

# Validation of CFD Wind Resource Modeling in Highly Complex Terrain

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## **Abstract**

Within work package 7 of the Interreg IIIb (Alpine Space Program) project "Alpine Windharvest", CFD wind modeling was performed with WindSim for 7 sites in Austria, Italy, Slovenia and Switzerland in order to gain know-how on CFD modeling in complex Alpine terrain, validate modeling results and promote wind power projects at the mentioned hot spots.

Validation of the modeling results was performed by comparisons of modeled to measured wind climatologies and by comparing modeled vertical wind profiles to profiles measured by SODAR. It was shown that WindSim provides a CFD modeling solution that fulfills the requirements for wind modeling in this type of terrain, in contrast to WAsP or similar diagnostic models.

Discrepancies between modeled and measured data could mainly be ascribed to terrain discretizations inherent to modeling as well as insufficient representation of obstacles, especially forests and hedges.

As is the case with any model of this type, WindSim is especially suitable for extrapolation of measurements within short horizontal distances and extrapolations from high enough measurement heights to hub height in nearby terrain with similar characteristics as the measurement site. High quality measurements at a height of at least 30 m above ground within the modeled perimeter are essential.

## 1. Modeling Concept

### 1.1. Introduction to Computational Fluid Dynamics

The physical aspects of any fluid flow (such as wind flow) are governed by three fundamental physical principles:

- Mass is conserved
- Newton's second law (force equals mass times acceleration)
- Energy is conserved

These fundamental principles can be expressed in terms of mathematical equations, which for fluid flow take the form of unsteady Navier-Stokes equations.

Computational Fluid Dynamics (CFD) is the science of determining a numerical solution to these equations whilst advancing the solution through space or time to obtain a numerical description of the complete flow field of interest.

In order to compute a numerical solution, the situation is discretized: Space is split into numerous small elements (boxes) for which the flow is determined for small time steps. In wind energy applications this procedure is repeated until a steady-state flow is found for certain boundary conditions.

In contrast to diagnostic models, e.g. to WAsP, which calculates wind statistics by parametrizing the influence of topography, roughness and obstacles, CFD modeling computes the three-dimensional wind flow field. It can be compared to a virtual wind tunnel.

By using transport equations for all variables including the turbulent quantities it is possible to capture downstream effects of terrain and roughness changes. In Figure 1 a simplified terrain with a sinusoidal variation illustrates how the development of a flow field evolves with a gradually growth of the boundary layer.

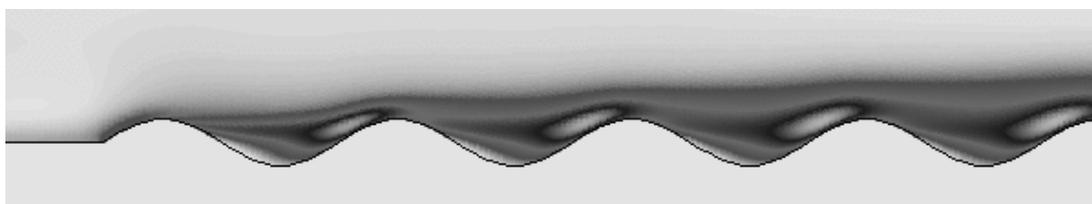


Fig. 1: Development of a flow field over a simplified, hilly terrain.

These characteristics cannot be captured with simplified models commonly in use within the wind industry today. Notice that the flow condition depends on the number of hills upstream. A refined modeling around one of the hills would require information about the upstream conditions. This problem of setting proper boundary conditions is one of the challenges within numerical flow simulations in complex terrain.

## 1.2. WindSim

WindSim is a PC-based CFD package for micro-siting, based on the more general finite-volumes CFD solver Phoenix. Validations of WindSim [1] have already been performed in both, smooth and gently complex terrain [2, 3, 4, 5].

The input basis for WindSim consists of a digital terrain model on a proper length scale, according to the phenomenon under consideration. WindSim can be used in a variety of length scales ranging from detailed micrositing up to larger meso scale wind resource assessments. WindSim uses so called body fitted co-ordinates (BFC) with refinement towards the ground.

