# EERA DeepWind 2025 Conference:

# Probabilistic Load Estimation for Ageing Wind Turbine Blades Using a Bayesian Network Framework

**Author:** Hannah Mitchell

**Co-authors:** Nigel Pready, David Garcia Cava, Ali Mehmanparast, Philipp Thies

**Industrial CDT in Offshore Renewable Energy (IDCORE) | Frazer-Nash Consultancy**

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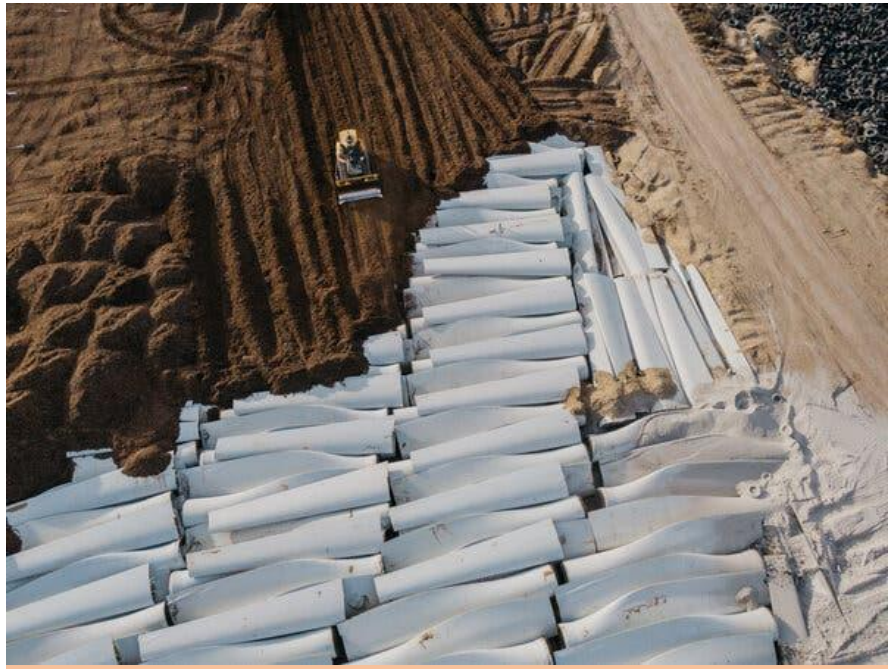
# Industrial CDT in Offshore Renewable Energy (IDCORE)

- **EPSRC** and **NERC** funded industrial CDT for offshore renewable energy (IDCORE) [1]
- **Partner universities:** Edinburgh, Exeter, Strathclyde, Swansea, and the Scottish association for marine science (SAMS)
- **Frazer-Nash Consultancy** are sponsoring the EngD project
- Probabilistic structural integrity assessment for offshore wind turbine rotor blade life extension

The authors are grateful to EPSRC and NERC for funding for the Industrial CDT for Offshore Renewable Energy (EP/S023933/1)

# Research Motivation

- Rotor blade end of life (EoL) is a big area of research.
  - Currently there is no easy recycling solution for old blades
- **27 GW** of wind energy to be decommissioned between now and **2030** [2]
- **Life extension** (LE) could slow down the generation of waste while we implement an appropriate solution



European landfill ban for wind turbine rotor blades by 2025 [2]. Image: [6]

# Research Aim

**Aim: To develop a Bayesian network (BN) methodology for assessing the remaining useful life (RUL) of offshore WTG rotor blades.**

- The BN is the framework used to perform the **probabilistic RUL calculations** for a WTG rotor blade.

- The framework has different **modules** that can be changed depending on the required functionality or the available information/data.

