



Perceived Uncertainty Sources in Wind Power Plant Design

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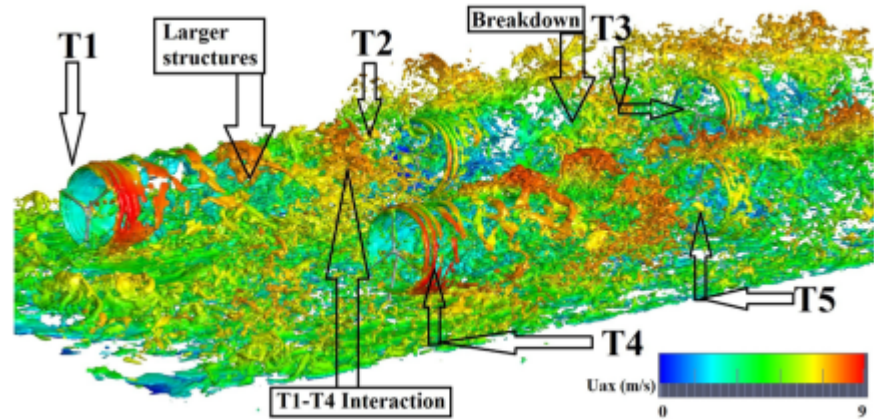
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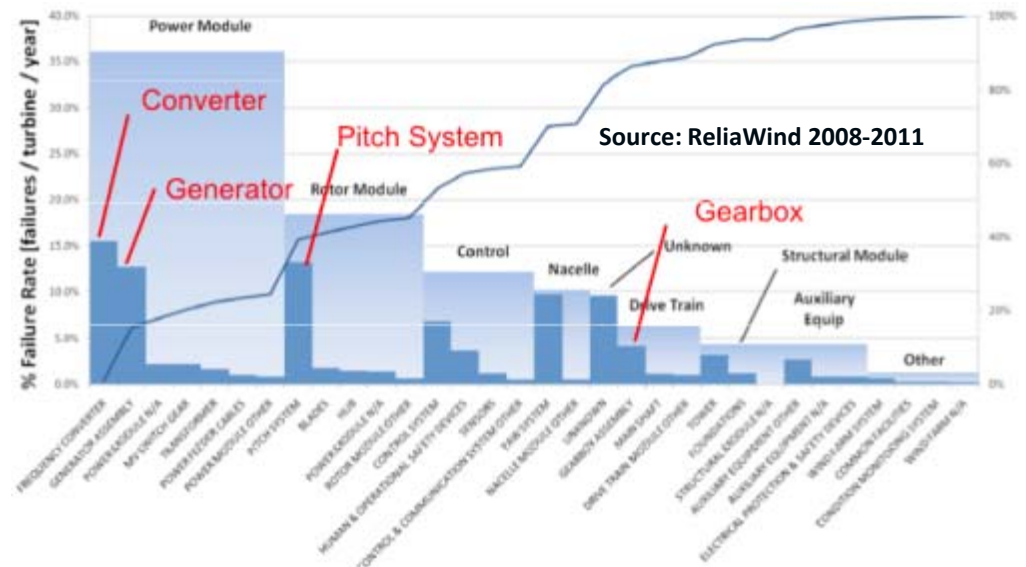
PR-5000-70653

Motivation

- Turbulent wind operation still laden with uncertainties
- Uncertainties affect design and structural reliability
- Failures still occur
- Risk/mitigation → levelized cost of energy (LCOE)
- Downtime → LCOE.



