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# Optimization of Wind Farm Configurations with Variable Number of Turbines

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## Abstract

In planning a wind farm the losses in energy production due to shading effects must be taken into account. The production of the individual turbines in a farm depends on the number of turbines and their geometrical arrangement. Thus the economical success of a wind farm is a function of the number of turbines installed and the losses caused by the mutual shading of the turbines which may be expressed by the farm efficiency. We present an optimization procedure for an automatic identification of combinations of turbine number and geometry showing a maximum economical profit. This approach is based on Genetic Algorithms.

In various cases the optimization procedure approaches profits in the range of expert guess configurations automatically.

However it appears that the optimization procedure finds a number of turbines far from the expert guess leading to a substantial higher economical profit.

**Keywords:** Optimization, Wind Farm, Economics, Noise

## 1 Introduction

To optimize the yearly energy yield of farms with a fixed number of wind turbines we presented a procedure based on Evolutionary Strategies in /1/,/2/. For a given site and a given number of turbines this energy yield is influenced by the geometrical arrangement of the turbines. The algorithm locates optimal coordinates for the turbines of the farm.

To characterise the energy yield of wind farms as compared to single turbine installations we used the parameter 'farm efficiency'. It is defined as the ratio of the total yearly energy yield of a wind farm and the sum of the yearly energy yield of the same number of single turbines. In the optimization procedure the farm efficiency was evaluated via the Risø farm model (/3/).

In planning a wind farm, not the efficiency but the possible economical profit is the most important parameter. It depends on both the farm efficiency governed by the geometrical arrangement of the farm and the total number of turbines.

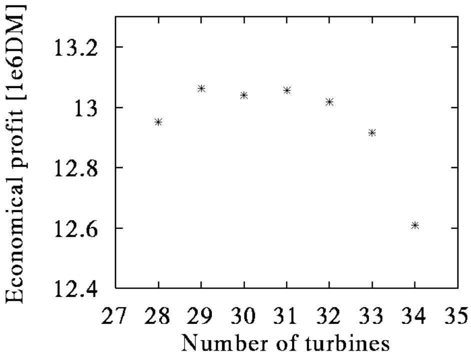

Figure 1: Economical profit of a farm in dependence on the number of turbines

If the number of turbines is fixed, the profit is roughly proportional to the efficiency. Thus in principle the Evolutionary Strategies procedure, taking the number of turbines as fixed during one optimization run, may be applied for several runs with different numbers of turbines. The comparison of the profit of the different optimized configurations then leads to the best configuration and turbine number. An example of the resulting profit values is shown in figure 1.

Procedures for a direct identification of the optimal number of turbines with the respective geometrical configuration by one optimization run in view of an economical optimum had been presented e.g. by /4/. We adapted this approach which involves Genetic Algorithms.

As measure for the quality of the farm we applied the results of usual procedures to calculate the economical profit.

## 2 Optimization strategy

### Representation of the problem

In Evolutionary Strategies the system to be optimized is represented by a set of n variables which can take continuous values. In case of a 2-dimensional search $n = N \times 2$ variables must be dealt with (N: number of turbines). In our case the variables are the x- and y-coordinates of the turbines on the ground plan of the site. Each farm configuration is represented by one point in this n-dimensional space. During the optimization, the problem's dimension n (and thus the number of turbines) may not be changed.

To be able to vary N, it's necessary to use another kind of representation of the problem. The configuration of a farm may be described by a set of binary variables. Each variable is associated with one pair of fixed (x,y)-

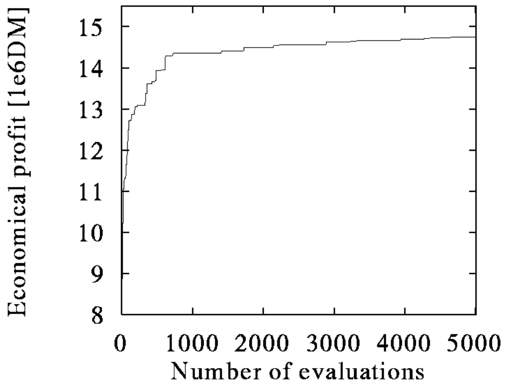

Figure 2: Development of the profit during an optimization

coordinates inside the farm area which is given by its boundaries. The variables can take the values 0 or 1 (no turbine / turbine). The number of these points, the problem's dimension, depends on the installation area and on the choice of the (x,y)-mesh size.

