Mathematical optimization for offshore wind farm design

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Myself

Double degree in **Automation Engineering** from Padova University (Italy) and Aalborg University (Denmark)

Industrial **PhD in Operational Research**: Collaboration between Technical University of Denmark (DTU Management) and Vattenfall BA Wind

Now Lead Engineer in Operations Research Vattenfall BA Wind

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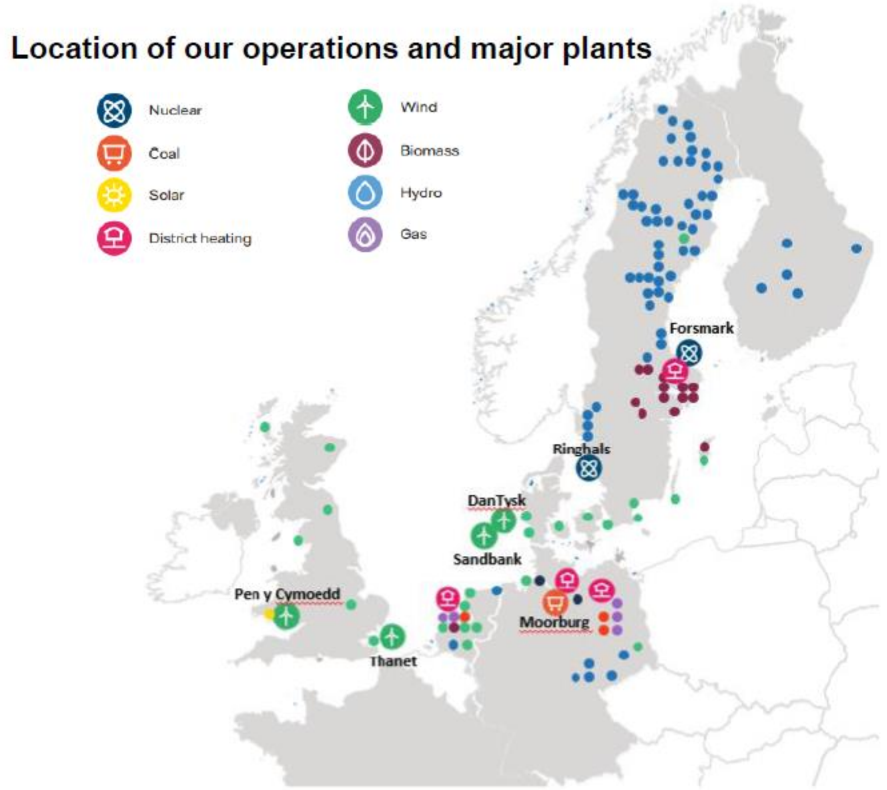
Awards

- 2020 **YoungWomen4OR**
- 2020 **Winner of BIRD (Best young Italian Researcher in Denmark)**
- 2019 **Glover-Klingman prize 2018**
- 2019 **Winner of the EURO Doctoral Dissertation Award (EDDA)**
- 2019 **Finalist for the INFORMS Franz Edelman Award**
- 2019 **Erhvervsforskerprisen (Best Industrial Ph.D.) from Innovation Fund Denmark**
- 2018 **AIRO Best Application Paper Award 2018**
- 2018 **Finalist for EURO Excellence in Practice Award**
- 2017 **Best student paper award at ICORES**

Vattenfall

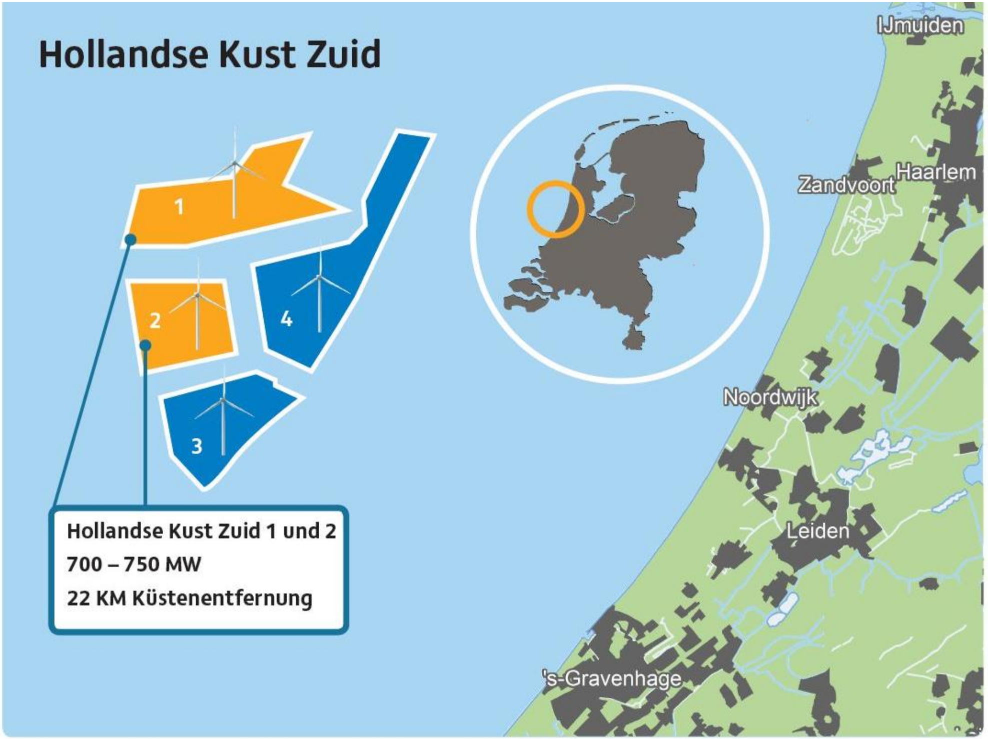
Key data

- One of Europe's largest producers of electricity and heat
- Owned by the Swedish state
- Main products: electricity, heat, gas and energy services
- Main markets: Sweden, Germany, Netherlands, Denmark and the UK
- About 20,000 employees




