CASE STUDY // TURBO MACHINERY

MODEL-BASED ANALYSIS AND OPTIMIZATION OF VERTICAL AXIS WIND TURBINES

Wind turbines are highly complex devices. They are very sensitive to poor design and faulty operation. optiSLang helps to mitigate such potential problems and to develop effective optimization strategies.

Introduction

In Germany the energy transition is already well underway and it is only a question of time before this scenario is adopted by other nations. The energy transition is revolutionizing the production of electricity in favour of renewable energy sources. In the future, solar and wind energy are likely to become the most important sources of energy. In this context, it is hardly surprising that small, decentralized wind turbines are becoming increasingly important.

Wind turbines are highly complex devices. They are very sensitive to poor design and faulty operation. To mitigate such potential problems requires an effective optimization strategy.

Large wind turbines invariably consist of a single design type: they operate with a horizontal axis. In contrast, smaller wind turbines may use one of two very different design concepts: those that operate with a horizontal axis, and those that use a vertical axis. The latter have a number of advantages compared to the horizontal axis variant: they are generally simpler in design, cost less, and manifest greater efficiencies at low wind speeds.

The last point indicates why this design is preferred for small wind turbines, as they operate closer to the ground where wind velocity is predominantly lower.

Fig. 1: Left - horizontal axis wind turbine; right - vertical axis wind turbine

Figure 1 shows the different types of construction. The left-hand frame shows a large, horizontal axis wind turbine. The right-hand frame shows a typical small vertical axis wind turbine. Vertical axis turbines require thoughtful installation as the blade profiles are subject to airflow from different directions during rotation. The following sections describe a workflow developed by the Computer Simulation in Mechanical Engineering Research Centre which makes it possible not only to define the complete geometry of such turbines for given wind velocities and determine power output at optimal efficiency, but also to characterize the operational behaviour of an existing wind turbine at different wind velocities.

The workflow

The development of the workflow was based on decades of experience working on the optimization of turbomachines. Figure 2 shows a comparative compilation of the major projects undertaken by the research group. As can be seen in Fig. 2, the optimization of wind turbines is a category of project that calls for a relatively high degree of numerical complexity, with only the geometric optimization of turbo compressor deemed more demanding.

