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Published in:
Energy Procedia

Link to article, DOI:
[10.1016/j.egypro.2013.07.184](https://doi.org/10.1016/j.egypro.2013.07.184)

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Larsen, G. C., & Réthoré, P-E. (2013). TOPFARM – A Tool for Wind Farm Optimization. Energy Procedia, 35, 317-324. DOI: 10.1016/j.egypro.2013.07.184

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10th Deep Sea Offshore Wind R&D Conference, DeepWind'2013

TOPFARM – a tool for wind farm optimization

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Abstract

TOPFARM takes the investors perspective and performs an *economical optimization* of a wind farm layout throughout the lifetime of the wind farm. The economical optimization approach of wind farm layout differs significantly from the traditional power output optimization. The major differences are highlighted, and the TOPFARM platform is described in brief. The capability of the platform is illustrated in two demonstration examples. In the first example we perform a sanity check of basic features of the TOPFARM objective function. The second example demonstrates the power of economical layout optimization, when applied on the Danish Middelgrunden offshore wind farm. The paper concludes by describing planned future developments of TOPFARM.

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Selection and peer-review under responsibility of SINTEF Energi AS

Keywords: Economical optimization; wind farm flow field; wind farm layout; aeroelastic codes; cost models

1. Introduction

Economical optimization of wind farm layout deviates *significantly* from traditional power output optimization. The differences between these two approaches range from description of the wind farm flow field, over description of the wind farm turbines to formulation of the optimization objective function. These differences are highlighted in Section 2 of the paper. Section 3 describes in brief the basic modules of the TOPFARM platform dealing with: 1) wind farm flow field modeling; 2) aeroelastic modeling of the wind farm wind turbines, including control of these; 3) cost modeling, including financial costs, operation and maintenance (O&M) costs, and cost of fatigue degradation of wind turbine main components; and 4) the synthesis of all these basic elements into the optimization objective function.

The capability of the TOPFARM platform is illustrated in two examples. Section 4 deals with an artificial offshore site, designed with the purpose of performing a sanity check of basic features of the TOPFARM objective function. Section 5 demonstrates the applicability of the TOPFARM when used for

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re-design of the Danish Middelgrunden offshore wind farm. The paper is concluded by presenting the visions for the future development of the TOPFARM platform.

2. Economical optimization contra power optimization

Today, the design of a wind farm is typically/largely based on an optimization of the power output only, whereas the *load aspect* is treated only in a rudimentary manner, in the sense that the wind turbines are required only to comply with the design codes. However, to achieve the optimal economic output from a wind farm over its lifetime, an optimal balance between capital costs, operation and maintenance (O&M) costs, fatigue lifetime consumption of turbine components and power production output is to be determined on a rational background.

A key difference between economical and power output optimization is thus the inclusion of the individual dynamic wind turbine load patterns in the economical optimization approach. This has implications not only for the *wind turbine modeling*, but certainly also for the *wind farm flow field modeling*. Whereas stationary flow field modeling may suffice for wind farm power prediction [1] and thus for power optimization, in-stationary flow field modeling are required to capture the fluctuating inflow conditions, which dictates the wind turbine fatigue loading and the derived O&M costs.

Within an optimization context, the basic challenge in describing the in-stationary wind farm flow, composed of a complicated mixture of atmospheric boundary layer turbulence and wind turbine wakes emitted from upstream wind turbines, is computational time. The resulting turbulence field with its intermittent characteristics, resulting from the wind turbine wake interaction, can be resolved using e.g. CFD Large Eddy Simulation (LES) with the wind farm turbines simplified as actuator lines (ACL) [2]. However, the computational requirements prevent this approach from being used in an optimization context, where the wind farm flow field has to be re-compiled in each iterative step. Consequently, the need for an engineering type of flow model arises, which is capable of computing the essential wind farm flow field characteristics within an acceptable computational effort, and the Dynamic Meandering Wake (DWM) model [3] becomes handy in this respect.