Fossil-free within
one generation

Strong competition



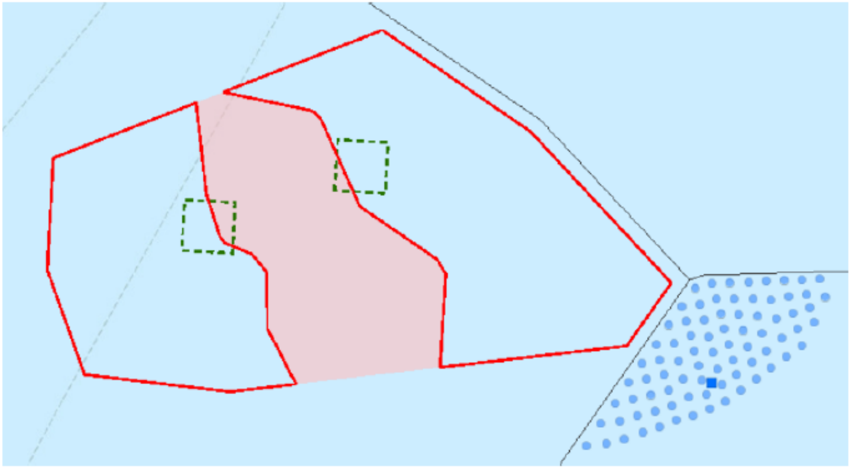
"<u>Innovation and competition</u> are making sustainable energy cheaper and cheaper, and much faster than expected too."

Eric Wiebes - Dutch Economic Affairs and Climate Minister, 2018

OR for more competitive bids

OR-based tools for

- Wind farm layout optimization
- Cable routing optimization



M. Fischetti, and D. Pisinger (2018). Mathematical Optimization for offshore wind farm design: an overview. Business and Information Systems Engineering.

M. Fischetti (2018) Mathematical Programming Models and Algorithms for Offshore Wind Park Design, PhD thesis, DTU Management & Vattenfall

OR for more competitive bids

OR-based tools for

- **Wind farm layout optimization**
- Cable routing optimization

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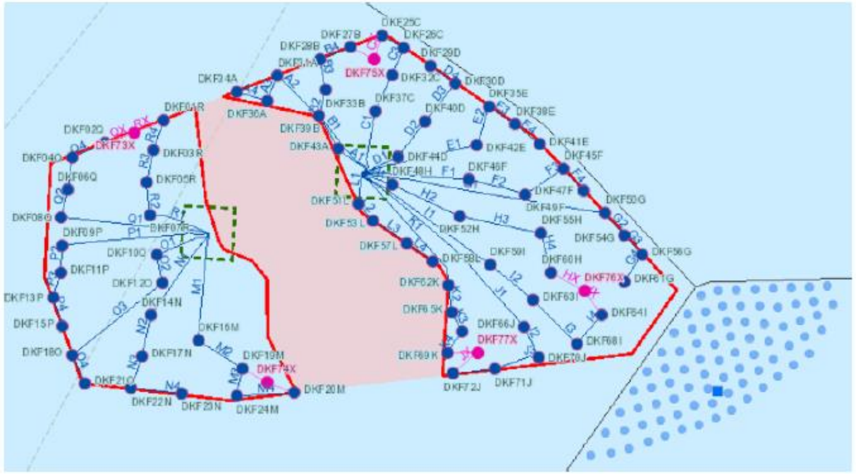
OR for more competitive bids

