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Evaluation of the Wind Direction Uncertainty And Its Impact on Wake Modelling at the Horns Rev Offshore Wind Farm

**Pierre-Elouan Réthoré*, Mathieu Gaumond,
Andreas Bechmann, Kurt Hansen, Alfredo Pena,
Søren Ott, Gunner Larsen**

Aero-elastic Section, Wind Energy Department, DTU, Risø

Windpower Monthly's Wind Farm Data
Management and Analysis forum
23-25 September

Outline

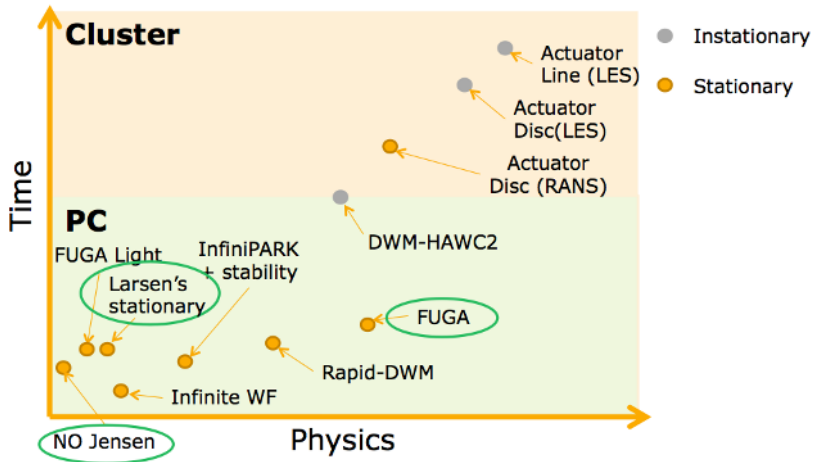
- 1 Why Uncertainty Matters?
 - Introduction
 - Method: Modelling the wind direction uncertainty
 - Results

- 2 Adding Value to Wind Farm Data
 - Machine Learning and Physical Modelling
 - The FUSED-Wind project
 - A Future Business Concept

- 3 Conclusion and Future Works

Introduction

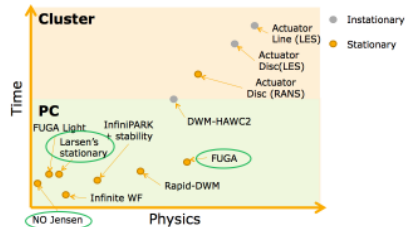
Overview of DTU's Wind Farm Flow Models



Introduction

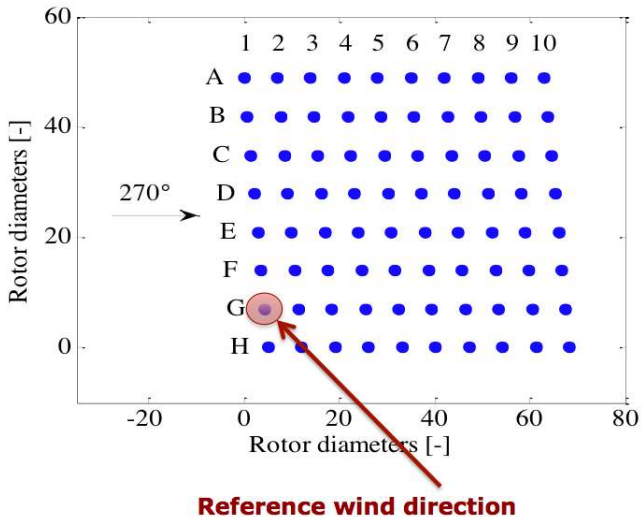
What Are Those Models used for?

