13 LOADS - SITE COMPLIANCE

13.0 LOADS - SITE COMPLIANCE

13.1 Introduction, definitions and step-by-step guide

Establishing a proper layout and selecting a suitable turbine model are important steps in developing a wind energy project. Wind turbines are designed for 20 years lifetime and according to a number of standard climatic design classes, e.g. the IEC classes IA or IIIC. The Roman numeral defines the wind speed class I, II or III and the letter defines the turbulence class A, B or C. Class IA is the strongest standard class and the least strong class is IIIC.

Installing a turbine of the incorrect class on a site could result in premature structural failure and ruin a project. On the other hand installing a turbine from a class above that required could add unnecessary extra costs making a project financially unviable.

The WindPRO module SITE COMPLIANCE helps the user determine which particular turbine class is suitable for a site. The module also helps the user identify critical risks of a project in terms of the various IEC classification measures.

The requirements of the wind turbine design classes are defined in the International standard:

> IEC 61400-1 ed. 3 (2010) "Wind turbines Part 1 - Design requirements" [1, 2]

Most sections concern design requirements of the standard wind turbine classes. However, Section 11 describes "assessment of a wind turbine for site-specific conditions", i.e. the assessment of whether a wind turbine class complies with the conditions in a particular site and layout or, in other words, SITE COMPLIANCE.

13.1.1 Requirements of the IEC 61400-1 ed. 3 (2010) standard

Table 1 in the IEC 61400-1 ed. 3 defines the fundamental design parameters of the standard wind turbine climate classes described above.

Wind turbine class		I	II	III	S
	Vref [m/s]	50.0	42.5	37.5	Values
A	Iref [-]		0.16		Specified
B	Iref [-]		0.14		by the
C	Iref [-]		0.12		designer

Figure 1. Table 1 from the IEC 61400-1 ed. 3.

Section 11 of the IEC 61400-1 ed. 3 (2010) standard (henceforth referred to as the "IEC standard") describes seven main parameters used to classify the site. Firstly, there is a parameter describing the terrain complexity then six parameters relating to the site's wind climate. Together these seven main parameters are:

- Terrain complexity
- Extreme wind
- Effective turbulence
- Wind speed distribution
- Wind shear
- Flow inclination
- Air density

The standard also lists a number of "other environmental conditions" to be assessed for a site. Of these additional parameters we have selected three parameters which are more likely to be critical and which are best suited for estimation. These parameters referred to as "Other checks" are:

- Earthquake hazard
- Lightning rate
- Extreme and normal temperature range

The omitted parameters (for the initial release of the module) are "Icing, hail and snow", "Humidity", Salinity", "Solar radiation" and "Chemically active substances".

13.1.2 Typical modes of use

SITE COMPLIANCE can be used with various qualities of input data and external software licenses. The following three main modes are available:

1. Mast data and flow model
2. Mast data only
3. No mast data

Full functionality is obtained for projects with site mast(s) with multiple measuring heights and valid external licenses for both WAsP[1] and WAsP Engineering (WEng 3.0)[2]. With WAsP used, the module is considered to be operating in its main mode. In this mode a WAsP Engineering license is not a requirement but it adds additional calculation options which improve the quality of results.

Minimum data level is the second mode *Mast data only.* This mode requires only an on-site mast with multiple measuring heights and no external software licenses to calculate all main checks.

Mode three, *No mast data* is, for projects with no on-site mast as is typically the case in mature markets with many installed WTGs like Denmark or Germany. This mode requires valid external licenses for WAsP and WEng 3.0 as well as a regional wind statistics (wind atlas / lib file) to complete all seven IEC main checks.

In *Mode one* there are two sub-modes for the WAsP setup: *Long term corrected wind statistics* and *Mast directly*. The first sub-mode covers the situation where a long term corrected wind statistics have been generated via MCP for each on-site mast. This mode ensures a WAsP calculation which is consistent with any PARK calculations based on these wind statistics. The second sub-mode (*Mast directly*) integrates the Statgen calculation for each mast and so includes both steps of the two-step WAsP procedure taking the on-site mast data directly as input. This sub-mode opens the possibility to perform a simple long-term correction within SITE COMPLIANCE, as this is required in the IEC standard if on-site data are not representative of the long-term.

13.1.3 Step-by-step guide

❑ Select the main mode of use:
- (I)   *Mast data and flow model*
- (II) *Mast data only*
- (III) *No mast data*

---

[1] http://www.wasp.dk/Products/WAsP.aspx
[2] http://www.wasp.dk/Products/WEng.aspx

Mode one (Mast data and flow model)
- ❑ Select the Flow models to include
- ❑ Select WAsP option *Mast directly* or *Long-term corrected wind statistics*
- ❑ Define the WTG design class – if not set individually in each WTG object
- ❑ Select the Site mast(s) with main height and shear heights
- ❑ Select a mast with *purpose "*Long term reference" if one is available
- ❑ Define the *WTG* Layout
- ❑ Define the *Mast-WTG* link if multiple masts are available
- ❑ In WAsP *Mast directly* mode: – setup, calculate and evaluate *Long term correction*
- ❑ Choose site data object(s) and run WAsP calculation
- ❑ Choose site data object and run WEng calculation if a license is available
- ❑ On *Calculations* tick the relevant *Main checks* and *Other checks*
- ❑ Press *Edit* for each selected calculation, change setup if needed and press *Calculate*
- ❑ Review the results of each check and the overall result of all checks
- ❑ Press OK and review the reports and export results via result-to-file

Mode two (Mast data only)
- ❑ Define the WTG design class – if not set individually in each WTG object
- ❑ Select the Site mast(S) with main height and shear heights
- ❑ Select a mast with *purpose "*Long term reference" if one is available
- ❑ Define the *WTG* Layout
- ❑ Define the *Mast-WTG* link if multiple masts are available
- ❑ Setup, calculate and evaluate *Long term correction*
- ❑ On *Calculations* tick the relevant *Main checks* and *Other checks*
- ❑ Press *Edit* for each selected calculation, change setup if needed and press *Calculate*
- ❑ Review the results of each check and the overall result of all checks
- ❑ Press OK and review the reports and export results via result-to-file

Mode three (No mast data)
- ❑ Select the Flow models to include
- ❑ Define the WTG design class – if not set individually in each WTG object
- ❑ Define the *WTG* Layout
- ❑ Choose site data object(s) and run WAsP calculation
- ❑ Choose site data object and run WEng calculation
- ❑ On *Calculations* tick the relevant *Main checks* and *Other checks*
- ❑ Press *Edit* for each selected calculation, change setup if needed and press *Calculate*
- ❑ Review the results of each check and the overall result of all checks
- ❑ Press OK and review the reports and export results via result-to-file

13.2 Setting up a SITE COMPLIANCE calculation

Before starting the SITE COMPLIANCE calculation make sure you have a licensed version of SITE COMPLIANCE and that your project in WindPRO 2.8 contains the following data/licenses:

1. A layout of WTG objects

2. A digital elevation model, line object or elevation grid object (TIN)

3A. A site mast with multiple heights (all carefully checked and cut to a number of full years)

And/Or

3B. A site data object (with a wind statistic)

A valid WAsP license

A valid WEng 3.0 license

The following sections 13.2.1-13.2.6 describe the important setup steps of a SITE COMPLIANCE calculation tab by tab. Note that not all tabs described in the following will be available in each of the main modes.

13.2.1 Main

On the Main tab of SITE COMPLIANCE the general mode of use (described previously) is selected under *Site and layout using:*. The appropriate choice depends on the availability of on-site measurements and licenses for the flow models WAsP and WAsP Engineering (WEng).
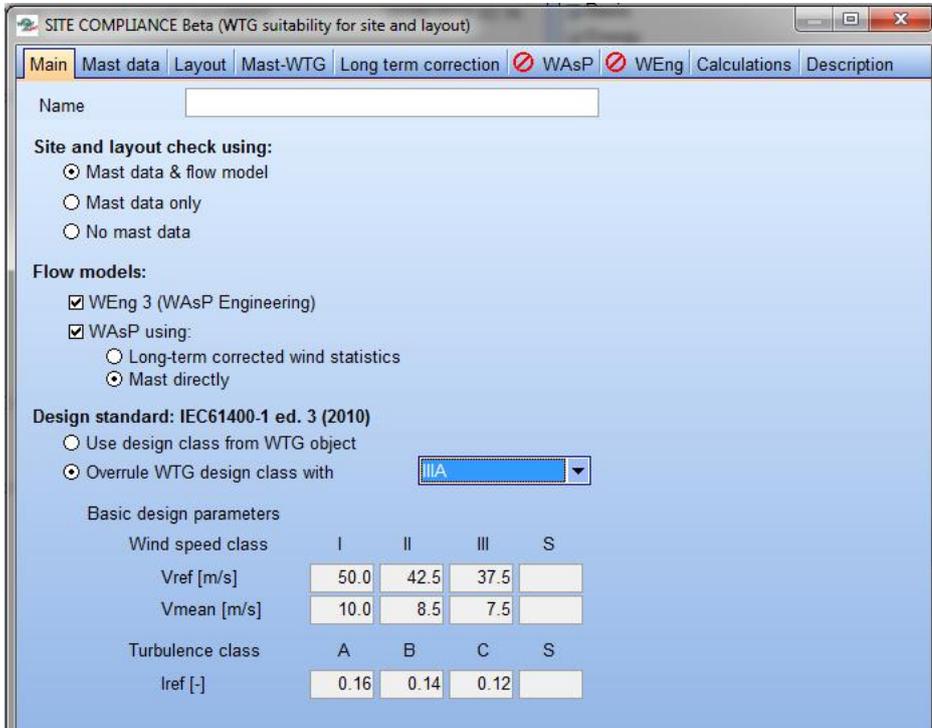

Figure 2. Main tab in SITE COMPLIANCE setup.

The *Flow models* with valid license should be ticked. WEng 3 is only selectable if a valid license is available. Note that selection of WEng requires that WEng 3.0 is installed and licensed but also that the PC has internet access. WEng's license system checks license status regularly via the internet.

If a *Design class* has not been set individually in each of the relevant WTG objects of the project the *Overrule* option may be selected and the appropriate *Design class* defined. Notice the basic design parameters are summarized for each design class in the table below the overrule selection. If *Class S* is selected the empty fields for class S in the summary table becomes editable and must be filled in with the relevant entry.

13.2.1 Mast data

On the *Mast data* tab the relevant *Site masts* must be selected by checking them. Once a mast is selected it expands and the *Main height* must be selected. This is the height used as basis in all IEC calculations and in WAsP calculations if run in *Mast directly* mode. If multiple heights are available the heights to be used in calculation of vertical shear (i.e. wind speed variation with height) must be checked (including the main height).

Note that if any fields such as *Sample rate*, *Duration* or *Recovery* are shaded red, this indicates potential problems, as the IEC standard requires 10-minute data to be used for on-site measurements, and that data should not be seasonally biased, i.e. duration should be an integer number of years.

If available, one or more *Long term reference* series may be selected as well. This is done by checking it and setting the *Purpose* to *Long term reference*. A third *Purpose* available is *Climate*, which may be used in case no temperature series has been measured on the site mast.

Name	Purpose	Main height	Use in shear calc (min 2 heights)	Sample rate [min]	Duration (enabled) [years]	Recovery (enabled) [%]	First	Last
☐ ☑ MERRA	Long term refe ▼							
⊞ 50.0m -		⊙		60.0	30.3	99.9	31/12/1981	30/04/2012 17:00:00
⊞ ☐ NCAR								
☐ ☑ Quick Mast	Site mast ▼							
⊟ 40.0m -		⊙	☑	10.0	1.0	100.0	01/07/2001	30/06/2002 23:50:00
Mean wind speed								
Wind direction								
Turbulence intensity								
⊞ 30.0m -		○	☑	10.0	1.0	100.0	01/07/2001	30/06/2002 23:50:00
⊞ 10.0m -		○	☑	10.0	1.0	100.0	01/07/2001	30/06/2002 23:50:00

Figure 3. Mast data tab showing a typical setup with a Site mast and a Long term reference series.

13.2.2 Layout

On the *Layout* tab the WTGs of the project are selected. In SITE COMPLIANCE the IEC checks are performed only for WTGs classified in the project as *New* WTGs. *Existing* WTGs which are selected are included in relevant calculations (e.g. wake effects) but no individual results appear for such WTGs. Check the layer(s) with the *New WTGs* and adjust individual selection at the bottom of the tab if only some WTGs in the layer are to be included.

Note that at the bottom of the page you may select whether you want to have the object description or the user label in the site tables, graphs and reports.

WTGs in noise reduced modes should generally be avoided as the wind speed at rated power is extracted from the power curve as part of a main IEC check. This may not work well for power curves in reduced mode.
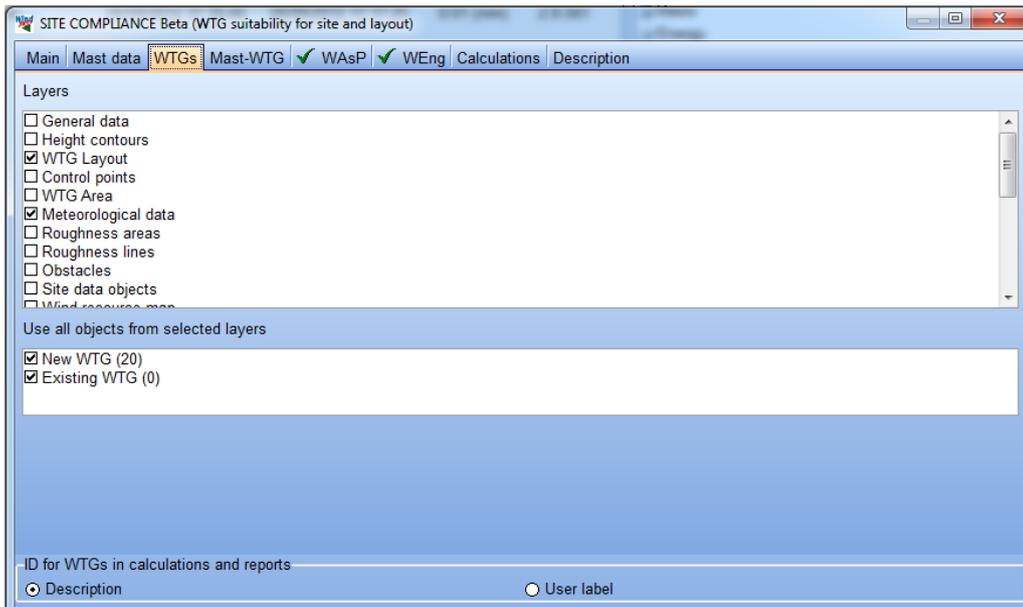
Figure 4. Layout tab, where the relevant project WTGs (New WTGs) are selected.

