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CFD WIND MODELING BEST PRACTICES

Will Increasing the Number of Calculated Wind Directions Improve Accuracy?

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WHITE PAPER- PUBLIC REPORT

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Abstract

The presented case study is part of an extensive parametric analysis performed on microscale wind modeling of base-case sites. In this white paper, the number of CFD directional computations considered is varied to assess the impact in terms of modeling accuracy, reliability and wind phenomena spotting.
The studied site is the one used for the onshore Comparison of Resource and Energy Yield Assessment Procedures (CREYAP) exercise proposed by the European Wind Energy Association (EWEA) in 2013. While the number of directional computations has shown no significant impact on speed and energy modeling accuracy and reliability due to the relatively moderate complexity of the terrain, this number appeared to be of major importance for IEC site-suitability (inflow angles, turbulence intensity...). Dangerous wind flow phenomena at several turbine locations cannot be numerically modeled with a limited number of calculated directions.

New best practices are defined in complex sites, with a minimum number of 48 directional computations (72 for extremely complex sites) that need to be performed to ensure site suitability at every machine location. The impact on the total computation time along with available solutions to tackle the issue are discussed in the latter part of the article.

1 Introduction

A CFD microscale wind modeling process involves the definition of several quantitative parameters (number of cells -i.e. resolution-, number of directional computations, number of solver iterations...) along with a qualitative approach to define the resolution distribution inside the mesh. This process is roughly common to every existing commercial CFD software for which users are provided with suggestions on how to define such quantitative parameters. Yet, there has been no formal study undertaken to verify whether these common practices can actually be considered as best practices.
This case study is part of a larger work undertaken by MeteoPole to define best practices for microscale CFD wind modeling. More specifically, it is part of an extensive parametric analysis performed on the well-known base-case site proposed for the onshore Comparative Resource and Energy Yield Assessment Procedures (CREYAP) exercise by the European Wind Energy Association (EWEA) in 2013.
The number of CFD directional computations considered is varied to assess its influence on modeling accuracy, reliability and wind phenomena spotting. Results provide guidelines to define a minimum number of directional computations to be considered to perform an acceptable CFD site modeling. The impact of this minimal setting on the total computation time needed along with available solutions to tackle this issue are latter discussed.

2 Modeling Parameters

For complex terrains such as in the CREYAP project, MeteoPole uses a calculation model based on the three-dimensional solving of the fluid dynamics equations (RANS 2-equations closure scheme, steady-state, incompressible, isotherm): **ZephyCFD**.

2.1 Calculation Domain

The calculation domain consists in a cylindrical volume covering the project layout. A rectangular area -over which the wind maps (Wind Resource Grids) will be generated- has been defined at hub height in order to fully cover project's boundaries. The project is centered on this surface. The seven masts installed on-site and from which measurements will be extrapolated have been defined in the form of vertical profiles.

The project is visualized on Figure 1.

2.2 Topography Data

The topography data used were provided to the CREYAP exercise's participants from **RES** company.

In order to feed the model with terrain variations, a Digital Terrain Model (DTM) is used with a resolution of 50 meters, which is considered sufficient in view of the terrain's complexity.

Land cover data were provided as shape files from which a roughness map was generated and then interpreted by the CFD model. The local roughness for each surface cell at ground level can then automatically be taken into consideration by the model.

2.3 Discretization of the Calculation Domain - Meshes

Two different meshes are usually generated in order to optimize calculations configuration and reduce simulations costs:

- A relatively loose mesh is used to evaluate the wind characteristics for the non-prevailing directions of the wind rose;
- A highly refined mesh is used to evaluate the wind characteristics for the prevailing directions of the wind rose.

In this study, a fine mesh was used for every calculated direction to allow accurate analyses without time constraints.
In ZephyCFD, the mesh algorithm generates boundary-fitted unstructured meshes. The mesh is made of prismatic cells. It is refined around domain center, and coarsened near the side boundary conditions. In vertical direction, the mesh is refined toward ground boundary conditions.
A coarse version of the mesh is automatically generated, to allow a flow initialization calculation.
While generating a mesh with ZephyCFD, the number of computable directions also defines the number of

nodes at the domain boundaries. Several meshes are generated by varying this parameter while keeping a constant total number of cells (2 millions). Table 1 presents the resulting mesh characteristics. We can observe the different resolution levels in both the central refined area as well as at the domain boundaries for different number of computable directions with a fixed number of cells.

Table 1: **Mesh Characteristics**

Parameter	Mesh 1	Mesh 2	Mesh 3	Mesh 4	Mesh 5	Mesh 6
Computable Directions	12	18	24	36	48	72
Number of Cells	2020800	2036400	2024640	2045160	2050320	2088360
Calculation Domain Diameter	25 km					
Refined Area Diameter	5 km					
Calculation Domain Height	5000 m					
Horizontal Mesh Resolution in Refined Area	41.9 m	42.9 m	44.1 m	46.8 m	50.4 m	59.7 m
Horizontal Mesh Resolution near Side Boundary Conditions	3276.9 m	2184.6 m	1638.5 m	1092.3 m	819.2 m	546.2 m
Ground Vertical Resolution	2 m					

Figure 4 presents surface visualizations of these meshes.

2.4 Calculation Parameters

To perform the Computational Fluid Dynamics (CFD) calculations, ZephyCFD runs **OpenFOAM** which is an open source CFD solver developed primarily by OpenCFD Ltd. since 2004. A total of 210 calculations were performed on the six considered meshes with 12, 18, 24, 36, 48 and 72 directions. Each calculation was performed with a ZephyCFD predefined set of parameters called *ZS_normal*. It is one of the 4 predefined CFD calculation configurations. It uses *k-epsilon turbulence model* with modified constants.
Table 2 gives the main calculation parameters.

Table 2: **Main Calculation Parameters**

Parameter	Value
Maximal Number of Iterations for Flow Initialization Run (Coarse Mesh)	1325
Maximal Number of Iterations for Final Calculation (Fine Mesh)	1250
Convergence Criterion on Pressure solution	5.00e-04
Convergence Criterion on Momentum solution	1.00e-05
Convergence Criterion on Turbulent Kinetic Energy Solution	1.00e-05
Convergence Criterion on Turbulent Dissipation Rate Solution	1.00e-05
Relaxation Factor on Pressure Solution	0.30
Relaxation Factor on Momentum Solution	0.70
Relaxation Factor on Turbulent Kinetic Energy Solution	0.50
Relaxation Factor on Turbulent Dissipation Rate Solution	0.50

2.5 Comparison between Extrapolation Results and Measured Data

To assess results accuracy, a time series of wind speeds and directions measured at one of the meteorological masts (called the reference mast) is extrapolated to the entire domain by each of the 6 models under consideration. Extrapolated time series can then be generated at other masts locations (called the target masts) and compared to the measured ones at the same location and height. On the CREYAP site, seven different masts were used during the measurement campaign. M49 was deployed as the primary site assessment mast for a period going from October 2001 to September 2006. As a result, this mast will be the one used as the reference mast to perform the wind flow extrapolations. For the period from October 2001 to March 2002, two additional masts were deployed on shorter measurement campaigns at six locations around the site, thus increasing the spatial resolution of site measurement data.