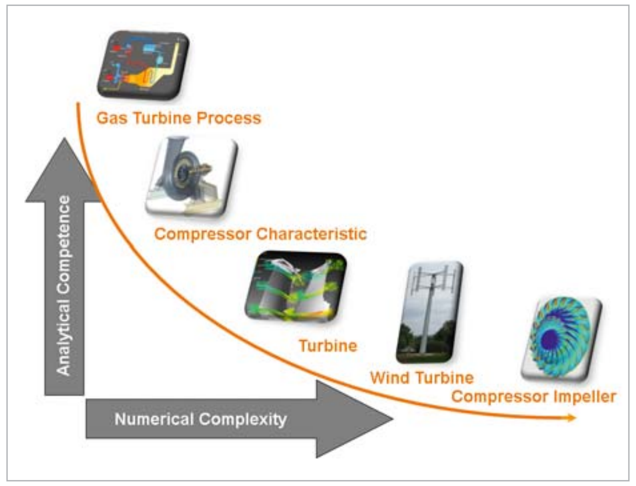

Fig.2: Optimization projects from turbomachine construction sector

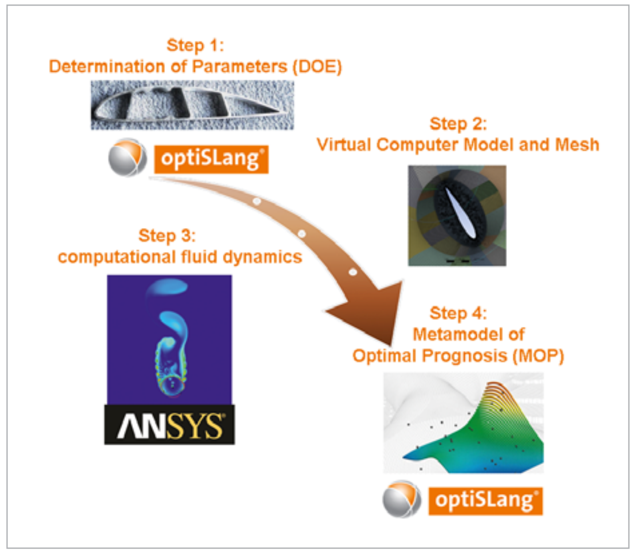

Fig. 3: The main workflow steps

The four important steps and accompanying software used in the workflow are illustrated in Figure 3. The first step entails geometric definition and parametrization. This step is vital for success of the project and typically the most time-consuming. Steps 2 and 3 call for considerable experience to ensure complete integrity of the final results. Each of these work phases presents its own challenges, described in detail in the following sections.

The functional principle of a vertical axis wind turbine

In contrast to 'conventional' wind turbines, those with a vertical axis require further explanation as the direction of airflow relative to the blade profile varies (Fig. 4) during rotation. The left frame of Fig. 4 shows a wind turbine profile with three arms. The turbine rotates anti-clockwise in the plane shown, with the wind blowing from the left-hand side with velocity c (see Fig. 4).

The velocity triangle at the leading edge of the blade reveals that it receives a relative wind velocity, w. The direction and velocity is determined when the wind velocity, c, and the rotational velocity of the turbine, u, are given. This is generally the case for each blade position. The relative incident wind velocity, w, determines the lift, Fa and the resistance, Fw. The subsequent angle and also the resultant blade force, R, are explicitly defined. Figure 4, shows force R as torque which develops in the same direction as rotation of the turbine. This ensures that blades in the opposing direction to the wind develop a positive driving torque.

The distribution of pressure around the rotating blades shown in the right-hand frame of Fig. 4 provides further information about functionality of the turbine. The pressure distribution clearly shows suction on the inner side of the blade.

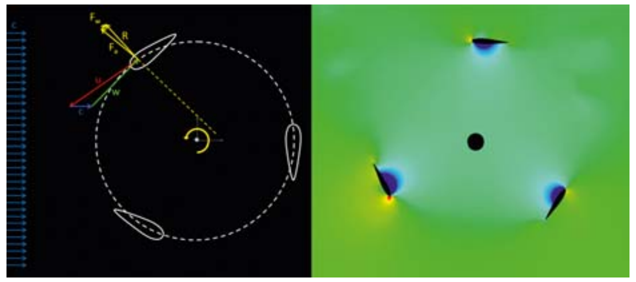

Fig.4: The working principle of a vertical axis wind turbine (left) velocity vectors and pressure distribution on blades (right)

Parametrization

Optimizing wind turbine geometry requires a set of parameters that can provide a meaningful and workable description of such geometry. The parameters listed in Figure 5 were initially of interest: they are organized into parameters associated with main dimensions of the turbine, and those associated with its operational status.

1. Diameter 2. Height 3. Blade length 4. Number of blades	5. Wind velocity 6. r.p.m. or rotational velocity

Fig. 5: Left - main parameters for the turbine and right - parameters for operational status of the turbine

The blades themselves also require an equally demanding parametrization. Parameterization of the blade has a decisive influence on the veracity of the entire metamodel. Figure 6 shows a typical profile geometry of a blade. This is created using data points. It is not unusual to describe blade cross section with more than 100 data points. However, this type of geometry should be rejected as the basis of blade profile parameterization: the use of large numbers of independent data points poses a multitude of problems for stability of any later modeling.

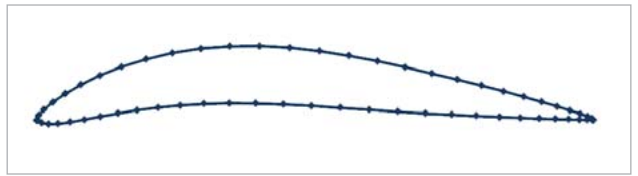

Fig. 6: Definition of blade profile geometry using data points

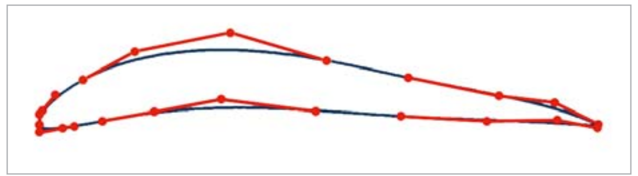

Fig. 7: The definition of blade profile geometry (blue) using control points (red)

An alternative is the use of splines. Figure 7 shows modelling with Bezier splines using the same blade cross section shown in Fig. 6.

