Robust wind farm layout optimization using pseudo-gradients

NWO Applied and Engineering Sciences

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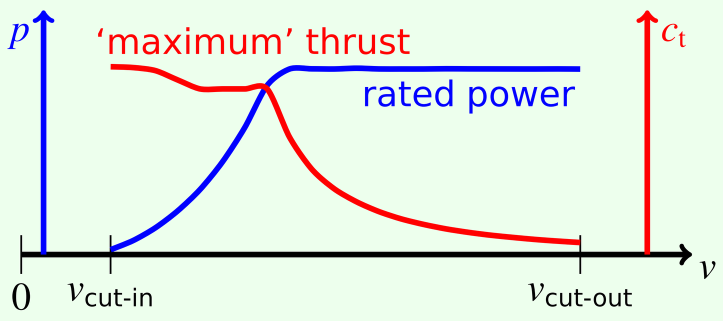
1 Wind energy systems

A **wind energy system** transforms wind into electrical power.

1.1 Wind turbines

Wind turbines (*picture left*) are the elementary wind energy systems. Important characteristics are its **rated power**, **rotor diameter**, and **hub height**.

A high-level model consists of the **power curve** and the **thrust curve**, which map wind speed at hub height to power and force exerted on the wind (*plot above right*).

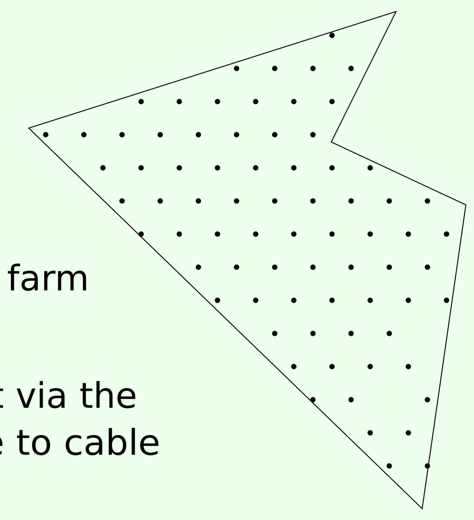


1.2 Wind farms

Wind farms are collections of wind turbines constrained to a specific **site** (*picture left*).

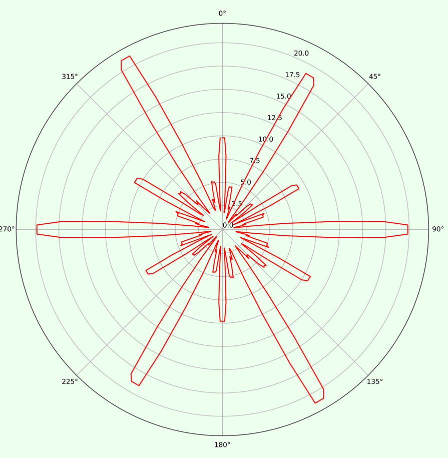
The placement of turbines within a farm is its **layout** (*drawing right*).

The layout influences the farm cost via the cabling and substructure cost, due to cable layout and depth & soil variations.



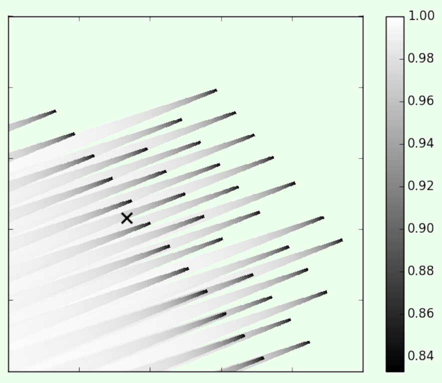
1.3 Wake losses

Wakes are regions of complexly perturbed wind behind turbine rotors (*picture right*).



Computationally simple **engineering wake models** are used when calculating farm power output (*simulation below right*).

