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A Complete CFD Methodology Based on Iterative Model Adjustment to Improve Wind Simulation Accuracy in Highly Dense Forest Area

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Abstract

Wind resource assessment (WRA) in densely forested and complex terrain remains challenging due to strong canopy-induced turbulence and enhanced wind shear, which significantly affect wind flow characteristics and increase modeling uncertainties. Based on a scientific collaboration between Meteodyn and EDF Power, this study proposes a complete and reproducible Computational Fluid Dynamics (CFD) methodology based on an Iterative Model Adjustment (IMA) procedure to improve wind simulation accuracy in highly forested areas using standard industrial inputs. The approach relies on Reynolds-Averaged Navier–Stokes (RANS) simulations implemented in Meteodyn WT™ software. The IMA procedure iteratively adjusts forest model parameters using wind speed profile measurements from a single reference mast until the simulated shear matches observations. The methodology was evaluated across three sites located in Finland, France, and Scotland, resulting in six calibration and cross-prediction cases under heterogeneous forest and complex terrain conditions. Results show that cross-prediction uncertainties were reduced significantly leading to a global mean absolute error of approximately 1.1%. Beyond its practical applicability, the study provides new insight into the physical role and parameter sensitivity of the canopy drag force term within RANS-based forest models. The refined parameterization improves the representation of forest-induced momentum sink effects, leading to enhanced wind speed and vertical shear simulation. These findings demonstrate that robust and accurate Wind Resource Assessment can be performed in complex terrain and forested areas without using advanced remote-sensing-derived canopy density datasets, and thereby offering a pragmatic and industrially applicable alternative.

Keywords: wind forest modeling; wind resource assessment; Meteodyn WT; CFD simulation

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1. Introduction

Due to favorable circumstances (fewer regulations and social resistance) and a shortage of space, wind farms are increasingly developed in densely forested areas. Developers of wind farms are encountering new difficulties in achieving high accuracy in wind speed simulations due to the significant impact of forests on wind flow. In the atmospheric boundary layer, perturbations induced by ground surfaces with high roughness values, such as forests, generate a high level of turbulence and strong wind shear, which have clearly an influence on the risk associated with wind farm development [1,2]. Numerous studies have recently examined a wide range of numerical models [3–15], such as linear models, RANS approaches using CFD or LES models, for simulating wind flow in wooded environments.

On the one hand, several studies have shown that the industry's linear flow models, which were based on a displacement height correction, were insufficiently precise [3]. On the other hand, Large Eddy Simulations (LES) approaches, accounting for forest effects via momentum and turbulence source terms seem not appropriate for engineering purposes. While LES approach has demonstrated accurate flow field in forested areas [4–6,9], this approach remains irrelevant for industrial applications due to its high computational cost.

In light of this, RANS CFD methods using different turbulence closures with reasonable computational costs, seem to be a relevant approach dedicated to wind simulation dedicated to industrial application. Wind resource assessments in wooded and complex terrain have already been frequently conducted using RANS CFD methods [3,9–20].

However, the application of RANS CFD tools for highly forested areas is still a challenge for developers. It has been noticed that the use of RANS-CFD has limitations in some situations, especially when it is not paired with high-precision roughness maps [9,15–17]. Unfortunately, these advanced maps based on Leaf Area Density (LAD) or Plant Area Density (PAD) require advanced remote sensing imagery from lidar, satellite or plane [8] which are neither compliant with industrial application.

Within this scope, this work has been initiated following a collaboration between EDF Power and Meteodyn. The initial objective was to develop a clear and reproducible methodology to improve the CFD simulation accuracy in highly forested areas dedicated to engineering purposes. As a result, the materials used in this study are limited to those typically found for operational wind resource assessment studies, such as public orography and roughness maps and measurements at one mast.

This article proposes a novel approach to define the CFD forest model parameters using an iterative approach based on in-situ data from a reference mast. In contrast to earlier and current research that are using constant drag coefficients in combination with PAD [7,9,12,15–17,21], the forest attributes are inferred here using wind speed measurements at several elevations on a single mast.

Three sites with two met masts each, common measurement periods, heights, and heterogeneous forest coverage and terrain complexity have been examined for this work using the commercial software Meteodyn WT™. Therefore, six calibration procedures (3 sites containing 2 masts) are used to evaluate this forest model calibration strategy in order to provide enough cases to draw conclusions on the method's relevance.

The main contributions of this work are:

1. Propose a precise and repeatable methodology to perform wind resource assessment in densely wooded and complex sites.
2. Use Meteodyn WT™ to investigate the methodology across a wide range of situations on simulation results (mean speed, shear, turbulence)
3. Gain a better understanding of wind flow modeling in densely forested regions.

2. Site Description and Simulation Strategy

2.1. Site Description

In this study, meteorological mast measurements at three sites have been provided by EDF Power in different countries Finland, France and Scotland. These sites have been specifically selected for their challenging conditions for wind simulation mixing high forest and different levels of terrain complexity. The publicly available orography and land cover maps used for the terrain description and derived from satellite data are presented in Table 1 and illustrated in Figures 1–3. Two different land cover maps have been used to match the measurement period and in situ observations as closely as possible. For sites 2 and 3, Corine Land Cover (CLC) roughness maps were chosen [22], however for site 1, a Copernicus Land Cover (LC) roughness map was utilized [23].

All sites use the NASADEM orography map with a 30 m resolution [24] except the site 1, which is based on the EU-DEM 1.1 [25] map because NASADEM orography map is unavailable for Finland. Different terrain conditions are depicted on orography maps, ranging from moderately complex terrain at site 1 to complex terrain at sites 2 and 3. The maximum altitude difference in the modeled area is ranging approximately from 100 m for site 1, 500 m for site 2 and 520 m for site 3.

Table 1. Site description

Site	Country	Roughness map	Orography map	Mast heights	Canopy height M1	Canopy height M2
1	Finland	LC 2019 (100 m)	EUDEM v1.1 (25 m)	100 m; 80 m; 60 m	30 m ± 5 m	30 m ± 5 m
2	France	CLC 2018 (100 m)	NASADEM (30 m)	100 m; 80 m; 60 m	35 m ± 5 m	10 m ± 5 m
3	Scotland	CLC 2018 (100 m)	NASADEM (30 m)	70 m; 50 m; 30 m	15 m ± 5 m	20 m ± 5 m

For wind engineering application, roughness length values are generally deduced from land cover maps using conversion tables [26–30]. According to previous studies, it is important to note that these conversion tables provide interesting roughness information but are recognized as uncertain and strongly depending of the geographical region where they are applied. As a consequence, a larger variety of conversion tables are proposed for the same dataset. In Meteodyn WT, conversion tables for roughness maps have been determined using a global averaging approach based on several available sources [18]. For instance, a 0.7 m roughness length value corresponding to coniferous forest area and displayed on Figures 1–3 has been determined from eight conversion table sources with roughness length values ranging from 0.5 m to 1.2 m.

As presented on roughness maps, the three sites propose a large variety of forest covering conditions. A roughness length variation from 0.003 m to 0.7 m can be observed for all sites on the 100 m-resolution roughness maps showing heterogeneous forest with some clearings. From on-site observations and google earth images, estimated canopy heights close to Mast 1 (M1) and Mast 2 (M2) are presented in Table 1. These canopy height values have been roughly estimated based on a quarter circle area centered at each mast position with an approximate 400 m-radius and oriented in the prevailing wind direction. These observations, in good agreement with roughness maps, show that forest conditions at sites 1 are almost identical between M1 and M2 in the prevailing wind direction measured around 200° in all sites. On sites 2 and 3, however, heterogeneous forest conditions are noted between M1 and M2. According to on site observations, most of the trees are coniferous.

