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Optimizing the Layout of 1000 Wind Turbines

Markus Wagner[1], Kalyan Veeramachaneni[2], Frank Neumann[1], Una-May O'Reilly[2]

[1]School of Computer Science
University of Adelaide
[markus.wagner, frank.neumann]@adelaide.edu.au

[2]Computer Science and Artificial Intelligence Laboratory
Massachusetts Institute of Technology
[kalyan, unamay,]@csail.mit.edu

THE UNIVERSITY OF ADELAIDE AUSTRALIA

Massachusetts Institute of Technology

Abstract

We demonstrate an accurate, efficient, and parallelizable optimization algorithm for the layout of 100's, then 1000, turbines. It is modular and therefore allows different wake effect models to be incorporated. Its computational cost is a relation which depends upon how many candidate layouts it investigates and the complexity of its wake loss calculation.

We demonstrate how well it maximizes energy capture and show how it allows one to examine how wake loss scales with energy capture and number of turbines.

1. Introduction / Motivation

Layout tools:

- Identify the best layout of wind turbines according to **energy capture**,
- model free stream wind flowing through an area with sited turbines, while taking wake effects and turbulence intensities into account.
- Key component: the optimizer algorithm.

Challenges for the optimizer:

- large numbers of turbines & large farm areas
- constraints on feasible sitings
- expensive wake models

2. Covariance Matrix Adaptation based Evolutionary Strategy

The *Covariance Matrix Adaptation based Evolutionary Strategy* (CMA-ES) is a powerful optimization algorithm:

1. Representation: Each turbine position is associated with a tuple of continuous x- and y-coordinates.
2. Sample using a multivariate normal distribution

$$x_k = N(m, \sigma^2, C)\ \forall k$$

3. Select a subset of best performing layouts
4. Update/re-estimate

$$N(m, \sigma^2, C)$$

using the selected layouts.

5. Go to Step 2 and Repeat

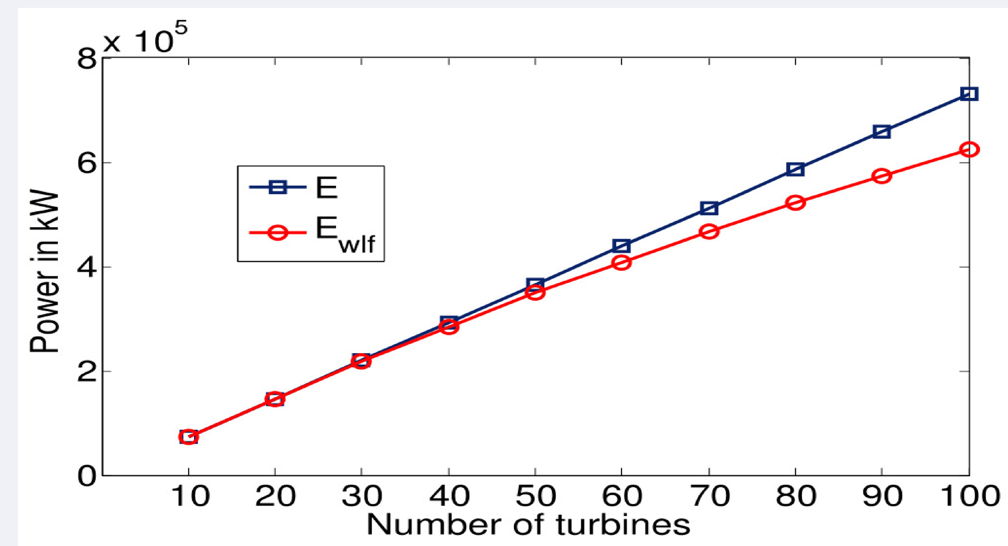
Assumptions and Constraints:

