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Challenges in wind farm optimization

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Outline (1)

- Introduction
- Definition of the problem
- Challenges
- What is an optimal layout?
- Differences between power output optimization and economical optimization

Outline (2)

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  - Vision
  - Basic elements
  - WF flow field module
  - WT aeroelastic module
  - Cost model module
  - Synthesis – the objective function
  - Numeric's ... and an example application
- Future developments

Introduction … it's all about money (COE)

- Given the large WF investments, large profit is hidden in a WF layout, where the following elements (dictating WF economics) are optimally balanced (i.e. minimizing COE):
  - Financial costs
  - WT loads … and (derived) O&M
  - WF production

Definition of the problem

- Given the ambient wind climate (measured or modeled) quantified as:
  - Wind direction distribution
  - Mean wind distribution … conditioned on wind direction
  - Roughness/shear … conditioned on wind direction
  - Turbulence characteristics … conditioned on wind direction
- … and imposed constraints (e.g. area, power quality, allowable turbine loads, etc., etc.)

  determine the ”optimal” WF topology … possible including (optimal) WT and WF control

Challenges (1)

- Objective function (discharging control aspects)

  $\Pi(P(\mathbf{x},\mathbf{y}), FC(\mathbf{x},\mathbf{y}), L(\mathbf{x},\mathbf{y}))$; with design space

  $\mathbf{x} = (x_{WT1}, \ldots, x_{WTN})$

  $\mathbf{y} = (y_{WT1}, \ldots, y_{WTN})$

- Challenge n^0 1 ... computational speed
  - Ex.: 100WT; 72WD (5 deg. bins); 20 WS (1m/s bins); 1000 iterations ... require
  - Aeroelastic computations: $100 \times 72 \times 20 \times 1000 = 144 \times 10^6$ 10-min simulations
  - WF flow field computations: $72 \times 20 \times 1000 = 1.44 \times 10^6$ (10-min) simulations

Challenges (2)

- Challenge n^0 2 ... WF flow fields
  - The WF wind climate deviates significantly from the ambient wind climate:
    - Wind resource decreased
    - Turbulence intensity increased and turbulence structure is modified
    - ... and the WF turbines interact dynamically though wakes
  - ... due to many scales, these (in-stationary) fields are not trivial to compute

Challenges (3)

- Challenge n^0 3 ... cost models
  - To "collapse" the multi-parameter WF optimization problem into a single objective function requires cost models; e.g.
    - Reliable grid cost models ... including determination of an optimal grid layout in each iterative step of the "overall" WF optimization – an embedded opt. prob.
    - Costs of foundation
    - Cost of fatigue dictated WT degradation
    - Cost of O&M

Challenges (4)

- Challenge n^0 4 … optimization strategy
  - Efficient and robust optimization strategy ensuring convergence to a global optimum … and potentially including sensitivity considerations

What is an optimal layout?

- Examples of potential approaches
  - One-parameter approach: Optimizing the *power output* … and subsequently ensuring that the loading of the individual turbines is beneath their design limit
  - Multi-parameter approach: Optimizing WF topology from a “holistic” *economical* point of view … throughout the life time of the WF

Differences between power output optimization and economical optimization (1)

- *WT:*
  - Power: WT strongly simplified and described in terms of power- and thrust curves
  - Econ.: Full aeroelastic simulation of each individual WF wind turbine … giving loads as well as production
- *WF flow field:*
  - Power: Stationary flow fields suffice for production optimization
  - Econ.: *In-stationary* characteristics of the WF flow field have to be considered to enable prediction of reliable WT dynamic loading ... considerable complication!

Differences between power output optimization and economical optimization (2)

- *Cost models:*
  - Power: No cost models are needed
  - Econ.: Cost models accounting for
    - WF production
    - WT fatigue degradation
    - WT O&M
    - Financial costs ... depending on interest rate!

