# Robustness - Offshore Wind Energy Converters

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# Research Project IMO-WIND
# German Federal Institute for Materials Research and Testing (BAM)

- **Development of an integrated monitoring and assessment system for the components structure, rotor blades and machine of Offshore Wind Energy Converters**
- Development and application of new methods for data analysis and early damage detection
- Investigations of the damage behaviour and long-term performance of rotor blades
- Investigations and tests for application of new sensors technologies (fibre optical systems, piezo-sensors) aiming at long-term monitoring

BAM VII.2 Ingenieurbau

BAM V.6 Mechanik der Polymerwerkstoffe

VIII.1 Mess- und Prüftechnik; Sensorik

Universität Siegen – ATM – Fachbereich 11, Institut für Mechanik und Regelungstechnik - Mechatronik, Arbeitsgruppe Technische Mechanik

Germanischer Lloyd OPERATING 24/7

PROKON Nord Energiesysteme GmbH

OWT

μ-sen Sensors Systems Solutions

Infokom GmbH

IGUS Innovative Technische Systeme

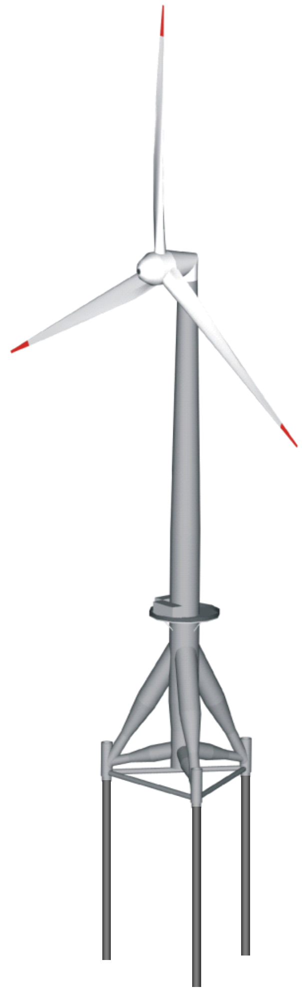
# Assessment of Offshore Wind Energy Converters

**Aims:**

- Online condition information
- Maintenance / repair planning support

**Challenges:**

- Development of overall assessment methods for the integrated system
- Development of quantitative criteria for assessment of the structure
- Design of a monitoring concept for the structure
- Integration of monitoring data in the assessment



Multibrid M5000

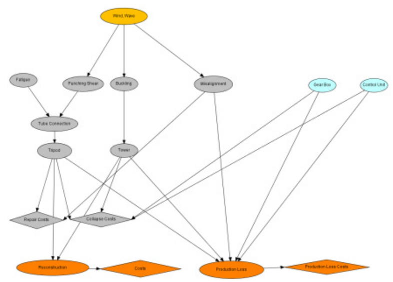
# General Approach

- **Risk Analysis**
    - Scenario definition and simulation
    - Barries and consequence
        - Deterioration processes
        - Gross errors
        - Actions
- Assessment criteria: **robustness** and **structural reliability**
- **Simulation** of **sensor-signals**
- **Field-testing** of **sensors** on prototypes of offshore wind energy converters

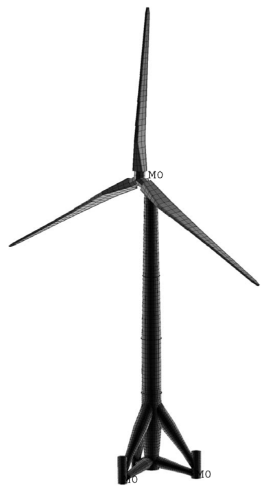
Multibrid M5000, Bremerhaven

# Approach: Methods

- **Bayesian network**
  - Analysis of the overall structural reliability and robustness
  - Incorporation of consequence modelling
  - Integration of the components rotor and machine into the assessment framework



- **Finite-Element-Method** and **Response Surfaces**
  - Simulation of structural reliability for each failure mechanism
  - Simulation of sensor signals