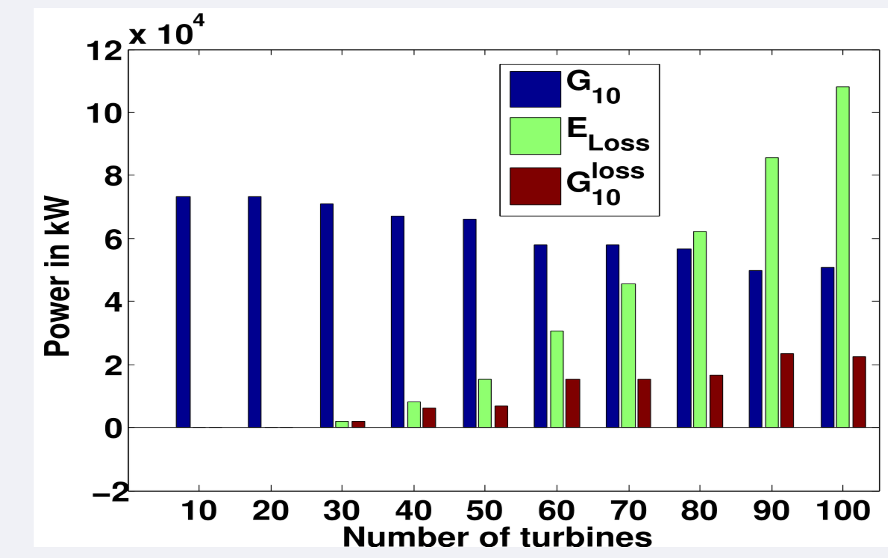
- We use the modified Park wake model .
- The distribution and intensity of the wind over the year is given by a direction-dependent Weibull-distribution.
- The outer dimensions of the available area is fixed, and infeasible solutions are corrected.
- A minimal safety distance between the turbines is enforced.

Key advantages of CMA-ES:

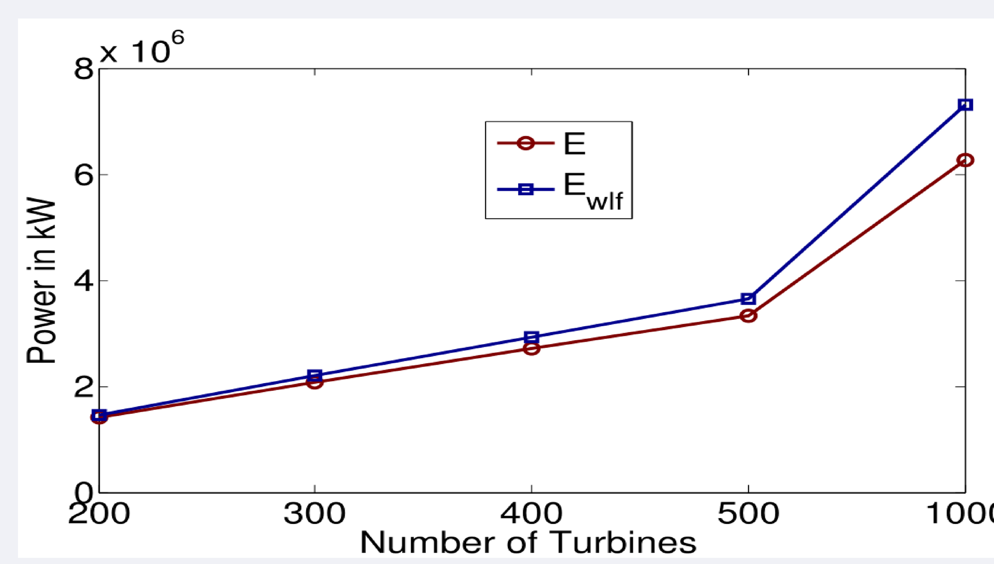
- It respects the correlations between the turbine positions via self-adaptation of the covariance matrix of a multivariate normal distribution.