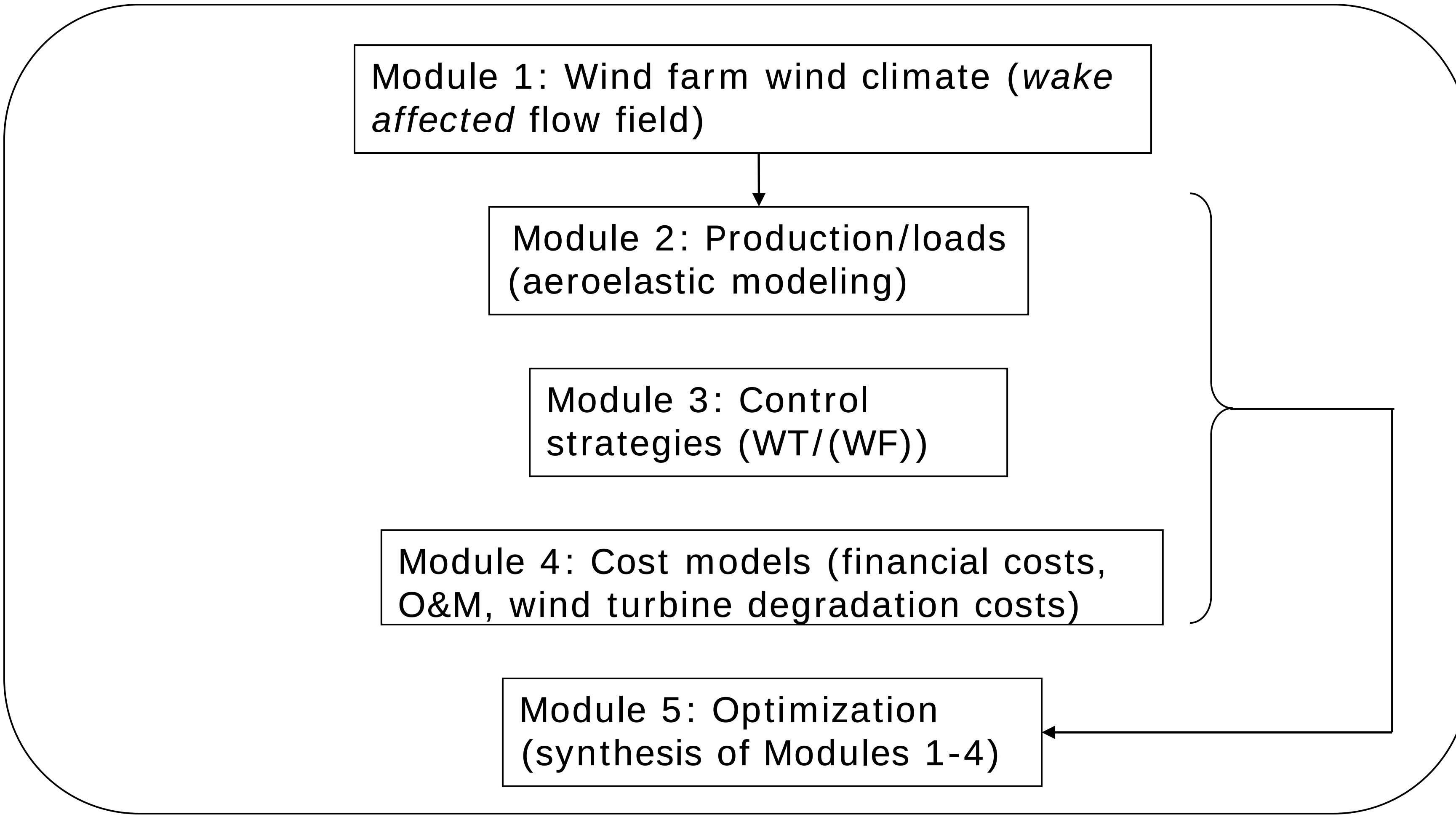
TOPFARM … an economical opt. platform

- Vision: A "complete" wind farm topology optimization, as seen from an investors perspective, taking into account:
  - *Loading*- and *production* aspects in a realistic and coherent framework
  - Financial costs (foundation, grid infrastructure, …)

  … and and subjected to various constraints (area, spacing , …)

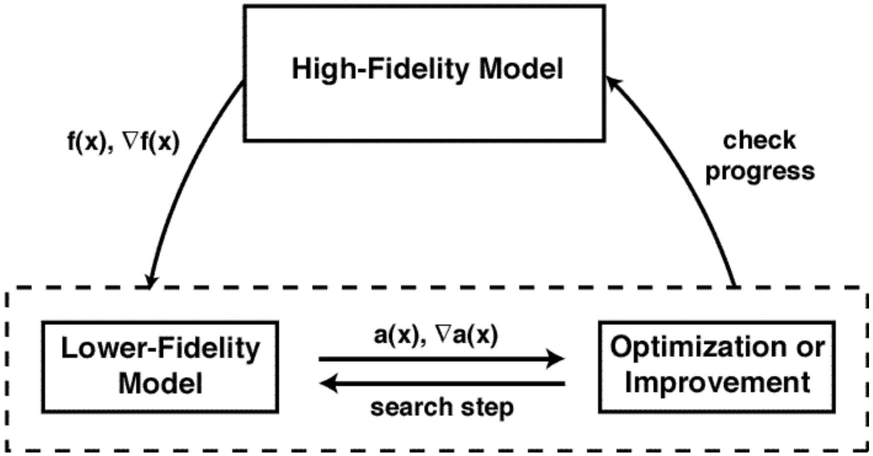
  as seen over the lifetime of the wind farm!

