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Early and Deterioration Stage Wind Turbine Reliability Models: A Case Study for the Converter System

Fraser Anderson, Julia Walgern, Katharina Fischer

Motivation and Goals

Technical Reliability

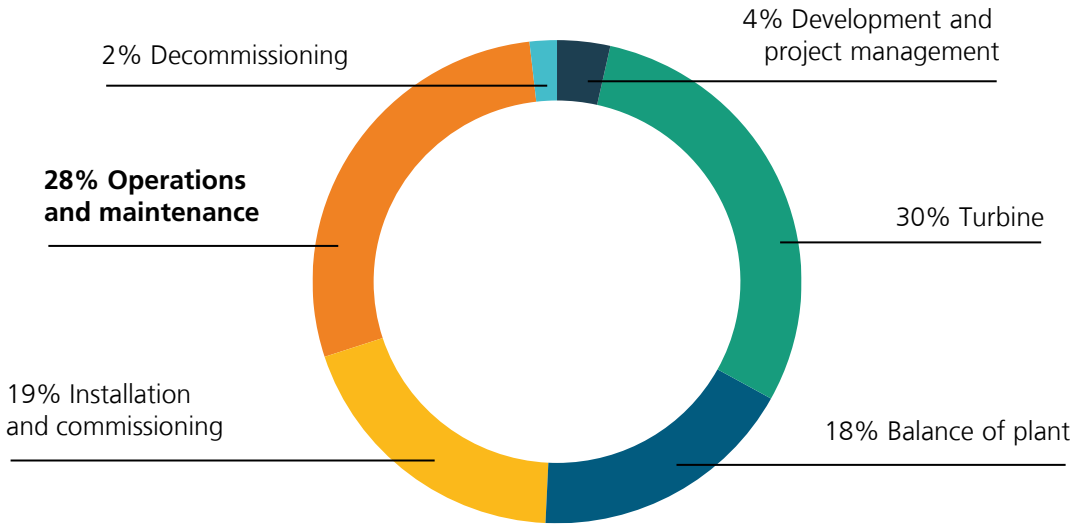
Motivation

- Distribution of Levelized Cost of Energy (LCoE): approx. one third is related to O&M
- Failure of wind turbine components causes repair costs and cost due to lost production
- Uncertainty during O&M phase due to unquantified reliability of WTs and their components

→ Reliability: Key for further cost and risk reduction

Goals

- Generation of added value from field data
- Utilising operational knowledge for reliability improvement
- Digitalisation and improvement of wind farms' O&M



Source: https://guidetoanoffshorewindfarm.com/wind-farm-costs

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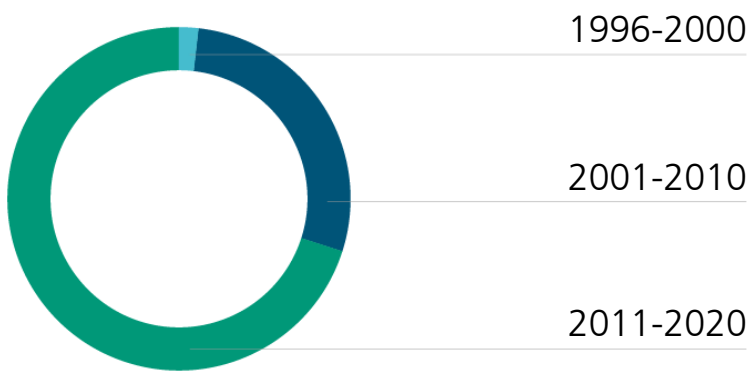
Extensive Field-Data Collection