After removing the erroneous data (due to anemometers or vanes failures), three periods (namely A, B and C) are available for comparing modeling results with actual measurements on a 10-min time basis. Figures 2 and 3 illustrate these measurement periods and show the measured wind rose at M49 mast location.

For each time series, the error on wind speed and wind direction can be calculated. These errors are functions of several factors in addition to the model quality (distance to the reference point, terrain complexity between the reference mast and the target mast...) but such factors are fixed from one model to another. Therefore, even if these errors cannot give an absolute rating of the site modeling quality, they allow ranking the different models and their associated sets of parameters for one given site.
The wind speed and direction Root Mean Squared Error (RMSE) have thus been calculated on every available measurement point. The averages of these RMSE are taken as indicators to assess accuracy and to rank the different models between them.
In each of the three available periods of comparison, the three masts provide values at heights of 40 and 50m. The values on M49 at 50m are used to extrapolate the results, which provides 5 comparison points for each period.

3 Results

3.1 Accuracy

Figures 5 and 6 show for each period and each available mast the average speed profile and the measured average speeds with 2% error bars, for 12 and 72 computable directions.
Table 3 gives the resulting mean RMSE for each set of parameters considered.

Table 3: **Accuracy Results**

Parameter	Mesh 1	Mesh 2	Mesh 3	Mesh 4	Mesh 5	Mesh 6
Computable Directions	12	18	24	36	48	72
Wind speed mean RMSE [m/s]	0.75	0.79	0.75	0.74	0.74	0.73
Wind direction mean RMSE [°]	7.44	7.36	7.31	7.31	7.32	7.31

The results are good for every model with speed errors of below 2% regardless the mesh. We can see on Table 3 that **no significant improvement can be seen in terms of pure accuracy on the CREYAP site by increasing the number of directional computations**

3.2 Reliability: Convergence Monitoring

The CFD calculations follow an iterative process. Throughout a CFD run, the equations tend to balance and the results tend to stabilize (the calculation is converged). Unstable results can possibly cause wrong wind resource assessment. With complex terrain, achieving convergence is more challenging, and thus it is particularly important to check that the solution is stationary when the calculation is stopped. It is also recommended to do it at several domain key locations since some of them could have reached convergence while solutions at other locations are either diverged or not fully converged.

Figure 7 shows the evolution of the solution during the iterative process for the prevailing direction (from 210° to 225° depending on the number of computable directions); the displayed variable is the wind speed at each of the 7 masts locations, for 3 different heights (40, 80 and 120 meters). This allows to verify that the model behaves well, and that the solution obtained is reliable for the prevailing sector.
Even though only results at masts locations and for the prevailing direction are showed here, similar verifications have been done at every turbine location, for every direction and for each of the 6 models of this study.
We can conclude that every calculation considered in this study give reliable -fully converged- results.
The convergence speed is not investigated since increasing the number of directions does not have any influence on this parameter.

4 Phenomena Spotting

In addition to accuracy and reliability, a criterion for choosing an optimal set of parameters is whether or not the model is able to spot specific wind phenomena:
After extrapolation of the CFD results, it is important to check wind shear, turbulence intensity, and inflow angles for every possible wind sector at each turbines locations to ensure IEC site suitability. Values higher than the acceptable IEC standards for any of these parameters represents a low wind quality resulting in power output reduction and fatigue loading increase. Under certain conditions, wind recirculations might occur which can greatly reduce any wind turbine's lifetime if not spotted before installation. Although prevailing directions are usually investigated in details by microscale wind simulation engineers, an unspotted flow recirculation on a non-prevailing direction can be harmful as well and should be identified.

4.1 Wind Inclination and Direction Variation

Changing the number of directional computations have shown no significant impact on wind inclination (vertical inflow angle) and direction variation (horizontal deviation angle) results.
Considering wind inclination, the maximum observed difference between the 12 and 72 directions computations results is found to be on T5 for a wind direction at M49 location of 144° and the difference is only of 1.4°. As for wind direction deviation, T21 shows the maximum difference and it is only of 2.4°.
Figures 8 and 9 show CFD results interpolations for the two parameters at the masts locations for both 12 and 72 computed directions models.

4.2 Speed Up and Turbulence Intensity

Between the 12 and 72 computed directions models, a maximum Turbulence Intensity difference of 16% was found on T19, and a maximum Speed-Up difference of 0.3 (normalized with M49 results) was found on T19 as well. These are significant differences and an **in-depth analysis of these quantities showed that results interpolations are greatly impacted by the number of directional computations**. This is especially surprising for Speed-Up results interpolations since the final extrapolation results were not significantly different in terms of accuracy.

Figures 10 and 11 plot interpolated Turbulence Intensity and Speed-Up results against wind direction for turbines T6, T14, T18 and T19, for each model with different number of directional computations. The prevailing wind sector is highlighted and we can observe little difference between the different models in the prevailing sector which largely explains the similar final extrapolation results in terms of accuracy.

At the four turbine locations, we can observe turbulence and speed peaks on a specific wind sector. We can also see that 12 and 18 computed directions models are not sufficient to correctly assess wind speed and turbulence at these locations. Values in some sectors are underestimated while some others are overestimated (120° to 150° for turbulence at T14 location for example). **The most outstanding turbulence intensity peak (35%) is observed at T19 location for winds blowing from 135° direction and this peak can be spotted with at least 24 computed directions.** There is a another significant peak (24%) observed at T18 turbine location which appears for winds blowing from 130° which is completely unseen with less than 24 computed directions and can be spotted with a minimum of 36 computed directions. We can also observe that some peaks are visible with 24 computed directions and not with 36 computed directions because the 105° direction is not computed anymore with the 36 computed directions model (One calculation every 10°).
Similar analyses and findings on all the results make 48 directional computations the minimum setting which allows to properly spot every Turbulence Intensity and Speed-Up peak.

4.3 Phenomena Interpretation

These observations could be due to the fact that the generated meshes are different from one model to another, especially since fewer computable directions involve a mesh with coarser resolution near the domain boundaries. To appreciate that, the same analysis was performed on results obtained by using only 12, 18, 24, 36 and eventually all of the 72 computable directions from the same mesh (i.e. the mesh with 72 computable directions and 144 nodes at the domain boundaries). Observations remained the same as it can be seen on Figure 12 and Figure 13 and it is thus possible to say that **these results are not grid-dependent**.

The observed differences are essentially due to the fact that the considered variables are interpolated between the available computed directions results. If there are less computed directions, the results interpolation process might ignore phenomena confined within a specific directional sector.

Finally, as previously stated, **it is possible to conclude from the observations that 48 directional computations is the strict minimum for a reliable turbulence and speed assessment on the CREYAP site.** It should be noted that the 30° step often used in the industry can lead to wrong turbulence and speed estimates at some of the key locations.