In each site, two met masts are equipped with cup anemometers at three elevations as detailed in Table 1, and all measurement data is in the common periods of one year with very good data quality and high data coverage (>98%). For this project, 2.5 % measurement errors are assumed for wind speeds in all sites according to wind engineering guidelines and similar mast observations [31–33]. As displayed in Table 1, the distance between two masts are respectively 6.6 km, 4.4 km and 3.1 km for site 1, 2 and 3. In this study, we assume that neutral conditions are satisfied in highly forested areas when using a full year period for meteorological data. CFD calculations are therefore simulated using only neutral thermal stability conditions, even though Meteodyn WT can account for the influence of thermal stability for simulations.

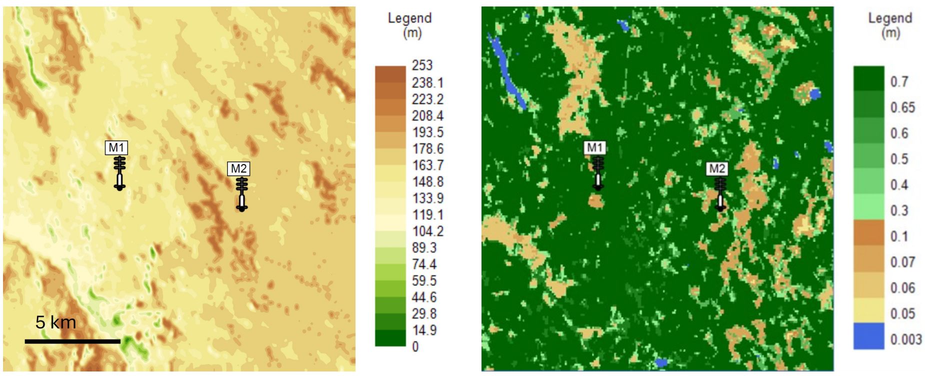

Figure 1. Site 1 Orography map (left) and Roughness map (right). The measured wind prevailing direction is 230° on both masts.

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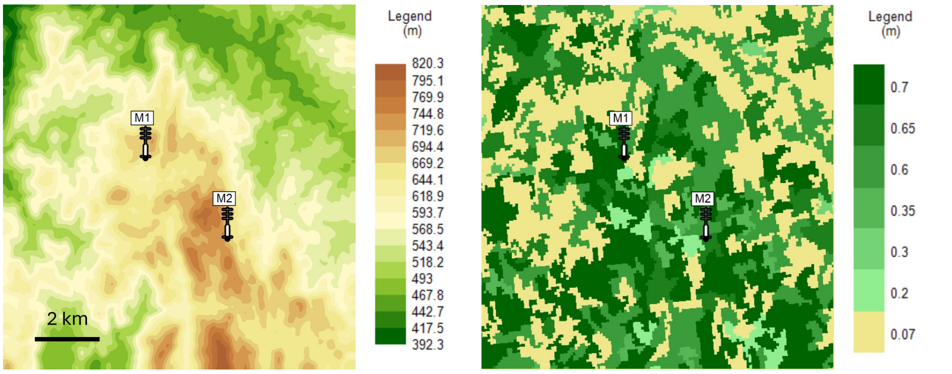

Figure 2. Site 2 Orography map (left) and Roughness map (right). The measured wind prevailing direction is 225° on both masts.

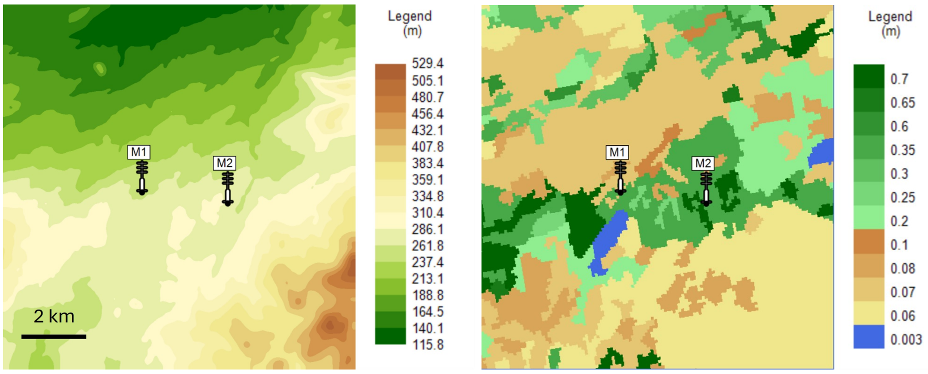

Figure 3. Site 3 Orography map (left) and Roughness map (right).The measured wind prevailing direction is 210° on both masts.

2.2. Methodology for Cross-Predictions in WRA

In this work, the validation of the CFD simulation methodology is made using cross-prediction approach and comparison of the wind conditions based on measurement points as recommended by wind industry guidelines [34]. It means that for each site, a single mast location is used to estimate the wind speed in the area considered and more specifically at the other mast location for different elevations. This approach is also consistent with engineering application since wind conditions are frequently estimated based on data measurements at a unique mast location. The model uncertainties are then deduced after comparison with wind speed measurements. The Mean Absolute Error (MAE) and Mean absolute percentage error (MAPE) described below are used in this study to produce a quantitative estimation of CFD model accuracy.

- **Mean Absolute Error (MAE):**

$$MAE(\%) = 100 \times |\frac{X_{obs} - X_{sim}}{X_{obs}}| \quad (1)$$

Where X_{obs} is the measured variable value and X_{sim} is the simulated variable. In this work, the MAE is applied to mean speed and shear values (α).

- **Mean Absolute Percentage Error (MAPE):**

The MAPE measures the average magnitude of error produced by the CFD model on one mast location at 3 different elevations.

$$MAPE(\%) = 100 \times \frac{1}{3}\sum_{i=1}^{3}|\frac{V_{obs_i} - V_{sim_i}}{V_{obs_i}}| \quad (2)$$

Where V_{obs} is the measured wind speed value and V_{sim} is the simulated wind speed value.

3. Meteodyn WT Forest Model

3.1. Governing Equations

The Computational Fluid Dynamics (CFD) approach is based on solving the full Reynolds-Averaged Navier-Stokes equations (RANS), which enable the simulation of flow separation and recirculation phenomena over complex terrains. Meteodyn WT™ is a commercial site-assessment software designed to model the atmospheric boundary layer. The turbulence is represented using the turbulent-viscosity hypothesis through a mixing-length model [35]. By incorporating advanced numerical methods-a coupled multi-grid solver-Meteodyn WT™ achieves an efficient solution [36] validated in various cases [3,13,14,20,37]. In Meteodyn WT™, the incompressible atmospheric flow is described by the Reynolds-averaged Navier–Stokes equations, which are given by:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{3}$$

$$\frac{\partial(\rho \bar{u}_j \bar{u}_i)}{\partial x_j} + \frac{\partial \bar{P}}{\partial x_i} - \frac{\partial}{\partial x_j}[\mu(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i})] + F_i = 0 \tag{4}$$

Here, ρ is assumed constant, and F_i represents external forces, including drag forces $\mathbf{F}_D$ from canopy friction. The Navier-Stokes equations are closed using the Boussinesq hypothesis:

$$-\rho\overline{u_i' u_j'} = \nu_T \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) = 2\nu_T S_{ij} \tag{5}$$

where S_{ij} is the mean rate-of-strain tensor. The turbulence viscosity is obtained using the Prandtl mixing-length model:

$$\nu_T = \sqrt{k} L_T \tag{6}$$

where k is turbulent kinetic energy which will be solved in the turbulent kinetic energy transport equation as below:

$$U_j \frac{\partial k}{\partial x_j} = P_k - \epsilon + \frac{\partial}{\partial x_j}(\frac{\nu_T}{\sigma_k}\frac{\partial k}{\partial x_j}) \tag{7}$$

The turbulent production term P_k can be expressed as:

$$\frac{P_\kappa}{\nu_T} = 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left[\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)^2\right] \tag{8}$$

The dissipation term ϵ is written as:

$$\epsilon = C_\mu \frac{\nu_T}{L_T^2} k \tag{9}$$

where C_μ is constant coefficient which depends on the thermal stabilty condition. The turbulence length L_T is given by [38] :

$$L_T = \sqrt{2} S_m^{1.5} l \tag{10}$$

where the coefficient S_m depends on the thermal stability [38]. And the mixing length l will be defined later in the Canopy model.