Although at first glance this method may appear better, it is not recommended for several reasons. Although the use of control points, which can be considerably fewer than when using data points, can reproduce smooth surfaces, they are not suitable for parameterization. It has been shown that Latin Hypercube sampling for definition of DOE's produces profile geometries that are almost always unsuitable for flow mechanics. This type of parameterizations is far too arbitrary to be reproducible. To ensure that only useful profiles are generated requires a more complex strategy. Using a complex morphing algorithm, it is possible to create geometries that are able to be used in flow mechanics studies.

To describe geometries, simple arithmetic values are not used but rather parameter values categorized by descriptive nomenclature (see Fig. 8).

A total of 15 parametric values are used to describe the geometry of the wind turbine and its operational status. These are listed in detail in Figs. 5 & 8.

7. Thickness ratio 8. x-max thickness 9. Camber ratio 10. x-max camber 11. Nose circle radius	12. Trailing edge radius 13. Reflex (trailing edge) 14. Wetted aspect ratio 15. Angle of attack

Fig. 8: Parameterization of the profile model

Figure 9 shows a selection of cross sectional profiles modelled using the parameters outlined in Fig. 8. The outline of the profiles demonstrate the quality and range of flow mechanics profiles that can be created.

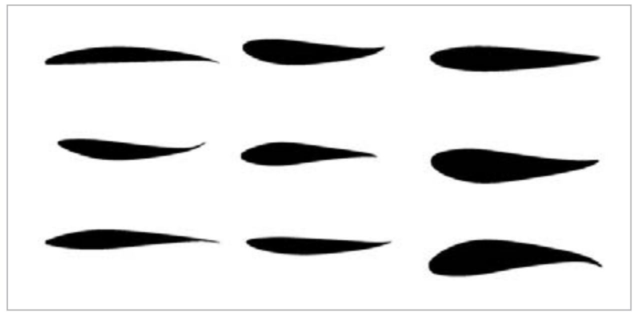

Fig. 9: A selection of parameter-based profiles

Meshing

High quality meshing is extremely important because the greatest deviation due to numerical error is manifest in the mesh. This is, in turn, also extremely important for the reliability of a metamodel.

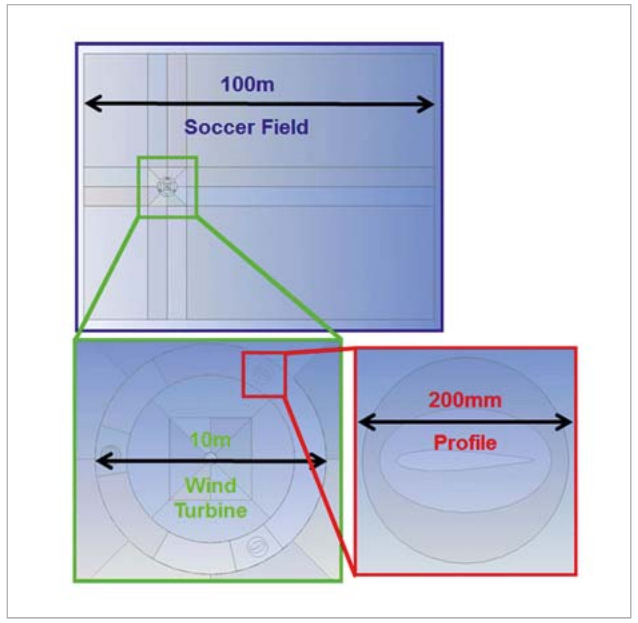

Fig. 10: Comparison of size relationships (scales)

The large difference in scales presents one of the greatest challenges for flow simulations. To maximize mesh quality, it was set to use only hexahedral elements.

