TOPFARM
A Wind Farm Optimization Framework

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System Engineering Workshop
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1. Introduction
2. FUSED-Wind
3. TOPFARM II
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5. Optimization under uncertainty
Motivation

- Aero-Elastic Design Section is principally interested in wind turbine design.
- Wind turbines design depends of inflow inputs (upstream wakes).
- Dynamic Wake Meandering (DWM) can calculate wake induced loads.
- Other wake models can calculate power production (e.g. FUGA).
- How can we introduce these tools together into wind farm design?
TOPFARM = Topology OPtimization of wind FARM
EU-FP6 Funded project 2006-2010
Multi-fidelity framework for wind farm layout optimization
Optimization from the wind farm developer perspective
Objective function is the wind farm lifetime financial balance
The cost models take into account:
- Wake effects on power production
- Wake effects on wind turbines components fatigue
- Offshore foundation costs
- Electrical grid cabling
- Financial parameters
System

Level 1
Optimizer: Genetic

Layout optimization

Stationary wake model: GCL

Foundation costs
Annual Energy Production
Electrical grid costs
Financial Balance

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DTU Wind Energy

TOPFARM
System

Level 2
Optimizer: Gradient

Meta model

Dynamic Wake Meandering Model
Aero-elastic model: HAWC2

Stationary wake model: GCL

Layout optimization

Financial Balance

Foundation costs
Annual Energy Production
Electrical grid costs
Fatigue induced costs

Annual Energy Production

Financial Balance

Fatigue induced costs
The Middelgrunden test case
The Middelgrunden test case

Main Wind direction

Allowed wind turbine region

Middelgrunden layout

Main

Wind direction
The Middelgrunden test case

Middelgrunden after iterations: 1000 SGA + 20 SLP

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

Middelgrunden after iterations: 1000 SGA + 20 SLP

Disclaimer: We are not suggesting that building this ugly wind farm is a good idea.

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

- Nice to be able to estimate the wake induced fatigue
- Workflow not ready for a push-of-a-button holistic solution
- Multi-disciplinary design tools are difficult to be use in large "bureaucratic" organizations.
- Integrate the expert(s) opinion(s) within optimization loop, somehow
- Wish for an open framework, to use their own cost & physical models they already have experience with.
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Connecting All Wind Energy Models in a Workflow

- Collaborative effort between DTU and NREL to create a Framework for Unified System Engineering and Designed of Wind energy plants.
- Based on OpenMDAO, a python based Open source framework for Multi-Disciplinary Analysis and Optimization.
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Main Ideas

- Framework based on **FUSED-Wind**
- Use **WAsP** & **WRF** engine to calculate accurate local wind resources
- Multi-fidelity wake model based on DTU’s wind farm flow model family
- 3rd level of fidelity: running the whole wind farm with dynamic wake models (**DWM** & **AL/LES**)
- More advanced multi-fidelity optimization strategy
- Higher degree of parallelization
- Expert driven iterative design process
- GUI connected to **WAsP**
DTU’s Wind Farm Flow Model Family

Engineering

- G.C. Larsen
- N.O. Jensen
- FUGA
- DWM

CFD

- EllipSys3D RANS Actuator Disc
- EllipSys3D LES Actuator Disc
- EllipSys3D LES Actuator Line

Should they compete or collaborate?
System

Level 1
Optimizer: ?

Layout optimization

Stationary wake model

Foundation costs
Annual Energy Production
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System

Level 3
Optimizer: ?

Layout optimization

Dynamic Wake Meandering Model
Aero-elastic model

Flow model
Stationary wake model

Foundation costs
Annual Energy Production

Financial Balance
Fatigue induced costs

Electrical grid costs

Financial Balance

Foundation costs

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DWM

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Level 3
Optimizer: ?
System

Level 3
Optimizer: ?

Layout optimization

EllipSys LES

Aero-elastic model

Flow model

Stationary wake model

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Financial Balance
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Level 3
Optimizer: ?

Layout optimization

EllipSys LES
HAWC2

Flow model
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Level 3
Optimizer: ?