13.2.3 Mast-WTG

This tab is only available in modes one and two. Here the user decides which mast to use for which WTG. The default setup for Mast-WTG link choses the nearest mast for each WTG. However, this may be adjusted manually where there are multiple choices for mast by selecting the *Manual mast-WTG matrix*.
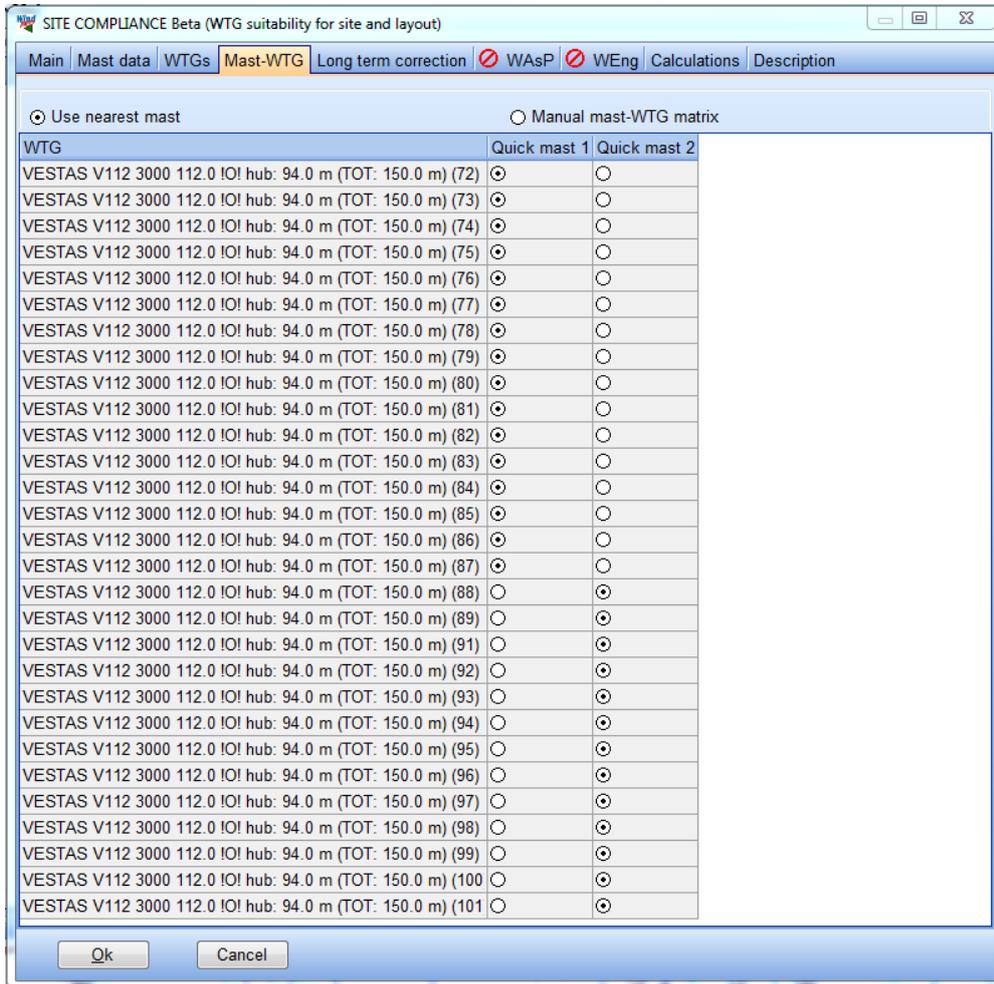
Figure 5. Mast-WTG tab – the appropriate site mast should be chosen for each WTG.

13.2.4 Long term correction

This tab is only available in modes one and two and when WAsP mode set to *Mast directly*. In these cases a long-term correction may be appropriate and can be applied from within SITE COMPLIANCE.

Note that this tab offers an alternative to the typical procedure of making a long term corrected wind statistics for each site mast via MCP and using the WAsP option *Long-term corrected wind statistics* on the *Main tab*.

The long-term correction available within SITE COMPLIANCE supplements the MCP methods in the MCP module as it is a wind speed index correction, where the index correction in MCP is based on an energy index. Another reason for this difference is that in SITE COMPLIANCE the focus is loads and not energy.

Where the selection is *No correction - data are representative*, no further action is required. If a long term series was setup on the *Mast data* tab and it fully overlaps with the Site mast data, then the option *Wind speed index correction* may be selected. By selection of the option the *Calculate corrections* button turns yellow and must be clicked. Evaluate the results for each site mast (if more than one) in terms of *Index* and R^2 (correlation coefficient). The plot is only shown for the one selected.
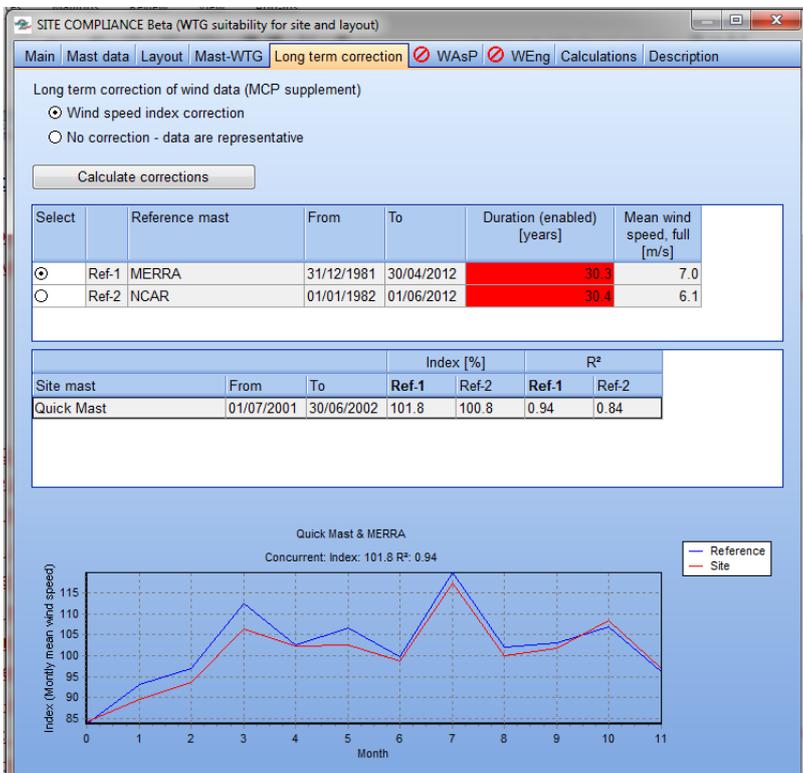
Figure 6. Long term correction tab.

An index of 100% means that the mast period is representative of the long-term; a value either above or below 100% means that the mean wind speed measured by the site mast must be corrected by the appropriate amount (inverse index) to represent the long term climate.

The index is calculated from the reference series as the ratio of the mean wind speed of the concurrent period divided by the mean of the full length of the series. Correlations coefficients are based on concurrent monthly mean wind speeds which are also plotted on the graph where they are normalized to an average of 100.

13.2.5 WAsP

The *WAsP* tab is available if *WAsP* was checked on the main tab. Options on this tab depend on the selected WAsP mode. In WAsP mode *Mast directly* a single *Site data object* must be selected to define the terrain and roughness maps to send to WAsP (see below).
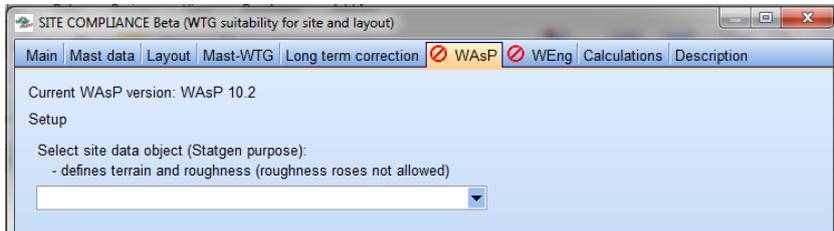

Figure 7. WAsP tab in WAsP mode Mast directly.

Running SITE COMPLICANCE in WAsP mode *Long-term corrected wind statistics* a *Site data object* with a wind statistics must be selected for each mast (only one in the case illustrated). Please ensure that the selected wind statistics in each site data object in fact holds a long-term corrected wind statics for that mast.
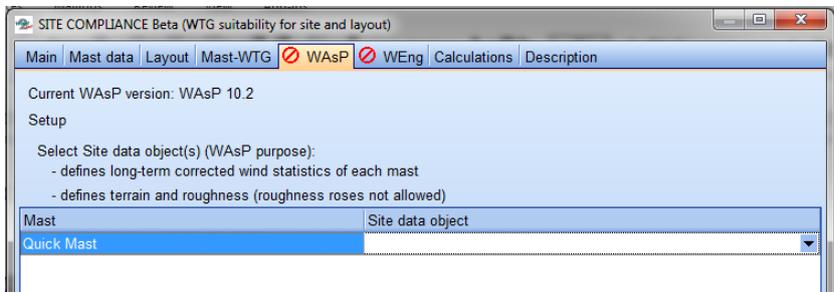
Figure 8. WAsP tab in WAsP mode Long-term corrected wind statistics.

In *No mast* mode the WAsP tab requires the user to check the *Site data objects* to be used in the calculation. The nearest will then be used for each WTG.
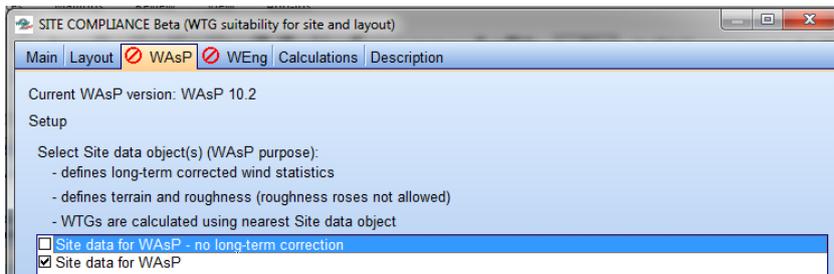
Figure 9. WAsP tab in No mast mode.

When the Site data object(s) has been selected the WAsP calculation is run by clicking the yellow *Run WAsP Calculation* button. WAsP parameters may be adjusted by clicking the *Edit WAsP parameters* button.
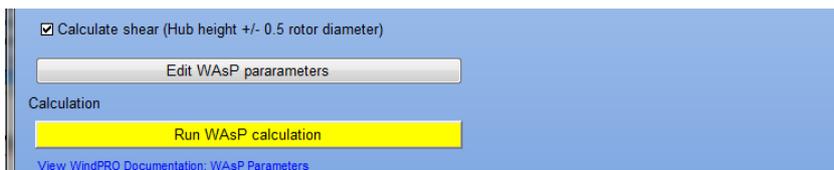
Figure 10. WAsP tab – ready to run the calculation or change WAsP parameters.

Figure 11. WAsP tab, before and after successful calculation.

When WAsP is complete the button turns grey and the red stop sign on the tab becomes a green tick mark.

If a displacement height has been set either for a mast or for a WTG object these will always be used in the WAsP calculation.

13.2.6 WEng

As a new feature in WindPRO 2.8, SITE COMPLIANCE offers an easy-to-use integration of WAsP Engineering 3 (WEng 3). The integration requires full external installation and licensing of WEng 3, and turns WindPRO into GUI of the flow model. This has enabled a significant simplification of setting up and running WEng. Contrary to WAsP, WEng is a grid-based model that calculates the flow parameters (except turbulence) for each grid point of an entire rectangular calculation domain defined by the user.

First a *Site data object* must be selected to define the terrain and roughness maps passed to WEng.

Then a *Buffer around all masts/WTGs* must be chosen. This buffer distance defines the extension of the calculation domain. Default is 5km, which is a compromise between accuracy and calculation time. In cases with prominent roughness changes just beyond 5km or large scale terrain features, the buffer should be extended as required.

The grid resolution defaults to 50m which typically is acceptable. In sites with rapid variations in terrain such as a narrow ridge, a finer resolution should be chosen.

Notice that if the *Buffer* or *Grid resolution* is changed the *Number of grid points* will update accordingly. The calculation time of WEng is optimized if the *Number of grid points* stays just below 170, 340 or 680 …etc. in both directions. This is due internal zero-padding inside WEng.

In the current version of SITE COMPLIANCE use of obstacles is not supported in the WEng modelling.
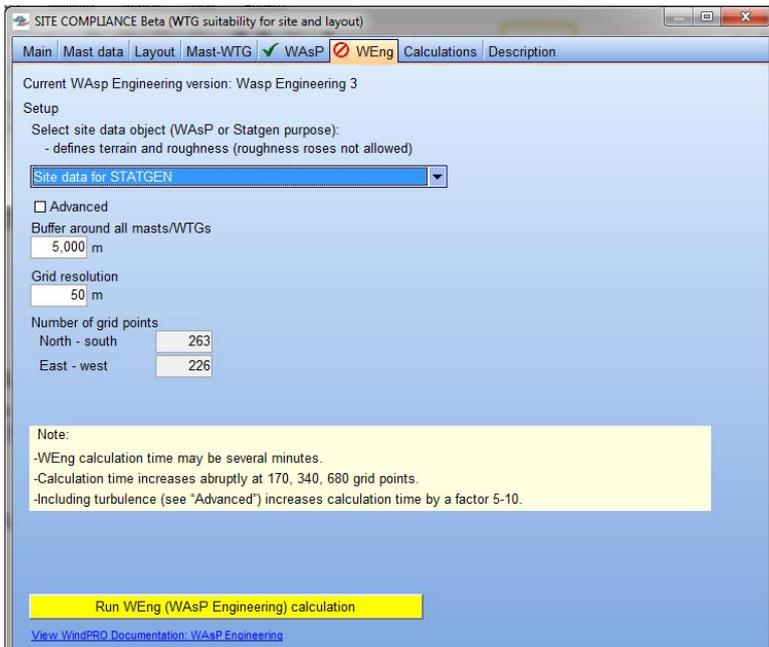

Figure 12. WEng tab.

Once appropriate settings are made, the calculation can be performed by clicking the yellow *Run WEng (WAsP Engineering) calculation* button. A WEng calculation may take several minutes. A main reason is that turbulence is predicted for each WTG and mast position.

Figure 13. WEng tab before and after successful calculation.

13.2.6.1 Advanced setup

Prior to running the WEng calculation the *Advanced* setup options may be reviewed and adjusted.
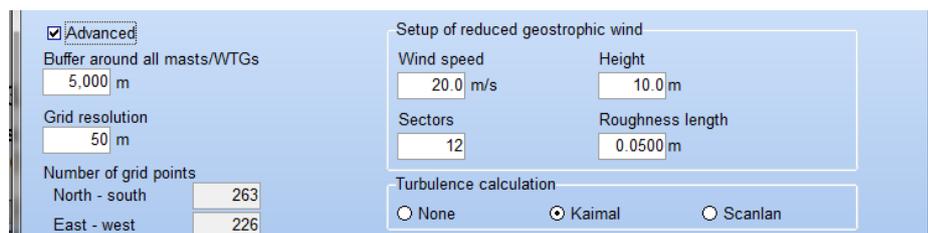
Figure 14. WEng tab, Advanced setup.

