TWAIN

Evaluating Impact of WTG Control Strategies on the Structural Integrity of Support Structures using FMECA

EERA DeepWind CONFERENCE 2026

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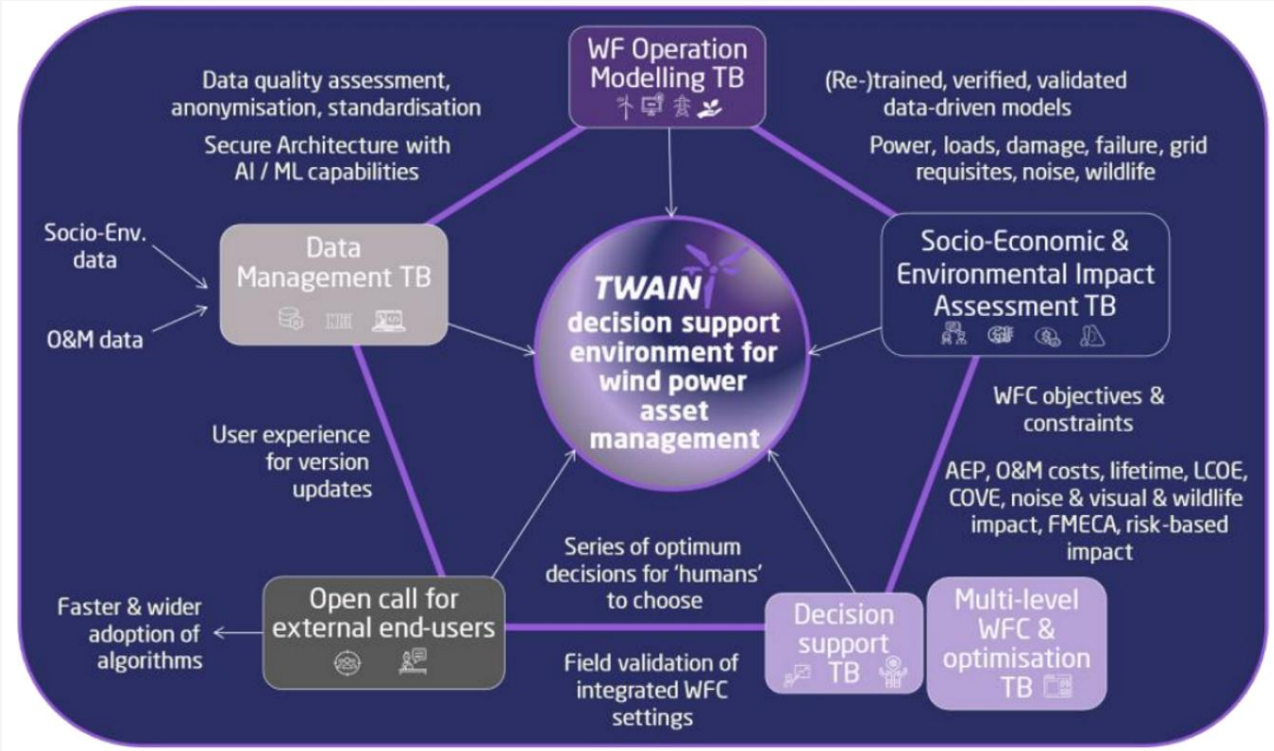
Use of AI to train surrogate models to enable multi-objective optimization of wind farm control

Set of toolboxes and case studies showcasing the functionality



About Ramboll

Assisting clients from pre-feasibility to operation

900+ wind experts

Offices in 26 countries

Technology agnostic consultant

Operations & Maintenance
- Strategy
- Lifecycle Planning & Support
- Structural Integrity Mgmt
- Lifetime extension

Strategic Advisory
- Strategic advisory for all aspects of wind farm development
- Technical, environmental & commercial due diligence
- Bid Support
- Market-entry & Go-to-market strategies
- Supply-chain assessment
- Sustainability assessments & evaluations

Foundation & Civil Design
- Bottom-fixed foundation design (monopile, jacket, gravity-based & novel concepts)
- Floating foundation design
- Substation foundation & topside design
- Port design
- Low-carbon design

Project Development
- Site identification & feasibility studies
- Technical concept development & selection
- Layout & micro-siting
- Cost estimation, LCOE analysis
- Procurement & Contracting
- Package & Project Management
- HSEQ Management
- Risk & Interface Management
- OFW-to-X