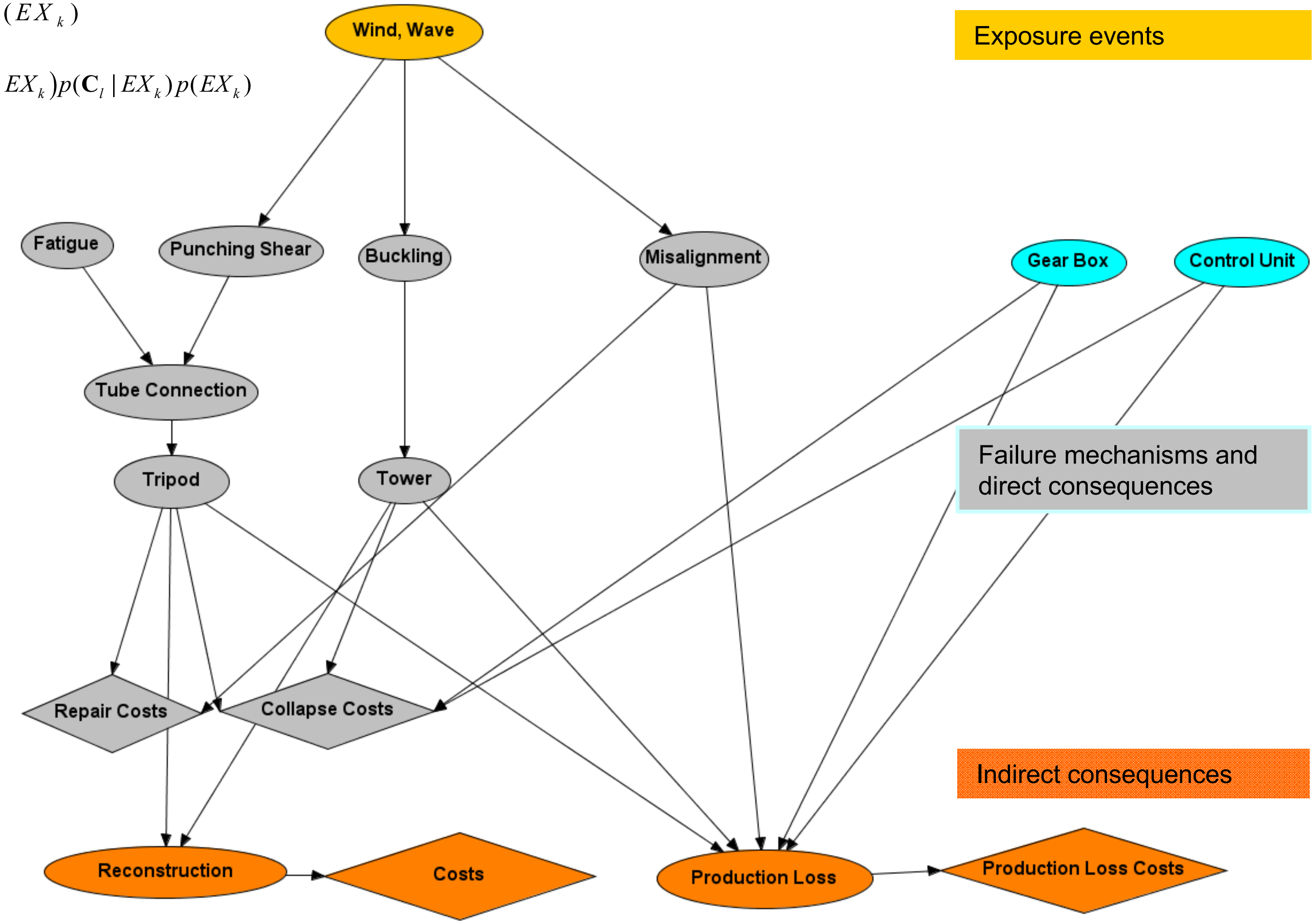


# Approach: Example for a Bayesian Network for Analysis of Robustness

$$R_D = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} c_D(\mathbf{C}_l) \times p(\mathbf{C}_l \mid EX_k) p(EX_k)$$

$$R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l)) \times p(S_m \mid \mathbf{C}_l, EX_k) p(\mathbf{C}_l \mid EX_k) p(EX_k)$$

