Wind Farm Layout Optimization
An application of wake models in wind farm design

Erik Quaeghebeur

Wind Energy Group — Delft University of Technology

AE4W30
14 November 2019
Wind farm layout optimization

1. What is it?

2. Why should I care?

3. How do we do it?
Wind farm layout optimization

1. What is it?
   Obtaining an optimal placement of the farm’s turbines
   - Objective function determines what is optimal
   - Constraints restrict what is allowed

2. Why should I care?

3. How do we do it?
Wind farm layout optimization

1. What is it?
   Obtaining an optimal placement of the farm’s turbines
   - Objective function determines what is optimal
   - Constraints restrict what is allowed

2. Why should I care?
   Your objective function value will be improved!

3. How do we do it?

   - Create a computational model for the wind farm
   - Generate an initial layout
   - Choose and apply an optimization algorithm
   - Deal with constraints
What is it?

*Obtaining an optimal placement of the farm’s turbines*

- *Objective function* determines what is optimal
- *Constraints* restrict what is allowed

Why should I care?

*Your objective function value will be improved!*

How do we do it?

- Create a computational *model for the wind farm*
- Generate an *initial layout*
- Choose and apply an *optimization algorithm*
- Deal with *constraints*
Place within the course

Related course objectives:

5) To *apply wake models* in a realistic wind farm situation

6) To *appreciate the importance to wind farm yield of* phenomena such as terrain complexity (onshore), proximity to the coast (offshore), atmospheric stability, mesoscale effects (e.g. gravity waves), *wind farm layout* and wind farm scale
Place within the course

Related course objectives:

5) To *apply wake models* in a realistic wind farm situation

6) To *appreciate the importance to wind farm yield of* phenomena such as terrain complexity (onshore), proximity to the coast (offshore), atmospheric stability, mesoscale effects (e.g. gravity waves), *wind farm layout* and wind farm scale

Learning goals:
After this lecture you will be able to

- give a general explanation of the what, why, and how of layout optimization;
- list multiple wind energy-related quantities that can play a role in the objective;
- discuss possible options for creating an initial layout and its impact;
- list the basic types of constraints and explain how violations can be corrected;
- list three defining characteristics of optimization algorithms and give an example algorithm for each of the choices
What: Objective function

- Defines *optimality* of a layout

- Expressed in terms of *design variables*

- Set of values for these variables is a *solution*
What: Objective function

- Defines *optimality* of a layout
  - AEP (or expected power production) — maximize
  - LCOE — minimize
  - Profit — maximize

  Involves: installation, cabling, O&M, decommissioning, interest rate, ... 

- Expressed in terms of *design variables*

- Set of values for these variables is a *solution*
What: Objective function

- Defines *optimality* of a layout
  - AEP (or expected power production) — maximize
  - LCOE — minimize
  - Profit — maximize

Involves: installation, cabling, O&M, decommissioning, interest rate, ...

- Expressed in terms of *design variables*
  - Turbine locations
  - Turbine type
  - Installation and O&M strategies

  Also: financing, number of turbines, turbine heights & diameters, ...

- Set of values for these variables is a *solution*
What: Objective function — Example expressions

\[ AEP = \sum_{k=1}^{n} AEP_k \]
What: Objective function — Example expressions

\[
AEP = \sum_{k=1}^{n} AEP_k
\]

\[
AEP(n, (x_k, y_k)_{k=1}^{n}) = \sum_{k=1}^{n} AEP_k((x_k, y_k), (x_{\ell}, y_{\ell})_{\ell=1, \ell\neq k}^{n})
\]
What: Objective function — Example expressions

\[ \text{AEP} = \sum_{k=1}^{n} \text{AEP}_k \]

\[ \text{AEP}(n,(x_k,y_k)_{k=1}^{n}) = \sum_{k=1}^{n} \text{AEP}_k ((x_k,y_k),(x_{\ell},y_{\ell})_{\ell=1,\ell\neq k}^{n}) \]

\[ \text{LCoE} = \frac{C}{\text{AEP}} = \frac{\alpha C_{\text{in}} + C_{\text{O&M}} + \beta C_{\text{decom}}}{\text{AEP}} \]
What: Objective function — Example expressions

\[ AEP = \sum_{k=1}^{n} AEP_k \]

\[ AEP\left(n, (x_k, y_k)_{k=1}^{n}\right) = \sum_{k=1}^{n} AEP_k \left((x_k, y_k), (x_\ell, y_\ell)_{\ell=1, \ell \neq k}\right) \]

\[ LCoE = \frac{C}{AEP} = \frac{\alpha C_{in} + C_{O&M} + \beta C_{decom}}{AEP} \]

\[ LCoE\left(n, (x_k, y_k)_{k=1}^{n}, T, r\right) = \frac{\alpha (T, r) C_{in}(n) + C_{O&M}(n) + \beta (T, r) C_{decom}(n)}{AEP\left(n, (x_k, y_k)_{k=1}^{n}\right)} \]
What: Objective function — Artist’s impression
What: Constraints

- Defines which layouts are *acceptable*

- Expressed in terms of *design variables*

- Solution that satisfies the constraints is *feasible*
What: Constraints

- Defines which layouts are *acceptable*
  - Site boundary
  - Minimal turbine distance
  - Minimal yearly energy production
  - Limit loads due to wake turbulence

- Expressed in terms of *design variables*

- Solution that satisfies the constraints is *feasible*
What: Constraints

- Defines which layouts are *acceptable*
  - Site boundary
  - Minimal turbine distance
  - Minimal yearly energy production
  - Limit loads due to wake turbulence

- Expressed in terms of *design variables*
  - Turbine locations
  - Turbine type
  - Installation and O&M strategies

  Also: financing, number of turbines, turbine heights & diameters,...