Unique due to the size, diversity and recentness

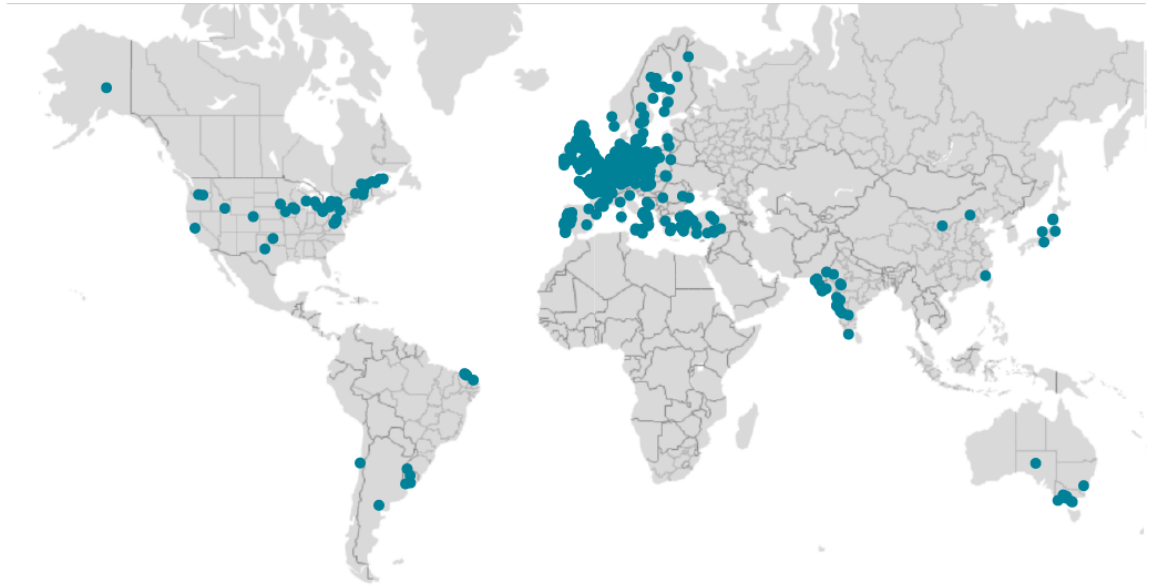
Current status and key characteristics of the field data set of Fraunhofer IWES (continuously growing)

Failure data available	>10,000 WTs
Total number of evaluated WT operating years	>20,000 years
Failure data from years	2003-2024
SCADA operating data available	>2,000 WTs