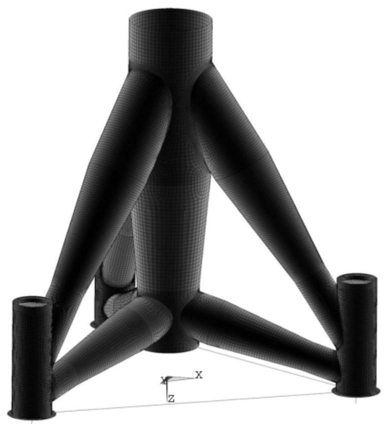
$$I_D = \frac{R_D}{R_{ID} + R_D}$$



# Approach: Structural Reliability with Stochastic Finite Element Simulations

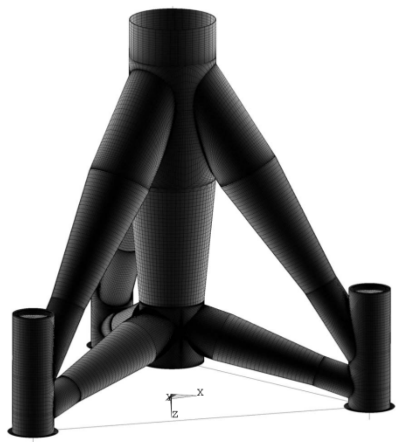
## Ultimate Limit State

3D shell
224 000 elements
118 000 nodes
Nonlinearities: material, geometry, contact



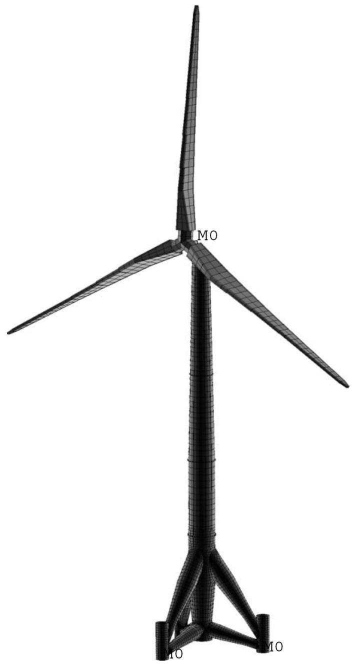
3D shell
213 000 elements
112 000 nodes
Nonlinearities: material, geometry, contact