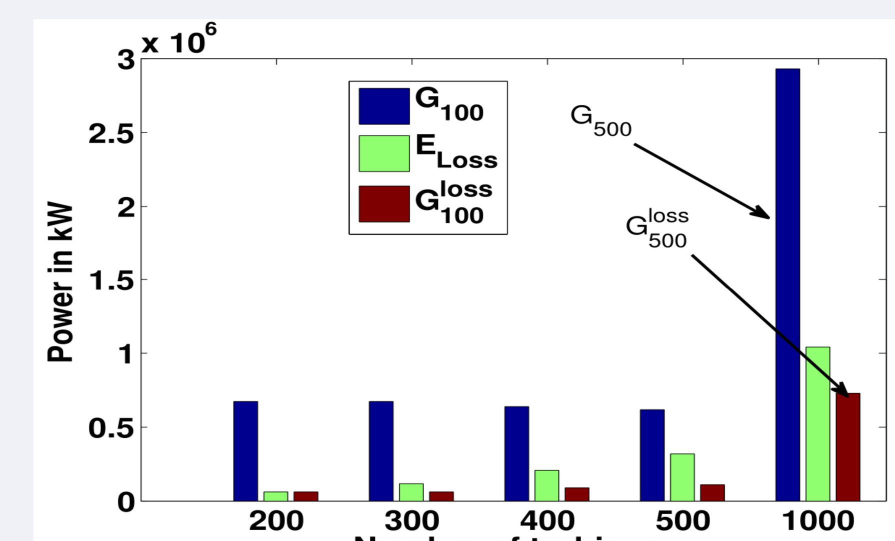
3. Results



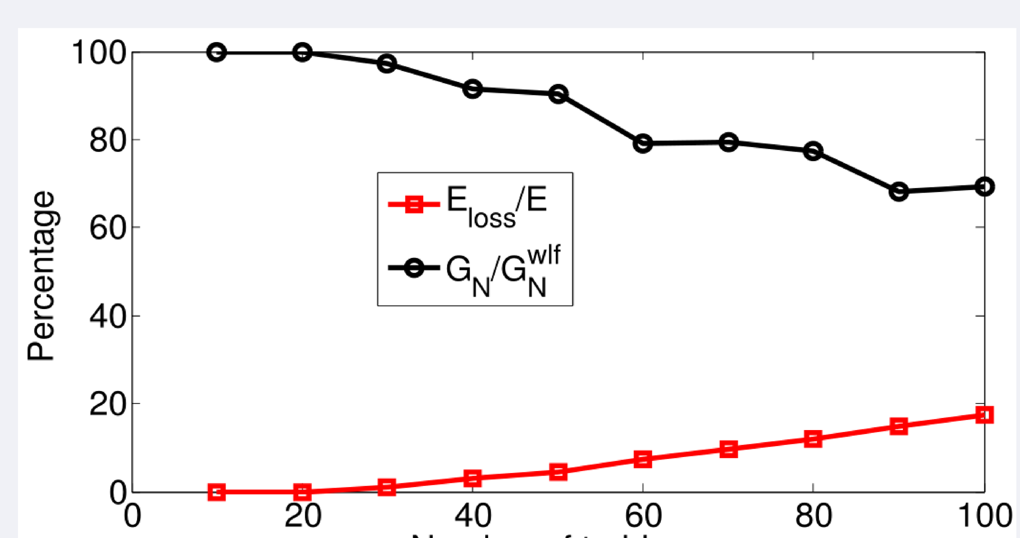


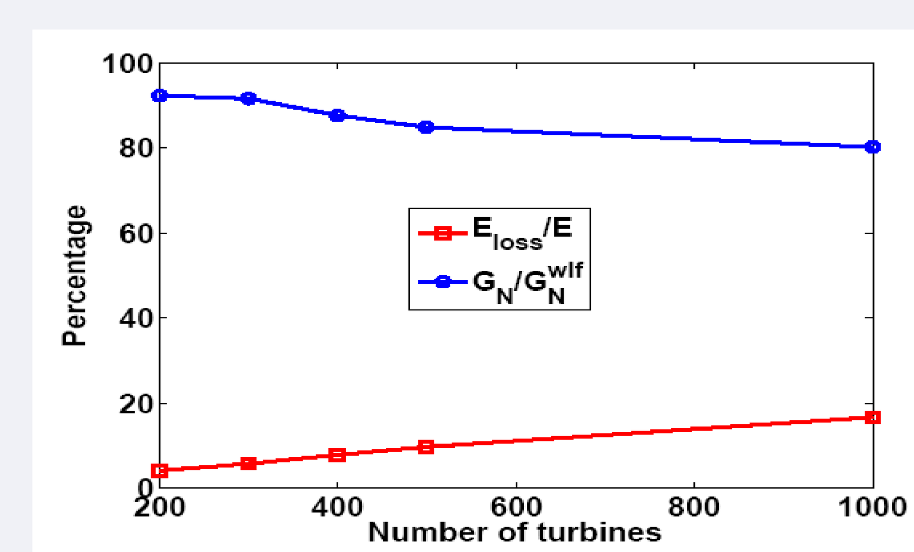
CMA-ES on 10 to 100 turbines
Left plot: energy capture climbs up as we add turbines to a 9 km^2 area
Right plot: adding each new set of 10 turbines helps despite the increase in wake losses