The turbulent fluxes are linked to the gradients of the mean variables via the concept of turbulent viscosity which can be modeled as the product of a wind speed scale, generally the square root of the turbulent kinetic energy k, and a turbulent length scale L_T. k is solved via the transport equation.

At the inlet, the logarithmic wind speed profile U_{in} and the turbulent kinetic energy profile k depend on the thermal stability condition. A free outflow condition is applied at the outlet. At the bottom boundary, turbulent production is assumed to be balanced by dissipation. At the top boundary,a free outflow condition is applied; symmetric boundary conditions are imposed for k. Symmetric boundary conditions are also imposed at the lateral boundaries.

3.2. Canopy Model

In Meteodyn WT™, canopy area is considered as the momentum energy sink where drag forces are applied, and turbulence length scales are modified. Perturbations induced by forests are modeled by including a drag force term described below in momentum conservation equations:

$$\mathbf{F}_D = -\rho C_D \overline{\mathbf{U}} \, |\mathbf{U}| \tag{11}$$

$\bar{U}$ is the wind speed in the main direction and C_D is a volumetric drag coefficient proportional to the forest density and a constant vertical leaf area profile. This leaf area profile is used to describe the tree shape by considering less leaves in the top of the trees. As a consequence, a linear reduction of the drag coefficient in the top 25% of the forest is considered.

When describing the forest effect on wind flow simulations, the forest density is considered. Three forest density values—low, normal, and high—can be chosen in the Meteodyn WT™'s roughness map selection corresponding to drag coefficient values of respectively 0.001, 0.05 and 0.01. Furthermore, the advanced CFD configuration ranging from 0.001 to 0.1 in Meteodyn WT also allows for the direct definition of the drag coefficient value. [18].

Inside forest canopy, [17] has applied the production term and dissipation term as:

$$P_k = \begin{cases} P_k \quad in\ 8, & \text{wo forest model} \\ \beta_p C_d \, |\overline{\mathbf{U}}|^3, & \text{w forest model} \end{cases}$$

The dissipation rate for high Reynolds number is modeled as:

$$\epsilon = max(\epsilon_{cc}, \epsilon_{fd}) \begin{cases} \epsilon_{cc} = C_\mu \frac{\nu_T}{L_T^2} k, & \text{wo forest model} \\ \epsilon_{fd} = \beta_D C_d \, |\overline{\mathbf{U}}| k, & \text{w forest model} \end{cases}$$

Following Liu [39], we consider $\beta_p = 1.0$ and $\beta_D = 4.0$. The forest canopy height h_c, and the depth of the roughness sublayer h_{RSL}, where the forest canopy directly impinges on the flow, can be expressed in function of the roughness length z_0, the parameters k_c and h_{add} in [16]:

$$h_{RSL} = h_c + h_{add} \tag{12}$$

$$h_c = k_c z_0 \tag{13}$$

where h_{add} is the height of the additional dissipation's zone. k_c is the forest ratio.

The mixing length l is assumed to be a constant 2 m within the forest canopy and increases linearly for $z \geq h_{RSL}$. Within roughness sub-layer, a weighting factor α is introduced to attenuate the forest effect.

$$l^{-1} = \begin{cases} l_0^{-1} + l_f^{-1}, & z < h_c \\ (1-\alpha)(l_0^{-1} + l_f^{-1}) + \alpha\left(l_0^{-1} + \frac{1}{\kappa z}\right), & h_c \leq z < h_{\mathrm{RSL}} \\ l_0^{-1} + \frac{1}{\kappa z}, & z \geq h_{\mathrm{RSL}} \end{cases} \tag{14}$$

where the dimensionless height with the canopy transition zone is defined as:

$$\alpha = \frac{z - h_c}{h_{add}} \tag{15}$$

The characteristic length scales are defined as $l_0 = 100m$.

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3.3. Forest Model Activation

Meteodyn WT™ forest model presented previously as a combination of a drag force term and a modification of the mixing length adjustment is automatically activated in the forest mesh area [18]. The canopy heigh H_{canopy} is utilized to determine the forest zone and activate the forest model in the corresponding cells of the CFD mesh as presented in Figure 4. Forest model is automatically applied in the CFD computation domain if the bottom of a mesh cell is lower than the canopy height, which is defined as $H_{canopy} = z_0 R_{forest}$with z_0 the corresponding roughness length value of the map. The forest ratio R_{forest} is set to 20 by default. This default value is obtained through the calibration of the wind speed profiles based on the analytical wind profiles in Eurocode 1 EC1 [19,40].

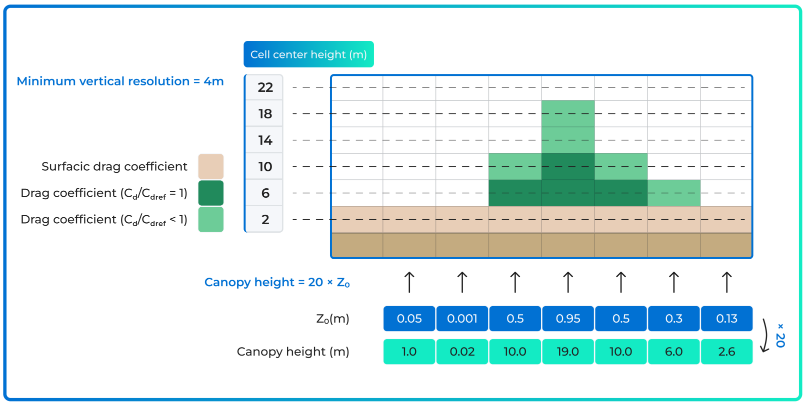

Figure 4. Description of Meteodyn WT forest model activation process on the CFD mesh

3.4. Iterative Model Adjustment (IMA) Methodology in Forested Areas

The methodology we propose in this work for wind resource assessment in forested areas uses an Iterative Model Adjustment (IMA) methodology based on wind speed measurements and described in Figure ??. This method is based on the hypothesis that the drag coefficient variable remains constant across the whole site area in forest environments and can be deduced from in-situ measurements at one single mast. In this approach, the CFD forest model is adjusted iteratively to approximate the wind speed profile measurement on real forest site properties at the reference mast. This method aims to enhance the forest model to make the simulated mean wind profile as near to measurements as feasible. In this work, we consider that forest model is valid when the shear difference between the simulated results and the measurements is lower than 10% at the reference mast. The following steps are recommended below for the IMA procedure:

- **Forest Model Initialisation: Canopy height/Roughness length adjustment:**
  As described previously, canopy height is defined by the roughness length z_0 and the forest ratio R_{forest}. Starting from initial roughness values and forest ratio, these variables can be first adjusted according to on-site observations. As Roughness length values are provided by roughness maps, the forest ratio can be deduced from the approximate height of the forest areas in a site.
  When estimating the canopy height evolution at a site using public roughness maps, a meticulous verification with on-site forest coverage should be carried out as recommended in previous work [26–30]. Various methods, such as on-site observations, photos, and/or Google Earth images can be employed. In case of significant differences between roughness maps and on site observations, different strategies can be performed. When the canopy height is constantly mis-estimated over the whole area, the forest ratio can be used to rescale the canopy height at a suitable level. In contrary, when local canopy height inconsistency are observed, then roughness maps should be corrected in this specific area by modifying the corresponding roughness length value in the conversion table or by modifying manually roughness length values in a specific area.