## Fatigue Limit State



3D solid
342 000 elements
1 700 000 nodes
Nonlinearities: contact

## Modal Analyses



3D shell
16 000 elements
52 000 nodes
Linear

# Structural Reliability: Example for Ultimate Limit State Analysis

**Loading:**

Nacelle / Tower loading based on an overall dynamic analysis

Envelope of ultimate loading

**Simulation:**

Static simulation

Load case and eigenvalue extraction using Block Lanczocs method

**Random variables:**

Imperfections

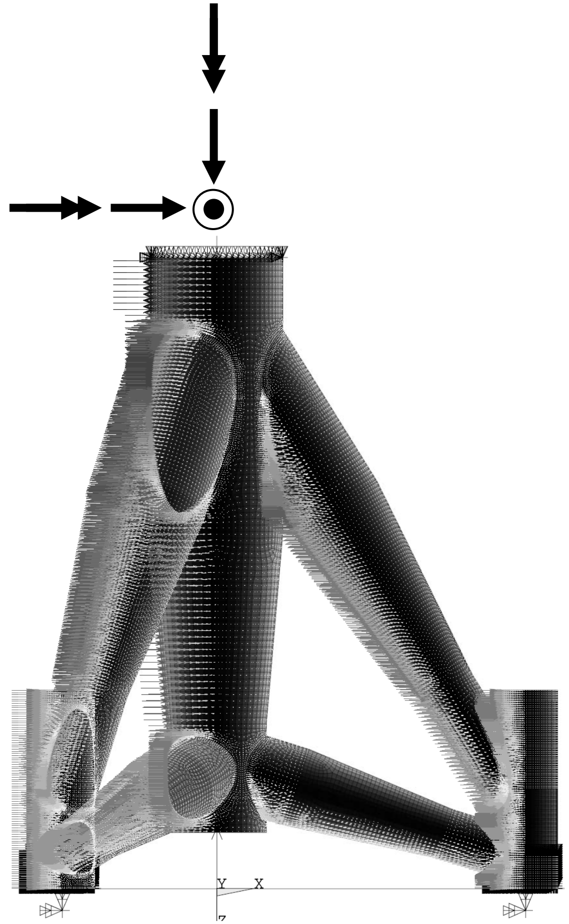
Material thickness

Wind pressure

Nacelle / tower loading

Youngs modulus

Yield stress



# Structural Reliability: Example for Ultimate Limit State Analysis Application of Response Surfaces

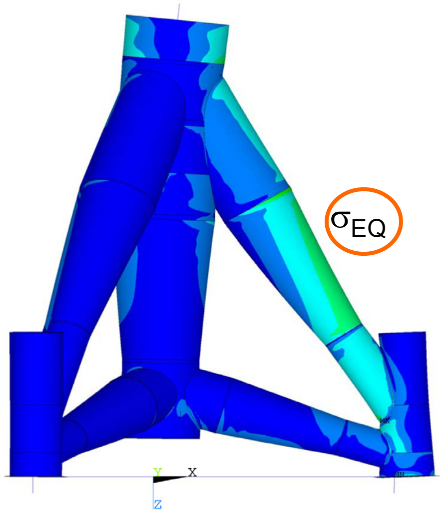
Buckling limit state function for a LA/GNA analyses (Eurocode 3-1-6 (2002)):

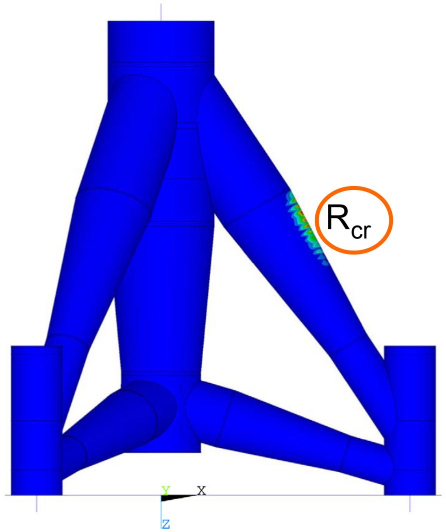
$g = \chi_{ov} R_{pl} - \Delta$ with the buckling reduction factor for entire shell $\chi_{ov} = f(\bar{\lambda})$

$R_{pl} = \frac{f_{y,k}}{\sigma_{EQ}}$ - Ultimate loading factor

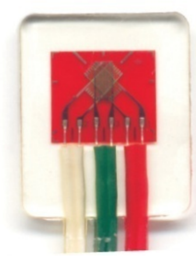
$\bar{\lambda}_{ov} = \sqrt{R_{pl} / R_{cr}}$ - Normalised slenderness ratio for the entire shell

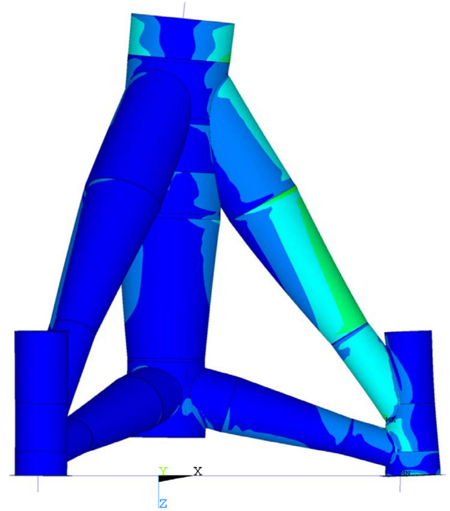
$R_{cr}$ - Ideal buckling load




Simulation of sensor data:



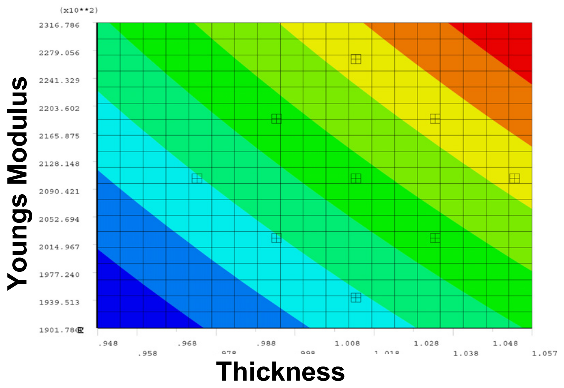


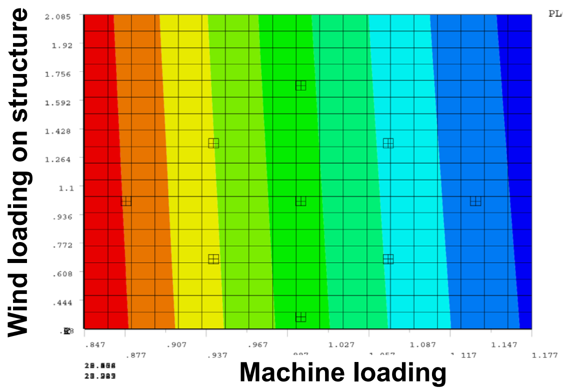
# Structural Reliability: Example for Ultimate Limit State Analysis Application of Response Surfaces

