Optimization of wind farms

G.C. Larsen

Risø DTU
National Laboratory for Sustainable Energy

Outline

- Background
- Optimal power production
- Optimal economical performance
- TOPFARM platform
- Solving the problem – the numerical strategy
- Demonstration example 1
- Demonstration example 2
- Conclusions
- Future refinements

Background (1)

- Wind Farm (WF) wind climate deviates significantly from ambient wind climate:
  - o Wind resource (decreased)
  - o Turbulence
    - Turbulence intensity increased
    - Turbulence structure modified (... incl. intermittency)
- ... and the WF turbines interact dynamically though wakes

Background (2)

- WF wind climate characteristics important for:
    - o Design of wind turbine (WT) control strategies
    - o Wind farm optimization … potential approaches:
        - Optimizing the power output ... and ensuring that that the loading of the individual turbines is beneath their design limit
        - Optimizing wind farm topology from a “holistic” economical point of view ... throughout the life time of the WF

Question (1)

- What is the major difference between a power production optimization and an economical optimization of WF layout/topology ?

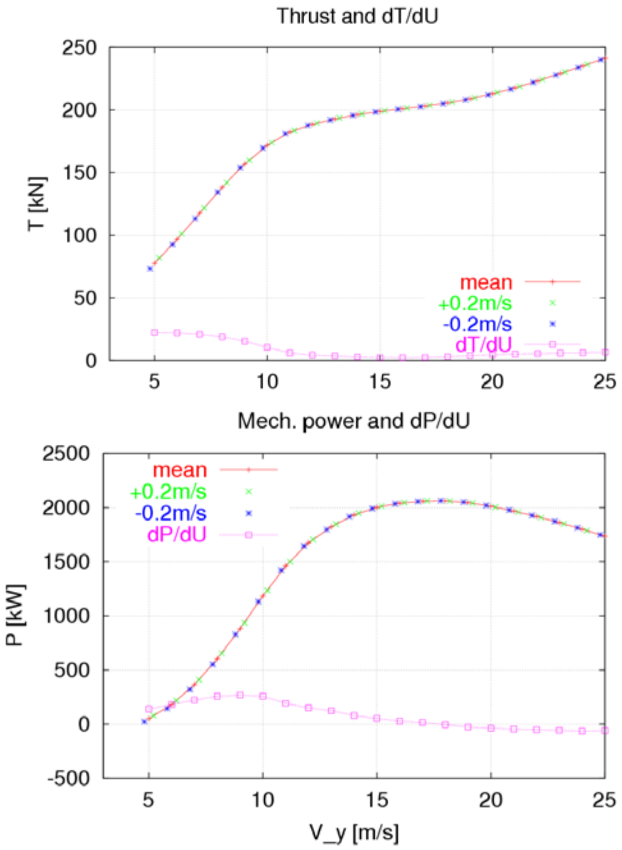
Optimal power production – input (1)

- Ambient/undisturbed *flow conditions* on the intended WF site assumed given! – measured or modelled (with meso-scale models or others…)
  - o Mean wind distribution … conditioned on wind direction (deterministic)
  - o Roughness/shear … conditioned on wind direction (deterministic)
  - o Turbulence parameter distributions … conditioned on wind direction (stochastic)

Optimal power production – input (2)

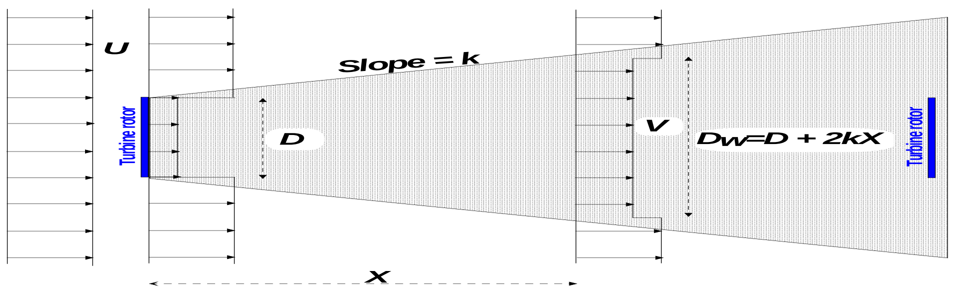
- *Wind Turbines* (WT) strongly simplified and basically represented by characteristics as:

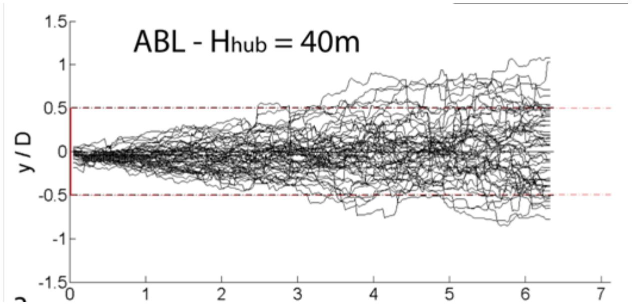
  - Thrust curve ("flow resistance")
  - Power curve (production)



Optimal power production – WF field

- Typically modelled using *stationary* approaches, such as e.g.
  - The N.O. Jensen model (simple top hat model based on momentum balance)





  - Parabolised CFD models with an eddy viscosity closure (UPM model (ECN WindPRO), Ainsley model (GH Windfarmer), ...)
  - Linearized RANS model (FUGA) based on a first order perturbation approach. Numerical diffusion omitted! (mixed spectral formulation)

Optimal power production – objective function

- Relatively simple … because all elements have the same unit
- No cost models required!
- Objective function … to be optimized:

$$P_{tot} = \sum_{life\ time} \sum_{pdf\ \theta} \sum_{pdf\ U} \sum_{i=1}^{N} P(x_i, y_i)$$

Optimal economical performance (1)

- In a “true” rational economical optimization of the wind farm layout, the goal is to determine the *optimal balance* between capital costs, operation and maintenance (O&M) costs, fatigue lifetime consumption and power production output … possibly under certain specified constraints
- Same input as used for optimizing power production … supplemented by
    - o Wind turbine information sufficiently detailed for setting up aeroelastic model(s) of the turbines in question

Optimal economical performance (2)