TOPFARM – basic elements



TOPFARM – WF flow field module (1)

- The TOPFARM multi-fidelity optimization approach requires a hierarchy of models



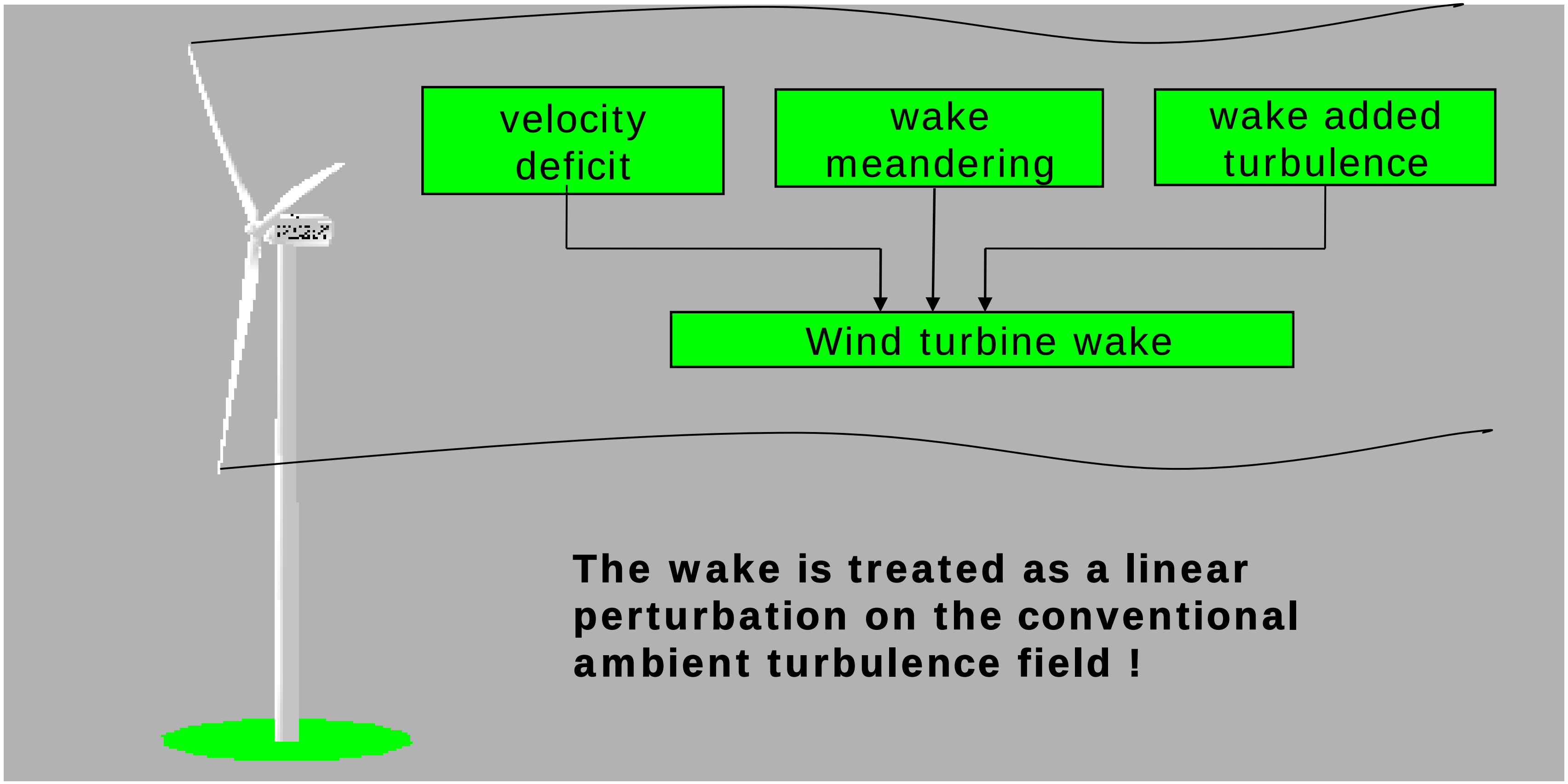
1. Stationary wake flow field (analytical model) + WT power curve
2. "Poor man's LES"; i.e. DWM (Database – generic production/load cases + interpolation)
3. DWM (simulation)