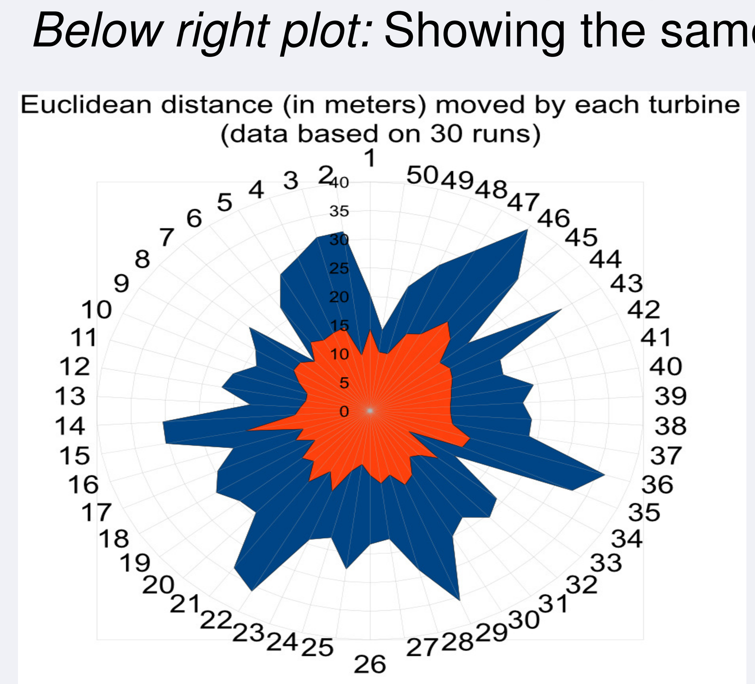


CMA-ES for 200 to 1000 turbines
Left plot: energy capture climbs up as more turbines are added to a 20 km^2 area
Right plot: adding each new set of 100 (500 between N=500 and N=1000) turbines helps despite the increase in the wake losses