- Stationary flow fields and rudimentary WT models may suffice for optimizing wind power production ... but is clearly not sufficient for achieving the overall economical WF optimum
  - The *non-stationary* characteristics of the WF flow has to be considered to achieve reliable WT dynamic loading ... which is essential for fatigue load estimation, cost of O&M, ...
  - Detailed WT modeling (i.e. *aeroelastic modeling*) is needed to obtain main component loading in sufficient detail and of sufficient accuracy
  - Cost models are needed to aggregate different types of quantities into an objective function

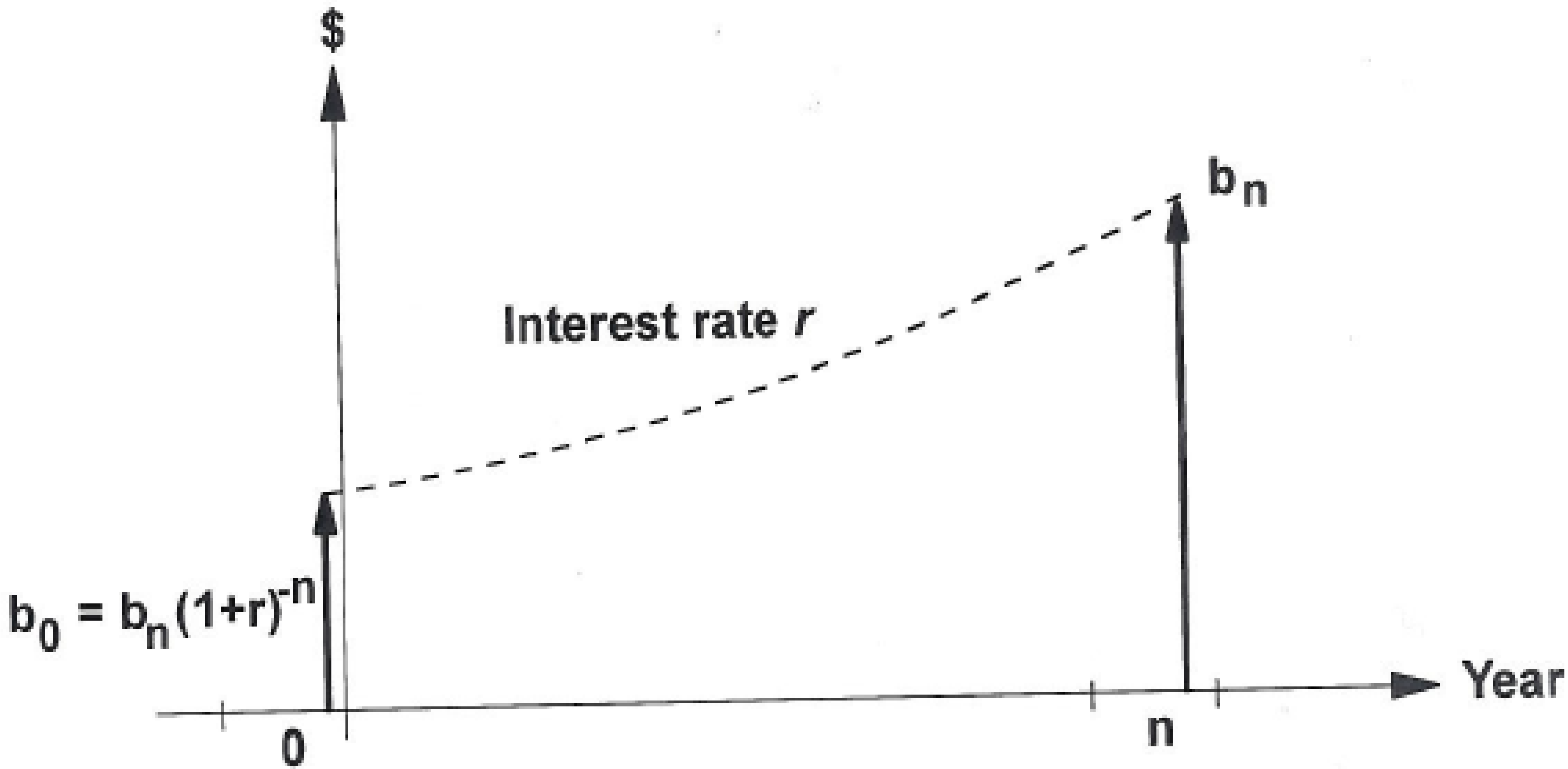
Optimal economical performance (3)

- The main parameters governing/dictating WF economics include the following:
  - Investment costs - including auxiliary costs for foundation, grid connection, civil engineering infrastructure, …
  - Operation and maintenance costs (O&M)
  - Electricity production/wind resources
  - Turbine loading/lifetime
  - Discounting rate

Optimal economical performance (4)

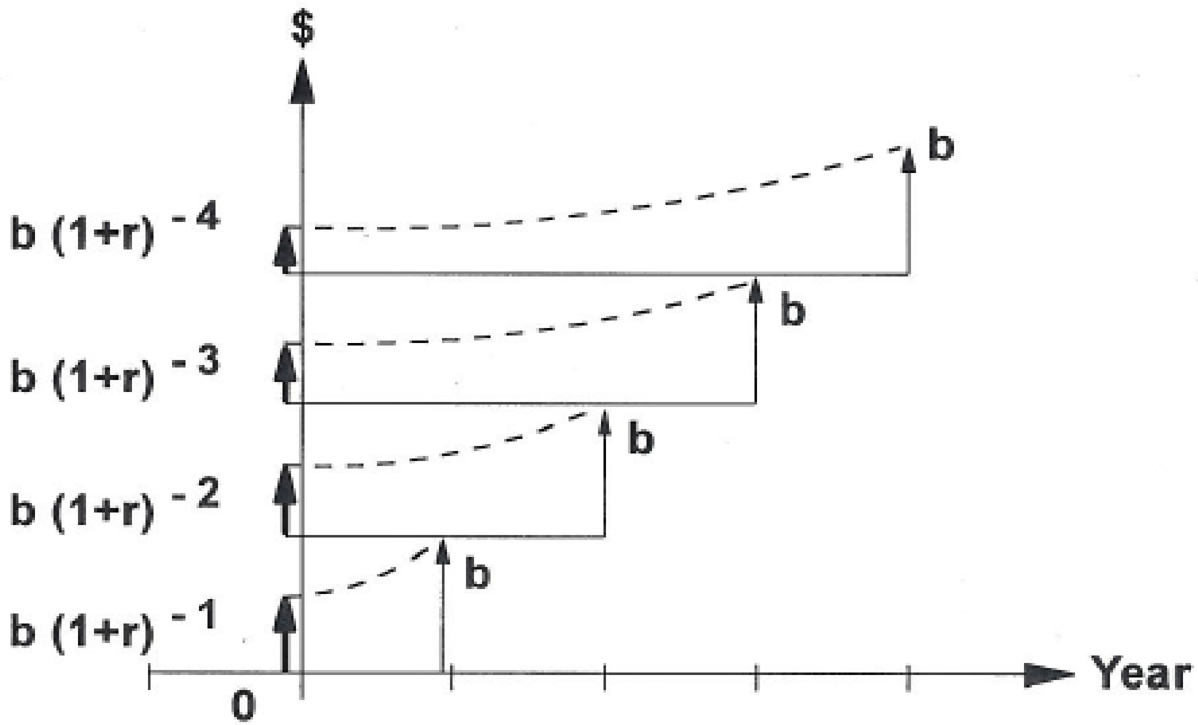
- Time and money … the value of having one Euro is larger today than in a year!
  - o $FV = PV\ (1+r)$ (one year)
  - o $FV = PV\ (1+r)^N$ (N years)
    - PV: Present value
    - FV: Future value
    - r: interest rate or discount rate
- With r=5%; N = 20, the present value of 1 Euro paid in 20 year is only 0.377 Euro
- The process is called *discounting* … and is required to establish a common *money reference* for payments at different times

