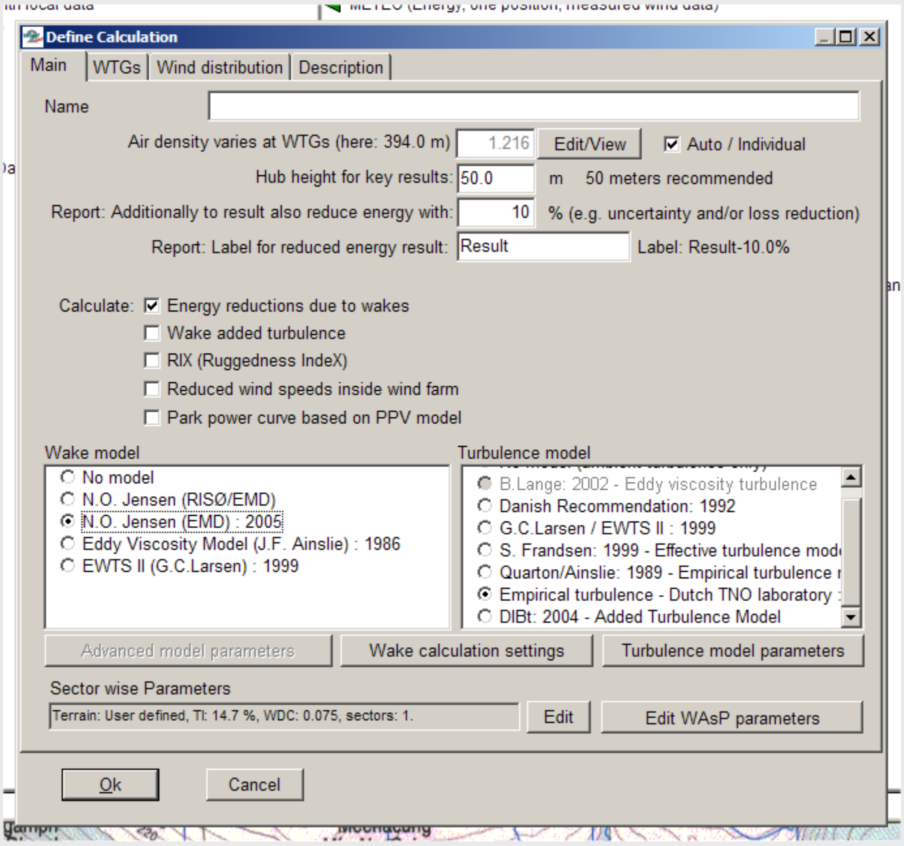
Wake and Turbulence Models in WindPRO



Name

Air density varies at WTGs (here: 394.0 m) 1.216 ☑ Auto / Individual

Hub height for key results: 50.0 m 50 meters recommended

Report: Additionally to result also reduce energy with: 10 % (e.g. uncertainty and/or loss reduction)

Report: Label for reduced energy result: Result Label: Result-10.0%

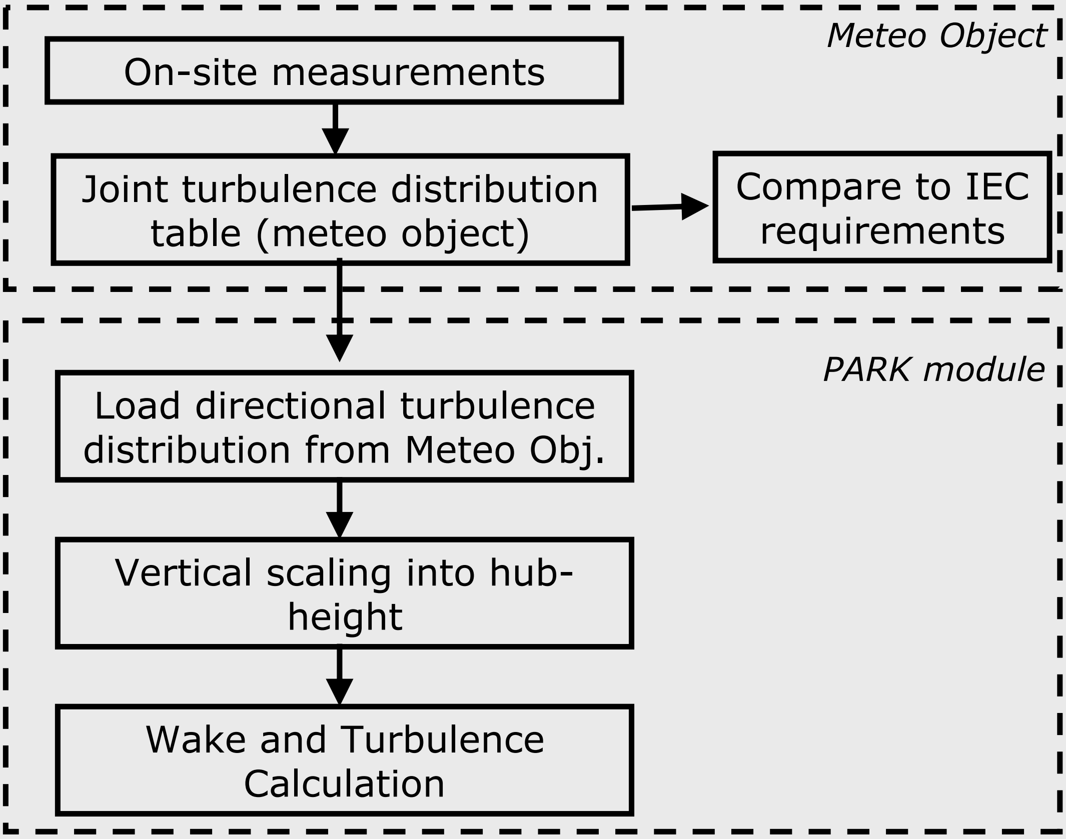
Calculate: ☑ Energy reductions due to wakes
☐ Wake added turbulence
☐ RIX (Ruggedness IndeX)
☐ Reduced wind speeds inside wind farm
☐ Park power curve based on PPV model

