Wind power resource assessment in complex urban environments:

MIT campus case-study using CFD Analysis

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MIT Renewable Energy Projects in Action

Abstract

Progress in Computational Fluid Dynamics (CFD) methods allows advance in natural resource assessment for wind energy production in complex urban terrain by modeling wind circulation around different urban obstacles. Compared to rural open spaces, the geometry in urban areas is more complex and has intricate influence on wind flow on micro-meteorological scale. The effects of the buildings on wind flow, such as vortices at the feet of the towers, Venturi effects or Wise effects, make the modeling of urban flows considerably more difficult. We simulate these effects with ***Urba****Wind* CFD model by solving the equations of Fluid Mechanics with a specific method which allows representation of the turbulence and the wakes around buildings.

The software model has been used to evaluate the wind energy potential on the campus of the Massachusetts Institute of Technology in Cambridge (MA) for the installation a free standing small wind turbine. The wind resource assessment has been performed by using long-term observations nearby the site to integrate the local climatology. In order to validate the results, two met masts have been installed on-site. Comparisons between the measurements and the predicted wind speeds allowed validation of the software results by offering a minor error margin on the wind speed prediction. This analysis provides an improved understanding of the micro-climate of wind resource on MIT campus and will facilitate the optimal siting of the turbine on campus.

Objectives

The aim of this study is to assess wind energy resource on MIT campus for optimization of installation of small wind turbine. The procedure of resource assessment includes prediction of average wind energy available for energy production on campus and identification of optimal location for turbine installation. We study the local micro-meteorological features of wind flow and the effects of the complex urban topography. Localization of zones of wind recirculation and turbulent wakes is important for both - high energy production and protection of the turbines from excessive gusts load by avoiding installation in a high turbulent area.

