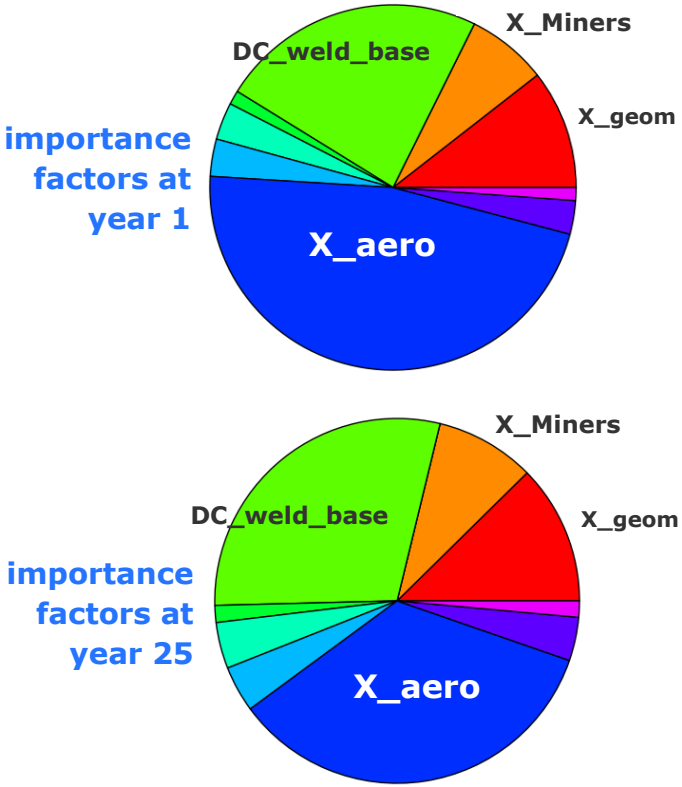
Probability of failure for tower fatigue - example

Probability of failure (Pf) calculated from all fatigue cases using FORM:





Annual P_f at year 25: **1.13e-4** ~ Pf_target (1e-4)

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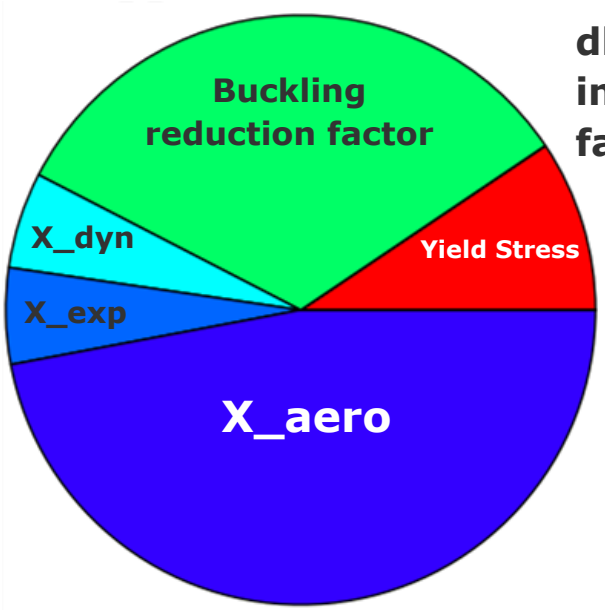
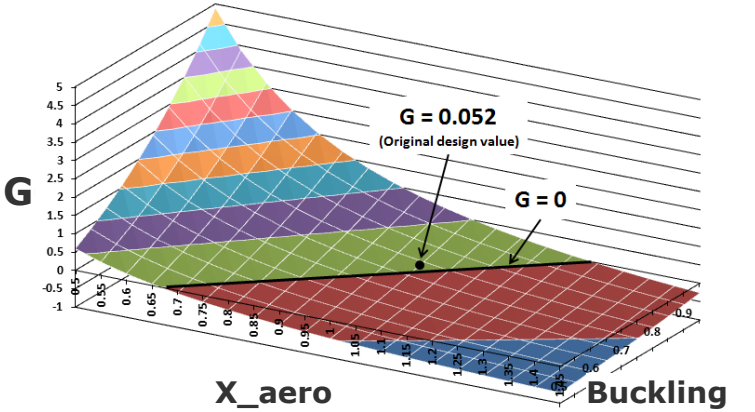
Limit state function for tower buckling – example