5 Conclusions: Minimal Setting

In terms of accuracy and reliability, the number of directional computations does not seem to have an impact for this particular site as results from the different models are satisfying with speed extrapolation errors below 2% and with fully converged solutions. A conclusion derived only from the final extrapolations results would therefore be that it is not necessary to compute more than 12 wind directions for this moderately complex site. Yet, when considering Turbulence Intensity and Speed-Up results interpolations, significant differences are identified between models with different number of computed directions. **The interpolation errors related to lower number of computed directions can be crucial in terms of IEC site suitability assessment, even though the final extrapolation results are satisfying in terms of energy yield assessment.**

We can conclude that **48 directional computations should be considered as a minimum for a reliable wind and site assessment of the CREYAP project.**

6 Impact on Computation Time

There is an obvious reason for the 12 sectors approach to be used in the wind modeling space as 48 computed sectors instead of 12 significantly increase the computational power requirement.
A relatively powerful hardware (HP Z400 6-DIMM WorkStation - Intel® Xeon(R) CPU W3680 @ 3.33GHz - 6 CPUs - 23.5 GiBRAM) was used to compare performances between local runs with ZephyCloud runs. Given that the generated meshes are made of approximately 2 million cells and that around one thousand solver iterations were performed for each of the computed directions based on ZephyTOOLS predefined set of solver parameters, **this study would have taken approximately 11 days with local runs based on this powerful hardware. It actually took less than 2 hours in total with ZephyCloud.**

The solution which Zephy-Science uses and offers to ZephyTOOLS users is to take advantage of cloud computing capabilities made available by Amazon Web Services directly through the software interface. This approach is unique in the wind modeling space and allows wind engineers calculating an unlimited number of directional computations and for different models of the same projects or different projects simultaneously thanks to parallel calculations on powerful cloud servers (usually 36 cores each, up to 128 cores each for massive jobs). This means that the total calculation time is equal to that of the longest directional computation, no matter how many directional runs are performed at the same time.

Table 4 sums up the differences in computation time between local runs with the above hardware configuration and ZephyCloud for each of the models under consideration in this study.

Table 4: **Performance Comparison**

Number of Directional Computations	Estimated Total Time with Local Runs	Total Time with ZephyCloud	Performance Improvement
12	17h 34mn	1h 15mn	× 14
18	22h 52mn	1h 12mn	× 19
24	1d 6h 53mn	1h 17mn	× 24
36	1d 15h 25mn	1h 28mn	× 27
48	2d 13h 26mn	1h 24mn	× 44
72	3d 21h 3mn	1h 51mn	× 50
Complete Study	**11d 1h 16mn**	**1h 51mn**	× **143**

As a result, calculating 48 directional computations as advised earlier could indeed take too long with local runs but this limitation no longer exists with cloud computing.