OR-based tools for

- Wind farm layout optimization
- **Cable routing optimization**



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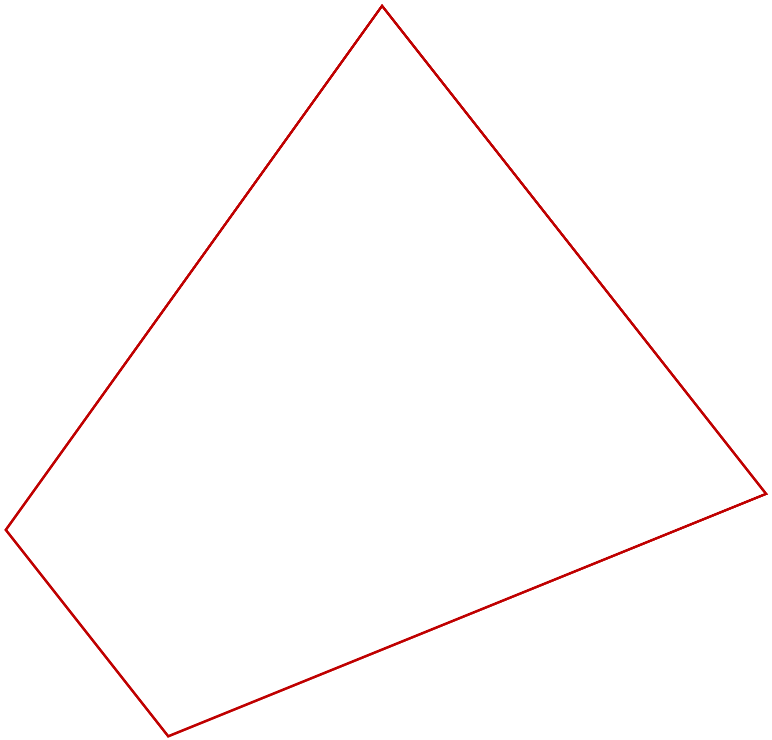
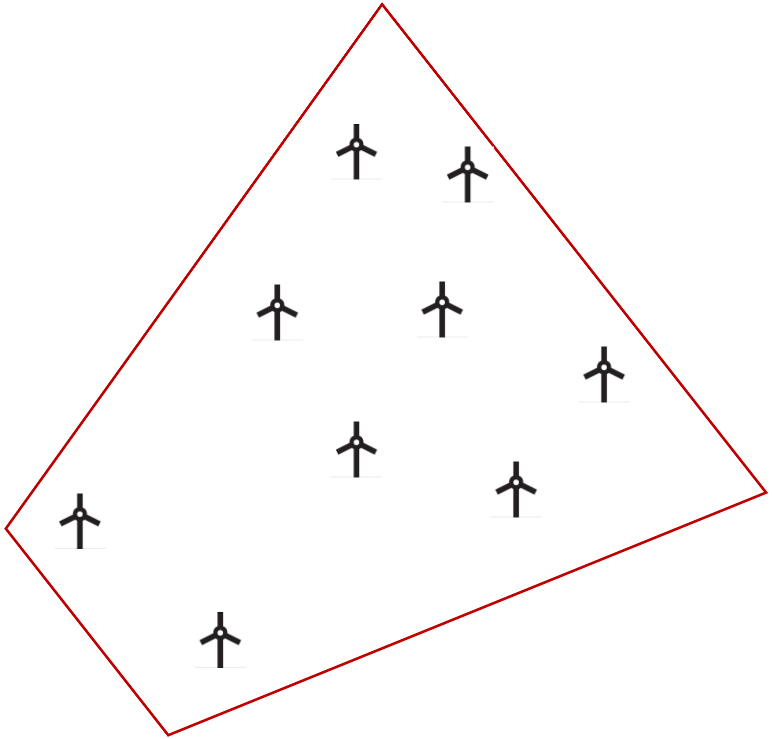
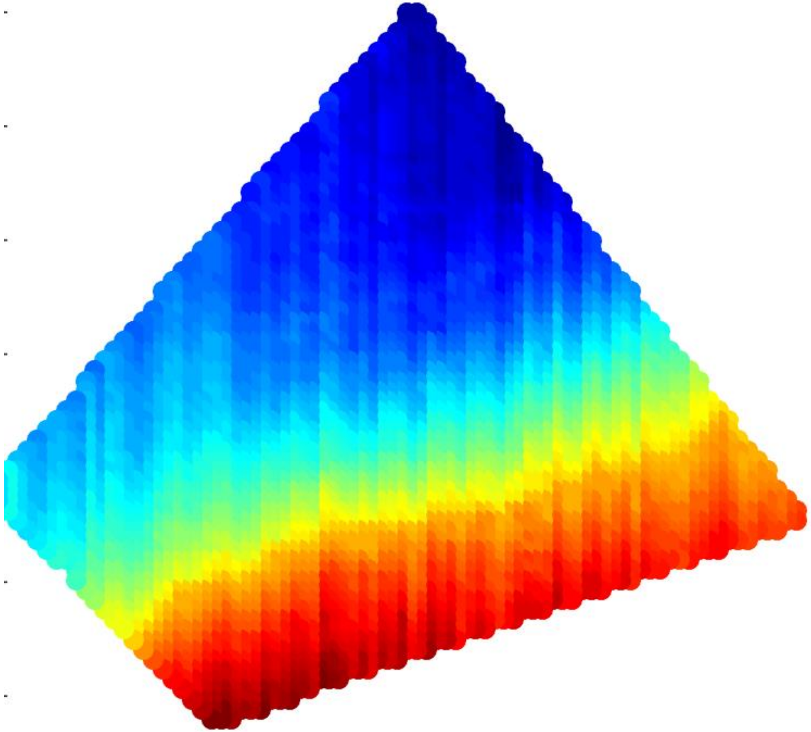
Turbine layout optimization

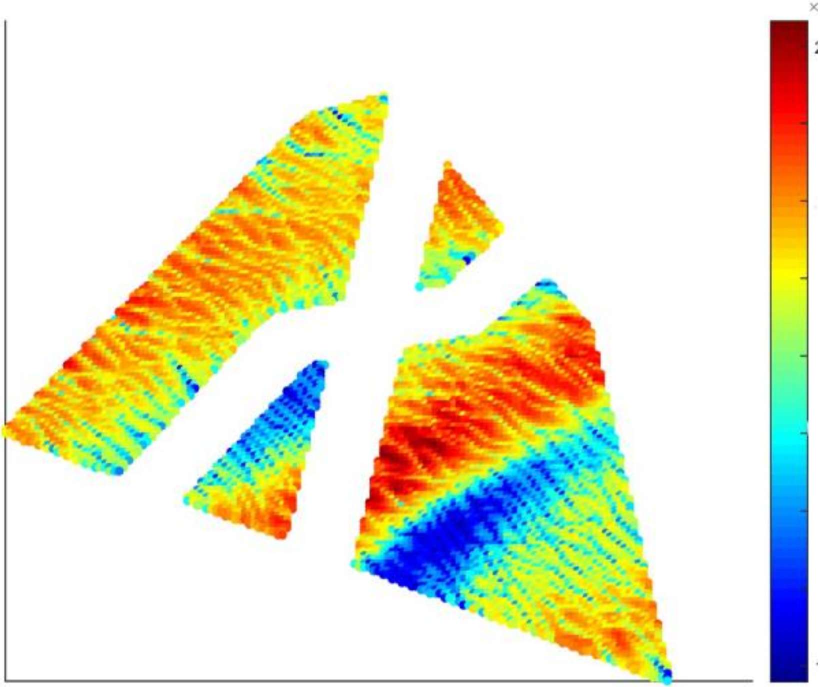






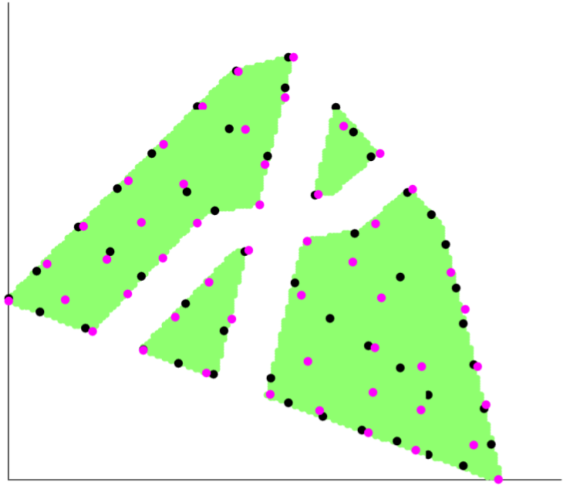
Martina Fischetti, and Michele Monaci, Proximity search heuristics for wind farm optimal layout, Journal of Heuristics (2016), Volume 22, Issue 4, pp 459–474