Figure 10 (see previous page) illustrates the differences in scale. A wind turbine with a rotor diameter of approx. 10 m and a typical blade profile length of 0.2 m requires a simulation area the size of a football field to include the necessary up- and down-stream air flow trails.

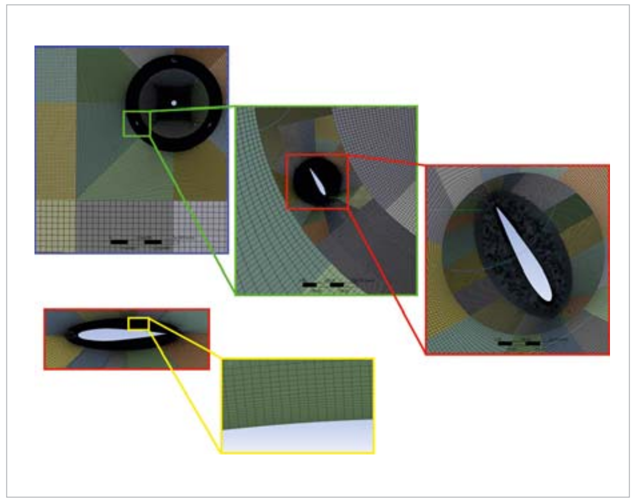

Fig. 11: Meshing of different scale sizes

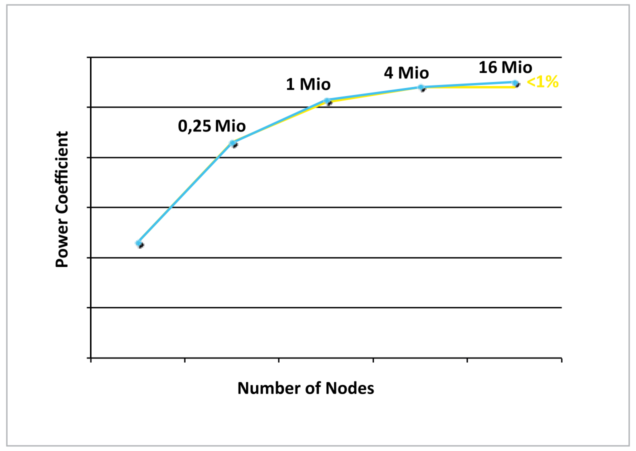

Fig. 12: Study of mesh dependency

The appropriate mesh, including all the extreme differences in element measurements, is shown in Figure 11. These differences become particularly apparent when comparing the mesh density in the area surrounding the turbine and the area close to the blade profile. Since boundary layer thickness is virtually uninfluenced by the dimensions of the turbine, and that 15 nodes vertical to the wall are assigned to achieve the appropriate mesh resolution, this region has mesh with smallest dimensions.

As a matter of routine, such projects always include a check of mesh independency: decades of experiences has shown that the integration of such studies is indispensable for the development of a robust workflow. The result of such a study is shown in Figure 12. This study was based on 2D simulation. A factor of 4 was selected for mesh refinement.

Meshes of more than 16 million nodes ensure reliable simulation results and are therefore suitable for generating a metamodel.

Flow simulation

All flow simulations need to be done transiently since the rotation axes of these wind turbines, in contrast to horizontal axes turbines, is vertical to the air flow. This dramatically increases the computational effort required since only after at least 10 revolutions of the rotor is it possible to determine whether the simulation is stable.

Furthermore, convergence cannot be established by conventional means, since the derived solution is not characterized by constant velocity or pressure, but rather by values that oscillate as a function of turbine revolutions multiplied by the number turbine arms.

The result of such a simulation is shown in Figure 13 (see next page) as a snap shot of a rotating wind turbine and the downstream air flow trails. This clearly indicates the relatively large area that needs to be included the simulation relative to blade area. The airflow trail clearly extends some considerable distance downstream from the turbine.

