Wind Farm Layout Optimization

An application of wake models in wind farm design

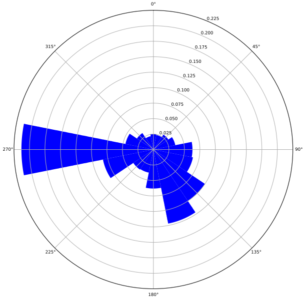
Erik Quaeghebeur

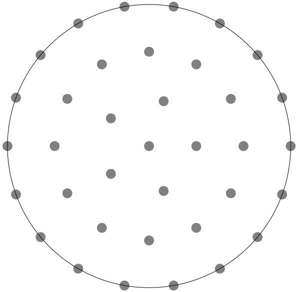
Wind Energy Group — Delft University of Technology

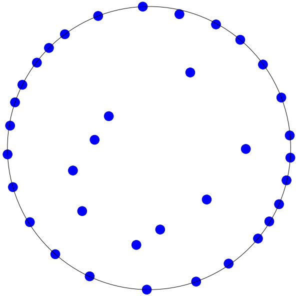
AE4W30

14 November 2019

TU Delft


0°
45°
90°
135°
180°
225°
270°
315°
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
0.225





Topic of this lecture

Wind farm layout optimization

1. What is it?

2. Why should I care?

3. How do we do it?

Topic of this lecture

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?

Topic of this lecture

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?

TU Delft

Topic of this lecture

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*

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*

TU Delft

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

$$AEP = \sum_{k=1}^{n} AEP_k$$

$$AEP\big(n, (x_k, y_k)_{k=1}^{n}\big) = \sum_{k=1}^{n} AEP_k\big((x_k, y_k), (x_\ell, y_\ell)_{\ell=1,\ell\neq k}^{n}\big)$$

What: Objective function — Example expressions

$$AEP = \sum_{k=1}^{n} AEP_k$$

$$AEP\big(n, (x_k, y_k)_{k=1}^{n}\big) = \sum_{k=1}^{n} AEP_k\big((x_k, y_k), (x_\ell, y_\ell)_{\ell=1, \ell \neq k}^{n}\big)$$

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

What: Objective function — Example expressions

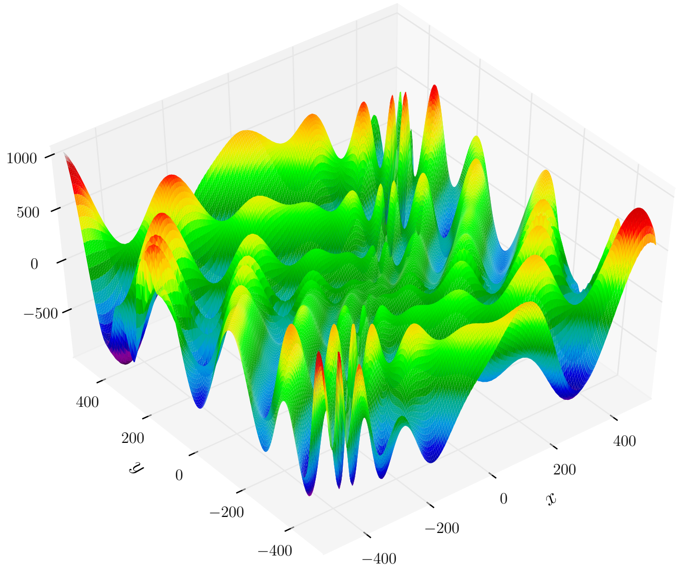
$$AEP = \sum_{k=1}^{n} AEP_k$$

$$AEP\Big(n, (x_k, y_k)_{k=1}^{n}\Big) = \sum_{k=1}^{n} AEP_k\Big((x_k, y_k), (x_\ell, y_\ell)_{\ell=1,\ell\neq k}^{n}\Big)$$

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

$$LCoE\Big(n, (x_k, y_k)_{k=1}^{n}, T, r\Big) = \frac{\alpha(T, r) C_{\text{in}}(n) + C_{\text{O\&M}}(n) + \beta(T, r) C_{\text{decom}}(n)}{AEP\Big(n, (x_k, y_k)_{k=1}^{n}\Big)}$$