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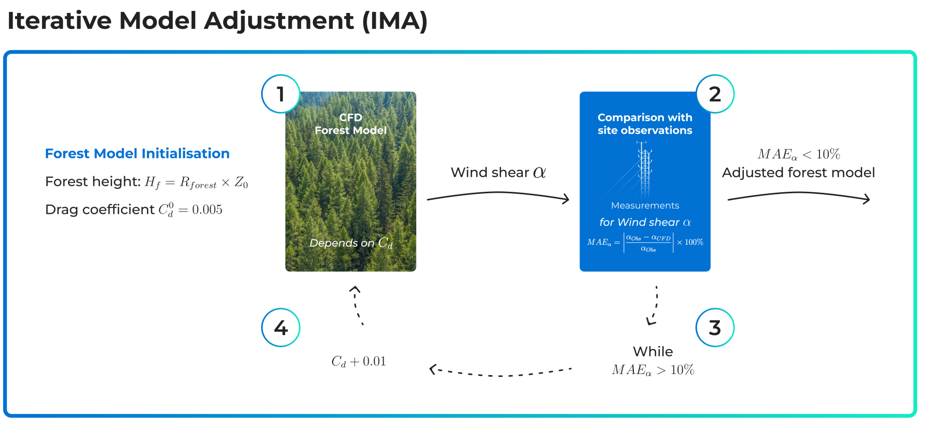
- **Iterative Forest density adjustment:**
  The forest density directly impacts the drag force term and the forest effect. This variable can be considered as a free parameter which depends on several factors, such as the density of the forest, the type of trees, and additional obstacles in the forest, etc...This variable can be directly controlled by the drag coefficient Cd ranging from 0.001 to 0.1 in Meteodyn WT™. During this step, the forest density is iteratively adjusted to match the measured mean vertical profile until the shear difference between simulation and measurements is lower than 10%.



The adjusted forest model is finally used to simulate the wind flow in the whole considered area using the reference mast. IMA methodology can be done for either the directional wind vertical profile or the mean wind vertical profile to infer the forest's characteristics. In this work, IMA is applied for the mean vertical profile including all wind sectors. In order to save CFD computation time, it is also recommended to apply the IMA methodology on a unique prevailing or representative wind sector.

3.5. CFD Simulation Configuration

All CFD parameters used in this study are presented in Table 2. Regarding mesh generation, minimal vertical and horizontal resolutions of 4 m and 25 m are used for modeling. A vertical expansion rate of 1.2 allows the cell size to progressively expand from the ground to the top. A horizontal expansion rate of 1.1 allows the horizontal cell size to grow from center to border. Furthermore, Meteodyn WT™ provides the surface mesh refinement option, also called "the mesh mapping", which ensures fine mesh resolution in any interesting area without the impact of horizontal expansion rate.

The wind direction is divided into 20 wind sectors. It means that for example, in the first sector, the wind is binned from the 0° direction (true north) to the 18° direction (north-east) and in the second sector from 18° to 36°. CFD computations are launched for 20 wind sectors for each site. CFD computations for all sites, sectors and conditions reach 100% convergence rate corresponding to suitable convergence results and consequently high reliability for CFD results.

For all sites, the averaged CFD computation duration per sector ranges from 13 min to 18 min depending on the input land-cover maps and the computation time necessary to reach a suitable convergence. All computations have been launched using a standard performance computer and multiple core parallel computation (4 cores, 64 GB RAM).

Iterative Model adjustment procedure:

When the canopy height has been correctly described on roughness maps according to on-site observations, Drag coefficient C_d value has been adjusted iteratively from 0.005 with 0.01-steps until the shear difference between simulation and measurements is lower than 10%.

Table 2. Computation parameters and information

Site	Site 1	Site 2	Site 3
Site radius	8 km	8 km	8 km
Horizontal resolution	25m	25m	25m
Vertical resolution	4m	4m	4m
Averaged Cell number	8.5 million	8.5 million	8.5 million
Total computation time (all sectors)	6 hours and 5 min	5 hours and 20 min	4 hours and 30 min
Averaged computation time per sector	18 min	16 min	13 min

4. Results and Discussion

4.1. Forest Model Sensitivity

In this chapter, we propose to investigate the sensitivity influence of the CFD forest model. It will show how much the cross-predictions can vary when the input variables that are the canopy height and the forest density are changing using default roughness maps. The model sensitivity has been studied on three sites using successively M1 and M2 as unique reference for each site and analyzing the cross predictions at the other mast. That means, for instance with Site 1, after selecting the reference mast M1, simulated wind speeds at mast M2 are compared to measurements and presented under the label "Site 1-M2" in Figure 5. For this purpose, two different scenarios are taken into account:

- **Influence of canopy height on wind flow:** For the sensitivity analysis, the canopy height influence has been investigated through the forest ratio R_{forest} for the three sites using the values 10, 20, 30, 40 and 50 with a fixed drag coefficient value at 0.005. This means that the canopy height on each mesh cell is calculated by multiplying the roughness length values by these ratios. For example, if considering roughness length value of 0.7 m corresponding to coniferous trees areas, the following canopy height influence are examined on the wind flow : 7 m, 14 m, 21 m, 28 m and 35 m.
- **Influence of forest density:**
  For the sensitivity analysis, the forest density influence is studied using the drag coefficient C_d parameter using the following values of 0.001, 0.005, 0.01, 0.02 and 0.05 and considering a fixed forest ratio (R_{forest}=20).

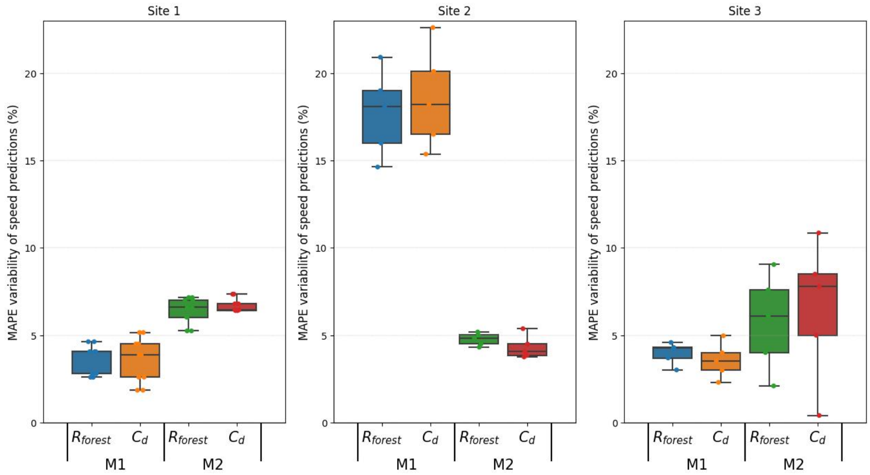


Figure 5. Sensitivity influence of input CFD forest model variables: Forest ratio R_{forest} and drag force coefficient C_d using MAPE variability. For each site, cross-predicted wind speed values are simulated using the other mast as a reference. It means that M1 is used as a reference mast to estimate M2 and M2 is used as reference mast to estimate M1.

