Robust wind farm layout optimization using pseudo-gradients

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Object of study: offshore wind farms

https://english.rvo.nl/subsidies-programmes/offshore-wind-energy

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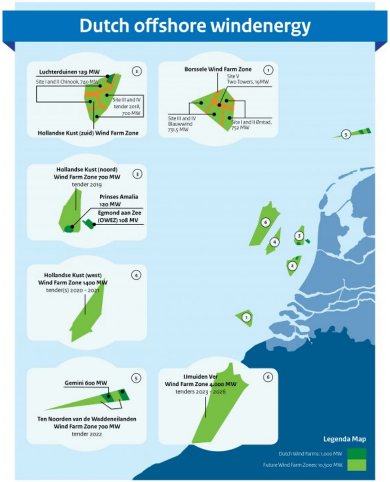
Object of study: offshore wind farms



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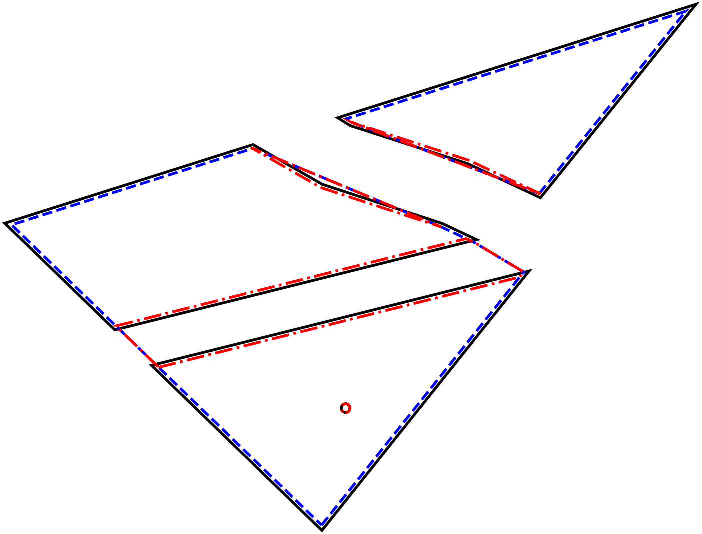


Object of study: offshore wind farms

Location determines

- *wind resource*,
- environmental conditions,
- bathymetry and soil composition

Site determined by *constraints*

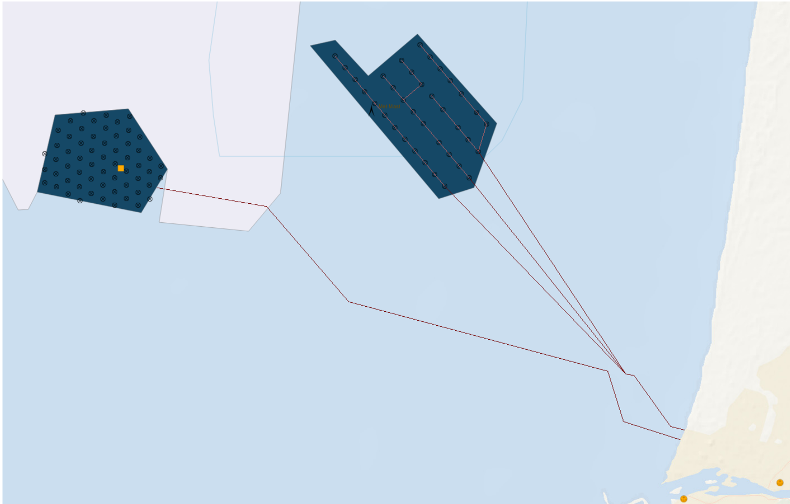
Regulations such as *turbine distance constraint*

Turbine type determines *how wind is transformed into power*

Layout

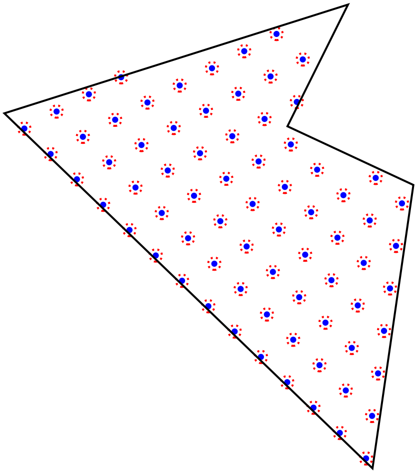
- *number and placement of turbines* within the site
- cable topology