### Method

Genetic Algorithms, just like Evolutionary Strategies, are based on ideas motivated by the theory of biological evolution. They were developed by Holland (/5/) in the 70's.

The optimization starts with $\mu$ random wind farm configurations at a time. For each configuration the value of the objective function is determined. The 'best' farms ($\alpha$ farms, mostly one or two) are kept for the next iteration ('elite'). Then from all $\mu$ farms ($2 \times (\mu - \alpha)$) farms are selected with a probability proportional to their quality, i.e. their objective function value. Some configurations have to be selected several times. The selected farms are sorted in pairs. Each pair's information (= two sets of binary variables) is combined to a new farm configuration.

Small random changes are made on these ($\mu - \alpha$) new farms. This slightly changed farms and the $\alpha$ best farms form the basis for the next iteration. The use of random changes together with the combination of multiple farm configurations reduces the chance to get stuck in a local optimum.

The evolution of a farm's value of the objective function during an optimization run is shown in figure 2. The process of optimization starts with a random configuration with very low profit. During the first optimization steps, a steep ascent in profit occurs. During the next iterations, the increase is getting smaller until the profit value converges.

## 3 Results

As example, we investigated three farms with different shapes and sizes of the installation area (figure 3-5).

The wind direction distribution refering to a site in Northern Germany is shown in figure 6. The used turbine type has a rated power of 450 kW, a hub height of 42 m and a rotor diameter of 37 m.

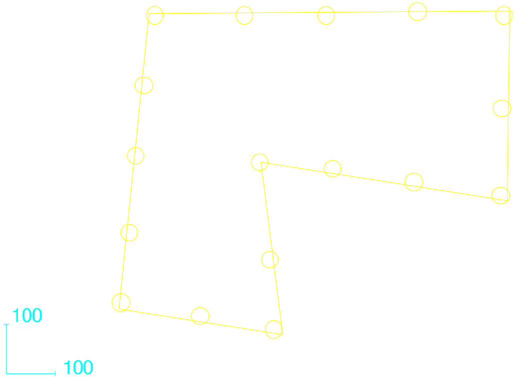

Figure 3: Farm 1, expert guess configuration (N=17)

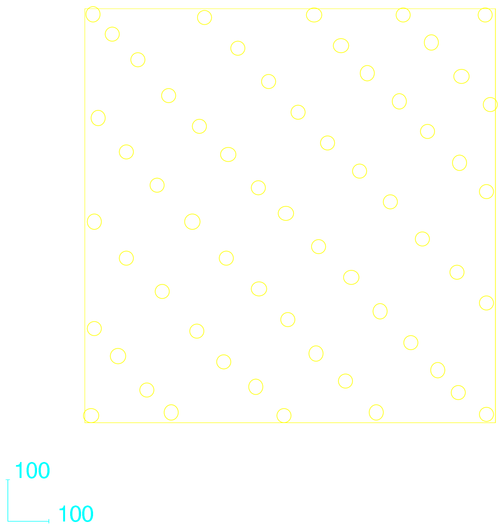

Figure 4: Farm 2, expert guess configuration (N=59)

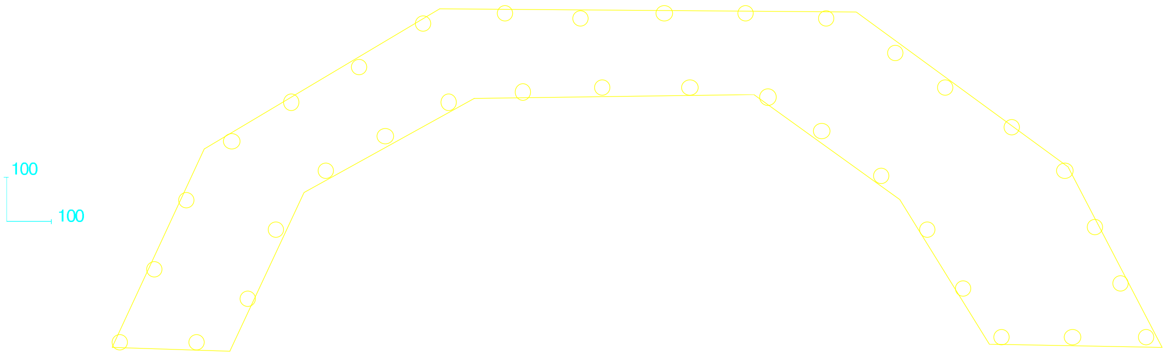

Figure 5: Farm 3, expert guess configuration (N=35)