Source: Jha et al. (2015) "Unraveling the Mysteries of Turbulence Transport in a Wind Farm"



Goal and Methods

- Identify key sources of uncertainty and prioritization for research and development (R&D)
- Analysis of current procedures, industry best practice , standards, and expert opinions
- Design Criteria Identification and Ranking Table (DCIRT)

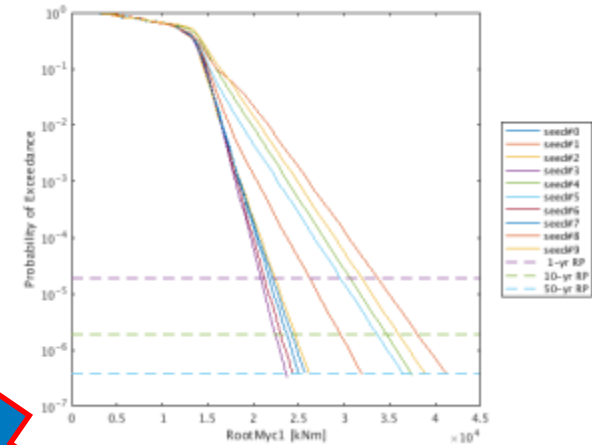
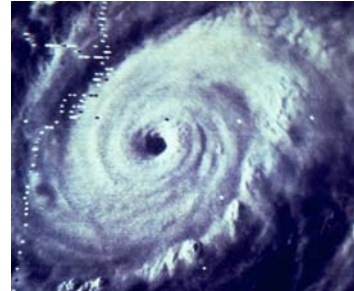
Design Criteria Identification and Ranking Table (DCIRT)

Design Criteria	Level of Understanding of the...			Expert Opinion: Impact on System Risk and Reliability
	Process Physics	Load Modeling	Uncertainty	
As-Built and Nonconformities	<ul style="list-style-type: none"> As-built nonconforming to specs Pitch errors Yaw errors Mass/inertia errors Temperature effects on material and system properties Material properties/manufacturing quality and variability Failures 'outside the box' 	<ul style="list-style-type: none"> Raise QA/QC level vs. design for lower QC → focus on increasing QC Cascading effects of errors (e.g., pitch/yaw) 	<p>Uncertainty, its propagation, and impacts are known, but they do not diminish</p>	<p>Human error filtered by QA/QC, but not covered by PSFs</p>
Standard Design Conditions	<ul style="list-style-type: none"> Dimensionality of design space Beyond tu, how do you handle other conditions (shear, veer, and so on) How do we improve turbine classes to be more representative of real site conditions? Perhaps develop new design classes to address location-specific issues Offshore DLC 6.2: how can the yaw error be better defined? What is missing? 	<ul style="list-style-type: none"> Extrapolation modeling (methods being used by OEM may be proprietary) Account for time spent under different-than-standard conditions (stability/shear, and so on) 	<p>This ties to site suitability; mapping capacity to particular site</p>	<ul style="list-style-type: none"> V_{ref} issue as in site suitability; Current standard not explicit in the intent of goals Expected values of gust factors vs. considering uncertainty PRUF-like exercise for loads Site-suitability standards? Adjustable products are the trend: mix and match components suitable for site-specific design

