GECCO

Genetic and Evolutionary Computation Conference

Madrid, Spain
July 11-15, 2015

On Evolutionary Approaches to Wind Turbine Placement with Geo-Constraints

July 13, 2015

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GECCO 2015, Madrid

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SUB CRUCE LUMEN THE UNIVERSITY of ADELAIDE

Context

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- Objective:
  Maximize power output of renewable energy sources

- University of Adelaide
  - Adelaide: City in South Australia
  - A lot of solar and wind potential

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- University of Oldenburg and Jade University of Applied Sciences
  - Oldenburg: City in Lower Saxony, Northern Germany
  - Not so much solar potential, but a lot of wind

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- Focusing on wind turbines

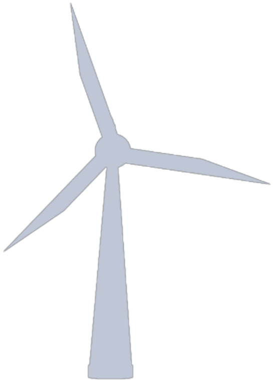
Motivation

- Behavior and effectiveness of wind turbines is strongly depending on their location
- ***Question: Where to place wind turbines to increase their power output?***
- Increase by:
  - Optimal positions caused by higher wind potential
  - Reduction of wake effects
- Modern Turbine, 40% full load hours, 0.1 €/kWh
  → 1 M€/a
- Even small improvements lead to large values

Content

1. Wind turbine placement scenario
   - How we calculate the power output of wind turbines?
2. Optimization
   - Fitness function definition
   - Solution representation
   - Optimization approaches
3. Experimental results

Wind



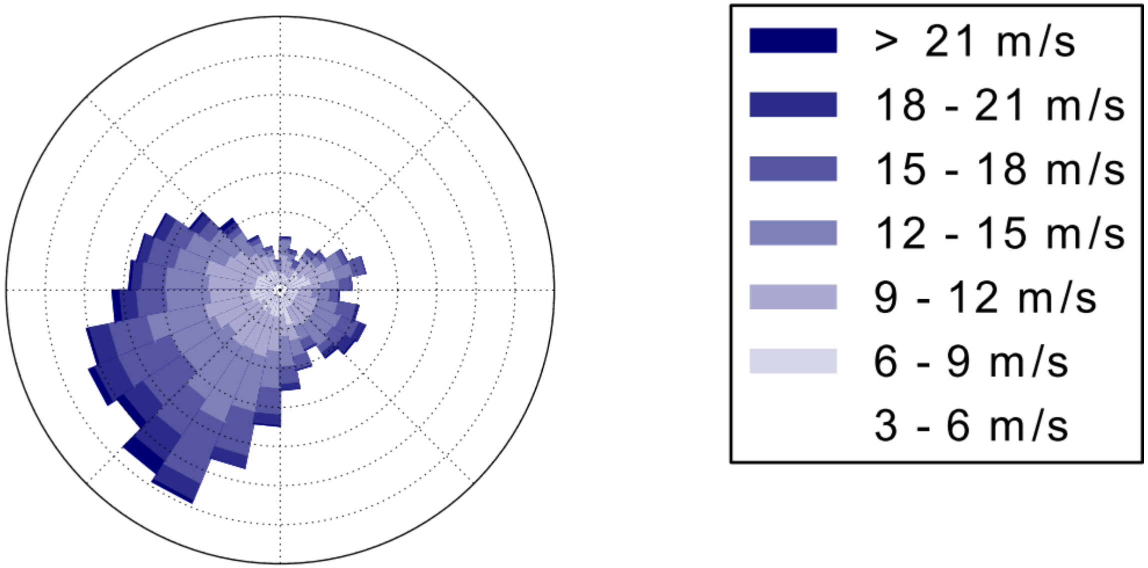
- Wind turbine
  - Produces power depending on wind speed at location
  - Power curve from Enercon E101
  - Constraint: Minimum distance between turbines

- Determination of the wind speed at location
  - Using COSMO-DE data from the German Weather Service (DWD)
  - Rotated grid over Germany (419 x 459 = 192,321, distance about 2.8 km)
  - Hourly wind vectors

  → more than 1.6 billion (419 x 459 x 365 x 24) wind vectors per year per height level

Wind Rose

- Rose: Distribution of wind speeds and directions
- Sort vectors by wind direction and location
- Wind rose for every grid position
- Bilinear interpolation using four grid positions



Wind Model

- Model based on wind distributions by Kusiak and Song (2010)
  - Weibull distribution to describe wind distributions
  - Discretization of wind speed and wind directions
  - Our modifications → see paper
- Model considers wake effects
  - Jensen wake model