This setup illustrates how the flow modelling actually works inside WEng via the *Setup of reduced geostrophic wind* that allows adjustment of *Wind speed*, *Height*, *Roughness length* and the number of *Sectors*.

As WEng is a linearized model the results of the WEng flow modelling in terms of relative speed-up factors and turbulence intensity will not depend on this setup. Only in the special case offshore or semi offshore conditions, extra caution is needed as here the linearity does not hold due to increasing sea roughness with wind speed. In such special cases it is advised to run WEng and close SITE COMPLIANCE and export the WEng flow results via right-clicking on the calculation and choosing *Result-to-file*. The wind speeds predicted for each WTG in the result should match approximately the expected extreme wind speed for the WTGs. If the result is too low or high the reduced geostrophic *wind speed* can be adjusted accordingly in the WEng advanced setup to properly model the flow conditions during the on-site extreme wind conditions.

Turbulence calculation lets the user deselect calculation of turbulence via the option *None* or choose the alternative model *Scanlan*. However, it is recommended to use the default choice of including turbulence with the model *Kaimal*.

If a displacement height has been set either for a mast in the Meteo object or for a WTG object these will always be used in the WEng calculation. The usual effect is to decrease wind speeds whereas turbulence and wind shear normally increase.

13.3 Calculations - Main checks

Once all the setup steps have been completed and WAsP and WAsP Engineering (where used) have been run, the actual IEC 61400-1 ed. 3 (2010) calculations can be performed on the *Calculations* tab. To start calculation of the *Main checks* mark the relevant checkboxes in the *Include* column. It is recommended to include all *Main checks*. If any steps in the setup are incomplete or missing this is indicated with a *Missing:……..* text in the *Setup/Calculate* of the affected checks.

Some checks will be shown as "*Missing*" until connected calculations have been completed. *Effective turbulence* always requires the *Terrain complexity* to be calculated first. If no WEng calculation result is available the *Flow inclination* also requires the *Terrain complexity* to be completed first.

Note also the *Result legend* as this is used extensively as a clear visual evaluation of all calculation results.

Result legend	■ Ok	No WTGs exceed IEC limits
	■ Caution	≥1 WTG exceed IEC limits - exceedance not considered critical
	■ Critical	≥1 WTG exceed IEC limits - exceedance potentially critical

Figure 15. The result legend from the Calculations tab.

The overall wind farm evaluation is shown in the *Result* column when then calculation of a check is completed and it is determined by the evaluation of the worst WTG of the wind farm. Inside each check he evaluation presented for each WTG.
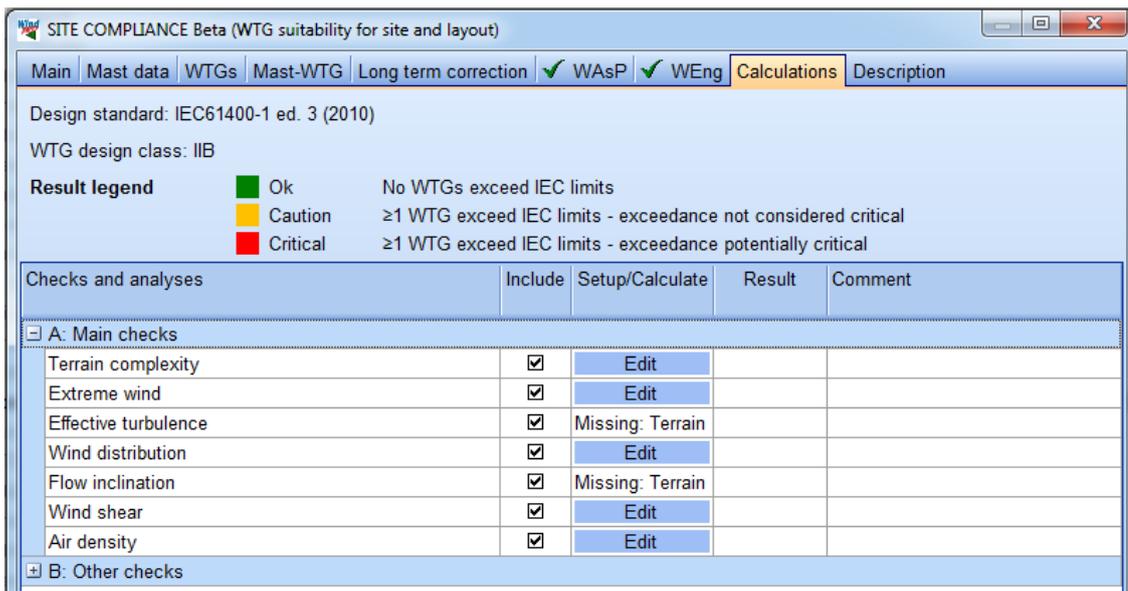
Figure 16. The Calculations tab with the Main checks expanded and checked, ready for calculation.

To start the calculation of the first *Main check,* click the *Edit* button. It is recommended to first calculate the *Terrain complexity* check.

Note:
A single or a few CRITICAL exceedances for a project may not always mean that a wind turbine class can be fully excluded as suitable. CRITICAL issues should always be addressed with the relevant turbine manufacturer. A turbine manufacturer knows the load margins and detailed aeroelastic model of their WTGs and can perform detailed load calculations for the particular model to evaluate if the buffer present for the OK checks or in the design can balance the identified CRITICAL issues.

13.3.1 Terrain complexity

Description and limit
The IEC standard describes quite elaborate details for the Terrain complexity check. The check evaluates the terrain steepness and variability in the vicinity of each WTG position. A number of circular and "pizza slice" planes must be fitted to the terrain and the inclination and terrain variation from each plane must be evaluated. These requirements are described in detail below.

The Terrain complexity check is not a "live or die" check that may kill a project in itself. Instead the check serves to identify complex sites / WTG positions mainly to enable an appropriate correction referred to as *Turbulence structure correction* to the measured turbulence. This correction is to compensate for the fact that cup-anemometers only measure the horizontal component of turbulence whereas in complex terrain a significant fraction of the turbulent kinetic energy may be transferred to the vertical component of turbulence.

Setup, Calculation and Results
Setup and calculation of the IEC Terrain complexity check is very simple in SITE COMPLIANCE. The module uses the active elevation model (i.e. the Digital Elevation Model) defined for the project. This model can be either a contour file in a Line object referred to as the "TIN" or can be defined by an Elevation grid data object.
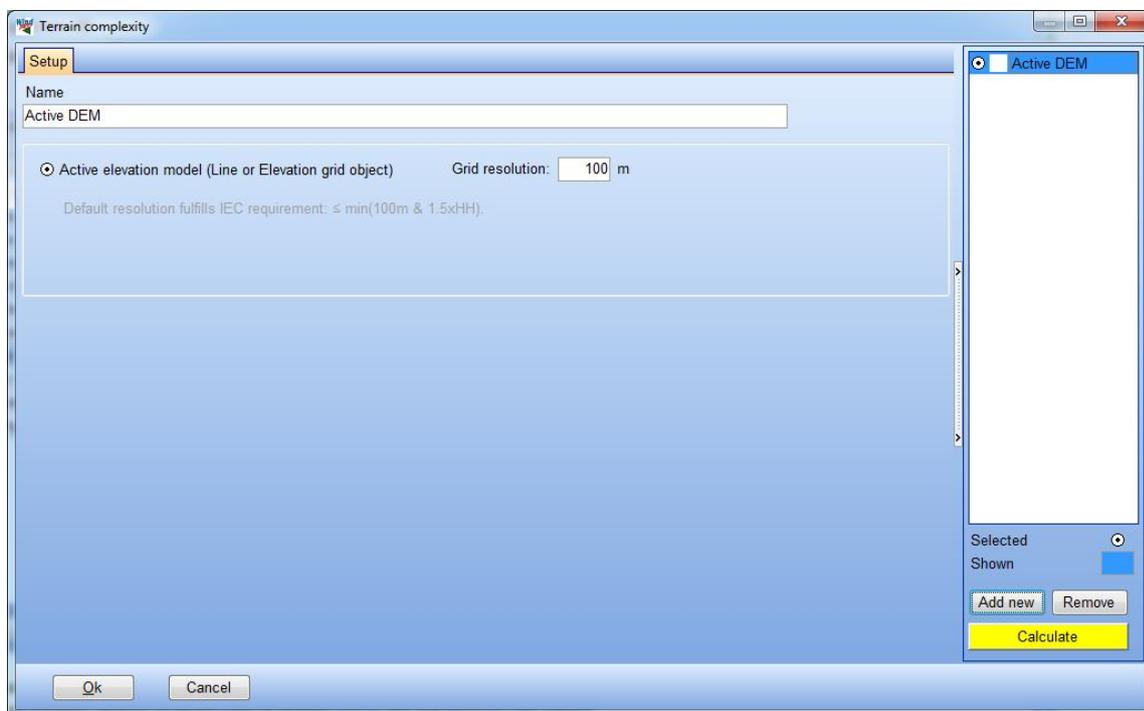

Figure 17. Setup and calculation of Terrain complexity check.

The only user option is the *Grid resolution*, which defines the resolution of a suitable quadratic grid of point elevations extracted from the elevation model to be used in the required terrain fits. The IEC states that the resolution may not be greater than the smallest of 100m and 1.5xHH. The default resolution automatically fulfils this criterion. However, often the quality of the available elevation data does not grant the use of a finer resolution.

Click the yellow *Calculate* button to perform the Terrain complexity check. Calculation may take longer if the full TIN has not already been calculated by the user. After successful calculation of the check several new tabs emerge presenting the results. The module jumps directly to the tab *Results (Graphics)* giving the main result overview. On this tab the so-called *Terrain complexity index* as defined in the IEC standard is illustrated for each WTG position. A WTG position is complex if the index equals 1, and not complex if it equals 0. An index between 0 and 1 indicates a partly complex WTG position.

Note also that in the case shown a green square has emerged besides the calculation name in the "calculation list" to the upper right. This indicates that the result of this check is *OK*, and that no problems or risks are expected relating to the Terrain complexity.
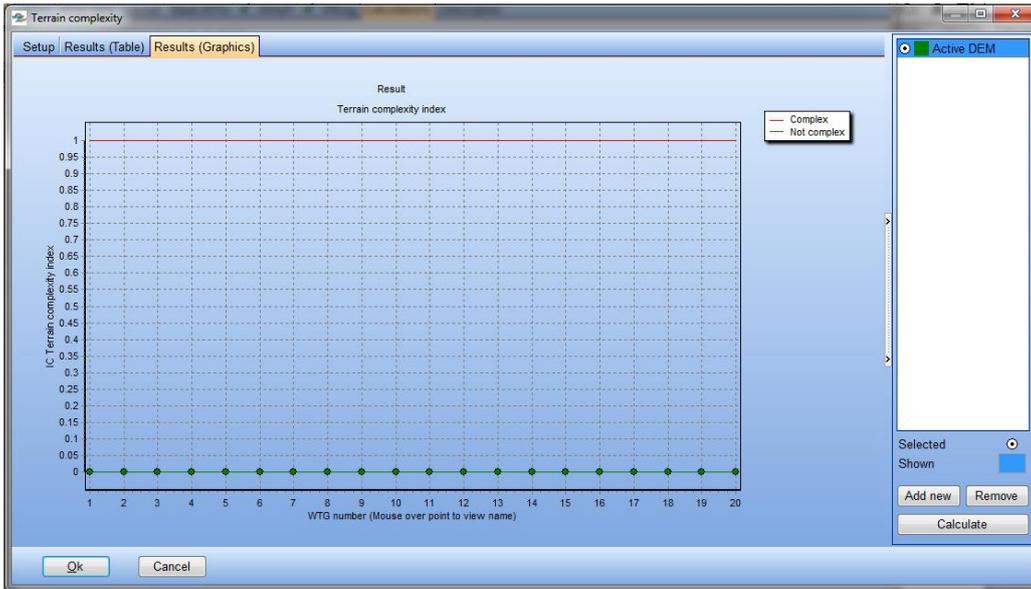
Figure 18. Results (Graphics) tab presents the Terrain complexity results as a simple overview.

SITE COMPLIANCE allows the user to *Add new* additional calculations with a different setup (in this case grid resolution). This is done by clicking the *Add new* button selecting the required new setup and clicking the yellow *Calculate* button again. In this way several supplementary calculations may be added to check how strongly the results depend on the setup/assumptions. It is recommended to adjust the names of each calculation on its *Setup* tab – this may also be done after calculation. The setup and result tabs of a calculation may be viewed by clicking on that calculation in the calculation list. The shown calculation is highlighted in blue.

Before finalising the check by clicking the OK button one of the performed calculations must be *Selected* as the final result.
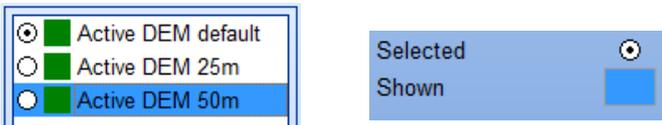
Figure 19. Left: The "calculation list" with multiple calculation setups and the upper one selected (marked) but the lower one is viewed (blue highlight). Right: the "view legend" defining shown and selected calculations in the calculation list.

The *Results (Table)* tab summarizes the results in terms of the Terrain complexity index for each WTG. A colour code highlights complexity indices in green if they are 0 (i.e. OK) and in orange (i.e. CAUTION) if an index exceeds 0.

Expand the results of a WTG by clicking the "+", this reveals the three sub-levels "R=5xHH", "R=10xHH" and "R=20xHH". Expanding one these levels reveal the results of the fit(s) with that radius in terms of the slope and its direction, and the energy that is available in the directional span represented by that fit. Further details of how these fits are performed are shown in the following.
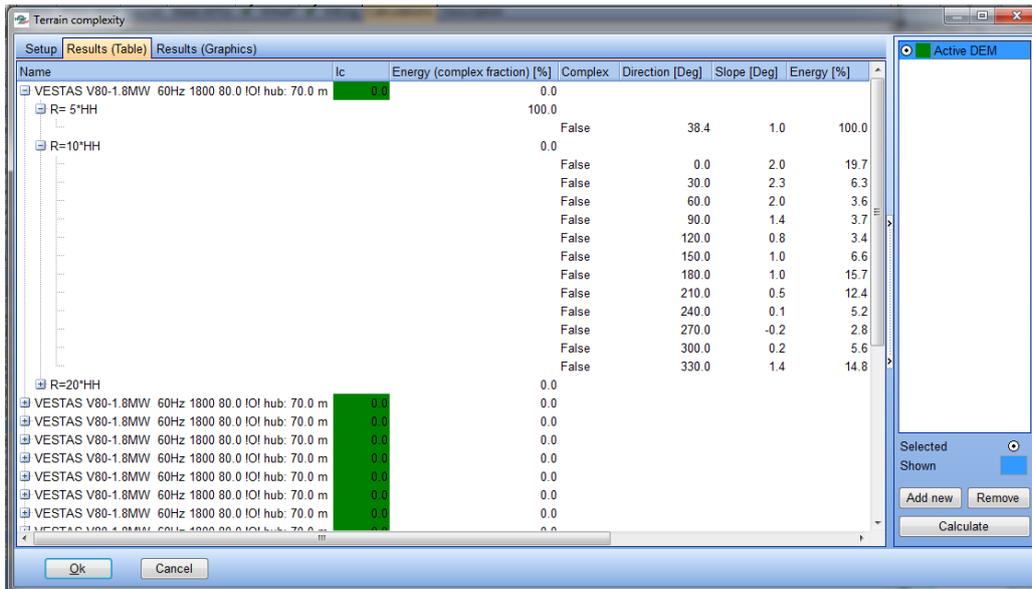
Figure 20. Results (Table) presents the many details of the fits performed in the Terrain complexity check.