Impact in practice



Area available - Cost map

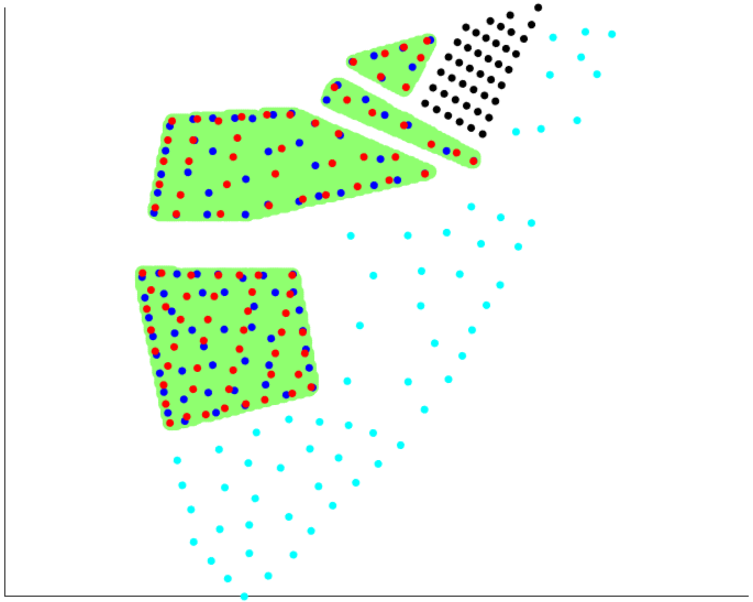
Impact in practice



Optimized layout considering wake effect and costs of foundations (black) versus ”manual” layout (pink)

Company experts certified that our layout allows for an extra 0.28% production while decreasing cost of foundations of more than 10M euro.
All in all, they estimated an increased income of **12.6Meuro in 25 years**.

Impact in practice



Our layout (red) allowed for a higher annual energy production: this difference has been evaluated to be worth **10.2 M euro** (Net Present Value) over the park lifetime.

M. Fischetti, J. R. Kristoffersen, T. Hjort, M. Monaci, and D. Pisinger. Vattenfall optimizes offshore wind farm design. INFORMS Journal on Applied Analytics (2019)

A new data-driven process

- Big savings
- Faster
- Streamlined & standardized process
- What-if analyses

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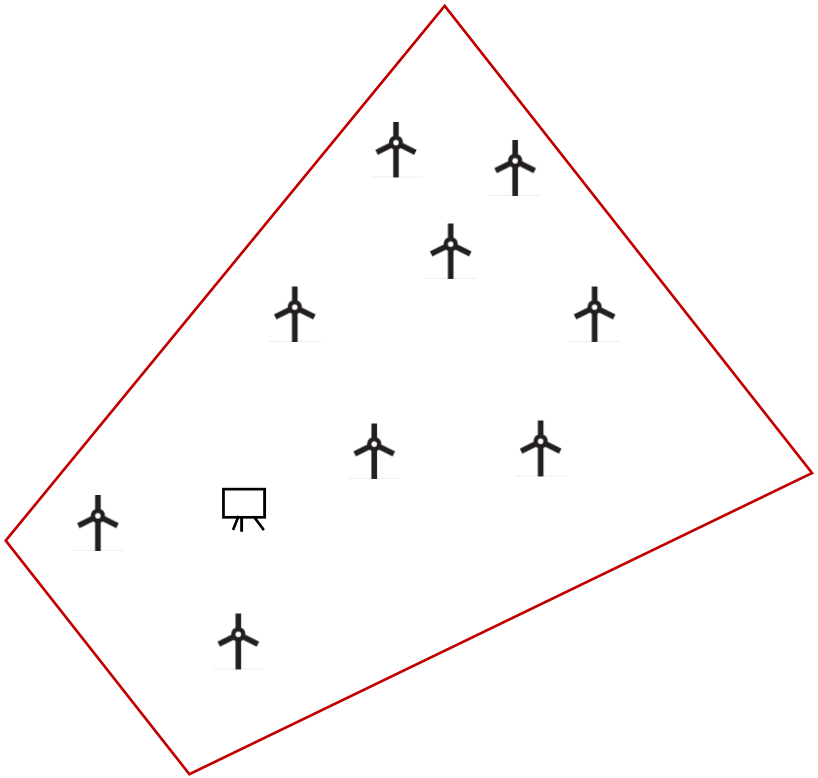
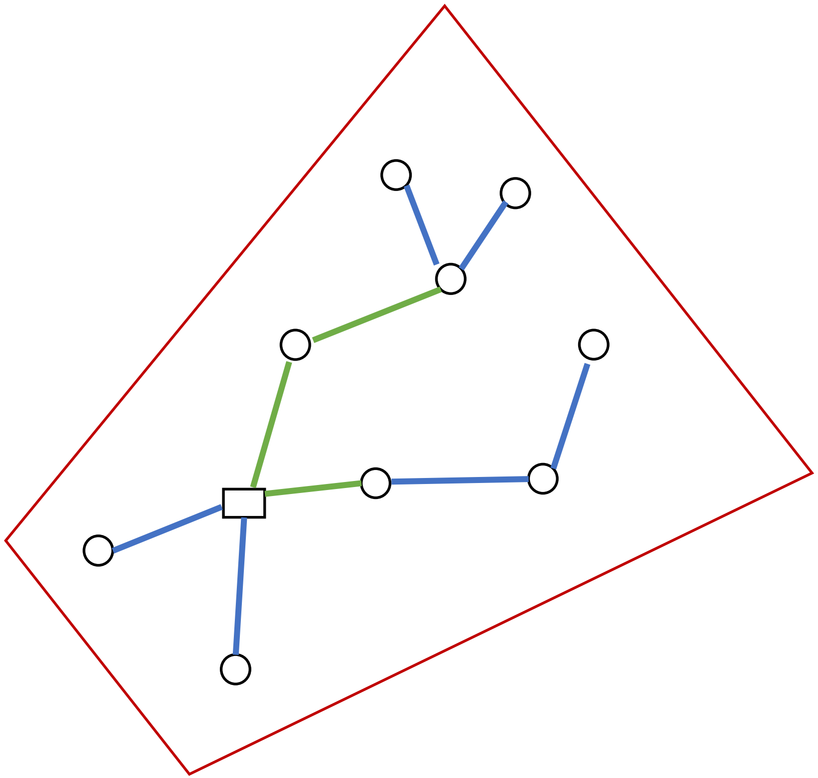
Cable routing optimization