Wind Model

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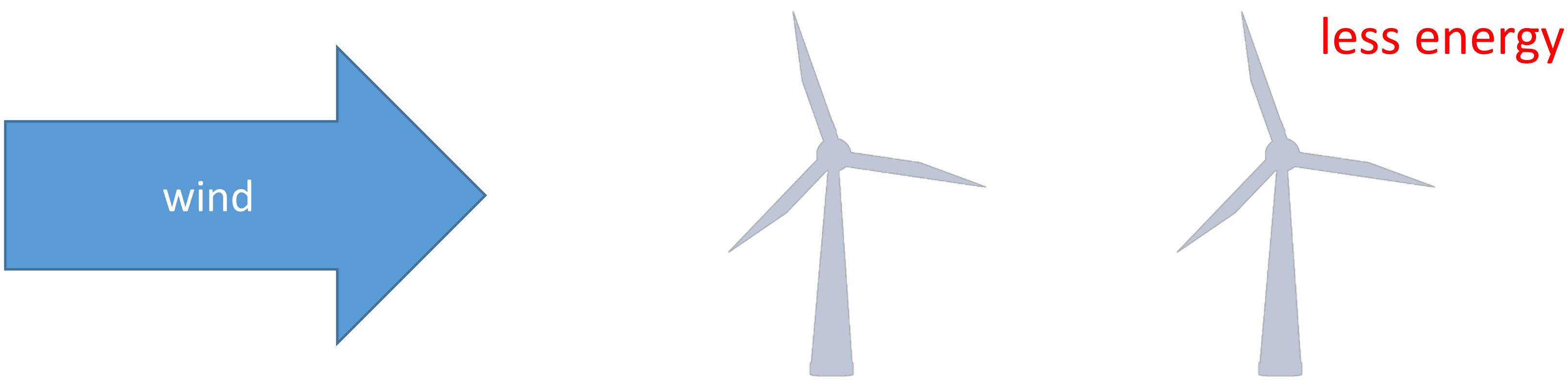
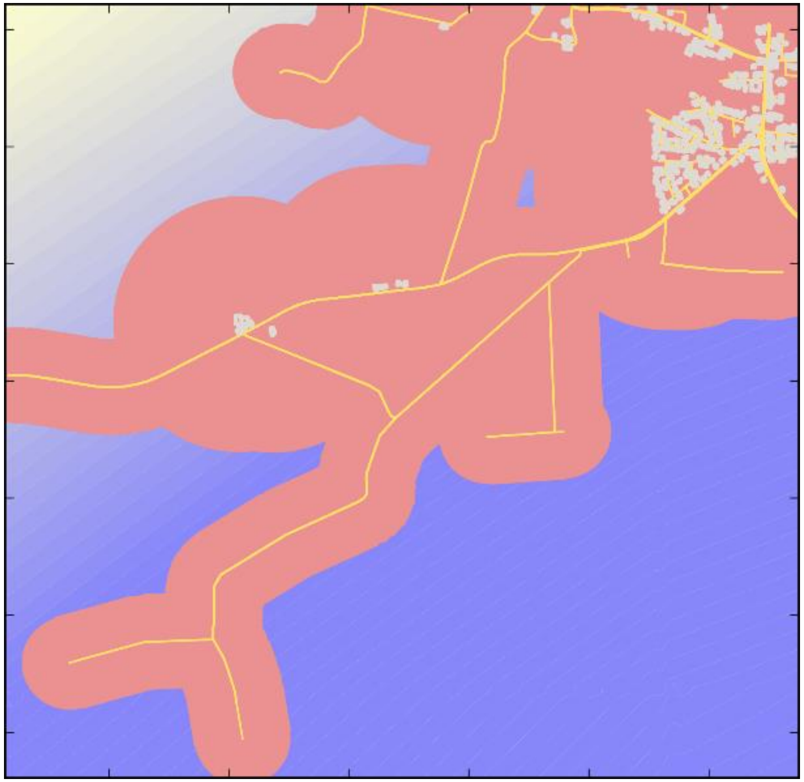


Geographical Data

- Geographical data from OpenStreetMap
- Constraints for areas around
  - Buildings
  - Streets
- Constraint handling with death penalty
- Scenario 2 (from paper):
  - 3.3 x 3.3 km
  - 250 buildings
  - 64 streets consisting of 489 parts



Fitness Function

- Produced energy for a wind farm: sum of all turbines

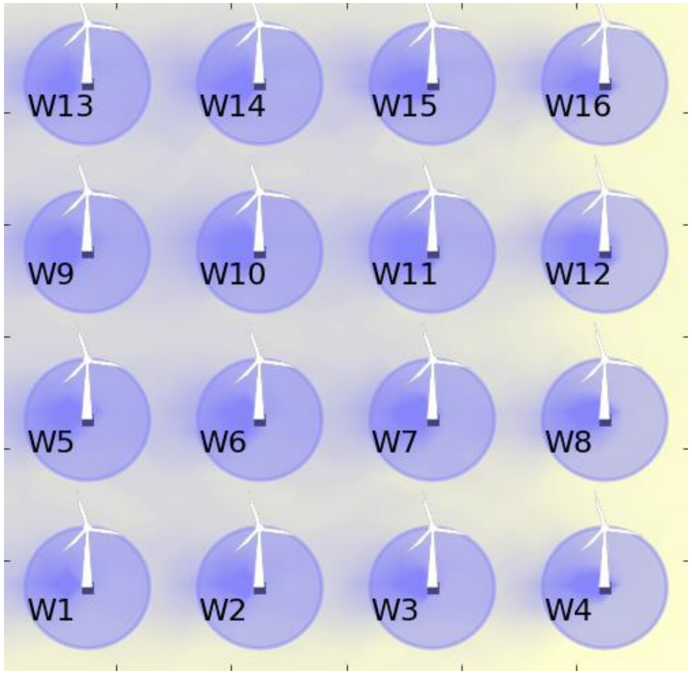
$$f(\mathbf{x}) = \sum_{i=1}^{N/2} E(\mathbf{t}_i)$$

- Fitness function depending on
  - Wind turbine E101 from Enercon
  - Wind data from COSMO-DE model
  - Power calculation based on Kusiak and Song with modifications
  - Jensen wake model
  - Geographical data from OpenStreetMap

Solution

- Solution $\boldsymbol{x}$ describes the positions of multiple turbines
  - e.g. $\boldsymbol{x} = [100, 300, 200, 200]$

- Initial solution:
  - Random
  - Chessboard pattern



- Circles:
  - Minimum distance between turbines

Evolutionary Strategies

- $\boldsymbol{x} = [100, 300, 200, 200]$
- Holistic approaches
  - Mutation will change every dimension of $\boldsymbol{x}$
- $\boldsymbol{x} = [100, 300, 200, 200]$
- Turbine-oriented approaches
  - Mutation will randomly pick the dimensions of one turbine

Evolutionary Strategies

- $\boldsymbol{x} = [100, 300, 200, 200]$

- Holistic approaches
  - Mutation will change every dimension of $\boldsymbol{x}$

- ***Adaptive*** $(\mathbf{1}+\mathbf{1})$***-ES***
  - ***Gaussian mutation to move turbines***
  - ***Rechenberg´s step size control***