Turning to the wind turbine modeling, a simple representation of the turbine quantified in terms of power and thrust curves, respectively, often suffices for power output optimization. The (stationary) flow field modeling thus results from e.g. an actuator disc formulation, with the actuator disc defined from the thrust curve information, whereas the power output subsequently are derived from modeled wind farm flow field combined with the power curve information. However, inclusion of the load aspect in the economical wind farm optimization requires aeroelastic modeling of the wind farm turbines. Selected component (fatigue) loads entering the optimization objective function, as well as the turbine power production, are thus resulting from the aeroelastic response of each wind farm turbine. With this approach, the wind turbine control are also accounted for, potentially including the possibility of improving control performance in wake affected flow fields as part of the optimization procedure.

Besides inclusion of the load aspect, with its derived consequence quantified in terms of fatigue degradation and O&M, an economical optimization also relies on the ability to take into account *financial aspects* as e.g. costs of (optimal) grid layout, cost of foundation etc. This in turn stresses the need for cost models in economical wind farm optimization. This is also contrary to the situation for power output optimization, where no cost models are needed. Being an economical optimization platform, the TOPFARM approach logically operates with an objective function formulated in economical terms. In addition to the financial cost models already mentioned, this consequently calls for cost models quantifying turbine component (fatigue) degradation costs and O&M costs.

3. The TOPFARM platform

The TOPFARM optimization platform is subdivided into 4 modules dealing with: 1) Wind farm flow field modelling; 2) Wind turbine modelling including wind turbine control; 3) Cost models; and 4) The synthesis of all sub-models into the optimization objective function and the solution of the resulting optimization problem conditioned on various constraints.

Taking a multi fidelity approach in the optimization procedure [4], the *flow field module* contains a “library” of flow models ranging from an engineering analytical model [5] to the DWM model. A central player for providing the required in-stationary inflow characteristics is the DWM model. Based on a priori knowledge of the undisturbed ambient wind climate on the wind farm site of interest, the DWM model provides detailed information of the inflow wind field to each individual wind turbine in the wind farm. The DWM model describes the essential physics of the problem, and accounts for both the observed increased turbulence intensity (TI) of wake flow fields and the modified turbulence structure. The model has been successfully verified against both full-scale measurements [6] and against detailed CFD LES actuator line (ACL) computations [7]. The core of the model is a *split of scales* in the wake flow field, with large scales being responsible for stochastic *wake meandering*, and small scales being responsible for wake *attenuation and expansion* in the meandering frame of reference as caused by turbulent mixing. Thus, essentially the DWM model assumes that the transport of wakes in the atmospheric boundary layer (ABL) can be modeled by considering the wakes to act as passive tracers driven by a combination of large-scale turbulence structures and a mean downstream advection velocity, adopting the Taylor hypotheses.

The *wind turbine module* offers simulations of the aeroelastic response of each individual wind farm turbine. The state-of-the art DTU in-house aeroelastic code HAWC2 [8] is used for this purpose. HAWC2 is a finite element code with all essential non-linearities taken into account. The structural part of this code is based on a multi-body formulation as described in [9] using the floating frame of reference method. Each body includes its own coordinate system with calculation of internal inertia loads, when this coordinate system is moved in space, and hence large rotation and translation of the body motion are accounted for, thus providing a fully non-linear kinematic formulation. The aerodynamic part of the code is based on the BEM theory, but extended from the classic approach to handle dynamic inflow, dynamic stall, skew inflow, shear effects on the aerodynamic induction and effects from large deflections to match the non-linear kinematic formulation of the structural part. In addition to structural elements and aerodynamics, the code includes modeling of generator, gear box and control system.

The *cost model module* encompasses simple cost models describing the wind farm fatigue degradation costs, the wind farm operational costs and the wind farm financial costs. Without imposing any restrictions, we have in the present context chosen to simplify the problem by considering only costs that depend on wind farm topology. This philosophy and the developed models are described in detail in [10].

The wind farm income, originating from the power production, and wind farm expenses, originating from financial as well as operational costs, are synthesized in the *optimization module*. A proper optimization approach is essential for successfully carrying out of the defined optimization problem. This is not a trivial task. One aspect is the choice of optimization algorithm(s) among global (i.e. generic) methods and gradient based methods, where the likelihood of arriving in a local minimum needs to be traded off against rate of convergence and total computational costs. Another aspect is the clever mapping of the wind farm layout design variables using as few variables as possible and how to include constraints on the wind farm performance characteristics. The TOPFARM optimization approach involves use of two types of algorithm – one genetic based and one gradient based. The optimization philosophy is described in detail in [4], [11].