Evaluation proved to be more demanding than usual because analysis of turbine power output or calculation of efficiency requires integration of the moment and loss per period. The power delivered to a generator fluctuates dramatically for each rotor arm during each rotation.

The Metamodel

The parameterization used for the metamodel has already been described in section 4. A DOE consisting of 200 Latin Hypercube Samples was used to generate the metamodel. Particularly worthy of note, is the contribution made by meshing to the painstaking construction of the geometry, such that only one of 200 samples needed to be discarded. Equally satisfying was the careful processing of parameter sets that benefitted from definitions based on flow mechanical interactions which resulted in the detection of no redundant parameters. In other words, the sensitivity analysis vindicated the selection of all the parameters defined at the start of the development work.

The metamodel shown in Fig. 14 describes the turbine power output dependent on the wetted aspect surface and the specific rpm. A Moving Least Squares (MLS) algorithm has been shown to be the best predictor of variation in turbine

power output. Somewhat (pleasantly) surprising was that for all the turbine-relevant parameters which determine the effective power output in a specific operational range, the predictive accuracy of the metamodel with respect to their variation was greater than 91%. This value was calculated as the Coefficient of Prognosis (CoP) using optiSLang.

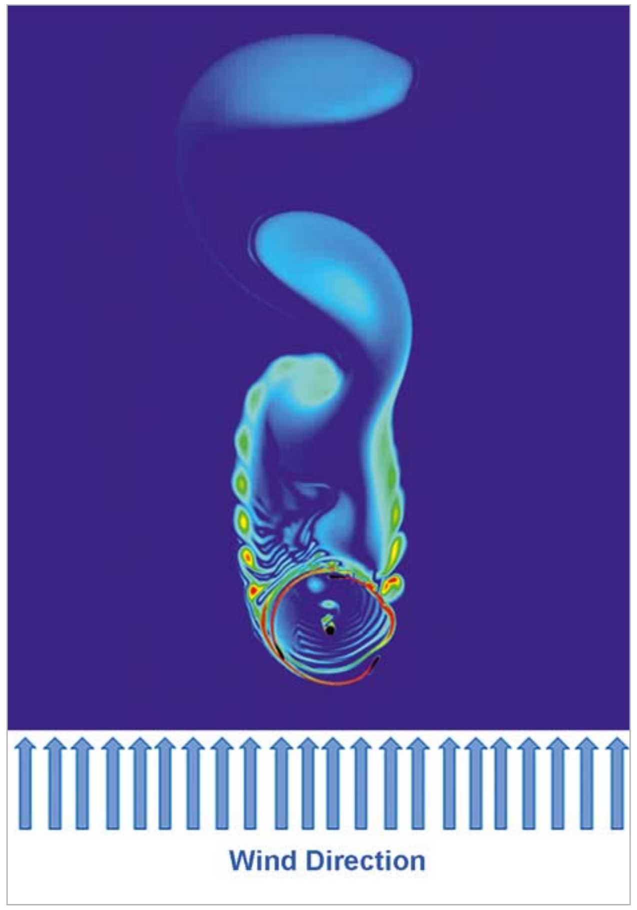

Fig. 13: Visualization of flow simulation

The reason for this high value, which exceeds the determined value of similar turbomachine projects, was the scrupulously careful definition of the parameters (see section 4.)

However, this ability represents only a fraction of the information a metamodel can deliver. It is normal practice to configure turbomachinery for a specific operational point or some optimal parameter. In reality, however, operational conditions occur that deviate considerably from the original configuration. These deviations are then usually plotted graphically as characteristic operational curves over a range of conditions.

The quality of the metamodel is shown in Figure 15 which shows a derived curve and four computed operational points, which show good congruence of the four evaluation points.

As a conclusion, the following can be stated:
It is possible with a metamodel to predict turbine power output and efficiency not only for a single operational point but also for the operational behaviour with a given wind velocity. Whereby, of course, the turbine rpm is optimally calculated for a given wind speed.

The obverse is also true: For a desired power output from the wind turbine it is possible using the metamodel to compute the turbine size or blade geometry. That the optimal turbine rpm can also be analysed is almost a matter course if the minimum loss is defined as a target value.