7 Figures

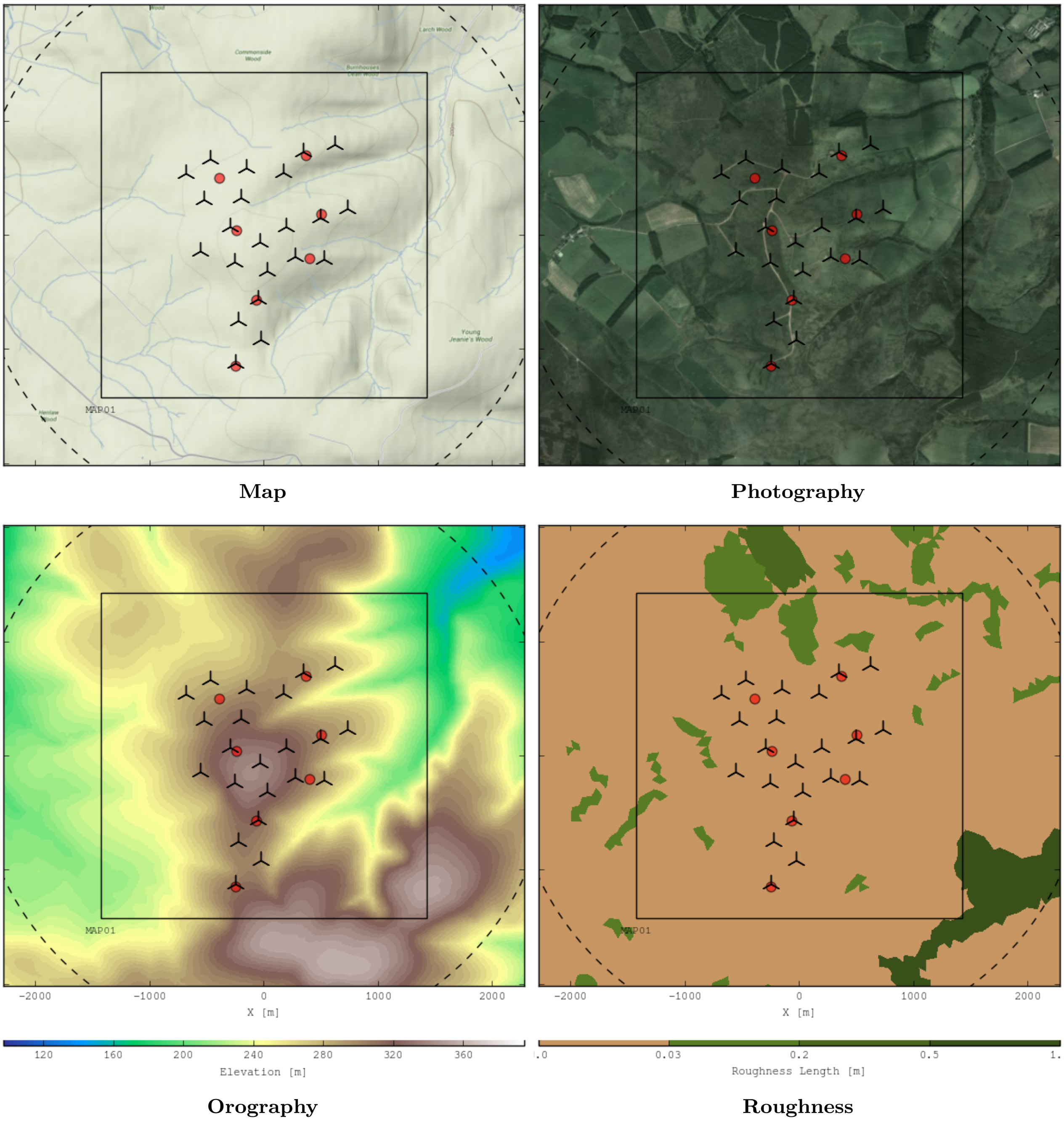


Figure 1: **The CREYAP Project as defined in ZephyCFD**

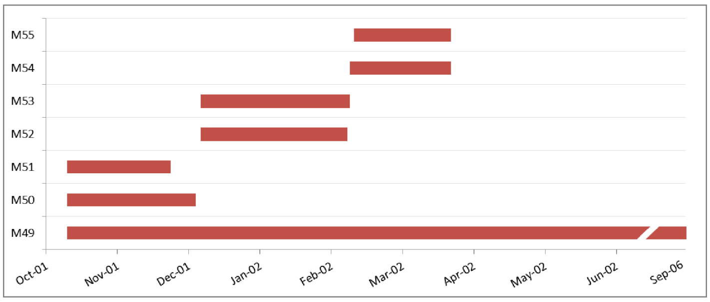


Figure 2: **Available Measurement Periods**

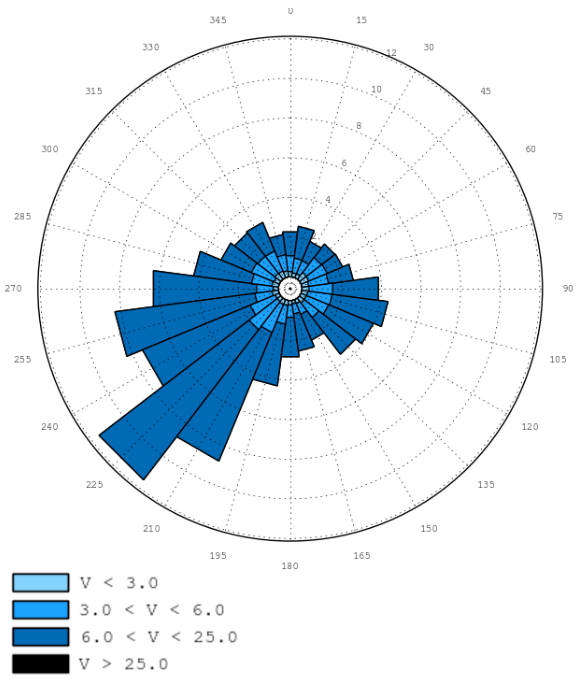
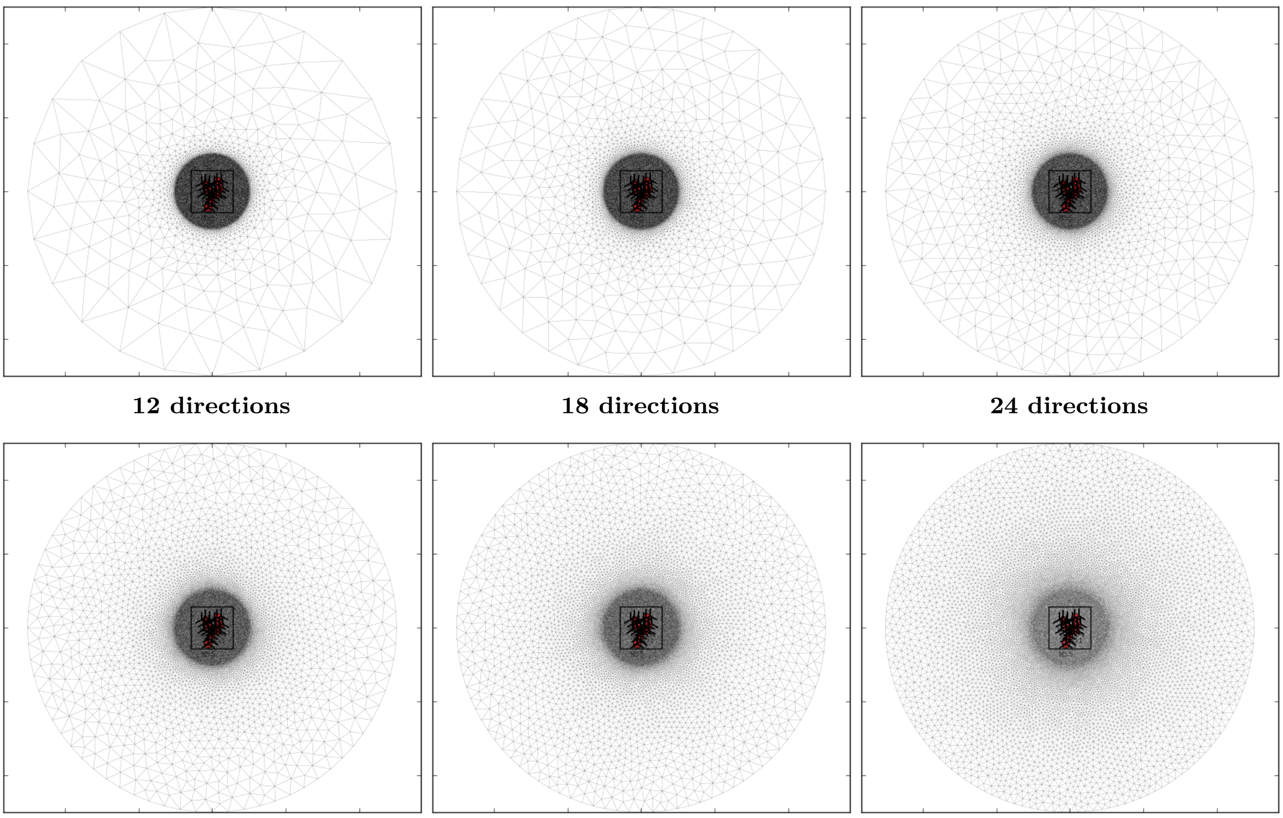


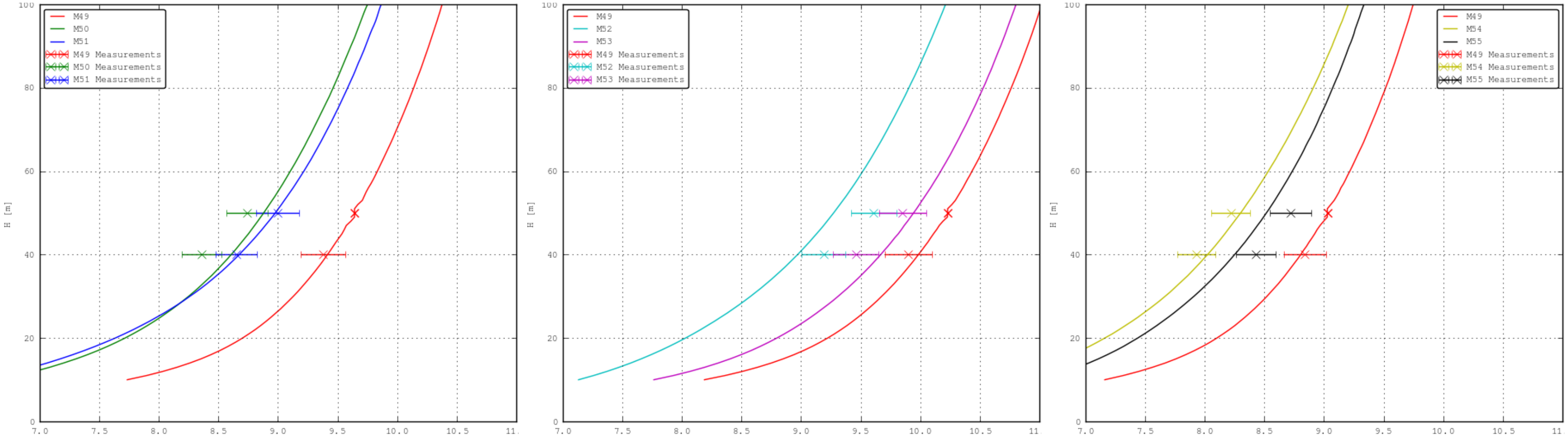
Figure 3: **Wind Rose at Reference Mast (M49)**