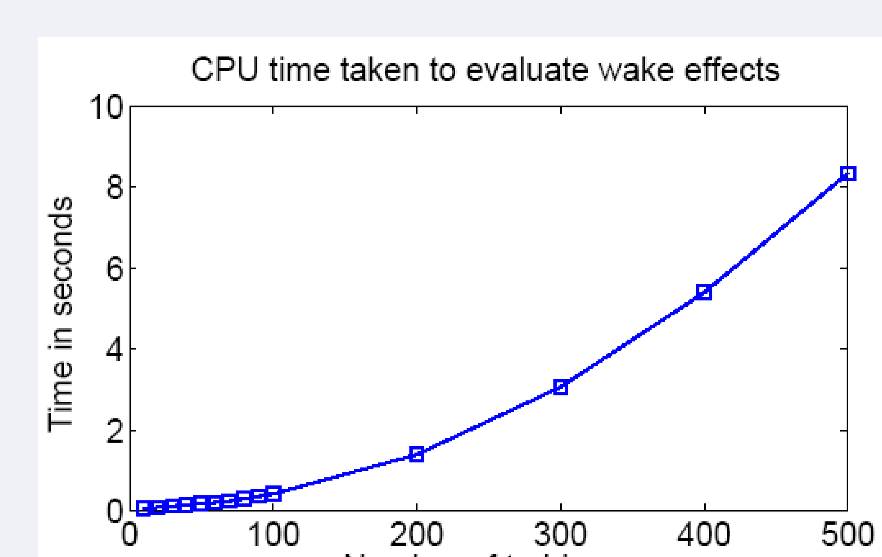




Below left plot: The ratio of energy loss due to wake to total capture increases with each additional set of 10 turbines. At the same time, the gain achieved by adding each additional turbines decreases. This is characteristic of the layout problem when more turbines are squeezed in the same area.
Below right plot: Showing the same metric evaluated for layouts consisting of 200-1000 turbines.



Example: mean and standard deviation of displacement of 50 turbines for 30 independent runs.



Example showing increase in a single wake evaluation time even when the code is semi parallelized.

4. Conclusions

The advanced evolutionary algorithm approach learns the statistical properties of better layouts and makes use of this knowledge to generate even better layouts.

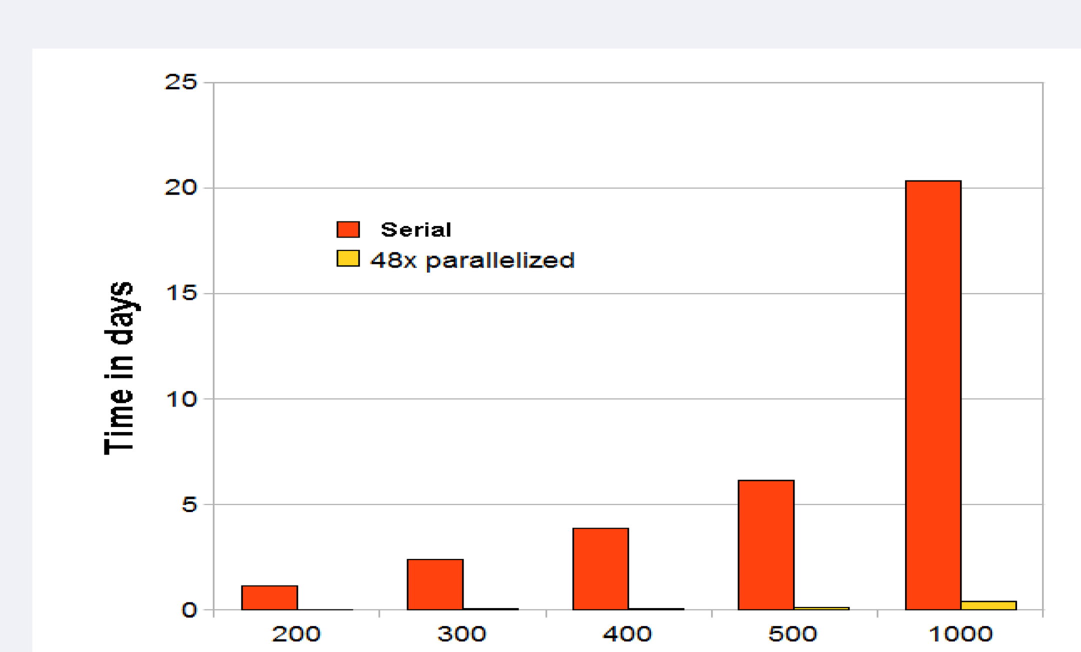
We demonstrated the algorithms capabilities on problems involving 100's and even 1000 wind turbines.

5. Outlook

Incorporation of multiple Objectives, such as energy output vs. required amount of land vs. connecting cables' lengths.

Evaluation of more realistic but computationally expensive wake models.

Mitigating the Computational Cost



Benefits achieved after fully parallelizing the algorithm on a 48 node cluster.