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

$$(x_k, y_k) \in S$$

TU Delft

What: Constraints — Example expressions

$$(x_k, y_k) \in S$$

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

TU Delft

What: Constraints — Example expressions

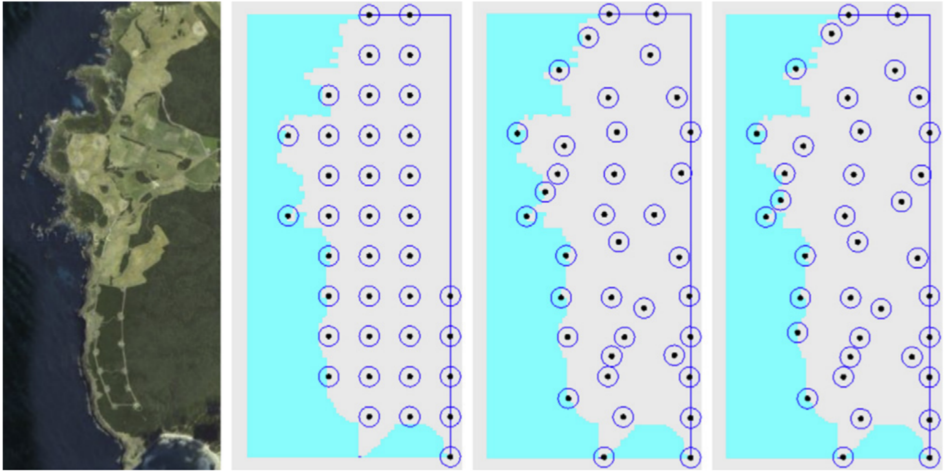
$$(x_k, y_k) \in S$$

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

$$AEP_t \geq AEP^*$$

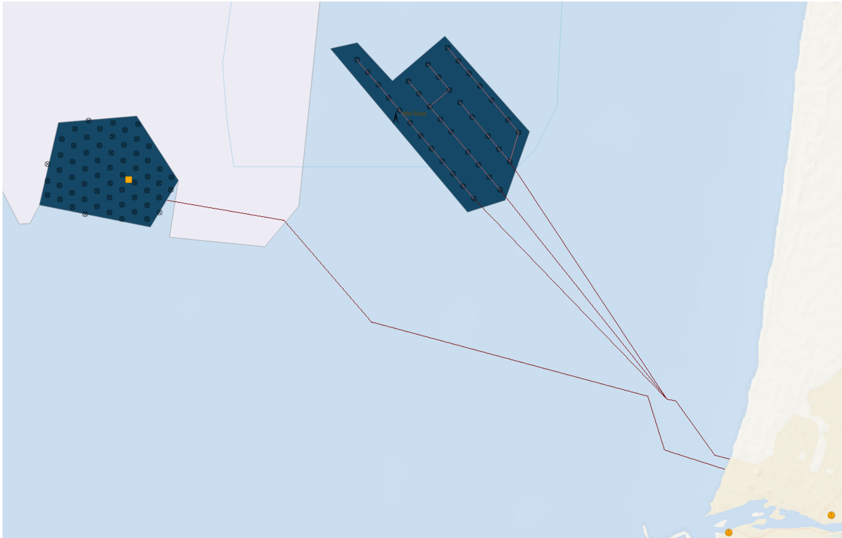
TU Delft

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

TU Delft

How: Wind farm model

Components:

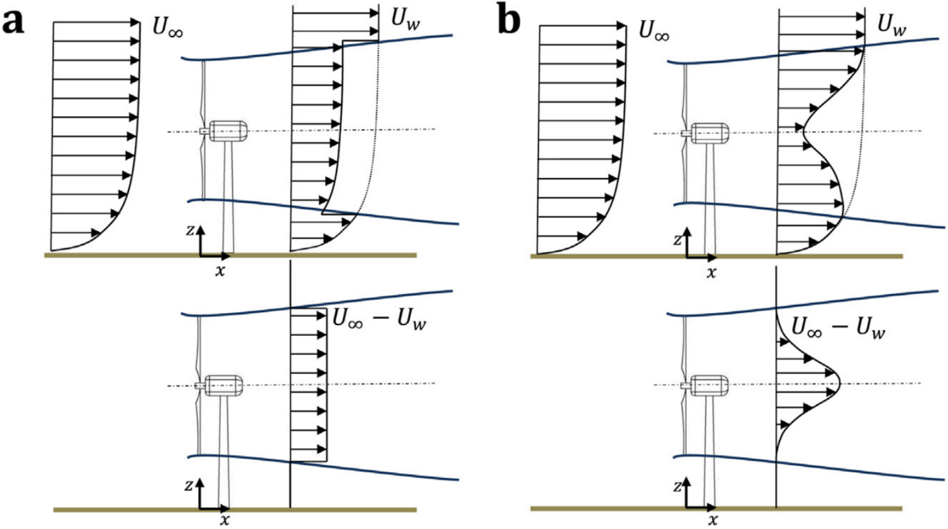
- Wind resource (*this course*)
- Wake effect (*this course*)
- Turbine
- Cost
- Loads