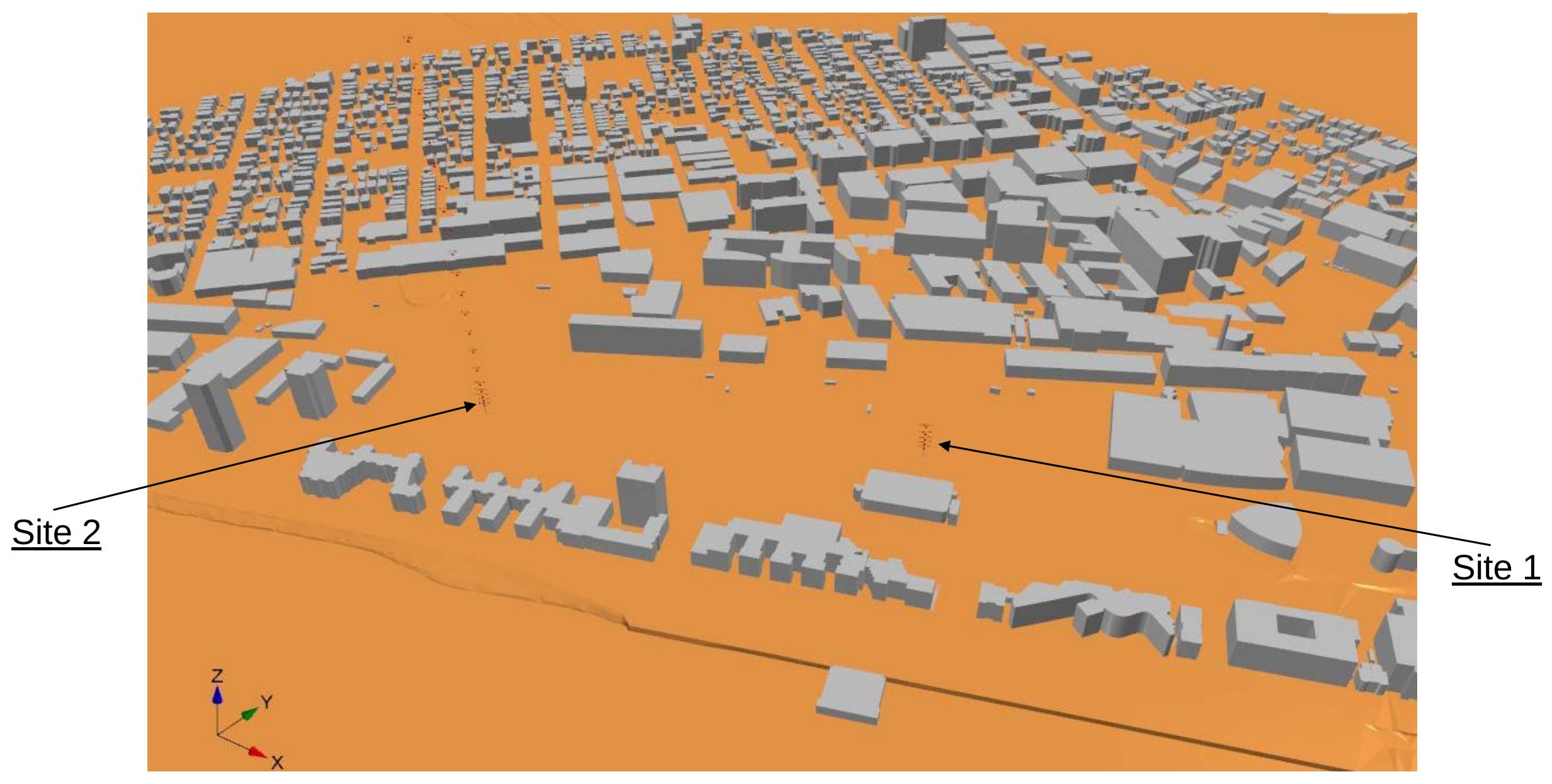


Figure 1: Domain of analysis – West Campus MIT

Moreover, this study aims to evaluate the methodology for site calibration in urban environment using CFD numerical methods for transfer long-term measurements from a remote station rather than installing a met tower on-site.

CFD Climatological Transformation

Because the fine resolution of the computation grid can lead to a large number of cells in urban areas, the typical size of the sites calculated with ***Urba****Wind* is around 1 mile by 1 mile. The Logan airport being located 4.6 miles away from the site, another tool is used to transpose the local long-term climatology from the airport to the site. The fine urban effects are then calculated with ***Urba****Wind*.

Two years of measurements from April 2008 to March 2010 are available at the Logan airport. The hourly data (wind speed and direction) are checked and quality controlled. The mast is 5.8 m above the ground. The rose is transferred to a point 100m above the site with the CFD code ***Topo****Wind* [1] by taking into account the local roughness and topography between the airport and the campus. A resolution grid of 4 meters in the vertical direction and 20 meters in the horizontal direction (resulting in approx. 500,000 cells depending on wind direction) was used to model wind flow over the site in 18 sectors every 20 synoptic degrees.