Wake model
○ No model
○ N.O. Jensen (RISØ/EMD)
● N.O. Jensen (EMD) : 2005
○ Eddy Viscosity Model (J.F. Ainslie) : 1986
○ EWTS II (G.C.Larsen) : 1999

Turbulence model
○ B.Lange: 2002 - Eddy viscosity turbulence
○ Danish Recommendation: 1992
○ G.C.Larsen / EWTS II : 1999
○ S. Frandsen: 1999 - Effective turbulence mod
○ Quarton/Ainslie: 1989 - Empirical turbulence
● Empirical turbulence - Dutch TNO laboratory
○ DIBt: 2004 - Added Turbulence Model

Sector wise Parameters
Terrain: User defined, TI: 14.7 %, WDC: 0.075, sectors: 1.

Turbulence: Procedure in WindPRO



Meteo Object

On-site measurements

Joint turbulence distribution table (meteo object)

Compare to IEC requirements

PARK module

Load directional turbulence distribution from Meteo Obj.

Vertical scaling into hub-height

Wake and Turbulence Calculation

Turbulence: Vertical Scaling (1)

The turbulence intensity in the height x meters is defined as:

$$IT(x) = \frac{\sigma_U(x)}{U_{10}(x)} \qquad (5)$$

Where

IT is the turbulence intensity
σ_U is the standard deviation of the wind speed
U_{10} is the mean wind speed averaged over 10 minutes

Experimental data has shown that the standard deviation of the wind speed only decreases very slowly. In Armit [6] & Dyrbye & Hansen [7], it is said, that it is reasonable to use constant standard deviations up to about the half-height of the internal boundary layer. This assumption is also used in WAsP and in most structural codes.

Using this assumption, the vertical scaling of turbulence intensity between two heights is simply calculated by assuming the same standard deviations in the two heights (x and y meters or feet).

Turbulence: Vertical Scaling (2)

$$\begin{aligned} &\sigma_U(x) = \sigma_U(y) && \Leftrightarrow \\ &IT(x) \cdot U_{10}(x) = IT(y) \cdot U_{10}(y) && \Leftrightarrow \\ &IT(y) = \frac{U_{10}(x)}{U_{10}(y)} IT(x) && \end{aligned} \qquad (6)$$

So now the problem is reduced into calculating the mean wind speed in the new height. The vertical scaling of wind speeds may be done using the power law vertical wind profile a purely empirical equation. The power law wind profiles also require quite homogenous terrain.