**Design of experiments** for response surface:

- Fractional central composite design
- Resolution V design
- 27 simulations for 5 random variables

**Response surfaces** for parameter ideal buckling load $R_{cr}$

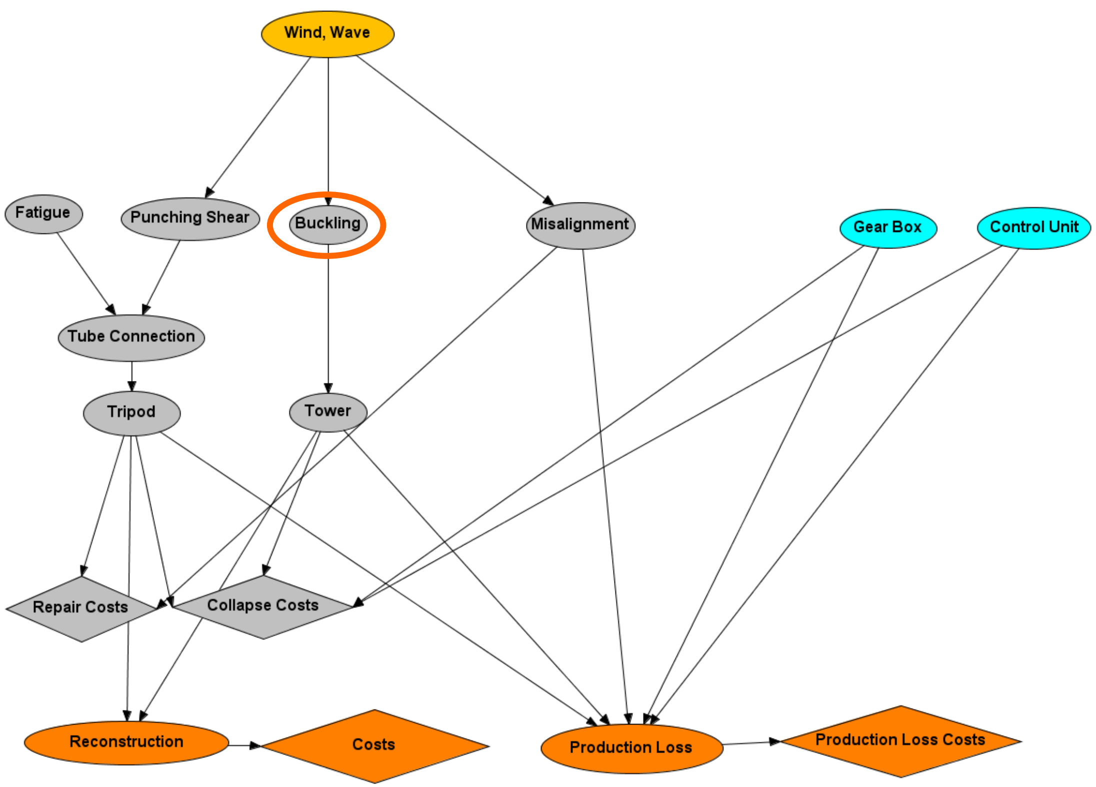



**Limit state function** for buckling: $g = \chi_{ov} R_{pl} - \Delta$

Calculation of **failure probability** with Monte Carlo using Response Surfaces.
Calculation of **sensor data** with Monte Carlo using Response Surfaces.
**Result** for failure mechanism buckling: Very low probability of failure.