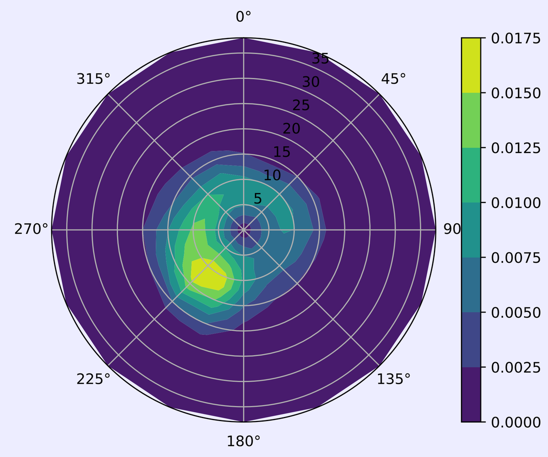
In a farm, wakes may reduce the wind speed at downstream turbines, causing lower power production: **wake losses**. Wake **wind speed deficits** for a given layout depend on the wind direction (*plot above, corresponds to layout shown in Section 1.2*).



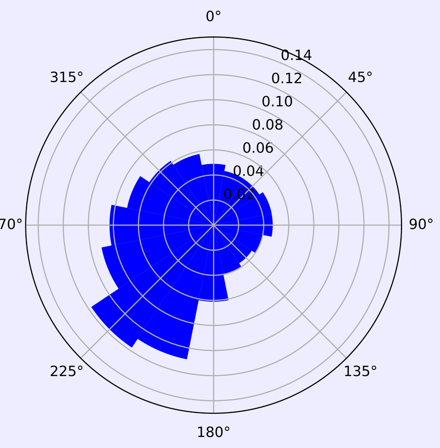
2 Wind resources

A **wind resource** is the wind available at a wind farm site.

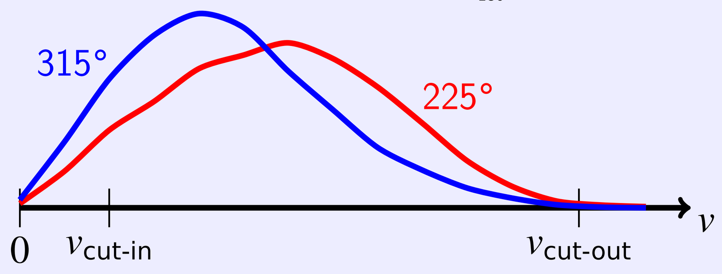
2.1 Wind direction & speed distributions



The minimal wind resource description required is a **joint wind direction & speed distribution** (*plot left*); there is a dependency between both components.



This joint is decomposed into the **wind rose**, the wind direction marginal (*plot above right*), and per-direction wind speed conditionals (*plot right*), for which Weibull distributions are often used.

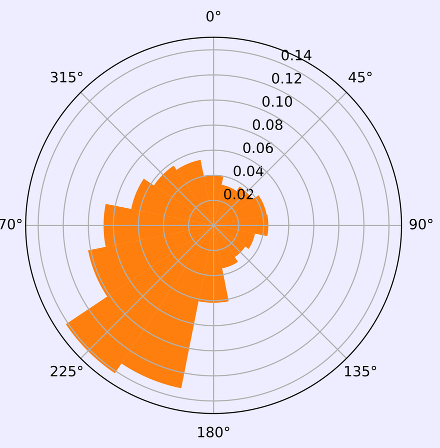


2.2 Annual energy production of a wind farm

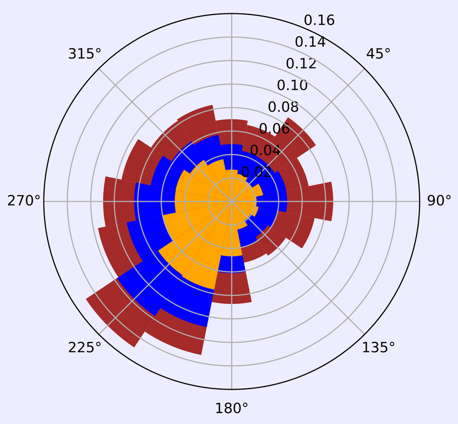
An essential quantity in the design of a wind farm is its **annual energy production (AEP)**: the electrical energy produced by a farm for a given wind resource.

Equivalent is the **capacity factor**, the ratio between the expected average power production and the farm's rated power.

Also of interest is the **power rose**, the distribution over wind directions of relative wakeless power production (*plot right*).