Transport & Installation Engineering
- Development of T&I concepts & equipment selection
- Development of construction schedules
- Port assessment

Wind & Site
- Planning & management of wind measurement campaigns
- Wind resource assessments
- Energy yield assessments
- Met-ocean studies
- Geophysical & geotechnical assessment and interpretation
- Digital ground modeling

Electrical Design
- System studies
- Grid connection concept
- LV, MV and HV grid design
- Substation design

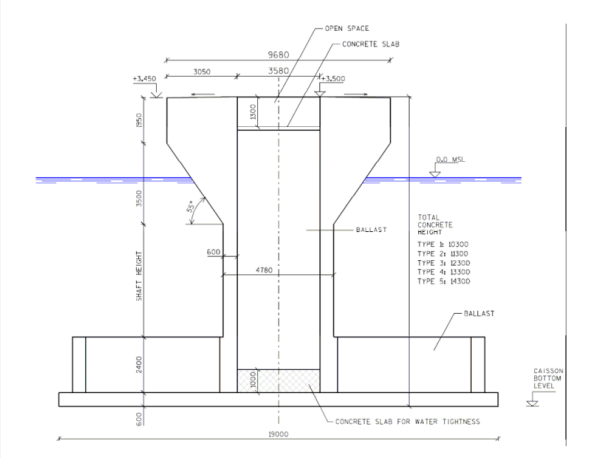
Environmental & Social Advisory
- Environmental & Social Impact Assessments
- Constraint assessments
- Cultural heritage studies
- Co-existing strategies and nature-inclusive design

Background

- Operators are focused on keeping their asset operational following a pre-determined inspection & maintenance schedule.
- Leading players are aiming to implement risk based inspection: planning more selective visits, using findings from remote monitoring and observations on site → Reliability Centered Maintenance.
- How should they change their approach in the context of wind farm control?

Research question
in the context of wind farm control

What is the impact of wind farm control on the structural reliability of wind turbines?



Case study on the tower & foundation of Lillgrund offshore wind farm, located in Sweden, operational since 2007, featuring gravity based foundations

Jeppsson, Joakim, Larsen, Poul Erik, and Larsson, Aake. *Technical Description Lillgrund Wind Power Plant*. Sweden, 2008.

Approach

- Methodology:
  - (Semi-quantitative) Failure Modes, Effects, and Criticality Analysis (FMECA).
  - Workshop with 11 experts from consortium partners (DTU, CENER, TUM, EDF, Engie)

- Objective:
  - Identify means to monitor and improve operational reliability, reduce failure risks, and inform strategies for spare part management and risk-based inspections.

- What control strategies do we consider?
  - Baseline (normal power production)
  - Derating
  - Yaw steering (up to 30 degrees)

Structured approach to evaluating risk

- Break down our system (wind power plant) into subsystems and components
- Assign functional descriptions of each component
- Describe failure modes, the failure cause and end effect
- Evaluate likelihood and consequential probability in the beta factor
- Score the consequence of the end effect for severity across multiple types of impact (safety, production availability, environmental, intervention, spare part costs)
- All scores are given on a 3 tier scale (low – medium – high) with defined categories
- Continuous improvement: reassess scoring based on feedback from operations

How do we evaluate risk?