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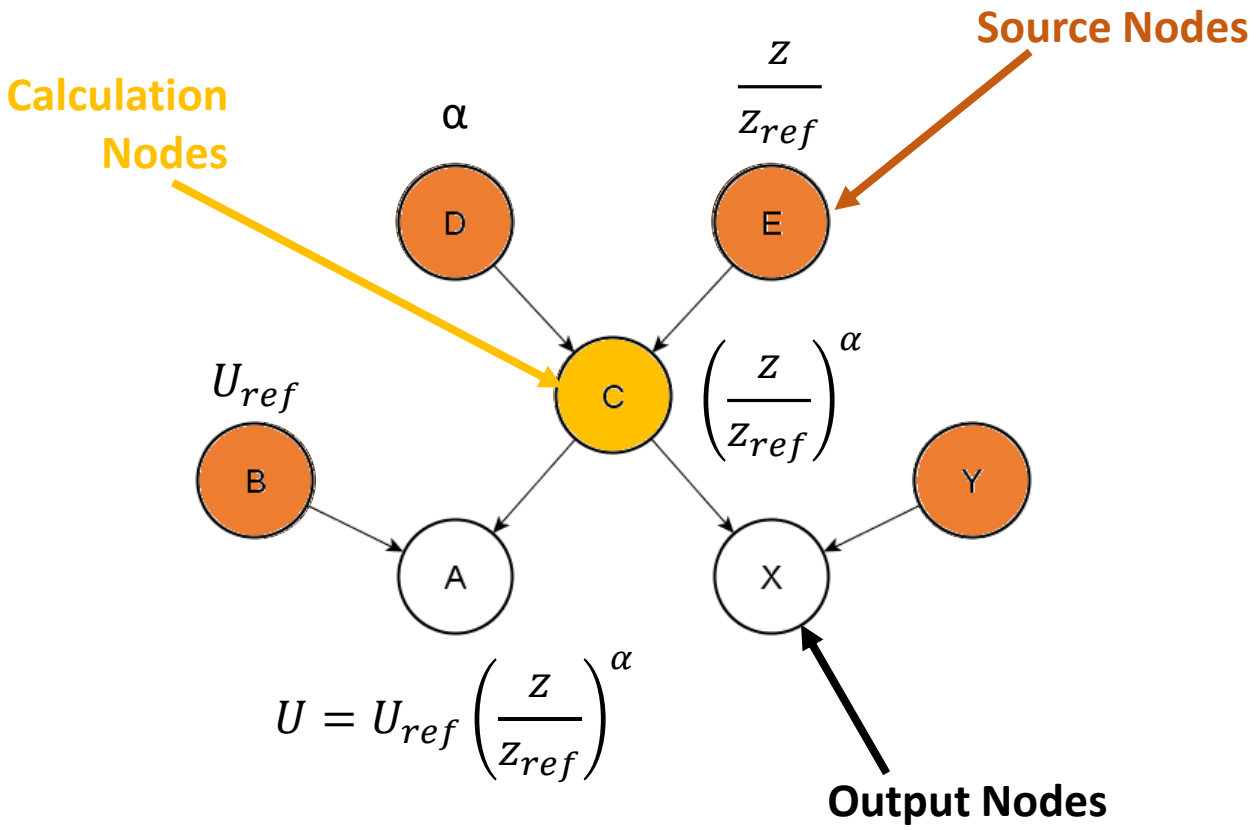
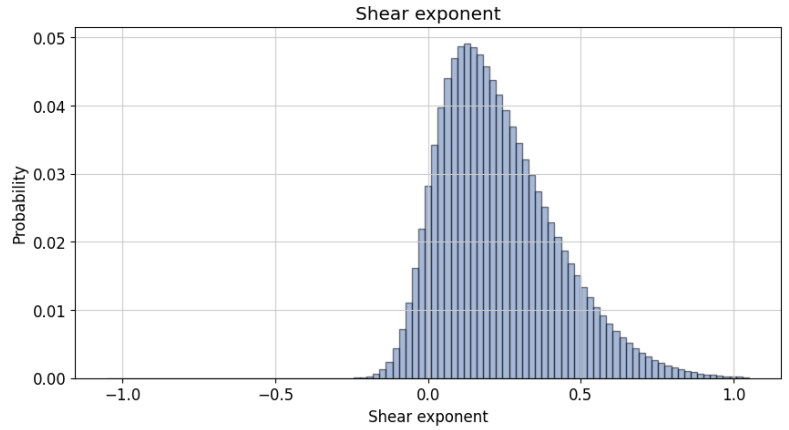
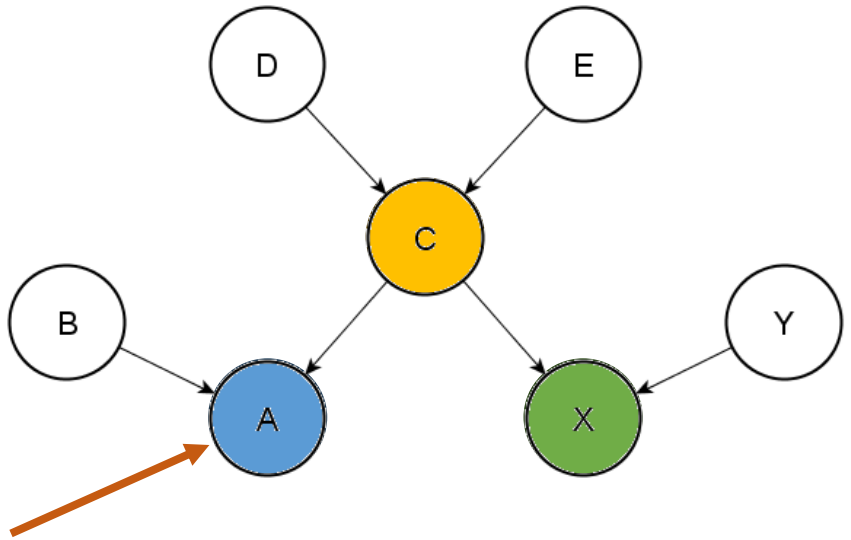
# Bayesian Network Methodology