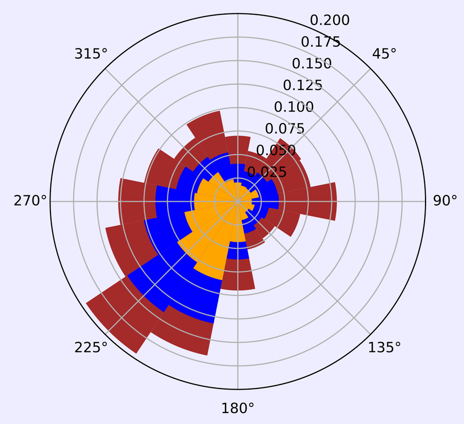


2.3 Inter-year wind resource variation



We consider **35 yearly wind resources** for a North Sea site from the Dutch meteorological institute's 'KNW atlas' (plot left: orange lower, blue average, and red upper wind roses for this set of distributions; plot right: corresponding power roses).

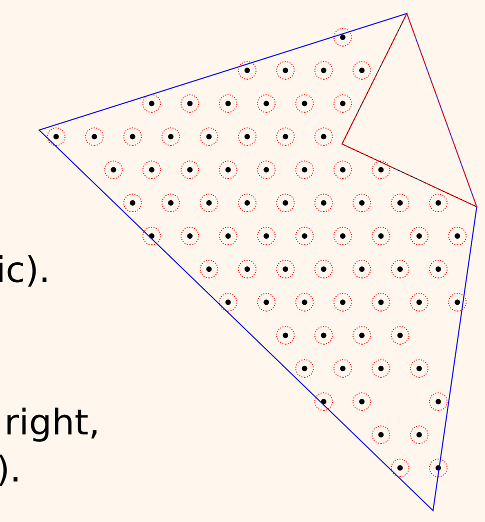
Note the substantial variation.



3 Wind farm layout optimization

3.1 Objectives

- **AEP**: Maximize for expected power production only (used in our study).
- **LCoE**: Minimize **levelized cost of energy**, the ratio between farm cost and power production (more realistic).



3.2 Constraints

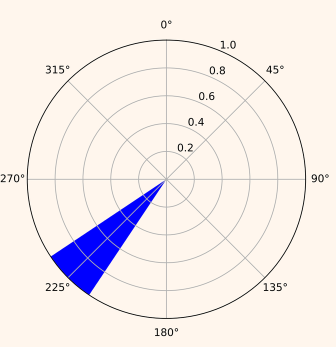
Turbines in a farm must satisfy a **distance constraint** (drawing right, red circles) and **site constraints** (drawing right, red & blue lines).

3.3 Typical layout optimization algorithms

type	gradient-based	heuristic (usually random search-based)
examples	steepest ascent	evolutionary, genetic, particle swarm
pros	high-quality solutions	flexible (generic)
cons	computationally expensive, can get stuck in local optima, problem-specific preparation	computationally expensive, does not use domain knowledge, low-quality solutions

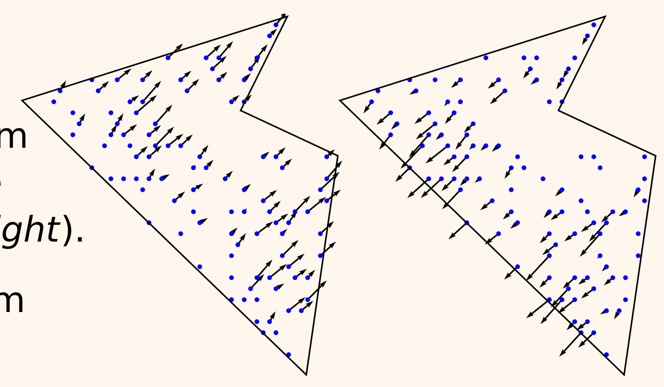
Computational cost is crucial in robustness studies, so **we developed a fast heuristic approach that uses domain knowledge and produces medium-quality solutions**.

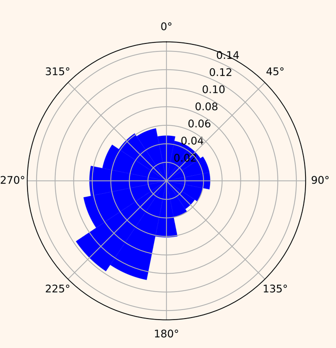
3.4 Pseudo-gradient-based optimization



For one wind direction (*plot left*), the power deficit of a downstream turbine due to an upstream one determines a vector. Average over all upstream turbines (*plot right*).