Excerpt

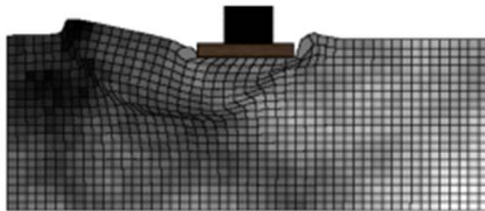
Uncertainty Category I

$$\gamma_{LL} \leq \frac{R}{\gamma_R}$$

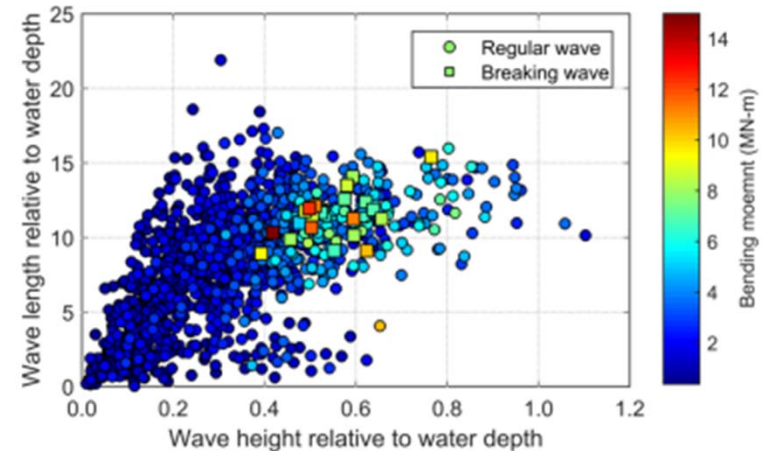


1. Inflow and Environmental BCs (direct impact on Loads)

Bearing Capacity



- Turbulence spectrum, coherence, shear, veer, stability, wakes, terrain effects, wave field, higher order hydrodynamics, breaking waves
- Deterministic vs. Stochastic Turbulence parameters
- Extreme Events
- Soil-structure interaction
- Load Extrapolation.

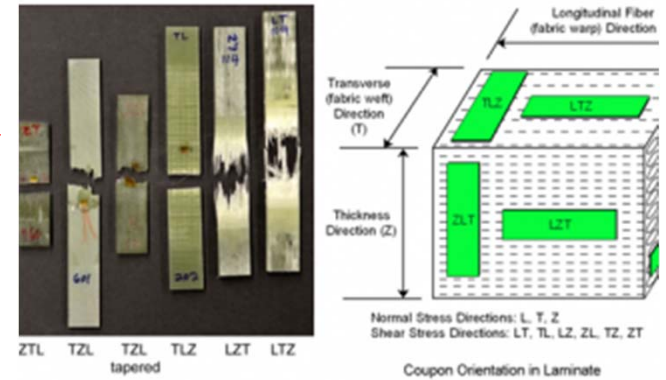


Uncertainty Category II

$$\gamma_L L \leq \frac{R}{\gamma_R}$$

2. Material behavior and strength (direct impact on Resistance)

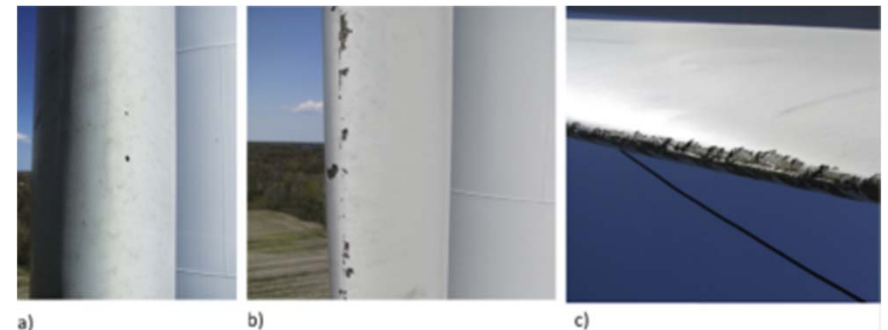
- Quality assurance and control → need codification
- Nonconformities (e.g., pitch settings, surface characteristics)
- Human error (applications outside the envelope)
- Thermal effects and humidity effects on power electronics.



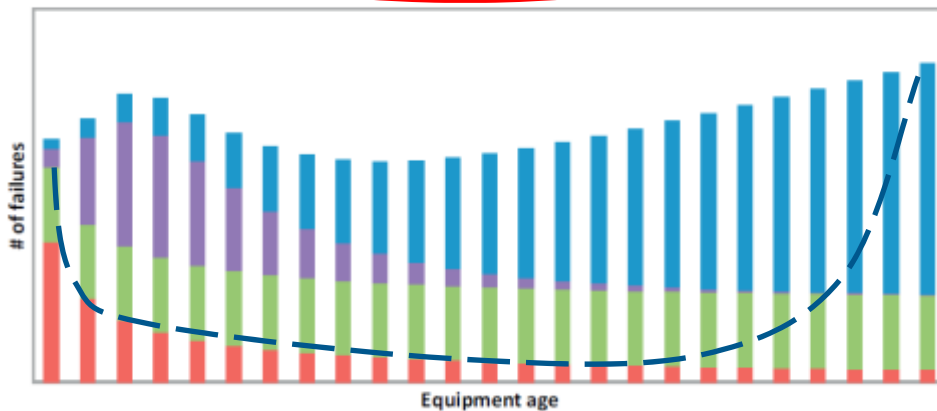
Source: Sandia National Laboratories (SNL)