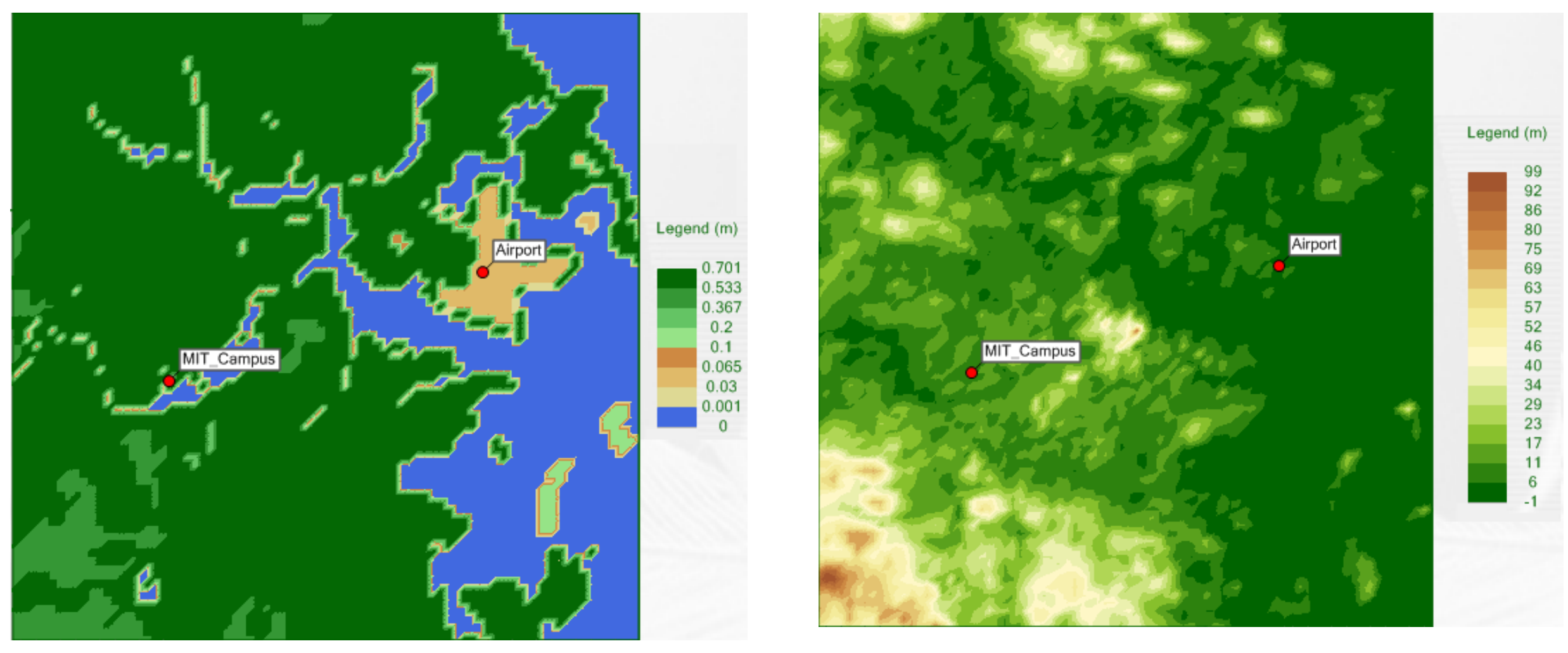
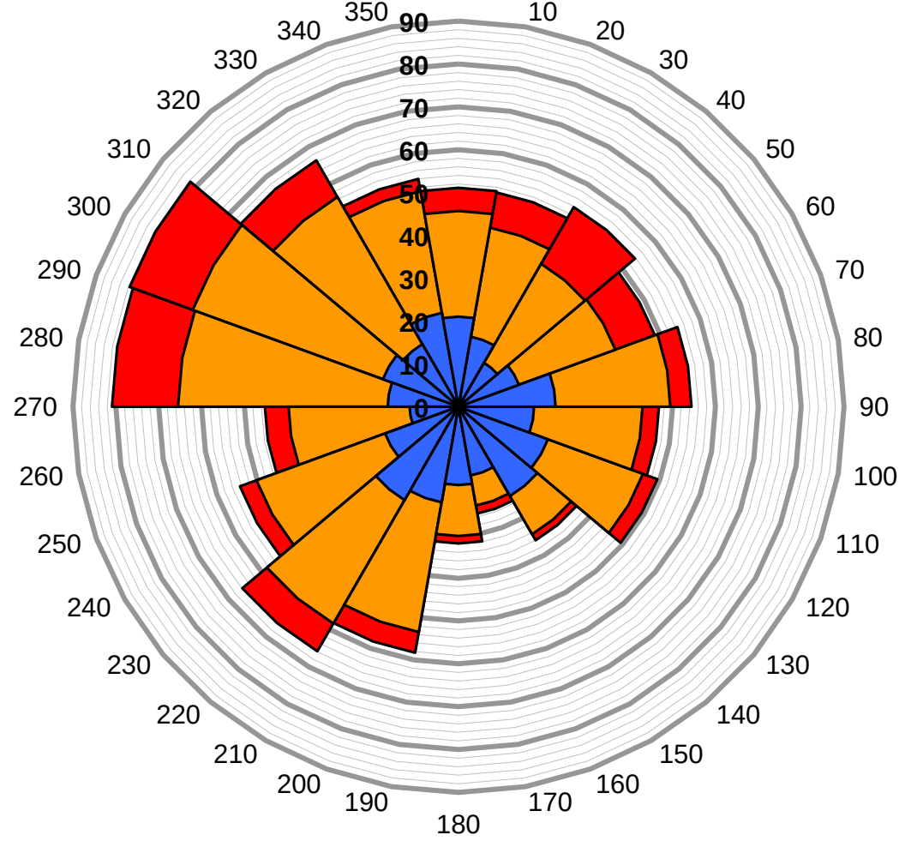
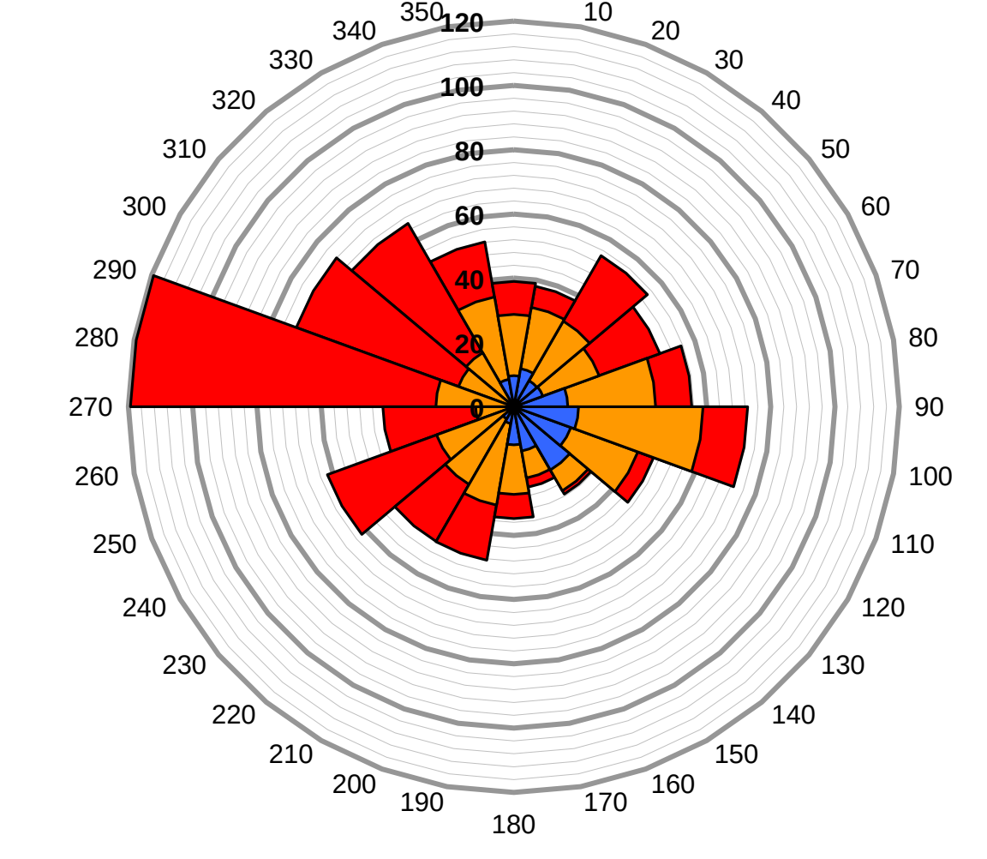