- From original design: **Safety Margin ~5%** at worst height, driving uload from dlc4.2
- Probability of failure (Pf) calculated for each DLC independently using FORM:

DLC	Annual Pf (inc. Prob occ)
dlc1.3	
dlc1.4	
dlc1.5	
dlc1.6a	...
dlc2.1	
dlc2.2	
dlc2.3	
dlc4.2	**3.93E-05**
dlc5.1	
dlc6.1a	
dlc6.2a	
dlc6.3a	...
dlc7.1a	
dlc8.1	
dlc8.2	



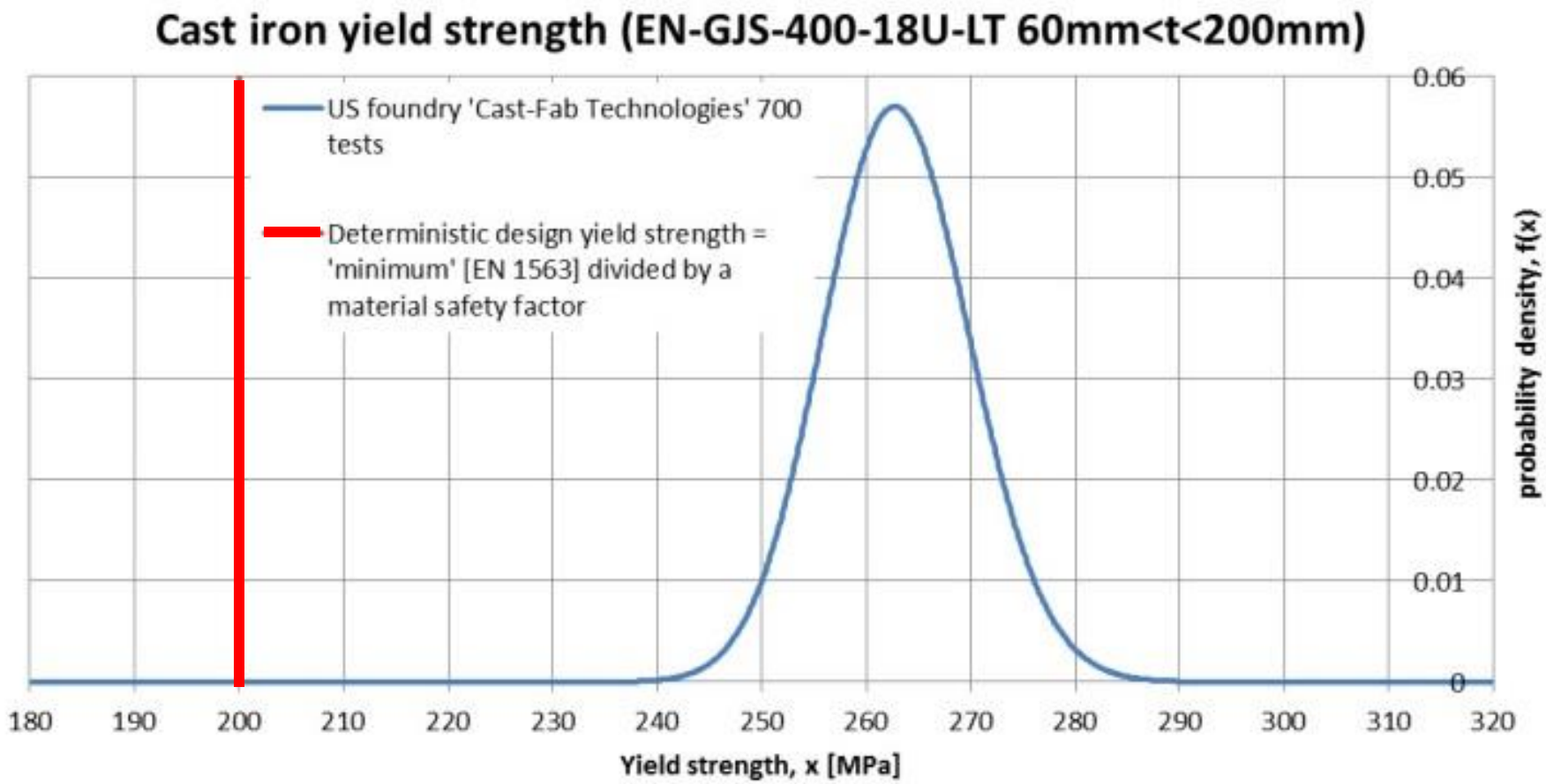
dlc4.2 importance factors



- Pf from dlc4.2: **3.93e-5** < Pf_target (1e-4)

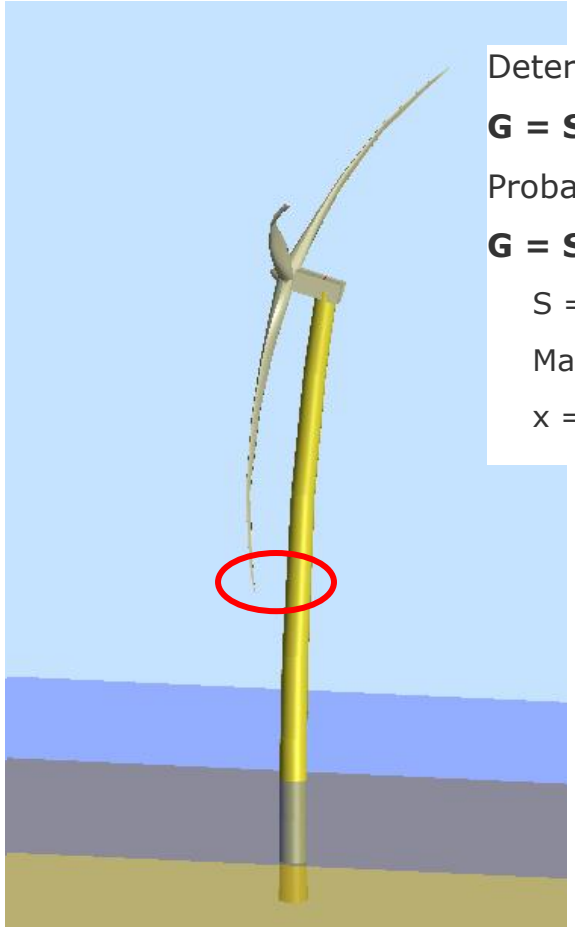
Probability of failure for mainframe extreme – example