Compilation of wind turbine commissioning years

+ site-specific environmental data (ERA5) for each wind farm



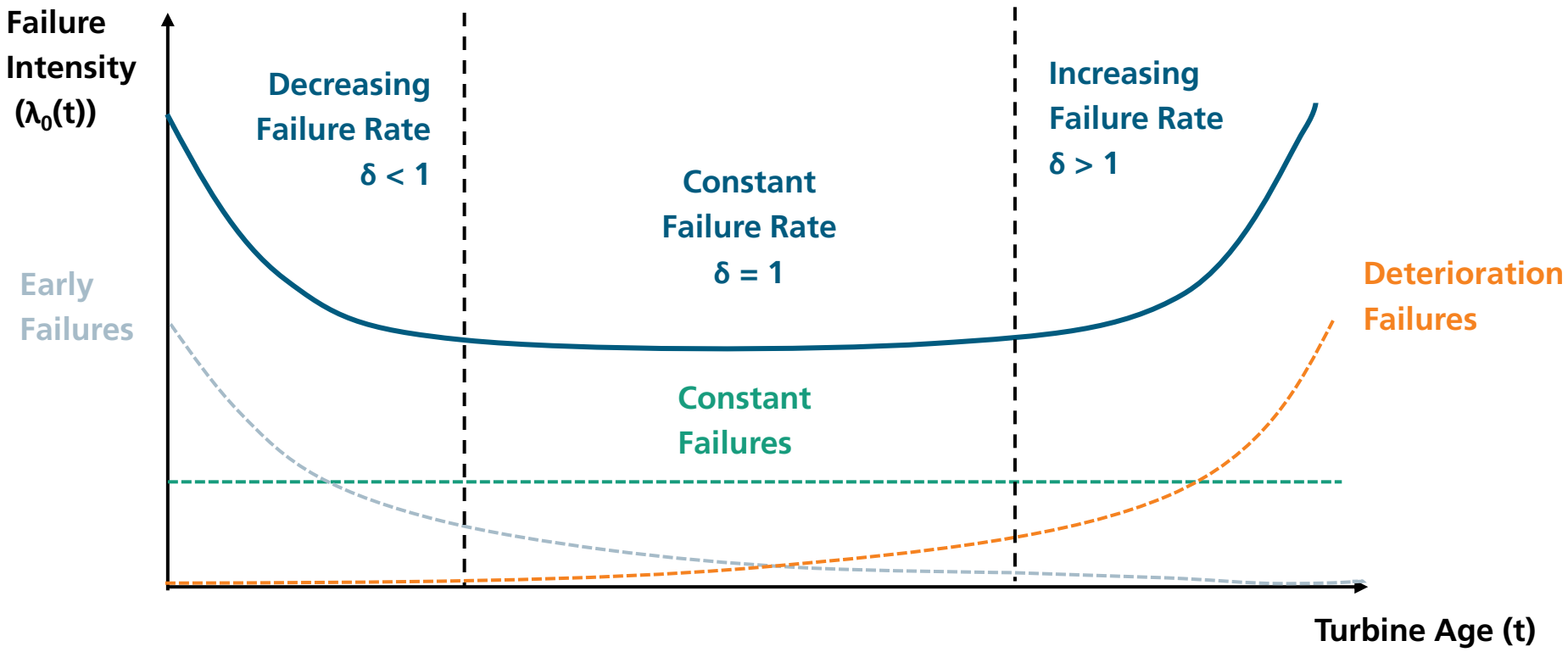
Operating sites

- onshore and offshore sites
- WTs of >10 different OEMs
- WTs with different generator types (DFIG, SCIG, PMSG, EESG)

Failure Behaviour Through Time

The bathtub curve of repairable systems

Power law process $\lambda_0(t) = \exp(\beta_0)\delta t^{\delta-1}$



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Failure Behaviour Through Time

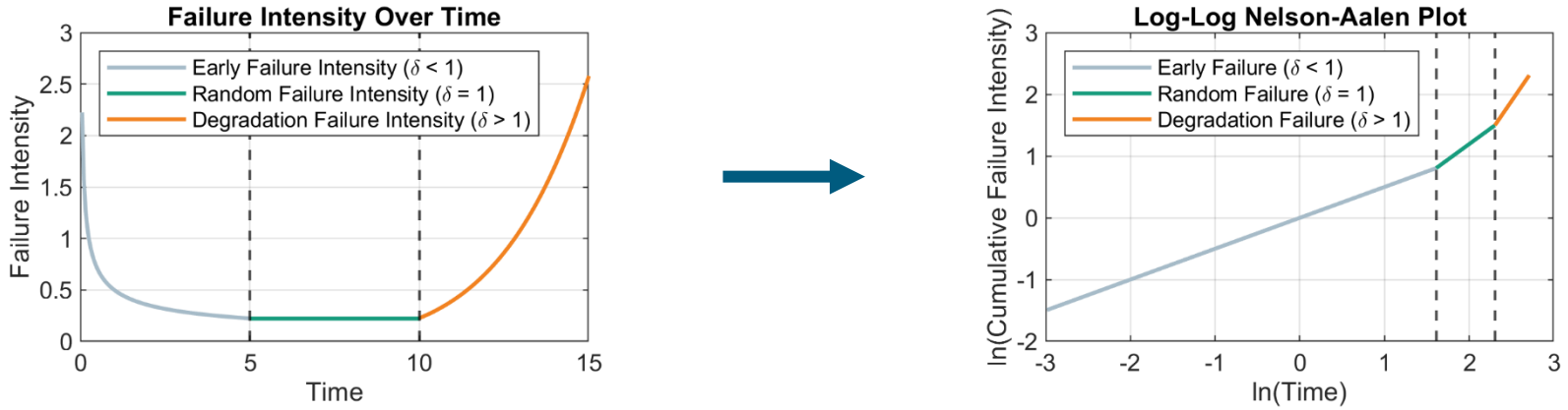
Nelson-Aalen plots

- The Nelson–Aalen estimator is a non-parametric estimator of the **cumulative intensity function** Λ_0 in case of censored data or incomplete data

$$\Lambda_0 = \sum_{t_i \leq t} \frac{d_i}{n_i}$$

where d_i is the number of failure events at time t_i and n_i is the total number of turbines at risk at t_i

- The **log-log** plot of the cumulative intensity function with respect to time is used to identify the shape parameter δ of a power law process. δ is determined by the gradient of the line:



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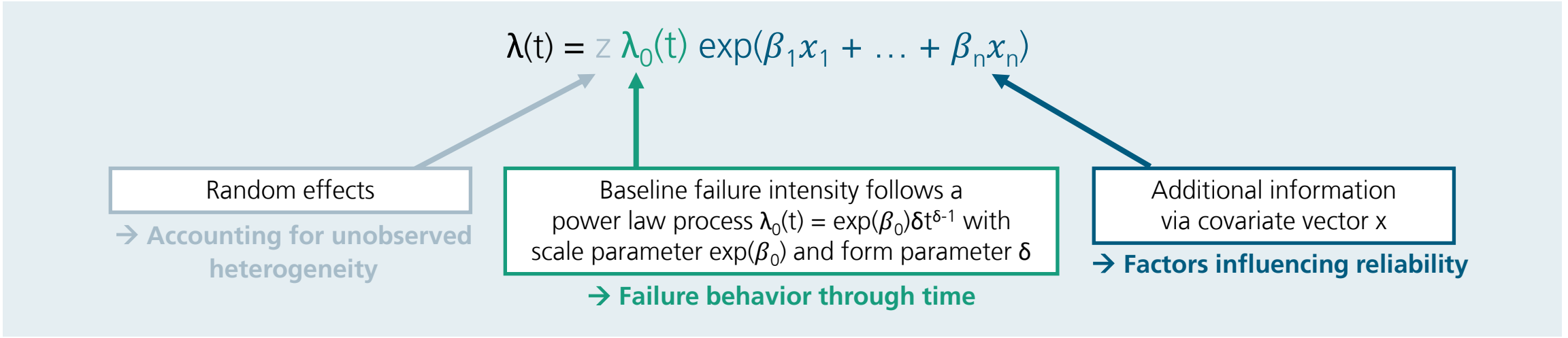
Identification of Relevant Covariates

NHPP regression with explanatory variables (covariates)

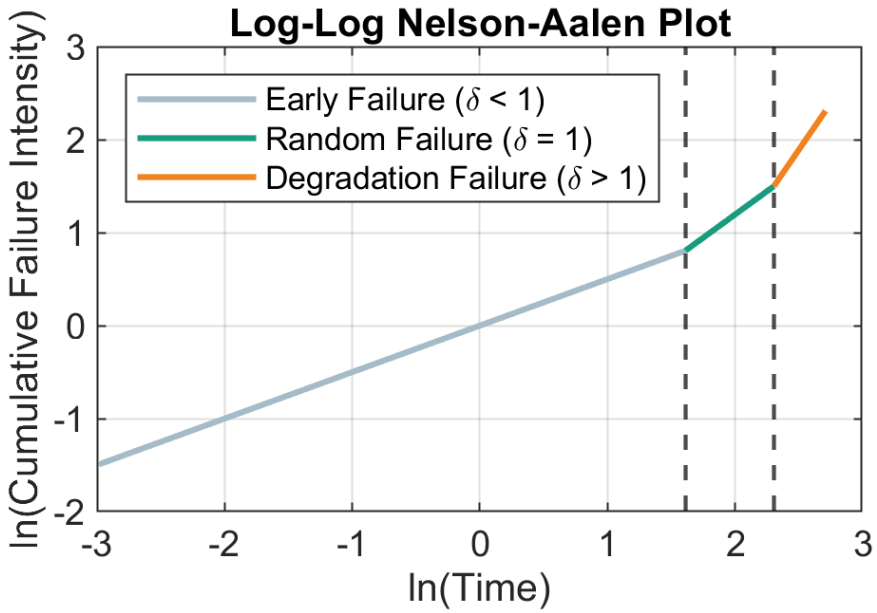
- Failure events are modeled using reliability theory for repairable systems
- Failure intensity of the non-homogeneous Poisson process (NHPP) including covariates:



- Estimation of the parameters: Maximum likelihood method
- Covariate selection procedure: Likelihood ratio statistics + subsampling procedure
- Correlated covariates handled by Principle Component Analysis (PCA)