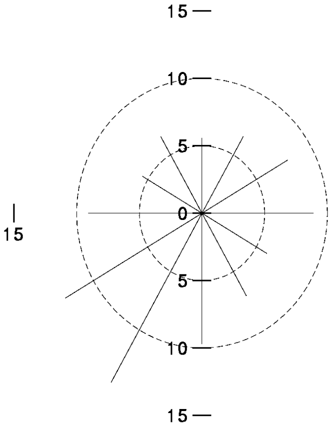

Figure 6: Angular wind direction distribution. The mean wind speed is 6.7 m/s in 50 m height.

For comparison purposes, we present 'expert guesses' for the configurations of the wind farms (figure 3-5) which use typical values for the averaged spatial density of the turbines (one turbine per area of 3 - 4 rotor diameter sqare, see table 1). In two cases the optimizations of the wind farms by Genetic Algorithms lead to only marginal improvements in comparison to the expert guesses (figure 7 and 9, table 1). Thus the optimal number of turbines doesn't differ much from the number guessed. In one case nevertheless the optimal turbine number was much smaller then the number chosen after typical values for the averaged spatial turbine density. The qualitative change of the farm's performance is evident (figure 8, table 1).

| | Farm 1 | | Farm 2 | | Farm 3 | |
|---|---|---|---|---|---|---|
| | exp. | opt. | exp. | opt. | exp. | opt. |
| N | 17 | 18 | 59 | 33 | 35 | 32 |
| E | 7.71 | 7.87 | -12.82 | 13.10 | 14.42 | 15.06 |
| η | 90.7 | 89.8 | 78.0 | 88.9 | 89.8 | 90.6 |
| A | $(3.9\ D)^{-2}$ | $(3.8\ D)^{-2}$ | $(3.5\ D)^{-2}$ | $(4.7\ D)^{-2}$ | $(3.6\ D)^{-2}$ | $(3.8\ D)^{-2}$ |

Table 1: Results of comparison expert guess ⇔ optimized configurations. N: number of turbines, E: economical profit [$10^6$ DM], η: farm efficiency [%], A: averaged spatial density of turbines (D: rotor diameter).

**Computation time**

To get a solution for an optimization problem with a dimension as high as in wind farms (e.g. 261, 494 and 729 in the shown cases) many thousands of configurations have to be evaluated. Quite strongly the necessary computation time depends upon the complexity of the calculation procedure for the objective function. For optimizing the example farms the objective function was calculated 5000 times. This

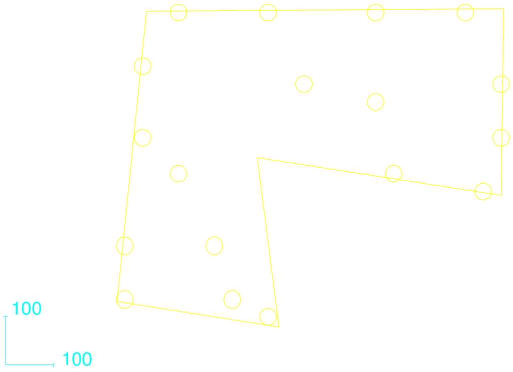

Figure 7: Farm 1, optimized with Genetic Algorithms (N=18)