- ◆ Estimating Annual Energy Production
- ◆ Wind Farm Optimization



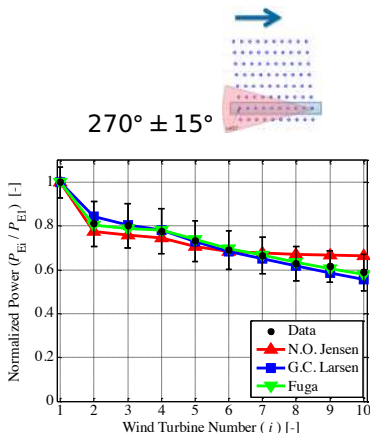
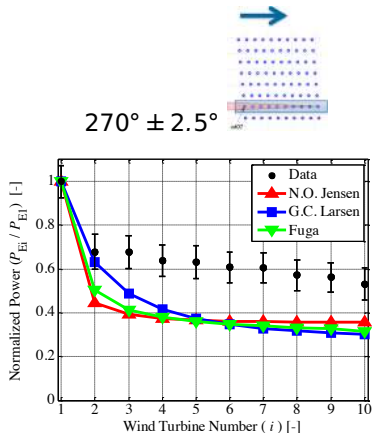
Introduction

The Horns Rev test case - Western winds



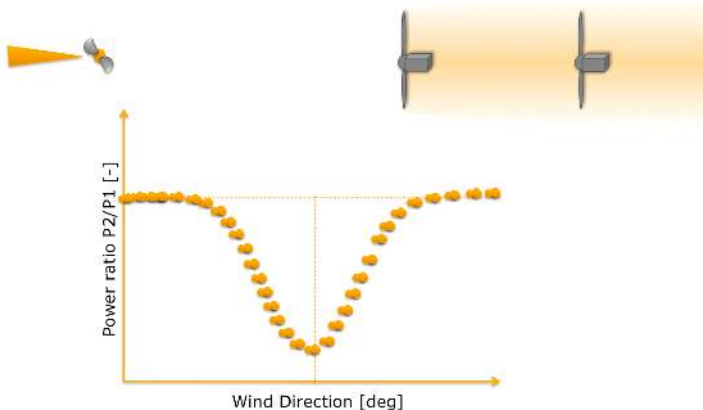
Introduction

Results of the Wake Model Benchmarking: Confusion!



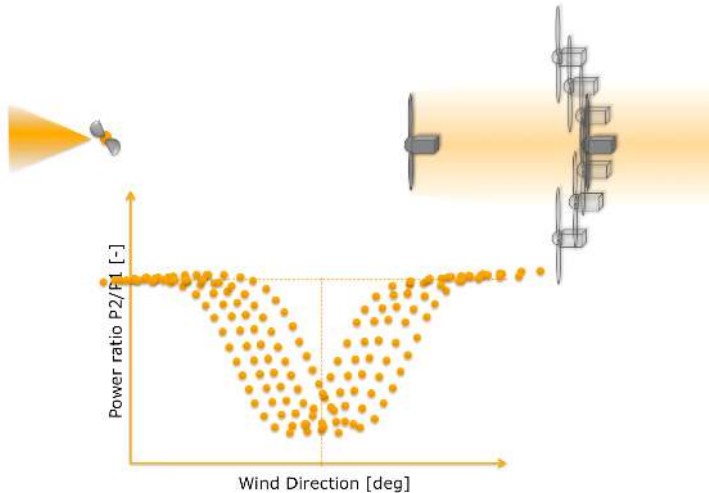
Introduction

The effect of wind direction uncertainty on wind farm wake measurement



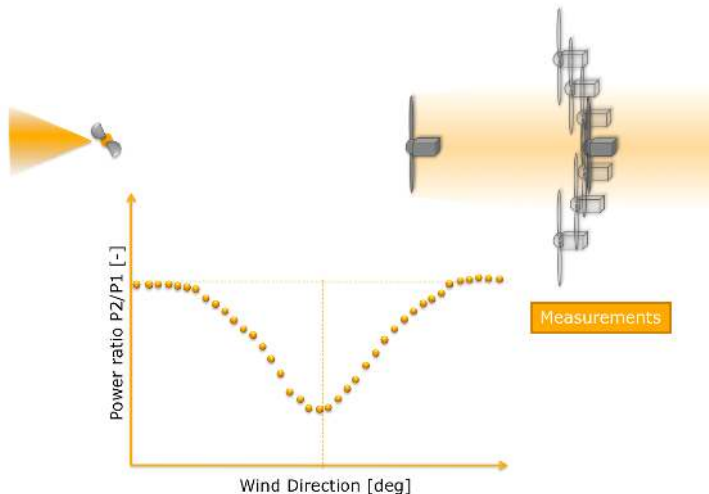
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The effect of wind direction uncertainty on wind farm wake measurement



