Recent developments in wind farm flow modeling and wind farm control

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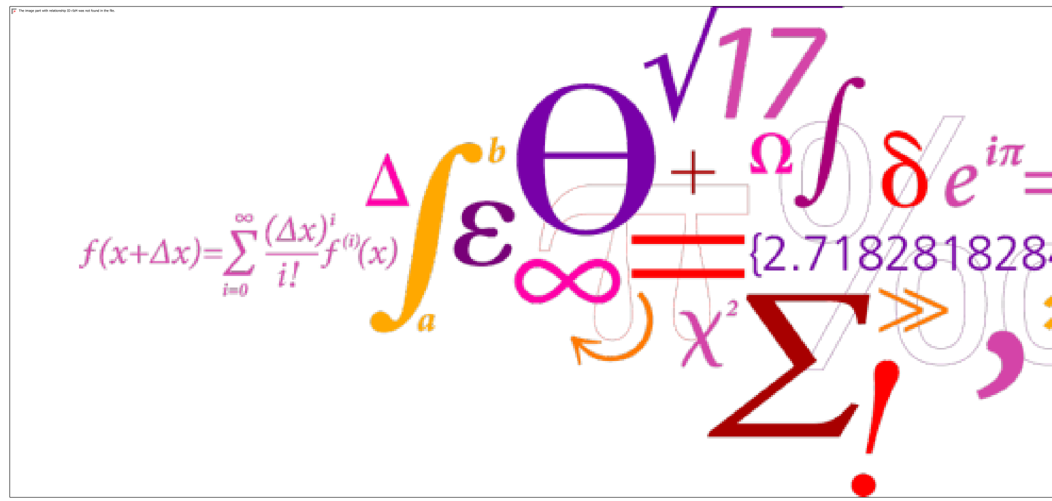

DTU Wind Energy
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Outline (1)

- **Medium fidelity DWM simulation approach extended to the non-neutral flow regime**
  - Motivation
  - ABL stability
  - DWM “classic”
  - DWM under non-neutral stability conditions
  - Lillgrund WF case study
- Conclusions

Outline (2)

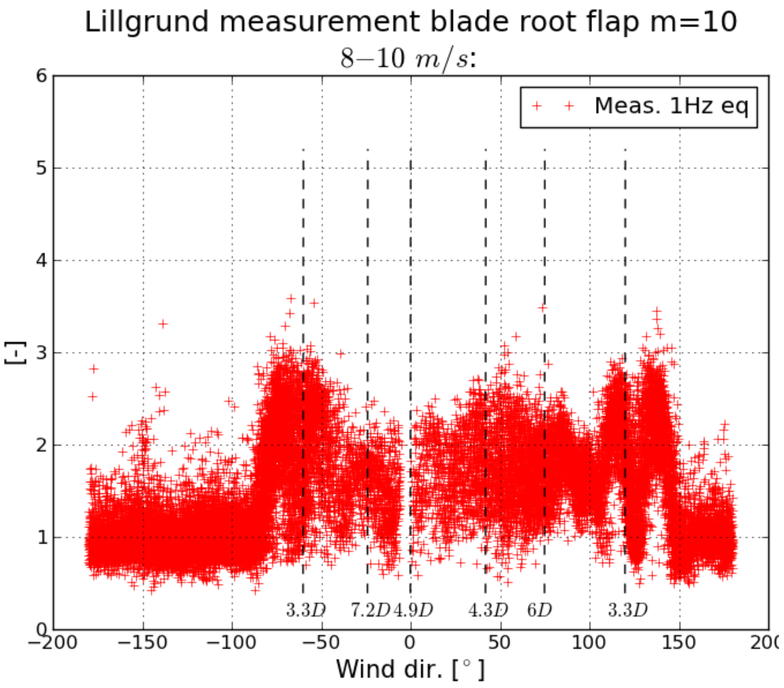
- **Platform for open loop WPP control WT control**
  - The 'collaborative' WT ctr. the greedy WT
  - Flow field model … incl. wake model
  - Aerodynamic WT model … incl. a surrogate
  - The optimizer
  - The Lillgrund case study
- Conclusions & Future work

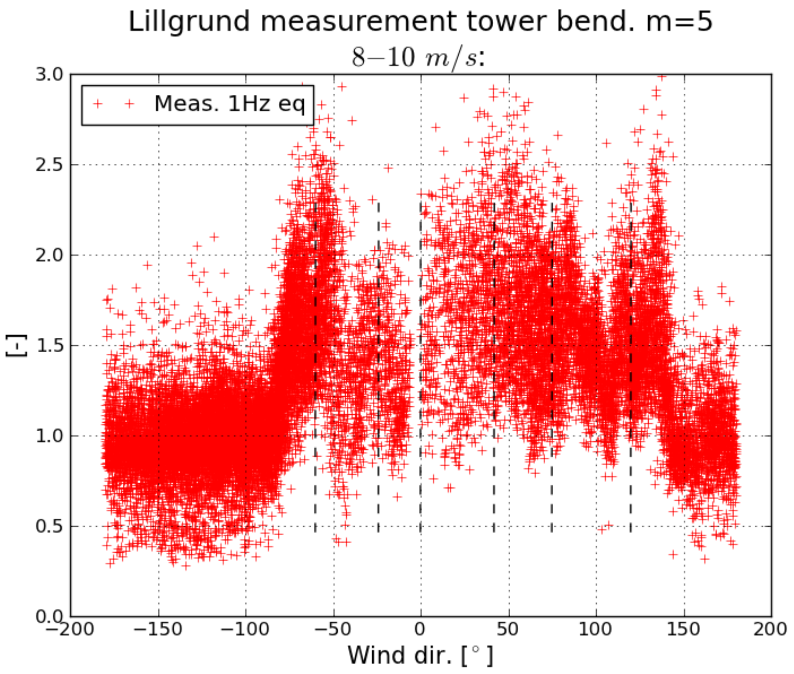
Motivation … why medium fidelity?

- Un-steady flow fields are required for WT load estimation
- High-fidelity CFD-LES modeling is CPU-costly and challenged by meso-scale boundary conditions.
- A coupled aeroelastic/CFD-LES approach is **not** feasible for a large number of WF simulations! … wind farm design/optimization
- Need for medium-fidelity flow field models that
  - Preserves the essential physics of un-steady wake flows
  - Is (relatively) CPU in-expensive
  - Allow for a straight forward coupling with aeroelastic models

Motivation … why **non-neutral**?

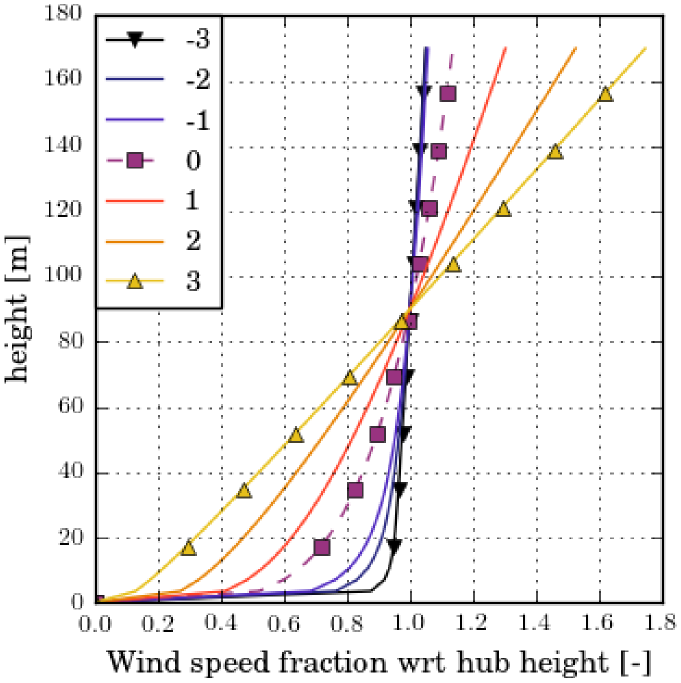
- Huge scatter is observed in full-scale load measurements