Evolutionary Strategies

- $\boldsymbol{x} = [100, 300, 200, 200]$

- Holistic approaches
  - Mutation will change every dimension of $\boldsymbol{x}$

- Adaptive $(1 + 1)$-ES
- ***Covariance Matrix Adaptation Evolution Strategy (CMA-ES)***

Evolutionary Strategies

- $\boldsymbol{x} = [100, 300, 200, 200]$
- Turbine-oriented approaches
  - Mutation will randomly pick the dimensions of one turbine
- ***Adaptive*** $\mathbf{(1+1)}$***-ES***
  - ***Gaussian mutation***
  - ***Special Case: 1 dimension***
  - ***Rechenberg´s step size control***

Evolutionary Strategies

- $\boldsymbol{x} = [100, 300, 200, 200]$
- Turbine-oriented approaches
  - Mutation will randomly pick the dimensions of one turbine
- Adaptive $(1+1)$-ES (1 dim.)
- ***Replacing***

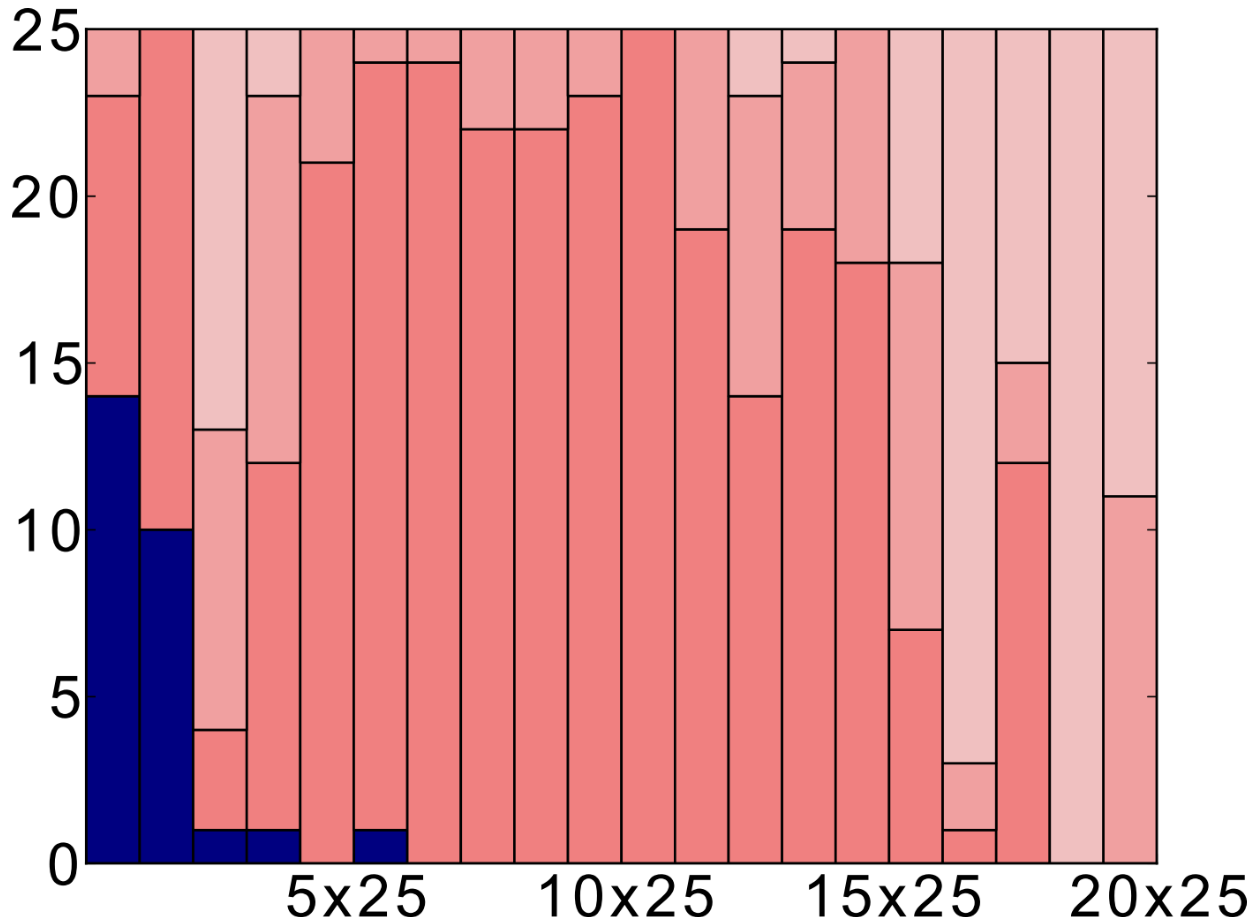
Evolutionary Strategies

- $\boldsymbol{x} = [100, 300, 200, 200]$
- Turbine-oriented approaches
  - Mutation will randomly pick the dimensions of one turbine
- Adaptive $(1+1)$-ES (1 dim.)
- Replacing
- ***Deterministic*** $\mathbf{(1+1)}$***-ES***
  - ***Gaussian mutation***
  - ***Starting with step size equal the map size***
  - ***Decreased*** **linearly**
  - ***Ending with step size: 1 / "fitness function calls" x map size***

Evolutionary Strategies

- $\boldsymbol{x} = [100, 300, 200, 200]$
- Turbine-oriented approaches
  - Mutation will randomly pick the dimensions of one turbine
- Adaptive $(1+1)$-ES (1 dim.)
- Replacing
- Deterministic $(1+1)$-ES
- ***Self-Adaptive*** $(\mathbf{1}+\boldsymbol{\lambda})$***-ES***
  - ***Choose between replace and Gaussian mutation***
  - ***Can also mutate multiple turbines in one generation***
  - ***Operation and number of turbines are controlled self-adaptively***