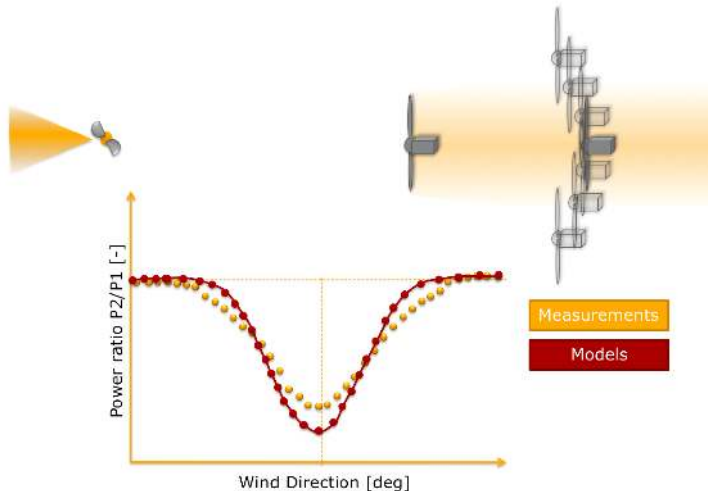
Introduction

The effect of wind direction uncertainty on wind farm wake measurement



Introduction

The effect of wind direction uncertainty on wind farm wake measurement



Introduction

Sources of wind direction uncertainty

Random/temporal bias from the measurement device

- ◆ Yaw misalignment (when yaw sensor is used to measure direction)
- ◆ Time drift of the calibration
- ◆ Failures

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Atmospheric turbulence

- ◆ Small scale turbulence (sub 10-minute)
-> This *should* be accounted by the models
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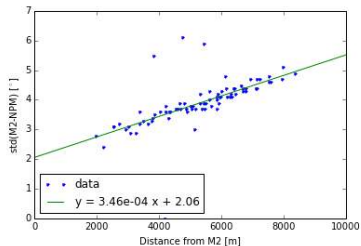
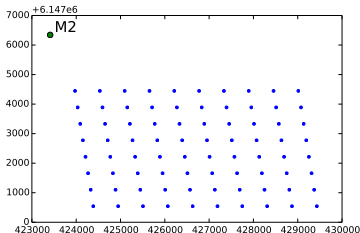
Wind direction coherence

- ◆ Spatial variability of the wind direction
- ◆ Different time-control volume averaging

Introduction

Spatial decorrelation of wind direction

The wind direction correlation between M2 and the wind turbines decreases linearly with the distance



Introduction

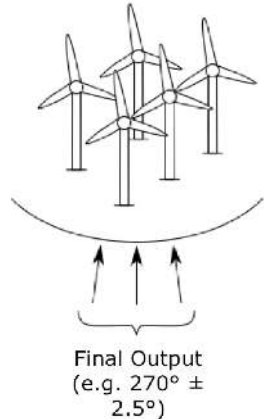
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Method: Modelling the wind direction uncertainty

The "traditional" method

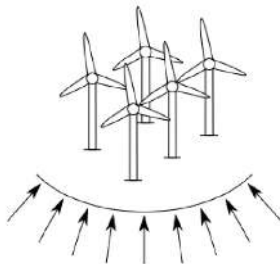
- ◆ Step 1: Run simulations with fixed and homogeneous wind direction covering the desired wind direction sector
- ◆ Step 2: Apply a linear average to reproduce the data post-processing