Figure 5 presents the sensitivity influence of input CFD forest model variables on wind speed cross-predictions using the Mean absolute percentage error (MAPE) described in 2. Results indicate that both variables have a similar impact on wind speed cross predictions. Result variability ranges from 1% and 7% in the range of forest ratio [10-50] while the forest density variability ranges from 1 to 10% in the range of drag coefficient [0.001-0.05]. The model variability is very different on each site and mast. While it is difficult to interpret all variations, it can be noted that the maximum and minimum variability are observed on site 2 respectively for M1 and M2 showing the most extreme forest conditions on this project. As described in Table 1 and later in this study, on this site, M1 is located in very high and dense forest conditions while for M2, the wind measured at this mast position, located close to a clearing area is less affected by forest.

This analysis is also interesting to estimate the sensitivity influence of canopy height estimation around each mast position. As presented in Table 1, these values are roughly estimated from on-site observations and large uncertainties can be expected in some cases. As displayed on Figure 5, the MAPE variability due to a 7 m-canopy height variation is ranging between 0.04% to 2.3% with an averaged value of 0.8%. It is important to add that similar mean variability close to 1 % are also observed with higher drag coefficient values in the considered range. It means that a 7 m-mis-estimation of the canopy height only impacts cross-predicted MAPE by around 1% in average. A relative tolerance is thus observed on the forest height estimation around a mast.

It is interesting to note that in most cases, taking each parameter separately is not sufficient to obtain satisfying cross-predictions results. Specifically, unless unrealistic overestimated canopy height value is taken into account, the forest ratio adjustment is unable to produce proper results as noted in previous work using RANS approach [9]. It confirms that the canopy height is not the only variable affecting the wind simulations. The forest density is also a key parameter and should be considered carefully in the wind forest modeling approach as noted in previous studies [14,41]. Finally, this analysis highlights the necessity to provide a clear methodology to correctly combine these forest model parameters as presented in the IMA approach.

4.2. Iterative Model Adjustment (IMA) Method Applied on Each Mast Independently

The objective of this chapter is to describe in detail the IMA methodology on each site and reference mast. Table 3 displays the model parameters used on every site for both masts taken into consideration separately. For each site, The IMA methodology described in Figure ?? has been applied

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(same setup for 20 wind CFD sectors at each site) to simulate the forest influence on the mean wind profile at each mast location. Starting from initial parameters, forest model parameters have then been modified with IMA procedure to reach a suitable adjustment between the measured wind vertical profile and CFD simulation at the reference mast. As described previously, the initial forest ratio is set to be $R_{forest} = 20$ and the volumetric drag coefficient is set to be $C_D = 0.005$ as shown in 3. These forest model parameters have then been modified to fit better the measured wind vertical profile. In this work, we consider that forest model parameters are acceptable when the shear difference between the simulated results and the measurements is lower than 10%. This final result has been respectively obtained after 2, 7 and 1 iterations of the IMA procedure for sites 1, 2 and 3.

Here is the detailed Iterative model adjustment (IMA) procedure:

1. At site 1 and site 3, forest ratio has been deduced first from the tree height h_c presented in Table 1. For example, at site 3, the forest ratio $R_{forest} = \frac{h_c}{z_0} = \frac{20}{0.7} \approx 30$.
2. At site 2, forest ratio is set to default, the roughness map has been locally corrected according to on-site observations to increase the tree height from 14 m to 35 ± 5 m in coniferous forest areas. For this reason, the roughness length corresponding to coniferous forest areas has been modified from 0.7 m to 1.7 m in the roughness map conversion table.
3. After determining the forest ratio R_{forest}, we then adjusted the forest density using the drag coefficient value to adjust iteratively the wind shear.

Table 3. Forest model parameters used for IMA procedure

	Initial parameters	**Parameters with IMA**	**Roughness map modified**	**IMA iterations**
Site 1	$C_d = 0.005, R_{forest} = 20$	$C_d = 0.035, R_{forest} = 40$	No	3
Site 2	$C_d = 0.005, R_{forest} = 20$	$C_d = 0.075, R_{forest} = 20$	Yes	7
Site 3	$C_d = 0.005, R_{forest} = 20$	$C_d = 0.025, R_{forest} = 30$	No	2

Effects of IMA method are summarized on shear values in Figure 6 and illustrated on each vertical profile in the Figure 7 for all sites and masts. For each site, the highest mast elevation (100 m for Site 1 and 2 and 70 m for Site 3) is chosen as reference height.

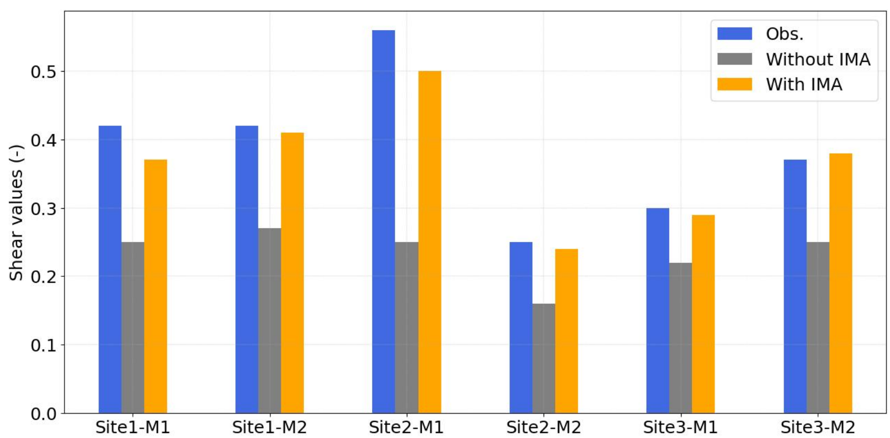

Figure 6. Influence of Iterative model adjustment (IMA) method on each reference mast shear value.

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Similar forest effects are observed for every site and met mast after IMA process shown in Figure 6. The default parameters in these dense forest areas generate lower shear values than expected. The parameters determined after the IMA procedure and presented in Table 3 allow to better consider the more dense forest and to increase the wind shear to match the mast data. As displayed on Figure 7, Vertical profiles at the reference masts are better depicted at lower elevations when the height and forest density are adjusted to more realistic values. This observation is especially evident at site 2 with Mast 1 as reference which is situated in the most forested area and has the highest difference in the shear value—nearly 0.3.

It is interesting to find that the IMA effect based on similar forest model parameters is constant across each site, allowing for the independent selection of each mast to determine the forest attributes for a given project. Once again, Site 2 is especially interesting because both masts are located in very different forest conditions showing very different shear values. While M2 observes standard forest conditions with a shear value around 0.25, M1 is strongly affected by forest presenting a wind shear value close to 0.6 also confirmed with pictures and google earth images (not presented here). In this case, similar forest conditions are inferred from both masts during the IMA procedure, although M2 is outside the forest and distant (>1 km) from very thick forest. This example shows that, depending on canopy height and forest density, forest effects can be observed up to 1 km away. According to this observation, IMA process seems to be applicable not only in the forest but also in the surrounding area. While it is generally advised to estimate WRA using a representative mast, i. e. with similar wind turbine roughness conditions [34], these results indicate that it would be feasible to estimate wind flow in forest areas utilizing an outside nearby mast.