Analysis of Operator Ratios



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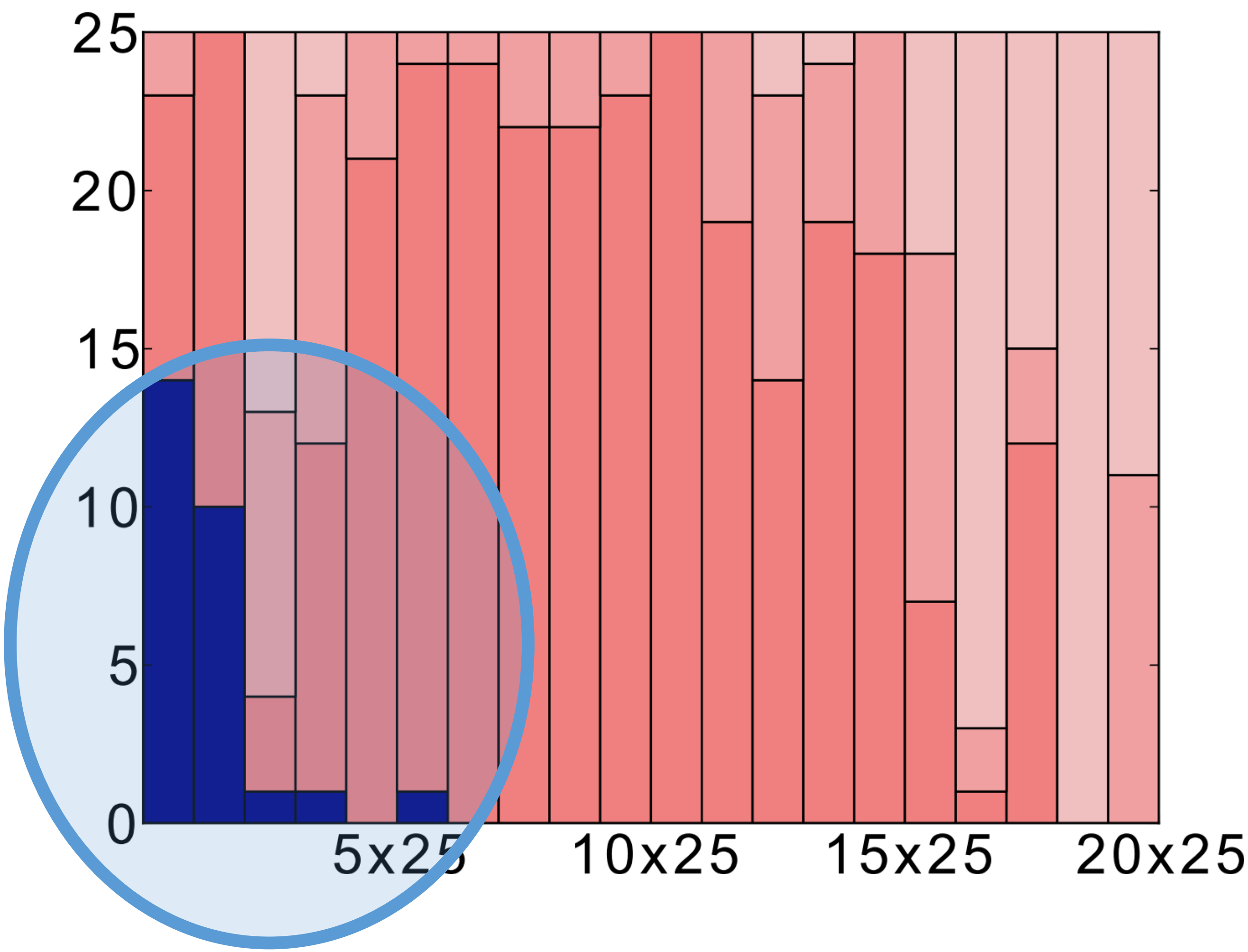

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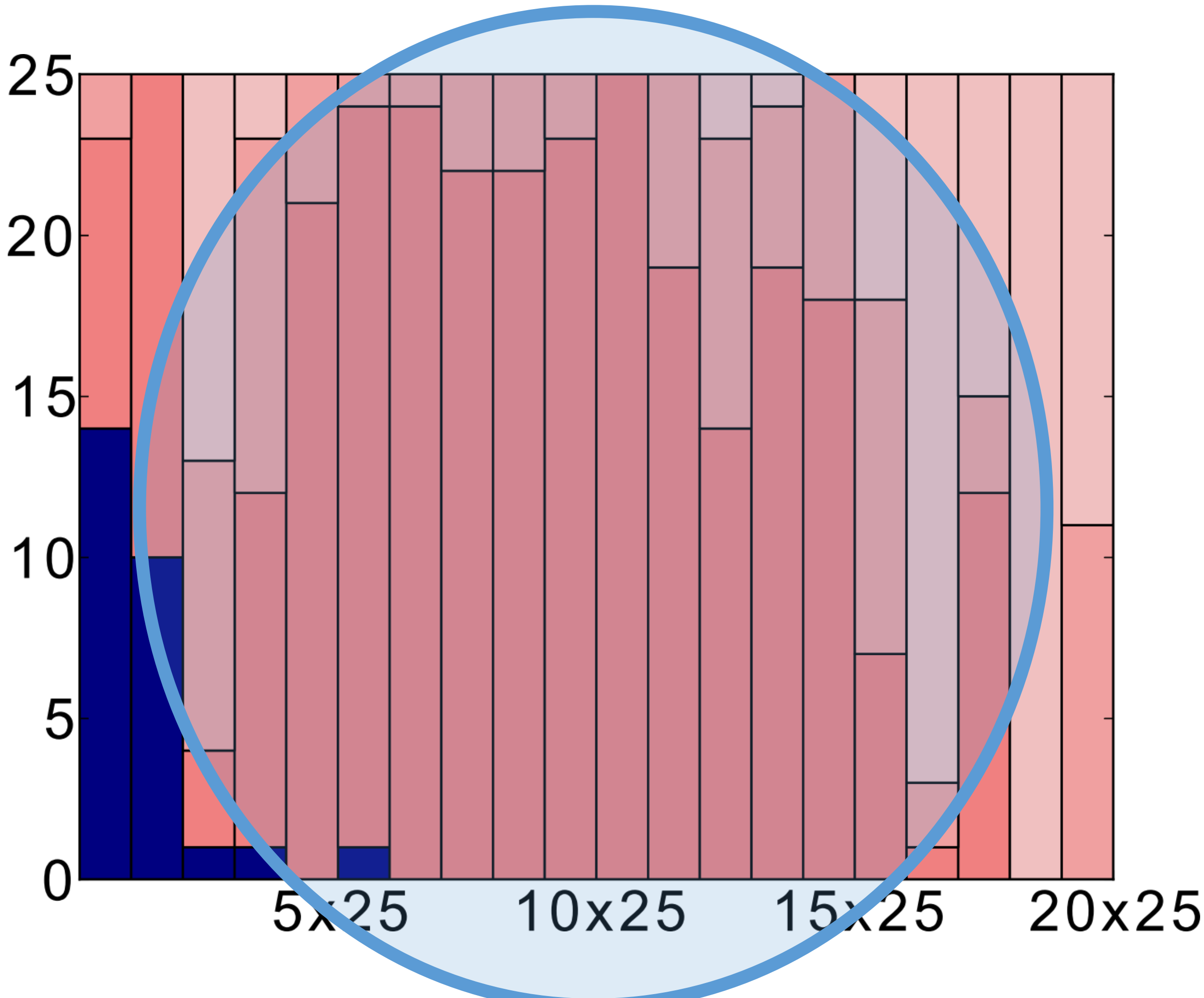