Fischetti, M., Pisinger, D. Optimizing wind farm cable routing considering power losses. European Journal of Operational Research 270(3), 917-930 (2018)

Results

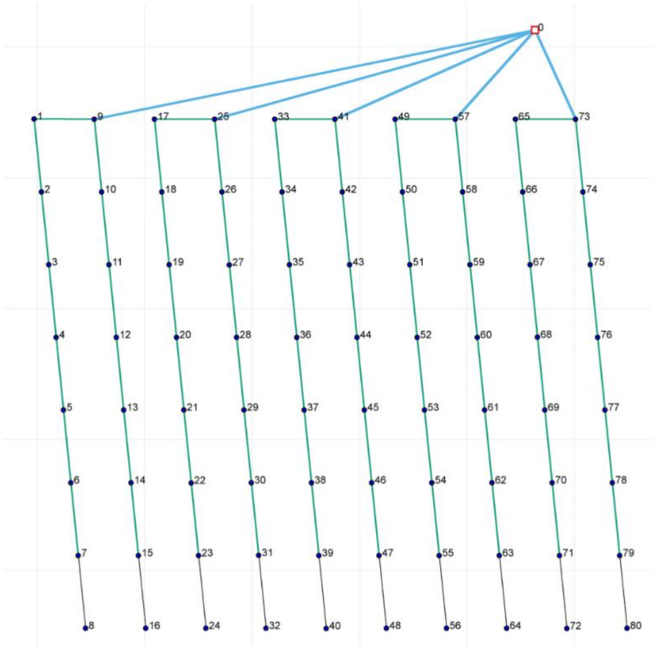


Figure: Existing cable routing for the wind farm Horns Rev 1 in Denmark

Cable data:

- Black: supports 1 turbine, 345€ /m (CAPEX)
- Green: supports 8 turbines, 385€ /m (CAPEX)
- Blue: supports 16 turbines, 500€ /m (CAPEX)

Results

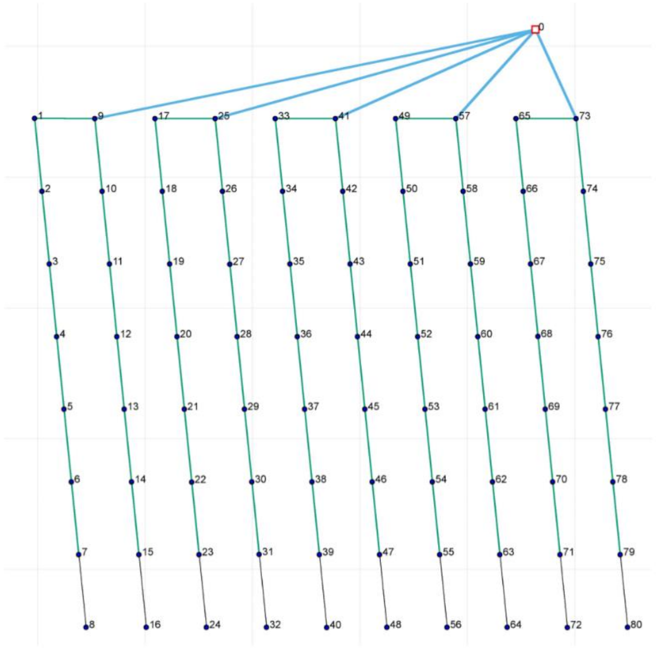
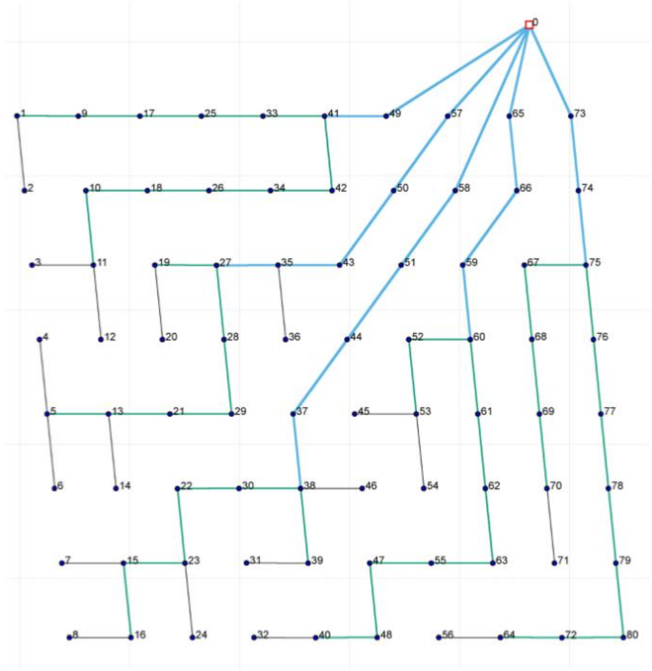


Figure: Existing cable routing for the wind farm Horns Rev 1 in Denmark

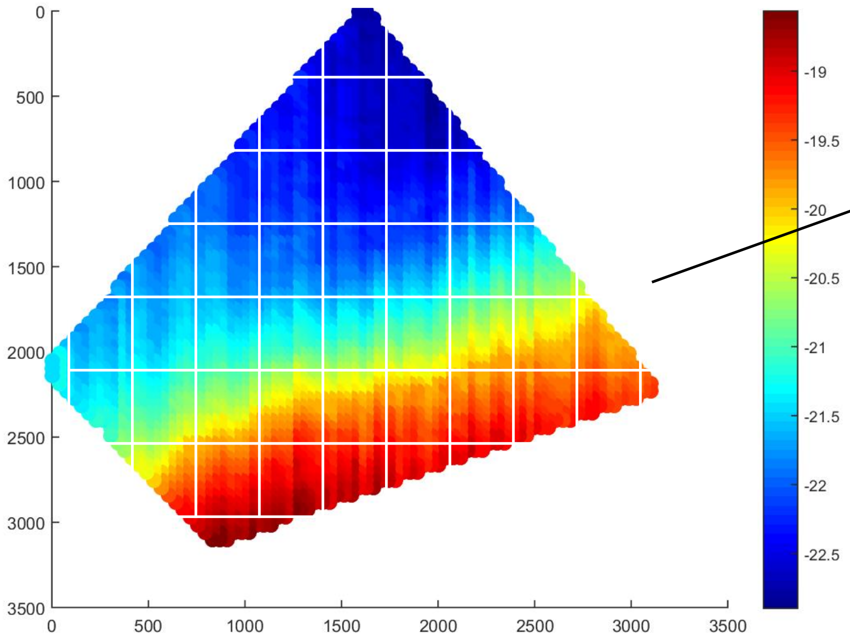


Optimized:
- 1.5 M€

Thanks

Extra

Mathematical model



The layout problem can be formulated as a MIP problem.
Variables:

$$x_i = \begin{cases} 1 & \text{if a turbine is built at position } i \in V; \\ 0 & \text{otherwise} \end{cases} \qquad (i \in V)$$

where V is the set of potential turbine positions.

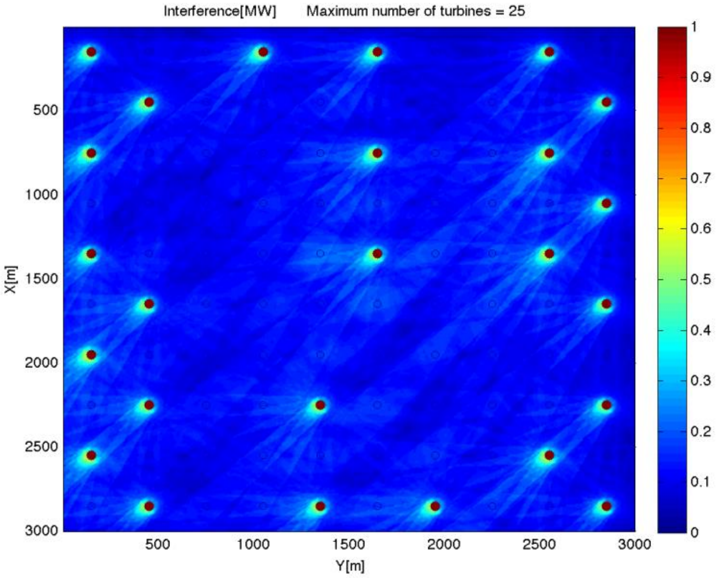
Mathematical model

$$
\begin{array}{lll}
\max & \sum_{i\in V}[(P_i - \frac{c_i}{K_{euro}})x_i - w_i] & \\
\text{s.t.} & N_{MIN} \le \sum_{i\in V} x_i \le N_{MAX} & \\
 & x_i + x_j \le 1 & \forall \text{ incompatible } i,j \in V, i<j \\
 & \sum_{j\in V} I_{ij}x_j \le w_i + M_i(1-x_i) & \forall i \in V \\
 & x_i \in \{0,1\} & \forall i \in V \\
 & w_i \ge 0 & \forall i \in V
\end{array}
$$

where $M_i >> 0$ (big-M).

$$
w_i := \left(\sum_{j\in V} I_{ij}x_j\right) x_i = \begin{cases} \sum_{j\in V} I_{ij}x_j & \text{if } x_i = 1; \\ 0 & \text{if } x_i = 0 \end{cases}
$$

Stochastic programming



It is important to consider wind variability!

Hundred thousands wind scenarios in practice

Layout optimization - matheuristics

Why?

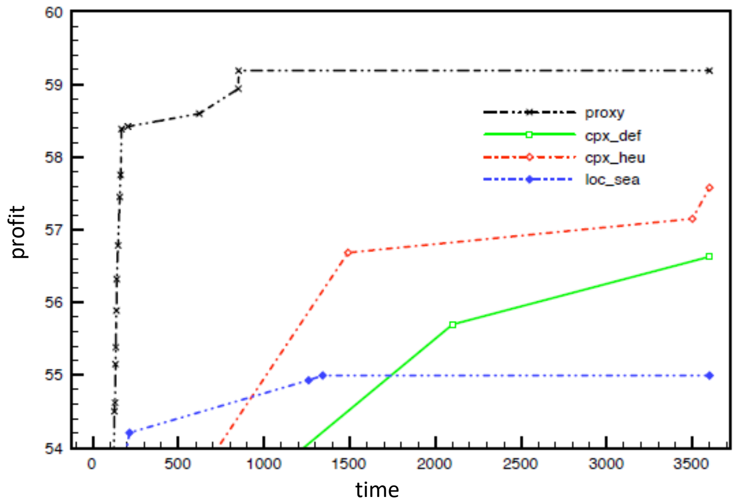
- To solve instances with 20,000+ possible positions

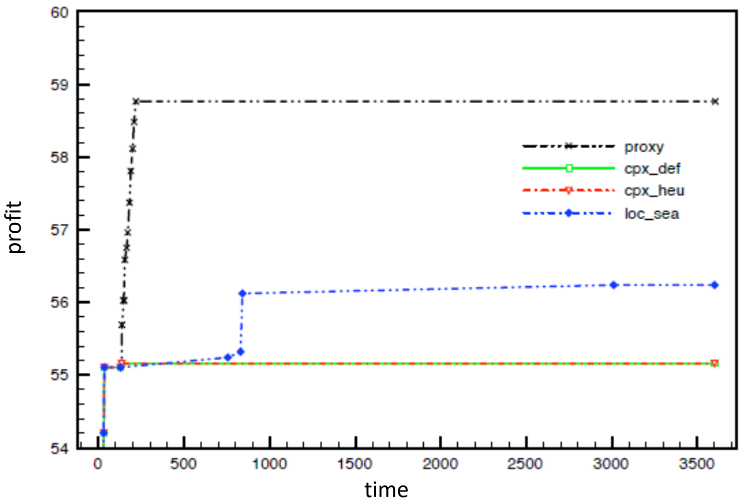
How?