4. A sanity check of the objective function

As part of the TOPFARM validation, a hypothetical 2×3 5 MW offshore wind farm was designed. The base layout appears from Figure 1, where the gray-scale background indicates the site water depths ranging between 4 and 20m, and the imposed area constraints are symbolized by the dotted square boundary. The right hand part of the figure shows the initial turbine spacings.

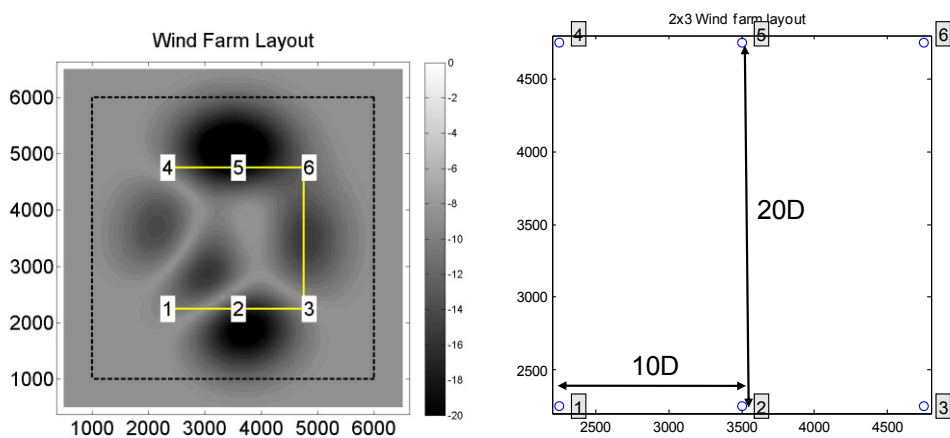


Figure 1. Base line layout of hypothetical offshore wind farm.

The outcome of the TOPFARM layout optimization appears from Figure 2. The optimized wind farm topology is shown in the left hand part of the figure, with the yellow lines symbolizing the wind farm grid infrastructure. The right hand part of the figure shows economical performance deviations from the base line layout distributed on the basic elements of the objective function. The input for this optimization is, apart from site water depths and wind turbine basic information detailed enough for an aeroelastic modeling, the site wind climate characteristics in terms of mean wind direction distribution as well as mean wind and ambient turbulence intensity distributions, conditioned on the wind direction. With reference to Figure 2, the optimization objective function (FB) contains the following elements: wind farm production (WP); costs of foundations (CF); cost of grid infrastructure (CG); cost turbine fatigue degradation (CD); and costs of O&M (CM).

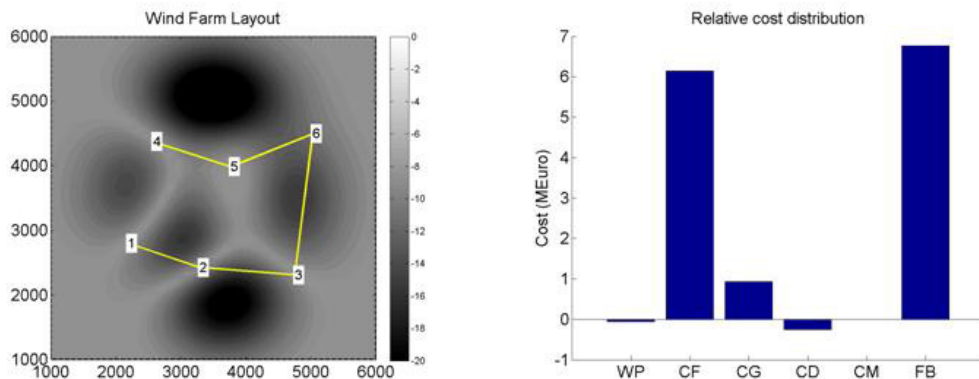


Figure 2. Optimized layout of hypothetical offshore wind farm.

As seen the financial balance (FB) for the optimized wind farm layout is considerably improved compared to the base line layout. The improvements are mainly due to reductions in foundation costs (CF) gained from positioning the wind turbines in shallow water areas. In addition shorter, and thereby cheaper, grid connections (CG) also contributes, whereas only marginal influences are due to wind farm power production (WP) and O&M costs (CM).