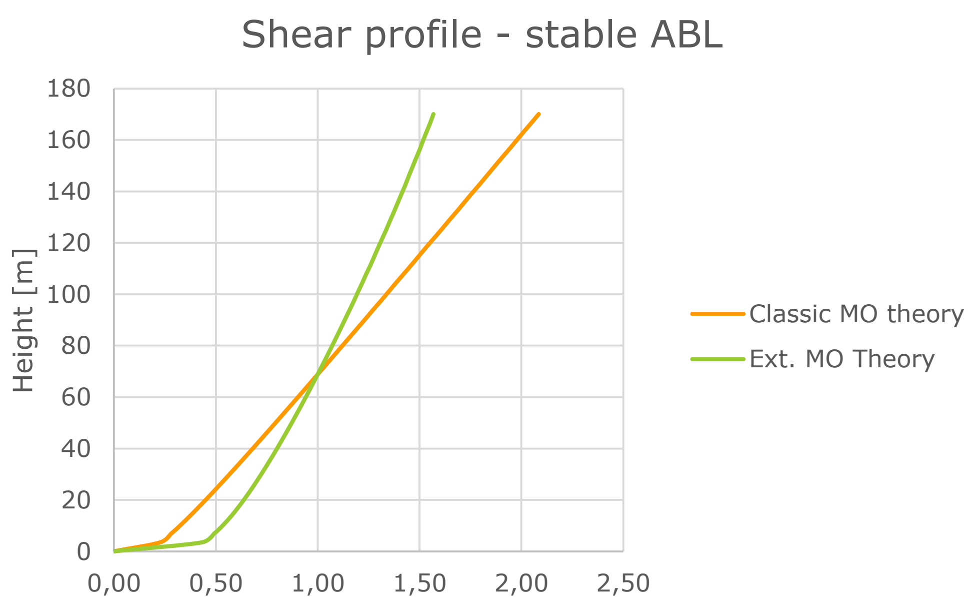
ABL stability (1)

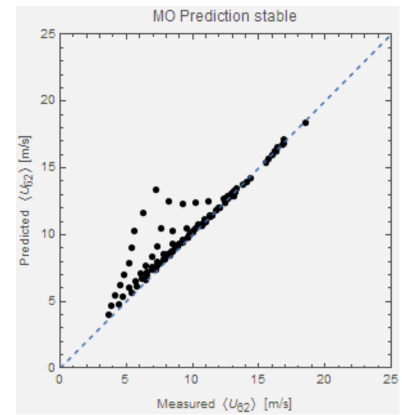
- ABL stability … buoyancy included
  - Increased/decreased turbulence intensity for unstable/stable conditions
  - Modified turbulence structure … mainly in the large scale regime
  - Modified shear profile

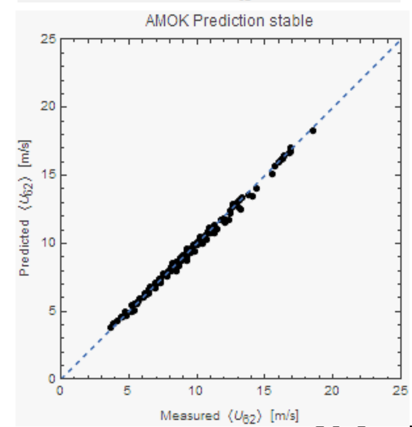


ABL stability (2)

- Classic vs. Extended MO theory
  - Unstable case unaffected
  - Stable case may be significantly affected





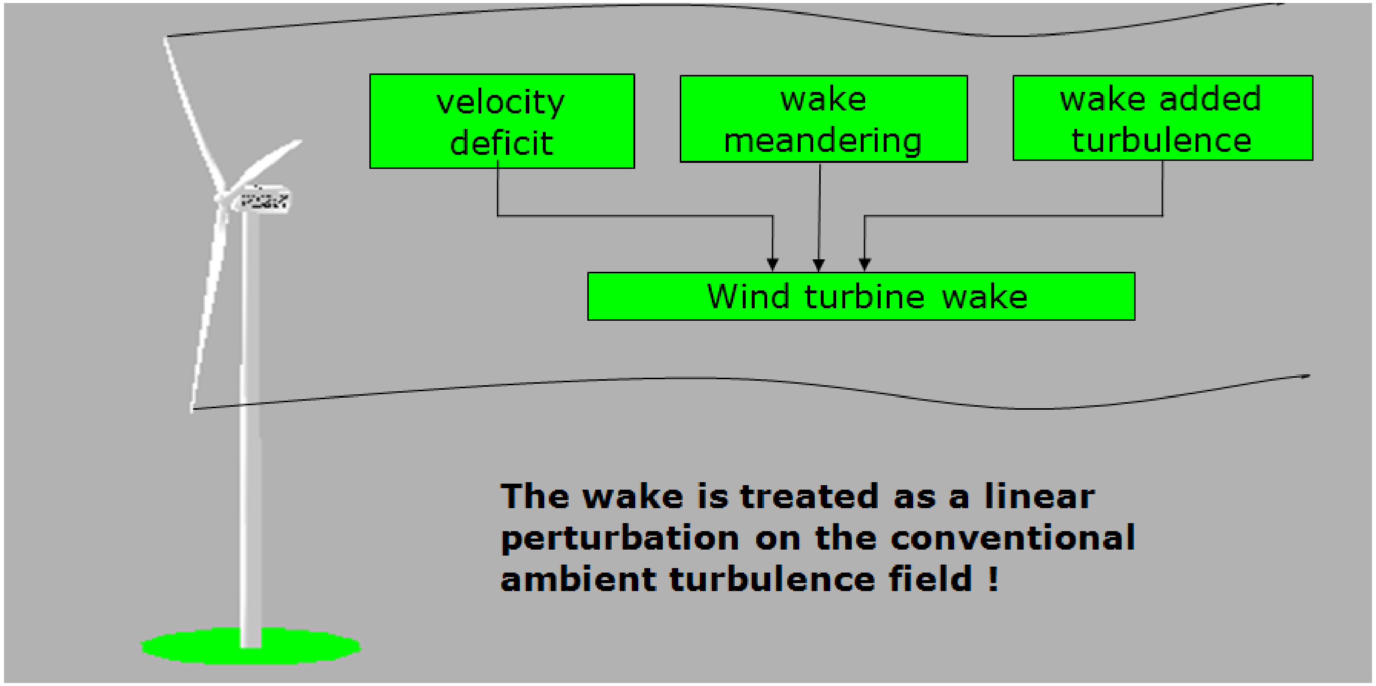


[Reference: Larsen G. C. et al. (2016). Impact of atmospheric stability conditions on wind farm loading and production. DTU Wind Energy Report-E-0136]

DWM "classic"

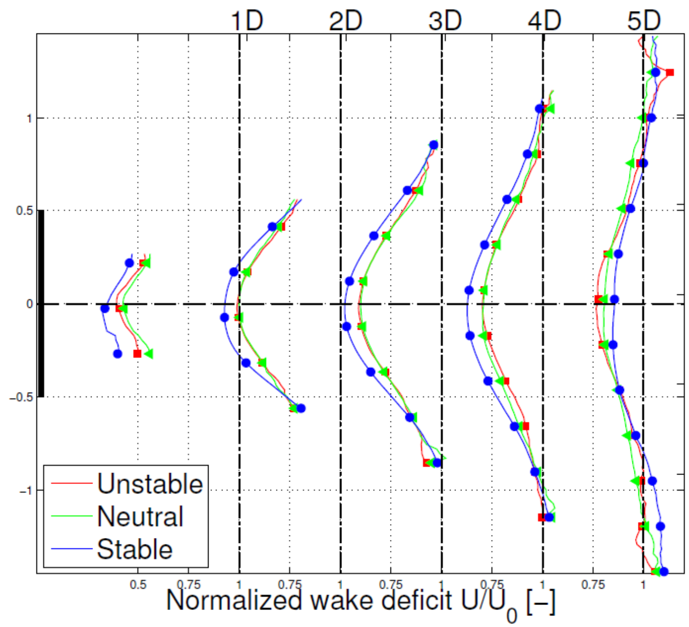
- Included in the IEC-code as recommended practice
- "Poor man's LES" … based on a passive tracer analogy