In addition to the digital terrain model, a similar model with terrain roughness must be supplied. The terrain roughness has a particular impact in a zone towards the ground.

Finally, WindSim needs climatological data from at least one point within the modeled area. With these primary inputs the wind resources for the whole area can be calculated, the energy production from any number of wind turbines can be obtained, and the area with infrastructure can be visualized in the 3D interactive visualization module.

Figure 2 illustrates the procedure of CFD modeling.

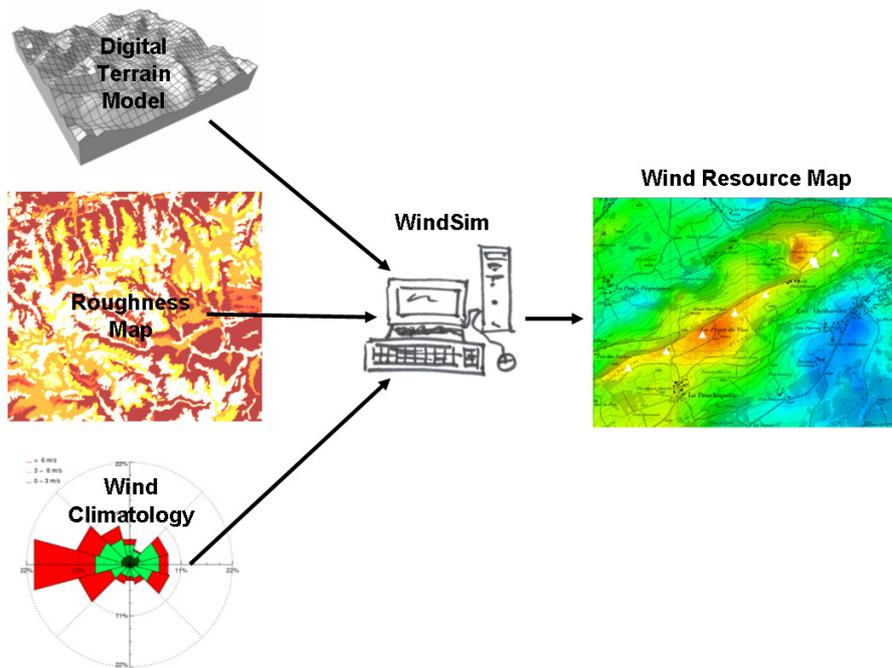


Fig. 2: Procedure of CFD modeling.

## 1.3. WindSim Modeling Techniques

### Gridding

The model domain is gridded into cells, for the nodes of which the calculations are performed: the higher the number of boxes, the better the resolution. The computing time needed is exponentially proportional to the number of cells.

### Nesting

Nesting allows calculating high resolution results with acceptable computing resources. The model can be refined in several nesting steps. The first step includes the whole model domain. Here, very general boundary and initial conditions are assumed: vertical wind speed as log profiles up to a defined height and constant wind speed above. The results of this step are used as boundary and initial conditions for the second nesting step, which is performed for a smaller area at a higher resolution. Further nesting steps can follow, until the desired resolution is reached.

### Sectoring

Flow calculations are performed for a number of predefined wind directions at the model boundaries. Usually, 12 or 16 wind direction sectors are used. For each of these sectors, a flow calculation is performed until a steady-state solution is found. For laminar flow, it can be assumed that the flow fields for a certain sector will be proportional to the incoming wind speed and will not change their characteristics for different wind speeds.

### Climatology and Weighting

In order to compute the wind resources, a local wind climatology (e.g. from a measurement station within the model domain) is needed. This climatology is split into the same wind direction sectors that were used for modeling. For all wind directions, the climatology's wind statistics are transferred to all other locations in the model domain by weighting it with the ratio of the computed wind speed between the climatology's location and the new location.

## **2. Scope**

Within work package 7 of the Interreg IIIb (Alpine Space Program) project "Alpine Windharvest", CFD wind modeling was performed for 7 sites in Austria, Italy, Slovenia and Switzerland in order to gain know-how on CFD modeling in complex Alpine terrain, validate modeling results and promote wind power projects at the mentioned hot spots.