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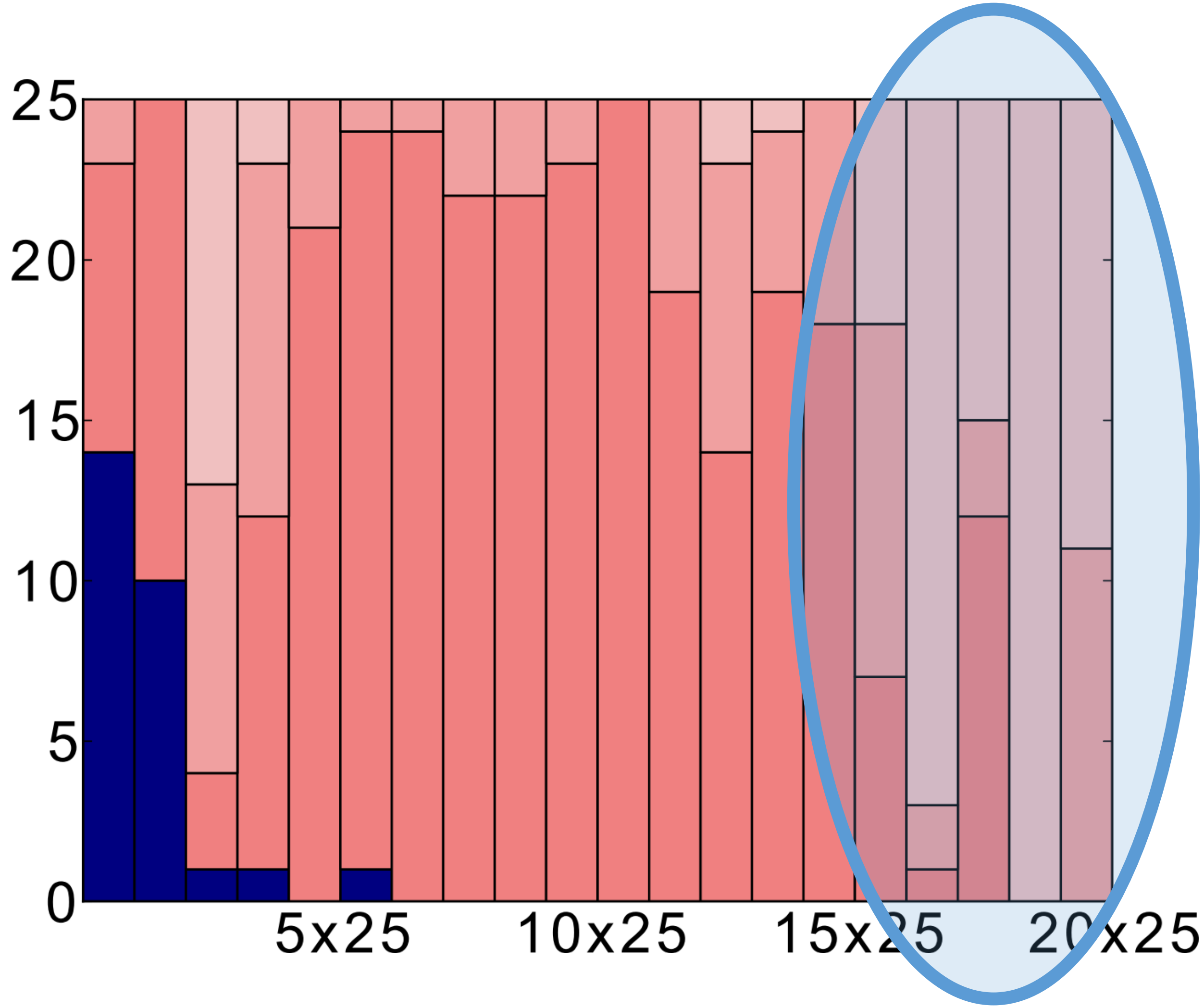

Comparison of Evolutionary Algorithms

- Scenario 2: 36-dimensional optimization problem (18 turbines) (results for random initialization in paper)