Source: Forte Renewables



■ Infant failure ■ Random failure ■ Premature failure ■ Wear-out failure

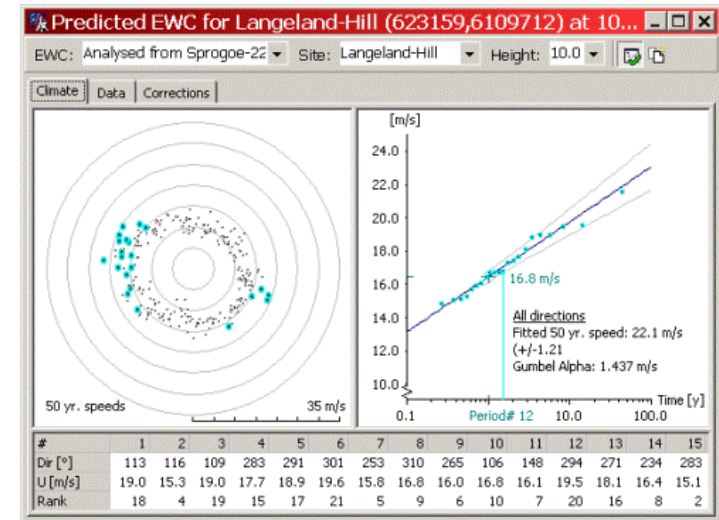


Uncertainty Category III

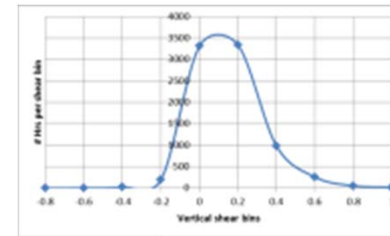
$$\gamma_{LL} \leq \frac{R}{Y_R}$$

3. Site Suitability and Due Diligence

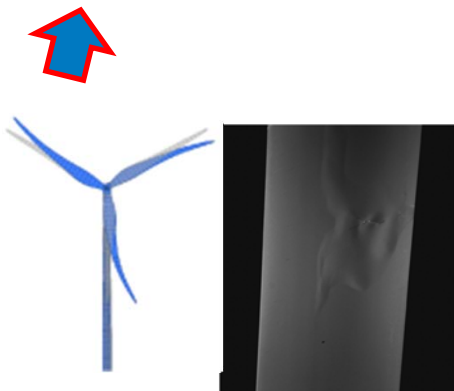
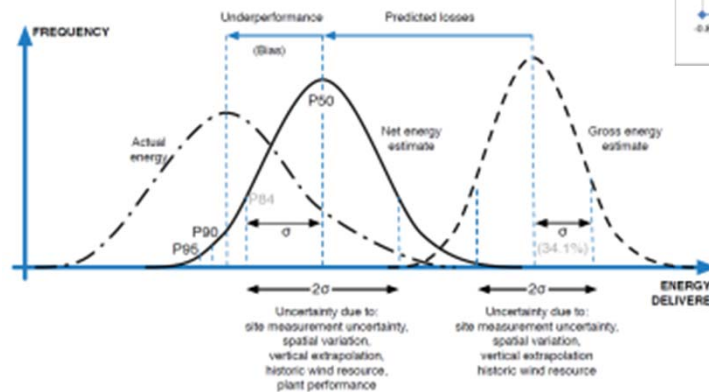
- Lack of transparency between manufacturer and independent engineer (e.g., controller algorithms, site assessment)
- New failure modes (e.g., edgewise vibrations and chordwise cracking)
- Suitability lags design progress
- Variable vs. averaged shear
- Plant underperformance
 - No correlation between predicted uncertainty and AEP predicted error.