TOPFARM – WF flow field module (2)

- The requested *in-stationary* flow field modeling is based on the DWM approach (... Poor man's LES)
- The core of this model is a *split in scales* in the wake flow field, with
    - large turbulent scales being responsible for stochastic *wake meandering*, and
    - small turbulent scales being responsible for wake *attenuation* and *expansion* in the meandering frame of reference as caused by turbulent mixing
- The wake deficit is thus basically treated as a *passive tracer* in the large scale turbulent field – conveniently defined by the cut off frequency $f_c = U/2D$

TOPFARM – WF flow field module (3)

- Basic DWM elements:

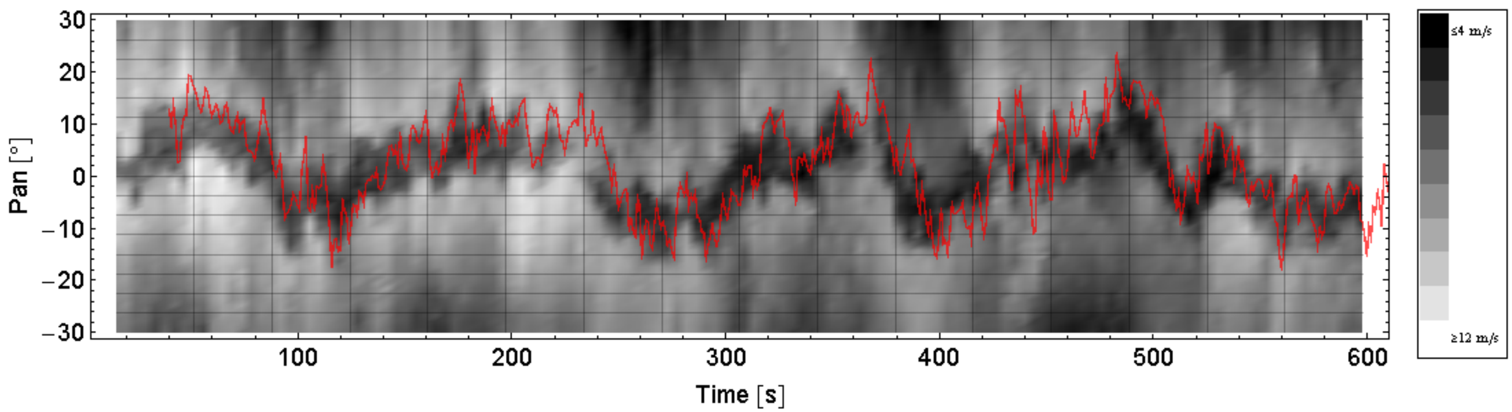


TOPFARM – WF flow field module (4)