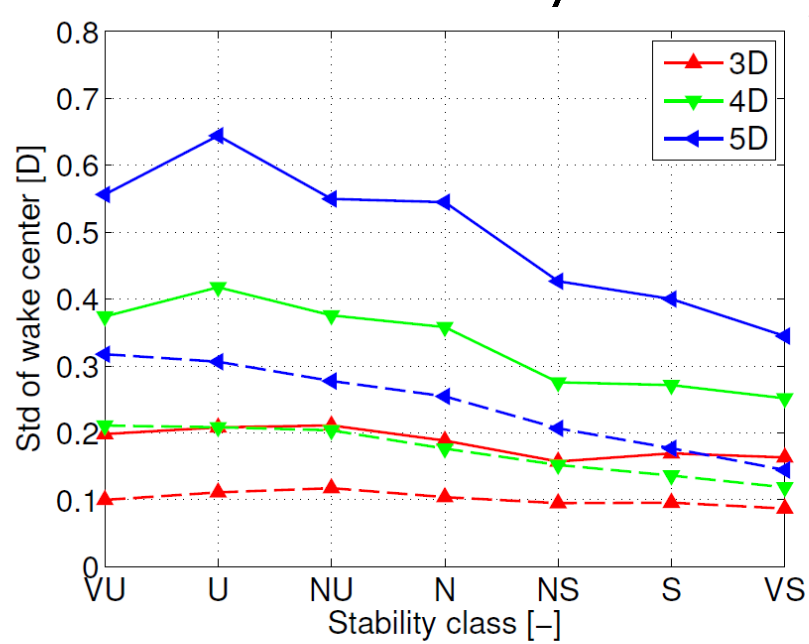
[Reference: Larsen GC et al. (2008). Wake meandering – a pragmatic approach. WE]



DWM under non-neutral stability conditions (1)

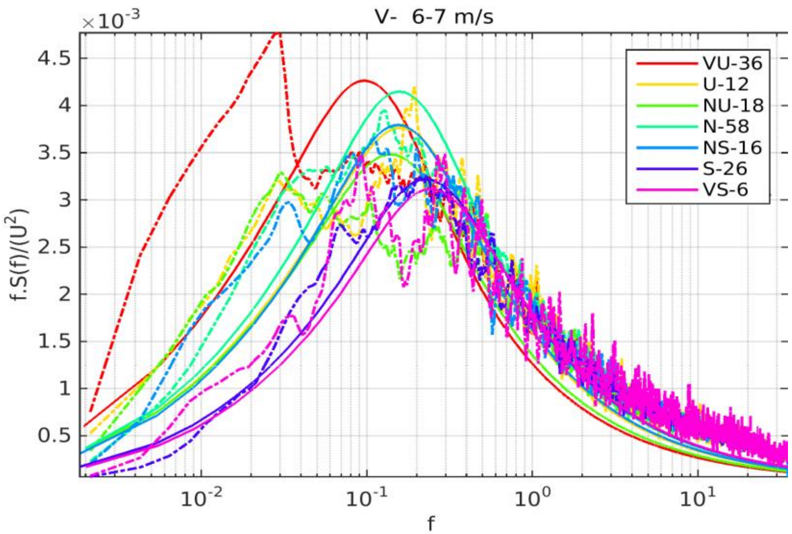
- Full-scale LiDAR experiments [Machefaux et al. (2015) WE; Larsen et al. (2015) Journal of Physics] have justified:
  - *ABL stability impacts primary the* “large” (meandering) turbulence scales
  - “small” scale turbulence regime can be considered invariant with respect to ABL stability conditions





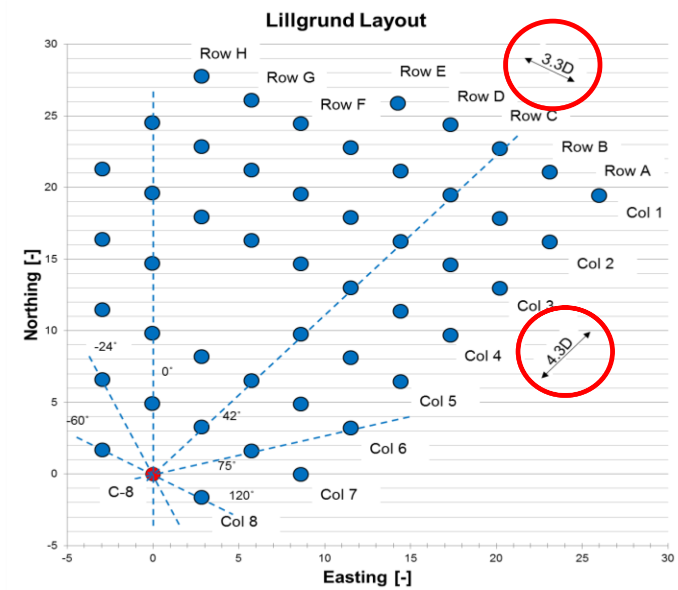
DWM under non-neutral stability conditions (2)

- Synthetic turbulence fields are generated using a generalization of the Mann spectral tensor
  [Chougule A, Mann J, Kelly MC and Larsen GC (2017). JAS]
  - Buoyancy included!
  - Homogeneous velocity and temperature fields
  - Turbulence production driven by (linear) vertical shear and (constant) vertical temperature gradient



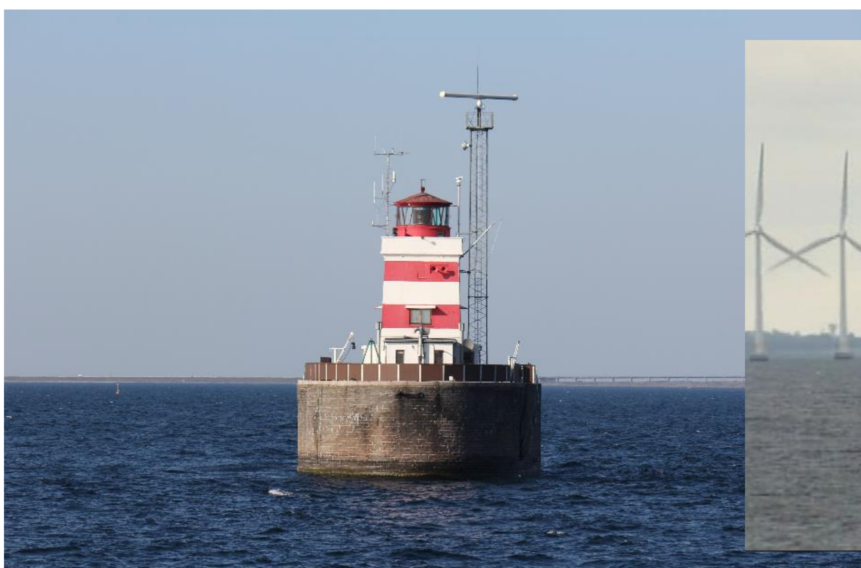
Case study – Lillgrund WF

- Blade flap and tower bottom moments
- Turbine C-8
- 2008-06-03 to 2013-03-19 … almost 5 years of data
- Un-stable, neutral and stable ABL conditions in focus … but met. mast is missing 



Case study – the Drogden supplement

- Offshore light tower … a few kilometres WNW of the WF (about the characteristic scale of the WF)
- Available 10-min recordings
  - U and T_a at h = 22m
  - T_w at h = -1m
  - Appr. 15.600 hours of measurements (2008–2013)