Wind farm layout



https://www.4coffshore.com/offshorewind/

Wind farm layout: regular



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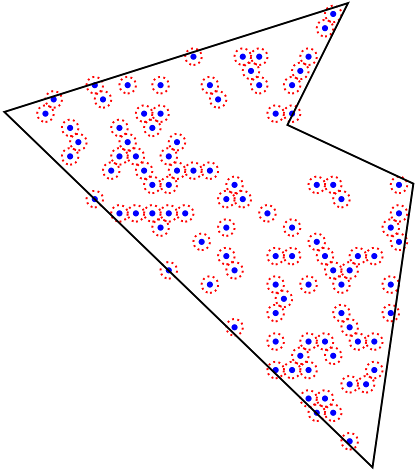
Wind farm layout: random



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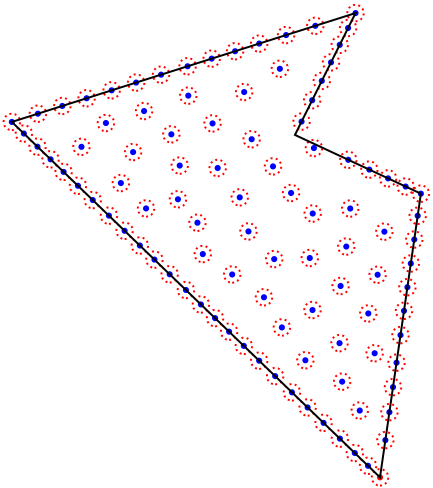
Wind farm layout: irregular



Wind farm layout

Fixed number of turbines n

Ignored cable topology, bathymetry, and soil composition

Design variables turbines' coordinates $\ell = \begin{bmatrix} (x_1, y_1) \\ \vdots \\ (x_k, y_k) \\ \vdots \\ (x_n, y_n) \end{bmatrix}$

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The optimization objective

Options:

AEP Maximize "*Annual Energy Production*"

- Actually, the *expected* energy produced in a year
- Equivalently, the expectation of the power output (in a given year)

LCoE Minimize "*(Levelized) Cost of Energy*"

- Ratio of lifetime costs and lifetime energy production
- Useful when considering cabling and substructure installation (not done here)

The optimization objective

We continue with:

AEP Maximize "*Annual Energy Production*"

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LCoE Minimize "*(Levelized) Cost of Energy*"

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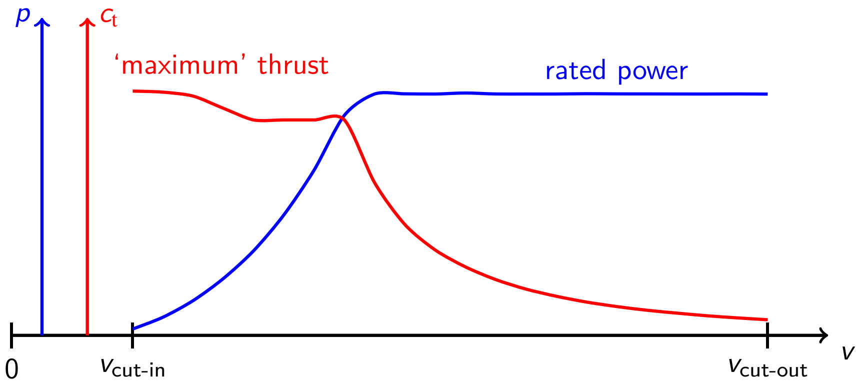
What affects power output? Turbine type(s)

Via their

- *power curve*, which maps wind speed to power
- *thrust curve*, which maps wind speed to the thrust coefficient; the amount of thrust affects the downstream wind field



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What affects power output? Number of turbines

Scales power output *roughly* linearly

- determines a farm's name-plate capacity
- may vary because of non-availability of some turbines (ignored here)