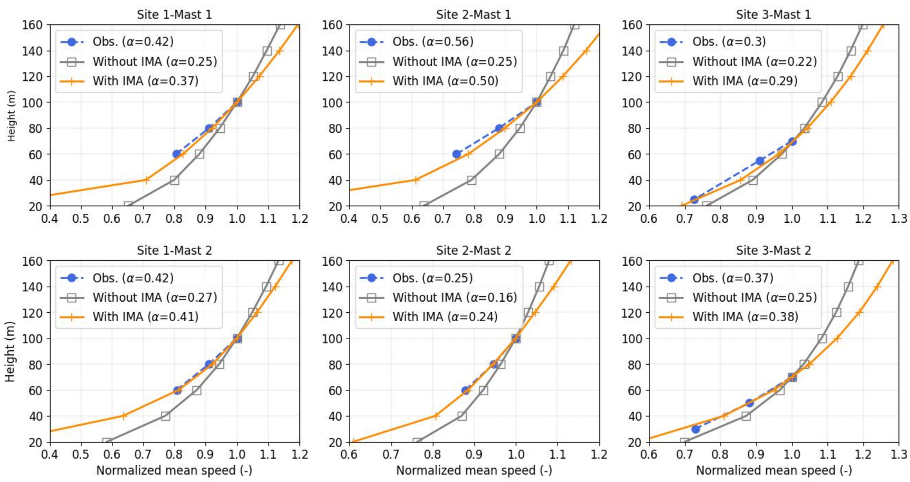

Figure 7. Influence of IMA methodology on each site and reference mast. The corresponding shear values (α) are also displayed in the legend.

4.3. Influence of Iterative Model Adjustment (IMA) on Cross-Predictions

The IMA methodology for wind forest modeling has been examined in this chapter on cross predictions for both horizontal and vertical extrapolation and results on all sites are presented on Figures 8–10. In this approach, the wind vertical profile at the other mast position is simulated using CFD computation for each site and reference mast and compared to measurements using the extrapolated mean wind speed values at several elevations. That means, for instance with Site 1, after selecting the reference mast M1, simulated wind shear and wind speeds at mast M2 are compared to measurements on Figures 8 and 9 and simulation uncertainties are quantified using MAPE on wind speeds presented on Figure 10.

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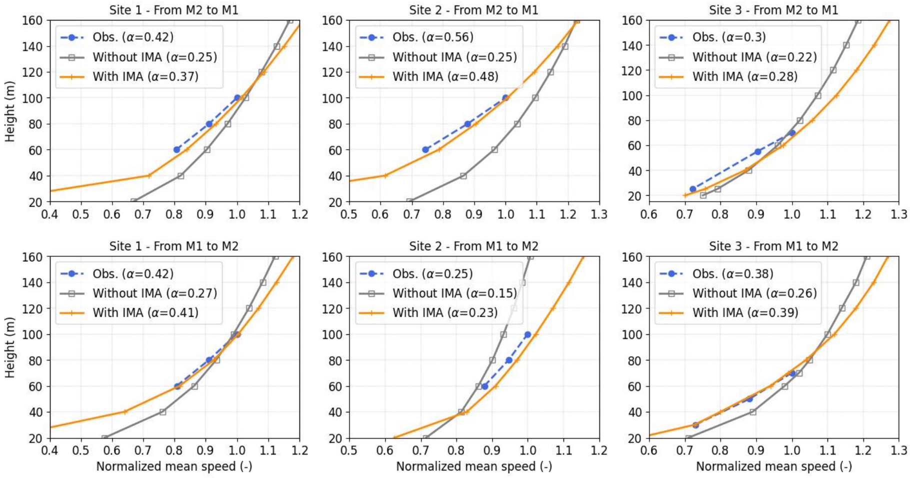

Figure 8. Influence of IMA methodology on cross-predicted wind profiles for each site and mast. For each site, cross-predicted wind speed values are simulated using the other mast as a reference. It means that M1 is used as a reference mast to estimate M2 and M2 is used as reference mast to estimate M1.

We observe a noticeable impact of the IMA methodology on the cross-predicted vertical profiles which is also clearly visible on shear values. In all cases, a wind profile twist is observed when the density of the forest and/or the roughness lengths are increased: the wind speed decreases at lower elevations and increases above. As presented on Figure 10, MAPE is reduced in all cases indicating that CFD model uncertainties are reduced using the IMA approach. In moderately high forest conditions observed in most cases, except in site 2 for M2, the MAPE reduction ranges from 0.8% to 4.4%. However for extreme forest conditions observed in Site 2 for M2, an improvement of 15.8% is observed. As expected, IMA methodology seems to be especially relevant when forest height and density are intense and different from the initial forest model.

As a consequence, shear differences between measurements and simulations are reduced significantly from the range [0.08-0.3] to [0.01-0.07] confirming that IMA method improves the vertical profile simulation. Additionally, Figures 6 and 9 show comparable patterns, indicating that an accurate estimation of forest model properties like the forest density determined at the reference mast can improve significantly the wind simulation in the whole area.

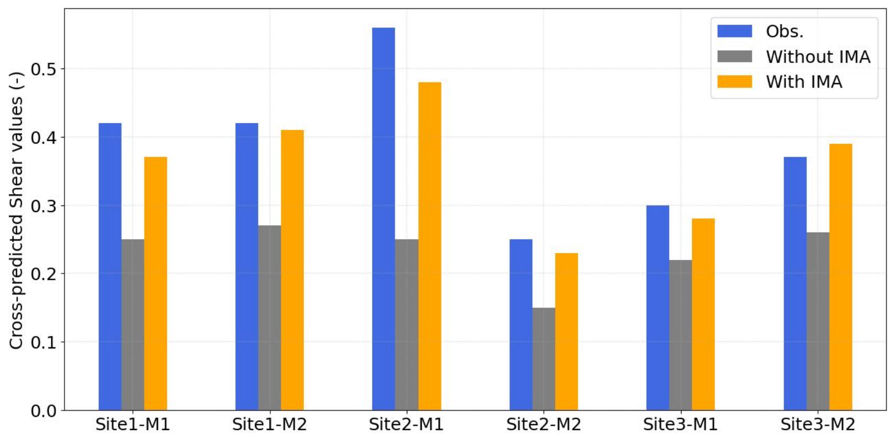

Figure 9. Influence of IMA methodology on cross-predicted wind shear values. For each site, cross-predicted wind speed values are simulated using the other mast as a reference. It means that M1 is used as a reference mast to estimate M2 and M2 is used as reference mast to estimate M1.

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This work also demonstrates that applying IMA methodology improves the simulation accuracy for horizontal extrapolation based on the highest elevations in most cases (100 m in site 1, 100 m in site 2 and 70 m in site 3). As displayed on Figure 10, except for case Site 3-M1, MAE applied on horizontally simulated wind speed is always reduced. Once again, this effect is especially highlighted in site 2 showing the maximal wind speed error decrease from 9.5% to 0.7%. Since wind turbine hub heights are often above 80 meters, this point is particularly crucial for estimating wind turbine production. At low elevations as well as above, near hub heights, the impact of IMA approach is evident.

Accurate cross-prediction results in all sites seem to validate the main assumption of IMA approach which is based on a constant drag coefficient value across each site. This means that forest drag force is similar close to both mast and one single mast can be used to determine the forest drag force properties of the site area. It is important to note that this assumption has been verified under particular conditions in this work, which include heterogeneous forest covering, dominant coniferous forest, and cross predictions in the distance range [2 km-6.6 km]. Although this distance range is typically used for industrial Wind Resource Assessment, the question of whether IMA is applicable across longer distances (>7 km) or including different forest types would still remain.