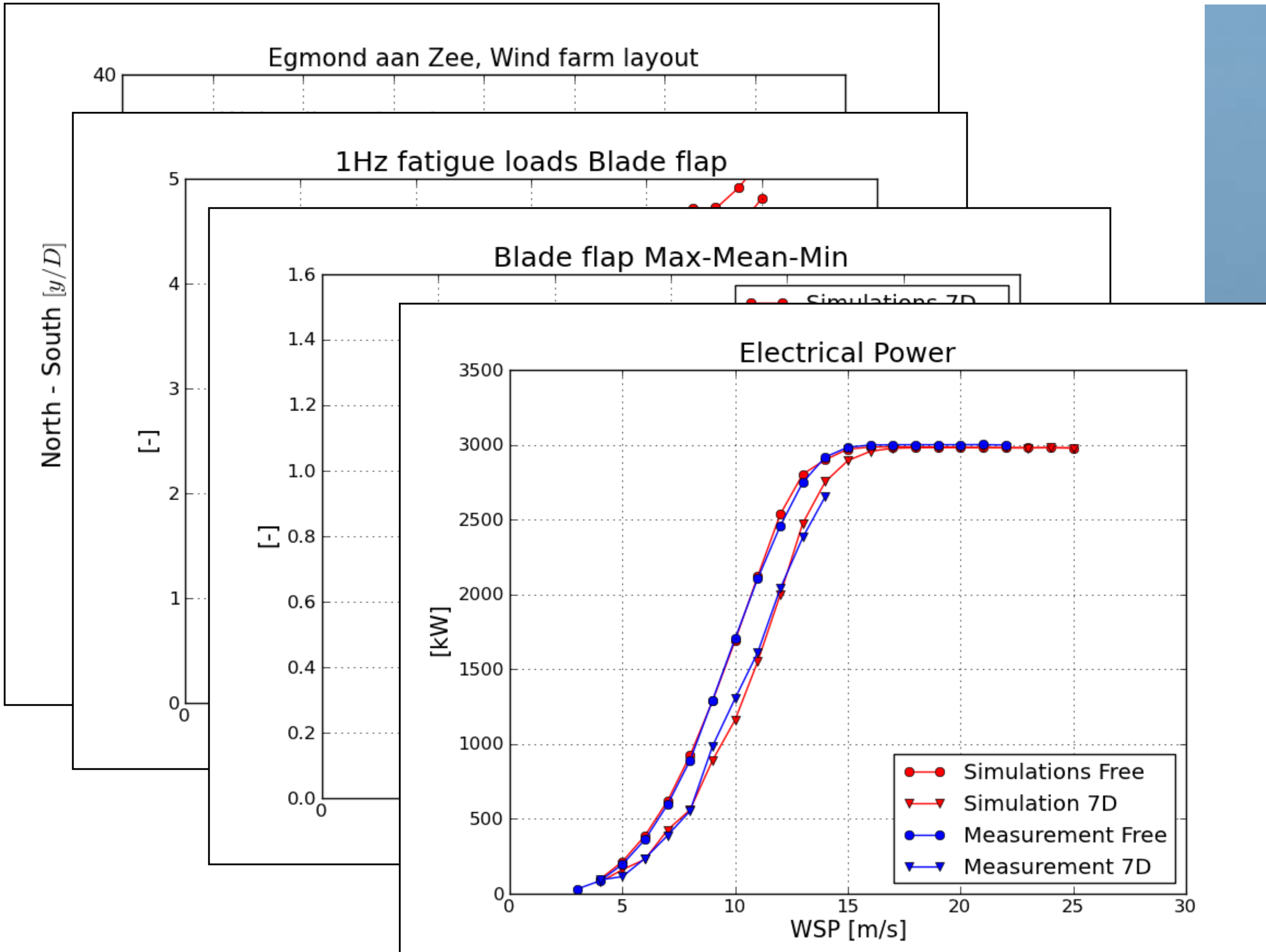
- DWM – validation (1):

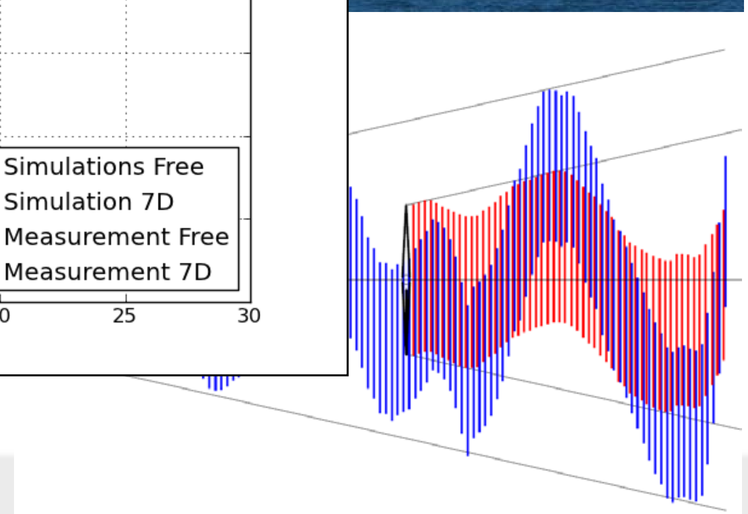
Date 2005–11–15 Time 21:20 Number of Scans 78501

LiDAR				Turbine				Met.Mast							
WS [m/s]				Yaw [°]				WS [m/s]				WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
7.76	3.07	13.10	1.56	279.0	258.0	296.0	5.6	8.74	5.43	12.40	1.37	277.0	265.0	289.0	6.0



TOPFARM – WF flow field module (5)





TOPFARM – WT aeroelastic module

- HAWC2:
  - Non-linear FE model resolving WT dynamics … based on a multi-body formulation
  - Aerodynamics based on Blade Element Momentum algorithm and profile look-up tables … which in turn “delivers” the boundary conditions for the quasi-steady wake deficit simulation used in the DWM model
  - WT generator model included
  - WT control algorithms included
  - Wave loading … including floating turbine option
  - Output is power and forces/moments in arbitrary selected cross sections

TOPFARM – cost model module (1)

- Basic simplifying approach:
  - Only costs that depend on wind farm topology and control – variable costs – are of relevance in a topology optimization context … and therefore included

TOPFARM – cost model module (2)