What affects power output? Wind resource

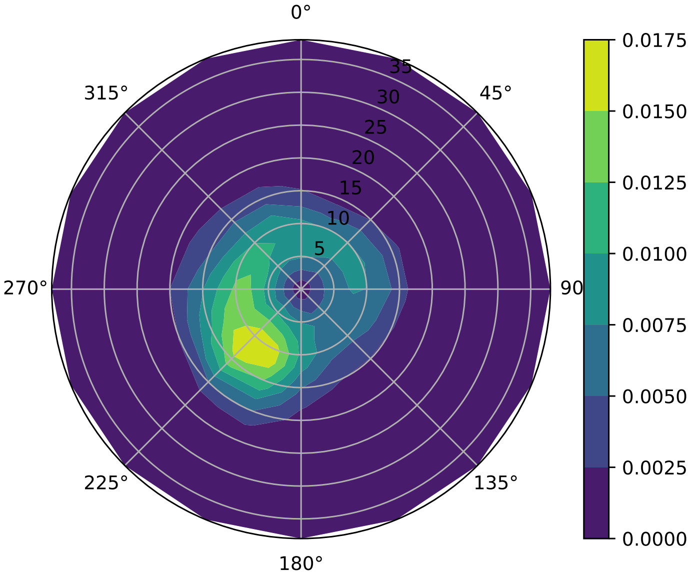
Joint probability distribution for wind speed and wind direction

- Usually given as
  - marginal wind direction distribution (‘wind rose’)
  - conditional wind speed distributions (usually Weibull-like)
- Estimated from measurements at the location or nearby
- Depends on the time period considered
- Main determinant of *capacity factor*

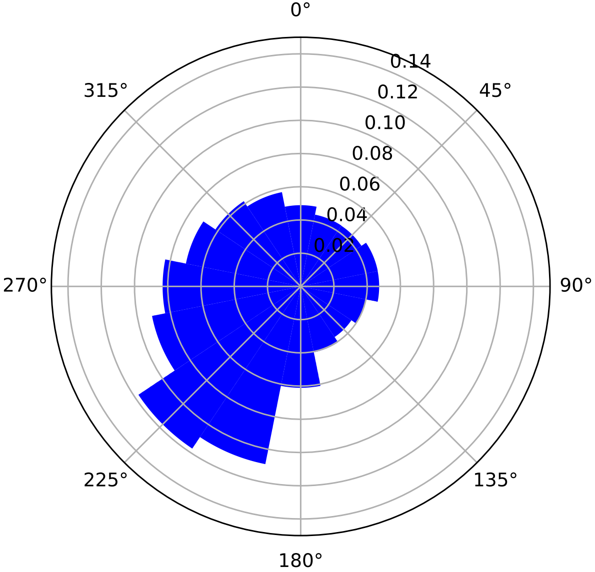
Speed marginal distribution determines power output expectation upper bound

Direction Determines the prevalence of *wakes*, which lower power output

Wind resource: joint distribution (KNW 53.01°N 3.01°E)



Wind resource: wind rose



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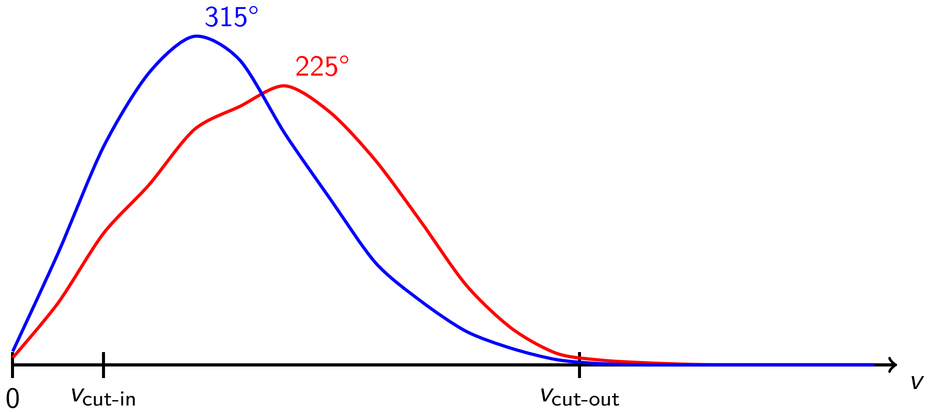
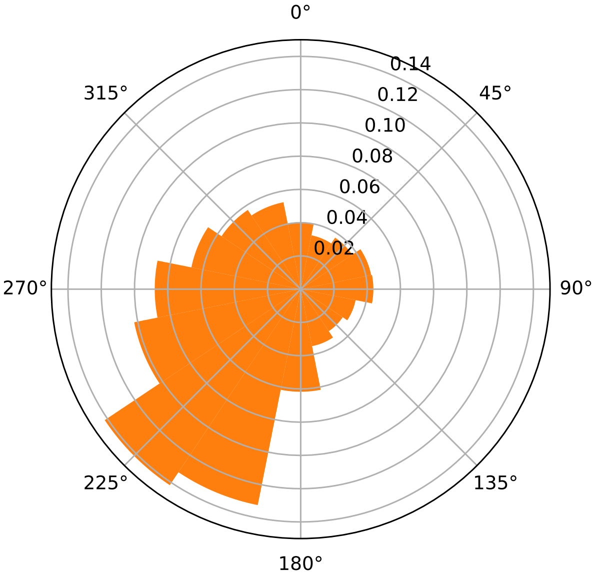
Wind resource: speed distribution