- Structural reliability (e.g., FORM) methods enable the design team to incorporate non-generic material strength statistics derived from testing, e.g.,:



Other examples of limit state functions (G)

Tip to tower closest approach



Deterministic approach:

G = S – MaxDef*PSF*1.1

Probabilistic approach:

G = S(x) – MaxDef(x)

S = static clearance

MaxDef = Max blade def in front of tower

x = stochastic variables

Blade flutter point

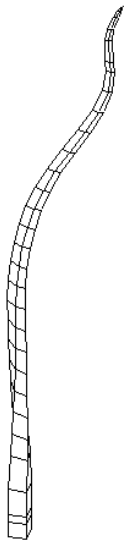
Probabilistic approach:

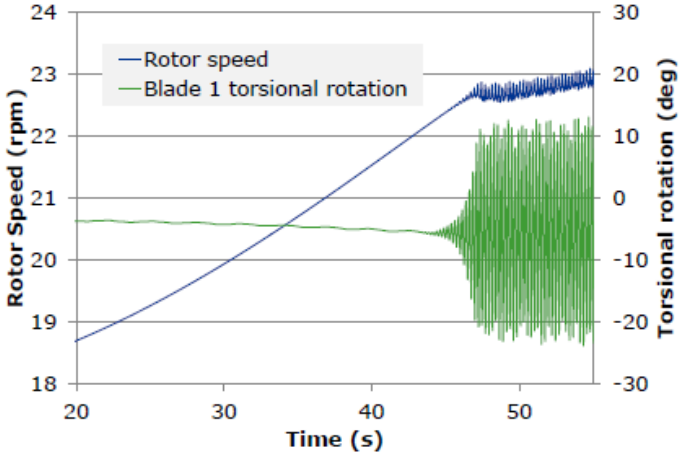
G = 1 – Flutter(x)?

