Open source model for micro-siting design and analysis of wind farms

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SUMMARY:

An open source model for design and analyze micro-sitting wind farm was developed. Based on the use of hourly or ten-minutes meteorological time serial including wind velocity and direction and temperature at two heights. The model handle a frame defined by the user where topography, wind turbine locations and roughness length are specified. The wind velocity is calculated in each site where a wind turbine is located by previously determining the terrain slope and speed up factor in each site. Although the model supports different wake models to describe the flow in the wake produced by each wind turbine, only the model proposed by Crespo, et al., 1999 was considered in this study. A test case is presented in which a time series of the power production of a wind farm is calculated using the model and compared with the production of a wind farm in operation obtained from the SCADA. A root mean square error in the energy production of each wind turbine of about 20% was obtained, while only 0.9 % was obtained when comparing the overall production of the wind farm.

Keywords: wind power, wind turbine wake model, micro-sitting wind farm, optimization wind farm production

1. INTRODUCTION

The analysis of the wind and a wind turbine interaction is a multi-scale problem. When the air flow around the wind turbine runner, as consequence of the interaction forces are applied on the flow and as reaction on the blades. This process depends on wind velocity, air density and the blade geometry and it would be affected by the turbulence level and scales of vortices embedded in the flow. The tools to analyze this process are mainly based on Blade Element Momentum Theory (BEMT) and CFD as Burton, 2011, Martínez-Tosas, et al., 2014, among others.

As consequence of forces applied on the flow a wake is developed downstream of the runner. Several analytical models have been developed to describe the wake produced by the interaction between the wind and a wind turbine rotor. From the early very simple model presented by Katic, et al., 1987 which modelled only the velocity deficit, through Crespo, et al., 1999 where turbulence is described, to more complex models such as those presented by Bastankhah, et al., 2014 and Grebaad, et al., 2014 where the deviation of the wake and the flow in different wake sub-regions is described, could be mentioned. A performance analysis of each of these models is presented in Campagnolo, et al., 2019.

Large scale wind power use is made with wind farms composed of clusters of wind turbines. The distance between machines follow a trade-off between wind power availability, wind power directions, topography and terrain availability. At this scale the wake and wind turbine interaction is relevant, but the principal result is the wind farm annual energy production. The micro-sitting tools must include the effect of the terrain on the flow, a wake model and wind turbine performance curves. Examples of such include the widely used WAsP, 2023 and Wind Pro.

In Uruguay, between 30 % and 45 % of annual electrical energy production is obtained from wind. In this context, the authors decided to analyze the performance of an operating wind farm located in Uruguay and develop an open-source tools oriented to optimize its micro-sitting. The main objective of this study is to validate the open-source model by predicting the energy production of an operating wind farm.

2. REQUIRED DATA

The model analyze the performance of wind farms supposed integrated with several wind turbines, all equal each another. But it is possible analyze the use of different wind turbine. For each analyzed machine (aero) is required to know the performance curves power – wind velocity and thrust coefficient – wind velocity each 0.5 m/s between 0 and 30 m/s. For each machine it must be known the rate power, runner diameter and hub height.

The meteorological data are measured from a mast and stored in time series with an hourly or ten minutes time step. After, this time step is used to describe the evolution of the wind farm production. The time series include mean wind velocity (at one or two heights), wind direction, velocity fluctuation root mean square and the temperature at two heights. Also, measurement height, length roughness and zero displacement plan height around the mast for different wind direction each 10° should be described.

Each wind turbine location site is specified with a coordinate in a framework geographically indexed. Around each site the roughness length is determined each 10°. The topography is described from satellite information available in **http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp)**. Once the SRTM region is identified, a rectangular zone is defined where the wind farm is located. From the digital information about the topography as preliminary result the contour lines are obtained and verified. For each possible wind turbine location altitude and slope are calculated and speed up factor guessed each 10° wind direction.
For each time serial component, the temperature gradient is calculated as 2.1 and the atmospheric thermodynamic condition is determined.

$$\frac{\partial T}{\partial Z} \cong \frac{T(Z_2)-T(Z_1)}{Z_2-Z_1} \qquad (2.1)$$

Through temperature gradient the Pasquill´s stability class from Arya, 1999 is determined as table 2.1 presents. From the stability class and the roughness length an estimation of Monin-Obukhov length scale is determined from figure 2.1 from Golder, 1972.