Wind resource: power rose



Wakes

Photo by Christian Steiness / Vattenfall (Horns Rev Offshore Wind Farm, Denmark); http://i.imgur.com/qruVcnu.jpg

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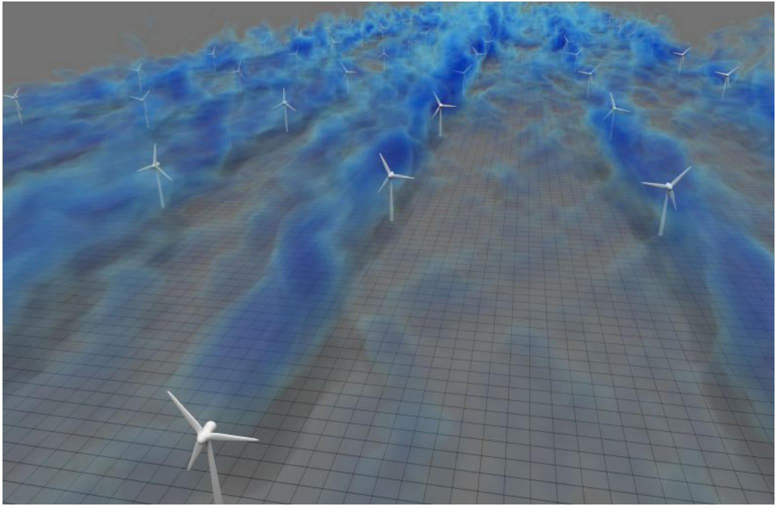
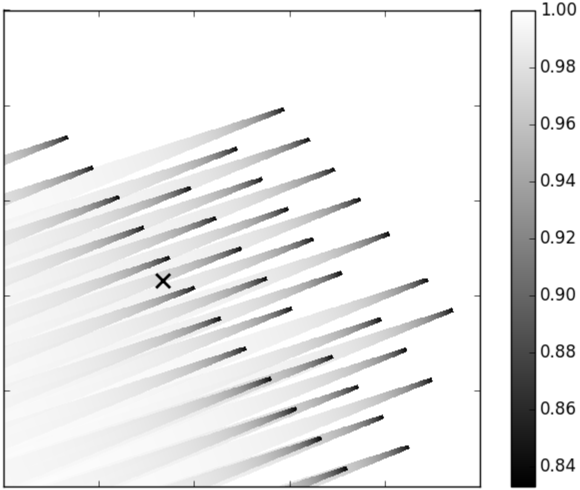
Wakes: CFD



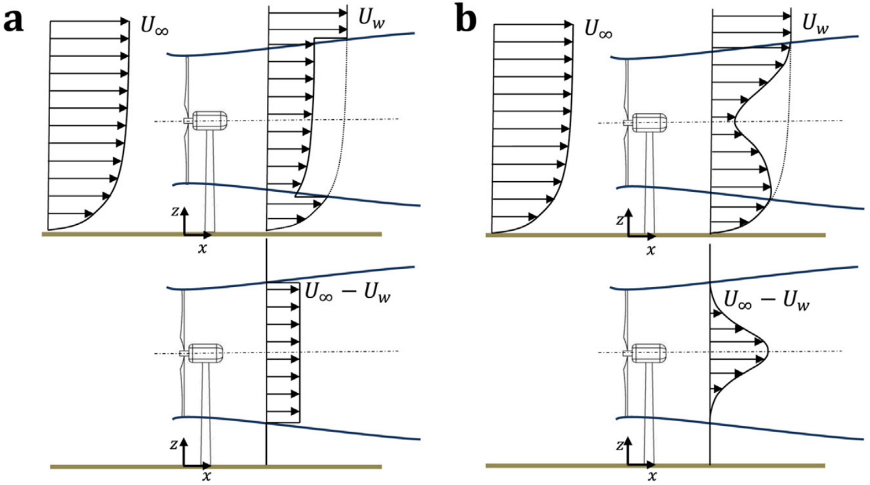
Richard Stevens/UTwente http://stilton.tnw.utwente.nl/people/stevensr/research_windles.html