Init.	Chess	
Algo.	Mean ± Std	Max
Init.	10944.2 ± 0.0	10944.2
$(1+1)^N$	11221.3 ± 33.0	11287.3
CMA	11359.7 ± 12.5	11386.6
$(1+1)^1$	11399.3 ± 17.5	11444.5
Rep.	11484.0 ± 9.7	11505.0
$(1+1)^{\mathbf{t}}$	**11524.1** ± 8.4	**11538.2**
$(1+\lambda)$	11516.5 ± 11.7	11537.2

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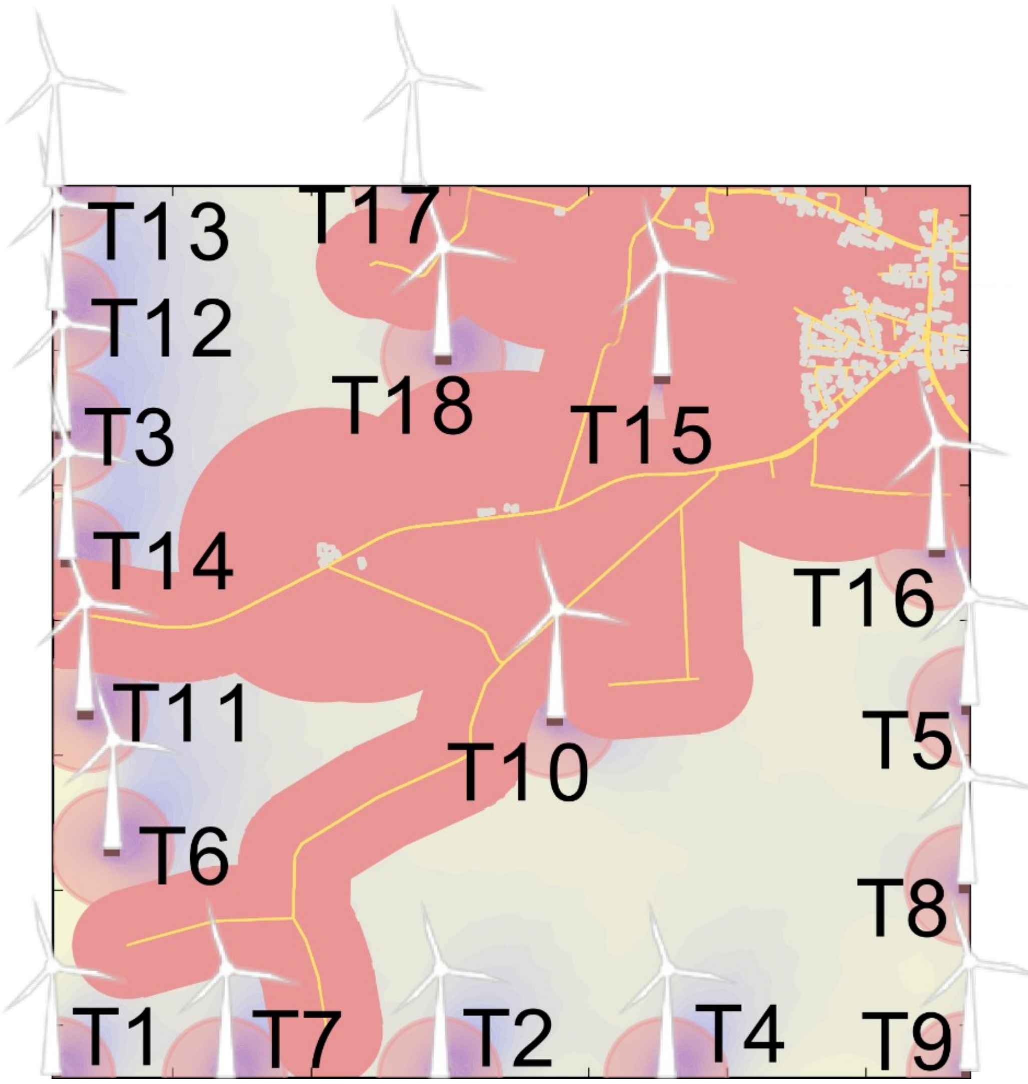
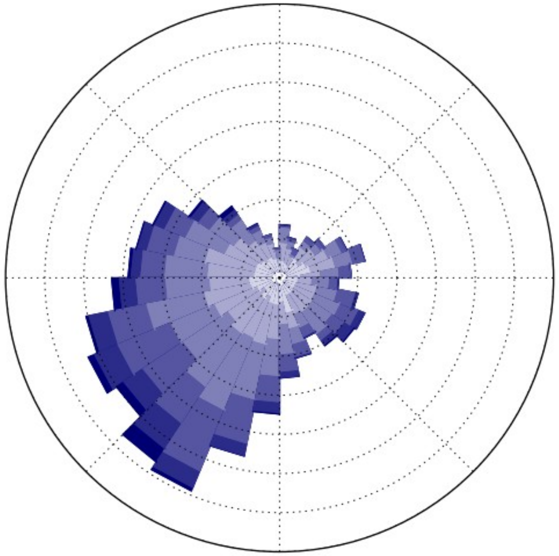
Best Turbine Placement Result





Conclusion & Future Work

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- Wind turbine placement leads to different optimization problem
- Self-adaptive approach first replaces, **then** moves turbines
- Turbine-oriented approaches outperform holistic approaches

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Future Work

- Advanced contraint handling methods
- Add more features to the model

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- Wind turbine placement leads to different optimization problem
- Self-adaptive approach first replaces, **then** moves turbines
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Thank you!