It was decided to perform Computational Fluid Dynamics (CFD) wind modeling with WindSim, a PC-based commercial CFD software for wind assessments, in order to achieve the following goals:

- gain know-how on CFD modeling procedures in alpine terrain
- validate CFD modeling results for alpine terrain
- promote regional development by supplying state-of-the-art wind assessments for wind energy projects

The results are available on the internet [6].

### 3. Validation

#### 3.1. Climatology Transfer

Climatology transfer is achieved using the wind fields calculated by WindSim: A measured climatology location is transferred from the measurement location to an arbitrary location within the model domain by comparing the wind fields at both locations in all corresponding wind direction sectors.

For validation purposes, two measured climatologies from parallel measurement series at two locations are required. These climatologies are each transferred to the other location. The transferred climatologies are then compared to the original ones.

Wind direction shifts were very nicely reproduced (fig. 3). Changes in wind distribution were well reproduced while changes in mean wind speed were only roughly reproduced, with some 0.2 m/s difference between measured and modeled values. The deviation in wind speed is not surprising: The measurements were performed at 12 m above ground, which is in a very turbulent zone where small differences between real and model topography lead to significant changes in wind speeds. Additionally, horizontal model resolution was partly quite low. Therefore, the result can be considered as very promising.

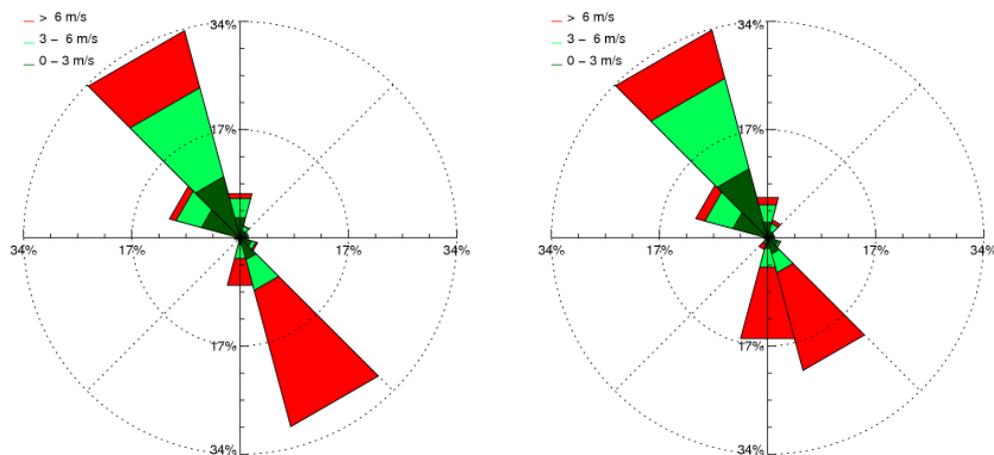


Fig. 3: Wind roses of measured (left) and transferred (right) climatology.

#### 3.2. Comparison to SODAR Profiles

Generally WindSim reproduced the measured profiles of wind speed very well, as it is shown in figure 4 on the left.

WindSim seems to have difficulties to reproduce profiles where wind speed declines with height (figure 4 middle). These profiles have in common that they were measured close to the edge of a steep slope in the wind direction. Is this discrepancy the result of "wrong" modeling behavior or of insufficient representation of the real topography in the model? Discretizing the terrain for modeling smoothes the topography. With rougher resolution, more details are lost and the

smoothing effect is stronger, which leads to less pronounced speed-up effects in the model. As situations as described above are common in complex terrain, this question needs further investigation.

Wind speed increases very strongly with height, when influenced by nearby forests and hedges. As shown in figure 4 on the right, these effects are insufficiently reproduced and wind speeds at hub height are underrated by the model, even though a relatively high roughness length of 1.5 m was defined for forest. However, it has been established that the effects of trees can not be reproduced by roughness alone [7]. In WindSim there is a possibility to include semi-permeable obstacles, which might reproduce these effects more satisfactorily. Investigating this possibility was outside of the scope of the current project but will be addressed in the future. In the recent version of WindSim, which appeared after the end of the Windharvest project, a canopy model was included.