Wakes: Engineering models



"Estimation of Offshore Wind Energy Production Using Meteorological Data" (2016 student project)
Harms, Heilig, Knyszewski, Van de Krol, Martens, Nachtergaele, Seres, Vakaet, and Wennink.

Wakes: Engineering models (Jensen & Bastankhah–Porté-Agel)



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

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Wakes: Engineering models

Jensen The simplest, most popular wake model:

$$\text{speed deficit in wake} = 1 - \frac{v}{v_\infty} = \frac{\text{induction factor}}{\text{wake radius}} = \frac{1-\sqrt{1-c_\mathrm{t}(v)}}{(1+kd)^2}$$

- d: the downstream distance in rotor radii
- k: the wake expansion factor (sometimes function of c_t)

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Wake variation over rotor area geometrical integration or quadrature

Wake combination root-sum-square of deficits

Return to the optimization objective

The objective:

maximize the *expectation of the power output*

or equivalently

minimize the *relative expectation of the wake power loss*

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Steps:

1. Transform turbine coordinates to downwind/crosswind form for each direction
2. Calculate wake deficits from individual turbines for each wind speed
3. Combine wake deficits
4. Obtain waked speeds at turbines
5. Apply power curve to waked speeds
6. Take expectation over wind speeds and wind directions
7. Average power output over all turbines
8. Convert to loss form

Optimization approaches in the literature

Random search Genetic algorithms, particle swarm optimization, etc.
- Not much domain knowledge is used
- Computationally demanding

Gradient descent Using analytical or numerical gradients
- Domain knowledge used (gradients)
- Very computationally demanding

Mathematical programming Using linear or quadratic model approximations

Exhaustive search Using a discretized site and iterative addition of turbines

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N.B.: Constraint handling is a non-negligible step in the optimization, but underdiscussed in the literature.

Yet another optimization approach

Why? Existing methods are too slow to run the multiple cases needed for uncertainty quantification and robust optimization

How? Combine domain knowledge (per-turbine deficits) with heuristics (emulate gradient-descent)

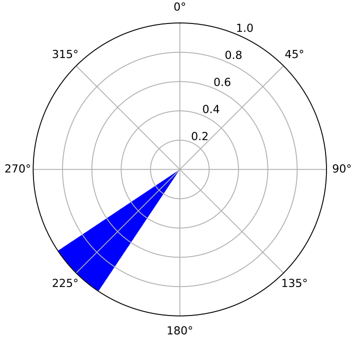
Does it work? Yes, at least an order magnitude faster and resulting in relatively good-quality layouts

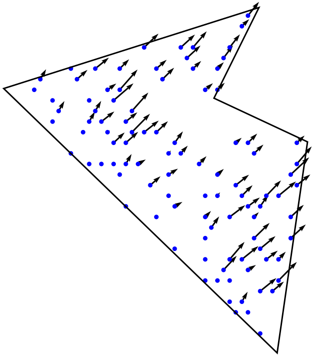
Downsides? Tendency to get stuck in a particular class of local minima

Pseudo-gradients

Basic idea “*Push-down*”

- Multiply the unit vector between an upstream and a downstream turbine by the deficit caused by the upstream one at the downstream one
- Sum over all upstream turbines