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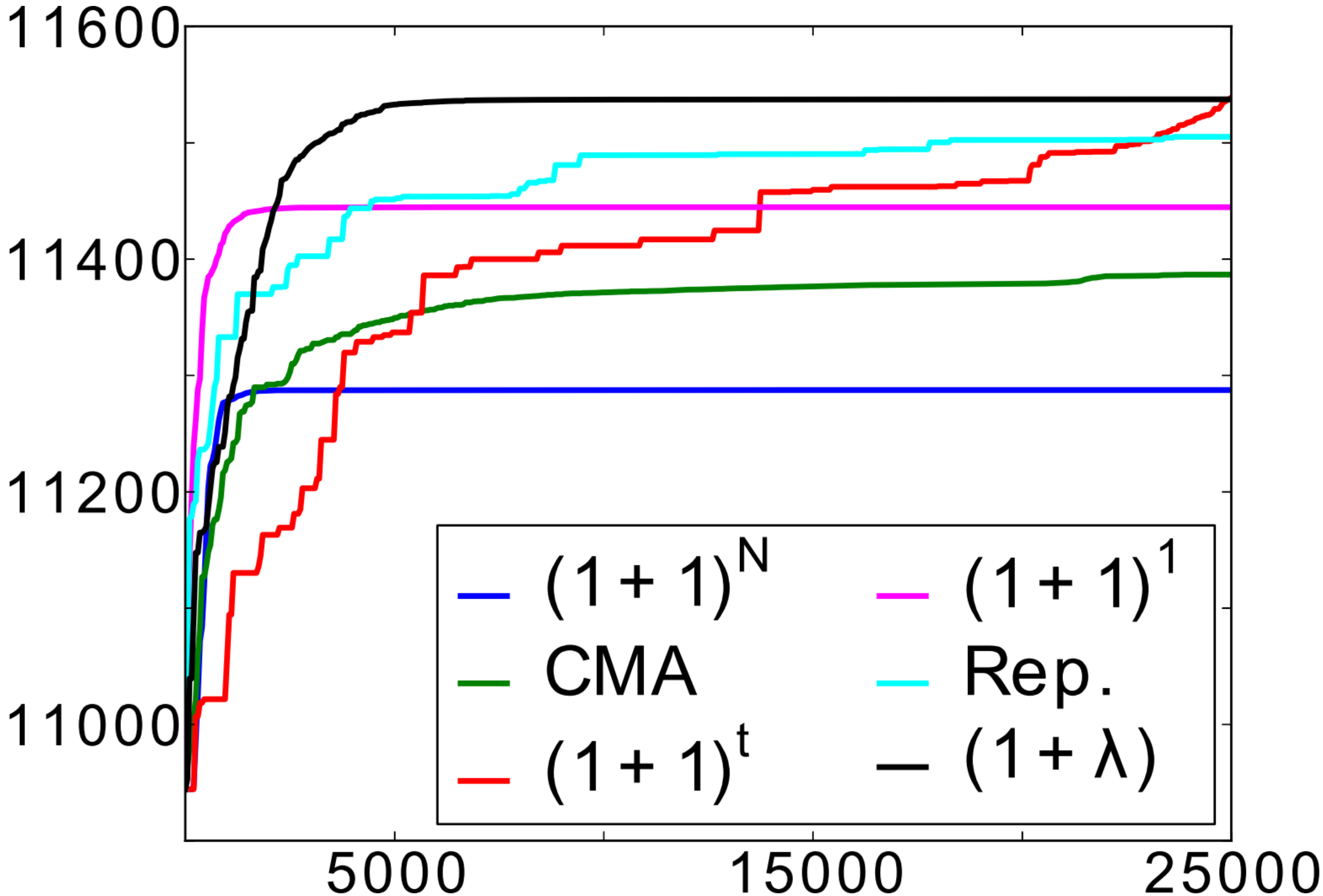
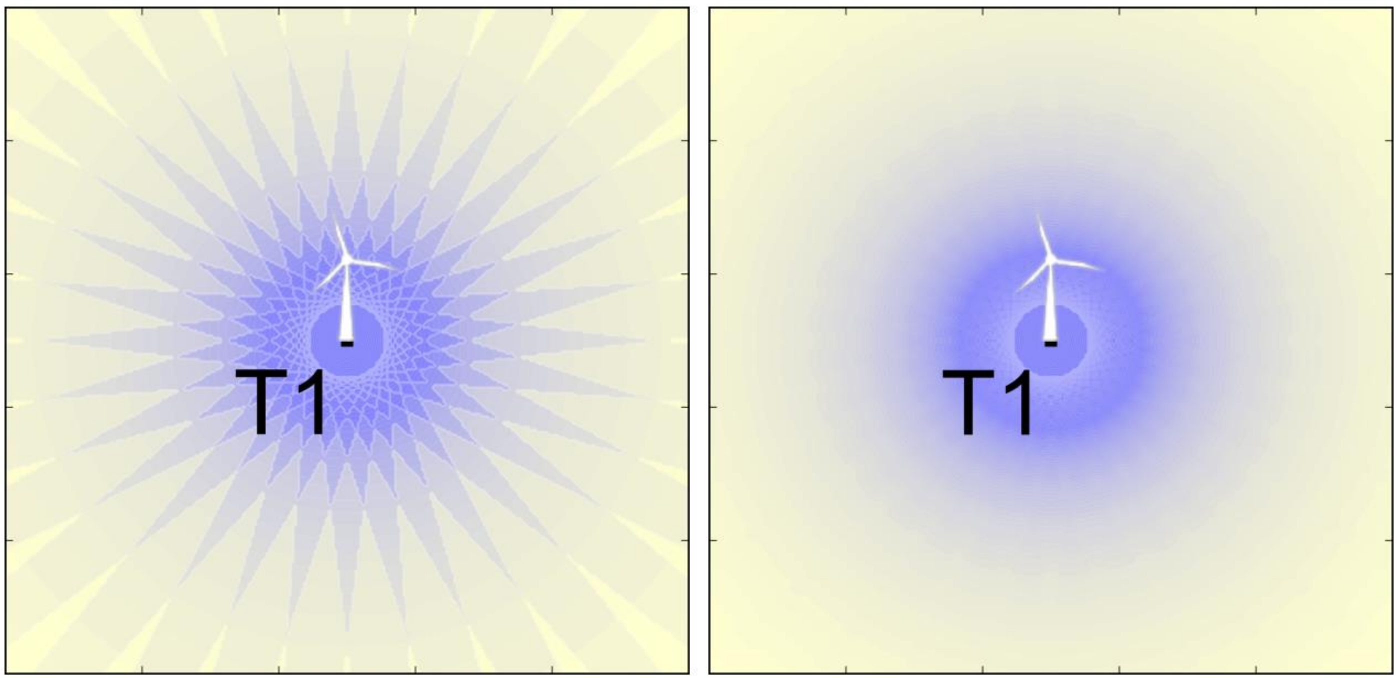
Context