Optimal economical performance (5)



Optimal economical performance (6)

- A series of payments every year



TOPFARM platform
- basic elements/modules

Module 1: Wind farm wind climate (in-stationary *wake affected* flow field)

Module 2: Production/loads (aeroelastic modeling)

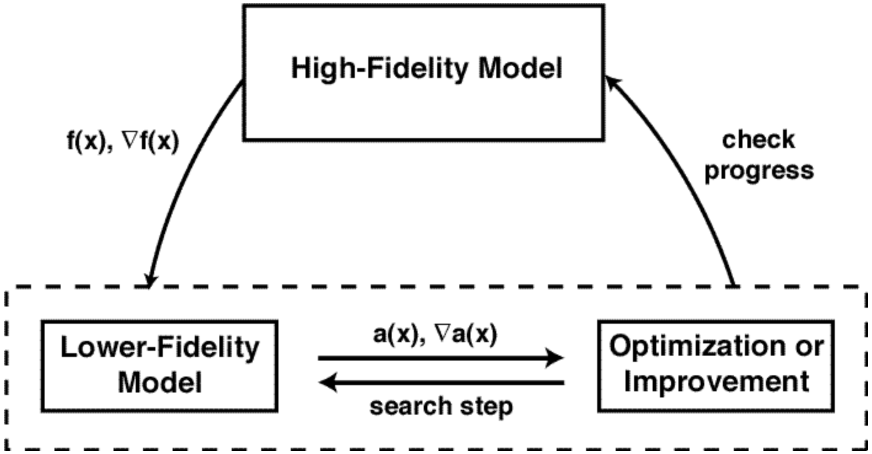
Module 3: Control strategies (WT/WF)

Module 4: Cost models (financial costs, O&M, wind turbine degradation costs)

Module 5: Optimization (synthesis of Modules 1-5)

TOPFARM platform
- Module 1 step-by step (1)

- Multi-fidelity optimization approach requires a hierarchy of models



1. Stationary wake (analytical model) + Power curve
2. DWM (Database – generic production/load cases + interpolation)
3. DWM (Simulation)

TOPFARM platform
- Module 1 step-by step (2)

- Stationary wake model:
  - o Closed form analytical wake model … with empirical boundary conditions depending on wind turbine C_T and ABL TI
  - o Based on an asymptotic formulation of NS boundary layer equations and similarity assumption
  - o Rotational symmetry and uniform inflow assumed
  - o Reynolds stresses modelled using Prandtl's mixing length approach … only self-induced turbulence thus accounted for
  - o Loading not - or only indirectly - accounted for

TOPFARM platform
- Module 1 step-by step (3)

- DWM (database):
  - o 7500 generic flow cases of 600s … under the assumption that flow effects from the nearest turbine is dominating
    - Wind speeds from 4m/s to 26m/s with a step of 2m/s
    - Inflow turbulences of 1,5,10 and 15%
    - 13 azimuth angles from 0 to 45^{o}
    - Distance from upstream turbine from 1D to 20D
  - o 4D interpolation in this database (production/loading)

TOPFARM platform
- Module 1 step-by step (4)

- DWM (full simulation):
  - o Under a linear perturbation approximation, the resulting field is obtained by superposition of deterministic and stochastic contributions
  - o Deterministic part of the flow field described by mean shear
  - o Stochastic part consists of the ABL turbulence (e.g. generated from the Mann spectral tensor) and the DWM contribution … resulting in an intermittent type of stochastic field

TOPFARM platform
- Module 2/3 step-by-step

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

TOPFARM platform
- Module 4 step-by step (1)

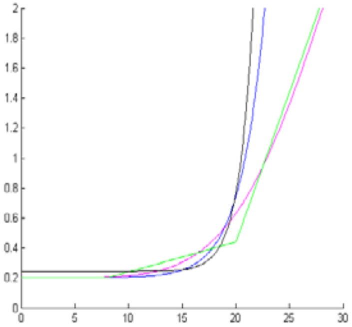
- Basic simplifying approach:
  - Only costs that depend on wind farm topology and control – variable costs - are of relevance in a topology optimization context
  - Fixed costs may be included in the objective function (Module 5). However, as seeking the stationary points for this functional involves gradient behaviour only the fixed costs will not influence the global optimum of the objective function

TOPFARM platform - Module 4 step-by step (2)

- Examples of required cost models … to transform the physical quantity in question into an economical value:
  - o Financial costs
    - ▪ Foundation costs
    - ▪ Grid infrastructure costs
    - ▪ Civil engineering costs
  - o Operational costs
    - ▪ Turbine degradation (fatigue loading/lifetime)
    - ▪ Operation and maintenance costs (O&M)
  - o Electricity production/wind resources