Pseudo-gradients

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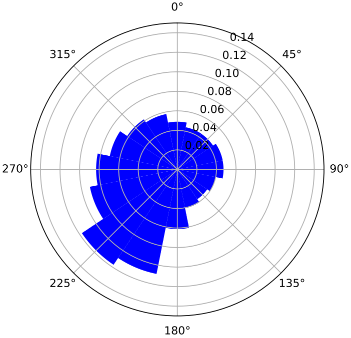
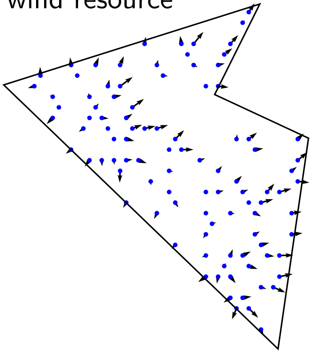
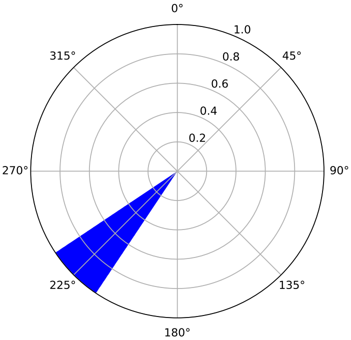


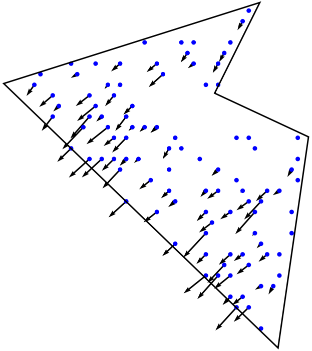


Pseudo-gradients

Variant "*Push-back*"

- Multiply the unit vector between *a downstream and an upstream* turbine by the deficit caused by the upstream one at the downstream one
- Sum over all *downstream* turbines





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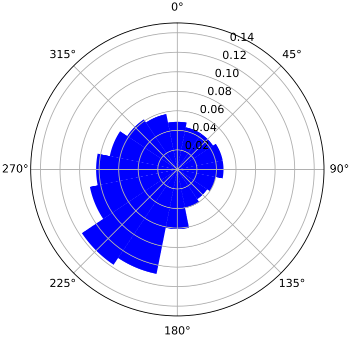

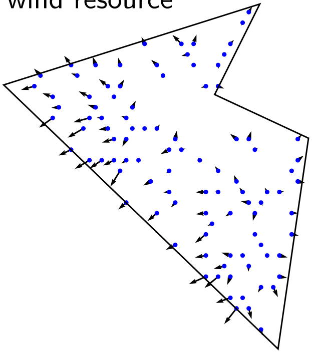

Optimization using pseudo-gradients

Building blocks

- The push-back, push-down, and push-cross steps
- Adaptive step size
- Constraint correction procedures:
  - Move to border if moved outside
  - Pull apart if too close together
- Stopping criterion: step becomes too small

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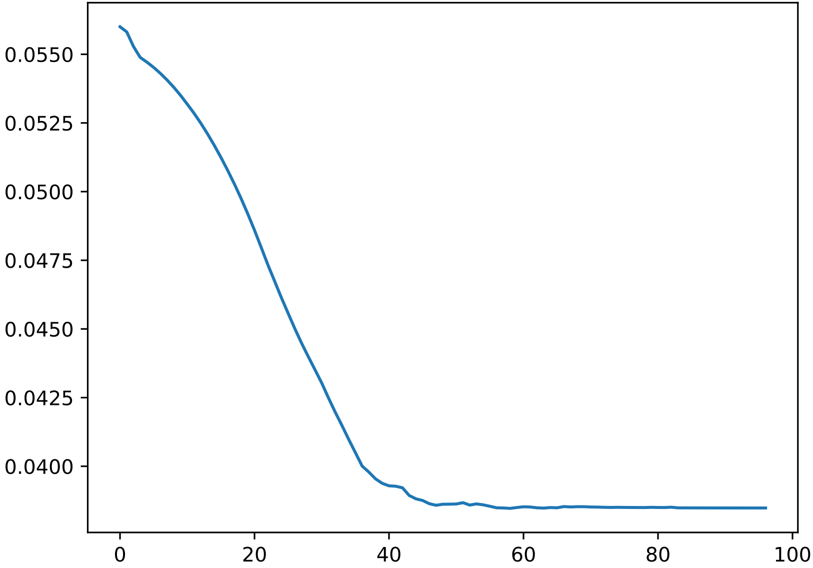
'Pure-down' approach

- Push-down steps only
- Increase step size if objective improves, decrease otherwise

'Multi-adaptive' approach

- Try all three step types concurrently
- Try larger and smaller step sizes concurrently
- Continue with best of the six generated layouts