12 directions **18 directions** **24 directions**

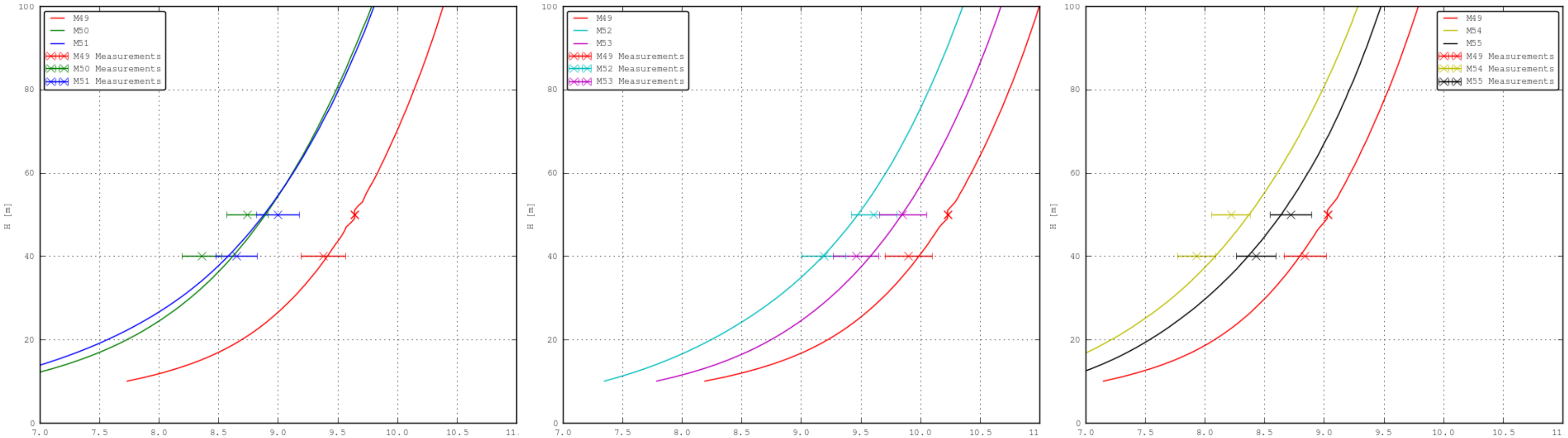
36 directions **48 directions** **72 directions**

Figure 4: **Mesh Ground Visualization of the Fine Meshes for the Different Models with Different Numbers of Computable Directions**



Period A **Period B** **Period C**

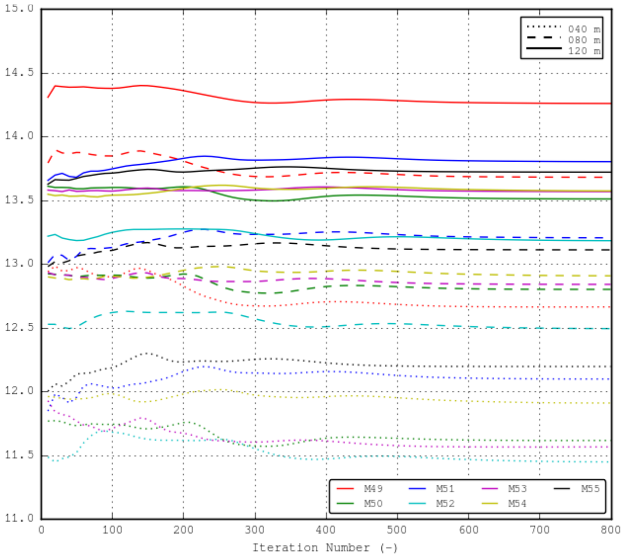
Figure 5: **Average speed profiles [m/s] at available masts obtained with 12 computable directions**



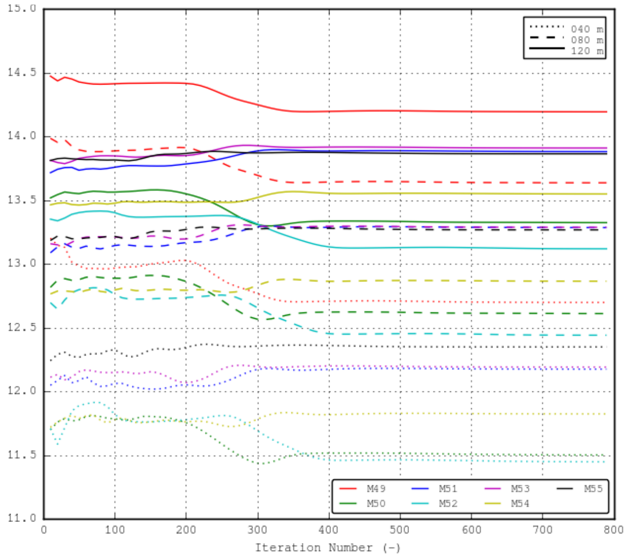
Period A **Period B** **Period C**

Figure 6: **Average Calculated Speed Profiles at Masts Locations obtained for 72 Computable Directions**

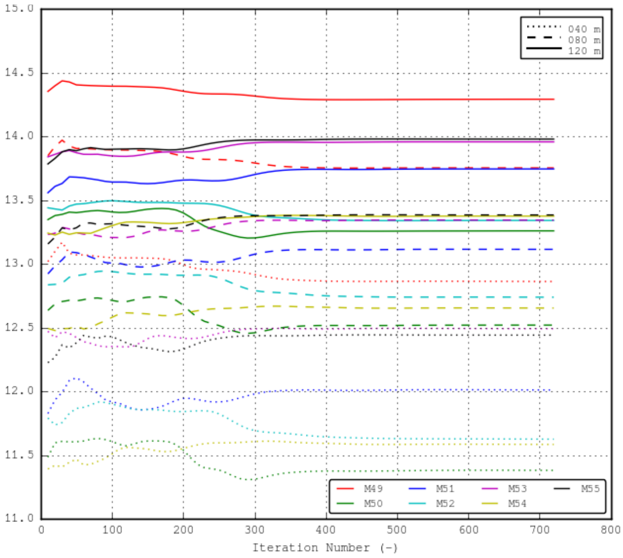
On all the figures, average speeds measured at 40m and 50m are given with 2% error bars.