Flutter: 1=Yes, 0=No

x = stochastic variables

for a particular rpm





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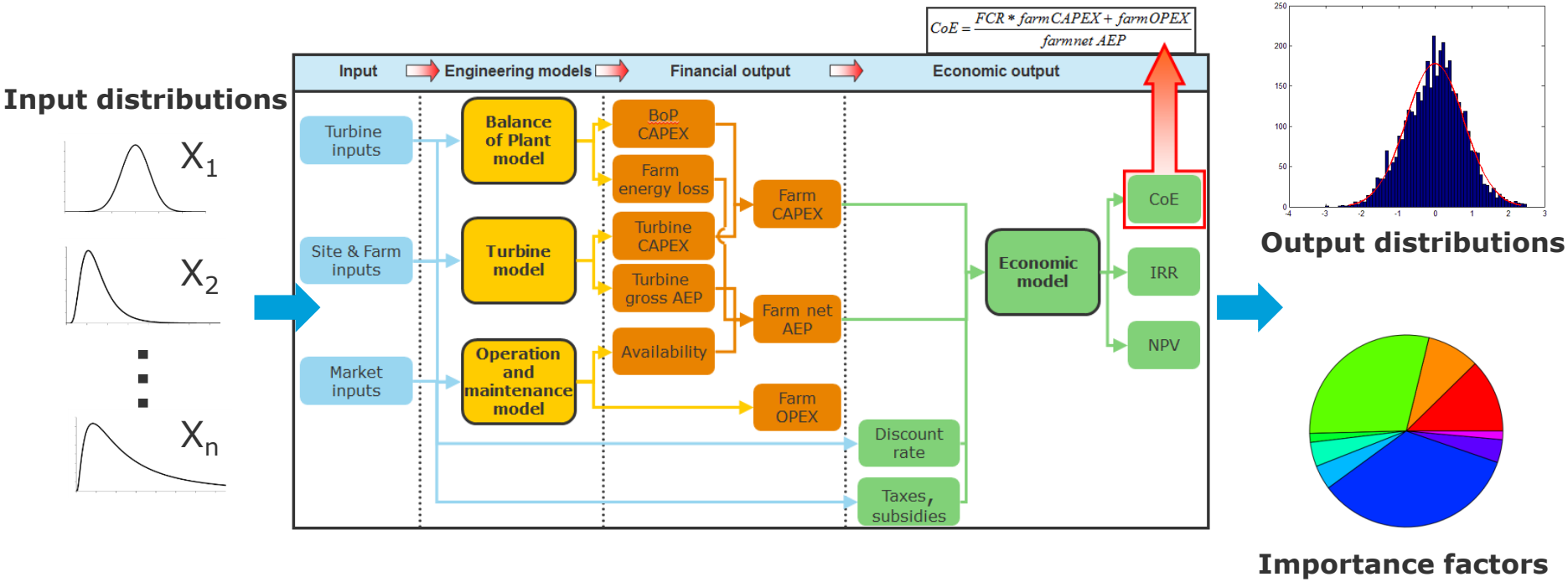
Probabilistic Turbine Conceptual Design Tool

- User can define a large range of probabilistic input variables relating to the turbine, its installation, and operation within the wind farm.
- Assess the cumulative impact of uncertainty on output variables such as cost of energy.
- Probabilistic technology evaluation and quantification of the design space



Probabilistic-based Design Support from DNV GL

- **Uncertainty quantification** analysis for loading and strength models and inputs, including the development of meta-models
- **Stochastic limit state** (g) function development for key structural components
- **Structural reliability analysis** using FORM, SORM and Monte Carlo techniques
- Statistical analysis of **material strength** derived through testing
- Comparison of **probabilistic-based design** outputs with the classical 'safety factor' approach
- Component **life assessment**, integrity management and risk-based inspection
- **Training** and knowledge transfer

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"What we know is a drop.
What we don't know is an ocean"

- Isaac Newton

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Thanks for your attention

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