In contrast to previous work [7,9,12,15–17,21], this work shows that accurate speed cross-predictions in highly forested areas can be carried out using a one-equation turbulence-closure RANS CFD without advanced PAD information determined from advanced remote sensing imagery. However, these results have required a meticulous estimation of the forest density value using IMA approach based on full year-period wind speed measurements.

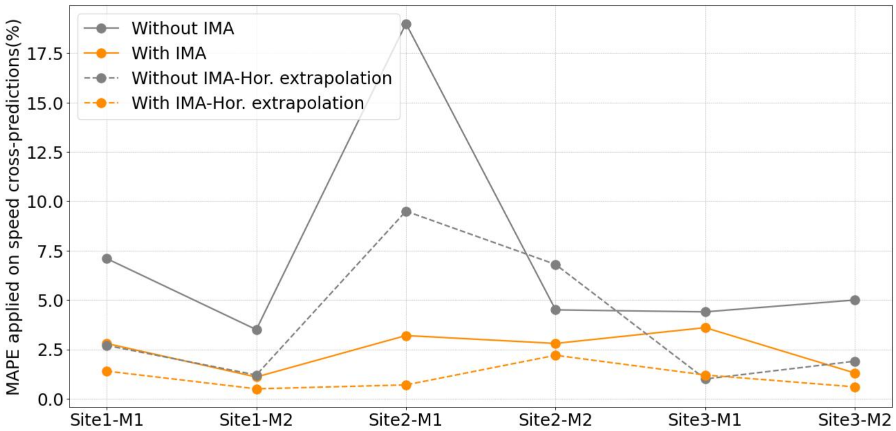

Figure 10. Influence of IMA methodology on Mean Absolute Percentage Errors applied on cross-predicted wind speed values. For each site, cross-predicted wind speed values are simulated using the other mast as a reference. It means that M1 is used as a reference mast to estimate M2 and M2 is used as reference mast to estimate M1.

5. Conclusions

This study proposes an innovative approach based on in-situ measurements to improve the accuracy of RANS CFD based wind resource assessment in complex and wooded areas. This methodology defined as "IMA" for Iterative Model Adjustment, is easily applicable and only requires wind speed profile measurements at one single mast to determine the specific forest properties and adjust the CFD forest model accordingly. In order to validate the relevancy of this approach, six calibration procedures (3 sites containing 2 masts) have been performed using the commercial software Meteodyn WT™. The key findings are summarized as follows:

1. **Accurate wind simulation based on IMA methodology**: Wind speed estimation accuracy improved significantly when using appropriate forest height and drag coefficient values determined using the IMA methodology. Shear differences compared to measurements have been reduced

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significantly from [0.08-0.3] to [0.01-0.07]. Horizontal mean speed errors have been reduced from [1.0-9.5 %] to [0.5-2.2%] leading to a *global mean absolute speed error of 1.1 % based on six cases*.

2. **Better understanding of wind forest modeling**: In addition to a complete methodology for WRA, this work also proposes a detailed analysis of CFD forest drag force input variables. It has been observed that the drag coefficient and canopy height both have a comparable impact on the calculation of wind flow.
   The assumption of a constant drag coefficient value across each site has been verified in all cases including heterogeneous forest covering, dominant coniferous forest, complex terrain and cross predictions in the distance range [2 km-6.6 km]. While cross-prediction distances exceeding 7 km are outside of established guidelines in complex terrain [34], the applicability of IMA over longer distances and in different forest types would remain an open question.
   We also observed that forest modeling effects can be seen on wind flow in clearing areas up to 1 km away from very thick forest. Because of this, we showed that the IMA process can be applied not only in the forest area but also in the surrounding area.
3. **Usage of land cover maps**: This work confirmed the relevancy of using land cover maps based on satellite data for wind forest modeling. However, conversion tables and/or forest ratio have been corrected in all cases to take into account more realistic canopy heights. We nevertheless noted a relative tolerance of canopy height mis-estimation on forest modeling with a 0.8% error variability on mean speed observed in average with a 7 m-canopy height modification.

We demonstrated that very accurate CFD results can be obtained using measurements and materials limited to those typically found for operational wind resource assessment studies, such as public maps and measurements at one mast. This project has been applied on six verification procedures with a large variety of complex and forest conditions. Therefore, observations and methods presented here can be considered relevant and applicable to other studies in wooded areas.

In this work, we assumed neutral conditions for the forest calibration procedure based on the hypothesis that neutral conditions where satisfied when considering a full year period. This assumption was necessary to separate forest effects and thermal stability effects, in order to facilitate the IMA procedure in first approach. Although the neutral condition assumption has already been validated with a full year measurement data in this work, the influence of atmospheric thermal stability effects on wind flow temporal variations remains an open question and would require further analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

CFD	Computational Fluid Dynamics
WRA	Wind Resource Assessment
RANS	Reynolds-Averaged Navier-Stokes
IMA	Iterative model adjustment
MAPE	Mean Absolute Percentage Error
MAE	Mean Absolute Error