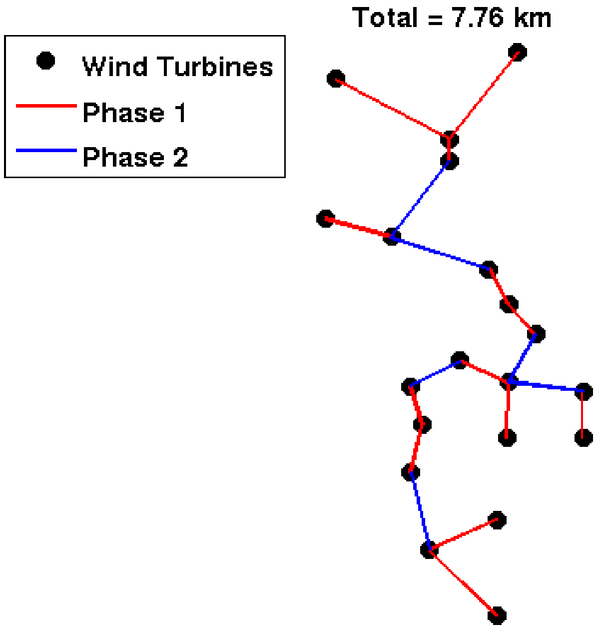
TOPFARM platform
- Module 4 step-by step (3)

- Foundation costs (CF):
  - o Cost of foundation is a variable cost in the sense that it depends on the soil conditions and/or the water depth at the location of each individual turbine
  - o Simple offshore foundation cost model:
    - Different models investigated
    - 20 % of turbine price ... at 8m
    - For depths above 8m an additional cost of 2% pr. meter ... depths above 20 meters very expensive (20% pr. meter)
    - Fast … and easy to refine



TOPFARM platform
- Module 4 step-by step (4)

- Grid costs (CG):
  - o Assume a constant price on cabling pr. running meter (including cost of cables, trenching and laying of these)
  - o Finding the shortest connection between all the turbines



Question (2)

- Any ideas of possible ways to put a price on fatigue degradation of WT’s in a WF topology optimization context ?

TOPFARM platform
- Module 4 step-by step (5)

- Cost of WT degradation (CD):
  - Assumed fatigue driven and estimated using Palmgren-Miner linear damage accumulation
  - Covers essentially writing off the investment of the turbines specified on main turbine components (S) (i.e. tower, blades, main axis, gear box, generator)
  - The writing off is presumed *proportional* to the *accumulated equivalent moments* (or accumulated equivalent stresses) in design critical "hot spots" on the respective components
  - Thus (D_S linear with accumulated fatigue loading)

$$CD = \sum_{N_T} \sum_{S} P_S D_S \ , \quad D_S = \frac{L_{Sa}}{L_{Sd}} \ ,$$

TOPFARM platform
- Module 4 step-by step (6)

- O&M costs (CM):
  - Maintenance Costs are based on the probability of occurrence of a fatigue driven component failure ... multiplied by the component replacement cost (incl. loss of production)
  - DS assumed determined with only insignificant uncertainty
  - Material fatigue resistance assumed Log-Normal distributed ... significant scatter on Wohler curves

$$CM_S = N_R \times P_{S_r} F\left(D_S; \mu_{S,(R+1)}, \sigma_{S,(R+1)}\right) + P_{S_r} \sum_{j=1}^{R} F\left(D_S; \mu_{S,j}, \sigma_{S,j}\right)$$

TOPFARM platform
- Module 5 step-by step (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) – in this case including grid costs (CG) and foundation costs (CF)

TOPFARM platform
- Module 5 step-by step (2)

- Objective function (OF):
  - o The value of the wind farm power production over the wind farm lifetime, *WP*, refers to year Zero
  - o 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 ... and that the inflation rate is the natural choice for the discounting factor transforming these running costs to *net present value*

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

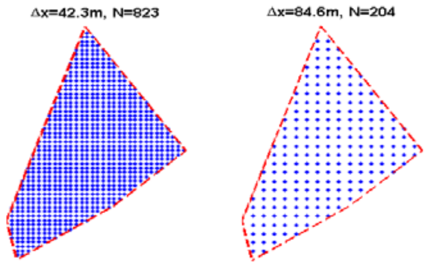
Solving the problem – the numerical strategy (1)

- Some tricks to reduce computational time:
  - o Structured grids (i.e. reduction of the design space)
  - o Multi fidelity approach

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

Solving the problem – the numerical strategy (2)

- Numerical approach is a mix of 2 algorithms:
  - o Genetic Algorithm (SGA) with key characteristics
    - Structured grid – coarse resolution
    - Slow (many iterations necessary)
    - Global optimum ... usually
  - o Gradient Based Search (SLP) with characteristics
    - Unstructured grid (good for refinements)
    - Fast (few iterations for converging)
    - Local minimum
  - o SGA+SLP is a good combination for searching a refined global optimum

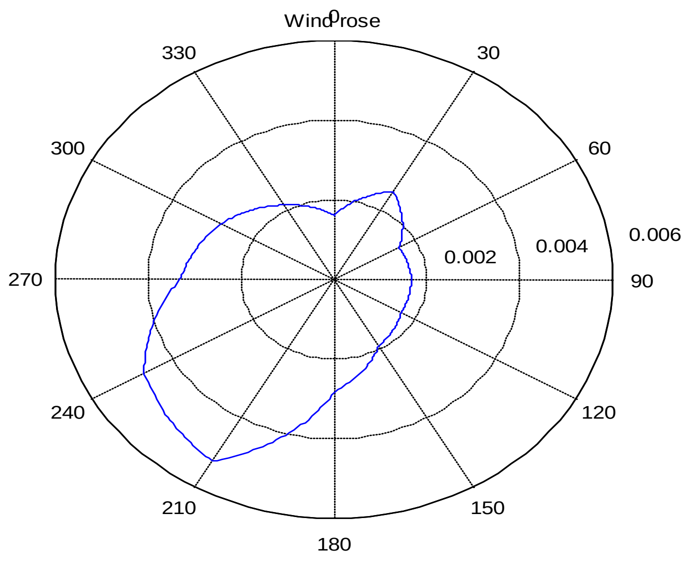


Solving the problem – the numerical strategy (3)