The Next Step

Separate reliability models



$$\lambda_{early}(t) = z\,\lambda_{0,early}(t)\exp(\beta_{1,early}\,x_{1,early} + \dots + \beta_{n,early}\,x_{n,early})$$

$$\lambda_{late}(t) = z\,\lambda_{0,late}(t)\exp(\beta_{1,late}\,x_{1,late} + \dots + \beta_{n,late}\,x_{n,late})$$

$$\lambda_{random}(t) = z\,\lambda_{0,random}(t)\exp(\beta_{1,random}\,x_{1,random} + \dots + \beta_{n,random}\,x_{n,random})$$

Case Study

The converter system

Component Categories

- Five converter component categories analysed in detail:
  - Phase module (IGBT modules, driver boards, DC link capacitors and busbars)
  - Converter control
  - Heating & cooling system (liquid-cooled converters only)
  - Main circuit breakers & contactors
  - Other converter components
- Additionally, the overall converter system

Relevant Covariates

Design-related covariates:

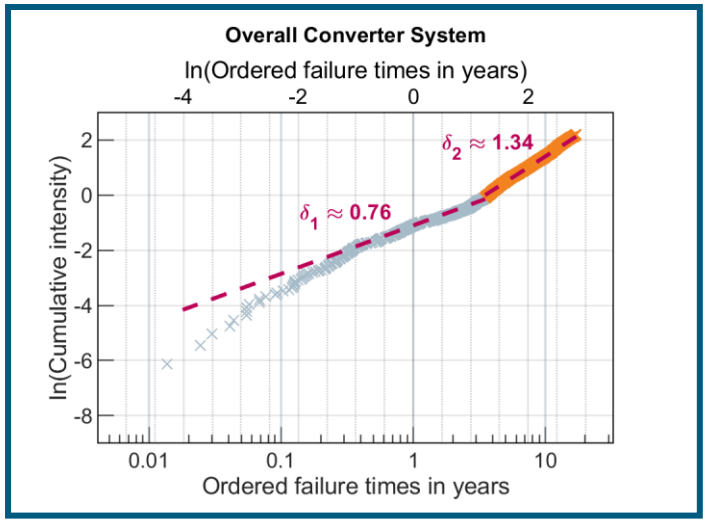
- Converter cooling system:
  air-cooled (A), liquid-cooled (W)
- Converter rated power: numerical, in MW
- Converter location: tower base (T), nacelle (N)
- IGBT module manufacturer: A, B, C and D
- Earthing system:
  unearthed (isolé terre, IT), earthed (terre neutre, TN)
- Turbine commissioning year: numerical, unitless

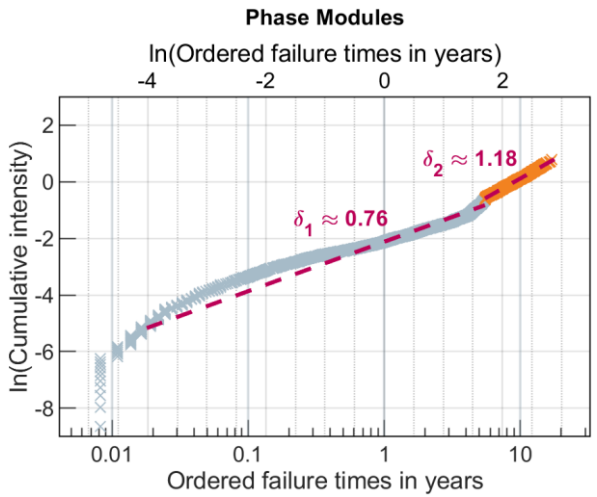
Site-specific covariates:

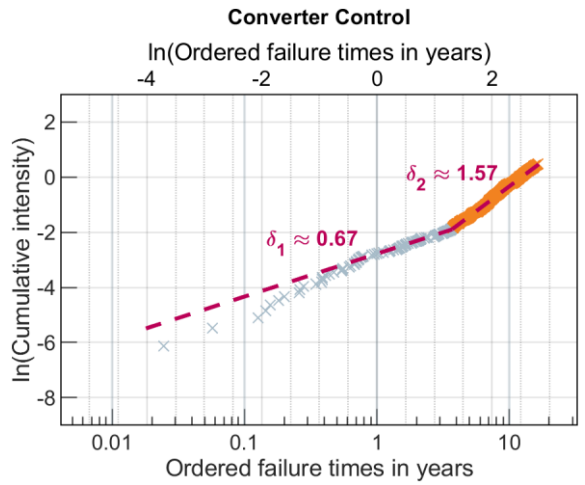
- Ambient absolute humidity: numerical, in g/m³
- Capacity factor: numerical, unitless
- Grid frequency: 50 Hz, 60 Hz
- Installation height, in m
- Mean ambient temperature, in °C