Method: Modelling the wind direction uncertainty

The proposed method

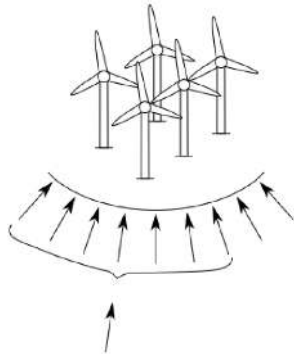
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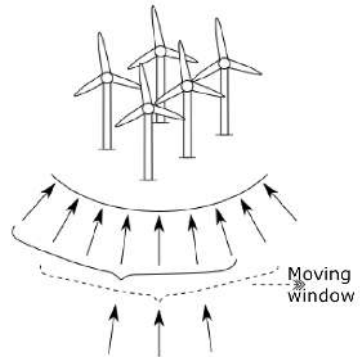
- ◆ Step 1: Run simulations with fixed and homogeneous wind direction
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Method: Modelling the wind direction uncertainty

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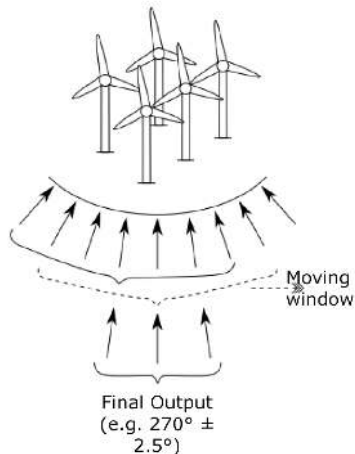
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Method: Modelling the wind direction uncertainty

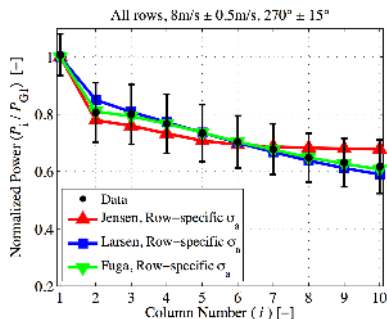
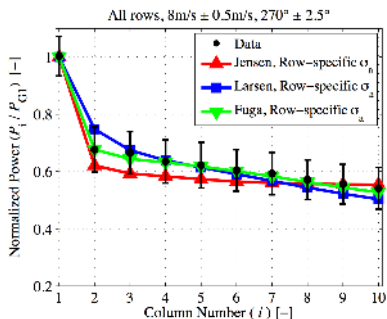
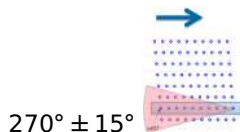
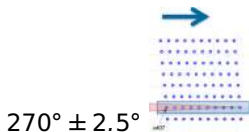
The proposed method

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Results

All the rows, using a row-specific wind direction uncertainty



Results

Result for the whole wind farm in $\theta = 270^\circ$

	$270 \pm 2.5^\circ$	$270 \pm 15^\circ$
Power Data	64.7%	73.9%
NOJ, Baseline	-20.9%	+0.4%
GCL, Baseline	-20.9%	-0.1%
Fuga, Baseline	-21.7%	-0.3%

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Fuga, $\sigma=3.5^\circ$	-8.5%	-0.2%
NOJ, row-specific	-3.1%	+0.1%
GCL, row-specific	-0.7%	-0.2%
Fuga, row-specific	-0.8%	-0.2%

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Machine Learning and Physical Modelling

From Deterministic to Stochastic

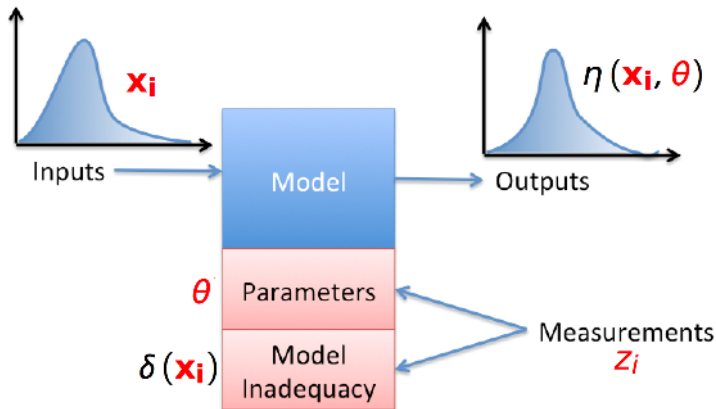
$$\zeta_i(\mathbf{x}_i) = \eta(\mathbf{x}_i) \quad (1)$$