Evaluation of results

Although the validation, as shown in Fig 15, provides highly significant information because of the high reliability of the simulation results, it nevertheless, made sense to compare the model with an existing wind turbine.

The University of Uppsala have made recordings from a test turbine (Figure 16a) which provided suitable data. In the right-hand frame is a plot of power output against wind velocity for the turbine as predicted by the model.

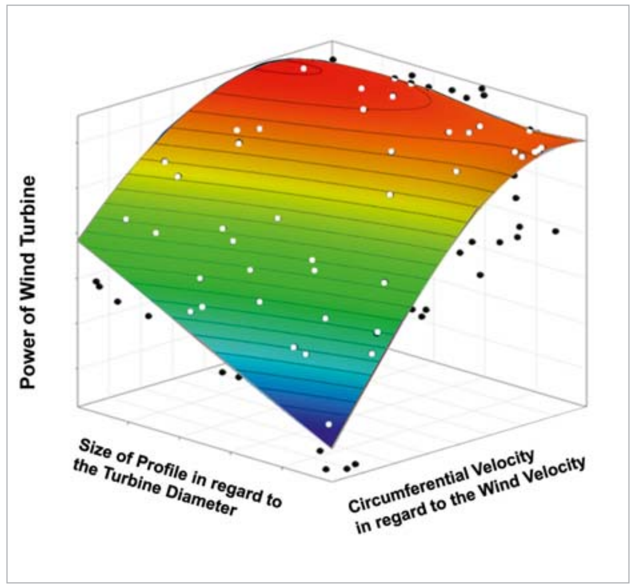

Fig. 14: The metamodel for a wind turbine as target value

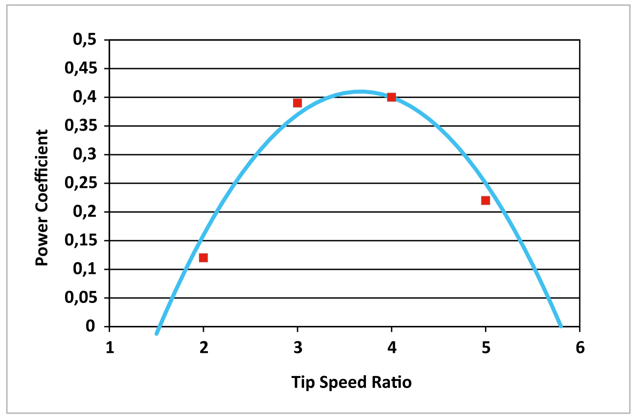

Fig. 15: Validation of parameters computed operational points

In addition, an operating point (red square in Fig. 16b) from measured data has been superimposed; deviation from the model was less than 5%. This vindicates the value of the approach described in this work. It should be said that no flow simulation has been computed for this turbine but rather the curve was derived from the metamodel.

Comparison of the metamodel with conventional methods

A model for semi-analytical computation of vertical axis wind turbines has existed for decades. The computations principle is based on the concept that the turbine rotor consists of a mesh comprised of a finite number of streamtubes, and that the flow size is calculated for each streamtube.

The Double Multiple Streamtube Model developed by Paraschivoiu is the most commonly used model. This model makes it possible to consider the rotor in both the downwind and upwind areas and the interaction of each rotor blade with the air flow.

As streamtubes are created separately in an upwind and downwind area, it is possible to recreate more realistically the effect of the upwind rotor blade on the downwind rotor blade. In this case it is assumed the trail from the upwind blade is fully developed and velocity is fully developed before interaction with the downwind blade.