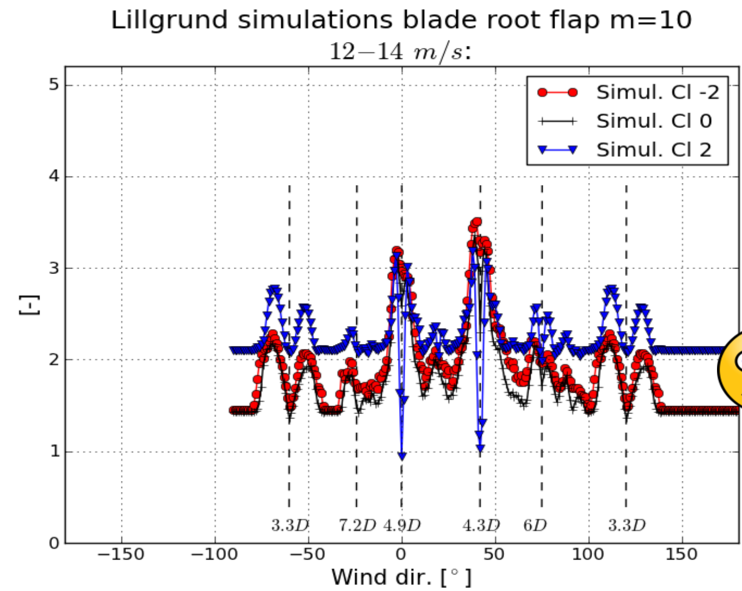


Case study – stability classification

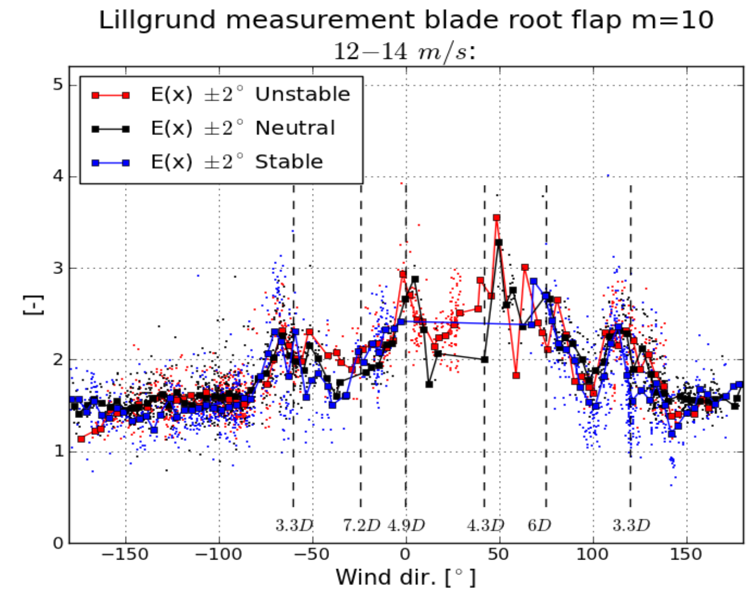
- AMOK approach for offshore sites [Larsen G. C. et al. (2016). Impact of atmospheric stability conditions on wind farm loading and production; DTU Wind Energy Report-E-0136]
  - Based on a newly developed version of the M-O theory suited for 'tall' profiles
  - Profile functions $\psi_m(z/L,\mu)$ are complex with an unstable branch for $z/L < 0$ and a stable branch for $z/L > 0$ … μ Monin-Kazanski parameter
  - Needs: T_a, U, T_w … e.g. from different heights
- Stability classes (1/L) [Gryning et al.; BLM **124**]

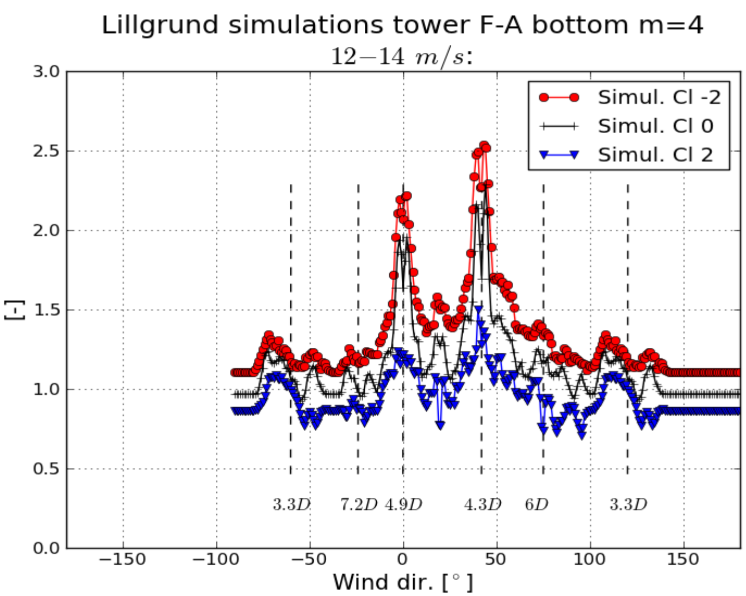
Stability Class iC	Description	Condition
-2	unstable	-200m< L <-100m
0	neutral	500m< $\|L\|$
2	stable	50m< L < 200m

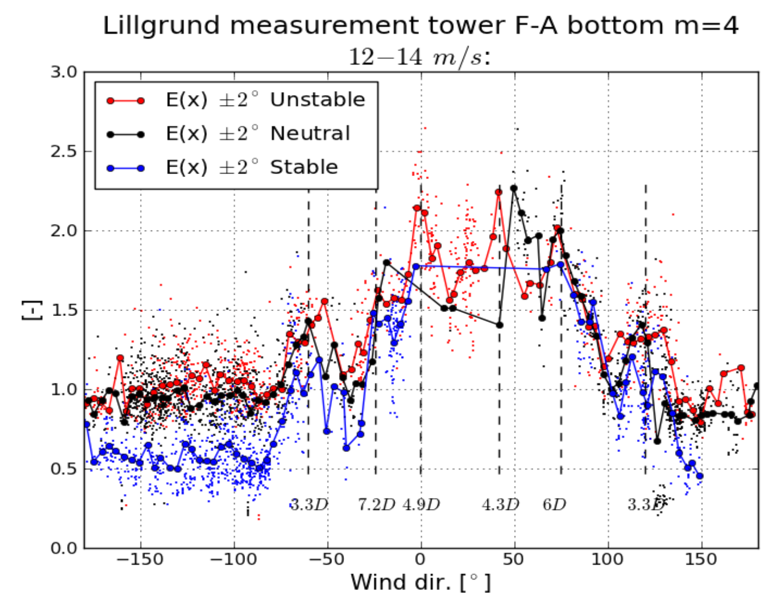
Case study – one-to-one results (1)