Modelling choices:

- Wind resource discretization
- Continuous or discrete turbine positions
- Analytical or computational wake model
- What other aspects to include: turbine height, cabling,...

TUDelft

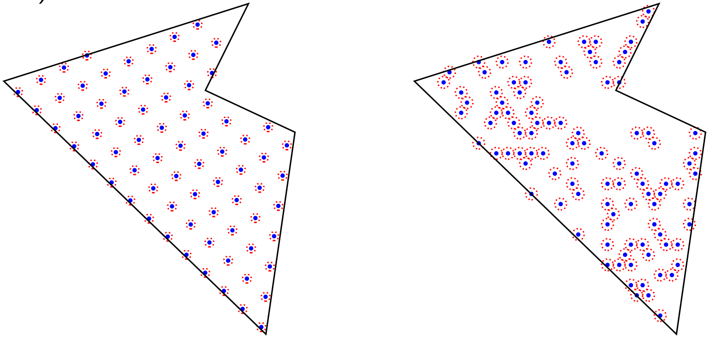
How: Wind farm model — Jensen vs. Bastankhah–Porté-Agel



[M. Bastankhah, F. Porté-Agel / Renewable Energy 70 (2014) 116–123]

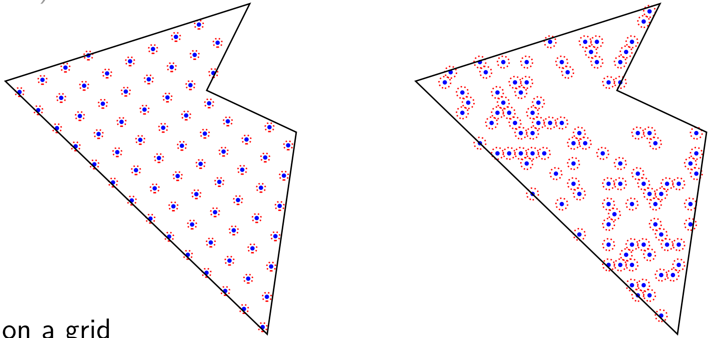
How: Initial layout

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.)

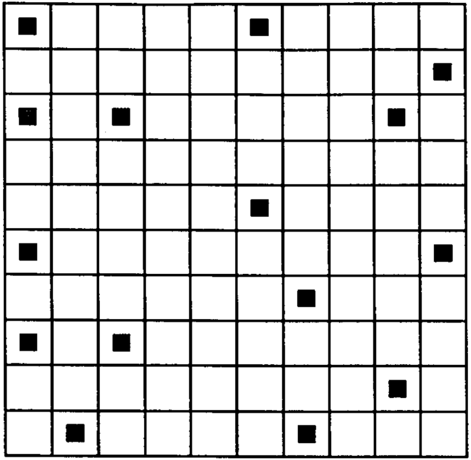


Options:

- 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



TU Delft

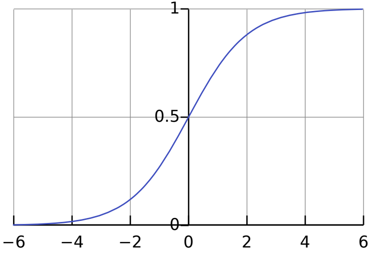
How: Constraint handling

- 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

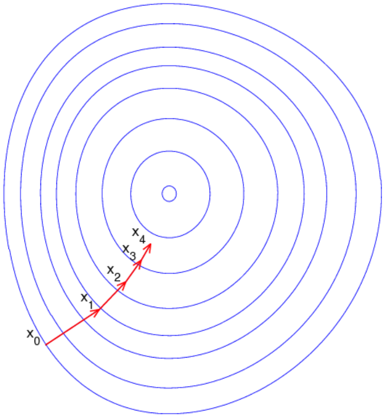
Often hybrids are created that make these choices non-binary.