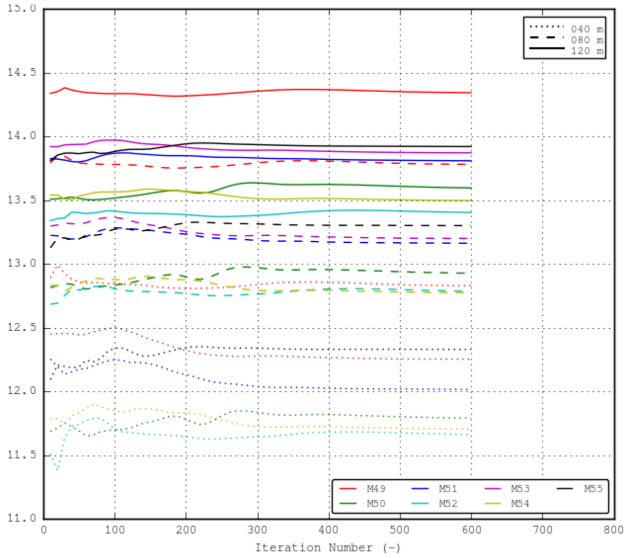
12 directions



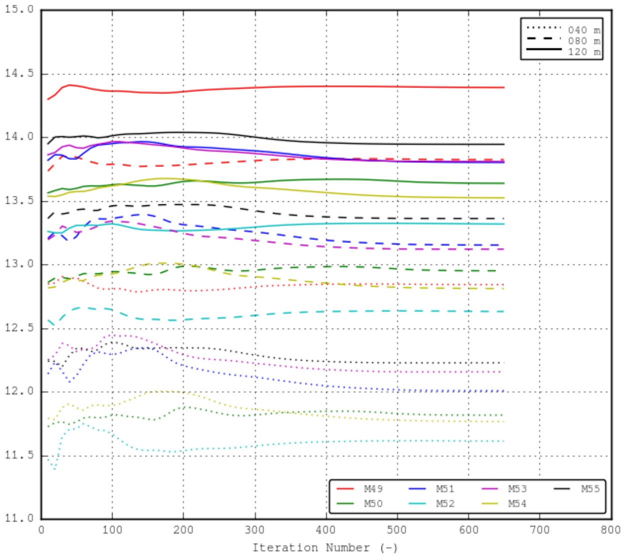
18 directions



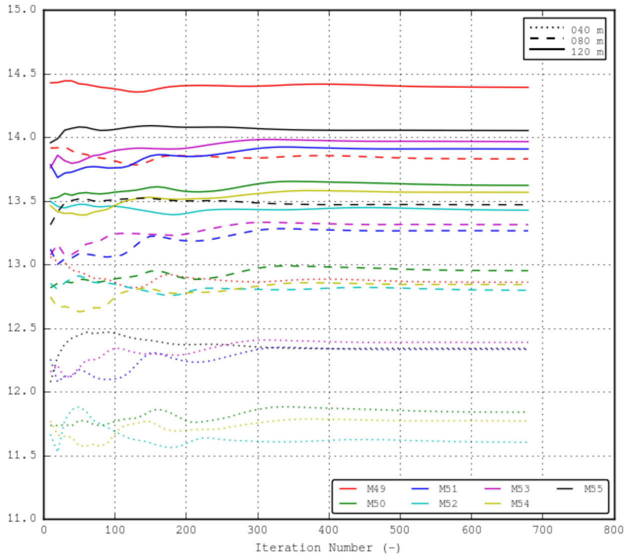
24 directions



36 directions



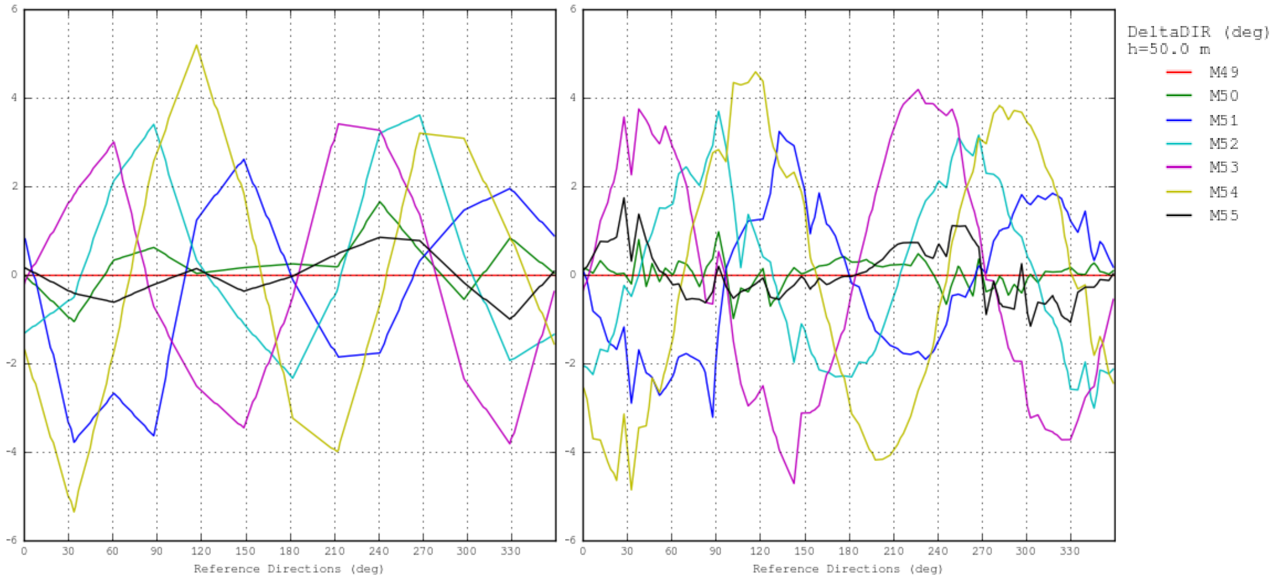
48 directions



72 directions

Figure 7: **Wind Speed Convergence Monitoring for the Prevailing Direction**

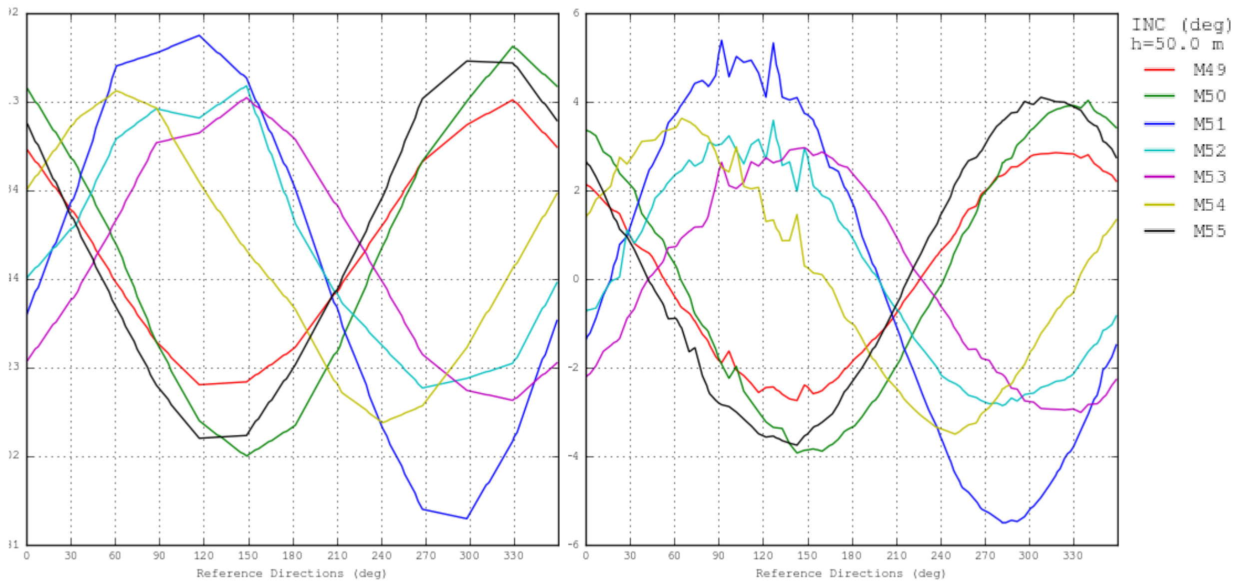
This allows to verify that the model behaves well, and that the solution obtained is reliable for the most energy-producing sector.