IEC requirement – Terrain complexity

For the Terrain complexity check the IEC standard describes how a number of planes of varying size and shape must be fitted to the terrain around each WTG position, the following text describes these requirements as defined in [2]. In total 25 planes must be fitted with the following characteristics, all passing the WTG base position:

- A circular plane with radius 5xHH centred on the WTG
- 12 "pizza-slice" fits with a radius of 10xHH, one fit in each sector
- 12 "pizza-slice" fits with a radius of 20xHH, one fit in each sector

The fits are illustrated for a contour file below showing the points used in some of the fits. For the "pizza-slice" fits all the points are shown but only the points used within the northern sector are highlighted. The standard requires that the grid resolution must not exceed the smallest of 100m and 1.5xHH.
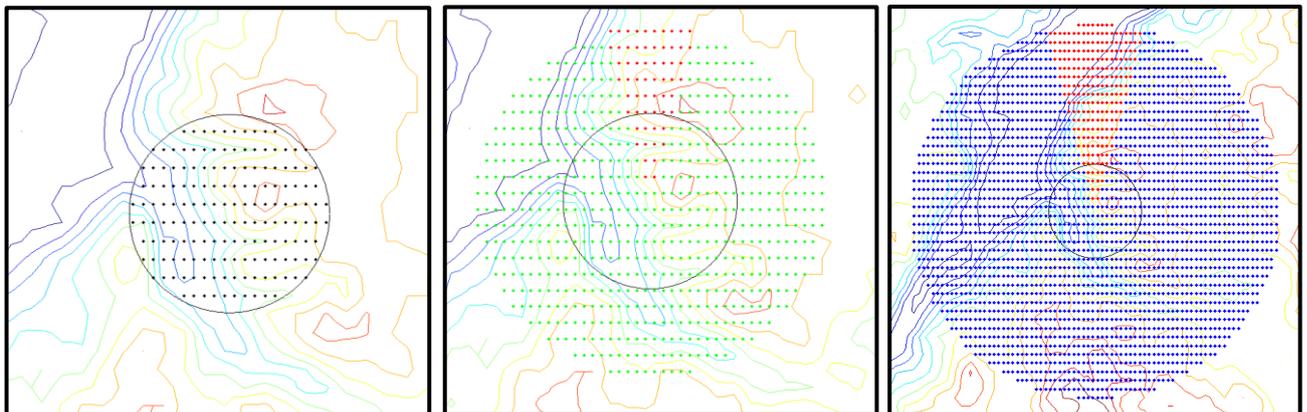
Figure 21. Illustration of the fits required in the Terrain complexity check. Left: outline of the 5xHH omni-directional fit and the included grid points. Middle: the grid points in a 10xHH sectorial fit, with points in the north sector highlighted (5xHH circle shown as scale). Right: the points in a 20xHH sectorial fit with the northern sector highlighted (5xHH circle shown as scale).

For each fit the slope is estimated. For the 5xHH fit the slope is in the direction of the gradient (i.e. max slope); for the 2x12 "pizza-slice" fits (10 and 20xHH) the slope is estimated along the sector median. If the estimated slope exceeds +/-10° the fit is regarded "failed".

In addition to the slope a "check area" must be estimated for each of the 25 fitted planes. This check is the area that has a vertical deviation from the fitted plane exceeding a certain threshold. The vertical thresholds for each radius as well as the slope demand as defined in the standard are summarized in the table below:

Fit radius	Count	Fit type	Max slope	Max vertical deviation	Max allowed area exceeding deviation
5xHH	1	Omni. (360°)	10°	0.3xHH	5xHH^2
10xHH	12	Sector (30°)	10°	0.6xHH	5xHH^2
20xHH	12	Sector (30°)	10°	1.2xHH	5xHH^2

Figure 22. Summary of the checks applied to each of the fits required in the Terrain complexity check [2].

The standard defines a Complexity Index, I_c, which is calculated based on the outcome of the fits. For each fit the relative energy fraction is estimated based on the relevant sector-wise Weibull parameters. The omni-directional fit (5xHH) represents 100% of the energy. If less than 5% of the energy is in the sectors which fail either the slope or the vertical deviation check, the WTG position is regarded *not complex*, and the complexity index $I_c=0$. If more than 15% of the energy is in sectors which fail either of the checks, the WTG position is regarded complex and $I_c=1$. In the interval when 5%-15% energy is in sectors which fail the complexity index is interpolated linearly between 0 and 1.

If the complexity index is larger than 0 extra caution is required. The standard requires that a correction is applied in the turbulence calculation. This is to compensate that cup anemometers only measure the horizontal component of turbulence and not the vertical. In complex terrain part of the turbulent kinetic energy is transferred from the horizontal component to the vertical component, and hence not accounted for by the measurements made by a cup anemometer. The standard defines a *Turbulence Structure Correction Parameter,* C_{CT}, which may be calculated from the complexity index. This correction parameter must be applied to the measured turbulence when the complexity index is larger than zero. This information is automatically transferred to the Effective turbulence check.

In a foot note the standard mentions that the inclination angle of the plane from the omni-directional fit with a radius of 5xHH may be used as the inflow angle estimate. We allow this option in SITE COMPLIANCE module and the relevant inflow angles are automatically transferred from the Terrain complexity check to the Flow inclination check.

13.3.2 Extreme wind

13.3.2.1 Description and limit

The Extreme wind speed check is one of the most important and potentially most critical checks in a SITE COMPLIANCE calculation. The reasons are the very high uncertainty associated with most extreme wind estimates and that the check represents an extreme load which may not be compensated by buffer in the results of other checks relating to fatigue.

In the context of the IEC standard extreme wind refers to a 10 minute averaged wind speed event with a recurrence period of 50 years. Recurrence period (T) is a statistical term derived from the more stringent statistical term "annual risk of exceedance" (R) via the simple relation $T = 1/R$. So by definition a 50 year wind speed estimate has an annual risk of being exceeded of 2%.

The IEC standard's design assumption for extreme wind is V_{ref} defined for each wind speed class in Table 1 of the standard (see Figure 1 of this manual). So e.g. a Class I WTG is designed for extreme wind speeds of up to 50m/s at standard air density of 1.225kg/m^{3}.

Most methods of extreme wind estimation rely in one way or the other on the theory developed by E. Gumbel in [3]. Appendix I describes the fundamentals of this theory and details of the theory relating to the models available in this module.

13.3.2.2 Setup, Calculation and Results

The following text describes the workflow in setting up, calculating and reviewing the results of a typical Extreme wind calculation. The setup of this check is split in three groups: *Statistical model, Propagation model and Additional model settings*. Details of the options within each of these groups are described in more detail after this description of the workflow. The figure below shows the *Setup* of the Extreme wind check. There are a number of input parameters with abbreviated names for the different methods.
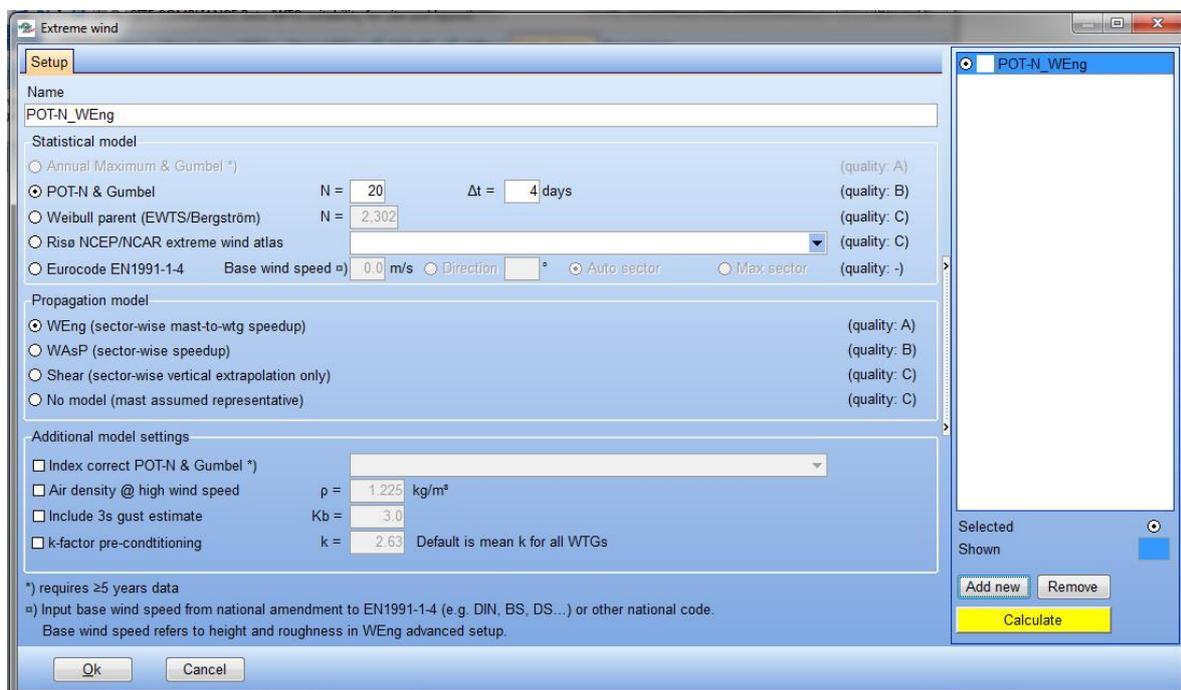
Figure 23. the Setup tab of the Extreme wind check. Note that the upper most option "Annual Maximum & Gumbel" is grayed out and not available in the case shown because not all site masts hold ≥5 years data.

For *POT-N & Gumbel,*
    N is the number of extreme events to extract from the time series
    Δt is the minimum time separation between two extreme events to be assumed to be independent
For *Weibull parent (EWTS/Bergström)*
    N is the assumed number of independent 10-minute wind speed samples in year.

For *Eurocode EN1991-1-4*

>*Base wind speed* is the design wind speed at standard conditions from the relevant national annex to the Eurocode (usually available from national standards authorities).
>
>*Direction* is needed for the base wind speed to select speed-up factors, if known or given in the national annex this should be input here directly.
>
>*Auto sector* let's SITE COMPLIANCE calculate the most likely extreme wind sector based on the Weibull parameters.
>
>*Max sector* takes the speed-up from the (worst) sector with the highest speed-up factor.

In *Additional model settings*

>ρ is the air density at high wind speeds.
>
>K_b is a normalized gust factor, where the default value 3.0 represents a 3 seconds gust.

Note that for the default setup no *Additional model settings* are activated. To include any of these additional settings, they must always be activated manually with the appropriate input parameter. If any additional modelling options are not selectable and greyed out the reason is that a required input source is missing in the general setup as e.g. a Long-term reference mast for the *Index correct POT-N & Gumbel* option.

Click the highlighted *Calculate* button to the lower right to run the Extreme wind calculation using the default setup. When the calculation is complete several new results tabs emerge:

The *Extracted data (Table)* tab shows a table of the extracted extreme samples from the mast time series.
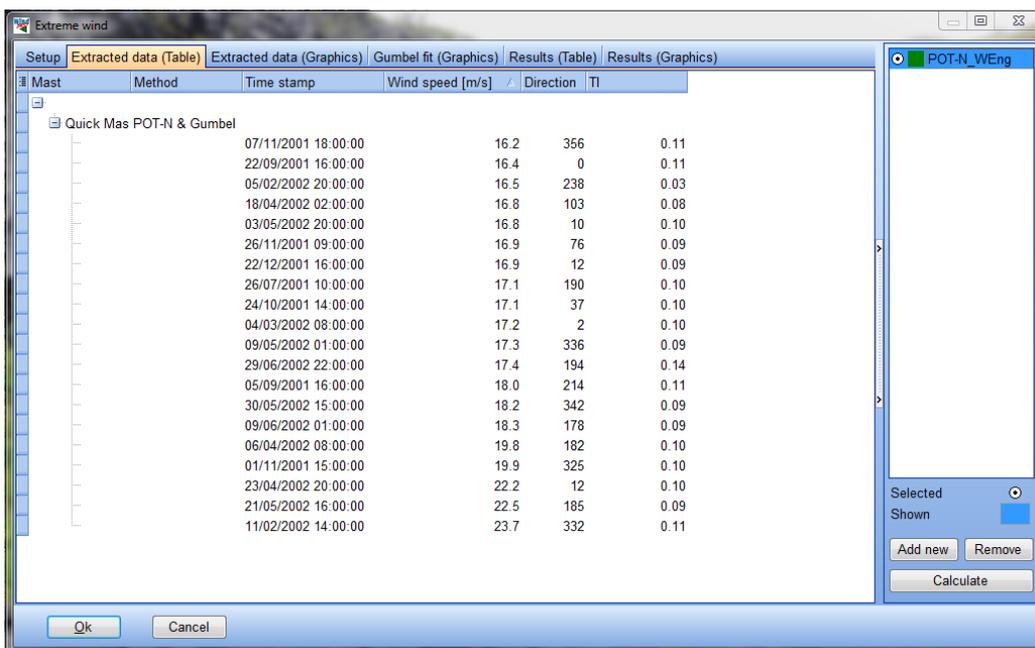
Figure 24. The Extracted data (Table) tab.