$$p(C) \propto \int_D \int_E p(C|D,E)p(D)p(E)dD\ dE$$

# Bayesian Network Methodology




**Updating Nodes A and X**

$$p(C|A,X) \propto \int_B \int_Y p(A|C,B)p(B)p(X|C,Y)p(Y)p(C)dBdY$$

# Why a loads module?

- Developing a loads module offered:
  - **Input Simplification:** wind speed as input rather than blade loads, making it easily updatable with SCADA data.
  - **Adaptability:** easily tailored to different WTG types
  - **Efficiency:** fast run times are achieved by evaluating the spanwise blade loading probabilistically
  - **Sensitivity Analysis:** Sobol variance analysis can be applied

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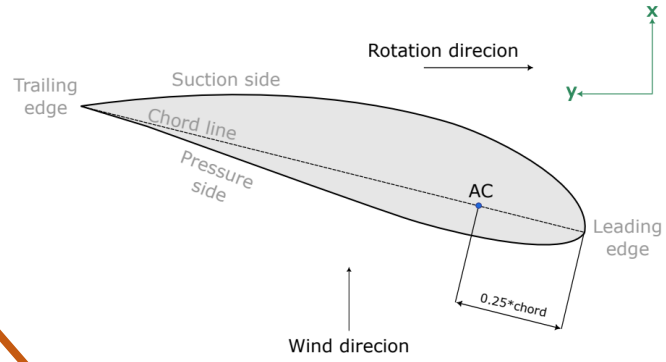
# Probabilistic Loads Modelling

## BEM Theory - as in AeroDyn v15 [4, 5]

- Reduces BEM equations to one residual equation
- Initialise inflow angle, $\varphi$
- Solve the residual equation iteratively using **Brent's root solving method**




$$R(\phi) = \frac{\sin\phi}{1-a} - \frac{V_x}{V_y} \cdot \frac{\cos\phi}{1+a'}$$

- **Outputs**: aerodynamics forces in x and y-direction and moment about the z-direction