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!]**

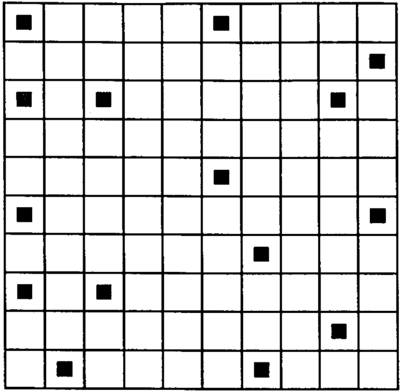
How: optimization algorithm — Gradient descent

- Needs analytical or computed gradients
- Solution moves according to gradient
- Can get stuck in local extrema



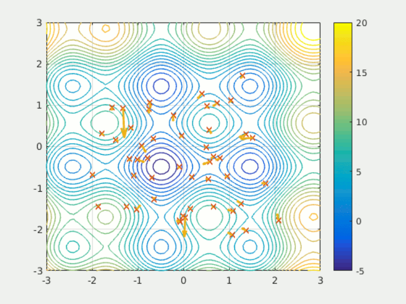
How: optimization algorithm — Genetic algorithm

- Population of solutions described by 'gene'
- New population created using mutation and inheritance
- Selection using objective function as 'fitness'



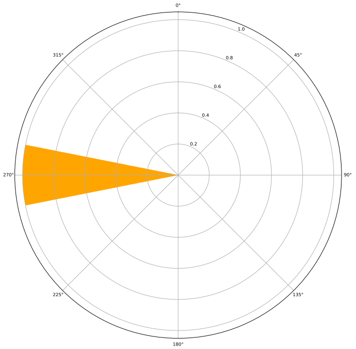
How: optimization algorithm — Particle Swarm Optimization

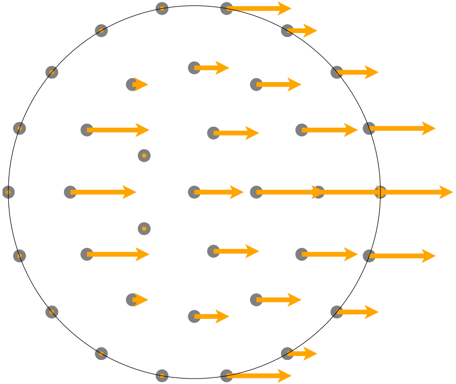
- Population of solutions called 'particles'
- Particles move both randomly and towards (local) best known solution
- Selection using objective function as 'fitness'



How: optimization algorithm — Pseudo gradient-based

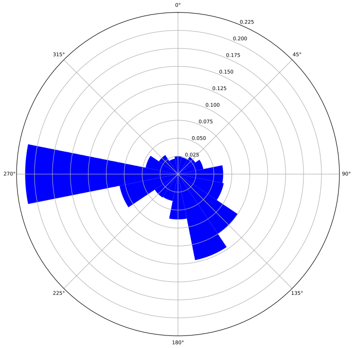
- For each wind direction, each turbine's wake loss is translated to a vector

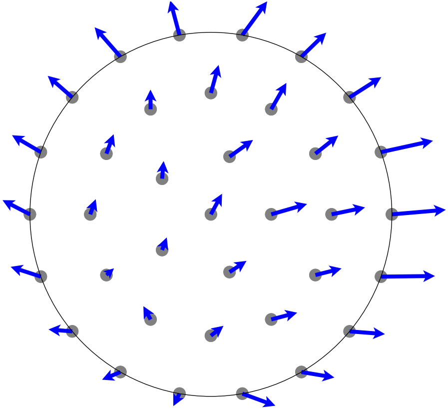




How: optimization algorithm — Pseudo gradient-based

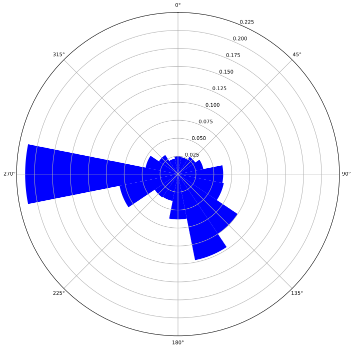
- For each wind direction, each turbine's wake loss is translated to a vector
- The average vector over all wind directions is calculated