Source: WaspEngineering



	m	% increase in loads resulting from Variable method relative to Standard method
Blade root Mx	4	0.10%
Blade root My	10	0.10%
Blade root Mz	4	6.40%
Blade root Fx	10	2.40%
Blade root Fy	4	1.90%
Blade root Fz	10	3.30%
Blade root Fx	4	6.30%
Blade root Fy	10	2.90%
Blade root Fz	4	0.00%
Blade root Fx	10	0.00%
Blade root Fy	4	0.30%
Blade root Fz	10	3.60%

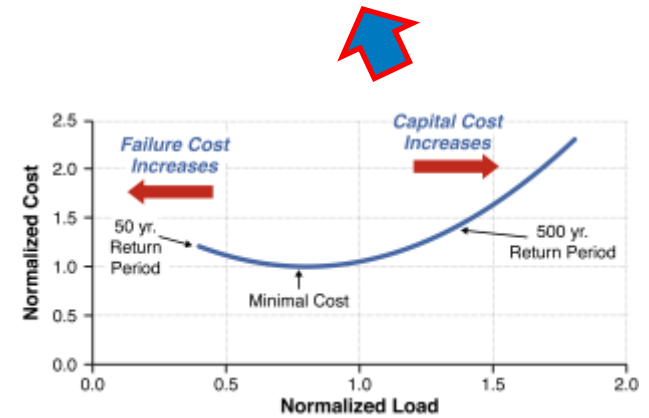


Uncertainty Category IV

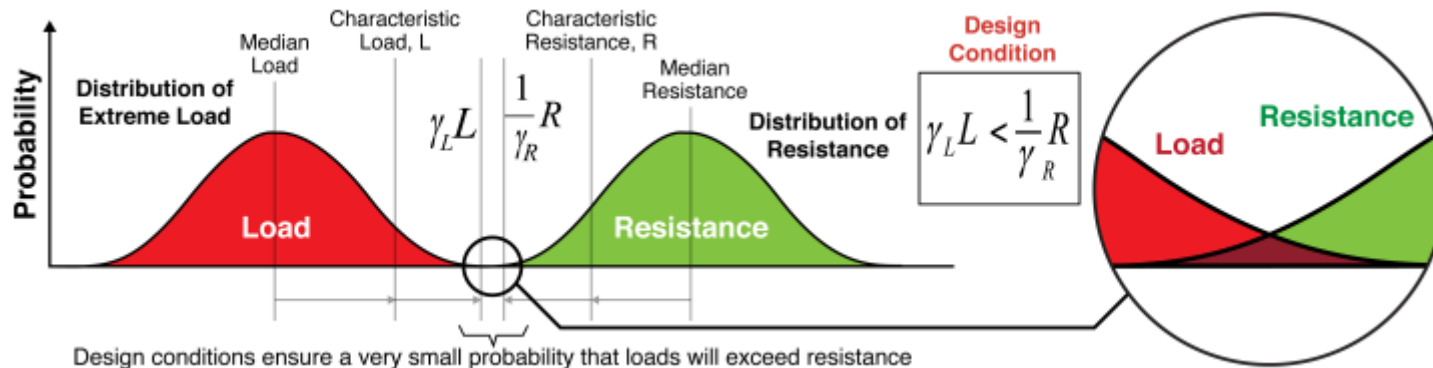
$$\gamma_L L \leq \frac{R}{\gamma_R}$$

4. Partial Safety Factors and Reliability Target

- Limit State Approach
- Moderate Consequence of Failure and Mid-High Cost of Safety Measures
- Partial Safety Factors Not Adequately Representing Actual Uncertainty
- Reliability-Based Design
 - Requires knowledge of uncertainty distributions and effects on design parameters
- Load Factors could be reduced if $COV(X_{aero} - X_{str})$ can be reduced.



$$g = z\delta_R R - X_{dyn}X_{exp}X_{aero}X_{str}L_x \geq 0$$



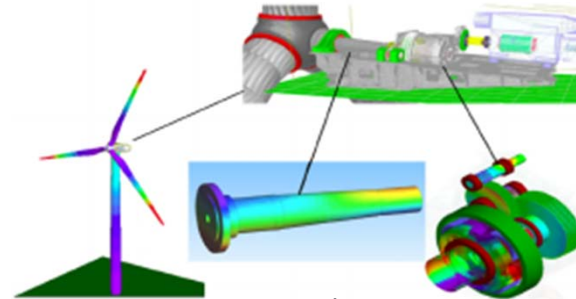
Design conditions ensure a very small probability that loads will exceed resistance