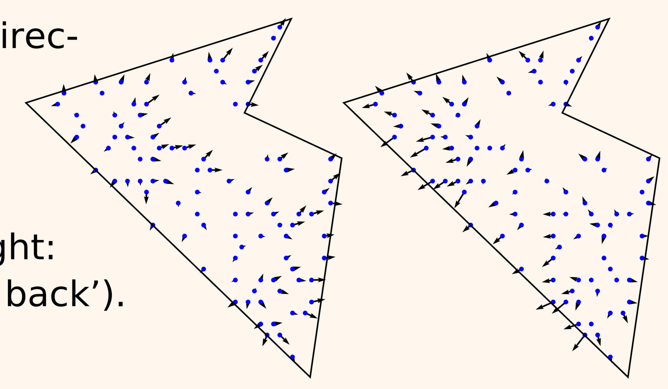
Variant: vectors pushing upstream turbines 'back' (*plot far right*).



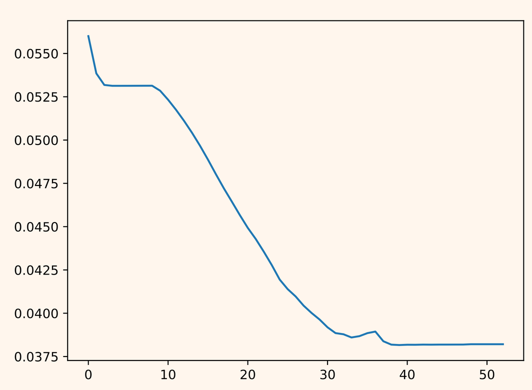


Taking the expectation over all directions (*plot left*) gives '**pseudo-gradients**' usable in a local gradient ascent-type algorithm.

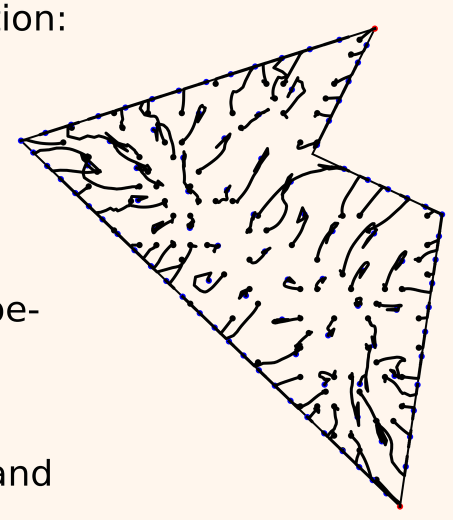
Applicable to all variants (plot right: 'push down'; plot far right: 'push back').



We have created a layout optimization **algorithm** that each iteration:



- uses an **adaptive step size**,
- considers pseudo-gradients for each of the variants,
- **greedily moves turbines** according to the best one, and
- **corrects constraint violations** between steps by iteratively moving turbines to satisfying positions.



We obtain good convergence (*plot above left, relative wake loss*) and medium-quality layouts (*drawing above right, turbine trajectories*).

4 Inter-year variation robustness

A wind farm's layout is usually optimized for one wind resource, the estimated average one over the farm lifetime. However, inter-year production stability is important for the financial attractiveness of a farm design. **Making a farm robust against inter-year wind resource variation** is therefore of practical interest.