On the *Extracted data (Graphics)* tab you see a plot of each of the mast time series with the extracted extreme samples highlighted. Scroll through the masts (if more than one) using the *Next* and *Previous* buttons to the lower left.
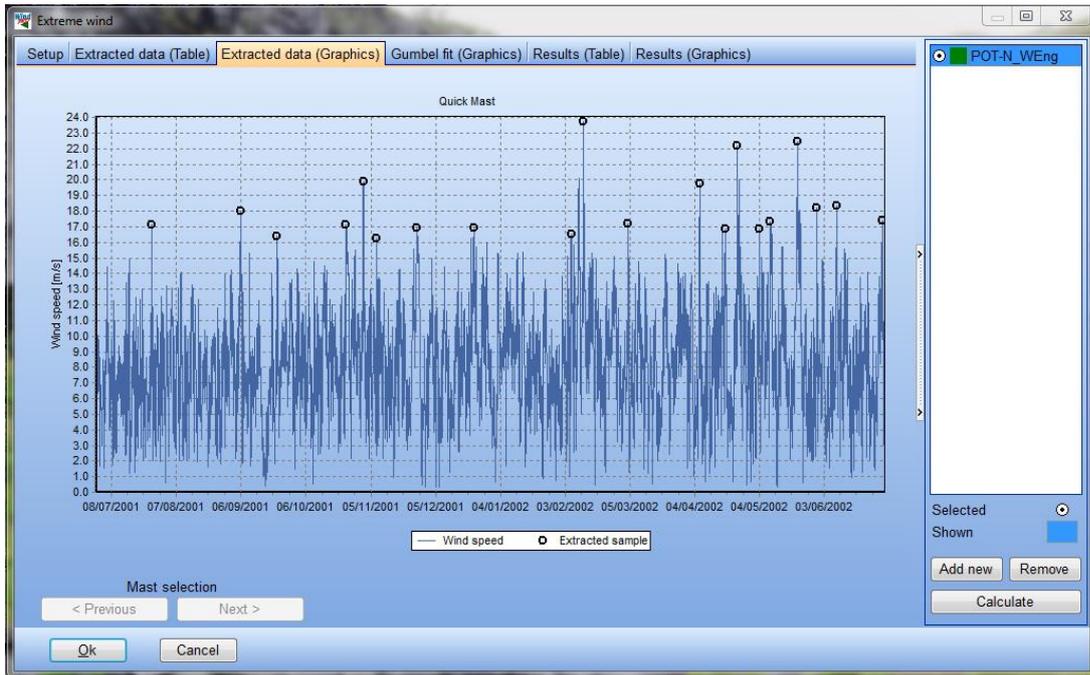
Figure 25. The Extracted data (Graphics) tab.

The Gumbel fit (Graphics) tab shows you the statistical fit for each WTG and the extrapolation to the required return periods (i.e. risk levels), typically 50 years. Click next (lower left) to scan through the WTGs.
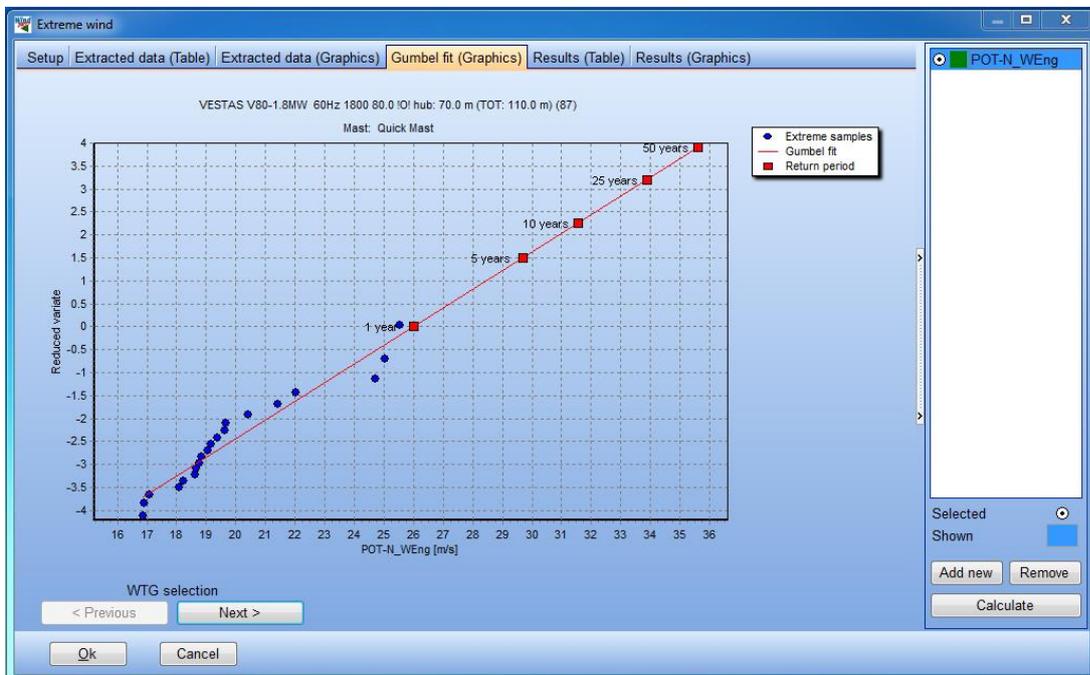
Figure 26. The Gumbel fit (Graphics) tab.

The *Results (Table)* tab gives you the final 50-year extreme wind speed result for each WTG as well as the IEC limit for the WTG class (V_{ref} for the relevant class). In the case shown all WTGs are OK (green), and hence the overall result for the park (upper right corner) is also green (OK).

*Figure 27. The Results (Table) tab.*

The *Results (Graphics)* tab gives a graphical overview of the results relative to the IEC limit. In the case illustrated the results are well within the IEC limit.
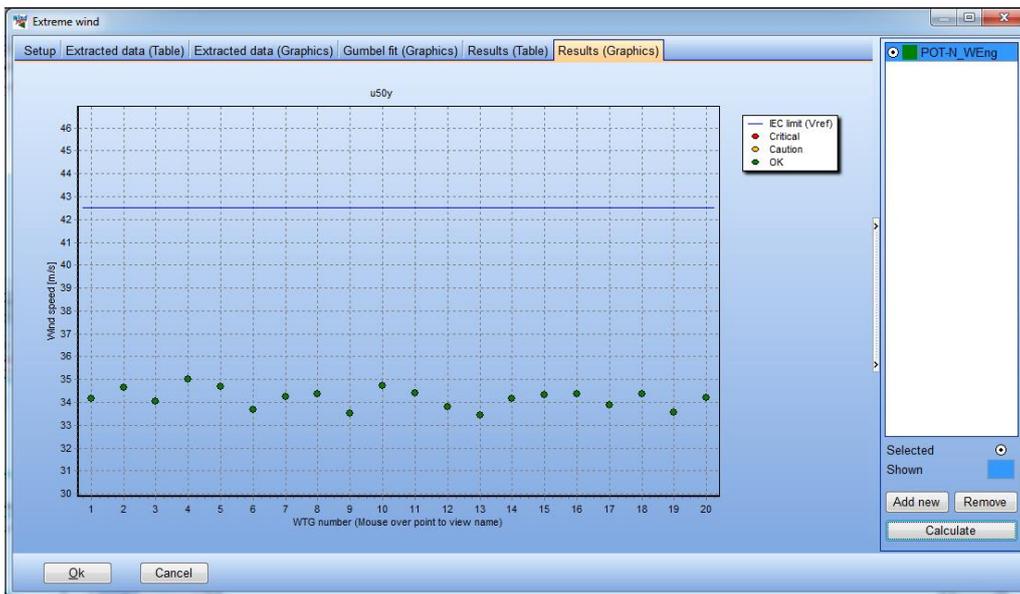
Figure 28. The Results (Graphics) tab.

You may click the *Add new* button (lower right corner) to add another calculation setup for extreme wind using a different method or different parameters for the same method. E.g. select *Weibull parent (EWTS/Bergström)* and press *Calculate*. Now you have two result options you can compare. If you have run a WEng calculation you may also try the *Risø NCEP/NCAR extreme wind atlas* which covers most of Europe and US. Each calculation adds a line in the right pane. Click on a calculation in the pane to highlight it and view its setup and results.

IMPORTANT: The results of the calculation which is marked with the ⊙ will be used in the final evaluation.

13.3.2.3 Statistical model

The setup in this group defines the statistical model used to extract the extreme wind data and how these data are fitted to the Gumbel statistical model if required in the method. The different models are described in the following text.

Figure 29. the Setup of the Statistical model in the Extreme wind check. Note that the uppermost option is only available with at least 5 years of measurements for all site masts.

Annual maximum & Gumbel (requires ≥5 years for all site masts)

This method is only available if all masts have at least 5 years of data because only the single most extreme wind speed measurement is extracted from each year from the time series. With less than five years and hence less than five samples the linear fit to the Gumbel model becomes very vulnerable to the individual data points. General recommendations suggest at least seven years of data for the annual maximum (AM) method to obtain reliable results for this method. The AM method is the classical method proposed by Gumbel and is still considered the most accurate provided that sufficient data are available, which unfortunately is rarely the case in wind energy project development.

Once the annual maxima samples are extracted they are processed according to the classical Gumbel method of extremes resulting in the so-called Gumbel plot. The fit of the Gumbel asymptote is performed using the Probability Weighted Moments (PWM). See [4] or Appendix I for further details of the theory.

POT-N & Gumbel

This method is available when at least one site mast with time series data was selected in the general setup. The statistical method is almost identical to the method available in the *Extreme wind estimator* in WindPRO 2.7 and older. The name abbreviates *Peak-Over-Threshold* and the *N* signifies the modification that the threshold is not defined in terms of wind speed as is usually the case, but instead in terms of a fixed number (*N*) of samples. Often this method is also referred to as Method of Independent Storms (MIS) (see [5] and Appendix I) although the original MIS method [5] uses a slightly different approach for data extraction.

There is no lower limit to the length of the time series needed for this method, but it is strongly recommended to use an integer number of full years, i.e. at least one full year. *N* defines the total number of storms to be extracted (default is 20) and *Δt* the minimum time separation required for storms to be independent (default is 4 days). The default time separation is chosen to match the typical time scale of synoptic storm events.

Once extracted the samples are processed according to Gumbels method with the additional step of correcting for the annual storm rate (see [5] or Appendix I for further details). The model fit to the Gumbel asymptote is performed based on the classical plotting positions (see [6]) and a traditional least squares fit with wind speed as the independent variable.

Weibull parent (EWTS/Bergström)

The European Wind Turbine Standard (EWTS) [7] describes an extreme wind method based on the tail characteristics of the Weibull mean wind speed distribution (*parent distribution*). A fundamental principle is that sites which exhibit wind distributions with a low Weibull k-factor have heavier tails and thus a higher likelihood of extreme events and hence higher extreme wind speeds.

This methodology relies on two main assumptions:
1) The wind distribution is Weibull
2) The number of statistically independent wind samples per year is known (and equal for all sites)

The EWTS publication uses the number 23037 10-min independent events per year with a reference to a 1992 publication by Bergström [8]. However, there is typographical error in the EWTS publication and the number is incorrect. In Bergström's original paper [8] the correct number is 2302.

For the Weibull distribution shape parameter we use the so-called "combined Weibull" [18] which results from combining the sector-wise Weibull distributions, typically resulting from the WAsP calculation, to a resulting omni-directional Weibull with the same first (mean wind speed) and third (energy) moments.

Risø NCEP/NCAR extreme wind atlas

The Risø NCEP/NCAR extreme wind atlas method uses a database of *Regional Extreme Wind Climate* (REWC) files established for WEng 2 as part of a research project at Risø [9]. These atlases are based on the NCEP/NCAR global reanalysis data with some ad hoc corrections established as part of the project to compensate for the coarse temporal and spatial nature of the NCEP/NCAR data.

This method requires that a WEng calculation has been performed in SITE COMPLIANCE. The user may select one of the nearest four REWC files. Each REWC file contains 12x30 reduced geostrophic wind speeds, one for each of twelve direction sectors in each of thirty reference years. The wind speed samples are adjusted for each WTG position using the predicted sector-wise flow corrections predicted by WEng to obtain the annual maximum samples for each reference year. From this point the method progresses identically to the Annual Maximum method described above.

Eurocode EN1991-1-4

During the past decade or so all national building codes within the European Community have been standardized into the Euro Codes (EN). The Euro Code EN1991-1-4 treats wind loads and defines the guidelines for handling of design extreme wind speeds. Each country has a national annex to EN1991-1-4 that describes the *Base wind speed* to be used in different regions of the country as well as appropriate corrections at high altitude and other exceptions or corrections. Thus, national codes like DIN (Germany), BS6399 (UK), DS (Denmark), SS (Sweden), PN (Poland), SFS (Finland) are now referred to as e.g. DS-EN1991-1-4.

The input *Base wind speed* is to be found in the relevant national annex. It is defined as a 50-year extreme wind speed at reduced geostrophic conditions typically the standardized conditions: 10m agl., flat terrain and uniform roughness (roughness class 2, $z_0 = 0.05$m).

A simple example is Denmark where the 50-year base wind speed is defined to 24m/s for all inland positions, except in a 25km wide belt along the Danish west coast. In this belt the base wind increases linearly from 24m/s to 27m/s at the west coast. In countries with mountainous areas such as Poland or Germany the national annex specifies base wind speeds but also adjustment factors to these base wind speeds for altitudes above a certain threshold.

In the calculation the base wind speed is propagated from the standardized reduced geostrophic conditions (10m, flat terrain and uniform roughness) to the specific terrain and roughness conditions of each WTG using the flow results of WEng, hence a WEng calculation is required for this method. If standard conditions for the base wind speed (i.e. the reduced geostrophic) differ from the standard ones available in the Advanced setup of WEng, the WEng calculation should be run with the reduced geostrophic adjusted to match the parameters specified in the national annex.

Several countries outside Europe have also adopted or are in the process of adopting the Euro Codes (or selected parts of them) as design standards. At the time of writing (2012), these countries include Singapore, South Africa, New Zeeland and Australia.

13.3.2.4 Propagation models

Once the extreme samples have been extracted from the measurement series either using the Annual Maximum method of the Peak-Over-Threshold method (POT-N) they are scaled to better represent the conditions at the WTG positions. This scaling using a *Propagation model* may be based on the methods summarized in the figure below.
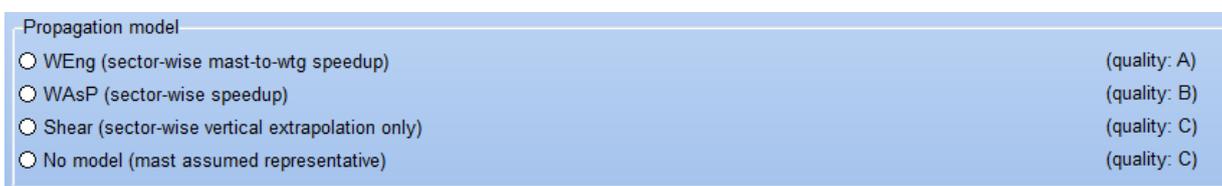

Figure 30. Setup of the Propagation model in the Extreme wind check.

For the choice *WEng* and *WAsP* the scaling is performed using the sector-wise mast-to-WTG speed-up factors predicted in the WEng and WAsP calculations respectively. In the *Shear* option the measured sector-wise shear is used to calculate the sector-wise speed-up factors from mast height to WTG hub height. For the choice *No model* no scaling is performed of the measured extremes.