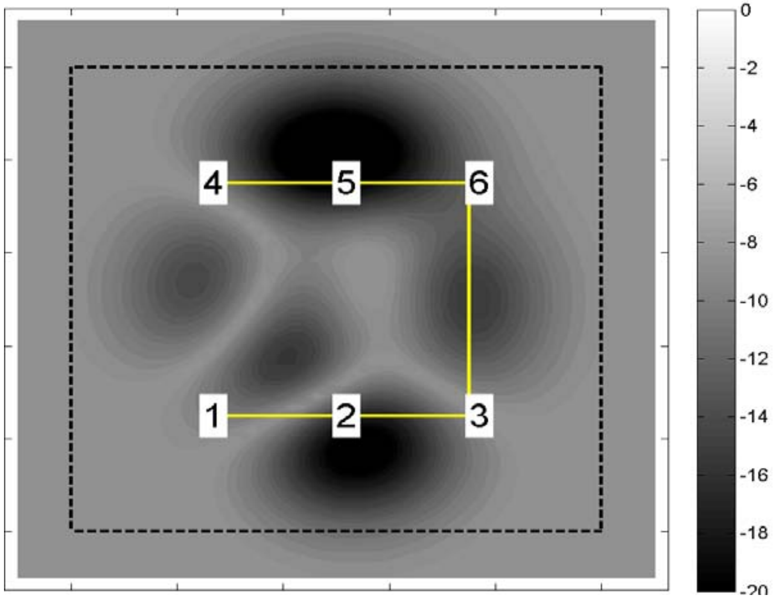
- A word on constraints:
  - o Domain boundaries (i.e. limit the domain spanned by the design variables)
    - Explicit limits: e.g. individual wind turbine coordinates within a predefined domain
    - Integral values: resulting from calculation in addition to the cost function (e.g. maximum allowable turbine loads, minimum distance between turbines, power quality – small sensitivity on wind direction changes)
  - o …

Demonstration example 1 (1)

- Generic offshore wind farm:
  - o 6 5MW offshore wind turbines
  - o Water depths between 4m and 20m



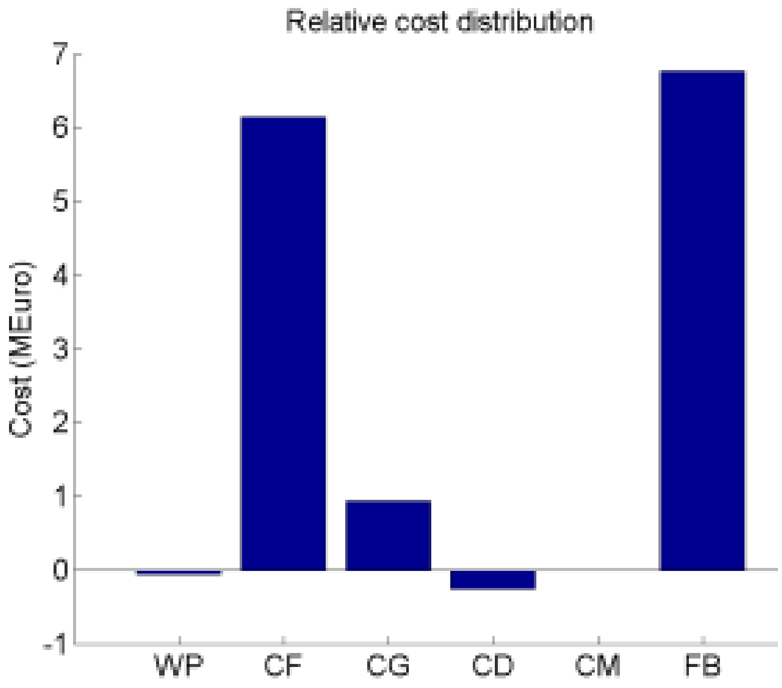
Wind direction probability density distribution

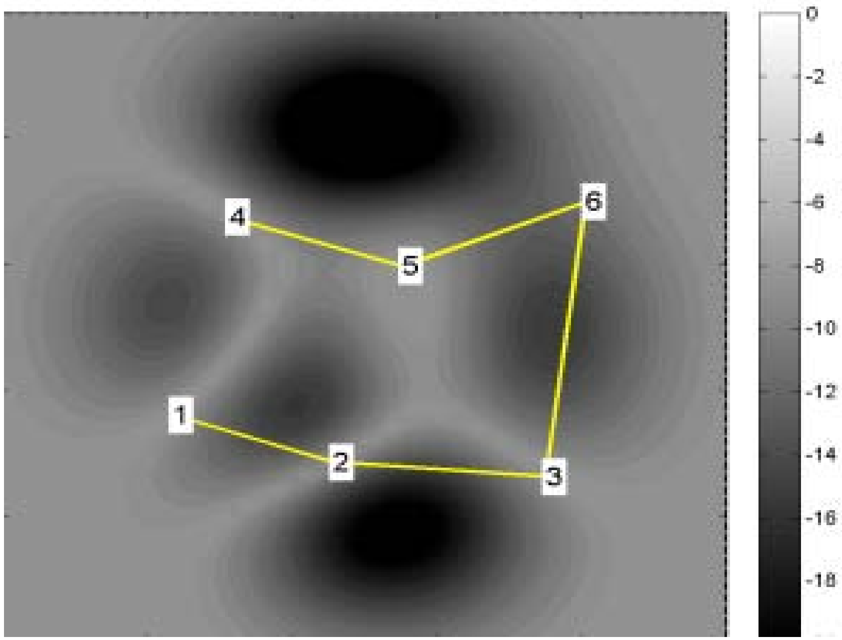


Gray color: Water depth [m]
Yellow line: Electrical grid

Demonstration example 1 (2)