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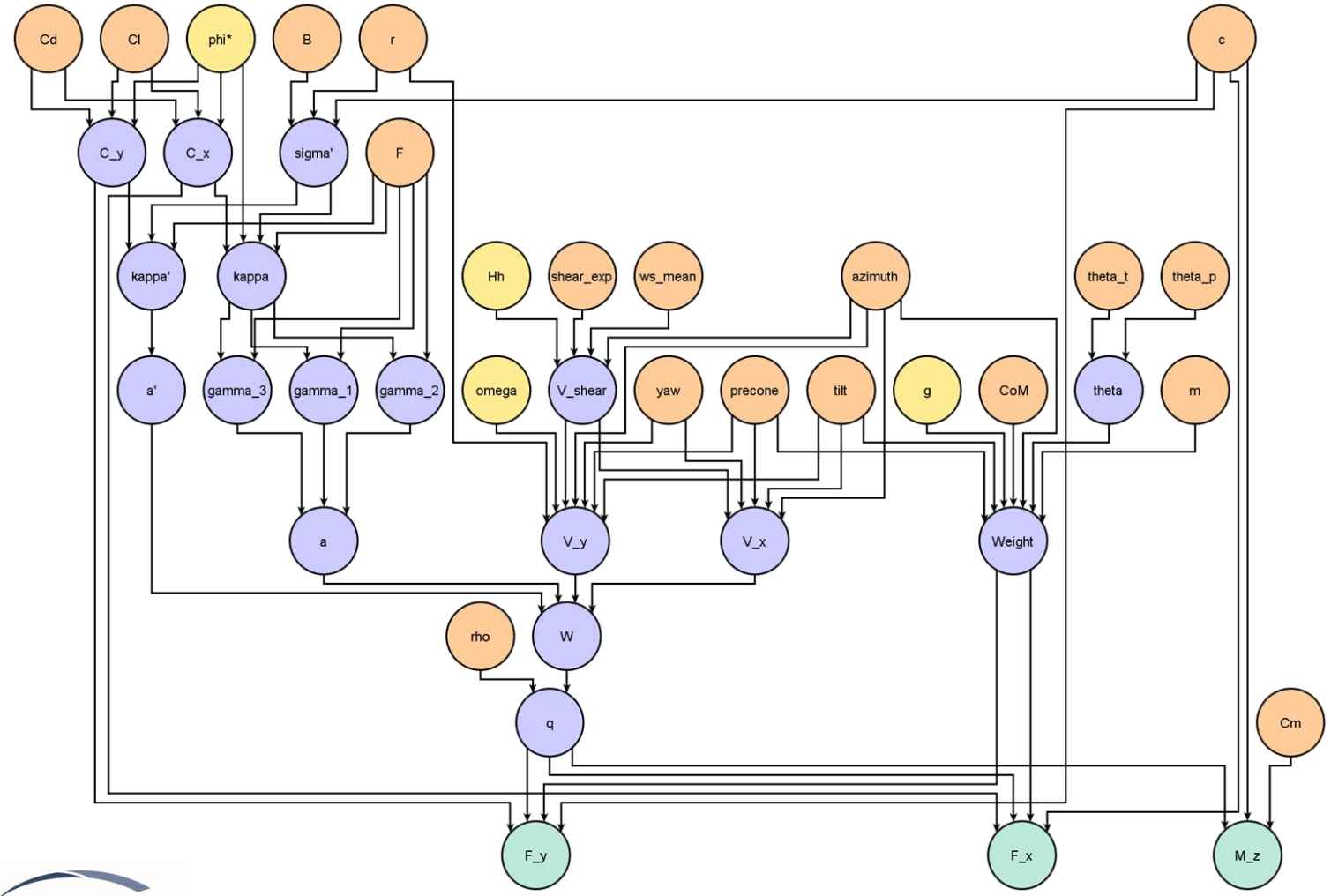