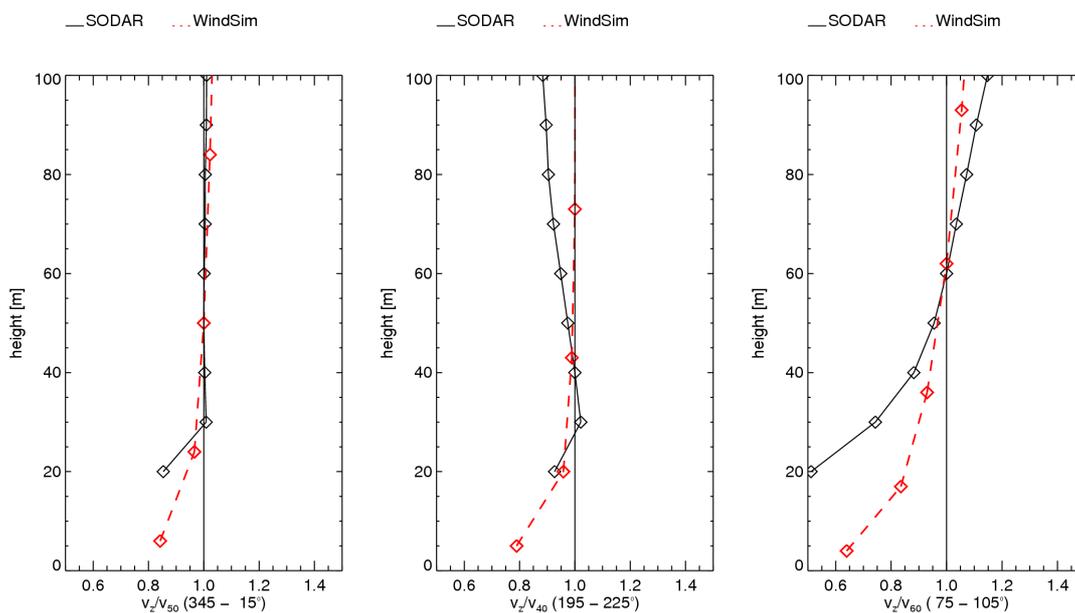


Fig. 4: Comparison of measured and modelled wind speed profiles. Left: Good agreement between measured and modelled profile. Middle: Speed-up on a steep terrain edge not reproduced by the model. Right: Influence of a nearby forest insufficiently reproduced by the model.

## 4. Recommendations

### 4.1. Input data

Any modeling result is only as good as its input data. What applies to wind assessments in simple terrain is even more important in complex terrain as errors can be multiplied in highly variable wind fields.

### Wind climatology

A highly accurate long-term wind climatology at an adequate position and height is the basic and most important requirement for accurate modeling results. Errors in the input wind climatology will be spread to the whole model perimeter by WindSim's weighting procedure. The following aspects should be considered:

- Perform professional on-site measurements according to the established standards.
- In cold climate, include some form of protection from icing (heated or ice-resistant sensors).
- Accurate wind direction measurements are essential (due to the highly variability of wind conditions in function of direction).
- Adapt redundancy in electronics and sensors to harsh conditions.
- Obtain at least one year of data (without gaps).
- Measure as high above ground as possible (at least 30 m; preferably 50 m), as lower measurements will be too strongly influenced by the small scale surface that can often not be reproduced in sufficient detail in modeling due to discretization.
- Wisely choose the measurement site: It should be within the planned wind park perimeter at a well exposed and characteristic location. Avoid obstacles, extreme locations (on top of ledges or cliffs) and locations where the wind is canalized.
- If topography characteristics within the wind park perimeter change significantly, measurement at several sites might be needed.
- Obtain accurate and homogenous reference data that correlate well with the on-site measurement data in order to calculate a reliable long term climatology.
- Precisely determine the measurement location (e.g. with GPS) and note coordinate system, map projection and datum. A 360° panorama from the measurement site can be very helpful when interpreting modeling results.
- Obtaining a climatology by climatology transfer from a nearby site when no on-site measurements are available is usually not a solution in complex terrain. Transferred climatologies reproduce wind direction shifts well, but there will be differences in absolute wind speed.