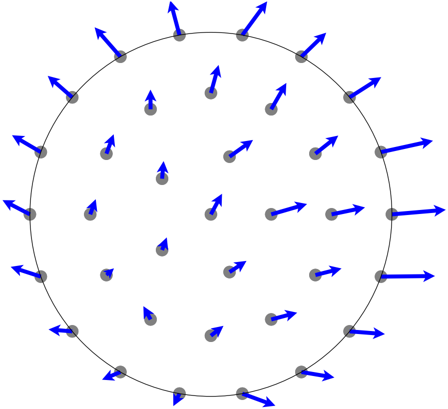




How: optimization algorithm — Pseudo gradient-based

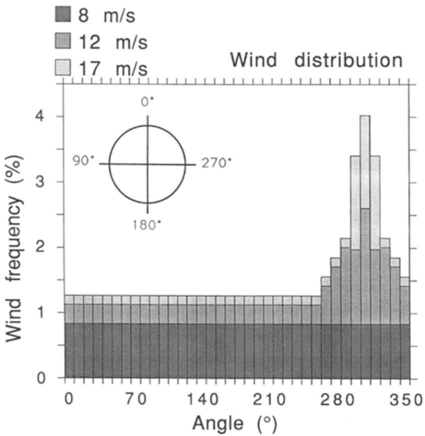
- For each wind direction, each turbine's wake loss is translated to a vector
- The average vector over all wind directions is calculated

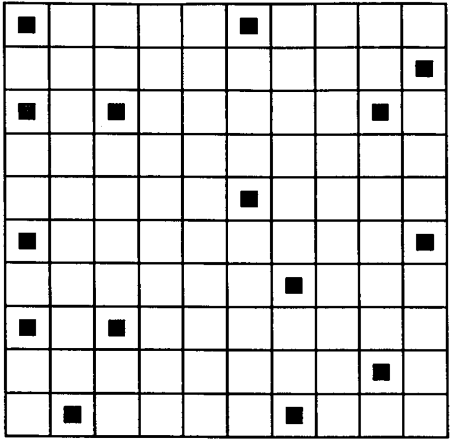




- Turbines are moved in this direction

Illustrations from the literature — Effect of optimizer

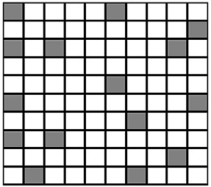




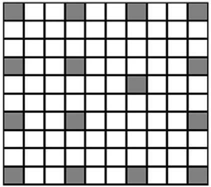
[Journal of Wind Engineering and Industrial Aerodynamics 51 (1994) 105–116]

Illustrations from the literature — Effect of optimizer

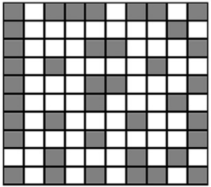
Mosetti et al. 1994 (15 Turbines)



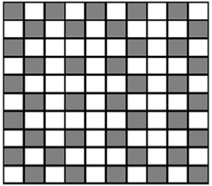
WFLO MILP (15 Turbines)



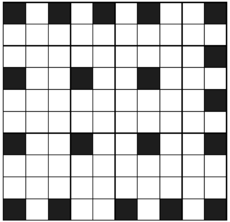
Grady et al. 2005 (39 Turbines)



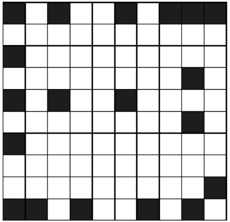
WFLO QIP + Bound (39 Turbines)



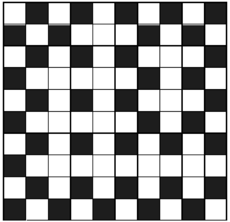
Turner et al. (19 Turbines)



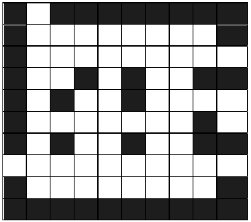
Present study (19 Turbines)



Turner et al. (39 Turbines)