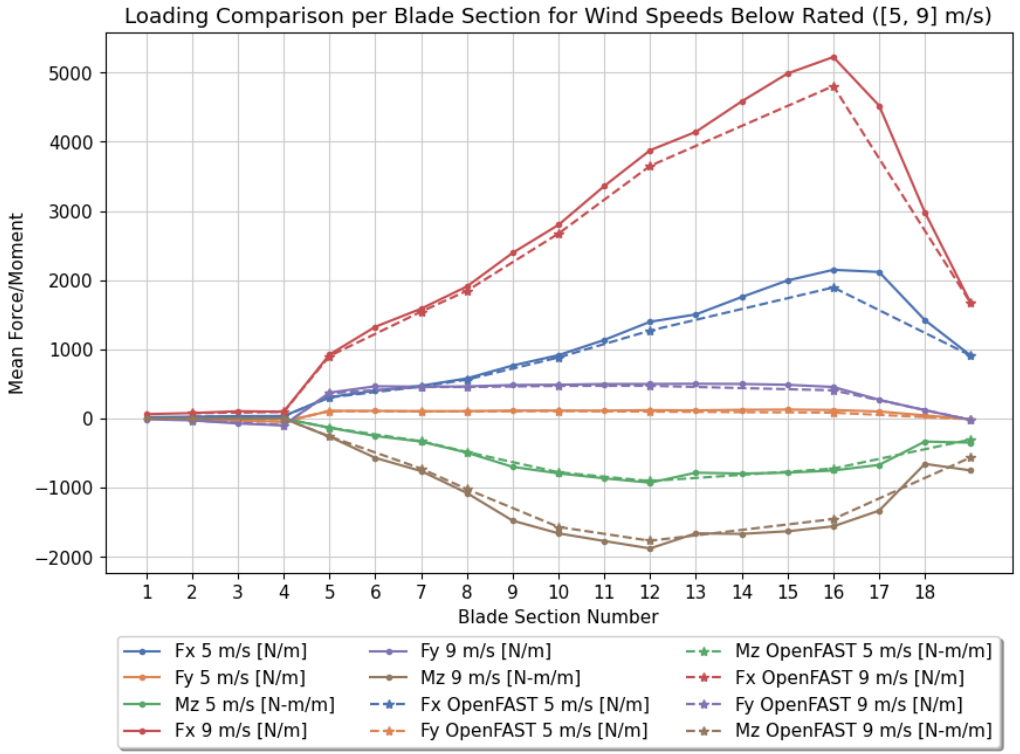
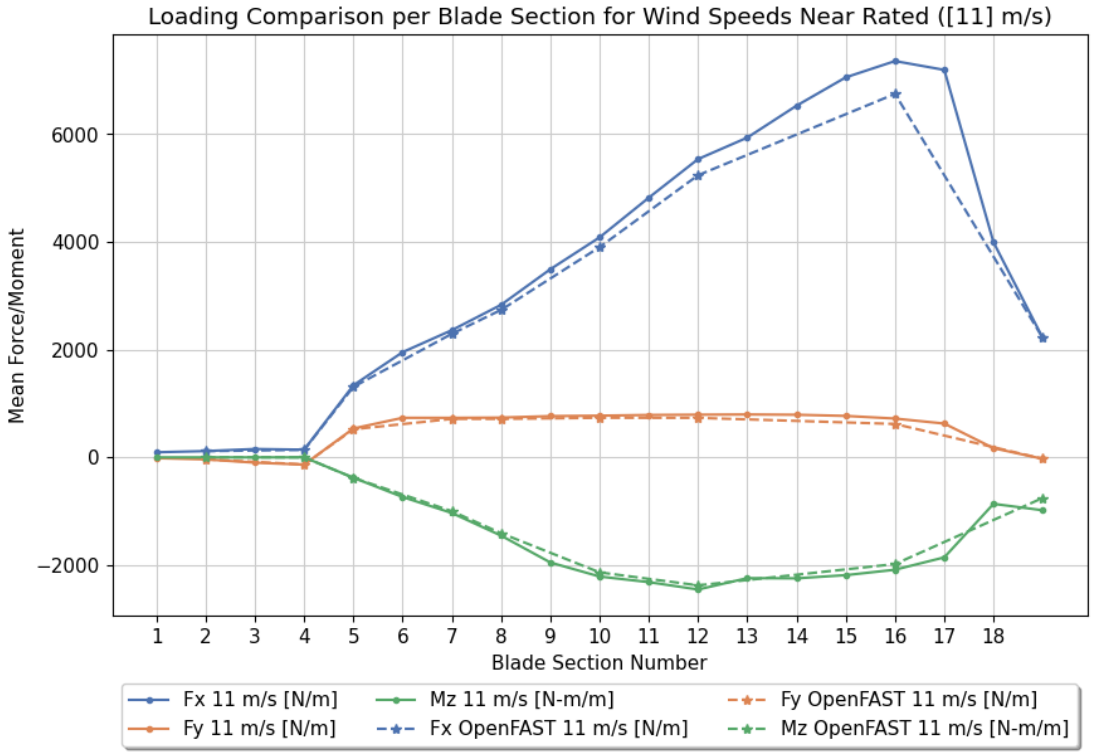
# Probabilistic Loads Modelling