Stability class	Temperature gradient (°K/km)
A	< -19
B	-19 a -17
C	-17 a -15
D	-15 a -5
E	-5 a 15
F	15 a 40
G	>40

Table 2.1- Pasquill´s stability class

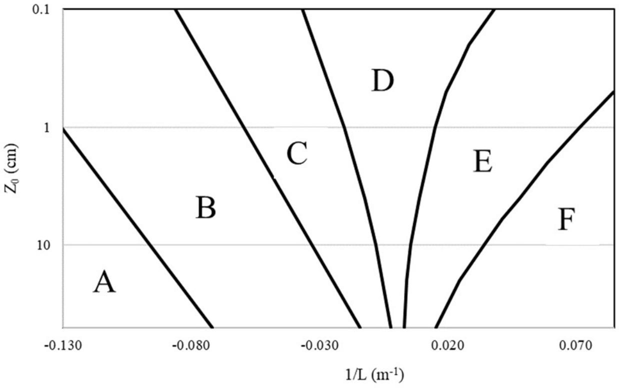

Figure 2.1 – Relation between roughness length, stability class and Monin-Obukhov length scale

Also, if the velocity in known at two heights, the Monin-Obukhov length scale could be estimated from Richardson number, defined as equation 2.2, and the result presented on figure 2.2 from Stull, 1988.

$$Ri = \frac{g}{\theta} \frac{\frac{\partial \theta}{\partial z}}{\left(\frac{\partial U}{\partial z}\right)^2} \tag{2.2}$$

Where θ is the potential temperature. We propose approximate potential temperature with temperature.

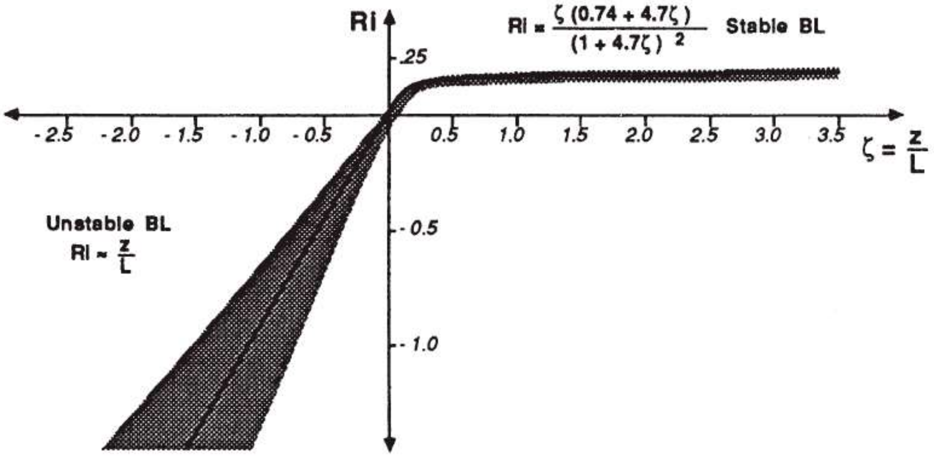

Figure 2.2 – Relation between Richardson number and Monin-Obukhov length scale (Stull, 1988)

3 – Model description

For each meteorological time series component, the production of each wind turbine is calculated and a power time series is obtained with the same times step as the meteorological data. A first micro-sitting guess is proposed taking into account wind rose, topography and wind turbine dimensions. A coordinate is assigned to each machine in the same framework as the topography.

For the wind diction φ a rotation of the frame is made. The new framework (lower case) would have the y-axis pointing upstream as it is showed in figure 3.1. The wind turbines are ordered in y-value decreasing, then the first wind turbine, with the greatest y-value, it is not affected by any wake of other wind turbine.

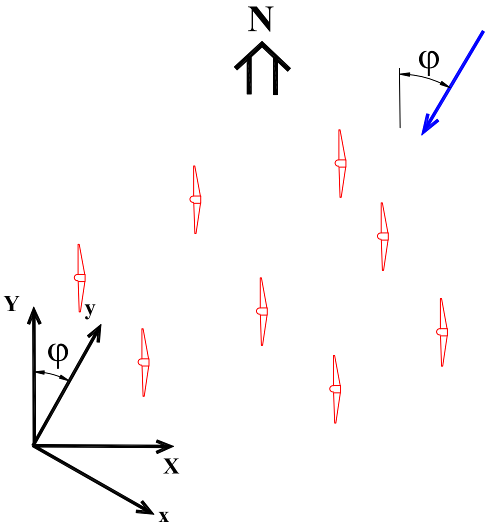

Figure 3.1 – Wind farm sketch, frame and rotation

Once the rotation is made the wind turbine are gone down from $\ell = 1$ (highest y value) to $\ell = s$ (lowest y value), where s is the amount of turbines.