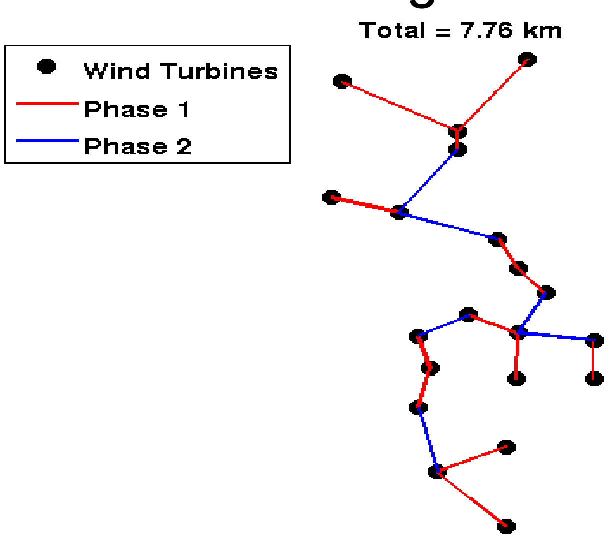
- Examples of cost models … required to transform the (physical) quantity in question into an economical value for the OF synthesis:
  - Financial costs
    - Foundation costs … e.g. depending on water depth
    - Grid infrastructure costs
  - Operational costs
    - Turbine degradation (fatigue loading/lifetime)
    - Operation and maintenance costs (O&M)
  - Electricity production

TOPFARM – cost model module (3)

- Grid costs (CF):
  - Presumes a constant price on cabling pr. running meter (including cost of cables, trenching and laying of these)
  - For each topology iteration step, the grid cost is defined as associated with the “shortest possible” connection between all turbines
  - “Idealized” cables able to carry all electricity produced by WTs connected to them

TOPFARM – cost model module (4)

- Grid costs (CF):
  - Approach allowing for branching:
    - Phase 1: Each turbine is connected to its closest neighbour
    - Phase 2: resulting sub-clusters are successively interconnected through their closest turbines



TOPFARM – cost model module (5)

- Cost of WT degradation (CD):
  - Only fatigue driven degradation considered
  - Based on writing off the investment of the turbines ... specified on main turbine components (i.e. tower, blades, main axis, gear box, generator)
  - Fatigue damage estimated using Palmgren-Miner linear damage accumulation
  - The writing off is presumed *proportional* to the *accumulated equivalent moments* (or accumulated equivalent stresses) in design critical “hot spots” on the respective components

TOPFARM – objective function (1)

- Objective function (OF):
  - The objective function represents the synthesis of all modules into an optimization problem
  - OF is formulated as a financial balance expressing the difference between
    - The wind farm *income* (power production (WP)) and
    - The wind farm *expenses;* i.e.
      - O&M expenses (CM)
      - Cost of turbine fatigue load degradation (CD)
      - Financial expenses (C)

TOPFARM – objective function (2)

- Objective function (OF) … an example:
  - The value of the wind farm power production over the wind farm lifetime, WP, refers to year Zero
  - All operating costs (in this example CD and CM) refer to year Zero ... with the implicit assumption that the development of these expenses over time follows the *inflation rate* (r_i) ... and that the *inflation rate* is the natural choice for the discounting factor transforming these running costs to *net present value*

$$FB = WP_n - C\left(1 + \left(\frac{r_{c1} - r_i}{N_L}\right)\right)^{XN_L} , \quad WP_n = WP - CD - CM ,$$

  - C denotes the financial expenses (here including grid costs (CG) and foundation costs (CF))

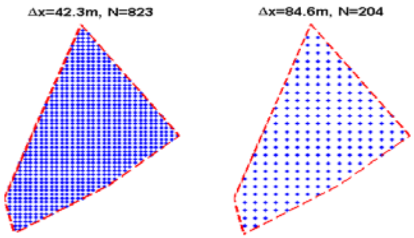
TOPFARM – numeric's (1)

- Optimization approach … some tricks to reduce computational time:
  - Structured grids (i.e. reduction of the design space)
  - Multi-fidelity optimization approach based on 2 (3) levels of sophistication

Fidelity Level	1st	2nd	3rd
Electricity sales	Stationary wake + Power curve	HAWC2-DWM Database	HAWC2-DWM Simulations
Fatigue costs	No	HAWC2-DWM Database	HAWC2-DWM Simulations
Foundation costs	Yes	Yes	Yes
Electrical Grid costs	Yes	Yes	Yes
Optimization algorithm	SGA	SLP or SGA+SLP	SLP
Domain discretization	Coarse	Fine	Fine
Wind speed and direction bin size	Coarse	Fine	Fine

TOPFARM – numeric's (2)