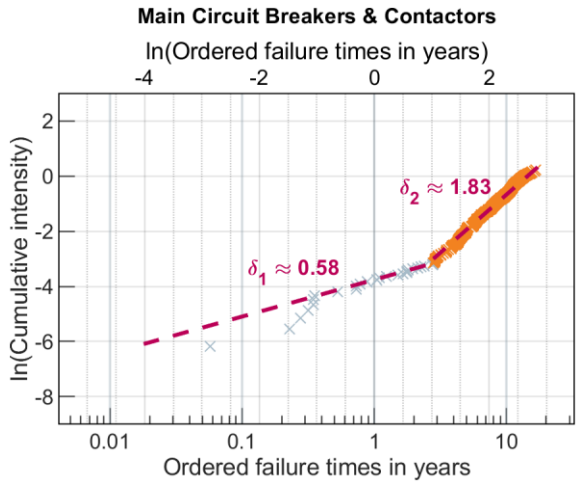
Results - Nelson Aalen Plots

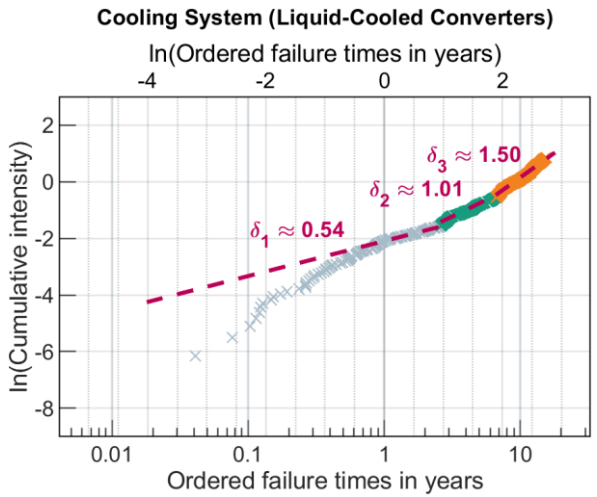
Identifying early, random & deterioration phases