In a particular wind turbine ℓ the turbulence intensity and the mean velocity, as a first approach, are extrapolated at the hub height in the site. In addition to the height, the changes of roughness and the speed up factor are considered. The extrapolation is made with equations 3.1 and 3.2.

$$I_X = \frac{\sigma_{EM}}{V_{EM}} . \frac{\ln\left({}^{Z_{REF}}/{}_{Z_0(\varphi)}\right)}{\ln\left({}^{Alt}/{}_{Z_{0,\ell}(\varphi)}\right)} \tag{3.1}$$

$$V_{nn} = V_{REF} . \left(\frac{Z_{0,\ell}(\varphi)}{Z_0(\varphi)}\right)^{0.0706} \frac{\ln\left({}^{Alt}/{}_{Z_{0,\ell}(\varphi)}\right) - \psi\left(\frac{Alt}{L}, \frac{Z_{0,\ell}(\varphi)}{L}\right)}{\ln\left({}^{Z_{Ref}}/{}_{Z_0(\varphi)}\right) - \psi\left(\frac{Z_{REF}}{L}, \frac{Z_0(\varphi)}{L}\right)} . SU_\ell(\varphi) \tag{3.2}$$

The ψ function depends of atmospheric stability as it is presented in equation 3.3.

Unstable atmosphere $\quad \psi\left(\frac{Z}{L}, \frac{Z_0}{L}\right) = \ln\left(\frac{(1+uu_2)^2.(1+uu_2^2)}{(1+uu_1)^2.(1+u\ {}_1^2)}\right) - 2atg(uu_2) + 2atg(uu_1)$

Stable Atmosphere $\quad \psi\left(\frac{Z}{L}, \frac{Z_0}{L}\right) = -4.7\left(\frac{Z}{L} - \frac{Z_=}{L}\right) \qquad (3.3)$

Neutral Atmosphere $\quad \psi\left(\frac{Z}{L}, \frac{Z_0}{L}\right) = 0$

For unstable atmosphere the magnitudes *uu₁* y *uu₂* are defined as equation 3.4.

$$uu_1 = \sqrt[4]{1 - 15\, {}^{Z_0}/{}_{L}}$$

$$uu_2 = \sqrt[4]{1 - 15\, {}^{Z}/{}_{L}} \tag{3.4}$$

For each wind turbine ℓ all the other turbines are gone down. For the m wind turbine, the relative coordinates X_i y Y_i are defined as equation 3.5.

$$X_i = x_m - x_\ell$$

$$Y_i = y_m - y_\ell \tag{3.5}$$

If Y_i is negative, then the m wind turbine does not affect the considered ℓ wind turbine and is added zero to the wind deficit *DELTAC*. If Y_i is positive, then there is aerodynamic interference and we add to *DELTAC* the produced deficit following the used wake model. The adition would be linear or quadratic in dependence of the used wake model. As reference we use the wake model proposed in Crespo, et al., 1999, whose propose the wind speed deficit calculate as equations 3.6.

$$\Delta V = 2.a.U \qquad si\frac{x}{D} < 2\ o\ 3$$

$$\Delta V = k.a.U\left(\frac{D}{x}\right)^{n} \qquad si\frac{x}{D} > 2\ o\ 3 \tag{3.6}$$

where 3.4 ***U*** is the wind velocity at the wind turbine upstream, ***D*** the runner diameter and ***a*** the velocity induction coefficient. k and n coefficient are associated to different wind exposure and the k values are between 2 and 4 and the n values between 0.75 and 1.25. Turbulence intensity additional is calculated agree equation 3.7.

$$I_{ad} = 0.725\,a \qquad \text{Si}\,\frac{x}{D} < 2ó3$$

$$I_{ad} = 0.73.a^{0.8325} I_{u,eje}^{-0.0325}\left(\frac{D}{x}\right)^{0.32} \qquad \text{Si}\,\frac{x}{D} > 2ó3 \tag{3.7}$$

where $I_{u,eje}$ is the turbulence intensity upstream at the hub height of the turbine that produce the wake.