# Structural Reliability: Example for Ultimate Limit State Analysis
# Integration of Failure Probability in Bayesian Network




Wind, Wave(C6)

| | |
|---|---|
| Extrem | 0.02 |
| No loading | 0.98 |

Fatigue(C4)

| | |
|---|---|
| Safe | 0.99999 |
| Crack | 1.0E-5 |

Punching Shear(C5)

| C6 | Extrem | No loading |
|---|---|---|
| Safe | 0.9999 | 1.0 |
| Failure | 1.0E-4 | 0.0 |

Buckling(C8)

| C6 | Extrem | No loading |
|---|---|---|
| Safe | 0.9999 | 1.0 |
| Failure | 1.0E-4 | .0 |

Misalignment(C9)

| C6 | Extrem | No loading |
|---|---|---|
| Safe | 0.85 | 1.0 |
| Missalignment | 0.05 | 0.0 |

Gear Box(C11)

| | |
|---|---|
| Safe | 0.9 |
| Failure | 0.1 |

Control Unit(C1)

| | |
|---|---|
| Safe | 0.59 |
| Failure | 0.41 |

Tube Connection(C3)

| C4 | Safe | | Crack | |
|---|---|---|---|---|
| C5 | Safe | Failure | Safe | Failure |
| Safe | 1.0 | 0.0 | 0.0 | 0.0 |
| Failure | 0.0 | 1.0 | 0.0 | 1.0 |
| Damaged | 0.0 | 0.0 | 1.0 | 0.0 |

Tripod(C2)

| C3 | Safe | Failure | Damaged |
|---|---|---|---|
| Safe | 1.0 | 0.0 | 0.0 |
| Failure | 0.0 | 1.0 | 0.0 |
| Damaged | 0.0 | 0.0 | 1.0 |

Tower(C7)

| C8 | Safe | Failure |
|---|---|---|
| Safe | 1.0 | 0.0 |
| Failure | 0.0 | 1.0 |

Repair Costs(U2)

| C9 | Safe | | | Missalignment | | |
|---|---|---|---|---|---|---|
| C2 | Safe | Failure | Damaged | Safe | Failure | Damaged |
| Utility | 0.0 | 0.0 | -100000.0 | -100000.0 | -100000.0 | -200000.0 |

Collapse Costs(U3)

| C1 | Safe | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| C11 | Safe | | | | | | Failure | | | |
| C7 | Safe | | | Failure | | | Safe | | | Fa |
| C2 | Safe | Failure | Damaged | Safe | Failure | Damaged | Safe | Failure | Damaged | S |
| Utility | 0.0 | -1650000.0 | 0.0 | -1650000.0 | -3300000.0 | -1.65E-6 | -800000.0 | -2450000.0 | -800000.0 | |

| C1 | Safe | | | Failure | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| C11 | Failure | | | Safe | | | | | | Fa |
| C7 | Failure | | | Safe | | | Failure | | | S |
| C2 | Safe | Failure | Damaged | Safe | Failure | Damaged | Safe | Failure | Damaged | S |
| Utility | -2450000.0 | -4100000.0 | -2450000.0 | -210000.0 | -1860000.0 | -210000.0 | -1860000.0 | -3510000.0 | -1.86E-6 | |