- This work follows the project *EnerGeoPlan*
  - 2011 – 2013
  - Objective: *To bring energy supply, spatial planning, and grid planning together*
  - Funded by the Ministry for Science and Culture of the State of Lower Saxony
  - Co-operation partners: *Gemeinde Ganderkesee, EWE Netz GmbH*
  - *http://www.offis.de/f_e_bereiche/verkehr/projekt/projekte/energeoplan.html*

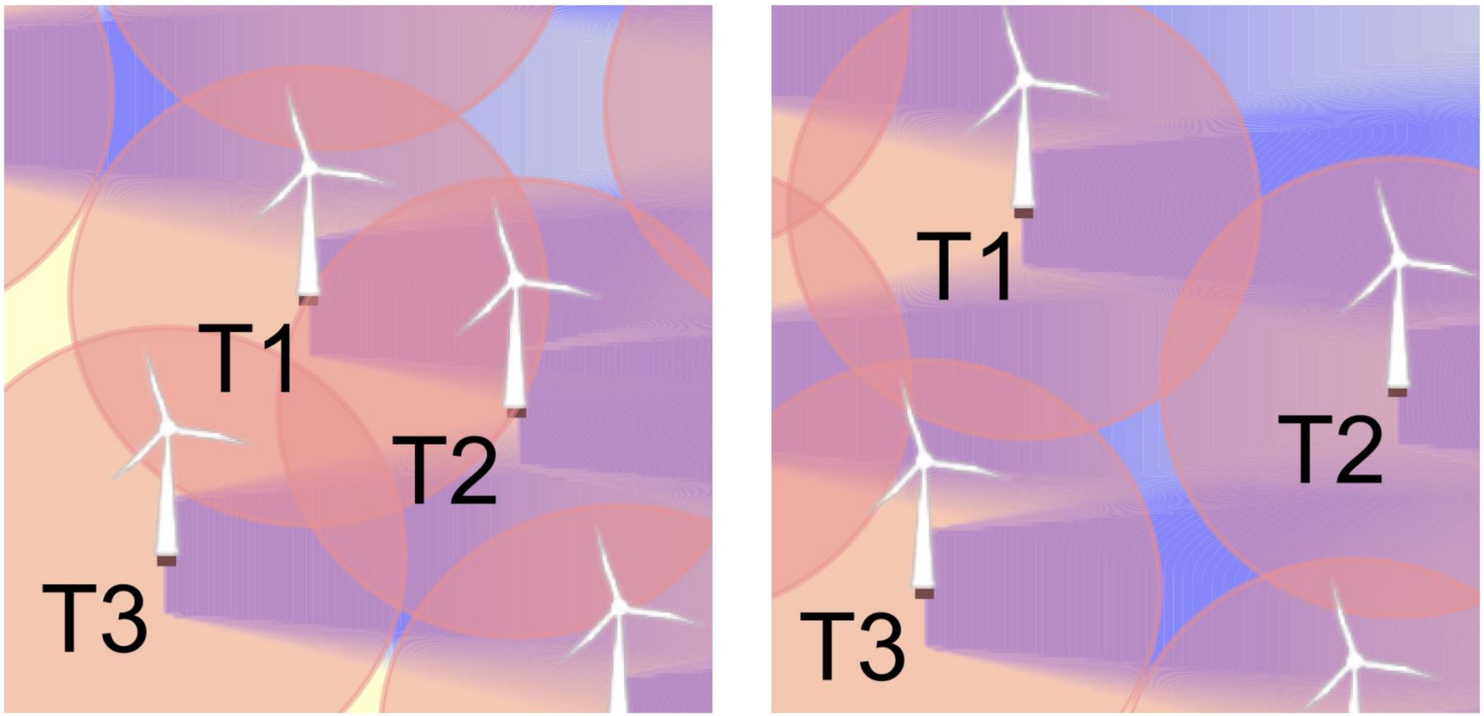
Evolutionary Runs (Chess)



Local Optima Through Wind Discretization



Rotor Size of the Affected Turbine



Example of a small wind farm

- Enercon E101 with 3 MW at 12 m/s
- Calculating with 40% full load hours
  → average 1.2 MW
- Small wind farm with 10 turbines
  → more than 100 GWh/a
- With price at 0.10 €/kWh
  → 10 M€/a
- Even small improvements lead to large values

CMA-ES

- By N. Hansen
- Newest Change
  - 14/12/06: meta_parameters now only as annotations in ## comments
- Python implementation

```
self.__sigma = 10: corresponds to 10m

res = cma.fmin(
            objective_function = fitness_function,
            x0 = XY,
            sigma0 = self.__sigma,
            options = {'maxfevals': evaluations,
                       'verb_log': True,
                       'verb_filenameprefix': file_prefix},
            args = [self.__solution]
)
```

Wind Model

- Model based on wind distributions by Kusiak and Song:

$$E(\mathbf{t}_i) = \int_0^{360} p_\theta(\mathbf{t}_i, \theta) \cdot E_\theta(\mathbf{t}_i, \theta) d\theta$$

$$E_\theta(\mathbf{t}_i, \theta) = \int_0^{\infty} \beta_i(v) \cdot p_v(v, k(\mathbf{t}_i, \theta), c(\mathbf{t}_i, \theta)) dv$$

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- ***Weibull distribution: Wind speed distribution from the wind roses***

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- Wind speed distribution from the wind roses
- ***Wind direction distribution from the wind roses***

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- Wind speed distribution from the wind roses
- Wind direction distribution from the wind roses
- ***Turbine power curve***