Layout optimization

EllipSys LES

FAST

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Financial Balance

Level 3

Optimizer: ?
System

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Layout optimization

Flow model

EllipSys LES

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EllipSys LES

FAST

WAsP-CFD

FUGA

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Level 3
Optimizer: ?

Layout optimization

- EllipSys LES
- FAST

- OpenWind
- FUGA

- Foundation costs
- Annual Energy Production
- Electrical grid costs
- Financial Balance
- Fatigue induced costs

Financial Balance

Level 3
Optimizer: ?

System

Layout optimization

- EllipSys LES
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- FUGA

- Foundation costs
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Financial Balance
System

Level 3
Optimizer: ?

Layout optimization

EllipSys LES
FAST

OpenWind

FUGA

Foundation costs

Annual Energy Production

Electrical grid costs

LCOE

Fatigue induced costs
# 50+ Optimizers Accessible in TOPFARM

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<th>DAKOTA (24)</th>
<th>pyOpt (20)</th>
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50+ Optimizers Accessible in TOPFARM

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- Genetic

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- OPTPP_NEWTON
- OPTPP_Q_NEWTON
- OPTPP_FD_NEWTON
- async pattern search
- coliny pattern search
- mesh adapt search
- optpp pds
- coliny cobyla
- coliny solis wets
- coliny ea
- soga
- moga
- ncsu direct
- coliny direct
- EGO

pyOpt (20)
- SNOPT
- NLPQL
- NLPQLP
- FSQP
- SLSQP
- PSQP
- ALGENCEPAN
- FILTERSD
- SOLVOPT
- SDPEN
- KSOPT
- ...
TOPFARM Roadmap

**v0.1** January 2015:
- Level 1
- wake: GCL

**v0.2** June 2015:
- Level 2
- Fatigue cost model
- wake: GCL, NOJ, Ainslie, FUGA
- Definition of DTU Wind new cost model
- Parallelisation of the optimization on cluster

**v0.3** January 2016:
- Connection to WAsP-CFD
- Level 3
- wake: EllipSys3D

**v0.4** June 2016:
- TOPFARM Cloud Service
- Load Atlas Cloud Service
- Wind Farm Flow Model Cloud Service
Future Research Work

- Benchmarking the optimizers
- Definition of reference wind farms
- Multifidelity of wind farm flow models
- Optimization under uncertainty
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The end-user is an expert
All the modelers consent is required
Autocratic hierachies structures make system engineering difficult
Autocratic hierarchies structures make system engineering difficult

SYSTEM ENGINEERING
OpenSource is a big plus
People prefer different models
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Dealing with uncertainty

Uncertainty within an optimization can come from different places:

- **Input uncertainty:** The inputs and constraints of the optimization can be uncertain (e.g. wt type, wt description, wind conditions, environmental constraints)

- **User uncertainty:** The user might not know which model to use, or how to use for the models

- **Model uncertainty:** The models add themselves an uncertainty to the results

- **Time pressure:** The optimization should be run fast, with lower fidelity models
**Multi-fidelity**

"The art of controlling uncertainty by running several similar models of different degrees of precision."

- How to orchestrate when to use which models, and how to project one model on the other one
- Projection: $M_1(x) = M_2(x) + \epsilon(x)$
- $\epsilon(x)$ is a machine-learning algorithm
- The optimization becomes a trade-off between minimizing the objectives and minimizing the variance of $\epsilon$
- Exemple: EGO
Integrating the expert opinion in a belief system
Sampling and Optimizing at the same time

A wind farm layout optimization requires an expensive AEP calculation. An AEP is in practice the integral of a PDF. It can be seen as a propagation of uncertainty through a wake model. What interest us is to obtain the most accurate AEP at the end of the optimization. During the optimization we can satisfy ourselves with a less accurate AEP. So in that sense we could progressively increase the discretization of the AEP as we converge to a solution. Another way to do it would be to allow slight modifications of a layout as part of the AEP calculation. In other words, we would integrate the AEP taking into considerations the power production of slightly different layouts in different wind speed and wind directions. This would produce of course a higher uncertainty in the AEP, but that might be an acceptable trade-off compared to the time gained.