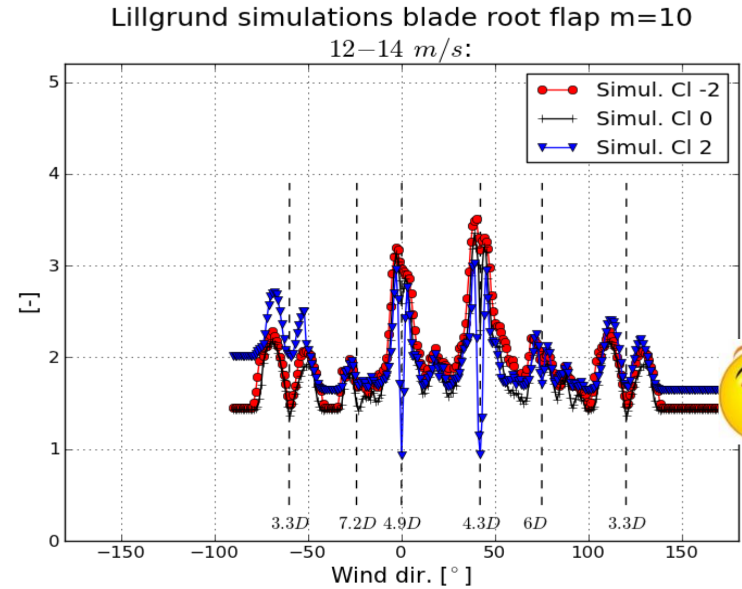
Classic MO



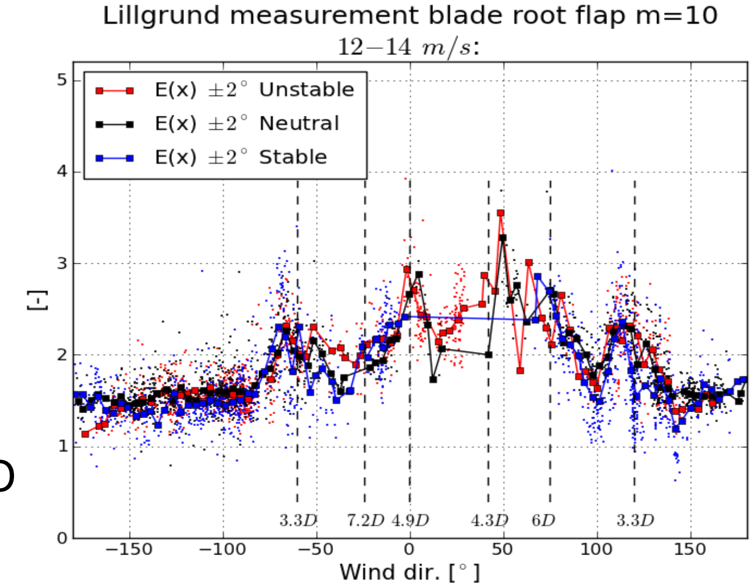


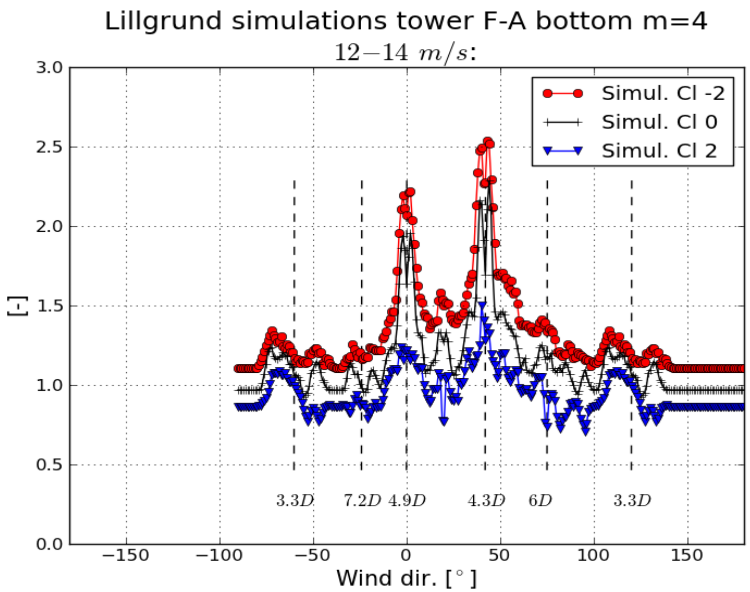


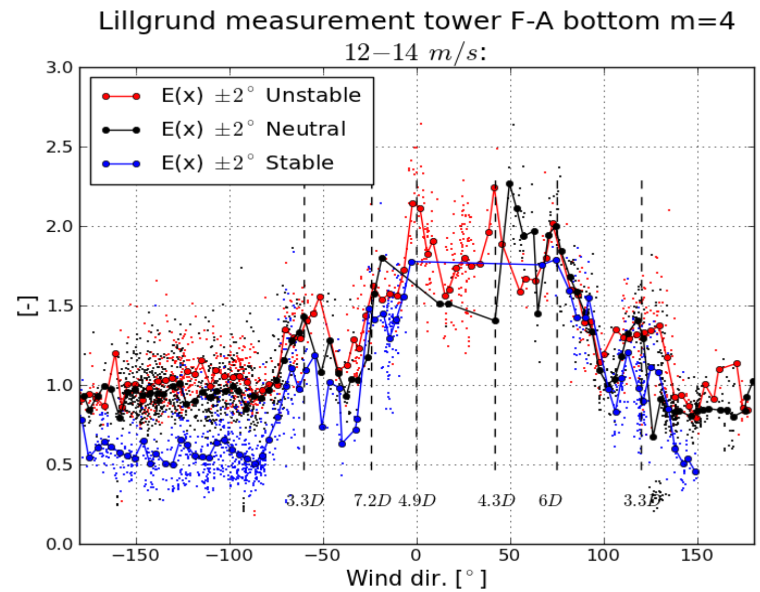
Case study – one-to-one results (2)



Ext. MO







Conclusions (1)

- A medium-fidelity un-steady flow field approach for non-neutral ABL conditions is established and coupled with the aeroelastic code HAWC2
- The approach is CPU in-expensive compared to high-fidelity CFD LES … and is potentially useful for WF layout optimization (TOPFARM) and WT/WF control design (EU TotalControl)
- Simulations:
  - For the rotating WT components the ABL stability impact on shear and turbulence has contra-acting influences on loading
  - Shear and turbulence tend to neutralize each other as fatigue load drivers for the flap-wise loading in the stable regime … which is contrary to previous investigations

Conclusions (2)

- Simulations:
  - Turbulence incl. wake meandering is the dominating load driver for flap-wise fatigue loading in the unstable regime
  - Turbulence incl. wake meandering is the dominating load driver for tower fatigue loading
- Measurements:
  - Agrees qualitatively well with simulations
  - Some uncertainty on mean values observed … e.g. not “perfect” symmetry of 3.3D cases

Outline (2)

- **Platform for open loop WPP control WT control**

  [Reference: Vitulli, J. A.; Larsen, G C.; Pedersen, M. M.; Ott, S.; Friis-Møller, M (2019). Optimal open loop wind farm control. Journal of Physics: Conference Series, Wake Conference, Visby]

  – The ‘collaborative’ WT ctr. the greedy WT
  – Flow field model … incl. wake model
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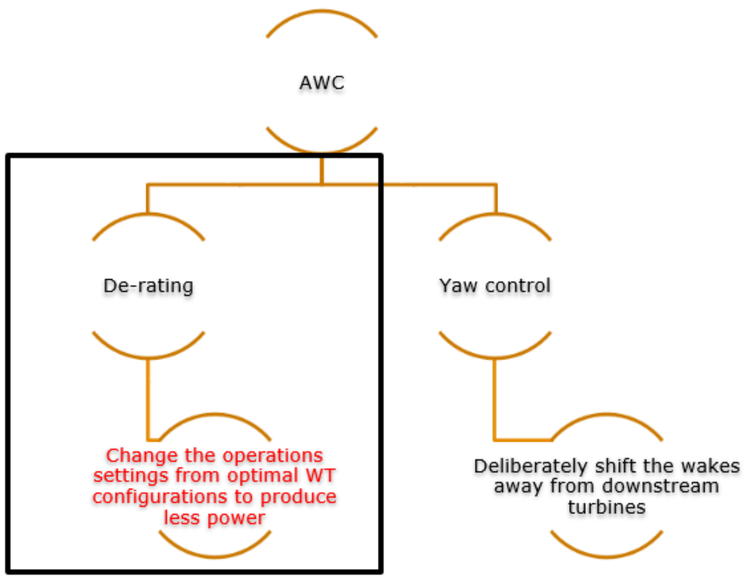
The collaborative WT (1)

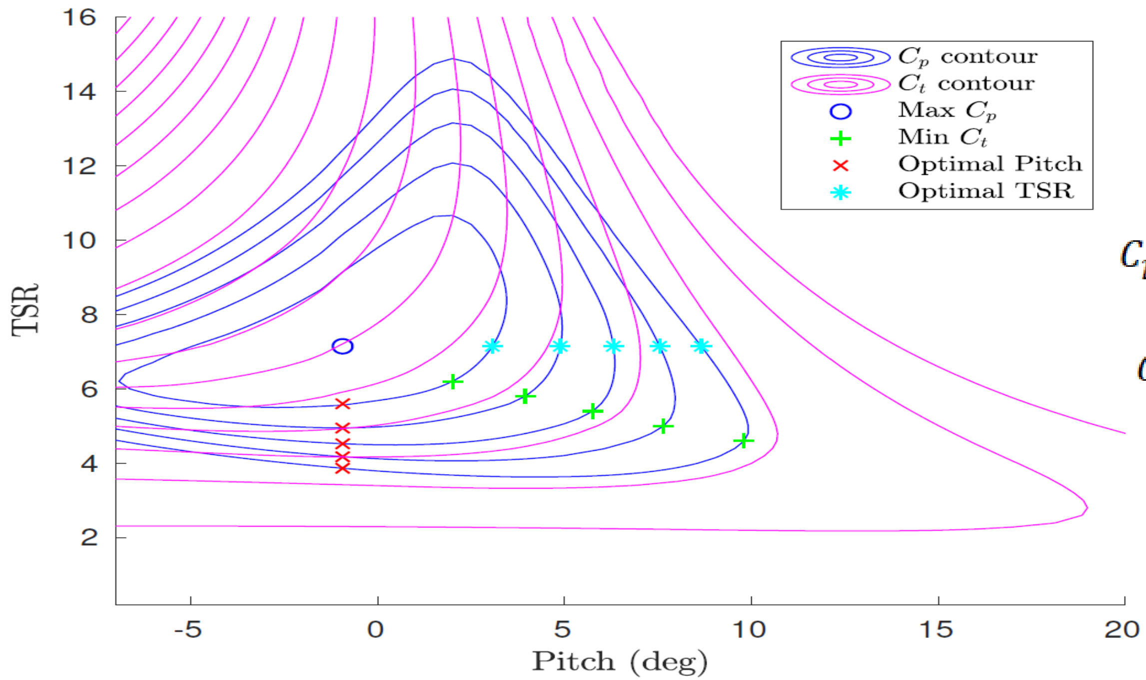
- Active Wake Control (AWC) → wake mitigation strategies