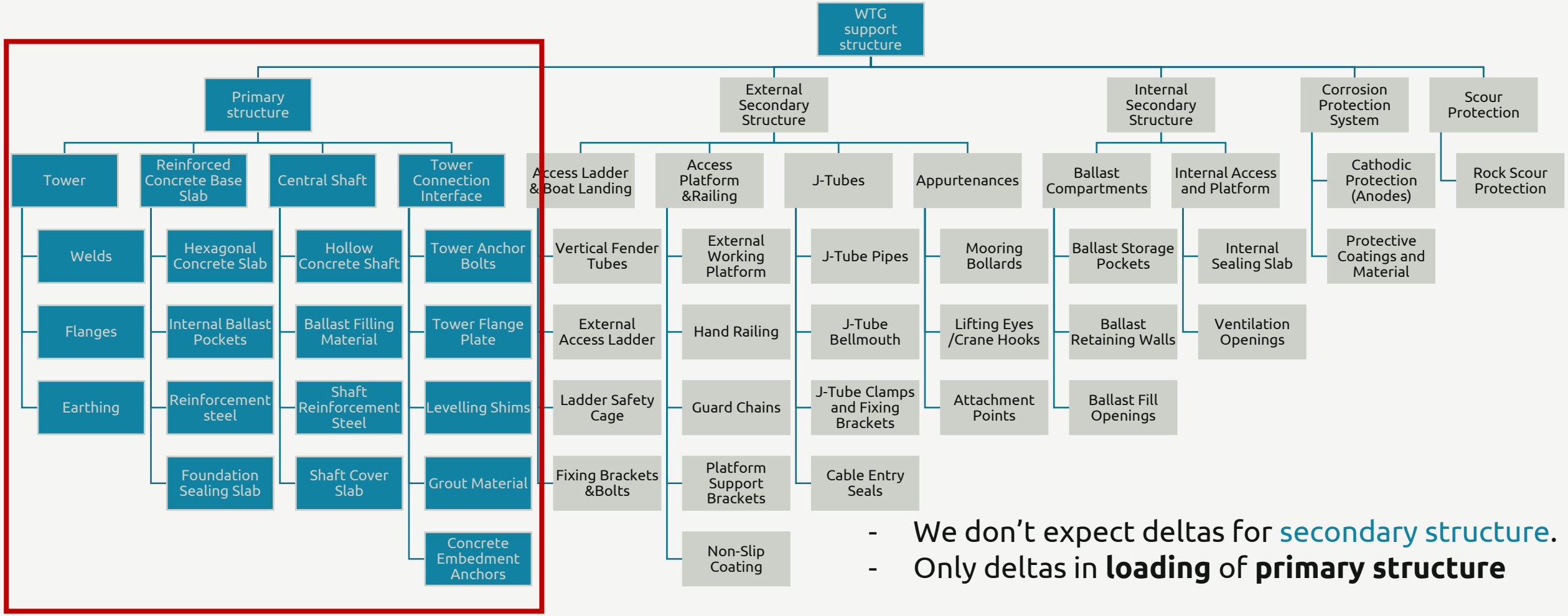
- Two parameter approach:
  - Risk = likelihood * consequence.
- Three parameter approach (IEC 60812:2018):
  - Risk Priority Number = likelihood * detectability * consequence
- Ramboll approach (Scheu et al 2019*)
  - Criticality Number $= \text{Likelihood} * \beta_{\text{factor}} * (\sum \text{Severity})$

Criticality level	Criticality number range
Low	5 – 43
Medium	44 – 90
High	91 – 135

* Scheu, M. N., Tremps, L., Smolka, U., Kolios, A., & Brennan, F. (2019). A systematic Failure Mode Effects and Criticality Analysis for offshore wind turbine systems towards integrated condition based maintenance strategies. *Ocean Engineering*, *176*, 118-133.