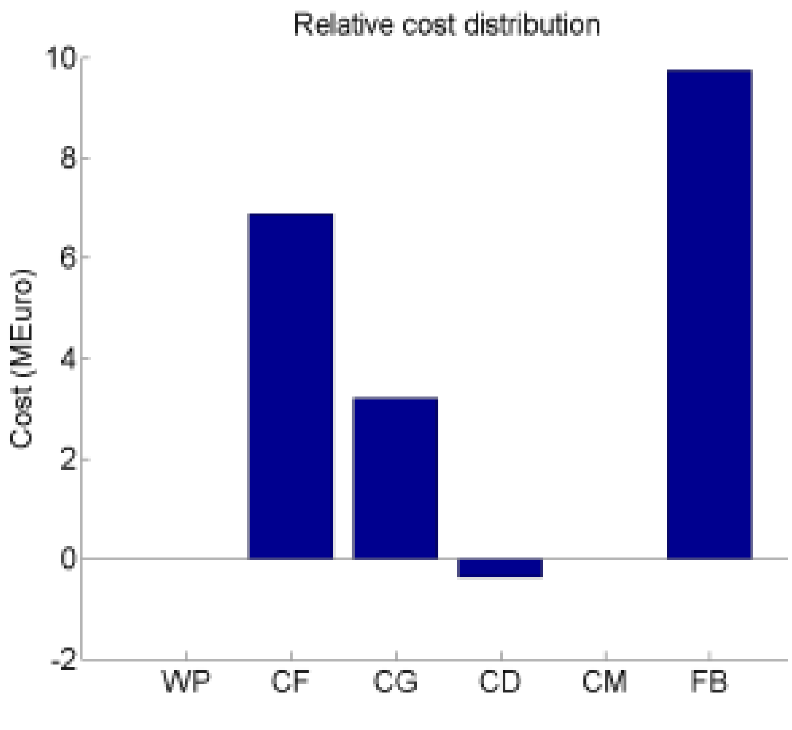
- Result of a gradient based optimization (SLP):

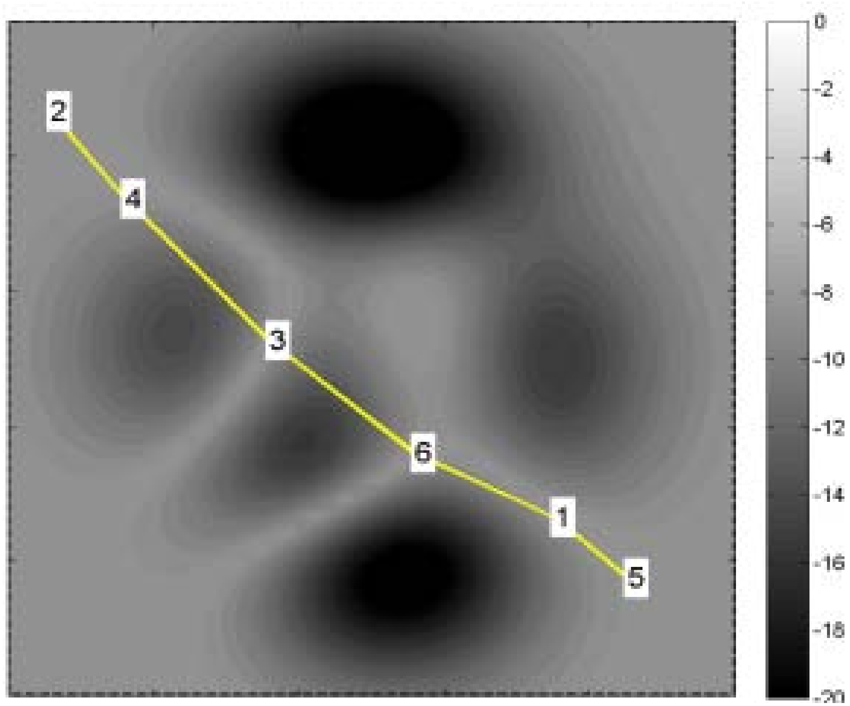




Demonstration example 1 (3)

- Result of a genetic algorithm + gradient based optimization (Simplex)



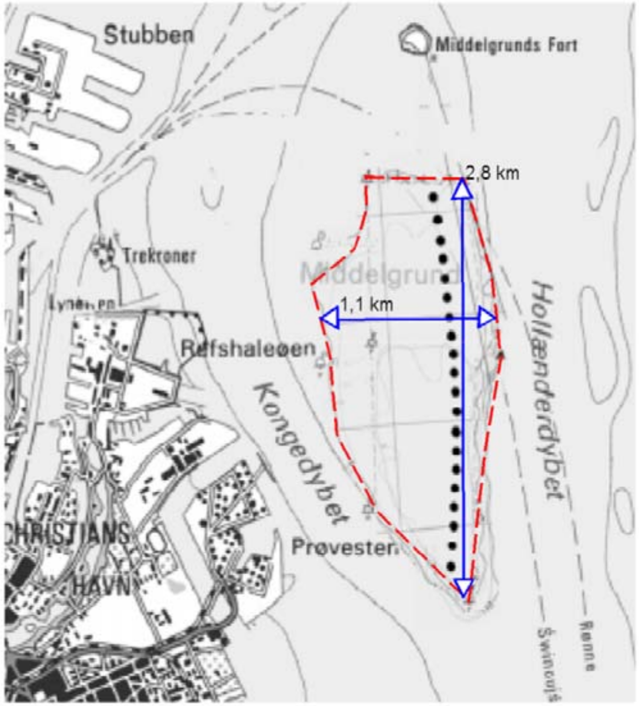


Demonstration example 2 (1)

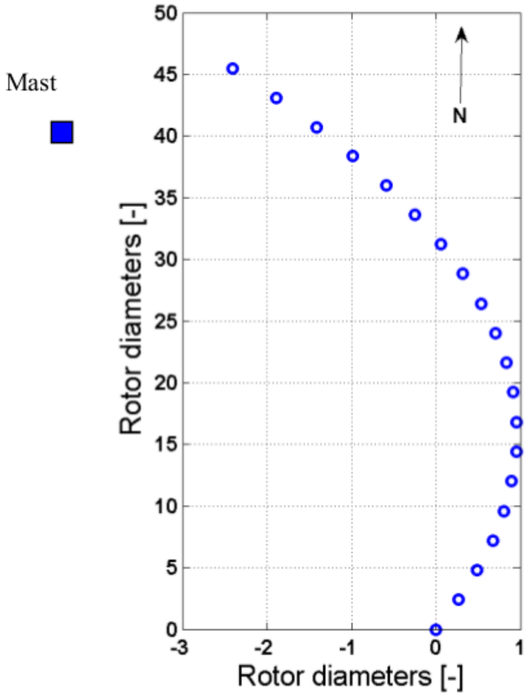
- Middelgrunden

Demonstration example 2 (2)

