Wind farm design in complex terrain: the FarmOpt methodology

Feng, Ju; Shen, Wen Zhong; Hansen, Kurt Schaldemose; Vignaroli, Andrea; Bechmann, Andreas; Zhu, Wei Jun; Larsen, Gunner Chr.; Ott, Søren; Nielsen, Morten; Jogararu, Madalina Marilena; Thøgersen, Mikkel; Hu, Y.; Xu, C.; Liu, W.

Publication date:
2017

Document Version
Peer reviewed version

Citation (APA):
Wind Farm Design in Complex Terrain: The FarmOpt Methodology

Ju Feng [冯驹], Wen Zhong Shen [沈文忠], et al.

Email: jufen@dtu.dk
Acknowledgements

This tool was developed in the project “Wind Farm Layout Optimization in Complex Terrain (FarmOpt)”, with funding from The Energy Technology Development and Demonstration Program (EUDP) under Danish Energy Agency.

Contributing organizations in this project include: DTU Wind Energy, EMD International A/S, Ho-Hai University, North West Survey Institute.
Outlines

0. About DTU Wind Energy
1. Introduction
2. Wind Farm Modelling
3. Layout Optimization
4. Test Case
5. Conclusions & Future Developments
DTU Wind Energy is one of the world’s largest centres of wind energy research and knowledge, with a staff of more than 250 people working in research, innovation, research-based consulting and education.
DTU Wind Energy (Technical University of Denmark)

- RAM: Resource Assessment Modelling
- MES: Meteorology and Remote Sensing
- INP: Integration and Planning
- LAC: Loads and Control
- FLU: Fluid Mechanics
- AER: Aerodynamic Design
- SAC: Structures and Component Design
- TEM: Test and Measurements
- MAC: Material Science & Characterization
- COM: Composites & Materials Mechanics

Multi-scale, multi-discipline coverage

Siting and integration

Offshore wind energy

Wind turbine technology

Education and teaching

Research based consultancy and tests
1. Introduction

- More wind farms in complex terrain (esp. China)
- Great potential & many challenges
  - Richer wind resources
  - More complex flow, more expensive O&M
- Wind resource based micro-siting insufficient
The FarmOpt methodology:

- State-of-the-art flow simulation tool (WAsP CFD) +
- Adapted wake model +
- Advanced layout optimization algorithm +
- Realistic constraints or requirements.

The FarmOpt tool:

- Standard-alone tool
- Modular design written in Python
- Will be integrated with WindPRO and WAsP.
The FarmOpt methodology:

- State-of-the-art flow simulation tool (WAsP CFD) +
- Adapted wake model +
- Advanced layout optimization algorithm +
- Realistic constraints or requirements.

The FarmOpt tool:

- Standard-alone tool
- Modular design written in Python
- Will be integrated with WindPRO and WAsP.

---

Flowchart of using FarmOpt:

- Clients receive Terrain, Wind, WT designs, Initial WF design
- FarmOpt processes Constraints, Requirements, Optimization specifications, etc.
- FarmOpt delivers Optimized WF design, AEP & other results
- WAsP/WindPRO takes these results (Optimized WF design, AEP & other results) and delivers their outputs (Terrain, Wind, WT designs, Initial WF design, Terrain flow field, etc.)
2. Wind Farm Modelling

- Wind resource
  - Sector-wise Weibull parameters, speed-up factors, turning-angles, mean wind speeds, etc.
  - Obtained from standard wind resource assessment tools (WAsP, WindPRO)

- Constraint modelling
  - Inclusive boundaries, exclusive zones, ...
  - Minimal mean wind speed, TI, ...
  - Maximal terrain ruggedness degree, slope, ...
  - Minimal distance between any two turbines, ...
Wake modelling (adapted Jensen wake model)

- Wake center follows terrain ground along wind direction
- Velocity deficit and wake zone radius develops linearly according to the travelling distance
- Multiple wakes and/or partial wakes merged at rotor satisfying the kinetic energy deficit balance assumption

\[ V_{ij} = S(x_j)V_0 \left[ 1 - \frac{1 - c_T(S(x_j)V_0)}{(1 + \alpha(s_{ij}/R_r))^2} \right] \]

\[ R_{ij} = \alpha s_{ij} + R_r \]

Wake influence wind speed and wake zone radius of WTj’s wake zone at WTi’s location:

3. Layout Optimization (Random Search)

Initial layout \(L_0 = (X, Y)\) (baseline or random)

\[L_{\text{now}} = L_0\]

Stop?

Yes

Optimized layout \(L_{\text{optimal}} = L_{\text{now}}\)

No

\[L_{\text{now}} = L_{\text{new}}\]

Randomly move one WT

\[L_{\text{new}}\]

Generate new feasible layout

Better than \(L_{\text{now}}\)?

Yes

Feasible?