- Optimization of overall WPP production over individual turbine performance … conditioned on wind speed and wind direction

The collaborative WT (2) – de-rating

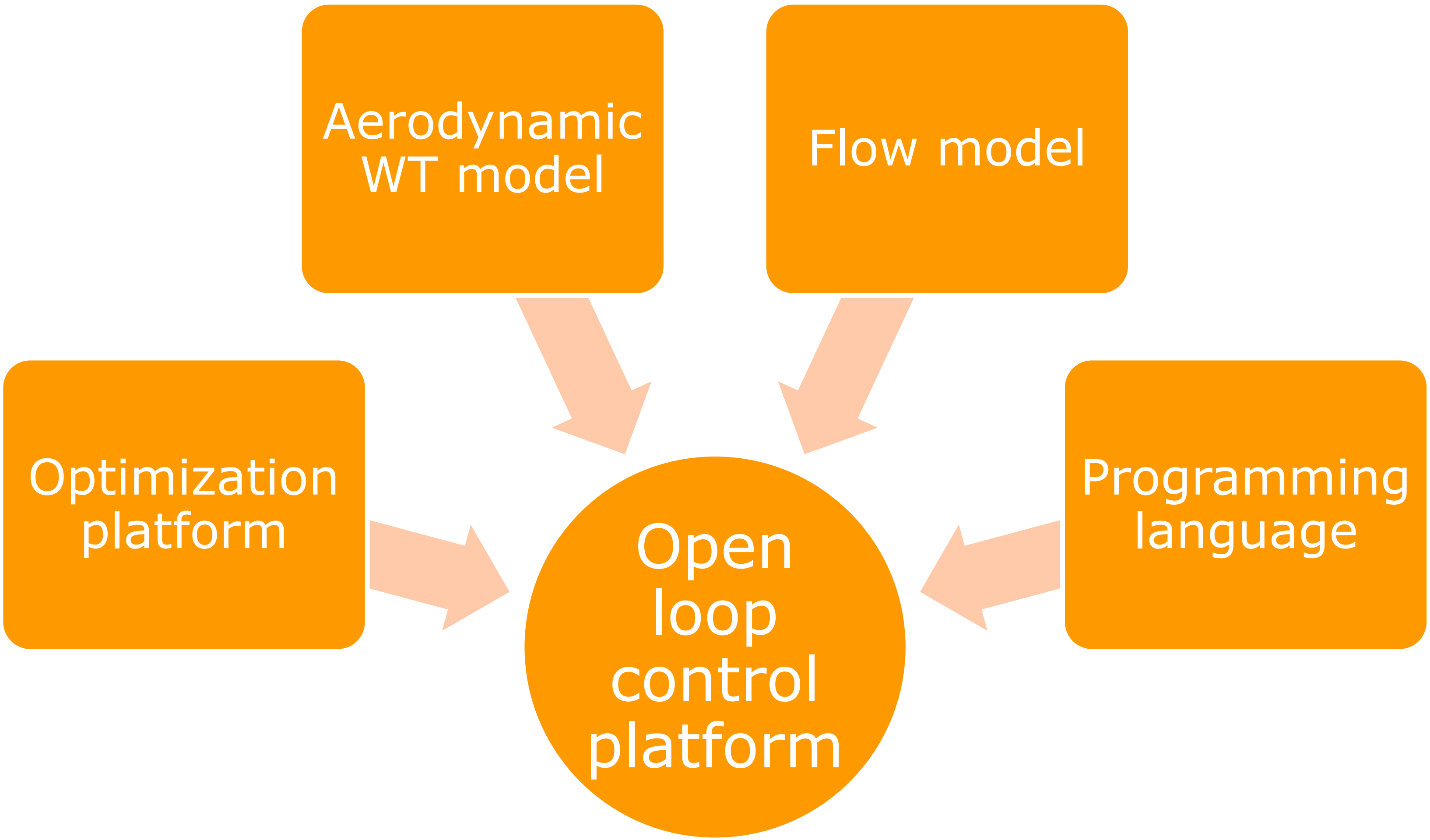
- Sacrifice power of upstream turbines to mitigate wake effects
- De-rating by changing the settings (*TSR*$_i$, pitch angle$_i$) → different points of lower C_p and varying C_t



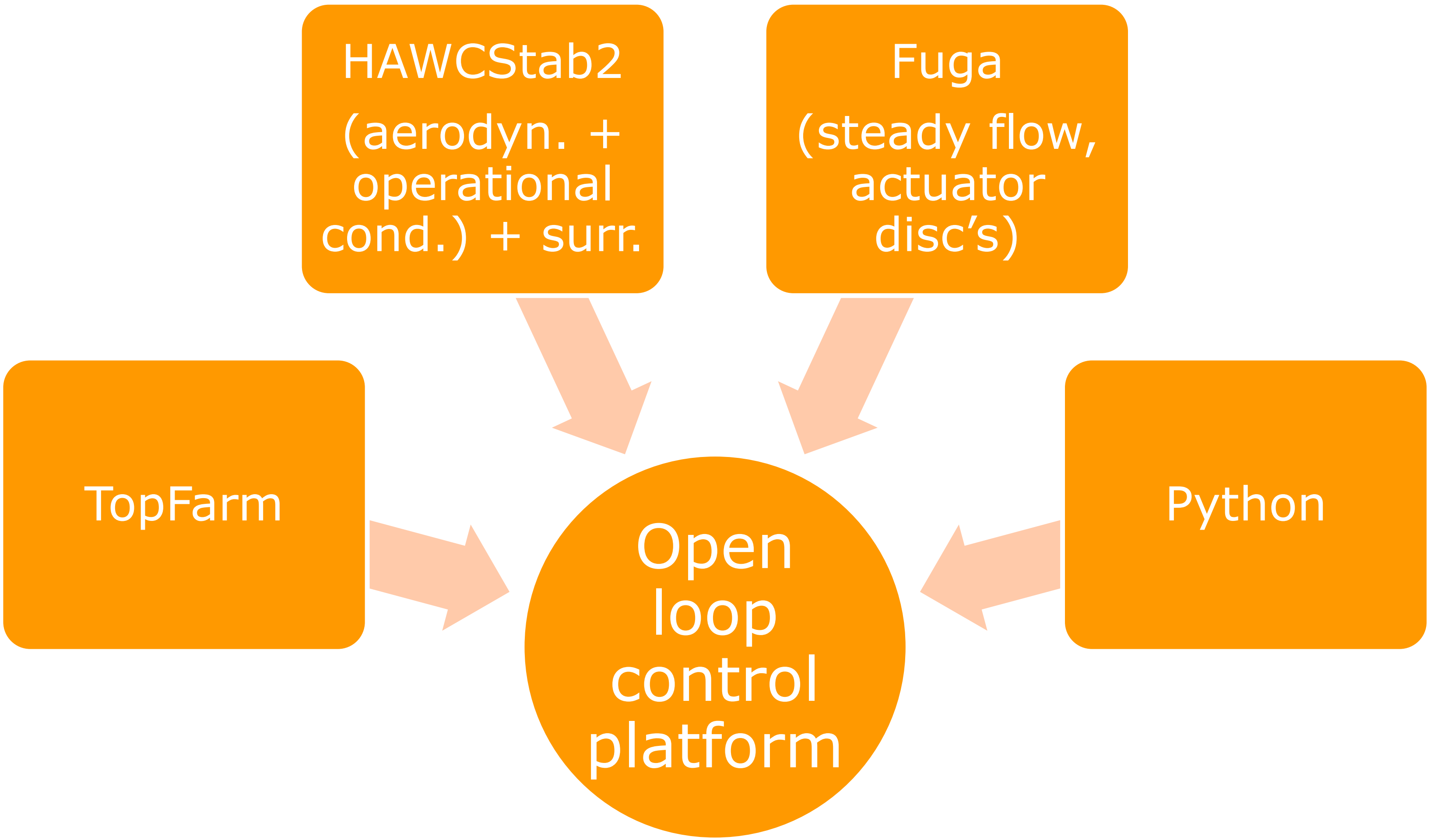
$$C_p(U|\alpha,\lambda) \equiv \frac{P_{WT}(U|\alpha,\lambda)}{½\rho A U^3}$$

$$C_t(U|\alpha,\lambda) \equiv \frac{T_{WT}(U|\alpha,\lambda)}{½\rho A U^2}$$

Platform for open loop WPP control (1) … what's needed?