Optimization using pseudo-gradients: Pure-down



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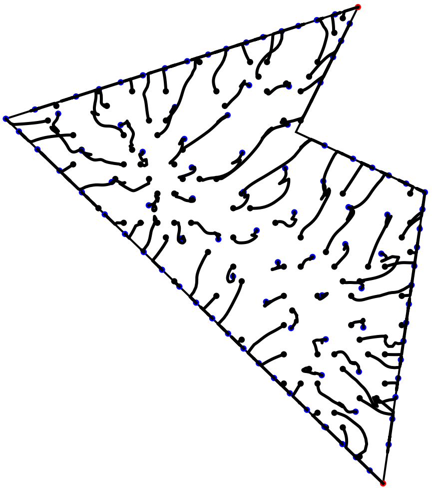
Optimization using pseudo-gradients: Pure-down



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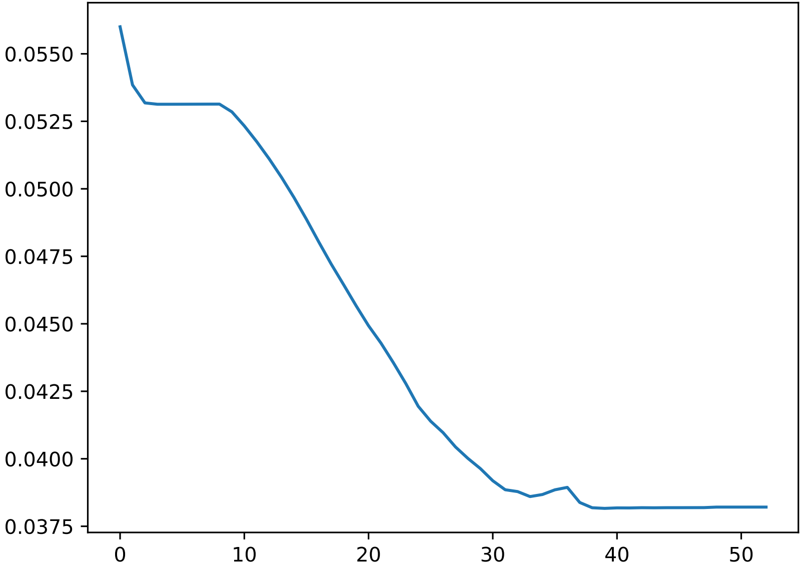
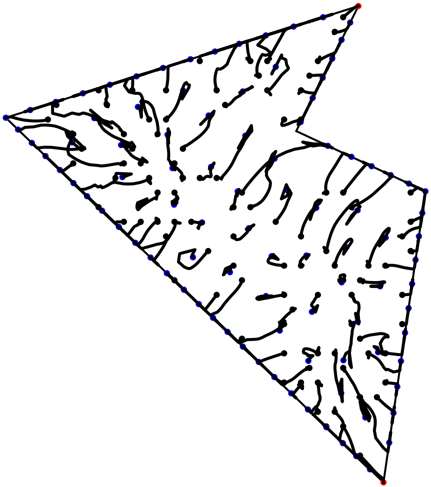


Optimization using pseudo-gradients: Multi-adaptive



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Sources of uncertainty

Wind resource

- Inter-year variation
- Estimation approach to distributions
- Bin size of discretization

Wake model uncertainty

- Which wake model (Jensen, Bastankhah–Porté-Agel,...)?
- Wake model parameters
- Wake at hub or integrated over rotor plane?

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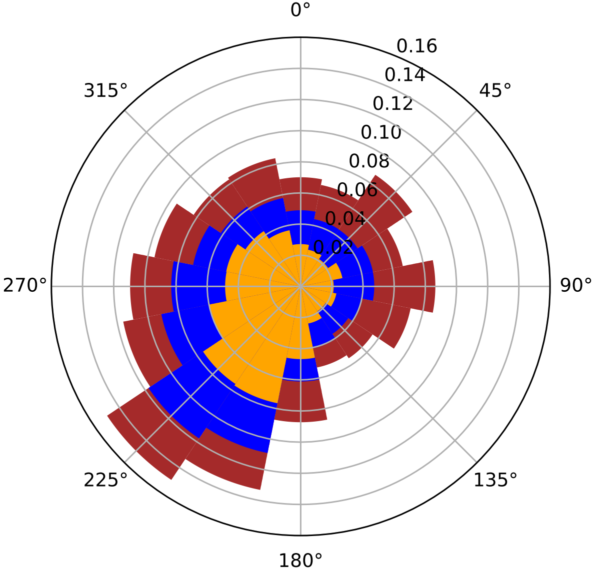
Inter-year variation in the North Sea