Figure 2: Visualization of the roughness and orography maps (8.5 x 8.5 miles)

The results of these calculations will be compared to a met tower on-site to validate the accuracy of this method. The picture below shows the wind rose at the airport and the wind rose 100m above the site.





The wind rose calculated on-site shows the effects of the topography between the site and the airport and particularly the river on the wind. It shows clearly that the main wind direction on campus is 280°.

Met Data Analysis and MCP normalization

As a first approach, the met tower data for the two sites on campus were processed according to traditional wind resource analysis techniques [2] and normalized using a set of techniques within the measure-correlate-predict framework. The statistics for the raw filtered data indicated significantly stronger performance of the second test site over the first during the three winter months of data collection. However, post normalization, the performance statistics of the two sites for wind speed and power density tended to converge. Details on the normalization will be made available in a future publication.

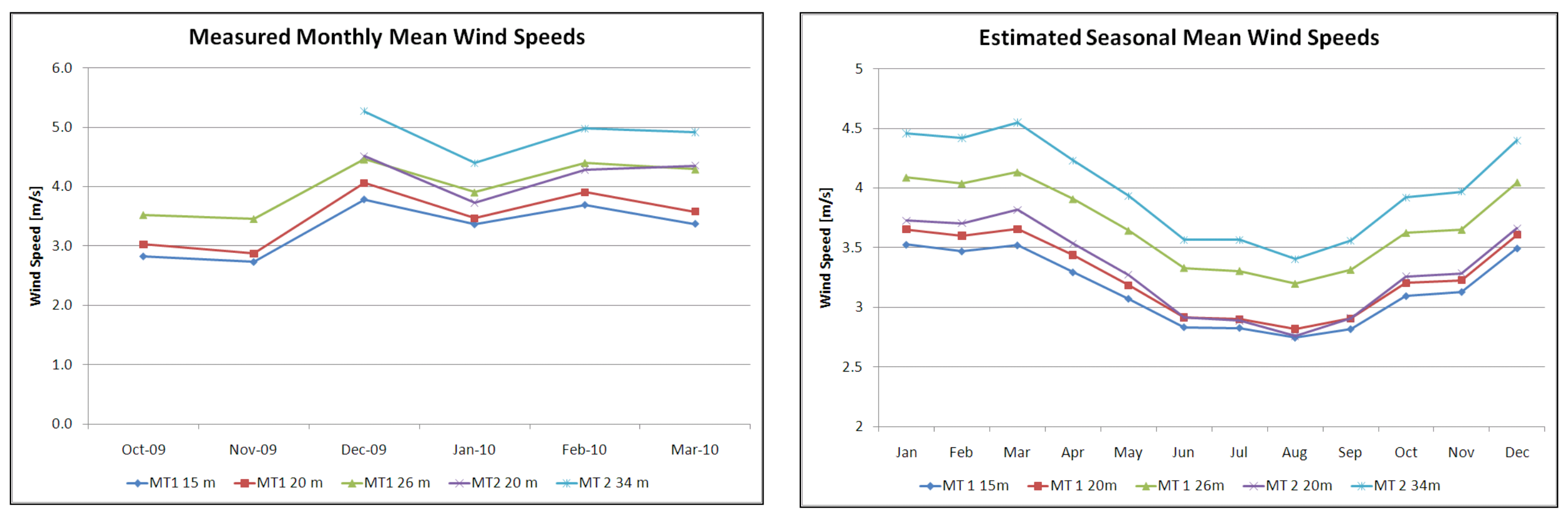


Figure 3: Wind speed averages based off of raw data and statistical MCP techniques

The difference in the results of the actual versus the normalized data were interesting and indicated that a more sophisticated analysis technique such as CFD might resolve some of the uncertainty surrounding the actual behavior of the wind resource within the complex campus environment.