- Ad-hoc heuristics
- MILP-based heuristics (Proximity Search)

Idea: Given an initial (heuristic) solution, explore its neighbourhood using the MILP solver as a black box

Layout optimization - matheuristics

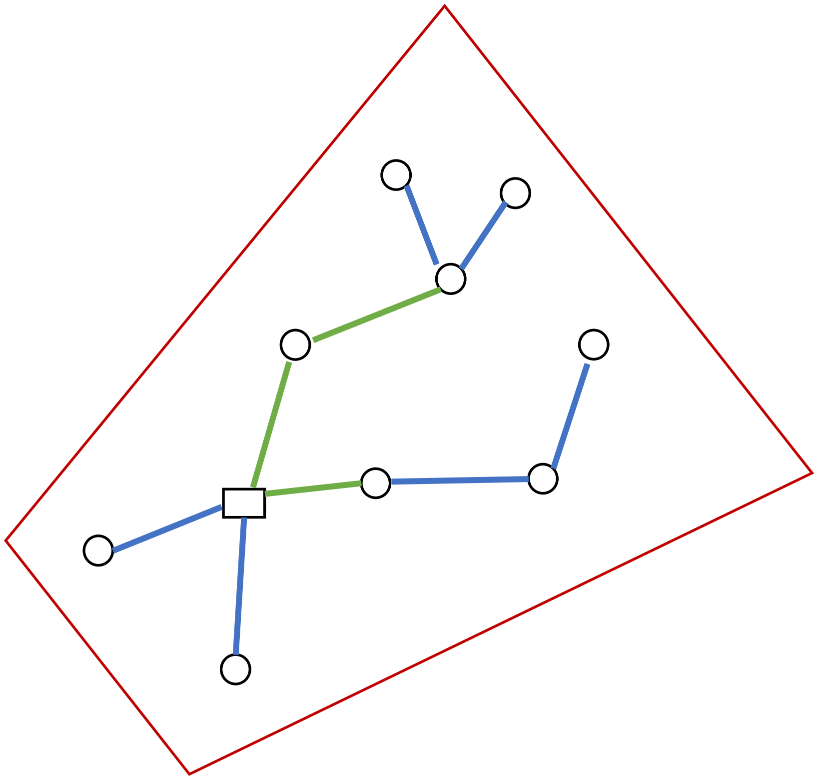




Solution profit over time for 2 sample instances with 5000 (left), and 10,000 (right) possible positions; the higher the profit the better.

M. Fischetti and M. Monaci (2016). Proximity search heuristics for wind farm optimal layout. Journal of Heuristics 22 (4), pp. 459-474.

Mathematical model

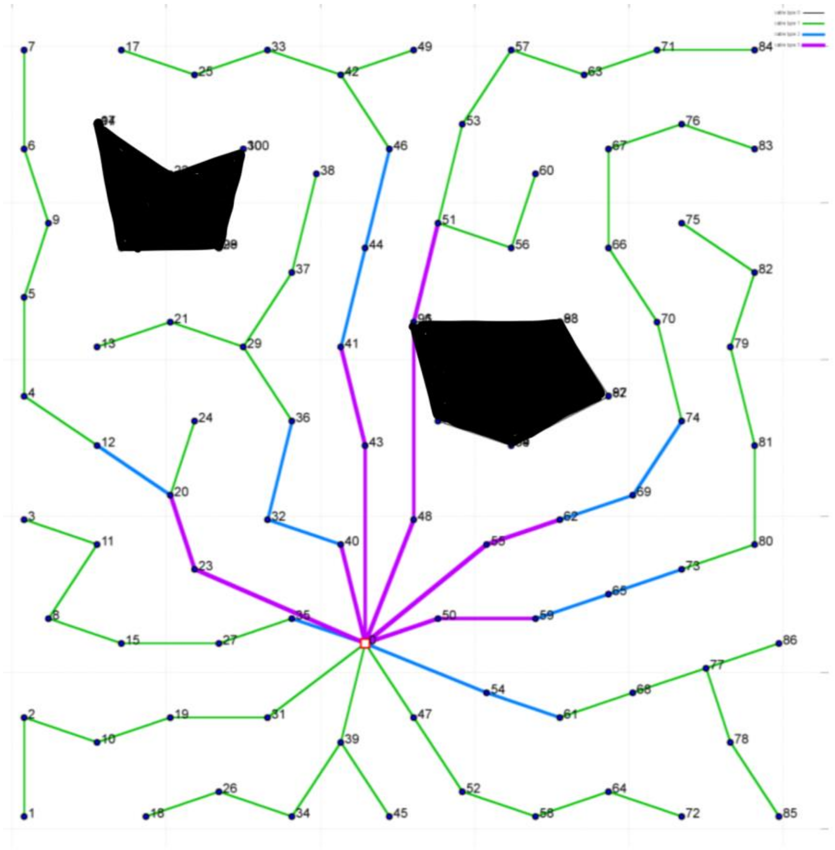


VARIABLES (on the arcs):
$f_{i,j} \geq 0$ is the flow (current) from i to j

$$x^t_{i,j} = \begin{cases} 1 & \text{if arc } (i,j) \text{ is built with cable } t \\ 0 & \text{otherwise} \end{cases}$$

$y_{i,j} = 1$ if an arc from i to j is built, with any type of cable $(\sum_{t \in T} x^t_{ij} = y_{ij})$

Cable routing - MILP formulation



Limitations:

- Only one cable can exit a turbine
- Capacity
- **No cable-crossings**
- Obstacles
- Maximum number of connections to the substation(s)
- Cable losses

Cable routing - MILP formulation

$$
\begin{array}{lll}
\text{min} & \sum_{i,j\in V}\sum_{t\in T} c_{i,j}^t x_{i,j}^t & \\
\text{s.t.} & \sum_{t\in T} x_{i,j}^t = y_{i,j} & i,j\in V : j\neq i \\
 & \sum_{i:i\neq h}(f_{h,i} - f_{i,h}) = P_h & h\in V_T \\
 & \sum_{t\in T} k_t x_{i,j}^t \geq f_{i,j} & i,j\in V : j\neq i, \\
 & \sum_{j:j\neq h} y_{h,j} = 1 & h\in V_T \\
 & \sum_{j:j\neq h} y_{h,j} = 0 & h\in V_0 \\
 & \sum_{i\neq h} y_{i,h} \leq C & h\in V_0 \\
 & x_{i,j}^t \in \{0,1\} & i,j\in V, t\in T \\
 & y_{i,j} \in \{0,1\} & i,j\in V \\
 & f_{i,j} \geq 0 & i,j\in V, j\neq i
\end{array}
$$