- Middelgrunden



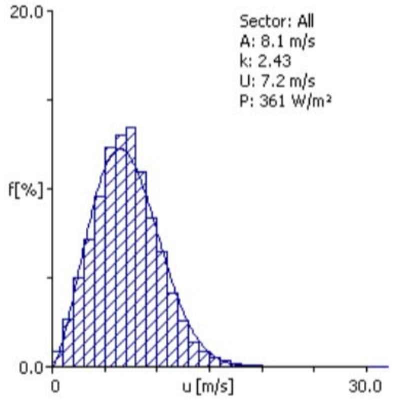
Allowed wind turbine region

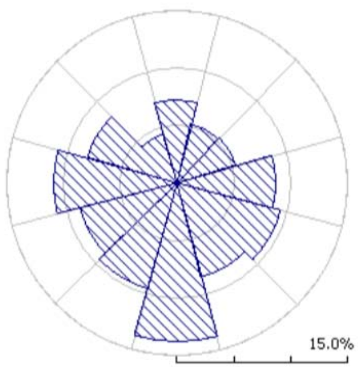


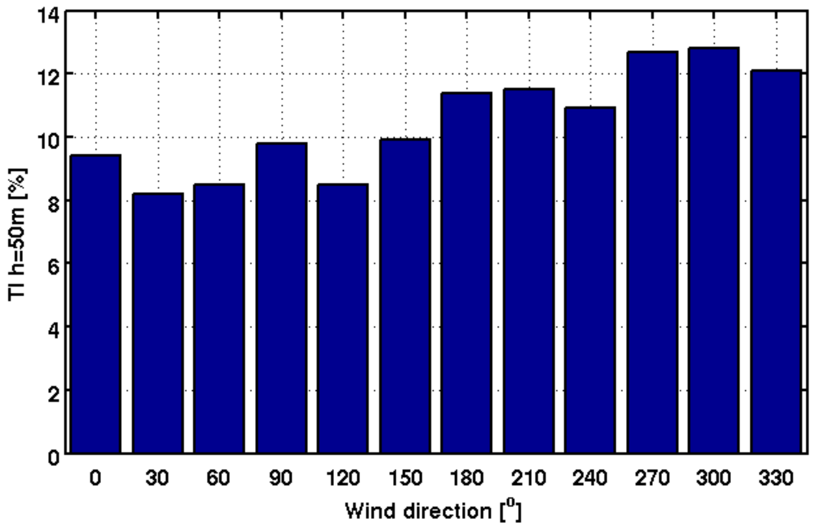
Middelgrunden layout

Demonstration example 2 (3)

- Middelgrunden - ambient wind climate

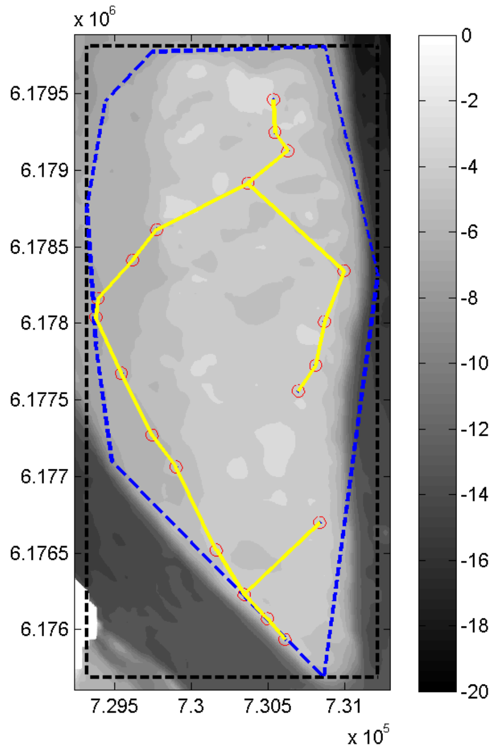


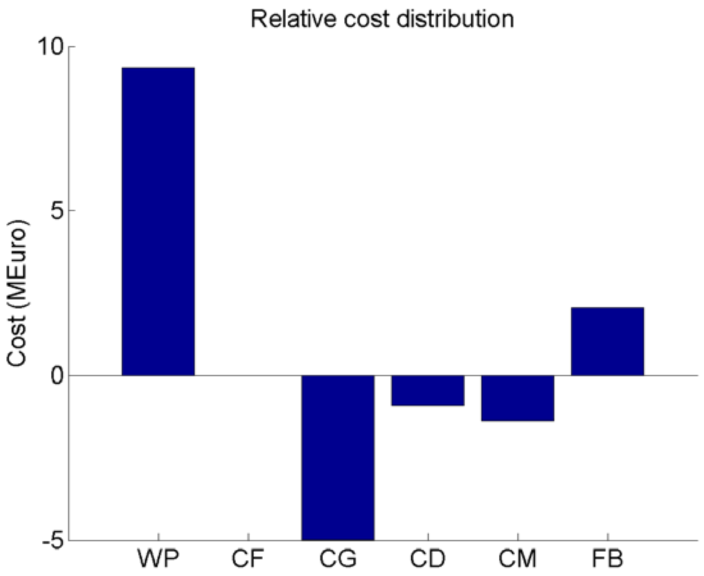




Demonstration example 2 (4)