### Air density and power curve

- Wind power is proportional to air density. Calculate the site's air density at hub height precisely from temperature and pressure measured on-site or at a nearby measurement station.
- WindSim (and other models) adapt power curves to air density proportionally. This correction does not exactly match the real behavior of the power curve at lower air densities. The power production can be under-estimated by up to 3.6% for low air density [8].

For best results, obtain a power curve that is adjusted to the site's air density and turbulence from the turbine manufacturer.

### Topography

- As was shown in the validation with SODAR measurements, generalized terrain can cause substantial modeling errors. It is therefore essential to obtain a precise digital elevation model with a good resolution of 50 m or better. Roughness information should be available at a resolution of 100 m or better.
- Account for horizontal shifts due to different map projections or datums. Small horizontal deviations will result in large height differences in complex, variable terrain. Check the topographical data well around the site for shifts, inconsistencies and errors.
- Carefully define and map roughness lengths around the wind park perimeter. For more distant regions, roughness can be estimated from land use data.

### Obstacles

- Obstacles can not be easily included in the model. Therefore chose measurement locations away from the influence obstacles.
- A known difficulty is including forests or hedges in the model. The effects of forests and hedges can not be sufficiently reproduced by roughness. Forests should be included as semi permeable obstacles, but experience has yet to be gained in this field.

## **4.2. Model domain, nesting**

Carefully choosing a modeling domain is essential in order to include all relevant effects, avoid undesirable effects and attain a sufficient result resolution.

Nesting enables including relevant up- and downstream effects at a lower resolution and still obtaining high resolution results for the wind park site with acceptable computational time.

As was shown in the validation with SODAR measurements, it is essential to do modeling at the best possible resolution in the final nesting step in order to obtain accurate results.

We recommend observing the following aspects:

- Preliminary test runs for main wind direction sectors help recognizing problematic input conditions early.
- Choose the initial model domain to include relevant up and downstream effects in the main wind directions.
- Wisely select nesting domains in order to ensure correct up- and downstream wind conditions (valley systems, blocking mountains etc.) and to avoid undesirable boundary effects.

### 4.3. Checking, Validation

Checking results in a variety of ways is an integral part of the modeling procedure:

- Check resulting wind field for absolute values as well as plausibility with respect to topography (wind speed maximums at implausible locations e.g. valleys, depressions).
- Check model edges and roof for blocking effects.
- Climatology transfers are a good validation method for short distances. Enough consistent, overlapping measurements free from small-scale surface influences are required at both locations.
- SODAR comparison is very good validation method. Care should be taken when comparing values close to the ground (< 30 m) as these are problematic in SODAR measurements as well as in modeling.

## 5. Limitations and Shortcomings of WindSim

Being a model, WindSim strongly simplifies the environment it represents. It is important to be aware of these simplifications when modeling and interpreting model results. It is often possible to adapt the model setup and input data in a way to minimize adverse effects on the results.

The following list contains some of the more important limitations of WindSim:

- WindSim assumes a neutrally stratified atmosphere. Of course, this does often not represent the real situation, especially in Alpine regions, where inversions and thermal effects have a big influence on wind. However, for a restricted area, wind flow will mainly be determined by the small-scale topography and can therefore be well reproduced by WindSim's "wind channel approach", if a wind climatology is available within this area.
- WindSim does not provide an easy method of including obstacles. Usually, problems can be avoided by positioning wind measurements outside of obstacles' influence. However, problems arise with forests and hedges, the effects of which can only insufficiently be by roughness. Investigations on how to include these effects – possibly by defining semi permeable obstacles – should be performed.
- The nesting procedure imposes artificial walls on the top border, as well as on the east and west borders for simulations for sectors 0° and 180° and on the north and south border for simulations for the sectors 90° and 270°, which could impose unphysical directional shifts and blocking effects. These problems can be avoided by raising the top boundary to a height where wind flow is horizontal and by choosing model boundaries for which there is little wind speed deviation on the side borders. Fulfilling the latter condition is often problematic in complex, Alpine terrain. According to Vector, a better procedure for determining in- and outlets will be developed for WindSim.
- As mentioned above, WindSim (and other models) proportionally adapt power curves to air density. This correction does not exactly match the real behavior of the power curve at lower air densities. The power production can be under-estimated by up to 3.6% for

low air density [8]. For best results, obtain a power curve that is adjusted to the site's air density and turbulence from the turbine manufacturer.