Machine Learning and Physical Modelling

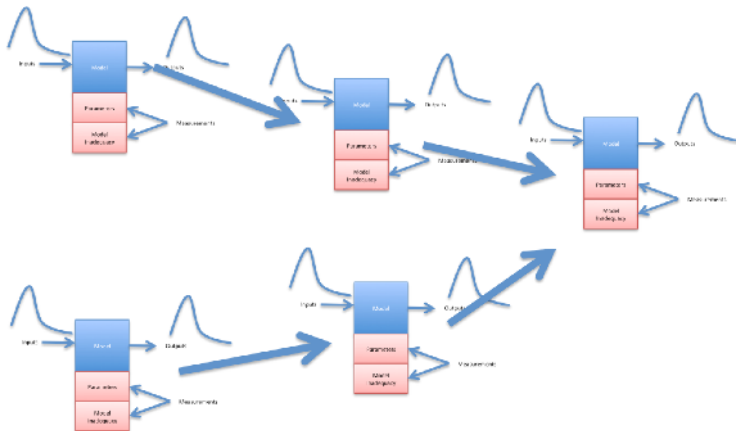
From Deterministic to Stochastic

$$z_i = \zeta_i(\mathbf{x}_i) + \varepsilon_i = \eta(\mathbf{x}_i, \theta) + \delta(\mathbf{x}_i) + \varepsilon_i \quad (2)$$



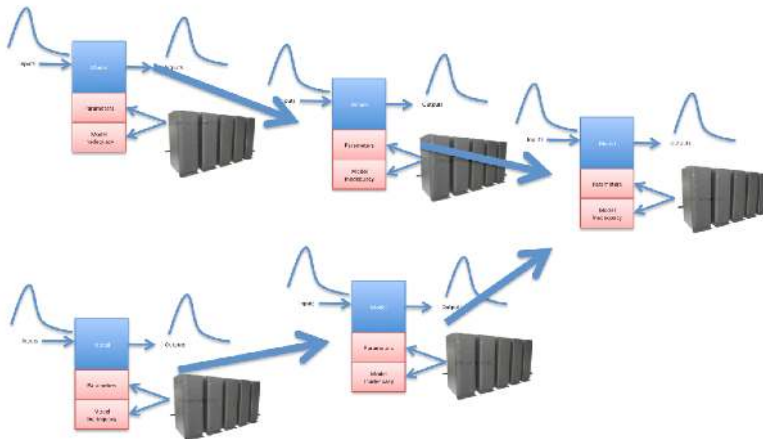
Machine Learning and Physical Modelling

System Engineering



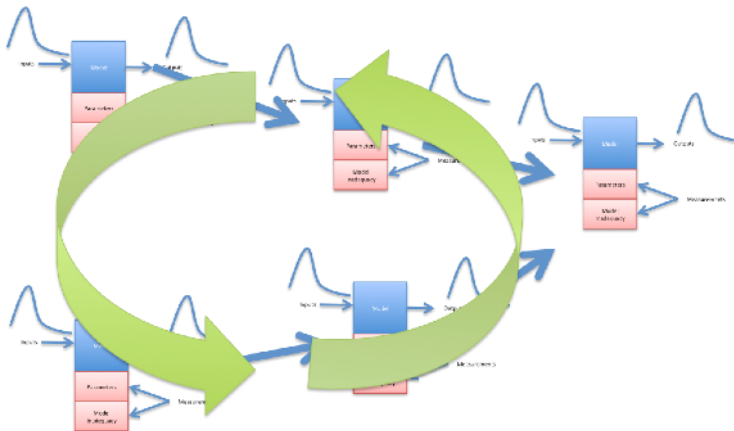
Machine Learning and Physical Modelling

System Engineering - Big Data



Machine Learning and Physical Modelling

System Engineering - Augmented Intelligence



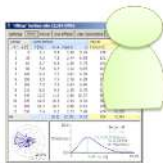
Connecting All Wind Energy Models in a Workflow