Yes

\[L_{\text{new}}\]

No

\[L_{\text{new}}\]

No

\[L_{\text{now}}\]

4. Case study (a 25 turbine wind farm in China)

- 2 MW turbine by a Chinese OEM
- D: 93 m, H: 67 m
- Located in Northwest China
- Mean wind speed: 6.23 m/s
Wind resource and terrain effects from WAsP

Mean wind speed map

Weibull-A map for 10th sector
wind direction: 270 deg

Speed-up map for 10th sector
wind direction: 270 deg

Turning angle map for 10th sector
wind direction: 270 deg
Constraints

- Minimal Umean
- Maximal ruggedness degree (RD)
- Minimal distance ($D_{min} = n \times D$)
- Inclusive boundary
- Exclusive boundaries
- Others such as turbulence intensity, total capacity, noise ...
Optimized layout: scenario 1

- Constraints: $U_{\text{mean}} \geq 6 \, \text{m/s}$, $RD \leq 0.08$, $D_{\text{min}} = 3D$
- No inclusive boundary
- Net AEP improvement: 161.839 GWh to 168.136 GWh (**3.89%**)
- Number of evaluations: 1000, cpu time: 12300 s.

[Time as running on a 5 year old Dell laptop with intel i5-2520M CPU]
Optimized layout: scenario 2

- Constraints: $U_{\text{mean}} \geq 6 \text{ m/s}$, $RD \leq 0.08$, $D_{\text{min}} = 3D$
- With inclusive boundary
- Net AEP improvement: 161.839 GWh to 164.338 GWh ($+1.54\%$)
- Number of evaluations: 1000, cpu time: 11257 s.
Optimized layout: scenario 3

- Constraints: $U_{\text{mean}} \geq 6 \text{ m/s}$, $RD \leq 0.08$, $D_{\text{min}} = 4D$
- With inclusive boundary
- Net AEP improvement: 161.839 GWh to 163.439 GWh ($+0.99\%$)
- Number of evaluations: 1000, cpu time: 11264 s.
Optimized layout: scenario 4

- Constraints: $U_{\text{mean}} \geq 6.5 \text{ m/s}$, $RD \leq 0.06$, $D_{\text{min}} = 4D$
- With inclusive boundary
- Net AEP improvement: $161.839 \text{ GWh}$ to $163.530 \text{ GWh}$ ($+1.05\%$)
- Number of evaluations: 1000, cpu time: 12099 s.
Optimized layout: scenario 5

- Constraints: $U_{\text{mean}} \geq 6.5 \text{ m/s}$, $RD \leq 0.06$, $D_{\text{min}} = 4.34D$ (current min.)
- With inclusive boundary
- Net AEP improvement: 161.839 GWh to 164.196 GWh ($+1.46\%$)
- Number of evaluations: 5000, cpu time: 63278 s.
Optimized layout: scenario 5

- **Constraints:** $U_{\text{mean}} \geq 6.5 \text{ m/s}$, $RD \leq 0.06$, $D_{\text{min}} = 4.34D$ (current min.)
- **With inclusive boundary**
- **Net AEP improvement:** 161.839 GWh to 164.196 GWh ($+1.46\%$)
- **Number of evaluations:** 5000, cpu time: 63278 s.
5. Conclusions & Future Developments

- FarmOpt: a valuable tool for wind farm design
- On-going developments
  - More accurate wake model by considering streamlines
  - Parallization and optimization for faster computation
- Planned developments
  - Overall design optimization
  - Integrated optimization of wind farm design and control
- A member of the synchronized DTU wind energy toolbox ...

![Data tools](image)  
![WAsP](image)  
![WEng](image)  
![WAT](image)  
![CFD](image)  
![Fuga](image)  
![FarmOpt](image)
Thanks for your attention!
Appendix

- Overall design optimization:

  optimizing number, configurations, locations of turbines, electrical cables, access road to min. LCOE or max. IRR with more realistic constraints, such as fatigue/extrem loads, noise, etc.

*Design optimization of non-uniform wind farm (number, configurations, locations of turbines)*

![Diagram of optimized design in Scenario 3](image)

- Optimized design in Scenario 3
  - Nwt = 76, Capacity = 152MW, CF = 52.30%, LCOE = 77.63€/MWh
  - LCOE = 77.63€/MWh

- Optimized design in Scenario 3
  - Nwt = 43, Capacity = 152MW, CF = 54.57%, LCOE = 77.46€/MWh
  - LCOE = 77.46€/MWh

Integrated optimization of wind farm design and control: including wind farm control strategies as optimization variables.

Automatic optimal sector management combined with design optimization

Allowing turbines placed closer to utilize limited high wind sites, and deal with excessive loads for certain wind directions by optimally stopping or derating certain turbines, to comply with IEC requirements on TI. The net AEP could be increased while constraints on loads satisfied.

Effective TI, no management

Effective TI with management

Check WAT for sector management: http://www.wasp.dk/wat