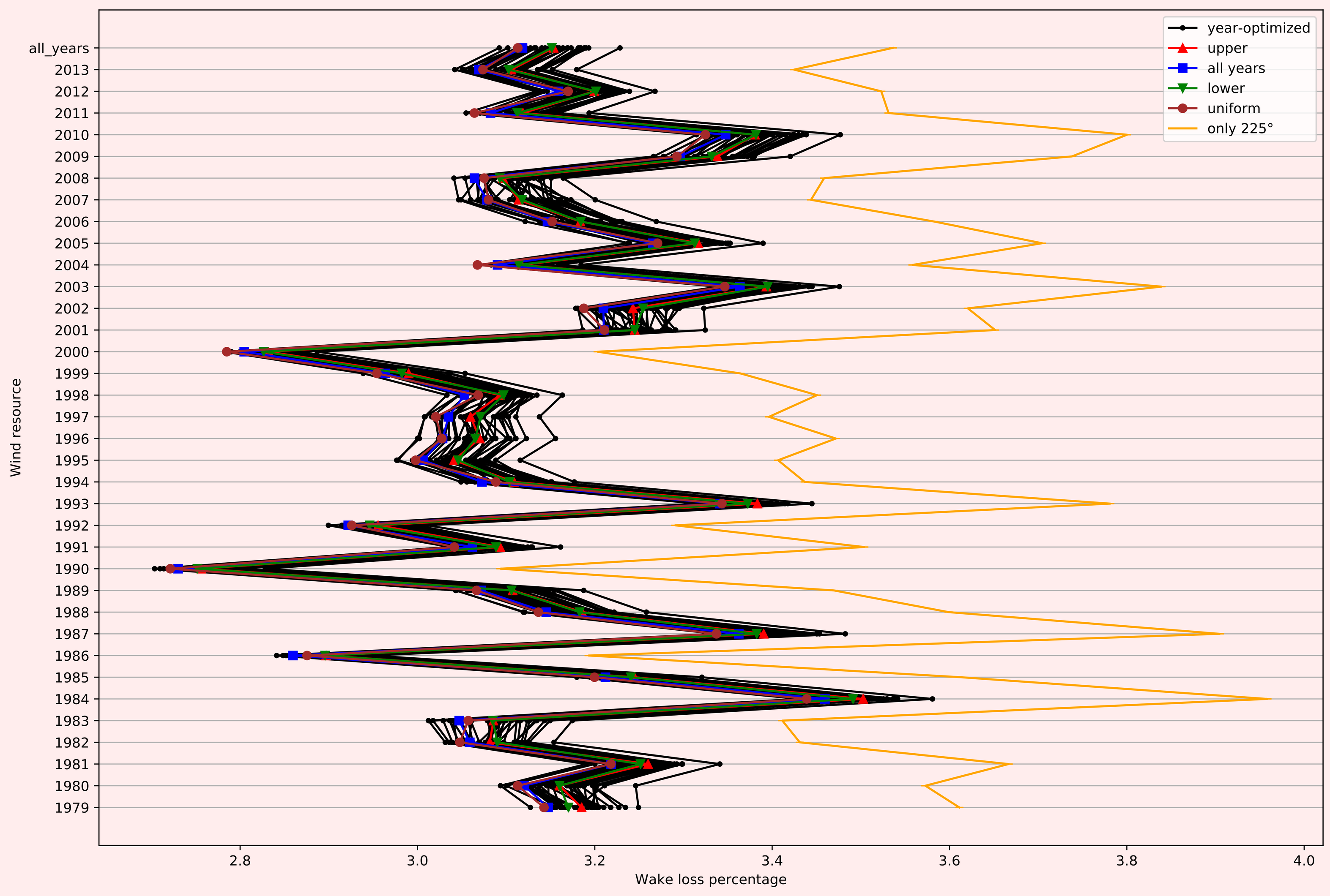
4.1 Goals

- Quantify inter-year wind resource variation (done).
- Quantify inter-year AEP variation (done).
- Determine existence of robust farm layouts (partly done).
- Develop robust layout optimization algorithm (not yet done).

4.2 Setup

- Realistic test site.
- Realistic & extensive set of yearly wind resources.
- Create optimized layout for
  - a degenerate wind resource ('225°'),
  - the uniform wind resource,
  - each wind resource in the set,
  - their average,
  - their lower & upper envelopes.

4.3 Results



4.4 Conclusions

- Inter-year variation is substantial.
- Observed inter-year variation is larger than inter-layout differences.
- The set of layouts with undominated production profiles is relatively small.
- No real trade-off achieved yet between robustness and optimality.

4.5 Recommendations

- Create a more diverse set of layouts:
  - by varying the optimizer parameters,
  - by using different optimization algorithms.
- Try out ideas for robust optimization:
  - by each iteration using the maximin solution over wind resources,
  - by following **your suggestion**.