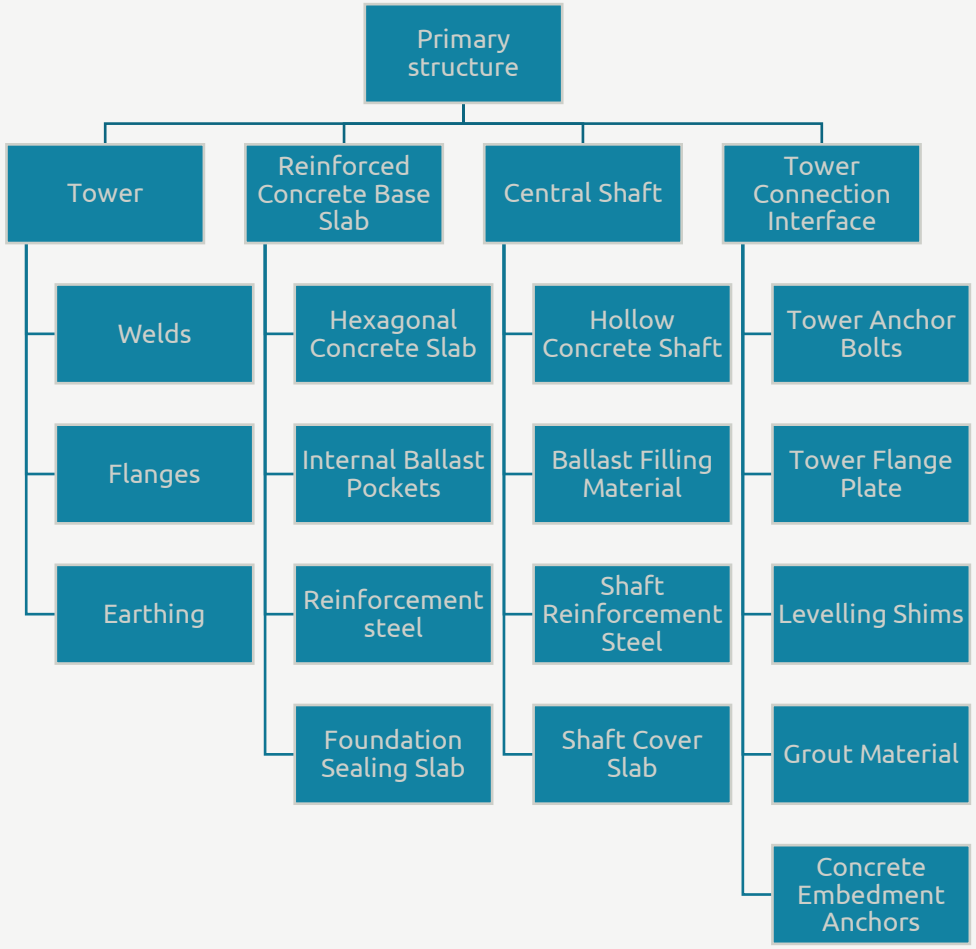
Step 1: System Breakdown

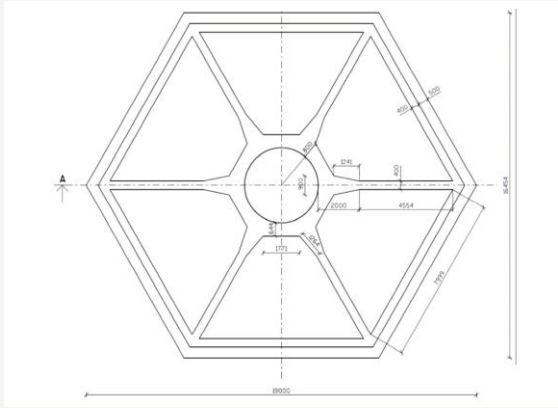
The asset/sub-system under consideration is divided into systems and components.

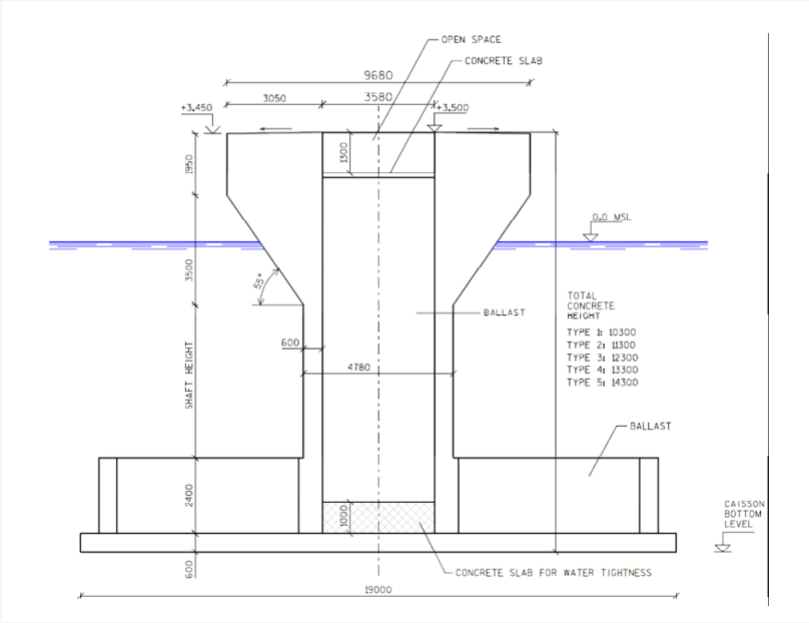


- We don't expect deltas for secondary structure.
- Only deltas in **loading** of **primary structure**

Primary Structure Breakdown







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Jeppsson, Joakim, Larsen, Poul Erik, and Larsson, Aake. *Technical Description Lillgrund Wind Power Plant.* Sweden, 2008.

Change in loading for control strategies

- Derating:
  - Damage equivalent loads decrease
- Wake steering
  - Damage equivalent loads increase
  - Different loading profile due to yaw offset

Example failure mode description

Failure mode: Aerodynamic force variations beyond design assumptions lead to increased dynamic loading on the tower. These repeated stress cycles accelerate fatigue crack initiation and propagation in critical tower locations.