# Probabilistic Loads Modelling

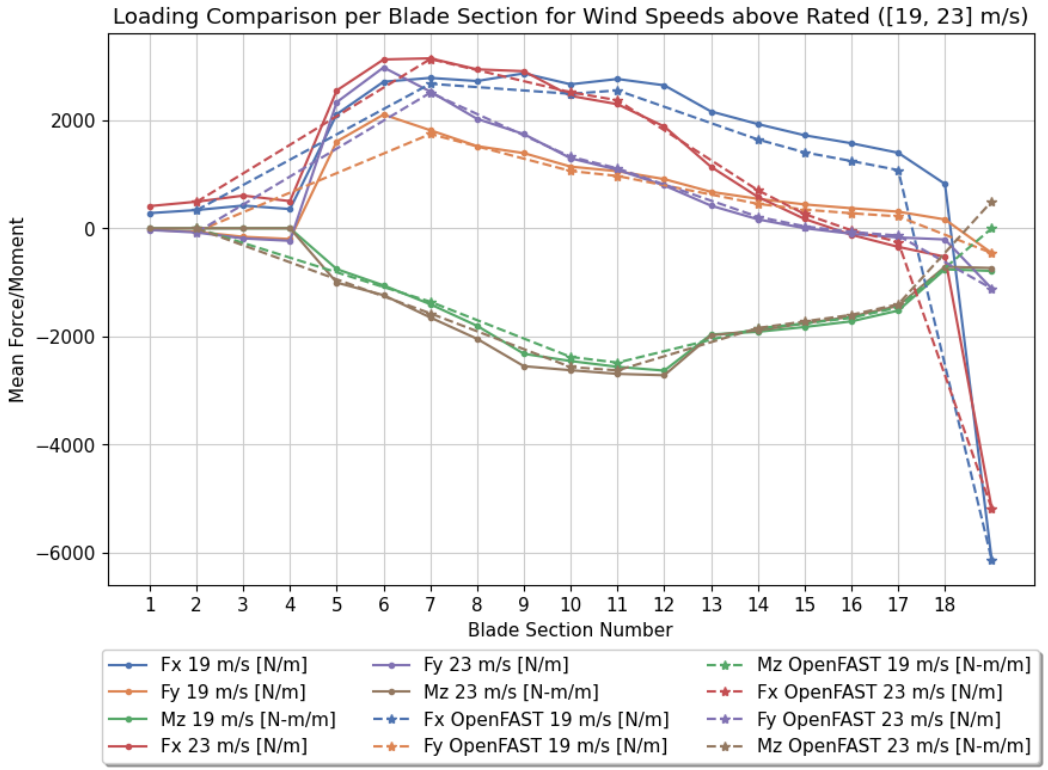
## **Comparison with OpenFAST:** below rated and at rated wind speed