- ◆ Collaborative effort between DTU and NREL to create a **F**ramework for **U**nified **S**ystem **E**ngineering and **D**esigned of **W**ind energy plants.
- ◆ Based on OpenMDAO, a python based Open source framework for **M**ulti-**D**isciplinary **A**nalysis and **O**ptimization.
- ◆ FUSED-Wind will offer built in capabilities for Uncertainty Quantification, Machine Learning and Optimization



A Future Business Concept

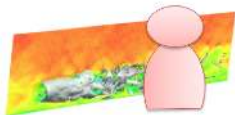
Concept



**WASP
SmartWake client**



**Cloud Cluster
SmartWake Server**



**P.-E. Røed
Wake Modelers**

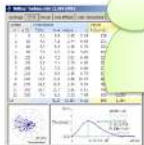


**Wind farm SCADA
owners**

A Future Business Concept

I want to plan
a wind farm

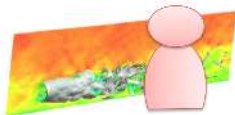
Concept



WASP
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Cloud Cluster
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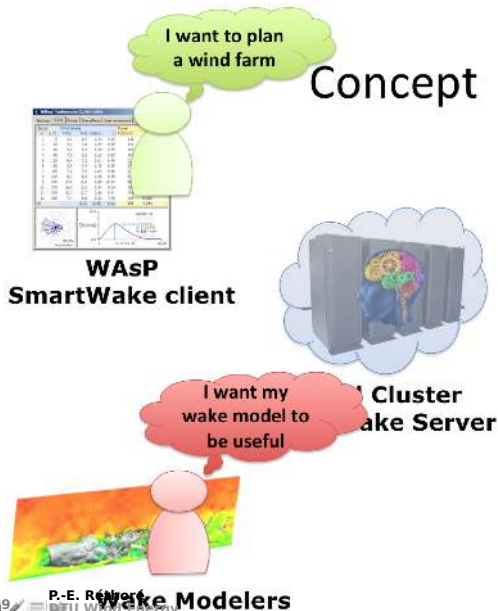
P.-E. Réthoré

Wake Modelers



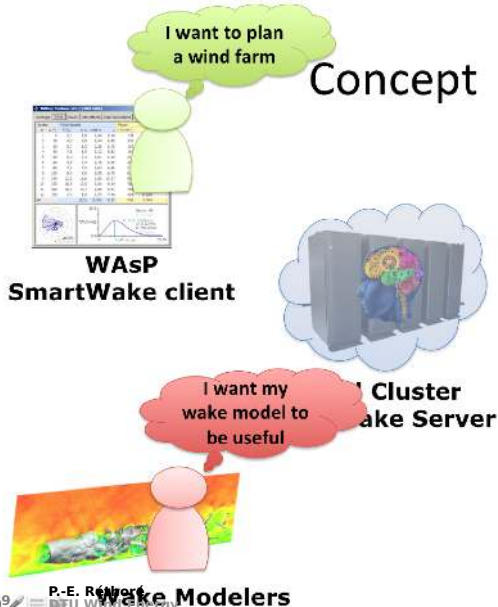
Wind farm SCADA
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A Future Business Concept



**Wind farm SCADA
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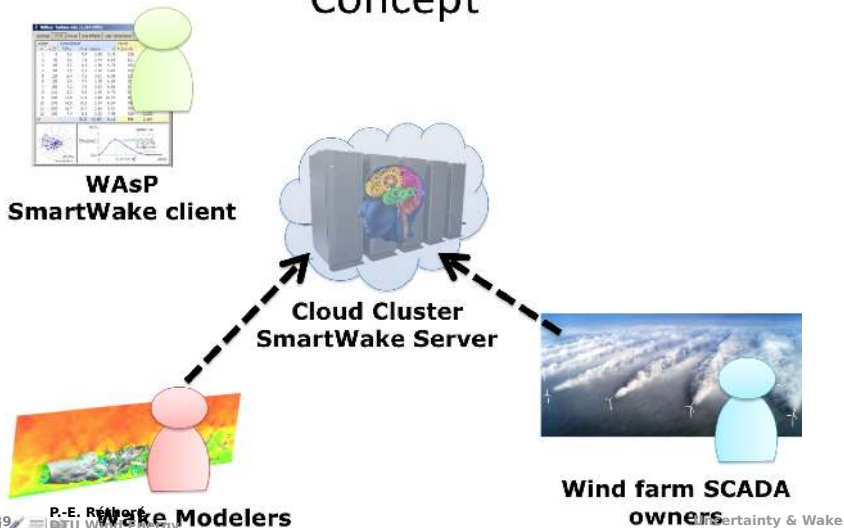
A Future Business Concept