Uncertainty Category V

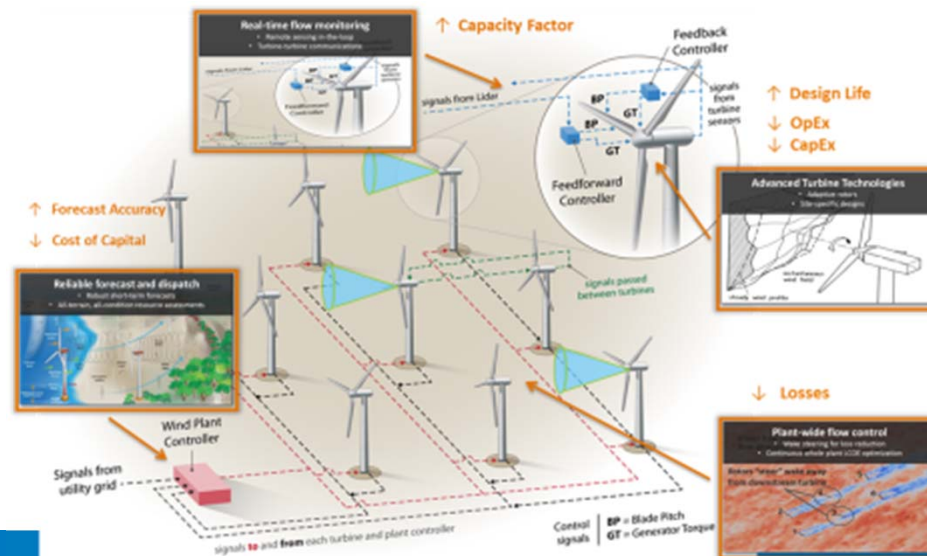
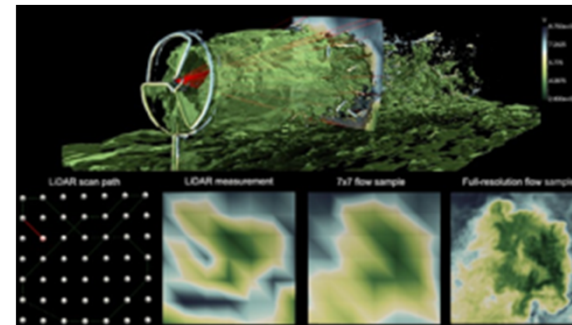
$$\gamma_{LL} \leq \frac{R}{Y_R}$$

5. Computational Modeling

- Multi-fidelity Requires Risk & Uncertainty Assessment
 - Uncertainty quantification (UQ) and verification and validation (V&V)
- UQ → Efficient and Robust Design Optimization
- Codified V&V → Prioritize Gaps and Needs for Model Improvement
- Surrogate Models
- System Management of Atmospheric Resources through Technology (SMART) Wind Plants
 - Improved load mitigation and performance.



Source: Jin et al. 2016



Higher Priority Recommended Actions from DCIRT

- Modeling
 - HPC + UQ + V&V → renewed basis for standards development
 - Improve engineering models for “ultra-large” composite structures
 - Design event definition
 - Design time scale reassessment (10-min, 3-s enough?).
- Site Suitability
 - Account for non-mean shear and site actual conditions
 - Evaluate reference wind speed and its impacts on survivability and number of shutdowns (U.S. vs. non-U.S.)
 - Increase transparency OEM-IE (surrogate modeling, control strategy informed exchanges)
 - Include manufacturing tolerances in the verification and certification process
 - Improve understanding of damping levels.
- Standards & Standard Classes
 - Improve class description to reflect site-specific conditions
 - Revisit partial safety factors through systems engineering of socio-techno-economic risk analyses
 - Improve definitions and modeling of shear, veer, stability
 - “Load Extrapolation” assessment
 - Assess soil temporal variability.

Thank you!

Acknowledgments

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