The Gumbel fitting is always performed after the chosen scaling is applied to the extracted extreme samples.

13.3.2.5 Additional model settings

The Extreme wind check offers several *Additional model settings* as shown in the figure below. These are described in the following.

Figure 31. Setup of Additional model settings for the Extreme wind check.

Index correct POT-N & Gumbel

This long-term index correction method for extreme wind estimates is only available for the POT-N method. It is based on work published at the EWEA conference 2010 [10]. The fundamental basis of this method is the observation that two main sources of error dominate in extreme wind estimation:

       1) Too short a time-series (resulting in a statistical sampling error)
       2) Bias introduced by the method of the Gumbel model fit.

In addition to this we know that the Annual maximum method with the PWM fit is virtually free of error source two, bias from the Gumbel fit [11].

The idea of this index correction is based on calculating an extreme wind index for the period of the site measurements by using an overlapping long-term reference series which is representative in regards to the storm events. The index is estimated by applying the same POT-N setup to the concurrent part of the reference series and the Annual maximum (AM) method and PWM fit to the full length of the reference series. The index is then defined as the ratio of the concurrent POT-N estimate to the full AM estimate for the reference. The appropriate correction which is applied to the extreme wind estimate using the site mast equals the inverse of the extreme wind index.

As a validation an index is calculated for each year of the site series and for the reference series. This allows a visual validation to check if the extreme wind climate is properly accounted for by the reference series. If this is the case the index curves will have the same shape.

Note: The Extreme wind index correction should be used with great caution if only one year site/reference overlap is available which prevents evaluation of the mast and reference index trends or if an evaluation based on several years overlap reveals very different trends.

Air density at high wind speed

The aerodynamic thrust force is proportional to the square of the wind speed and to the air density. Thus, a decrease of air density results in a decreased thrust. The IEC limit for extreme wind is defined at standard air density of $1.225 kg/m^3$. Extreme wind estimates at other air densities may be corrected to standard air density assuming that the thrust force is unchanged but that the site air density is replaced by the standard value.

The air density inserted by the user should represent the air density expected at high speeds. Often the expected mean air density is used as an approximation.

Include 3s gust estimate

Gust values may be estimated from measurements using the max of each 10-minute interval which is often logged. However, the averaging period of such estimates is unknown. The IEC standard requires 3-second

averages to be used for gust estimates. Instead of maximum 10-minute measurements 3-second gust estimates may be based on a simple model originally introduced by Davenport. The method uses the formula below to estimate the gust at averaging time t.

$$u_t = u_{10min}(1 + k_b(t)TI)$$

Where K_b is a normalized peak factor equal to 3.0 for t=3s according to Cook (1990) in [12], TI is the expected turbulence intensity (10-minute averaging) which is calculated as the mean turbulence intensity for the extracted extreme samples. No adjustment is made to the turbulence; hence the gust factor estimated at each mast is used directly for the relevant WTG positions.

k-factor pre-conditioning

The Gumbel model is an asymptotic model - it assumes that the number of independent event events per year is infinite. In [5] Cook demonstrates that the error due to this assumption depends on the Weibull k-factor of the wind speed distribution. If the k-factor is one (also called the exponential distribution) the error is zero no matter the real sample size. For k larger than 1 the error increases with k. The error introduced by this assumption makes the Gumbel plot of the extracted extreme samples curve slightly down. The curvature introduces an overestimation (conservatism) in the Gumbel fitting.

To reduce this error the wind speeds may be transformed prior to Gumbel fitting to turn the distribution into a Weibull with a k-factor of one. This is done by raising the wind speeds to the power of k. After the fit has been performed and extrapolated to obtain the 50-year estimate, the wind speeds are transformed back taking the kth root. Often a factor of two is used as a general estimate of the k-factor. The default value in this setup is the mean "combined" k-factor for WTGs [18]. The typical effect of the k-factor pre-conditioning is to reduce the extreme wind estimates by 5-10%.

Thus, the use of k-factor preconditioning rests on a solid statistical argument.

13.3.3 Effective turbulence

13.3.3.1 Description and limit

The Effective turbulence check is together wind the Extreme wind check one of the most important IEC checks. Where Extreme wind represents the extreme loads the Effective turbulence mainly represents the fatigue loads, a more long-term degradation of structural integrity of the turbine. Calculation of the Effective turbulence is described in a revised version in the 2010 Amendment to IEC61400-1 ed. 3 [2]. The Effective turbulence model is based on the publication [13] by the late Sten Frandsen from Risø/DTU, hence the model is also known as the "Frandsen model".

The design limit for Effective turbulence is called the "Normal turbulence model" in the IEC standard and is calculated from the basic parameter I_{ref} in Table 1 (see section 13.1.1). I_{ref} has the values 0.12, 0.14 and 0.16 for the standard turbulence classes A, B and C, respectively. The calculated Effective turbulence is based on the 90th percentile of measured ambient turbulence and must be compared against the Normal turbulence model (the design limit) for a range of wind speeds. When the power curve is known, the range is from 60% of wind speed at rated power to cut out wind speed. In SITE COMPLIANCE a WTG object and hence a power curve is always defined prior to calculating Effective turbulence. Appendix II describes further theoretical details of the Effective turbulence model.

Effective turbulence is calculated as a function of wind speed only. This is done by integrating the directional variation of turbulence over all directions for each wind speed bin. However, Effective turbulence is NOT a measureable quantity as it combines the directional contributions with a special weighting that accounts for material fatigue via use of the material parameter, the Wöhler exponent, hence the name Effective turbulence. Prior to the integration over all directions for each wind speed the estimated wake added contribution is combined with the 90th percentile of the ambient turbulence at each WTG. The normal turbulence model is illustrated below for each of the three turbulence classes.
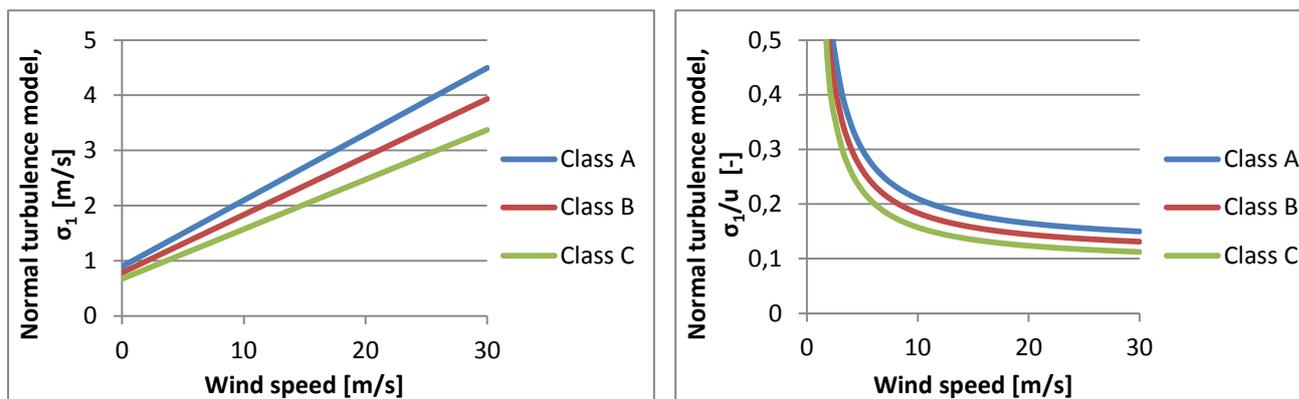
Figure 32. Illustration of the IEC "Normal turbulence model" which is the IEC design limit for the Effective turbulence check. Left: plotted as standard deviation of wind speed. Right: plotted as turbulence intensity.

13.3.3.2 Setup, Calculation and Results

> **Note:**
> Please be aware that the Terrain complexity check must always be completed before the Effective turbulence calculation can be initiated. The reason is that the results of the Terrain complexity check are used in the Effective turbulence calculation via a correction factor called turbulence structure correction factor which is required by the IEC standard.

The following text describes the workflow in setting up, calculating and reviewing the results of a typical Effective turbulence calculation. The setup of this check is split in five groups: *Turbulence data, Propagation model, Turbulence structure correction, Frandsen model* and *Sector management.* Details of the options within each of these groups are described after this description of the workflow and various tabs. The figure below shows the *Setup* tab of the Effective turbulence check.
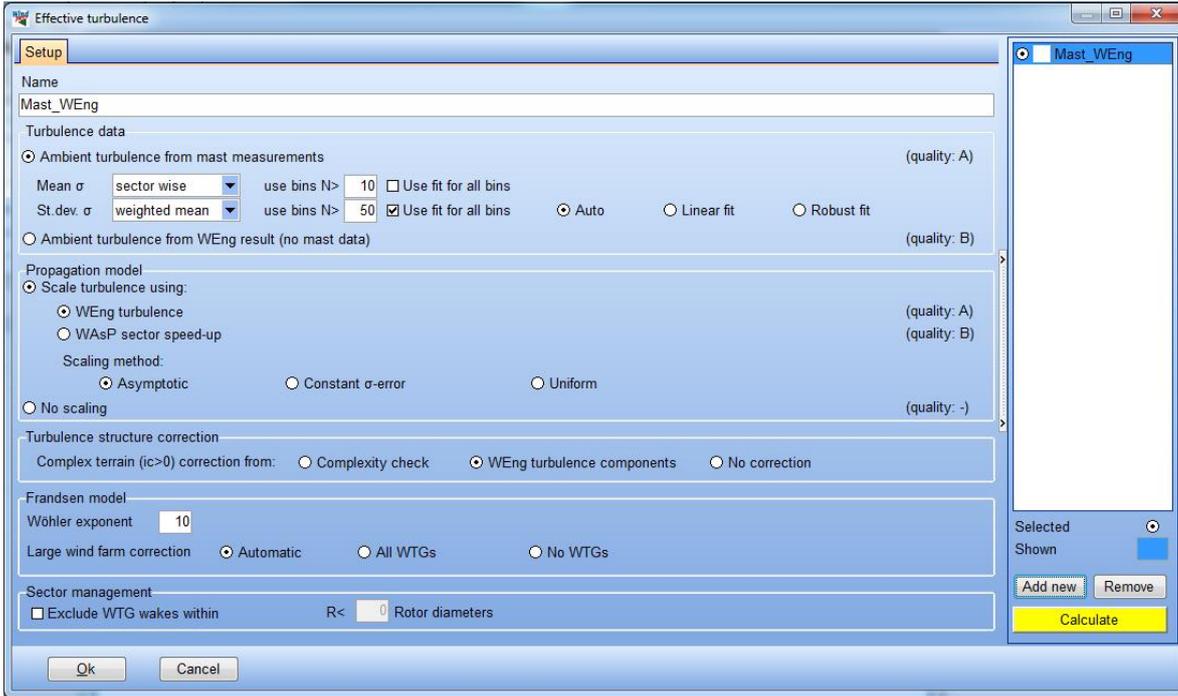
Figure 33. Setup tab of the Effective turbulence check.

Click the highlighted *Calculate* button to the lower right to run the Effective turbulence calculation using the default setup. When calculation is done several new results tabs emerge which are described in the following.

When measured turbulence data from a *Site mast* are used in the calculation these data must be analysed. A model must be fitted to the mean turbulence and to its standard deviation to fill in gabs in the data and to extrapolate them to the required wind speeds bins without data. The *Data fit (Table)* summarizes the sector-wise outcome of the procedure in a tabular form.

Note that at the bottom of the tab it is possible to toggle between viewing the table as standard deviation in m/s and as turbulence intensity. The standard deviation is recommended throughout as this is the measured quantity and because the fundamental assumption in the Frandsen model is that loads are proportial to the standard deviation. Using turbulence intensity tends to move focus to low wind speeds where loads are not as significant. Viewing turbulence data as TI also tends to overemphasize small insignificant deviations of the fits at low wind speeds.
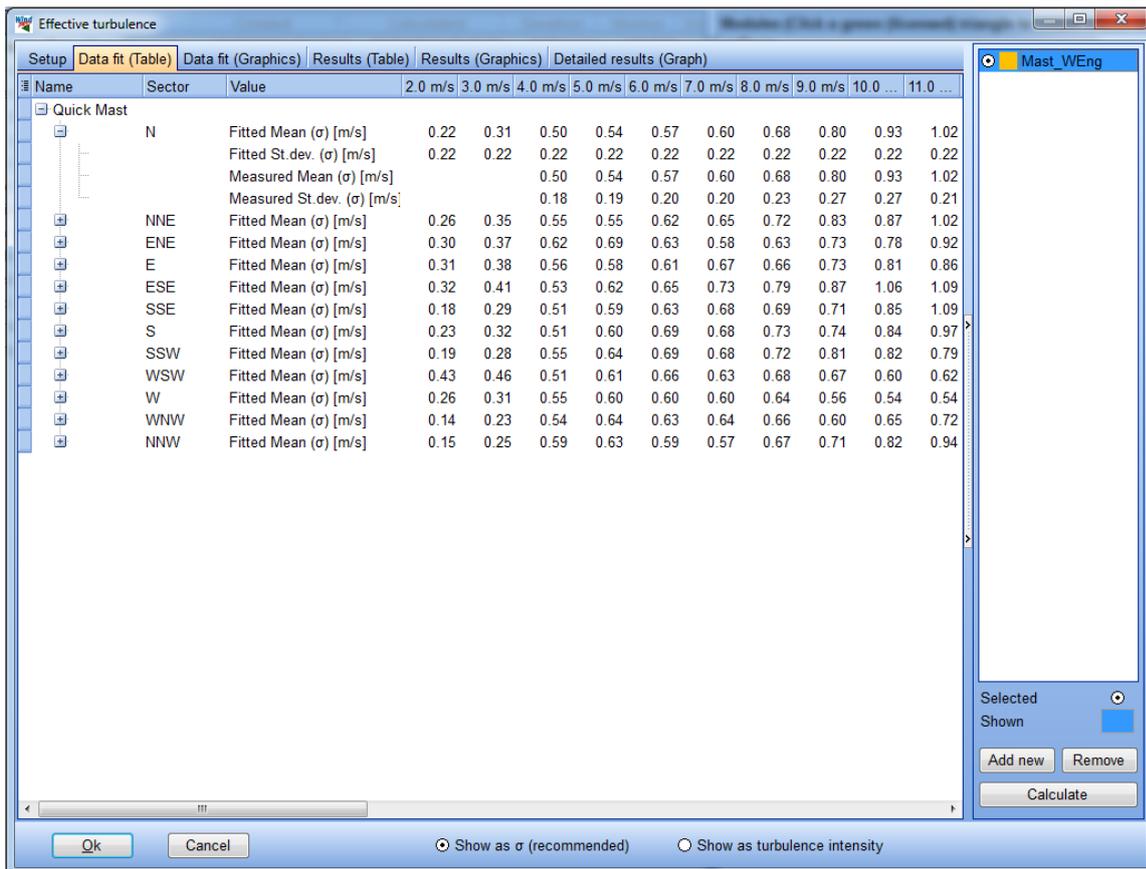
Figure 34. Data fit (Table) tab of the Effective turbulence check.