- Selected optimization algorithm is a mix of 2 algorithms:
  - Genetic Algorithm (SGA) with key characteristics
    - Structured grid – coarse resolution
    - Slow (many iterations necessary)
    - Global optimum ... usually



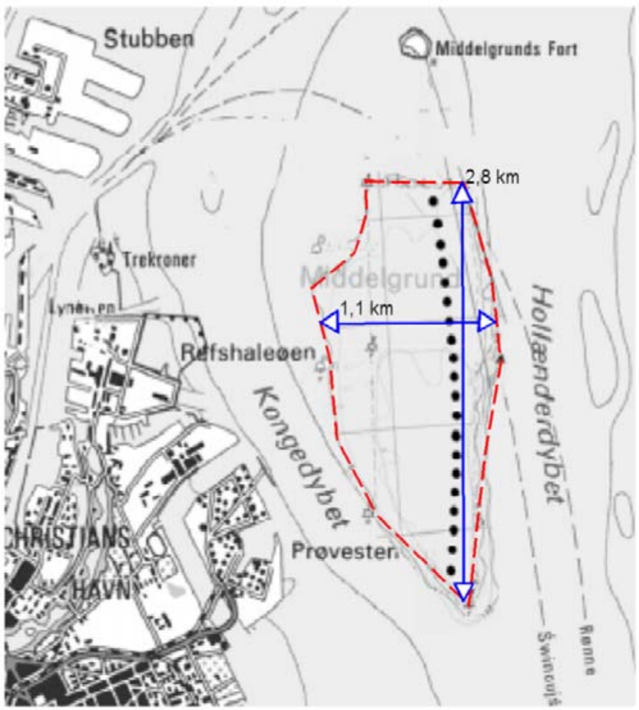
  - Gradient Based Search (SLP) with characteristics
    - Unstructured grid (good for refinements)
    - Fast (few iterations for converging)
    - Local minimum
  - SGA+SLP is a good combination for searching a refined global optimum

TOPFARM – example application (1)

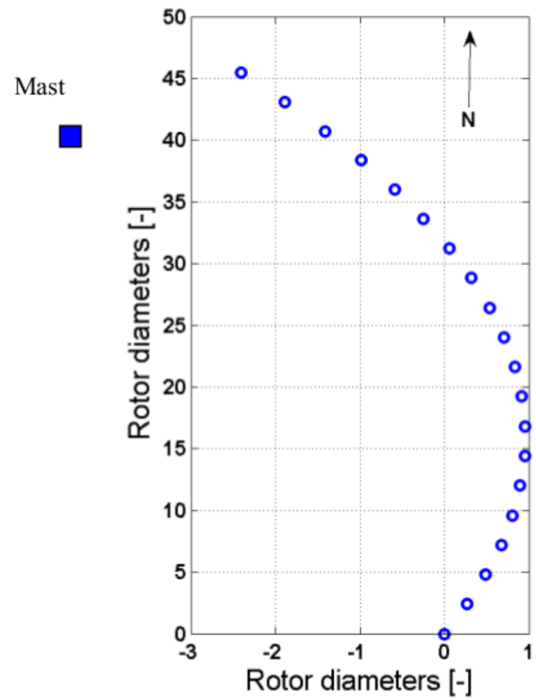
- Middelgrunden

TOPFARM – example application (2)