12 directions **72 directions**

Figure 8: **Wind Direction Variation Results Interpolation at Masts Locations for 12 and 72 Computed Directions**

Results are plotted considering wind directions measured at met mast M49 (at 50.0 meters height) as the reference direction.



12 directions **72 directions**

Figure 9: **Wind Flow Inclination Results Interpolation at Masts Locations for 12 and 72 Computed Directions**

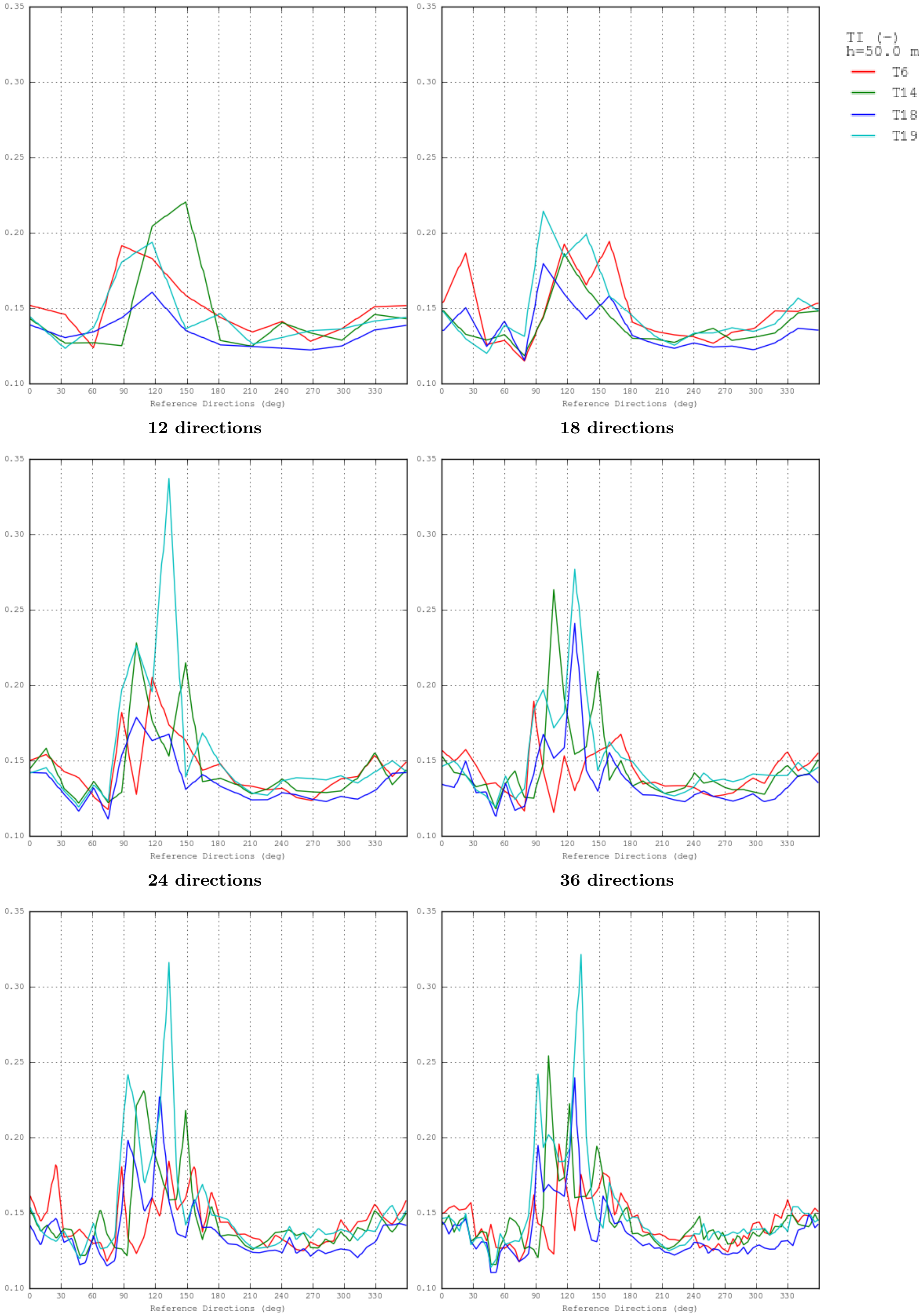
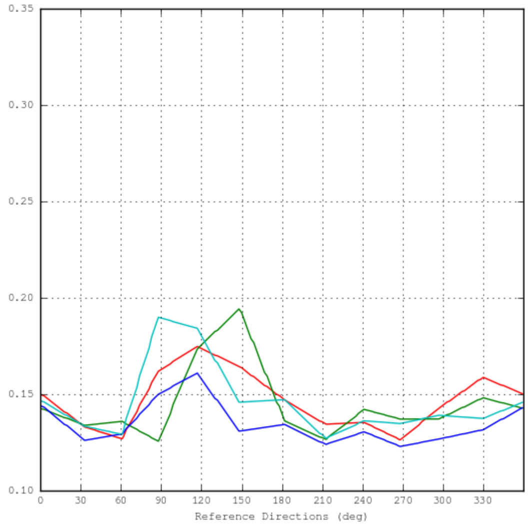


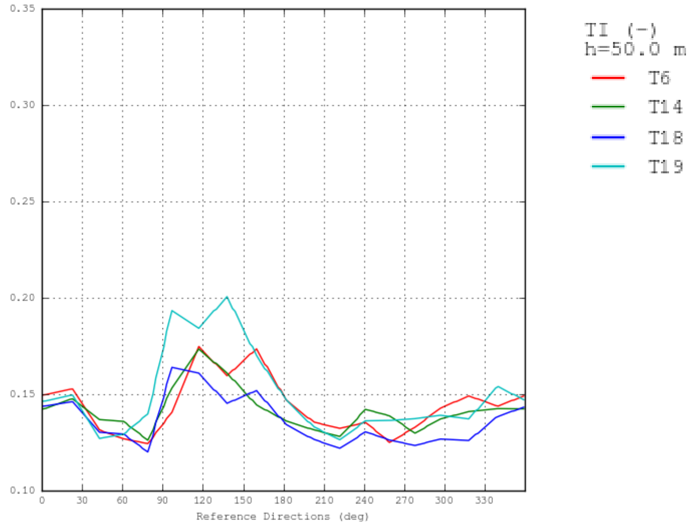
Figure 10: **Turbulence Intensity Results Interpolation against Wind Direction at Four Turbines Locations for Different Numbers of Computed Directions**

Figure 11: **Speed-Up Results Interpolation against Wind Direction at Four Turbines Locations for Different Numbers of Computed Directions**

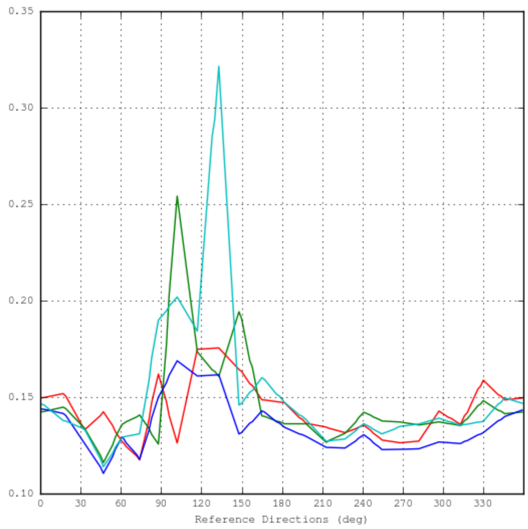
Results are normalized with met mast M49 (at 50.0 meters height) and plotted considering wind directions observed at met mast M49 (at 50.0 meters height).