The *Data fit (Graphics)* presents the turbulence measurements and fits in a graphical form. Use the buttons in the lower left corner to change to another mast (if available) or to skip through the sectors. It is worth noting that in the plots the…:
- asterisk illustrates the measurements
- open circles show the chosen value
- red lines are the fitted data model

If the asterisk and the open circles coincide it means that the measurements in the bin are accepted as the bin fullfills the selection criteria (minimum number of samples in each bin) defined on the *Setup* tab. If the asterisks and open circles deviate for a bin, the open circle will always fall on the redline indicating that the fitted value was selected because the bin failed the selection criteria.

Note that for the default setup the standard deviation of turbulence (σ_σ) is the same for all sectors. This is due to fact that this quantity (the standard deviation of the standard deviation) is ususally not well determined sector-wise with only one year of data. The IEC standard allows this use the weighted mean σ_σ instead of sector-wise values to stabilize the estimation, it is introduced in a footnote in [2].

If the data selection or the fits are not satisfactory, press the *Add* button to the lower right to try another setup where the data selection criteria have been changed. This setup is described in more detail below.
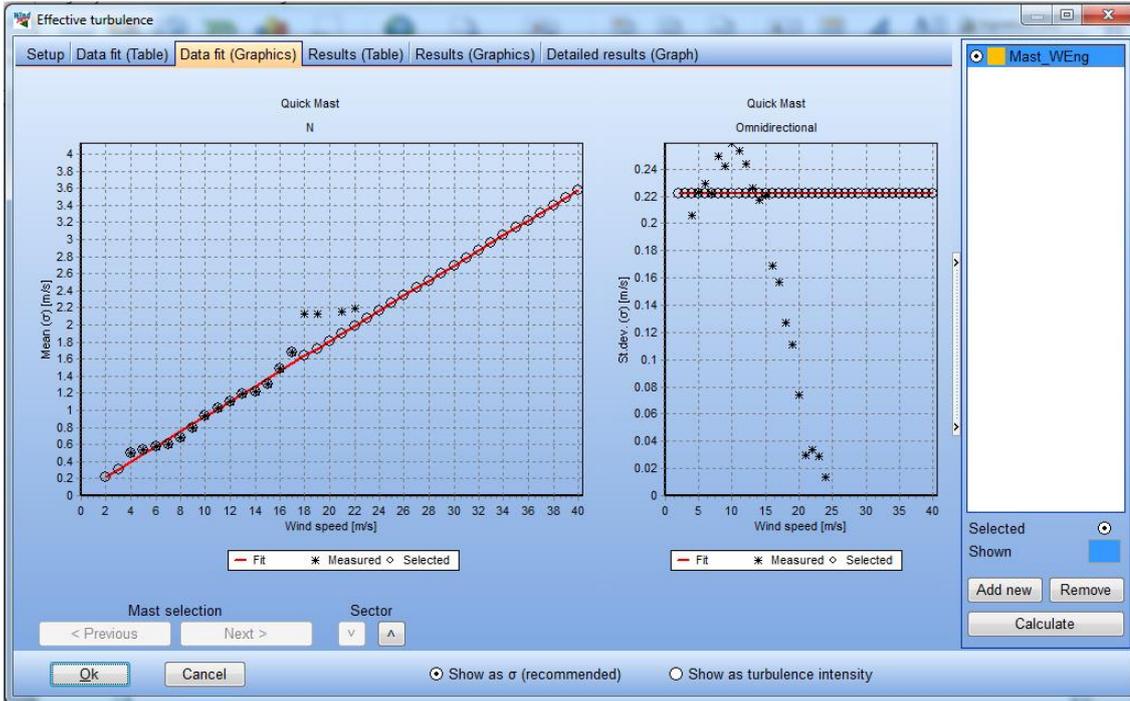
Figure 35. Data fit (Graphics) tab of the Effective turbulence check. Note the four highest samples on the left plot. These are measurements with too few samples in their bin to be selected for use. Thus, the asterisks (measurements) do not coincide with the circles (selected value) for those four bins. Instead those circles fall on the red line (the fit) as the fit is used for bins with too few samples. Sample thresholds are defined in the setup.

Results of the Effective turbulence calculation are summarized on the tab *Results (Table)* showing the results for each wind speed bin within the required check interval by the IEC standard. This check interval is described above (in *Description and limit*) and is relative to the wind speed at rated power which is estimated from the power curve defined for each particular WTG object in the calculation.

Any bins exceeding the IEC limit are highlighted in the table, so that a WTG with no highlighting is fully within the IEC limit for all required wind speeds. Orange highlighting is used for *Caution*, i.e. when the exceedances for the particular WTG are not considered critical and, thus, are compensated by the buffer at other wind speeds. Red highlighting is used when overall the exceedances for the WTG are expected to accumulate to a critical exceedance.

For each WTG the first line in the table shows the result of the Effective turbulence calculation for each wind speed bin. The second line shows the relevant IEC limit for the same bins. In the column *Equivalent*, the equivalent accumulated effective turbulence normalized to the IEC design climate is shown. Thus, the value of *Equivalent* is always one for the row *IEC demand* (second line). The threshold between *Caution* (orange) and *Critical* (red) is reached at value of *Equivalent* exceeding 1. The lines below summarize all the sector-wise part results and scaling factors used for each WTG.
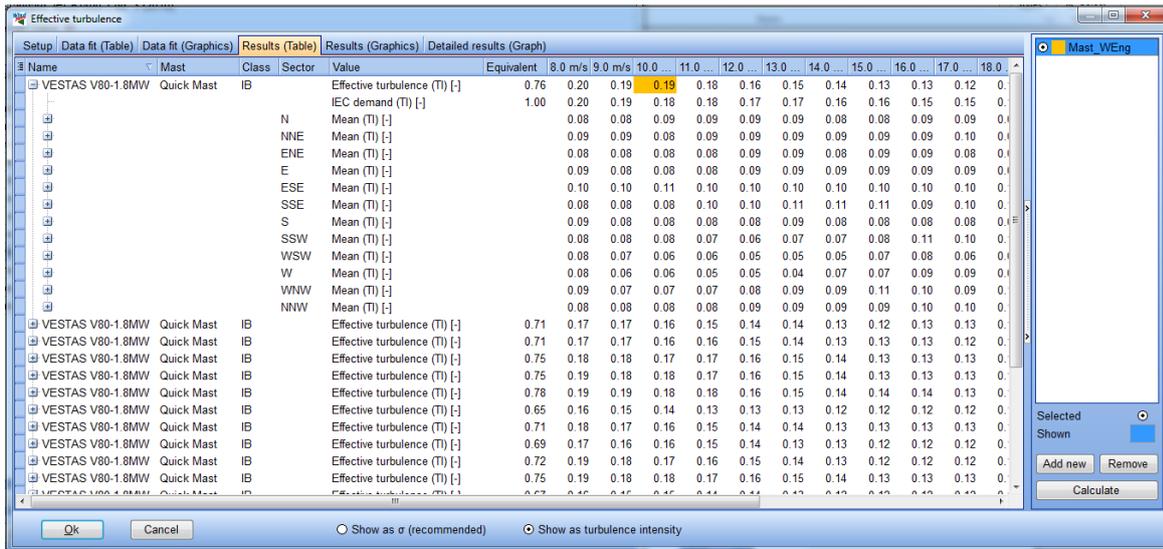
Figure 36. Results (Table) tab of the Effective turbulence check. Note that the Effective turbulence is exceeded for one bin for the first WTG in the table. That bin is highlighted in orange as the exceedance is not expected to be critical.

The tab *Results (Graphics)* illustrates the Effective turbulence results as a function of wind speed for each WTG. Use the buttons to the lower left to skip to next WTG. Any exceedance within the relevant IEC check interval is highlighted by light red shading of the windspeed bin.

Note that also the Effective ambient turbulence is shown as the dashed curve, which illustrates the result of the Effective turbulence calculation disregarding all wake-added turbulence contributions. The difference between the full and the dashed curve clearly illustrates the wake contribution of the wind farm to the Effective turbulence. The difference is usually highest up to 12-13 m/s, because at higher wind speeds the thrust coefficient decreases quickly for most WTGs and lower thrust results in less wake turbulence.

Figure 37. Results (Graphics) tab of the Effective turbulence check.

The rightmost tab *Detailed results (Graphics)* illustrates all the contributions and part results in the calculation of Effective turbulence as a function of wind speed. Each contribution may de-activated in the menu below the graph. The wind speed is adjusted using the slide bar. To skip through the graphs for the WTGs use the *Previous/Next* buttons to the lower left. If the box *All* is ticked all WTGs are plotted together with their relative positions. Use the mouse-over-effect to see the label of each WTG. If all contributions are unchecked except *Wake turbulence* this graph is particularly useful to identifying which neighbour WTG is the cause of a too high Effective turbulence level.

The graphics on this tab are also very useful to help better understand the calculation of Frandsen's Effective turbulence but also to analyze and help understand the cause of turbulence-related problems of a wind farm design. Is it the ambient turbulence or is it the wake-added turbulence that is causing the problem? And from which sector/directions are the problems caused?
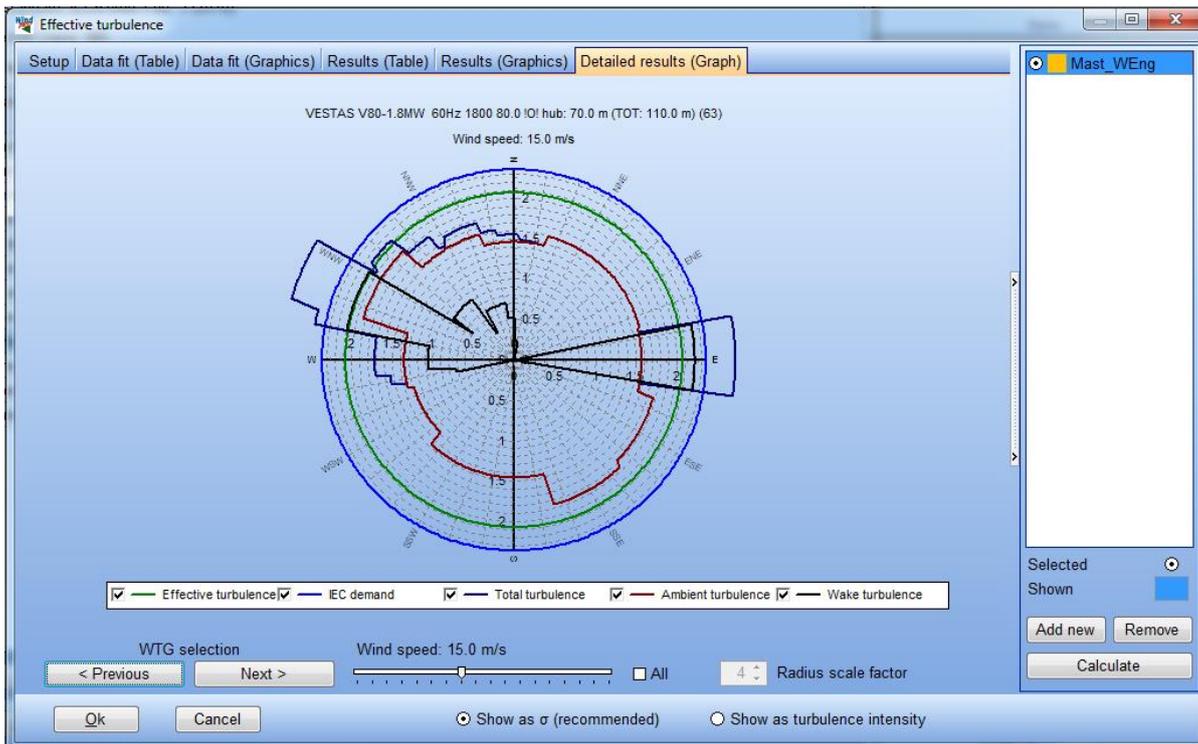
Figure 38. Detailed results (Graph) tab of the Effective turbulence check.

The following sub sections describe the setup options of the turbulence check in more detail.

13.3.3.3 Turbulence data (ambient)

The starting point of an Effective turbulence calculation is the ambient turbulence on the site.
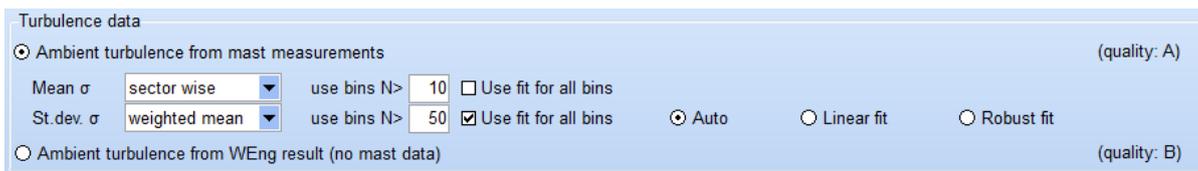
Figure 39. Setup of ambient turbulence data input and handling.

Ambient turbulence from mast measurements

When the ambient turbulence is measured it must be treated properly to ensure a robust outcome of the calculation as real data always have outliers, holes and other problems. This is handled applying selection criteria to the data and by fitting a model to the ambient turbulence measurements and using this for problematic or missing bins.

First setup choice for the mean turbulence (*Mean σ*) is the selection of *Sector-wise* or *Weighted mean*. The first option is default and highly recommended. The latter choice is only to be used experimentally as a very robust estimate for very problematic data, e.g. with a very short time span.

Second choice is the number of samples (*N*) in a bin for the bin-average turbulence to be used. Bins with less than *N* samples will be disregarded; they will not contribute to the fit and the turbulence of those bins will be replaced by the fit. The default value of *N* has been chosen by testing the methodology on a number of site masts. The fit is performed as a standard least squares fit to the bin values with equal weights. This disregards that fact there are many more samples in bins at low wind speeds compared to bins at higher wind speeds, thus, effectively increasing the relative weight of bins at higher wind speeds where loads are more critical. If a fit weighting each bin by the number of samples is used, any upward curvature of the σ(u) curve at higher wind speeds as in forests and off/near shore tends to be ignored, which can lead to falsely low estimates of turbulence at high wind speeds as illustrated in the figure below.
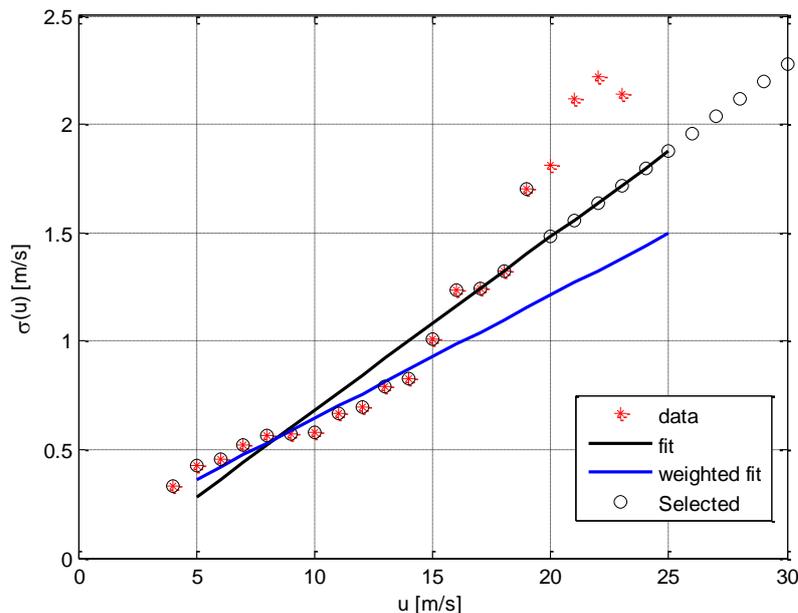

Figure 40. Plot showing the difference between a weighted fit and the fit employed in SITE COMPLIANCE. Note how the weighted fit severely underestimates values of accepted bins between 15 and 20 m/s.