The velocity in the ℓ turbine is calculated as equation 3.8.

$$V_P(\ell) = V_{nn}(1 - DELTAC) \tag{3.8}$$

Also, each wake models propose the modification of the turbulence intensity defining an additional turbulence ($I_{ad,m}$) induced by the m wind turbine on the ℓ wind turbine. The intensity of turbulence will be calculated at ℓ wind turbine as follow.

$$I_u(\ell) = \sqrt{I_x^2 + \sum_m I_{ad,m}^2} \tag{3.9}$$

When the calculated $V_P(\ell)$ is below zero, greater of cut out or greater than 15 m/s and turbulence intensity greater than reference value for the wind turbine class, the power is considered zero. In other cases, the power is obtained from the performance curve.

If the intensity of turbulence is greater than 10 % a factor is applied to the power as follow.

$$(1 - \ DELTAPT) = (1 - \ 1.11(I_u(\ell) - 0.1)) \tag{3.10}$$

Although this correction was get inspired in the methodology proposed in code IEC, 2107 to determine the normalized performance curve, it was proposed a simplification based on engineering approach.

As it was mentioned the model is operated for all meteorological time series and a power production time series for each wind turbine is obtained.

4 – TEST CASE

The performance of the model was evaluated for a wind farm named JPT and located in the north of Uruguay composed by 28 units NORDEX model N117/2400. Figure 4.1 shows the location and micro-sitting. In figure 4.2 probability density distribution and wind rose in the site.