Failure cause: Dynamic loading passed down from the rotor to the support structure

Likelihood

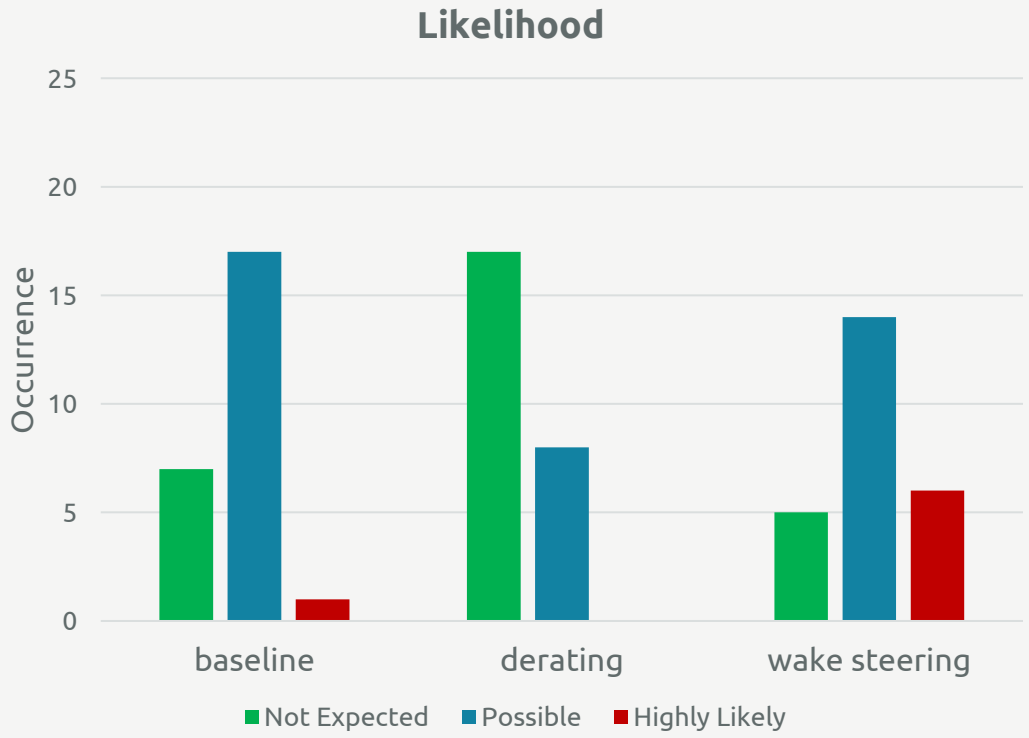
- Baseline: Possible
- Derating: Not Expected
- Wake steering: High

Beta Factor

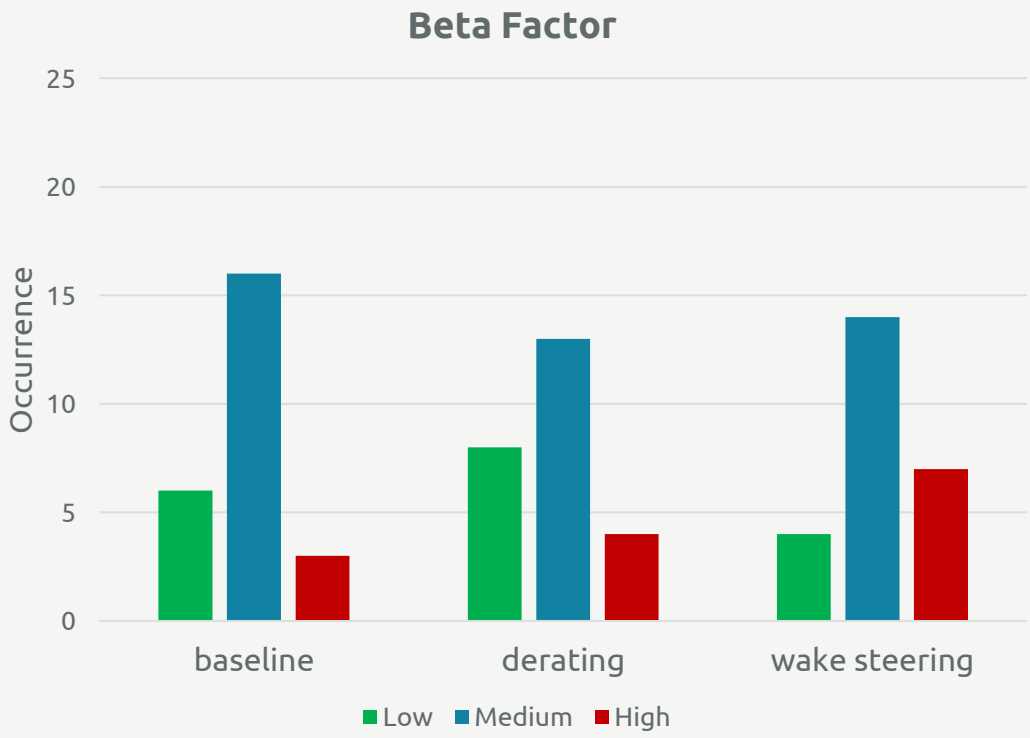
- Baseline: Medium
- Derating: Low
- Wake steering: High