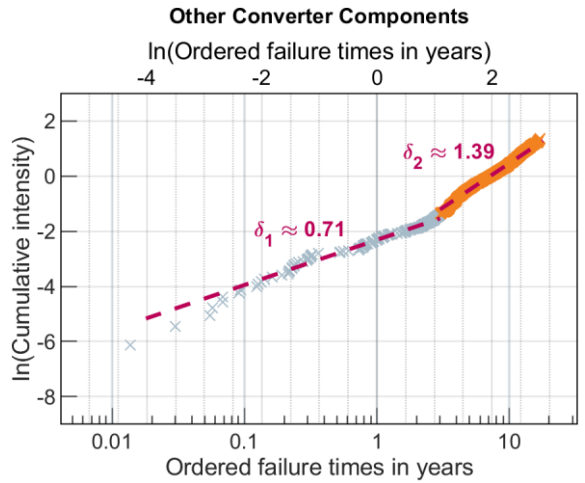












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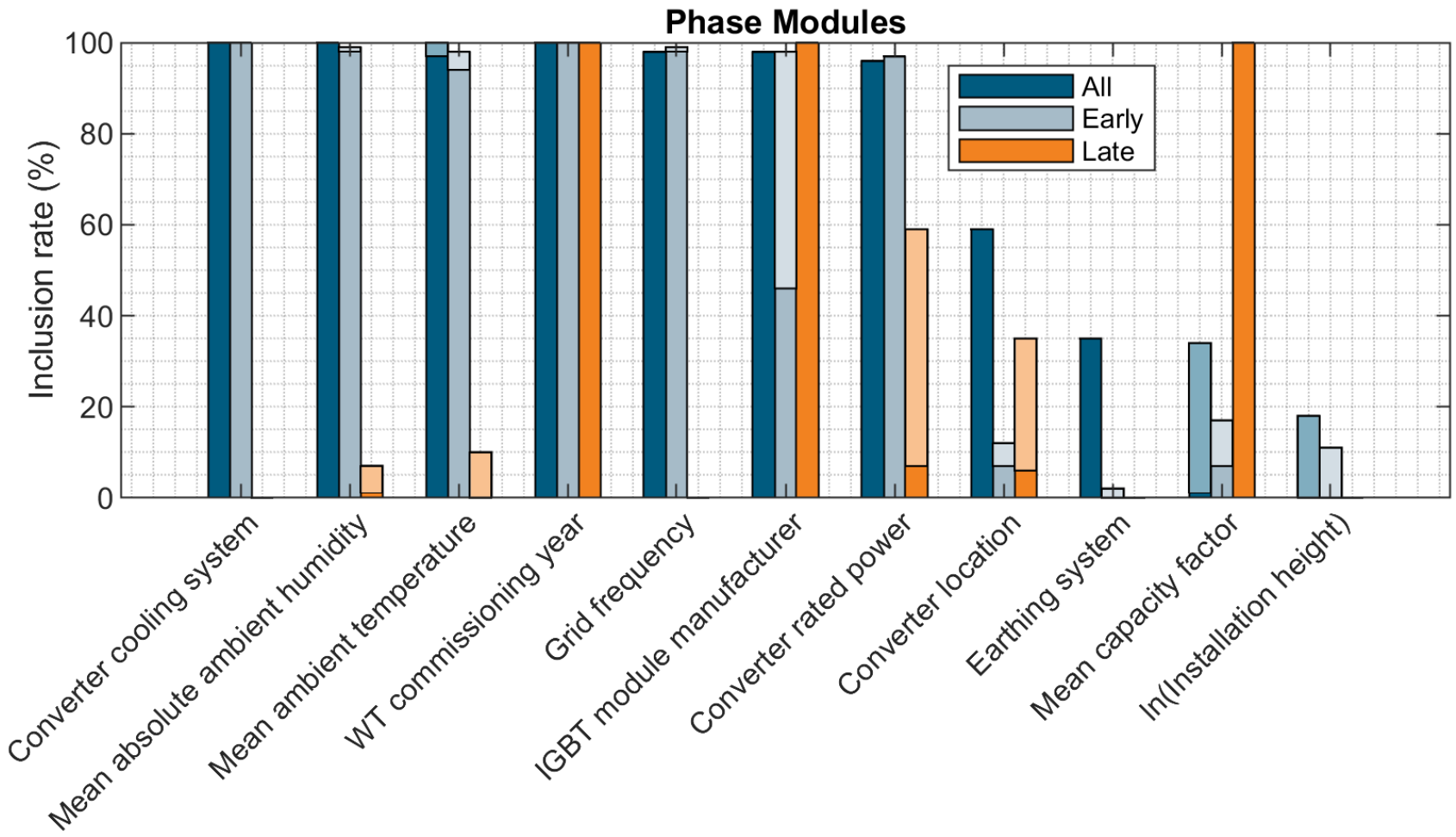
Results – Covariate Inclusion Rates

Phase modules

All – 8261 turbines
Early – 6641 turbines
Late – 1956 turbines



Conclusion

Key takeaways

- Reliability modelling of wind turbine components can be improved by more targeted models
- We can have more targeted models by identifying which failure mechanisms dominate different times in the turbine lifespan
  - Understanding how the influence of covariates evolves over the lifetime of the component can improve maintenance strategy → **O&M modelling and optimization**
  - Identifying the prevailing drivers of failure can provide valuable information on the different causes and mechanisms of early, random and degradation failures → **root cause analysis and reliability improvement**
- Future work involves applying reliability models to other wind turbine subsystems as part of RUN25+

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Contact

Fraser Anderson
Researcher
Fraunhofer Institute for Wind Energy Systems IWES, Fraunhofer UK Research Ltd

fraser.anderson@iwes-extern.fraunhofer.de