Fig. 16a: Turbine near Uppsala, Sweden (image source: see last paragraph)

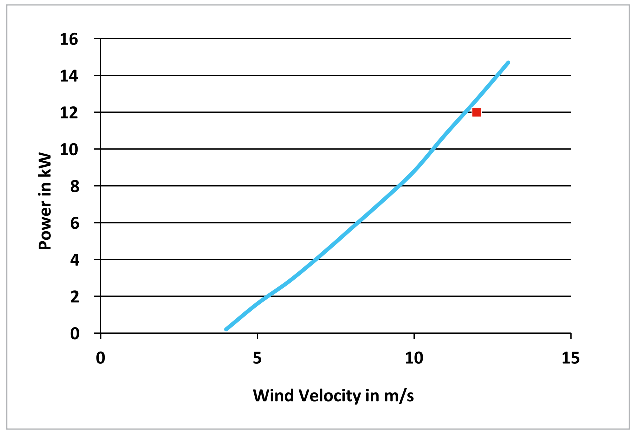

Fig. 16b: Validation of plot by comparison with measured data from an existing turbine near Uppsala, Sweden

Figure 17 shows plots derived from the metamodel (blue) and Double Multiple Streamtube models (yellow). In addition, CFD calculated operational points (red) have also been added for comparison. Greater congruence between the operational points and the metamodel curve strongly suggest it is the more accurate predictor.

Metamodel-based prognosis for three different sites

It is well-known that the effectiveness of wind turbines is strongly influenced by its location. Equally important is the influence of local factors and factors determined by given global boundary conditions. Both can be rapidly calculated using the metamodel, including the influence of local fluctuations in wind velocity, since the metamodel is capable of predicting power output for any given turbine geometry at any given wind velocity.

Figure 18 shows the power output of the turbine as a dimensionless power coefficient plotted against wind velocity as a function of rotational velocity. This graphic clearly indicates at which rpm for a given wind speed the turbine functions optimally.

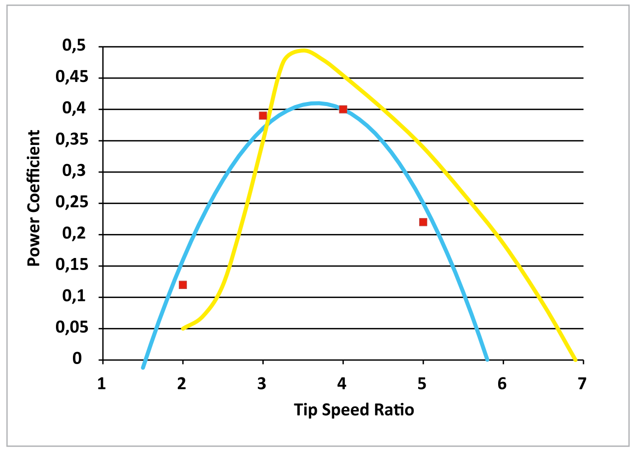

Fig. 17: Comparisons between the Metamodel (blue line), an analytical model (yellow line) and a CFD simulation (red squares)

Turbo Machinery

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Fig. 16a taken from the article: Evaluation of a Blade Force Measurement System for a Vertical Axis Wind Turbine Using Load Cells by Morgan Rossander, Eduard Dyachuk, Senad Apelfröjd, Kristian Trolin, Anders Goude, Hans Bernhoff and Sandra Eriksson (Energies 2015, 8(6), 5973-5996; doi:10.3390/en8065973)

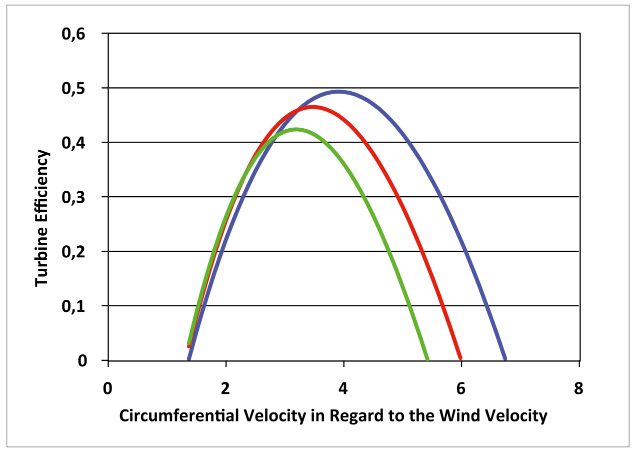

Fig. 18: Curves for different types of turbine location; blue-city; red-island; green-mountain