$$U_{10}(y) = U_{10}(x) \cdot \left[\frac{y}{x}\right]^{\gamma} \qquad (7)$$

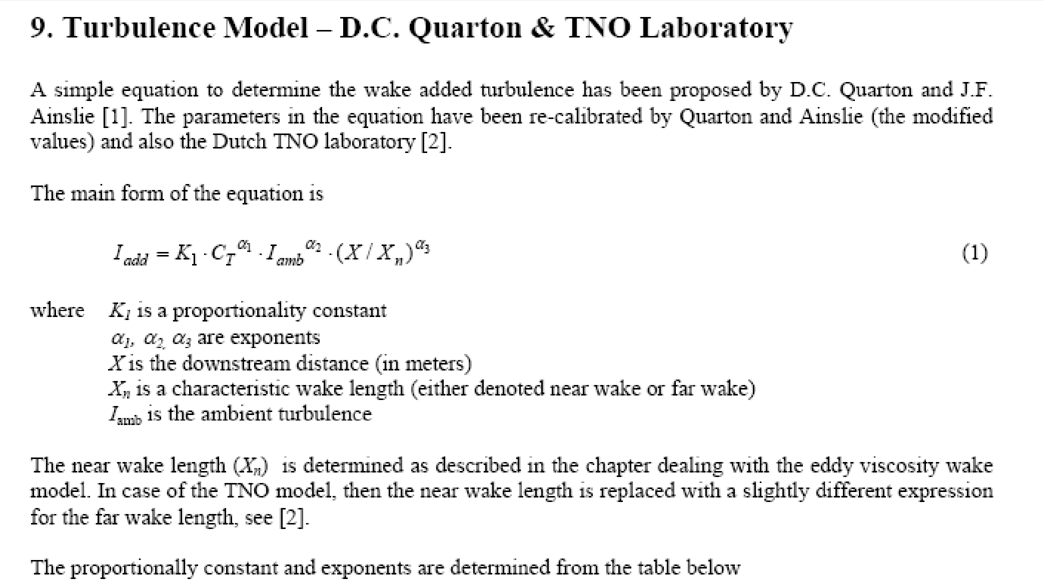
where

γ is the wind gradient exponent

Inserting the equation (4) into (3) we obtain the turbulence scaling law, valid for homogeneous terrain:

$$IT(y) = \frac{U_{10}(x)}{U_{10}(y)} IT(x) = IT(x) \cdot \left[\frac{y}{x}\right]^{-\gamma} \qquad (8)$$

Quarton & TNO models



9. Turbulence Model – D.C. Quarton & TNO Laboratory

A simple equation to determine the wake added turbulence has been proposed by D.C. Quarton and J.F. Ainslie [1]. The parameters in the equation have been re-calibrated by Quarton and Ainslie (the modified values) and also the Dutch TNO laboratory [2].

The main form of the equation is

$$I_{add} = K_1 \cdot C_T^{\alpha_1} \cdot I_{amb}^{\alpha_2} \cdot (X / X_n)^{\alpha_3} \qquad (1)$$

where K_1 is a proportionality constant
α_1, α_2, α_3 are exponents
X is the downstream distance (in meters)
X_n is a characteristic wake length (either denoted near wake or far wake)
I_{amb} is the ambient turbulence

The near wake length (X_n) is determined as described in the chapter dealing with the eddy viscosity wake model. In case of the TNO model, then the near wake length is replaced with a slightly different expression for the far wake length, see [2].

The proportionally constant and exponents are determined from the table below

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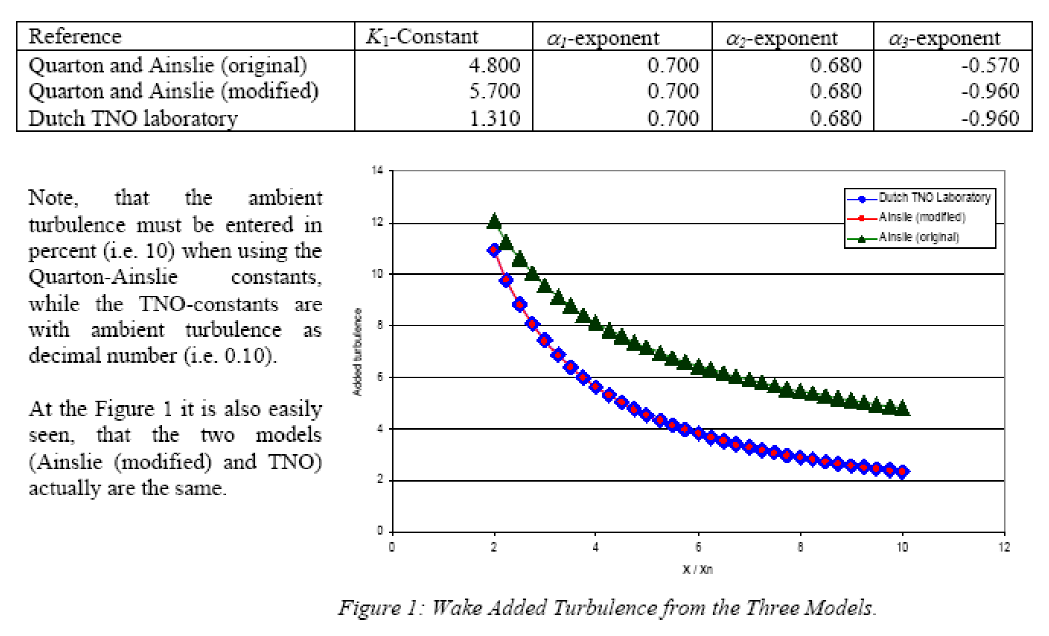
Quarton & TNO models