References

1. Alfredsson, P. Wind Farms in Complex Terrains: An Introduction. Philosophical Transactions of the Royal Society A: Mathematical. *Physical and Engineering Sciences* **2017**, *2091*, 375.
2. Enevoldsen, P. Onshore wind energy in Northern European forests: Reviewing the risks. *Renew. Sust. Energ. Rev.* **2016**, *60*, 1251–1262.
3. Pereira, R.; Ricardo, G.; Silva Santos, C. Comparing WAsP and CFD wind resource estimates for the "regular" user. *Proceedings of the European Wind Energy Conference, Warsaw, Poland* **2010**.
4. Shaw, R.H.; Schumann, U. Large-eddy simulation of turbulent flow above and within a forest. *Bound.-Lay. Meteorol.* **1992**, *61*, 47–64.
5. Kanani, F.; Träumner, K.; Ruck, B.; Raasch, S. What determines the differences found in forest edge flow between physical models and atmospheric measurements? – An LES study. *Meteorol. Z.* **2014**, *23*, 33–49.
6. Boudreault, L. Reynolds-averaged Navier-Stokes and Large-Eddy Simulation Over and Inside Inhomogeneous Forests. Phd thesis, Technical University of Denmark, Department of Mechanical Engineering, 2015.
7. Boudreault, L.E.; Bechmann, A.; Tarvainen, L.; Klemedtsson, L.; Shendryk, I.; Dellwik, E. A LiDAR method of canopy structure retrieval for wind modeling of het-erogeneous forests. *Forest Meteorol* **2015**, *201*, 86–97. https://doi.org/https://doi.org/10.1016/j.agrformet.2014.10.014.
8. Chávez-Arroyo, R.; Sanz-Rodrigo, J.; Gancarski, P. Modelling of atmospheric boundary-layer flow in complex terrain with different forest parameterizations. *J. Phys. Conf. Ser.*, **2014**, *524*. https://doi.org/https://doi.org/10.1088/1742-6596/524/1/012119.
9. Ivanell, S.; Arnqvist, J.; Avila, M.; Cavar, D.; Chavez-Arroyo, R.; Oliva-res Espinosa, H.; Peralta, C.; Adib, J.; Witha, B. Micro-Scale Model Comparison (Benchmark) at the Moderately Complex Forested Site Ryningsnäs. *Wind Energy Science* **2018**, *3(2)*, 929–946. https://doi.org/10.5194/wes-3-929-2018.
10. Crasto, G. Forest Modeling, A canopy model for WindSim 4.5 **2006**.
11. Delaunay, D. *Modelling the stable boundary layer for wind resource assessment*; 2013.
12. Monteiro, J.R.; Batista, V.T.P.; Palma, J.M.L.M. Assessing canopy models across forest edges on flat terrain. *Journal of Physics: Conference Series* **2024**, *2767*, 092011. https://doi.org/10.1088/1742-6596/2767/9/092011.
13. Jiang, Z.; Bullido-Garcia, M.; Houbart, J.C.; Bezault, C. CFD modeling of forest canopy flows: Input parameters, calibration and validation. 2013, Vol. 1, pp. 457–465.
14. Sanquer, S.; Berthaut-Gérentes, J.; Cosculluela Soteras, L. Modelling wind flow in forested areas: a parametric study. In Proceedings of the AWEA proceedings, 2016.
15. Melani, P.F.; Balduzzi, F.; Orlando, S.; Vitic, V.; Bianchini, A. Numerical analysis of the impact of forestry on the wind resource assessment in complex terrains. In Proceedings of the Wind Energy Science Conference 24 – 27 of June 2025 Nantes, 2025.
16. Lopes da Costa, J.; Castro, F.; Palma, J.M.L.M.; P., S. Computer Simulation of Atmospheric Flows over Real Forests for Wind Energy Re-source Evaluation. *Journal of Wind Engineering and Industrial Aerodynamics* **2006**, *94(8)*, 603–620.
17. Katul, G.G.; Mahrt, L.; Poggi, D.; Sanz, C. One and Two-Equation Models for Canopy Turbulence. *Boundary-Layer Meteorology* **2004**, *113(1)*, 81–109.
18. Meteodyn. Meteodyn user manual advanced notes. 2026.
19. Delaunay, D.; Wang, L.; S., B. Calibrating a CFD canopy model with the EC1 vertical profiles of mean wind speed and turbulence. 2011.
20. Konagaya, M.; Ohsawa, T.; Itoshima, Y.; Kambayashi, M.; Leonard, E.; Tromeur, E.; Misaki, T.; Shintaku, E.; Araki, R.; Hamada, K. Estimation of Wind Conditions in the Offshore Direction Using Multiple Numerical Models and In Situ Observations. *Energies* **2025**, *18*. https://doi.org/https://doi.org/10.3390/en18113000.

doi:10.20944/preprints202603.2044.v1

21. Queck, R.; Bienert, A.; Maas, H.e.a. Wind fields in heterogeneous conifer canopies: parameterisation of momentum absorption using high-resolution 3D vegetation scans. *Eur J Forest Res* **2012**, *131*, 165–176. https://doi.org/https://doi.org/10.1007/s10342-011-0550-0.
22. CORINE Land Cover 2018 (raster 100 m). https://land.copernicus.eu/en/products/corine-land-cover/clc2018. https://doi.org/https://doi.org/10.2909/960998c1-1870-4e82-8051-6485205ebbac.
23. Land Cover 2015-2019 (raster 100 m). https://doi.org/https://doi.org/10.2909/c6377c6e-76cc-4d03-8330-628a03693042.
24. NASADEM Global Digital Elevation Model. https://doi.org/https://doi.org/10.5069/G93T9FD9.
25. EU-DEM (raster) - version 1.1, Apr. 2016. https://doi.org/https://sdi.eea.europa.eu/catalogue/datahub/api/records/19cff95e-61ac-45ed-8ee3-c43220d709cf.
26. Dörenkämper, M.; Olsen, B.T.; Witha, B.; Hahmann, A.N.; Davis, N.N.; Barcons, J.; Ezber, Y.; García-Bustamante, E.; González-Rouco, J.F.; Navarro, J.; et al. The Making of the New European Wind Atlas – Part 2: Production and evaluation. *Geoscientific Model Development* **2020**, *13*, 5079–5102. https://doi.org/10.5194/gmd-13-5079-2020.
27. Abbas, M.R.e.a. An overview of wind-energy-production prediction bias, losses, and uncertainties. *IOP Conf. Ser.: Earth Environ. Sci.* **2021**, *722*, 012015. https://doi.org/https://doi.org/10.1088/1755-1315/722/1/012015.
28. Floors, R.; Enevoldsen, P.; Davis, N.and Arnqvist, J.; Dellwik, E. From lidar scans to roughness maps for wind resource modelling in forested areas. *Wind Energ. Sci.* **2018**, *3*, 353–370. https://doi.org/https://doi.org/10.5194/wes-3-353-2018.
29. Silva, J.; Ribeiro, C.; Ricardo, G., M.C.; Ulrich, F. Roughness length classification of Corine Land Cover classes. *Proceedings of EWEC 2007* **2007**.
30. WIKI-Windpro. https://doi.org/https://help.emd.dk/mediawiki/index.php/Corine_Land_Cover.
31. Lee, J.C.Y.; Fields, M.J. An overview of wind-energy-production prediction bias, losses, and uncertainties. *Wind Energ. Sci.* **2021**, *6*, 311–365. https://doi.org/https://doi.org/10.5194/wes-6-311-2021.
32. IEC 61400-12-1:2022. https://doi.org/https://webstore.iec.ch/en/publication/68499.
33. Cunha Pinheiro, J.; R., A.D.C. The uncertainties in the estimation of electricity production in the Brazilian onshore wind sector. *e-Prime - Advances in Electrical Engineering, Electronics and Energy* **2025**, *12*, 100996. https://doi.org/https://doi.org/10.1016/j.prime.2025.100996.
34. Organisation, M. MEASNET Procedure:Evaluation of Site-Specific Wind Conditions. *Version 3* **2022**.
35. Pope, S.B. *Turbulent Flows*; Cambridge University Press: Cambridge, 2000.
36. Ferry, M. New features of the MIGAL solver. In Proceedings of the Proc. Of the Phoenics Users Int. Conf., Moscow, 2002.
37. Maldonado-Correa, J.; Vásquez, G.; Paccha-Herrera, E.; Cuenca, J.; Rojas, M.; Solano, J.; Valdiviezo, M.; Samaniego, C.; Valarezo, J., Analysis of the Annual Energy Production of the Villonaco Wind Farm. In *Congress on Research, Development, and Innovation in Renewable Energies: Selected Papers from CIDiER 2022*; Espinoza-Andaluz, M.; Melo Vargas, E.; Santana Villamar, J.; Encalada-Dávila, Á., Eds.; Springer International Publishing: Cham, 2023; pp. 73–87. https://doi.org/10.1007/978-3-031-26813-7_5.
38. Yamada, T. Simulations of nocturnal drainage flows by a q^2–l turbulence closure model. *Journal of the Atmospheric Sciences* **1983**, *40*, 91–106.
39. Liu, J.; Chen, J.M.; Black, T.A.; Novak, M.D. E–ε Modelling of Turbulent Air-Flow Downwind of a Model Forest Edge. *Boundary-Layer Meteorology* **1996**, *77*, 21–44.
40. Garratt, J. *The atmospheric boundary layer*; Cambridge atmospheric and space science series, 1996.
41. Chaudhari, A.; Ashu, T.; Vita, G.; Hellsten, A. Impact of Forest Density on Atmospheric Boundary-Layer Flow and Turbulence for Wind Energy Applications. *Boundary-Layer Meteorology* **2026**, *192*, 91–106. https://doi.org/https://doi.org/10.1007/s10546-025-00959-0.