CFD Method

The wind rose calculated with ***Topo****Wind* at 100m above the site is used as input data in ***Urba****Wind* to define the reference local climatology.

Urba*Wind* solves the equations of Fluid Mechanics, i.e. the averaged equations of mass and momentum conservations (Navier-Stokes equations). When the flow is steady and the fluid incompressible, those equations become:

$$\frac{\partial \rho \bar{u}_i}{\partial x_i} = 0 \qquad (1)$$

$$-\frac{\partial\left(\rho \bar{u}_j \bar{u}_i\right)}{\partial x_j} - \frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \rho \overline{u'_i u'_j}\right] + F_i = 0 \qquad (2)$$

The turbulent fluxes are parameterized by using the so-called turbulent viscosity. This viscosity is considered as the product of a length scale by a speed scale which are both characteristic lengths of the turbulent fluctuations. Boundary conditions are automatically generated. The vertical profile of the mean wind speed at the computation domain inlet is given by the logarithmic law in the surface layer, and by the Ekman function [3]. A ‘Blasius’-type ground law is implemented to model frictions (velocity components and turbulent kinetic energy) at the surfaces (ground and buildings). The effect of porous obstacles is modeled by introducing a sink term in the cells lying inside the obstacle [4]:

$$\vec{F} = -\rho . C_d . V . \left|\vec{U}\right| . \vec{U} \qquad (3)$$

Where C_d is a volume coefficient of frictions, which is proportional to the porous obstacle density, and V is the volume of the considered cell.

The turbulence characteristics are given by the standard deviation of the velocity fluctuations, which is globally estimated by the ratio between the square root of the turbulent kinetic energy and the local speed of the flow.

The mesher, integrated in the software, builds for each computed direction a mesh aligned with the wind flow, Cartesian and unstructured (use of overlapped meshing), with automatic refinement near the ground, obstacles and the wind turbines.