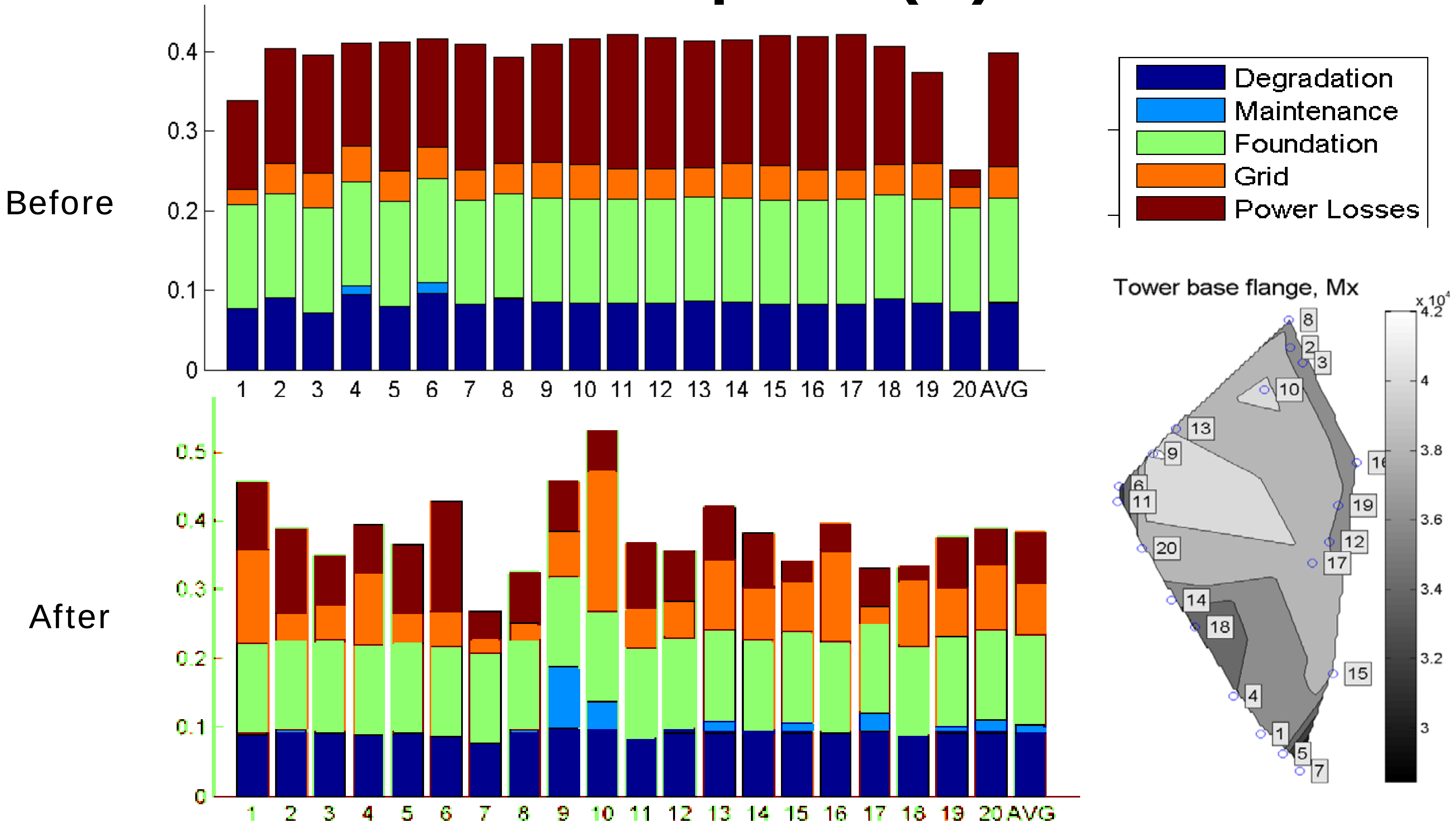
- Middelgrunden iterations: 1000 SGA + 20 SLP





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

Demonstration example 2 (5)



Demonstration example 2 (4)

- Evaluation (1):
  - The baseline layout was largely based on visual considerations
  - The optimized solution is fundamentally different from the baseline layout … the resulting layout makes use of the entire feasible domain, and the turbines are not placed in a regular pattern
  - The foundation costs have not been increased, because the turbines have been placed at shallow water
  - The major changes involve energy production and electrical grid costs … both were increased

Demonstration example 2 (5)

- Evaluation (2):
  - A total improvement of the financial balance of 2.1 M€ was achieved compared to the baseline layout … over the WF lifetime

Conclusions (1)

- A new optimization platform has been developed that allow for wind farm topology optimization in the sense that the *optimal economical performance,* as seen over the lifetime of the wind farm, is achieved
- This is done by:
  - o Taking into account both loading (i.e. WT degradation, O&M) and production of the individual turbines in the wind farm in a realistic and coherent framework .... and by
  - o Including financial costs (foundation, grid infrastructure, etc.) in the optimization problem

Conclusions (2)

- Proof of concept has, among others, included various sanity checks ... and optimization of a generic offshore WF, an existing offshore WF and an existing onshore WF
- The results are over all satisfying and give interesting insights on the pros and cons of the design choices. They show in particular that the inclusion of the fatigue loads costs gives some additional details in comparison with pure power based optimization
- The multi-fidelity approach is found necessary and attractive to limit the computational costs of the optimization

Future refinements (1)

- More detailed and realistic cost functions
- Improvement of the code (e.g. parallelization)
- Inclusion of WF control in the optimization problem
- Inclusion of atmospheric stability effects in the WF field simulation … basically by developing a spectral tensor including buoyancy effects
- Cheapest rather than shortest cabling between turbines
- Inclusion of extreme load aspects
- Simplified aeroelastic computations in the frequency domain ... to improved computational speed

Future refinements (2)

- Development of a dedicated “self-generated” wake turbulence spectral tensor
- Development of a more DWM-consistent eddy viscosity

References

- Larsen et al. (2011). **TOPFARM -** NEXT GENERATION DESIGN TOOL FOR OPTIMISATION OF WIND FARM TOPOLOGY AND OPERATION. Publishable final activity report
- Rethore, P.-E.; Fuglsang, P.; Larsen, G.C.; Buhl, T.; Larsen, T.J. and Madsen, H.Aa. (2011). TOPFARM: Multi-fidelity Optimization of Offshore Wind Farm. The 21st International Offshore (Ocean) and Polar Engineering Conference, ISOPE-2011, Maui, Hawaii, June 19-24

References

- Larsen, G.C.; Madsen, H.Aa.; Larsen, T.J.; Rethore, P.-E. and Fuglsang, P. (2011). TOPFARM – a platform for wind farm topology optimization. Wake Conference, Visby, Sweden, June 8-9
- Buhl T. and Larsen G.C. (2010). Wind farm topology optimization including costs associated with structural loading. *The Science of Making Torque from the Wind, 3rd Conference, Iraklion, Greece*
- Larsen, G.C. (2009). A simple generic wind farm cost model tailored for wind farm optimization. Risø-R-1710(EN)

References

- Larsen, G.C. (2009). A simple stationary semi-analytical wake model. Risø-R-1713(EN)
- Larsen, G.C. et al. (2008). Wake meandering: A pragmatic approach. *Wind Energy*, **11**, 377-395