5. Economical optimization of the Middelgrunden wind farm

This example demonstrates the capability of the TOPFARM platform when used for re-design of an existing offshore wind farm. Based on the same type of input information as for the previous example (i.e. site wind climate and wind turbine information), the Danish offshore Middelgrunden wind farm was re-designed using the TOPFARM platform.



Figure 3. Layout of the offshore Middelgrunden wind farm.

The original layout of the Middelgrunden wind farm was mainly based on aesthetic considerations. This resulted in a beautiful curved arc-like layout, with the 20 2MW turbines positioned with a mutual turbine spacing of $2.3D$. The layout is shown in Figure 3, where the slightly curved trace appears.

The outcome of the TOPFARM optimization is shown in Figure 4. As expected, the optimized layout has a somewhat more scattered appearance than the original layout, thus making use of the entire feasible domain.

The financial balance (FB) for the optimized wind farm layout is considerably improved compared to the original layout, however, on the cost of the nice looking regular pattern of the original layout. The improvement in economical performance is due to increased wind farm production (WP), whereas especially the cost to grid infrastructure (CG) is significantly increased. Costs related to wind turbine fatigue degradation (CD) and O&M (CM) are also increased. The foundation costs (CF), however, are hardly changed, which relates to the fact that the entire feasible area is a shallow water area with only marginal differences in water depth.

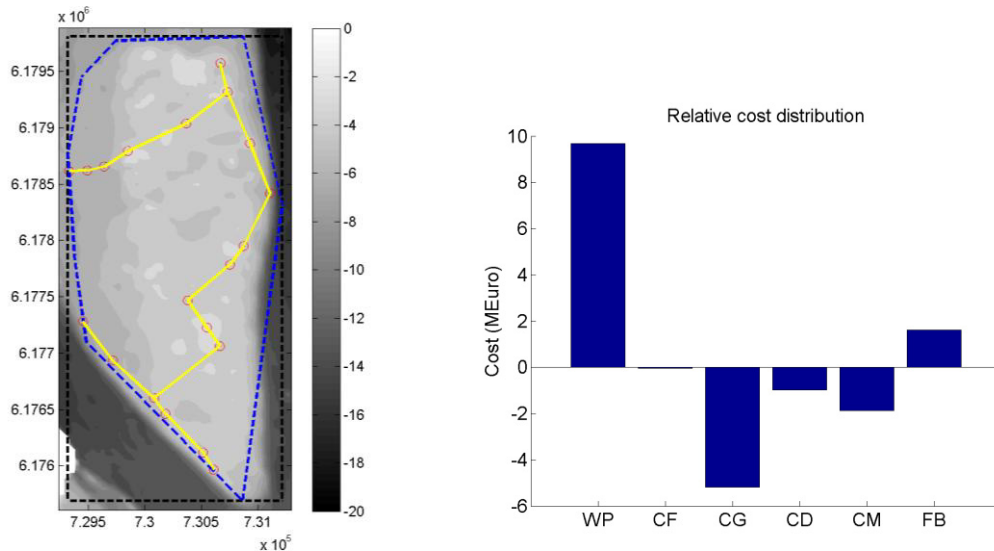


Figure 4. Optimized layout of the Middelgrunden wind farm. Left hand part of the figure shows the optimized layout with the yellow lines indicating the grid infrastructure. The right hand diagram shows the improved economical performance split on objective function elements.

6. Conclusions

A new approach has been developed, which allows for wind farm topology optimization in the sense that the *optimal economical performance*, as seen over the lifetime of the wind farm, is obtained. This is fundamentally different from conventional power output optimization and is achieved by determining the optimal balance between capital costs, operation and maintenance costs, cost of component fatigue degradation and power output income on a rational background.

From a modelling perspective, the main difference between conventional wind farm power output optimization and the present approach can be summarized as:

1. Contrary to conventional wind farm power output optimization, the economical approach requires a detailed *in-stationary* modelling of the wind farm flow field in order to enable realistic wind turbine load simulations. The DWM model offers simulation of in-stationary wind farm flow fields with an acceptable computational effort, which is essential in an optimization context;
2. Contrary to conventional wind farm power output optimization, the economical approach requires *main component loads/degradation* to be determined from detailed aeroelastic

simulations. This in turn enables wind turbine control to be accounted for, thus at the same time paving the way for tuning the control system to wind farm operation, which finally may impact the individual wind turbine power output that result from the aeroelastic simulations rather than from a simplistic power curve approach;

3. Contrary to conventional wind farm power output optimization, the economical approach requires *cost models* for the synthesis of different types of essential quantities (i.e. investment costs; wind turbine degradation costs; operation and maintenance costs; and power production) into the objective function defining the optimization problem.