KNW dataset

- KNMI hindcast dataset
- 35 years of hourly data for locations in and around the Netherlands
- Picked point in the middle of the North Sea, at 53.01°N 3.01°E
- Used wind direction and wins speed ‘measurements’ at 100 m
- Created wind resource for
  - the whole period,
  - each year, and
  - lower and upper envelopes of those

Inter-year variation in the North Sea: wind rose variation



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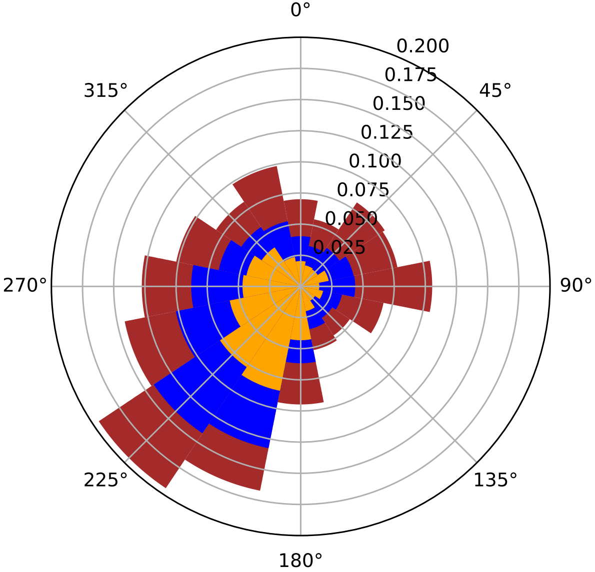
Inter-year variation in the North Sea: power rose variation



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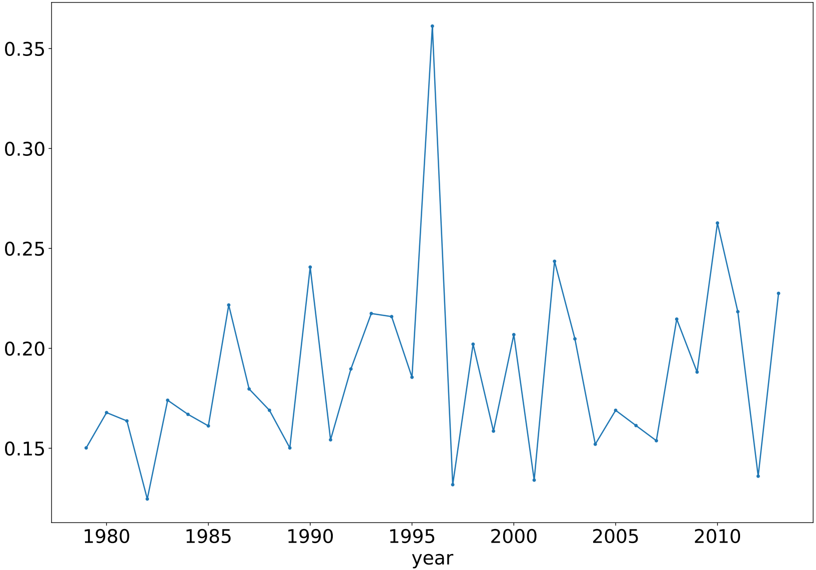

Robust optimization investigation

Setup

1. Optimize the layout against all wind roses created
2. Evaluate the optimized layouts against all other wind roses (except lower and upper envelopes)
3. Get a view on variation
4. Determine if average, lower, or upper windrose provides more robust layout

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Results

- absolute wake loss expectation varies *very* little over layouts
- the upper windrose seems to provide a more robust solution

Conclusions & Plans

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- It is possible to create faster wind farm layout optimization approaches than the ones used
- Inter-year wind rose variation is non-negligible per se
- The necessity of robust optimization has however not been demonstrated

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Plans

- Add layouts to comparison:
  - one optimized against the uniform wind rose
  - others optimized using different approaches
  - non-optimized ones
- Quantify effect of wake model uncertainty

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