Wind farm SCADA owners

A Future Business Concept

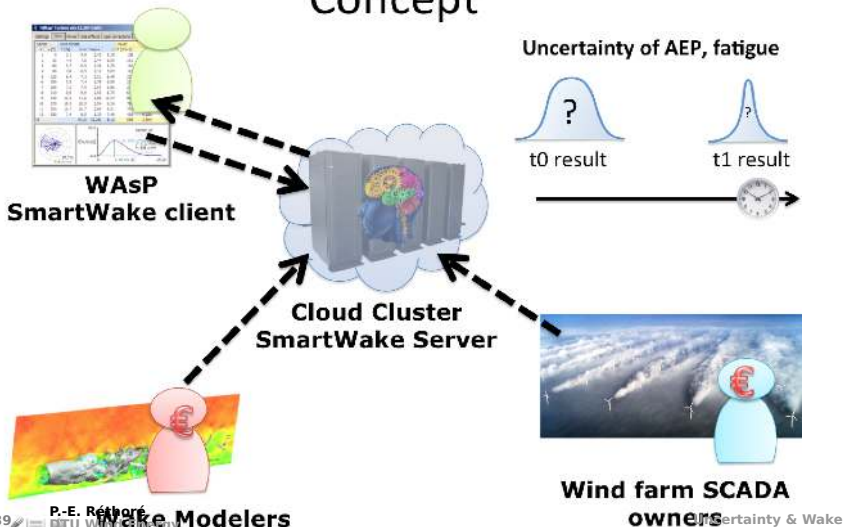
Concept



The diagram illustrates the SmartWake architecture. At the center is the **Cloud Cluster SmartWake Server**, represented by a cloud containing server racks and a brain icon. To the top left is the **WAsP SmartWake client**, shown as a person icon next to a screenshot of the WAsP software interface. To the bottom left is **Wake Modelers**, represented by a person icon next to a 3D visualization of a wind farm. To the bottom right is **Wind farm SCADA owners**, represented by a person icon next to an aerial view of a wind farm. Dashed arrows indicate data flow: from the WAsP client and Wake Modelers to the Cloud Cluster Server, and from the Cloud Cluster Server to the Wind farm SCADA owners. Above the Wind farm SCADA owners, there is a section titled **Uncertainty of AEP, fatigue** showing two probability density function (PDF) curves labeled **t0 result** and **t1 result**, with a clock icon indicating a time progression from t0 to t1.

A Future Business Concept

Concept



Conclusion

- ◆ The N.O. Jensen model, the G.C. Larsen model and Fuga are robust engineering models able to provide accurate predictions using wind direction sectors of 30°
- ◆ The discrepancies for narrow wind direction sectors are not caused by a fundamental inaccuracy of the current wake models, but rather by a large wind direction uncertainty included in the dataset
- ◆ We need some models and measurements for wind direction uncertainty to move forwards from this stage
- ◆ Do not "tune" your wake models to match the $\pm 2.5^\circ$ measurements!!!

Future work

Wind Farm Flow Model Uncertainty

- ◆ The method will be applied to other wake models and datasets
- ◆ Sample based uncertainty quantification to be investigated
- ◆ Work on estimating the wind direction uncertainty using the wind farm dataset

System Engineering

- ◆ Opening FUSED-Wind to the public
- ◆ Adding Uncertainty Quantification to FUSED-Wind

Thank you for your attention!

- ◆ Work funded by EUDP-WakeBench and EERA-DTOC
- ◆ Dataset graciously made available by DONG Energy and Vattenfall.
- ◆ Article submitted to wind energy and master thesis available on request