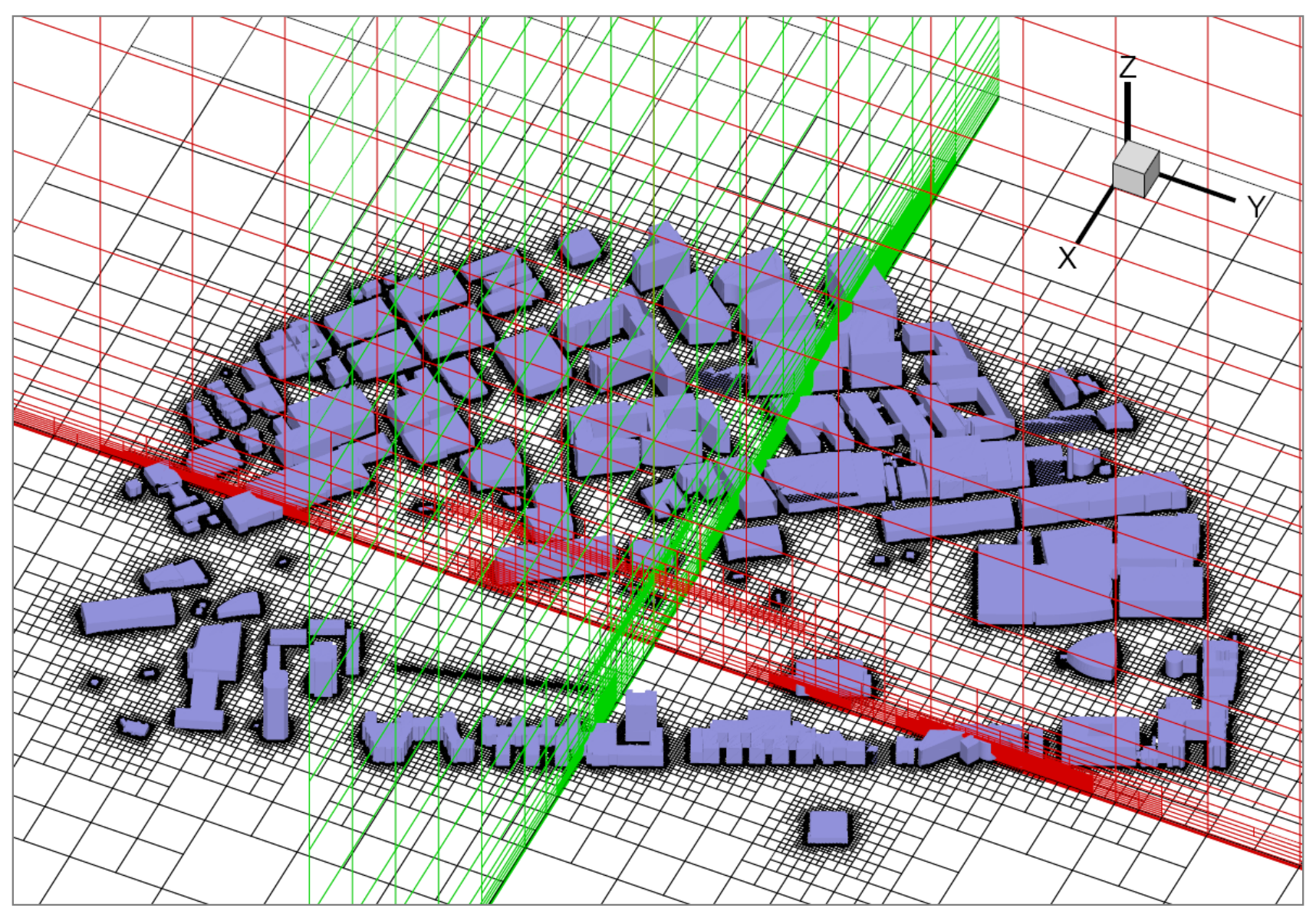


Figure 4: Meshing grid used for the calculation in the direction 360°

A resolution of 1m x 1m has been applied near the areas of interest resulting in a total of 4 million cells. The calculations are performed on 14 directional computations with a refinement around the prevailing wind direction 280°.

Urba*Wind* uses the solver Migal-UNS [5] with a GMRES-type preconditioner to improve the robustness and a multi-grid procedure to accelerate the convergence. It completely solves 3D equations for fluid mechanics (RANS method).

MIGAL employs a Galerkin’s projection method for generating the equations on the coarse grid. This technique, so-called "Additive Correction Multi-grid" consists in generating the equation of the coarse mesh as the sum of the equations of each corresponding fine cell. Once the solution is obtained on the coarse grid, it is introduced by correcting the values calculated previously on the fine grid with the calculated error.

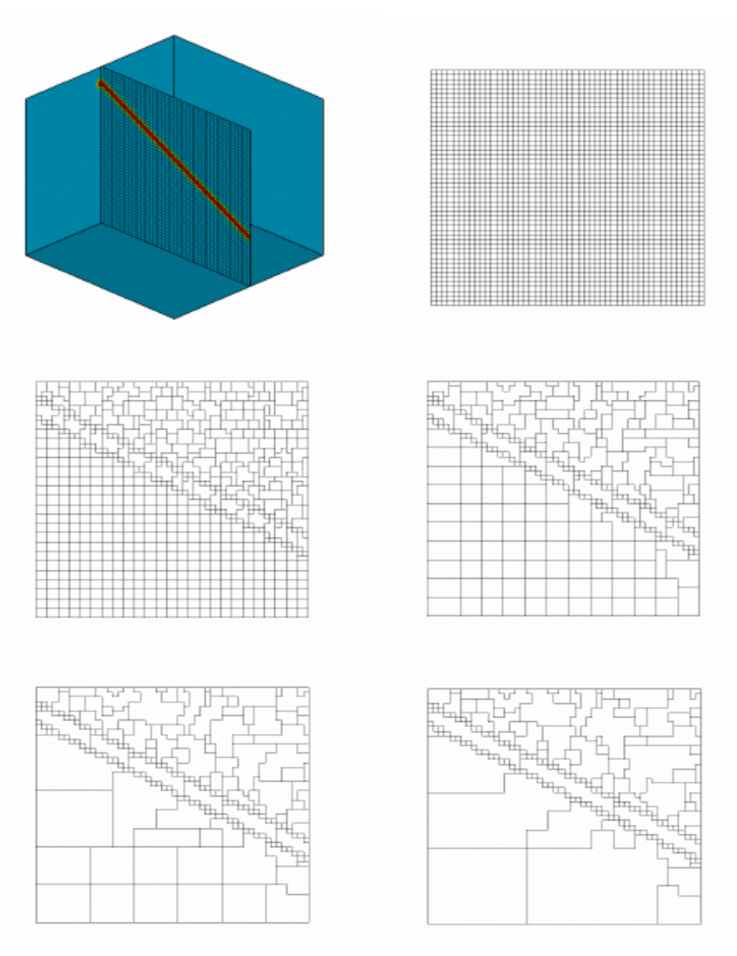


Figure 5: Scheme of the agglomeration method used by MIGAL-UNS in *UrbaWind*

Site Analysis and CFD Results

Site analysis begins with integration of directional wind statistics with urban GIS data. The directional statistics of the wind are presented as wind roses: the radial dimension represents the frequency of wind occurrence in each of the directional sectors.