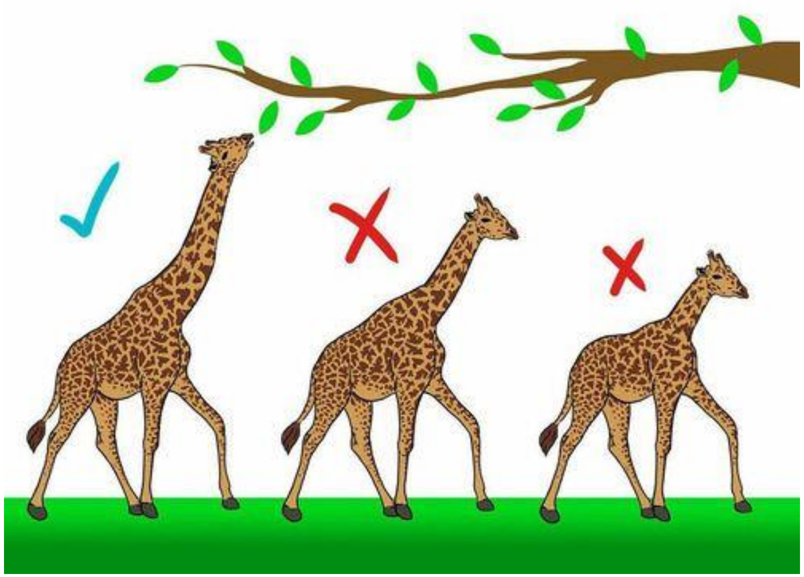


Platform for open loop WPP control (2) … what’s needed?



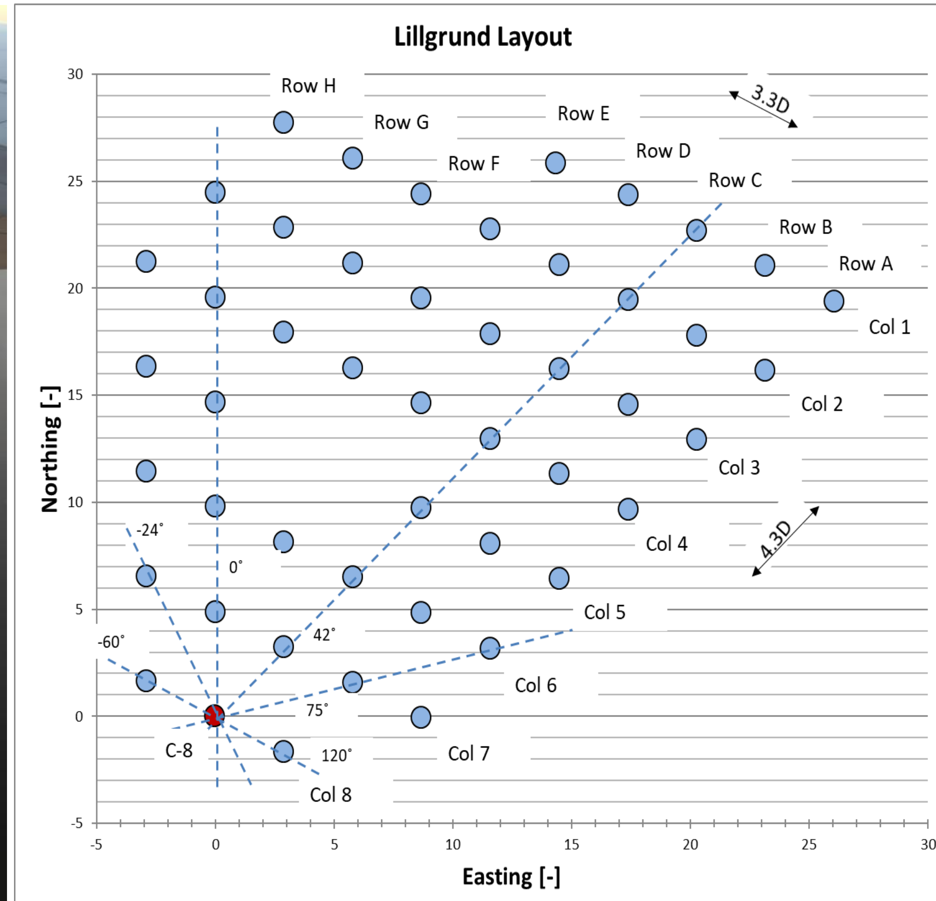
The optimizer

- Objective function: WPP power production
- Multi-fidelity concept:
  - Genetic algorithm for first pass of solution (GA)
  - Gradient based method for refinement (SLSQP)

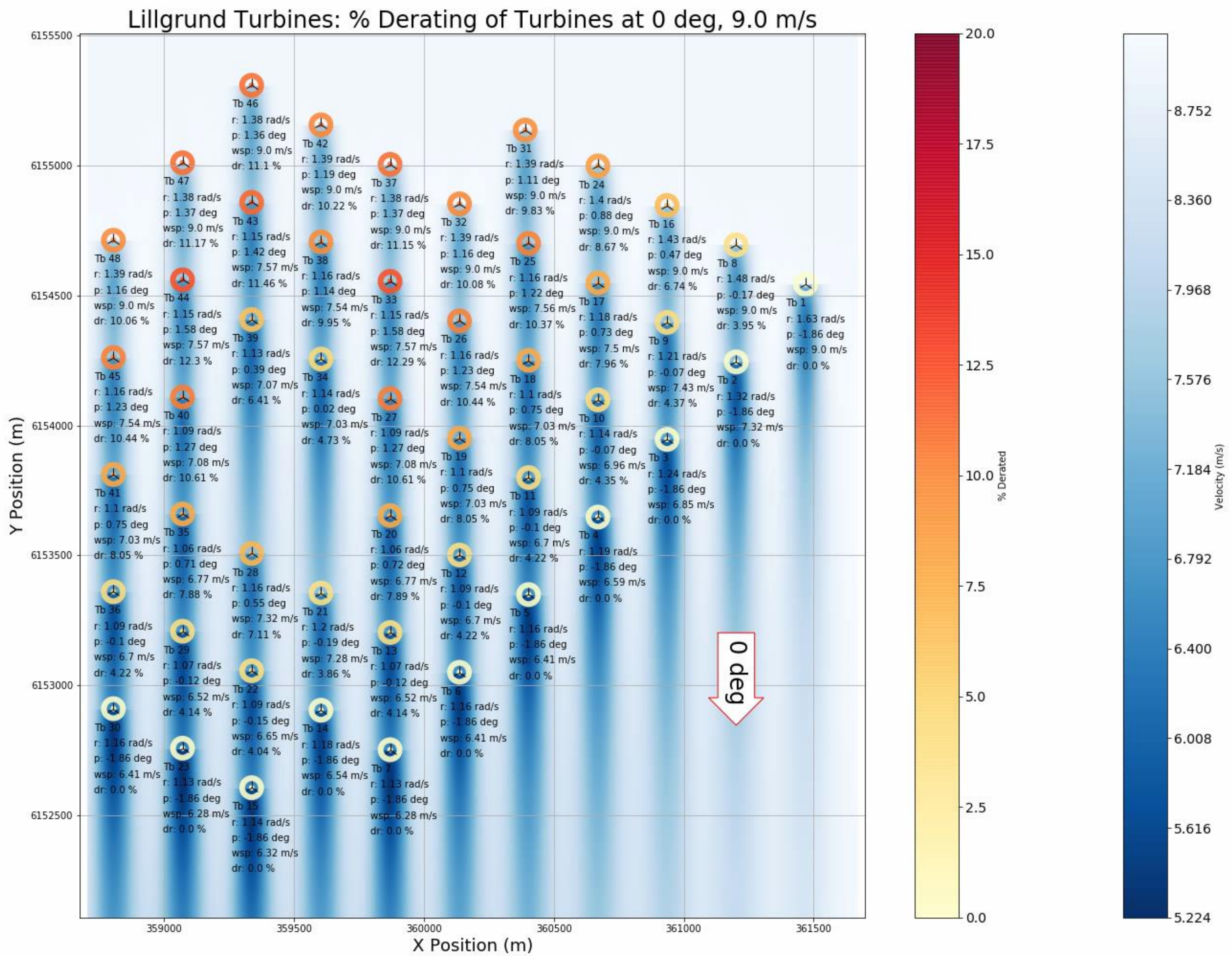


Lillgrund case study (1)