No-crossing constraints are separated on the fly

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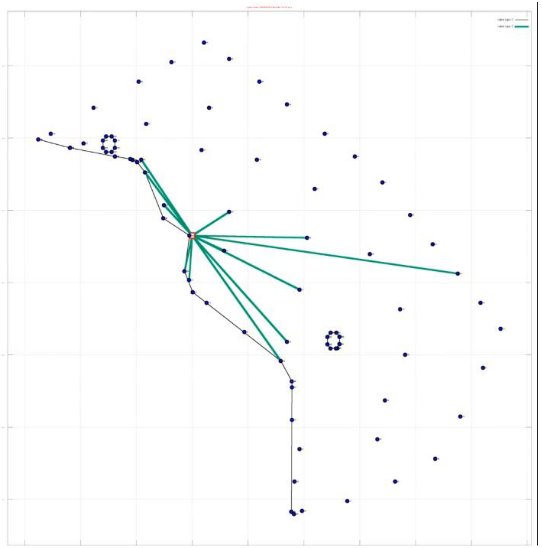
Cable routing

Problem: When lots of turbines are involved (or the problem is highly constrained) the model typically requires a long time before producing even the first feasible solution.

We used a **matheuristic approach:**

- First we relax the MILP model (allowing for disconnected solutions)
- Then we solve MILP subproblems to produce a sequence of improved solutions by solving restricted MILPs based on various variable-fixing strategies (random, distance based, by sector)
- Finally, we let the solver run to improve the current solution and (hopefully) solve the problem to proven optimality



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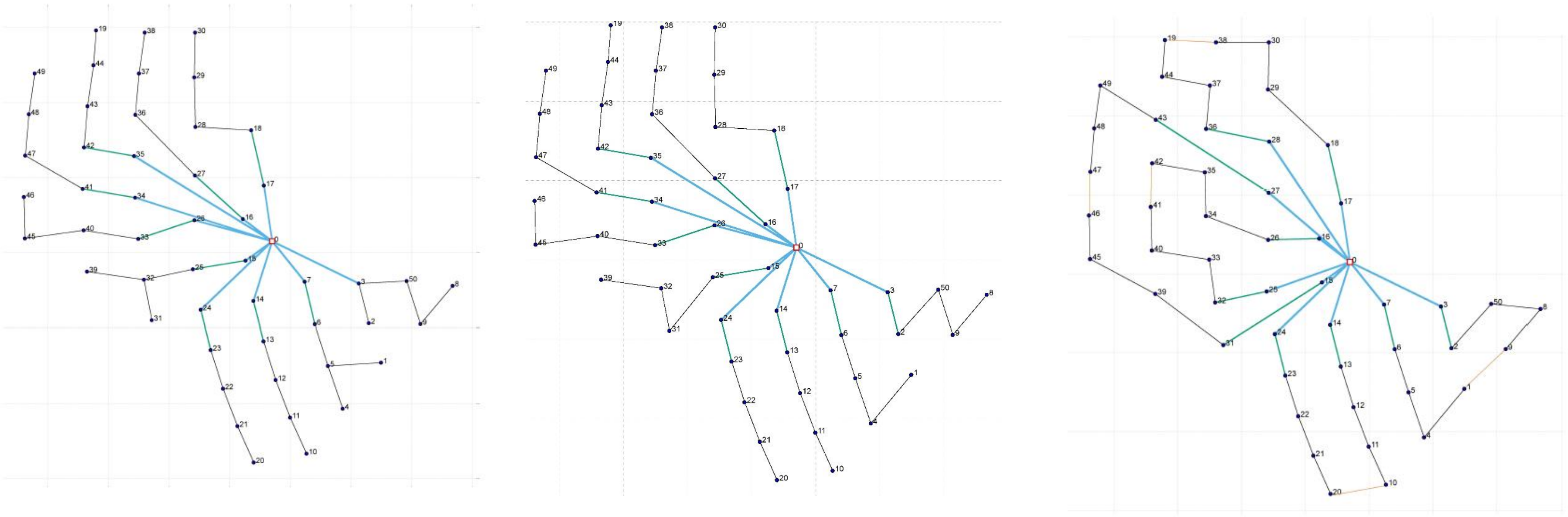
Cable routing – considering different design options



Fischetti, M., Pisinger, D.: Optimal wind farm cable routing: Modeling branches and offshore transformer modules. Networks 72(1), 42-59 (2018)

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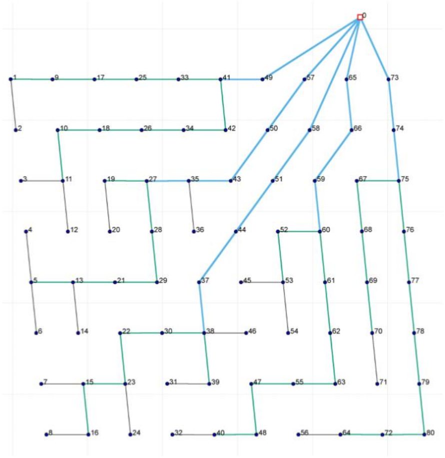
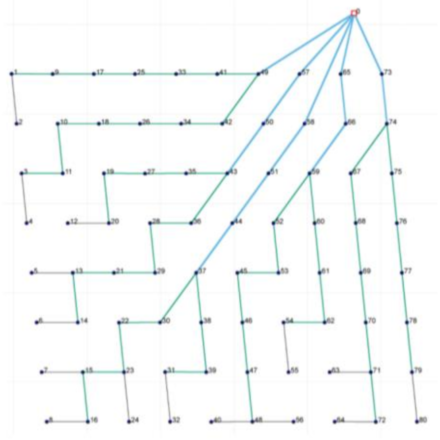
Results



CAPEX optimized:
- 1.5 M€ at construction time



CAPEX+losses optimized:
-1.5 M€at construction time and
-1.7 M€ in 25 years