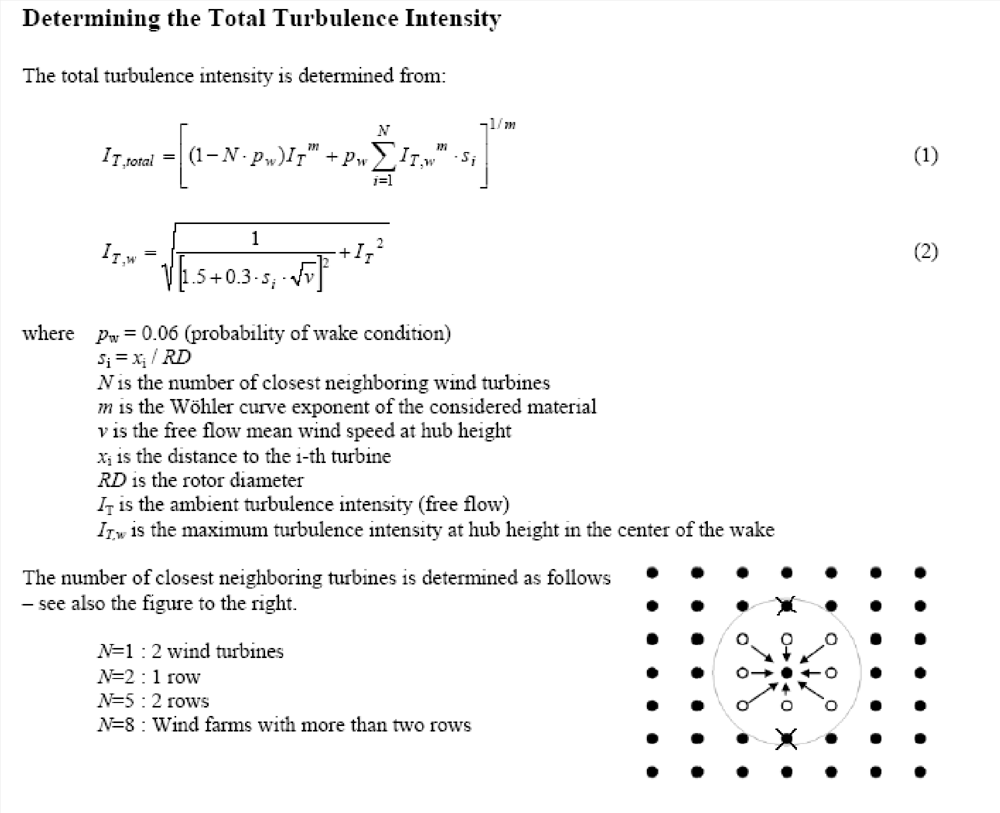
Reference	K_1-Constant	α_1-exponent	α_2-exponent	α_3-exponent
Quarton and Ainslie (original)	4.800	0.700	0.680	-0.570
Quarton and Ainslie (modified)	5.700	0.700	0.680	-0.960
Dutch TNO laboratory	1.310	0.700	0.680	-0.960

Note, that the ambient turbulence must be entered in percent (i.e. 10) when using the Quarton-Ainslie constants, while the TNO-constants are with ambient turbulence as decimal number (i.e. 0.10).

At the Figure 1 it is also easily seen, that the two models (Ainslie (modified) and TNO) actually are the same.

Figure 1: Wake Added Turbulence from the Three Models.

Frandsen Model



Determining the Total Turbulence Intensity

The total turbulence intensity is determined from:

$$I_{T,total} = \left[(1 - N \cdot p_w) I_T^{\,m} + p_w \sum_{i=1}^{N} I_{T,w}^{\,m} \cdot s_i \right]^{1/m} \qquad (1)$$

$$I_{T,w} = \sqrt{\frac{1}{\left[1.5 + 0.3 \cdot s_i \cdot \sqrt{v}\right]^2} + I_T^{\,2}} \qquad (2)$$

where $p_w = 0.06$ (probability of wake condition)
$s_i = x_i / RD$
N is the number of closest neighboring wind turbines
m is the Wöhler curve exponent of the considered material
v is the free flow mean wind speed at hub height
x_i is the distance to the i-th turbine
RD is the rotor diameter
I_T is the ambient turbulence intensity (free flow)
$I_{T,w}$ is the maximum turbulence intensity at hub height in the center of the wake

The number of closest neighboring turbines is determined as follows – see also the figure to the right.

N=1 : 2 wind turbines
N=2 : 1 row
N=5 : 2 rows
N=8 : Wind farms with more than two rows