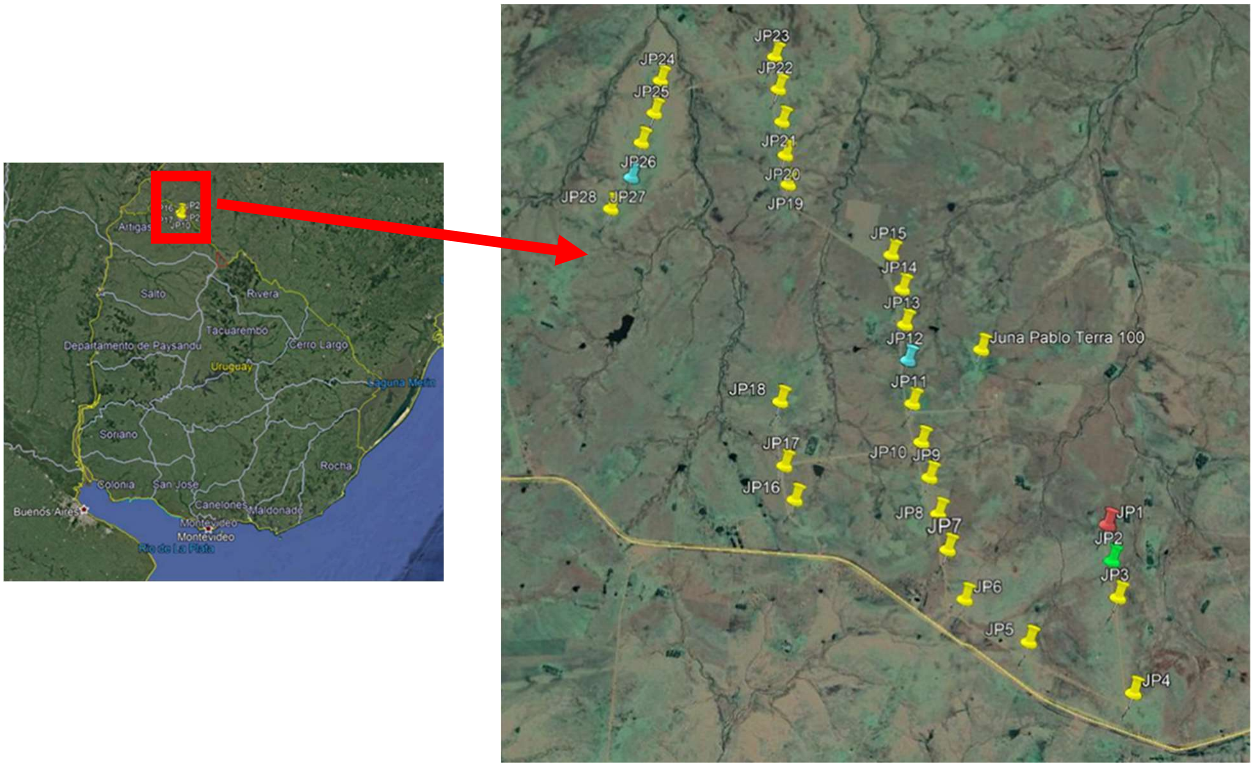

Figure 4.1 – Location and micro-sitting JPT Wind farm

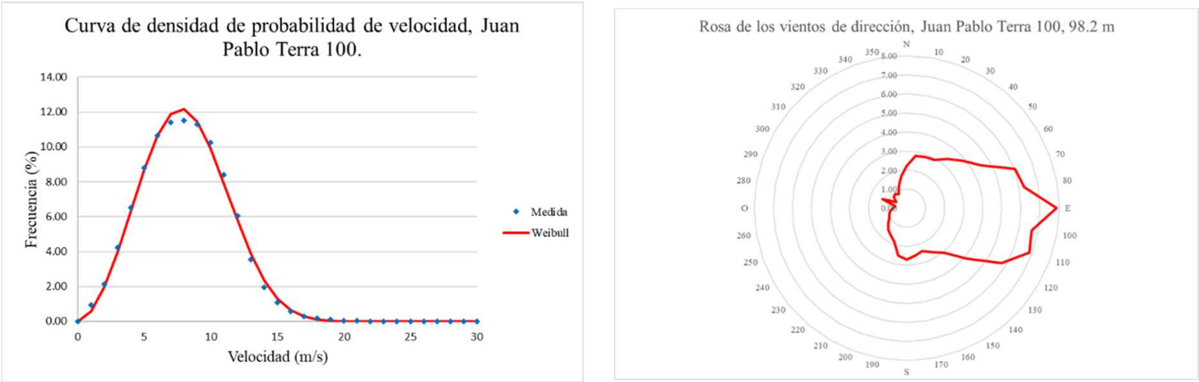

Figure 4.2 – Wind velocity pdf and wind rose

Production data for each wind generator from SCADA from year 2015 to year 2019 each 10 minutes were available and meteorological data from a nearby mast. Depuration data was made taking into account: all turbines in operation, operation of all turbines with non- error, meteorological data available. After this depuration a time series 1.37 yearlong was obtained. For such period the capacity factor was 51.09 %.

k and n value were determined with a three index optimization methodology. With parameters k and n values, the production of each wind turbine i was calculated for each time τ_j ($\widehat{P_i}(\tau_j)$). The real production of each wind turbine is $P_i(\tau_j)$. A first index was de capacity factor. The other two index are defined with equations 4.1 and 4.2

$$DifAero = \frac{\sqrt{\sum_{j=1}^{j=L}\sum_{i=1}^{i=N_{Aero}}\left(\frac{P_i(\tau_j)-\widehat{P_i}(\tau_j)}{P_i(\tau_j)}\right)^2}}{N_{Aero}\cdot L} \qquad (4.1)$$

$$DifParque = \frac{\sqrt{\sum_{j=1}^{j=L}\left(\frac{\left(\sum_{i=1}^{i=N_{Aero}} P_i(\tau_j)\right)-\left(\sum_{i=1}^{i=N_{Aero}} \widehat{P_i}(\tau_j)\right)}{\sum_{i=1}^{i=N_{Aero}} P_i(\tau_j)}\right)^2}}{L} \qquad (4.2)$$

where N_{Aero} is the number of turbines (28) and L the length of the time serial (72061).
The methodology implied adjust the wake model parameters k and n to obtain the same capacity factor deduced from the production and minimize the indices *DifParque* and *DifAero*. Following the methodology k equal 2 and n to 1.25 were obtained.

The calculated capacity factor was 51.09 %, while the square mean errors were *DifAero* 21.9 % *DifParque* of 0.9 %.

5 – CONCLUSION

An open source model for designing and analyzing micro-sitting wind farm was developed based on the use of use hourly or ten-minutes meteorological time serial including wind velocity and direction and temperature at to height.
The model handle a frame defined by the user where topography, wind turbine locations and roughness length are referred and an additional tool is used for calculate terrain slope and speed up faction each location on the terrain.

The wind velocity is calculated in each site where is located a wind turbine. Although the model supports different wake models to describe the flow in the wake produced by each wind turbine, only the model proposed by Crespo, et al., 1999 was considered in this study.

As result he production of each wind turbine is calculated with the same time step as the meteorological data time series.
A test case was presented. The production of a wind farm in operation was obtained from the SCADA. A square mean error in the description of each wind turbine around 20% was obtained while only 0.9 % between the wind farm production and calculated.

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