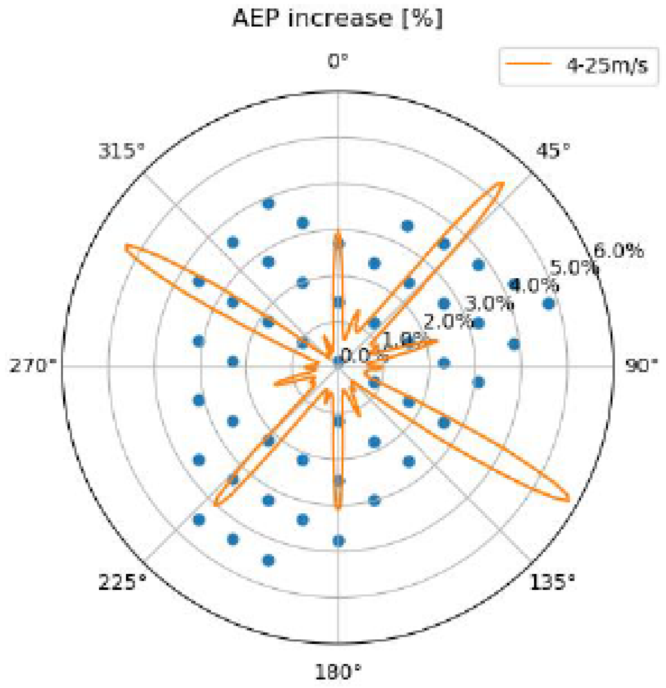
Flight into Copenhagen

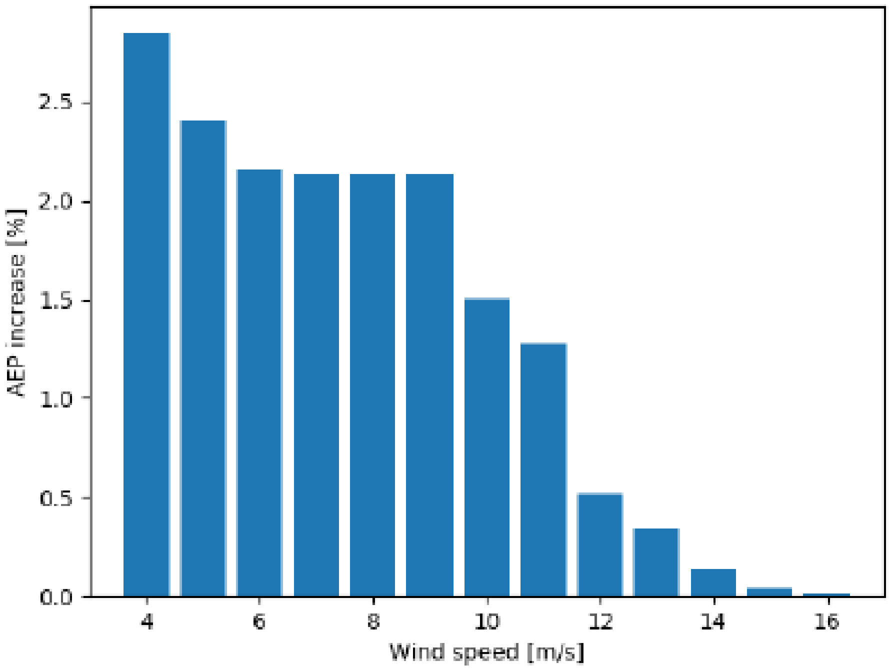


Lillgrund case study (2)



Lillgrund case study (3): AEP gain





Conclusions & Future work

- Developed a two-parameter optimization tool showing that production gains are possible through de-rating
  - Virtually no cost to the WPP control compared to the gain they potentially provide
  - Lower C_t means: 1) less wakes; 2) less turbulence; 3) likely to imply less fatigue loading
- Future: Include active yaw control de-rating
  - Fuga extended to yawed flows … validation against full-scale lidar measurements to be performed

Acknowledgements

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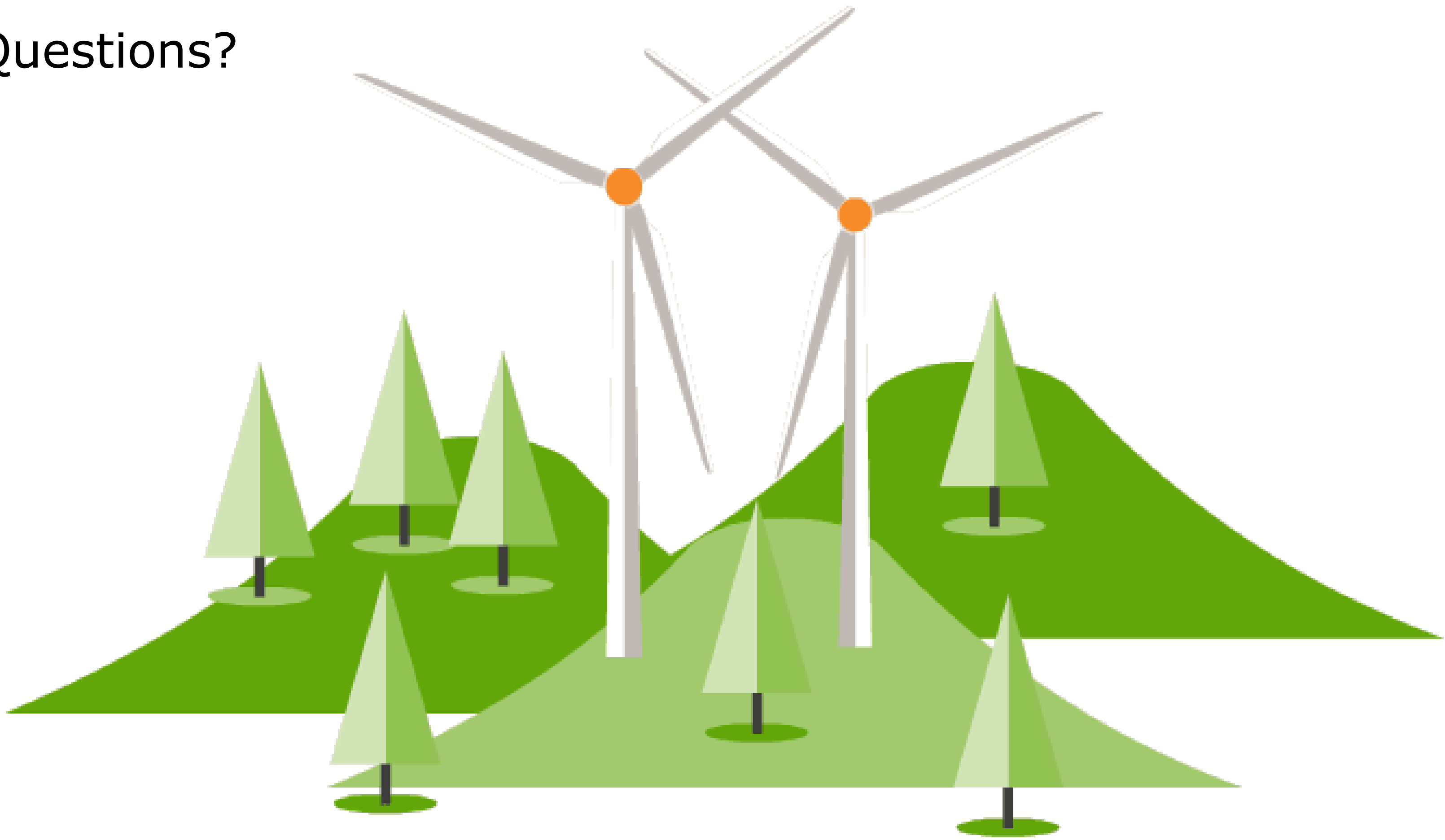
Siemens Wind Power is acknowledged for making the Lillgrund full scale load measurements available.

Thank You!

Questions?



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