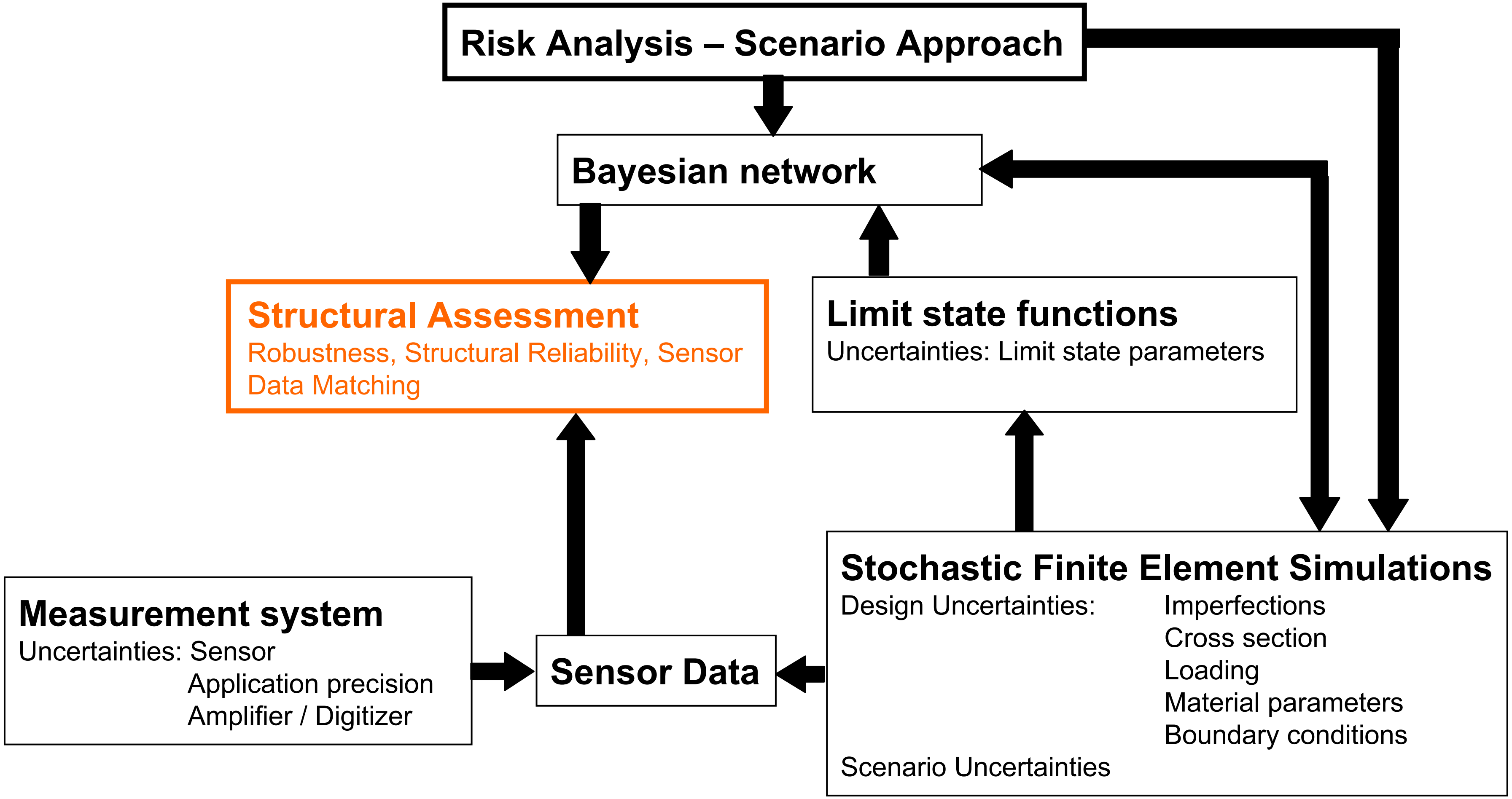
| C1 | Failure | | | | | |
|---|---|---|---|---|---|---|
| C11 | Failure | | | | | |
| C7 | Safe | | | Failure | | |
| C2 | Safe | Failure | Damaged | Safe | Failure | Damaged |
| Utility | -1010000.0 | -2660000.0 | -1010000.0 | -2660000.0 | -4310000.0 | -2660000.0 |

Reconstruction(C12)

| C7 | Safe | | | Failure | | |
|---|---|---|---|---|---|---|
| C2 | Safe | Failure | Damaged | Safe | Failure | Damaged |
| No Reconstruct | 1.0 | 0.0 | 0.99 | 0.0 | 0.0 | 0.0 |
| Reconstruction | 0.0 | 1.0 | 0.01 | 1.0 | 1.0 | 1.0 |

Costs(U3_1)

| C12 | No Reconst | Reconstruc |
|---|---|---|
| Utility | 0.0 | -7500000.0 |


Risk Analysis – Scenario Approach
Bayesian network
Structural Assessment
Robustness, Structural Reliability, Sensor Data Matching
Limit state functions
Uncertainties: Limit state parameters
Measurement system
Uncertainties: Sensor
Application precision
Amplifier / Digitizer
Sensor Data
Stochastic Finite Element Simulations
Design Uncertainties: Imperfections
Cross section
Loading
Material parameters
Boundary conditions
Scenario Uncertainties

## Conclusions

### Framework for assessment analysing robustness and structural reliability developed

- Development of overall assessment methods for the integrated system
  - Bayesian network
  - Integration of different components of wind energy converter
- Development of quantitative criteria for assessment of the structure
  - Robustness and structural reliability
- Design of a monitoring concept for the structure
- Integration of monitoring data in the assessment
  - Sensor signal simulation
  - Correlation with limit state function

### Outlook

- Refine scenario definition and probabilistic models
- Fatigue limit state
- Probabilistic model for sensor data – data matching
- Work on all levels!

**Thank you for your Attention!**