Results

Changes in distribution of likelihood

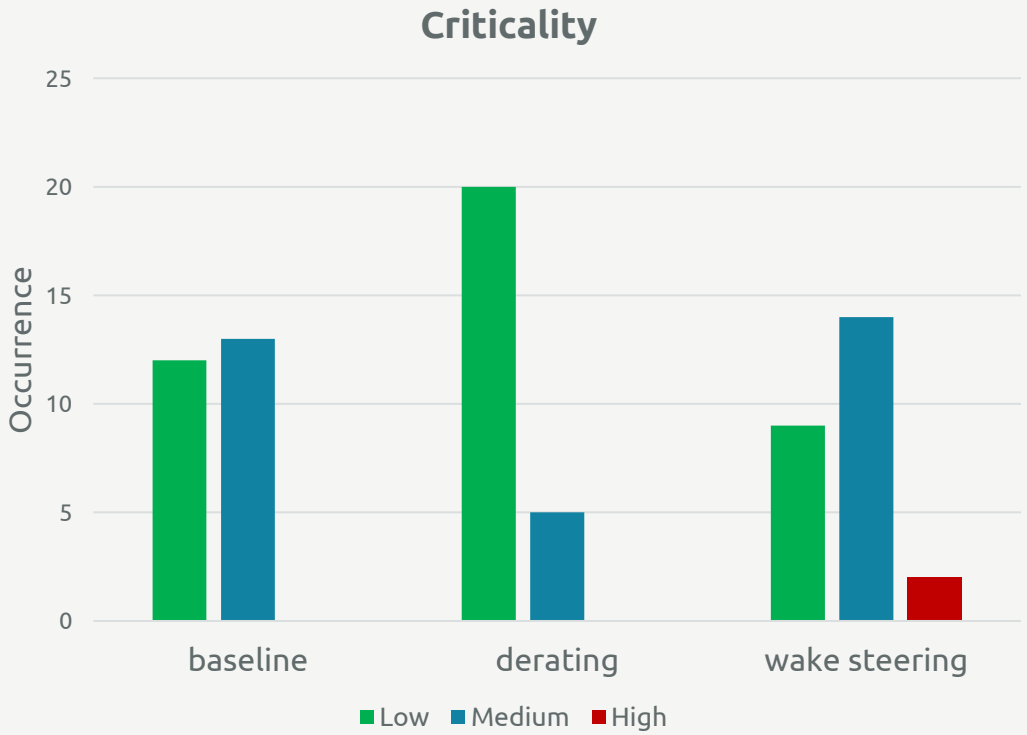


Changes in distribution of beta factor



Results

Changes in distribution of Criticality



$$\text{Criticality Number} = \text{Likelihood} * \beta_{\text{factor}} * \left(\sum \text{Severity} \right)$$

Conclusions

- We have applied FMECA to identify and evaluate failure modes that may be impacted by a change in wind turbine control
- Semi-quantitative scoring, based on experience of the participants and assumptions on the change in loading
- Focus on the differences in likelihood and beta factor to reflect different conditions.

Next steps

- Quantify the delta in DEL for Lillgrund and its effect on remaining lifetime and failure rates
- Evaluate failure modes for other components (e.g. blades, yaw bearing)

Thank you

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Funded by the European Union

Want to discuss more? Please send me an e-mail at **khermans@ramboll.com**