- Solution that satisfies the constraints is *feasible*
What: Constraints — Example expressions

$$(x_k, y_k) \in S$$
What: Constraints — Example expressions

\[ (x_k, y_k) \in S \]

\[ (x_k - x_\ell)^2 + (y_k - y_\ell)^2 \geq d^2 \]
What: Constraints — Example expressions

\[(x_k, y_k) \in S\]

\[(x_k - x_\ell)^2 + (y_k - y_\ell)^2 \geq d^2\]

\[AEP_t \geq AEP^*\]
What: Constraints — Real-life examples

[M. Wagner et al. / Renewable Energy 51 (2013) 64e70 ]
What: Constraints — Real-life examples

[4 C Offshore: https://www.4coffshore.com/]
Why

If the objective function actually describes the stakeholders’ goals, optimizing the layout for it will give them a better end result.

Challenges:
- Model uncertainty
- Simplification for computational purposes
How: Wind farm model

Components:

- Wind resource (*this course*)
- Wake effect (*this course*)
- Turbine
- Cost
- Loads
How: Wind farm model

Components:
- Wind resource (*this course*)
- Wake effect (*this course*)
- Turbine
- Cost
- Loads

Modelling choices:
- Wind resource discretization
- Continuous or discrete turbine positions
- Analytical or computational wake model
- What other aspects to include: turbine height, cabling, . . .
How: Wind farm model — Jensen vs. Bastankhah–Porté-Agel

How: Initial layout

The initial layout can have a substantial impact on the optimized layout. (Local extrema.)
How: Initial layout

The initial layout can have a substantial impact on the optimized layout. (Local extrema.)

Options:

- Free or on a grid
- For grids: regular or irregular, rectangular or triangular or ...
- Deterministic or random placement
- Satisfy the constraints or not?
How: Constraint handling

- Model automatically satisfies constraint
  - pre-defined turbine locations

- Penalty function
  - add a penalty to the objective if a constraint is violated
  - choice of penalty functions: step-wise or smooth
  - can be adaptive to allow temporary violations

- Repairing constraint violations when they occur
  - boundary constraint: move to border or inside
  - distance constraint: increase distance between turbines
  - deterministic or random
  - can also be adaptive
How: Constraint handling

- Model automatically satisfies constraint
  - pre-defined turbine locations

- Penalty function
  - add a penalty to the objective if a constraint is violated
  - choice of penalty functions: step-wise or smooth
  - can be adaptive to allow temporary violations

Example:

\[
AEP - \gamma f \left( \sum_{k,\ell} (x_k - x_\ell)^2 + (y_k - y_\ell)^2 - d^2 \right)
\]
How: Constraint handling

- Model automatically satisfies constraint
  - pre-defined turbine locations

- Penalty function
  - add a penalty to the objective if a constraint is violated
  - choice of penalty functions: step-wise or smooth
  - can be adaptive to allow temporary violations

- Repairing constraint violations when they occur
  - boundary constraint: move to border or inside
  - distance constraint: increase distance between turbines
  - deterministic or random
  - can also be adaptive
How: optimization algorithm

Characteristics:

- deterministic or random search-based
- population-based or single solution
- heuristic or grounded in theory

Often hybrids are created that make these choices non-binary.
How: optimization algorithm

Characteristics:

- deterministic or random search-based
- population-based or single solution
- heuristic or grounded in theory

Often hybrids are created that make these choices non-binary.

Typical choices:

- Gradient descent (deterministic, single, grounded)
- Genetic algorithms (random, population, heuristic)
- Particle swarm optimization (random, population, heuristic)
- Pure random search (random, single, heuristic)
- Mathematical programming (deterministic, single, grounded)
- Pseudo gradient-based (deterministic, single, heuristic) [Mine!]
How: optimization algorithm — Gradient descent

- Needs analytical or computed gradients
- Solution moves according to gradient
- Can get stuck in local extrema
How: optimization algorithm — Genetic algorithm

- Population of solutions described by ‘gene’
- New population created using mutation and inheritance
- Selection using objective function as ‘fitness’
How: optimization algorithm — Particle Swarm Optimization

- Population of solutions called ‘particles’
- Particles move both randomly and towards (local) best known solution
- Selection using objective function as ‘fitness’
How: optimization algorithm — Pseudo gradient-based

- For each wind direction, each turbine’s wake loss is translated to a vector.
How: optimization algorithm — Pseudo gradient-based

- For each wind direction, each turbine’s wake loss is translated to a vector
- The average vector over all wind directions is calculated
How: optimization algorithm — Pseudo gradient-based

- For each wind direction, each turbine’s wake loss is translated to a vector.
- The average vector over all wind directions is calculated.

- Turbines are moved in this direction.
Illustrations from the literature — Effect of optimizer

Illustrations from the literature — Effect of optimizer

Mosetti et al. 1994 (15 Turbines)  
WFLO MILP (15 Turbines)  
Grady et al. 2005 (39 Turbines)  
WFLO QIP + Bound (39 Turbines)

Turner et al. (19 Turbines)  
Present study (19 Turbines)  
Turner et al. (39 Turbines)  
Present study (39 Turbines)

Illustrations from the literature — Effect of wake model

Illustrations from the literature — Two turbine heights

Illustrations from the literature — Cabling and bathymetry

Returning to the learning goals

- give a general explanation of the what, why, and how of layout optimization;

- list multiple wind energy-related quantities that can play a role in the objective;

- discuss possible options for creating an initial layout and its impact;

- list the basic types of constraints and explain how violations can be corrected;

- list three defining characteristics of optimization algorithms and give an example algorithm for each of the choices