The resulting comprehensive optimization problem is solved in an iterative manner, taking advantage of a multi-fidelity optimization approach. Constraints on the design space may be imposed either as a direct pre-defined reduction of the design space or, indirectly, in terms of restrictions on integral values resulting from calculations in addition to the cost functions. Examples of the latter category could be power quality and maximum allowable turbine loads. Computational speed of all basic elements of the TOPFARM platform is of utmost importance, and this challenge has thus been met on all levels ranging from the wind farm flow field simulation to the aeroelastic simulation and the optimization strategy itself.

In a future perspective, inclusion of *wind farm control* features and refinements of the embedded (cheapest possible) grid layout sub-optimization problem are planned along with general improvements of the code and the optimization strategy in order to increase the computational speed.

Acknowledgements

This work has been funded by the European Commission in the Framework of the Non-Nuclear Energy Programme Sixth Framework under the contract no. REN07/FP6EN/S07.73680/038641 (TOPFARM—Next Generation Design Tool for Optimization of Wind Farm Topology and Operation) [12].

References

- [1] Larsen GC, Larsen TJ, Ott S, Hansen KS, Madsen HAa. Full scale verification of wind farm production predictions. XXIII ICTAM, 19-24 August 2012, Beijing, China.
- [2] Troldborg, N.; Larsen, G.C.; Madsen, H.Aa.; Hansen, K.S.; Sørensen, J.N. and Mikkelsen, R.F. (2010). Numerical simulations of wake interaction between two turbines at various inflow conditions. *Wind Energy* (ISSN: 1095-4244) (DOI: 10.1002/we.433), John/Wiley & Sons Ltd.
- [3] Larsen GC, Madsen HA, Thomsen K, Larsen TJ. Wake meandering: a pragmatic approach. *Wind Energy* Jul 2008; **11**(4):377–395, doi:10.1002/we.267.
- [4] Réthoré P-E, Fuglsang P, Larsen GC, Buhl T, Larsen TJ and Madsen HAa. TOPFARM: Multi-fidelity Optimization of Wind Farms. Accepted for publication in *Wind Energy*.
- [5] Larsen GC. A simple stationary semi-analytical wake model. *Technical Report Risø-R-1713(EN)*, Risø DTU, August 2009.
- [6] Bingöl F, Mann J and Larsen GC (2010). LiDAR Measurements of Wake Dynamics, Part 1: One Dimensional Scanning. *Wind Energy* **13**, 51-61.
- [7] Madsen HAa, Larsen GC, Larsen TJ, Troldborg N and Mikkelsen R (2010). Calibration and Validation of the Dynamic Wake Meandering Model for Implementation in an Aeroelastic Code. *Journal of Solar Energy Engineering*, Vol. 132 / 041014-1.
- [8] Larsen TJ and Hansen A. How to HAWC2, the users manual. *Technical Report Risø-R-1597(EN)*, Risø National Laboratory, Technical University of Denmark, 2007.
- [9] Shabana A (1998). *Dynamics of Multibody Systems*, Cambridge University Press.
- [10] Larsen GC. A simple generic wind farm cost model tailored for wind farm optimization. *Technical report Risø-R-1710(EN)*, Risø DTU, Roskilde, Denmark, 2009.
- [11] Réthoré P-E, Fuglsang P, Larsen TJ, Buhl T and Larsen GC. TOPFARM wind farm optimization tool. *Technical report Risø-R-1768(EN)*, Risø DTU, Roskilde, Denmark , 2011.
- [12] Larsen GC. et al.. TOPFARM - NEXT GENERATION DESIGN TOOL FOR OPTIMISATION OF WIND FARM TOPOLOGY AND OPERATION. *Publishable final activity report. Risø-R-1805 (EN)*, Risø DTU, Roskilde, Denmark, 2011.