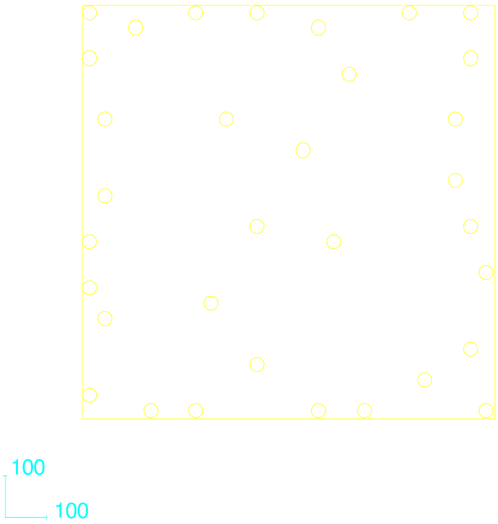

Figure 8: Farm 2, optimized with Genetic Algorithms (N=33)

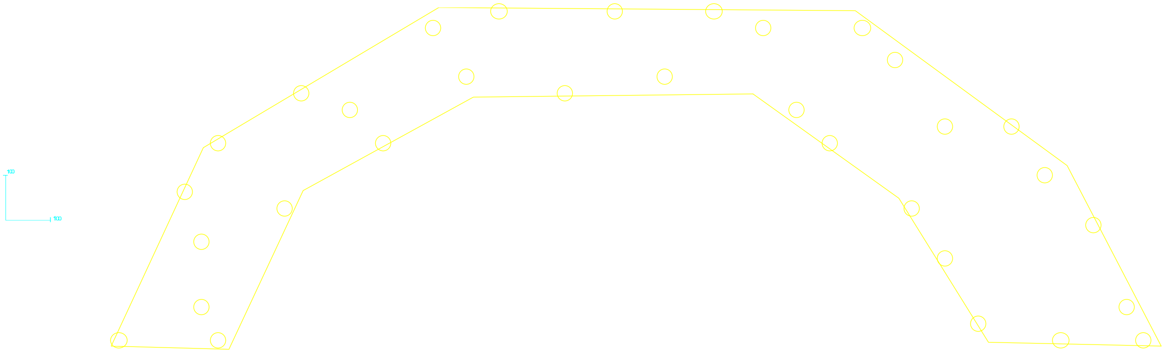

Figure 9: Farm 3, optimized with Genetic Algorithms (N=32)

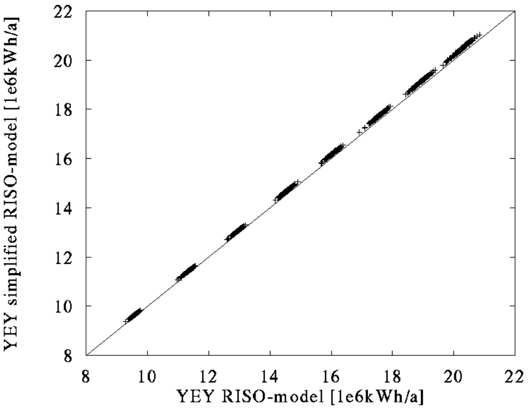

Figure 10: Comparison Risø-model and simplified Risø-model. The yearly energy yield is shown for 1000 random farm configurations. Both models agree well.

leads, in dependence on the dimension which differs with the farm size, to computation times in the range from some hours up to days (HPUX workstation). To accelerate this process, we tried to find a simple (and thus fast) but accurate approximation for the objective function. We concentrated on the Risø farm model which results in the yearly energy yield as basis for the economy calculation. A simplification neglecting the details of the wind distribution at the site but using only the mean as single wind speed input is applied. The good agreement between the results of this simplification and the Risø model for the type of site analysed is shown for 1000 random farm configurations in figure 10. Thus the optimization performance is nearly the same with both models. The computation time is reduced by a factor of 5.

**Additional constraints**

The advantage of the automatical procedure compared to manual selection of the farm configuration becomes even more evident if additional constraints have to be taken into account. An example for these constraints is given by the limitations set to the noise immission caused by a wind farm at habitated buildings. Restrictions of this type may be included in the optimization procedure by sorting out farm configurations which are produced during the optimization but do not fulfill the constraints.

## 4 Conclusion

The Genetic Algorithm based procedure presented may be used for the automatical optimization of wind farms in view of their economical profit. The algorithm identifies both the optimal number of turbines and their best geometrical configuration. It is especially useful if the optimal number of turbines for a given farm area isn't obvious. Furthermore additional constraints like acoustic limitations may be easily incorporated.

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