- In extremely complex terrain it was found to be difficult to run the model in the desired high resolution, as no convergent solution could be established. This could be caused by single cells which are too steep, improper boundary conditions from coarse model due to too small scale topography changes or flow separation out of model box.

A list of known bugs and shortcomings of WindSim is available at the WindSim homepage [1].

In the scope of this study, it was not possible to consider all aspects of CFD modeling with WindSim. We especially plan to examine the possibilities of including forests and hedges more closely in the near future. Additionally, we plan to perform more validation studies with more suitable measurements at higher model resolution.

## 6. References

- [1] <http://www.windsim.com>
- [2] Schaffner, Gravdahl, 2003: Wind Modeling in Mountains: Intercomparison and Validation of Models.
- [3] Gravdahl, 1998: Meso Scale Modelling with Reynolds Averaged Navier-Stokes Solver – Assessment of wind resources along the Norwegian coast. International Energy Agency Annex XI, Risø Denmark.
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- [6] <http://stratus.meteotest.ch/windharvest>
- [7] Presentations at Tree Workshop by BWEA on 17.03.2004.
- [8] <http://www.windpower.org/en/tour/wres/guidep.htm>

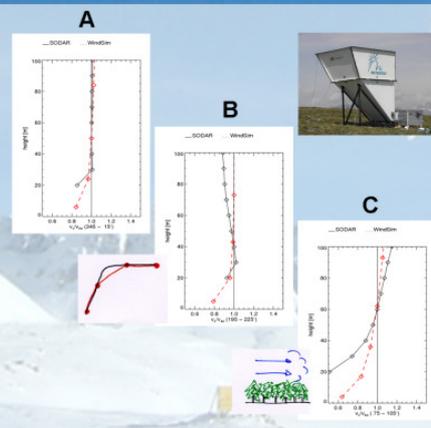
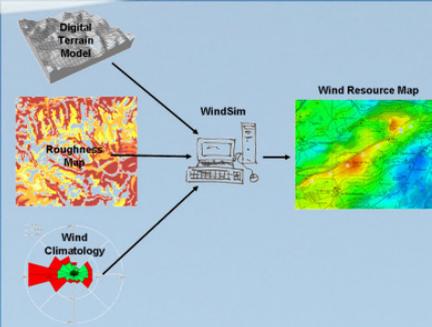
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In the framework of the Interreg IIIb project "Alpine Windharvest", METEOTEST performed CFD modeling with WindSim for seven highly complex Alpine wind energy sites in Austria, Italy, Slovenia and Switzerland. Validation of the modeling results was performed by comparisons of modeled to measured wind climatologies and by comparing modeled vertical wind profiles to profiles measured by SODAR. It was shown, that WindSim is a CFD solution that can produce accurate results in this type of terrain.

Computational Fluid Dynamics (CFD) is based on three dimensional, non linear flow modeling, comparable to a virtual wind tunnel. With this method, it is possible to capture downstream effects of terrain and roughness changes, which are very common phenomena in complex terrain.

The required input data consists of a digital terrain model, a roughness map covering the area of interest as well as a long term wind climatology at one point inside the model domain.



Validation of the modeling results were performed by comparisons of modeled to measured wind climatologies and by comparing modeled vertical wind profiles to profiles measured by SODAR.

It was shown, that in most of the cases, WindSim provides a CFD modeling solution that fulfills the requirements for wind modeling in this type of terrain (A).

Discrepancies between modeled and measured data could mainly be ascribed to terrain discretizations inherent to modeling (B) as well as insufficient representation of obstacles, especially forests and hedges (C).

The results of the model validations made clear, that CFD is a promising tool to predict wind power production in complex terrain. Still, the use of such models requires careful preparation of input data as well as numerous modeling cycles in order to define adequate boundary conditions.