It is seen that the prevailing wind direction at both sites during the measurement period is West-North-West. Qualitative analysis of the integrated GIS map reveals distinct micro-meteorological effects. The western site (MT2) exhibits jet and wind tunneling effects, presumably due to acceleration over the open space upwind and channeling by the surrounding buildings through the narrowing entry to the large open area (MIT sports field). At the eastern site (MT1) opposite wind characteristics are clearly observed. Although the average direction of the wind is the same, the angular spread is higher with significant reduction of occurrence in the central sector. The speeds are lower, rarely reaching 10 m/s. These observations suggest that the eastern site is subjected to turbulence and wind blocking conditions by the upwind buildings and due to stagnation pressure at the upwind side of the leeside building – the MIT Tennis Facility.

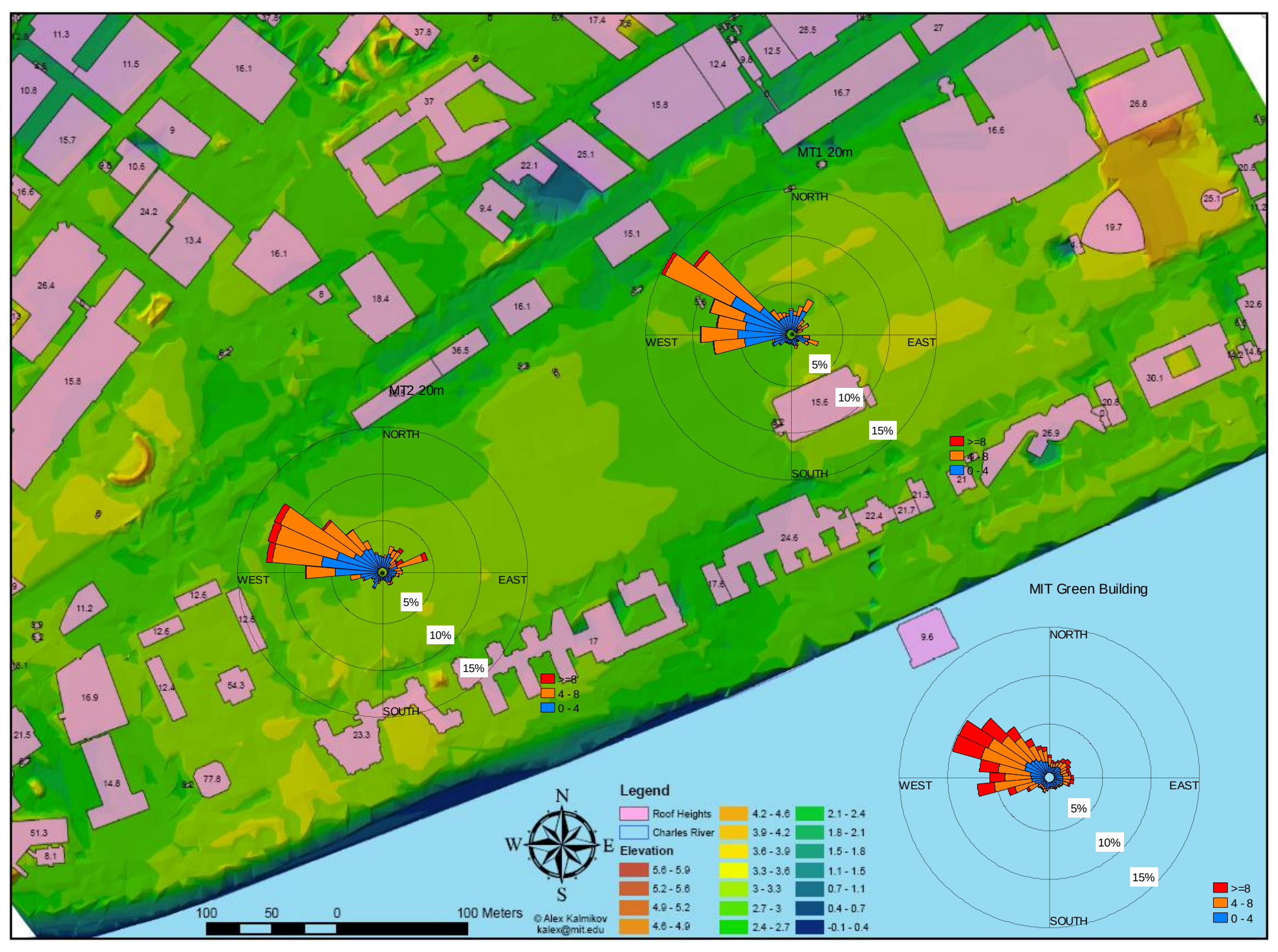
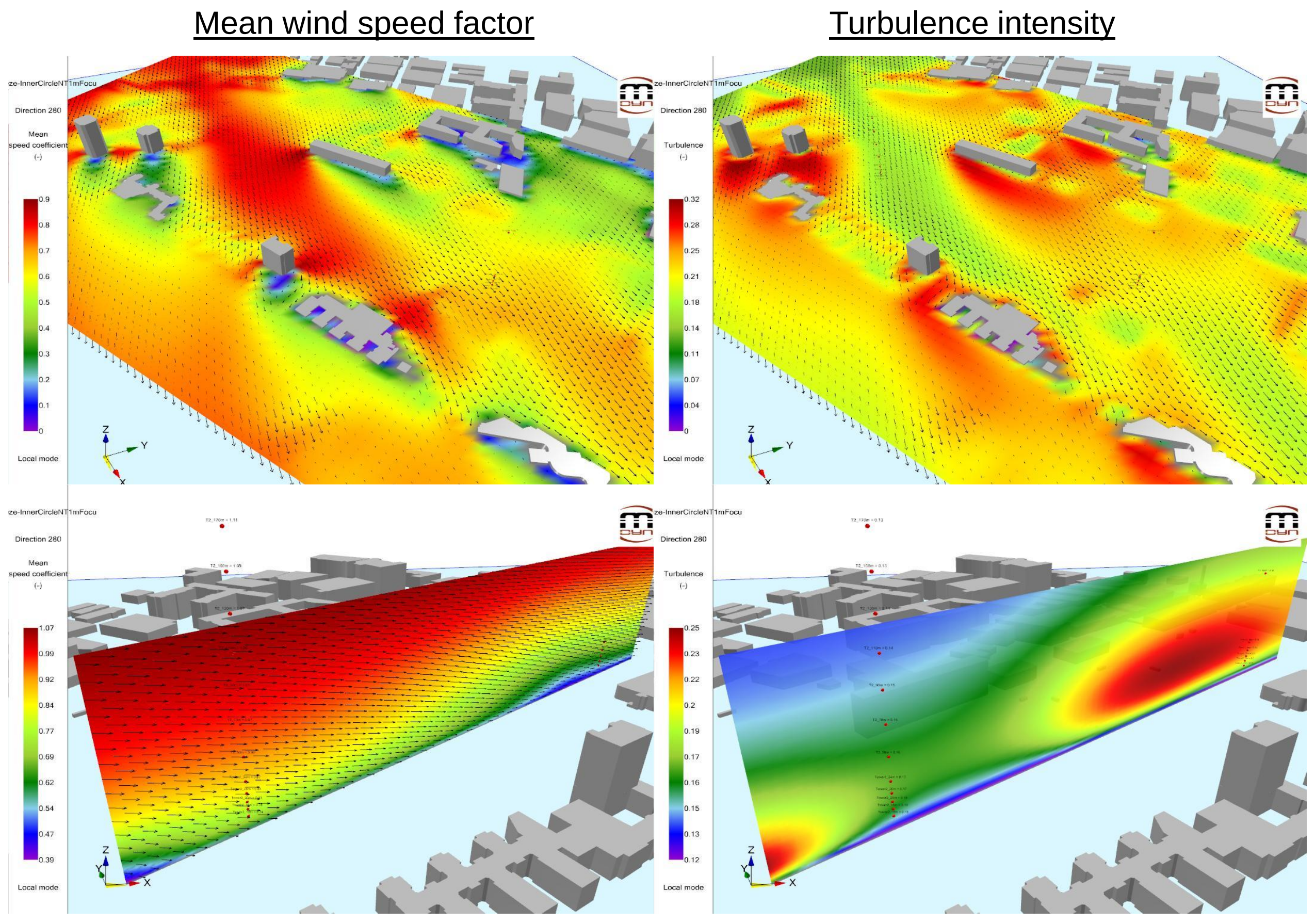