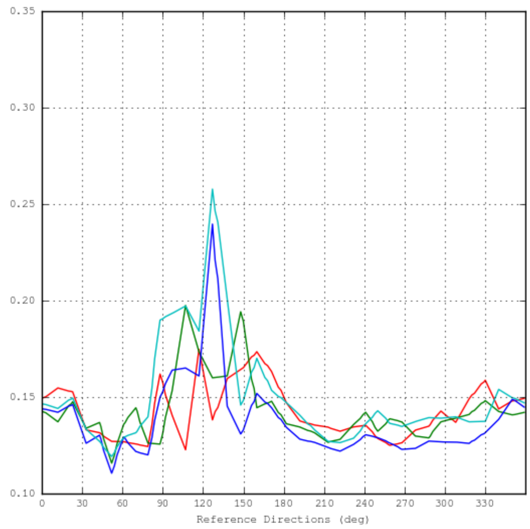
12 directions



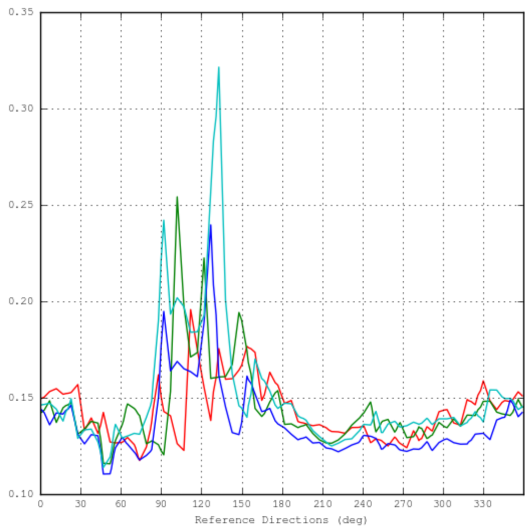
18 directions



24 directions

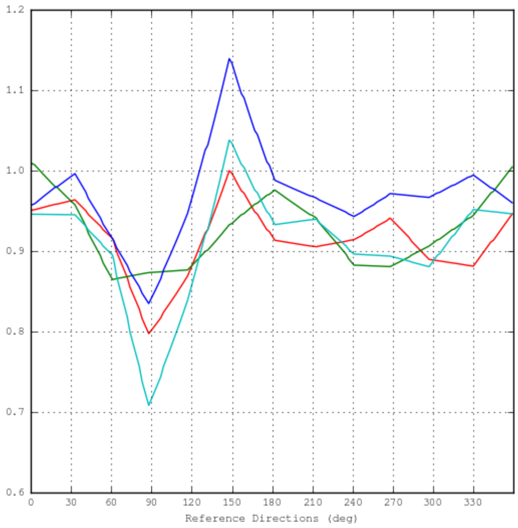


36 directions

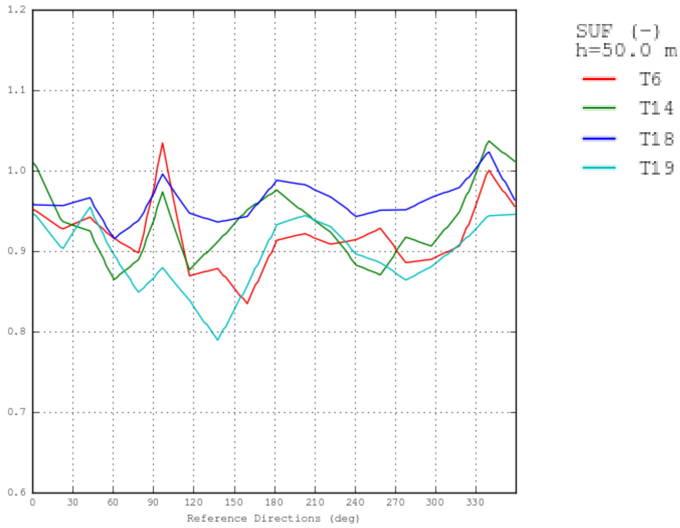


72 directions

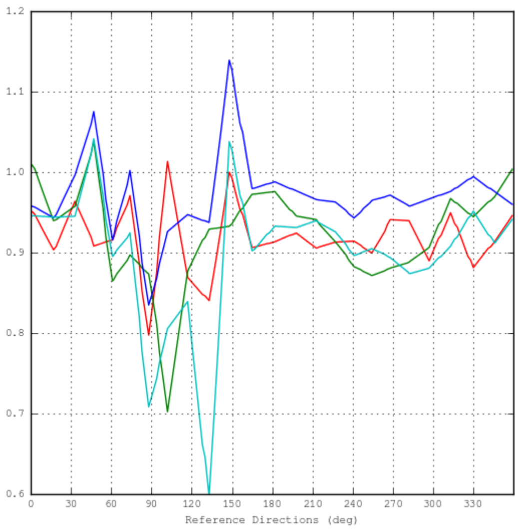
Figure 12: **Turbulence Intensity Results Interpolation against Wind Direction at Four Turbines Locations for Different Numbers of Directions Computed on the Same Mesh**



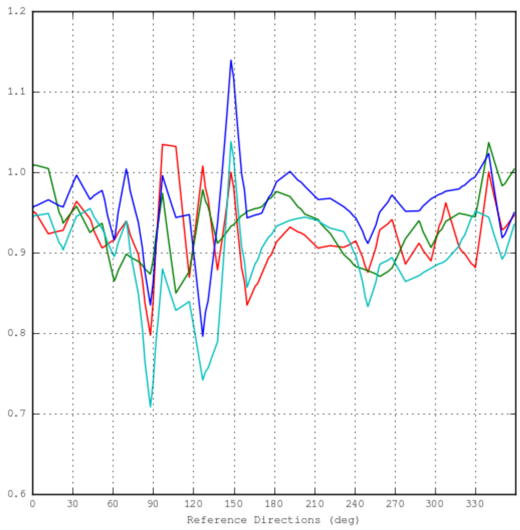
12 directions



18 directions



24 directions



36 directions

72 directions

Figure 13: **Speed-Up Results Interpolation against Wind Direction at Four Turbines Locations for Different Numbers of Directions Computed on the Same Mesh**

Results are normalized with met mast M49 (at 50.0 meters height) and plotted considering wind directions observed at met mast M49 (at 50.0 meters height).