# Probabilistic Loads Modelling

## **Comparison with OpenFAST:** above rated wind speed

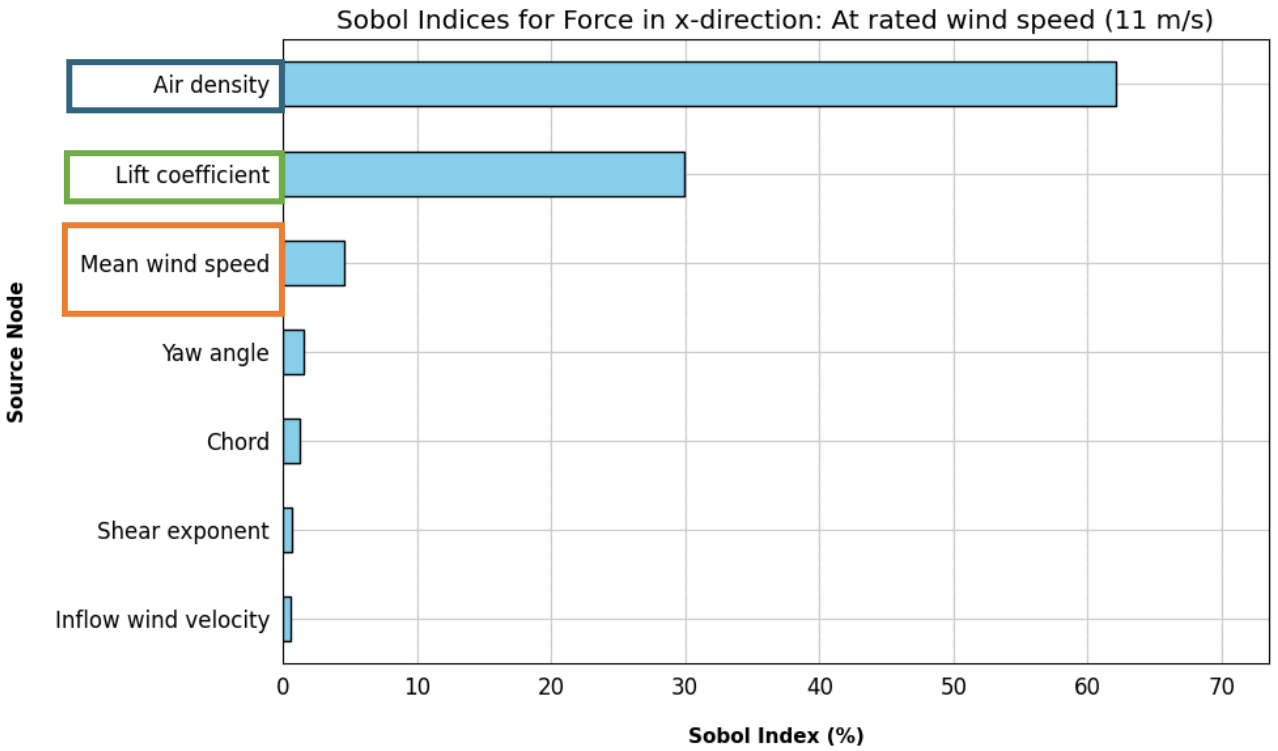


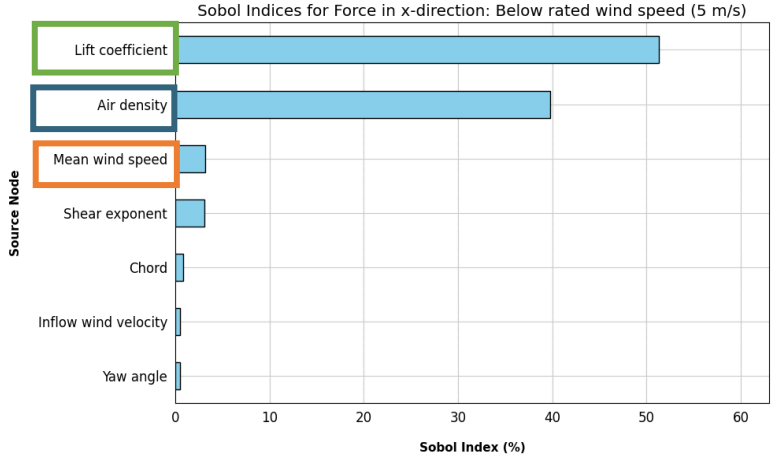

**Key takeaways:**

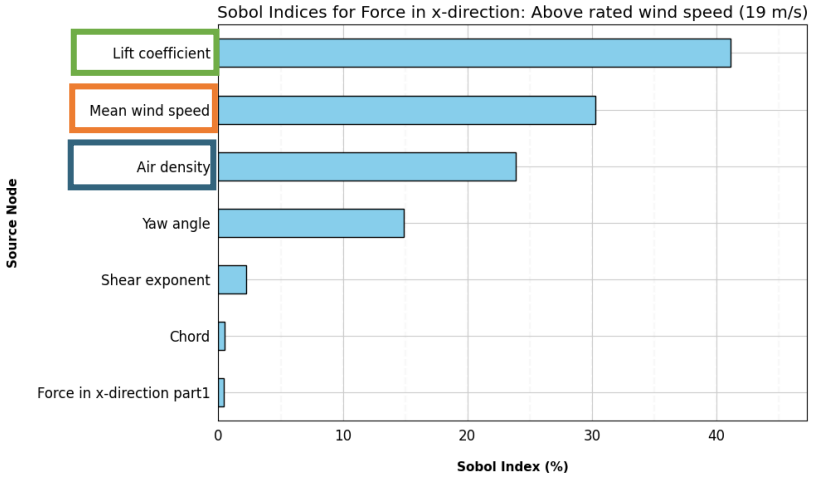
- Results generally compare well
- BEM calculations are intentionally simplified, prioritising computational efficiency over detailed modelling
- Provides a method for probabilistic loads modelling which can be easily integrated into the existing BN methodology

# Probabilistic Loads Modelling

## Sobol Analysis



# Conclusion

- The current study extends the **BN methodology** by adapting it for the **fatigue assessment of composite rotor blades** by including different **modules**

- **The load characterisation module:**
  - a physics-based simplification model was designed to provide a computationally efficient framework for probabilistic load modelling within the BN.
  - the results compare favourably with OpenFAST
  - it illustrates how modular components can be integrated into the BN

- **Future work** will address the other modules and updating the network with data

The authors are grateful to EPSRC and NERC for funding for the Industrial CDT for Offshore Renewable Energy (EP/S023933/1)

# Thank you!

**Author:** Hannah Mitchell (s1329690@sms.ed.ac.uk)
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