- Middelgrunden



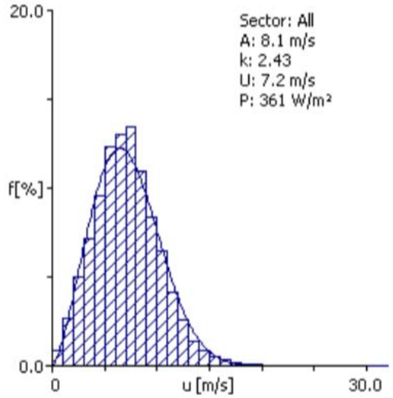
Allowed wind turbine region

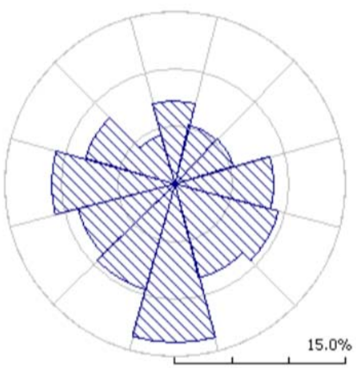


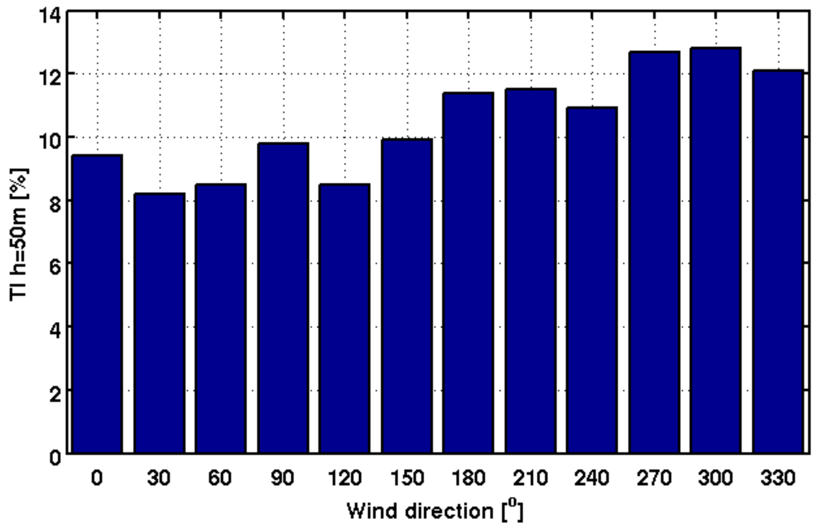
Middelgrunden layout

TOPFARM – example application (3)

- Middelgrunden - ambient wind climate

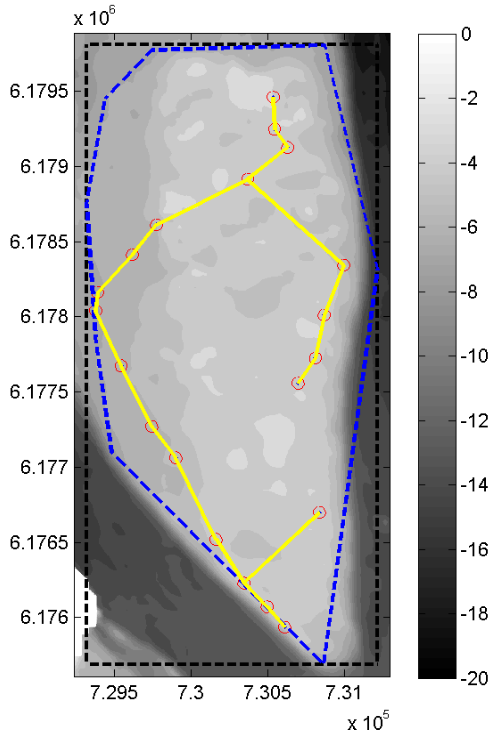


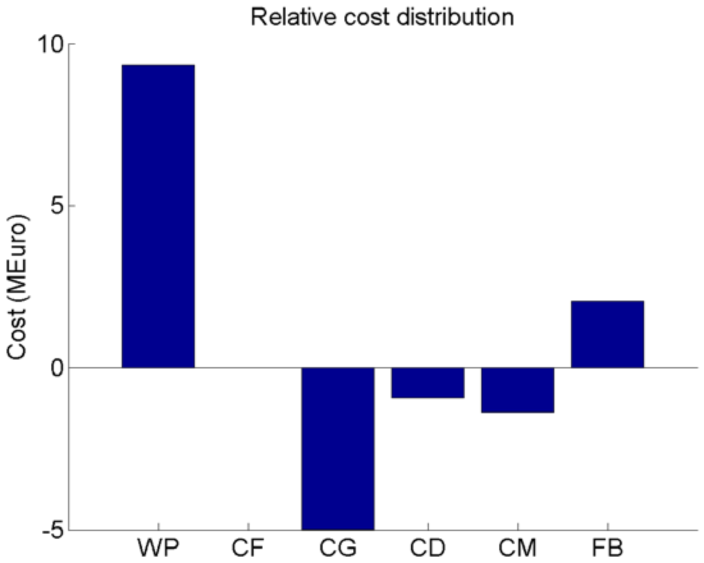




TOPFARM – example application (4)

- Middelgrunden iterations: 1000 SGA + 20 SLP





Optimum wind farm layout (left) and financial balance cost distribution relative to baseline design (right).

Future activities

- More detailed and realistic cost functions - e.g. inclusion of a detailed grid layout platform developed in a collaboration between University of Bergen and University of Aarhus ... taking advantage of the “vehicle rooting problem”
- Inclusion of WF control in the optimization problem
- Inclusion of atmospheric stability effects in the WF field simulation ... using a spectral tensor including buoyancy effects
- Accounting for meso-eddy scales (l>~10km; T > ~10 min)
- Inclusion of noise aspects

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