Figure 6: Spatial analysis of wind resource - GIS site map with directional wind statistics at measurement locations

CFD simulations confirm these assessments quantitatively. It can be seen that a high winds channel is formed through the sports field. This area is characterized by lower turbulence and higher mean speeds. The CFD simulations reveal the 3 dimensional structure of this flow feature. The high wind channel modifies the vertical shear and brings higher winds closer to the ground. The turbulent area is elevated and localized behind tall buildings’ roofs. The western site is confirmed to be centered in the high winds channel, the eastern site is in the turbulent building wake.


Mean wind speed factor

Turbulence intensity

Figure 7: Directional calculation of urban wind induction factors, shown for the prevailing wind direction - 280°

Conclusions

We demonstrate application of CFD analysis for wind power resource assessment in complex urban environment of MIT campus. Meteorological data directly measured at the sites is examined and compared to the results of CFD simulations. Qualitative comparison of the results exhibits satisfactory agreement. Detailed quantitative analysis is underway and will be reported in the future.

We show how CFD model is integrated in resource assessment procedure. The extensive available observations from a nearby airport can be transferred several miles to the area of interest. Next, calculations of the local speed-up factors with ***Urba****Wind* CFD model allow to estimate the mean wind speeds and the energy production at the site. A map of wind resource can be produced to identify the most productive areas and low turbulence zones.

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