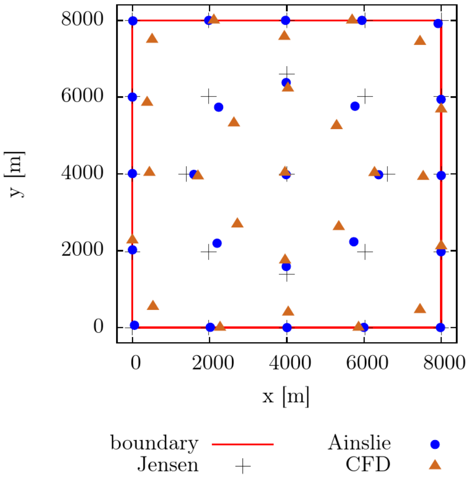


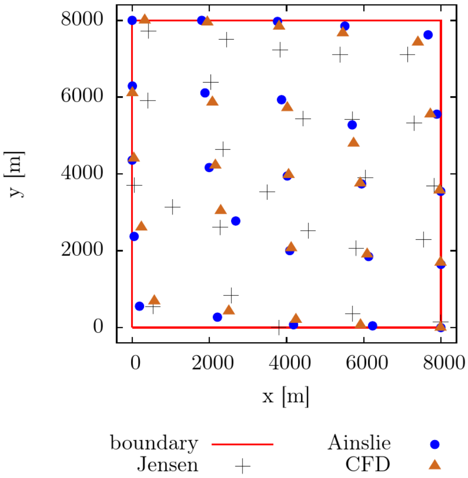
Present study (39 Turbines)



[S.D.O. Turner et al. / Renewable Energy 63 (2014) 674–680] [S.A. MirHassani, A. Yarahmadi / Renewable Energy 107 (2017) 288–297]

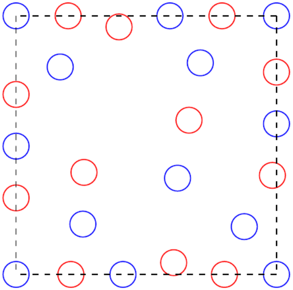
Illustrations from the literature — Effect of wake model

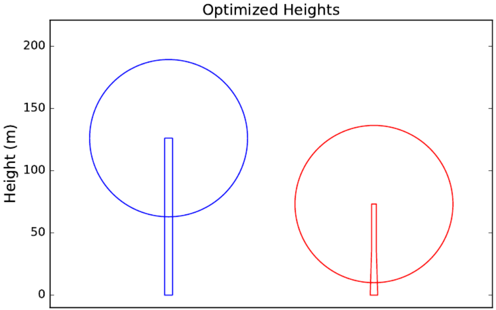




[Jonas Schmidt and Bernhard Stoevesandt 2015 J. Phys.: Conf. Ser. 625 012040]

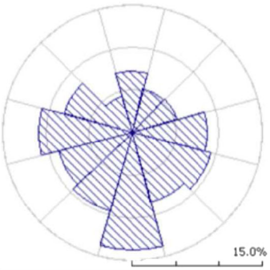
Illustrations from the literature — Two turbine heights

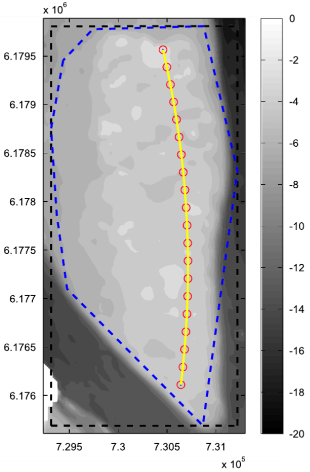


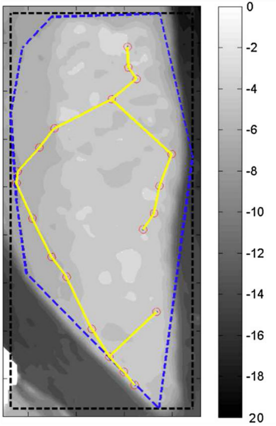


[Andrew P. Stanley, Jared Thomas, Andrew Ning, Jennifer Annoni, Katherine Dykes, and Paul A. Fleming. "Gradient-Based Optimization of Wind Farms with Different Turbine Heights", 35th Wind Energy Symposium, AIAA SciTech Forum, (AIAA 2017-1619)]

Illustrations from the literature — Cabling and bathymetry







[Réthoré P.-E., Fuglsang P., Larsen G. C., Buhl T., Larsen T. J. and Madsen H. A. (2014), TOPFARM: Multi-fidelity optimization of wind farms, Wind Energ., 17, pages 1797–1816]

TU Delft

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

TU Delft