Last choice is activating the *Use fit for all bins* option. If this is activated the fit is used for all bins no matter the number of samples. This is only recommended as a robust approach if the data seem very noisy and oscillatory.

Setup for handling of measured standard deviation of turbulence (i.e. σ_σ) has the same three choices as for the mean turbulence (σ), but the defaults are different. By default the weighted mean is used for σ_σ as this is allowed in the standard [2] and ensures a much more stable estimation of this otherwise quite unstable parameter. In addition a higher default bin acceptance limit of 50 samples is used, as well as using the fit for all bins. These defaults ensure a quite robust estimation of σ_σ. However, our analyses have shown that still for some sites with only a year of data an even more robust estimation is required. Therefore an extra fit criterion is included which controls the type fitting with the options *Auto*, *Linear* or *Robust*. The default setting is *Auto*. In this mode an ordinary linear fit is used if the R^2 of the fit is above 0.8. When R^2 is below 0.8, avery robust estimator is used namely the median sample which is an very robust estimate and very insensitive to outliers. The user may also force the fit to always be a *Linear* fit or a *Robust* fit (i.e. median) no matter the value of R^2 using the last to options.

Ambient turbulence from WEng result (no mast data)

If no measurements of turbulence are available the turbulence must be predicted using WEng. However, even with the predicted WEng turbulence for each WTG the contribution from thermally-generated turbulence and the standard deviation of turbulence are not accounted for. In the Risø/DTU WAT tool [14] integrated within WEng, a decision was made to take these missing parameters from the IEC standard. This leads to the

following equation for the 90th percentile of turbulence for each sector and each WTG position where the only input is the predicted WEng turbulence intensity (TI_{WEng}) for the sector and position:

$$\sigma_{90} = TI_{Weng} u_{HH} + 7.47\, TI_{Weng}$$

Is has turned out that this Risø/DTU (WAT) approach is conservative for most sites. An attempt to calibrate the above equation for use in SITE COMPLIANCE to better represent turbulence measurements is on-going. However, the analyses conducted for a number of sites are so far are not conclusive enough to base a calibration on. Hence, in the initial release of SITE COMPLIANCE the direct use of ambient turbulence predicted by WEng is setup consistent with the Risø/DTU approach [14, 15].

13.3.3.4 Propagation model

Turbulence measured on a mast only represents the mast position and measuring height. Conditions might be significantly different at other heights and at other locations across a site. To compensate for this SITE COMPLIANCE allows a number of scaling options to adjust measured turbulence to become more representative for each WTG position. This scaling is setup in the *Propagation model* group which also allows the option *No scaling* which is recommended only for sites where the mast is fully representative for WTG conditions.
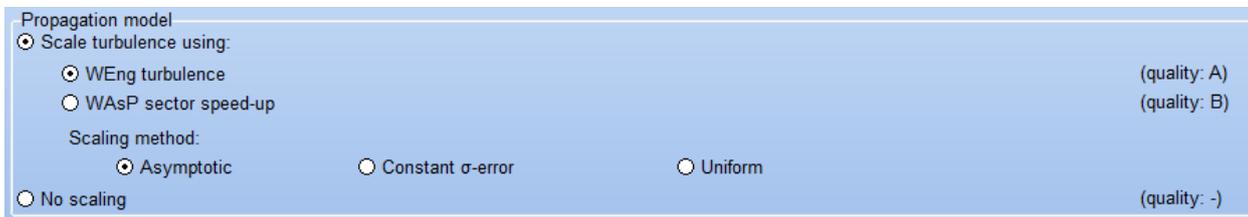
Figure 41. Setup of propagation model which defines the scaling method of measured turbulence from mast position and height to each WTG position and hub height.

The scaling can be based on sector-wise turbulence levels and speed-up predicted by WEng or sector-wise speed-up factors predicted by WAsP. Additionally, the actual scaling may be done using three different basic assumptions abbreviated as:
1) Asymptotic
2) Constant σ-error
3) Uniform

Scaling based on WEng turbulence allows all three scaling assumptions which are described in the following.

Asymptotic scaling using WEng turbulence
This method relies on two assumptions:
a) That WEng as a neutral model captures the variation of mechanically generated turbulence well. Hence, WEng turbulence ratios must approach the ratios of site turbulence in the high wind speed limit.

$$\sigma_{mast}^{t}(u,\theta)/\sigma_{WTG}^{t}(u,\theta) \to \sigma_{mast}^{p}(u,\theta)/\sigma_{WTG}^{p}(u,\theta) \qquad \text{for } \to \infty$$

b) That thermally-generated turbulence dominates at wind speeds approaching zero and is a general feature across the site (i.e. a constant).

$$\sigma_{mast}^{t}(u,\theta)/\sigma_{WTG}^{t}(u,\theta) \to 1 \qquad \text{for } u \to 0$$

Where index *t* indicates "true" which for the mast is the measured turbulence and for the WTG the quantity we want to estimate. Index *p* abbreviates "predicted" and represents WEng predictions.

The resulting scaling factor is a function of direction sector and wind speed.

Constant σ-error scaling using WEng
In this method it is assumed that the error of the WEng predicted turbulence (σ) is constant across the site, related to e.g. thermal or larger scale turbulence contributions not captured by the WEng micro-scale model.

$$\sigma_{WTG}^{t}(u,\theta) - \sigma_{WTG}^{p}(u,\theta) = \sigma_{mast}^{t}(u/c,\theta) - \sigma_{mast}^{p}(u/c,\theta)$$

Speed-up across the site is accounted for via the predicted WEng mast-to-WTG speed-up factor $c = u_{WTG}/u_{mast}$ (in the above equation u used for u_{WTG}). Indices on sigmas are used as in the previous scaling method and the resulting scaling factor in this case is also a function of direction sector and wind speed.

Uniform scaling using WEng
The uniform scaling relies on the very simplifying assumption that the "true" ratio of mast-to-WTG turbulence equals the ratio predicted by WEng which is constant for all wind speeds within a sector. The scaling factor depends on the sector.

$$\sigma_{WTG}^t(u,\theta)/\sigma_{mast}^t(u,\theta) = \sigma_{WTG}^p(u,\theta)/\sigma_{mast}^p(u,\theta)$$

No speed-up is included and the scaling factor does not vary with wind speed. This scaling assumption is coarser than the other WEng based methods, but on the other hand the simplicity of the underlying assumptions also makes this method quite robust.

Constant σ-error scaling using WAsP
This scaling approach is related to the *Constant σ-error* scaling using WEng (see above) but, in a simplified form as no predicted turbulence values are available. If the predicted turbulence values are set to zero in the equivalent WEng equation, the corresponding WAsP version is obtained.

$$\sigma_{WTG}^t(u,\theta) = \sigma_{mast}^t(u/c,\theta)$$

The fundamental assumption is that for a certain flow condition (speed and direction) at the mast the turbulence in terms of σ is constant across the site. But as wind speed varies across the site due to roughness and terrain speed-ups the turbulence intensity will vary.

Uniform scaling using WAsP
The uniform scaling based on WAsP relies on a similar simple assumption as the uniform WEng scaling is based on. The scale factor is assumed constant for all wind speeds and simply equal to the inverse of the mast-to-WTG speed-up factor predicted by WAsP.

$$\sigma_{WTG}^t(u,\theta) = 1/c \; \sigma_{mast}^t(u,\theta)$$

No scaling
This last option is to assume that the mast measurements are representative for all WTG positions, implying no scaling at all. The underlying assumption is rather trivial.

$$\sigma_{WTG}^t(u,\theta) = \sigma_{mast}^t(u,\theta)$$

This assumption is only recommended for simple and small sites with little variation in terrain or from mast to WTG or if the scaling options for some reason perform poorly. For offshore sites this setting may also be most appropriate depending on the mast setup.

13.3.3.5 Turbulence structure correction

The IEC standard specifies that if a WTG position is estimated to be complex or partly complex in the terrain complexity check, i.e. the complexity index is $I_C > 0$, then a correction should be applied to turbulence values. The argument is that in complex terrain turbulent kinetic energy is transferred from the horizontal component to the vertical component. Cup anemometers measure only the horizontal component. To compensate for the transferred turbulence the IEC standard introduces a correction factor C_{CT}, the *Turbulence structure correction factor*. This correction has its own setup group with several options as shown below.


Figure 42. Setup of the Turbulence structure correction requirement of the IEC standard.

The setup allows three options.

Complexity check

The IEC standard describes how C_{CT} may be calculated from the terrain complexity index (I_C) for each WTG position using the following equation.

$$C_{CT} = 1 + 0.15 I_C$$

The IEC standard [2] states that this equation is to be used when no measurements or modelling is available for the three components of turbulence.

So far experience from several complex sites has shown that this *Complexity check* option is quite conservative when compared to modelled components of turbulence. This is the case even when the modelling of these components is using a linearized model as WEng expected to over-estimate inflow angles and hence over-estimate transfer of horizontal turbulent kinetic to the vertical/transverse component.

WEng turbulence components

When measurements or modelling of the three components of turbulence are available the IEC standard states that the following equation for the turbulence structure correction factor (C_{CT}) may be used.

$$C_{CT} = \frac{\sqrt{1 + \left(\sigma_w/\sigma_u\right)^2 + \left(\sigma_v/\sigma_u\right)^2}}{1.375}$$

Where σ_u, σ_v and σ_w are the three components of turbulence (longitudinal, vertical and transverse). These three components are predicted for each WTG position in a WAsP Engineering calculation and are used when the setting *WEng turbulence components* is chosen. This setting is default when a WEng calculation is available.

The current release of SITE COMPLIANCE does not support the use of three-component measurements.

No correction

This option should only be selected if terrain complexity indices for all WTGs equal zero, i.e. for not complex sites. The only exception is when ambient turbulence is predicted using WAsP Engineering. In this case No correction is the default setting because WEng models the longitudinal component and not the horizontal component as measured by a cup anemometer. This decision is in-line with the comparable use of WEng calculation results in Risø/DTU's own software tools e.g. WAT.

13.3.3.6 Frandsen model

The Frandsen Effective turbulence model plays a central role in the IEC context and the model is described in detail in Annex D of the Standard [1, 2]. The theoretical details of the model are summarized in Appendix II of this manual.

In very brief terms the Frandsen model consists of several sub components. The first component is a model that predicts the wake-generated turbulence downstream of a WTG at a certain wind speed and for a given thrust coefficient. The second component is a model for combining wake-generated turbulence with ambient turbulence into a "total" turbulence for each direction and each wind speed bin. The third component is a special integral over all directions that accounts for frequency of each direction but also includes a non-linear weighting relating to the accumulation of material fatigue in different materials. Hence, a material parameter called the Wöhler exponent is needed as input. The integration is performed for each wind speed bin and the resulting integral is the Effective turbulence as a function of wind speed.

Figure 43. Setup of the Frandsen model also referred to as the Effective turbulence model.

Wöhler exponent

The general material parameter which is used in weighting according to fatigue accumulation as described above for the Frandsen Effective turbulence model. Usually, the value 10 is assumed as it represents reinforced fiberglass and thus the WTG blades. A value of approximately 3 represents steel and e.g. the tower or main shaft. Generally using a high value e.g. 10 will be a conservative assumption for materials with a lower Wöhler exponent.

Large wind farm correction

A fourth and additional component in the Frandsen model is a large wind farm correction which accounts for extra added turbulence levels inside very large wind farms. The original specification of the correction assumes a regular layout not generally applicable to the real world, but this has been generalized in [15]. Our implementation is in line with this generalization; It assess the need for large wind farm correction for each sector and adjusts ambient turbulence levels as requested in the standard. Only the number of neighbour WTGs in the sector decides if a sector is large wind farm or not.

13.3.3.7 Sector management (simple version)

A simple but effective version of wind sector management is included in this version of SITE COMPLIANCE. The method allows definition of a distance threshold in rotor diameters (RD) e.g. 3 RD. In the calculation all wake effects from neighbour WTGs within the set distance for a particular direction will be excluded, assuming therefore that those WTGs have been shut down.

This implementation makes it very easy to assess the effect of most manufacturers' standard requirement of shutting WTGs down in directions where distances are below 3 RD.


Figure 44. Detailed setup of sector management.

13.3.4 Wind distribution

13.3.4.1 Description and limit

The Wind distribution check evaluates the frequency of occurrence at different wind speeds for each WTG by comparing them to the frequency of occurrence assumed in the IEC design limit.

The IEC design limit for the Wind distribution check is a Weibull distribution with a shape factor of k=2. Mean wind speed is defined as 20% of the basic design parameter V_{ref} from Table 1 (see section 13.1.1) which are 10m/s, 8.5m/s and 7.5m/s for the wind speed classes I, II and III, respectively. A range of wind speeds ranging from 20% to 40% of V_{ref} must be checked, i.e. from the mean wind speed to twice the mean wind speed of each class.

In the IEC standard it is required that the wind distribution estimated for each WTG is long-term representative. Hence, an evaluation of the long-term level and possibly a long-term correction is required. This may be handled in three ways in SITE COMPLIANCE.

1) The first and typical way is by basing the WAsP calculation on a long-term corrected wind statistics saved from WindPRO's MCP module by choosing this WAsP-option in the *Main* setup tab of SITE COMPLIANCE.
2) The second option is to use the mast data directly (either in a WAsP calculation or without) and utilize the simple (MCP supplement) long-term index correction for wind speeds available in SITE COMPLIANCE (see section 13.2.4).
3) The third option is that the data are evaluated to be long-term representative in their own right, and no long-term correction is applied. The last option is not uncommon with around three or more years of site data.

13.3.4.2 Setup, Calculation and Results

The following text describes the workflow in setting up, calculating and reviewing the results of a typical Wind distribution calculation. The setup of this check is quite simple with few options as illustrated in the figure below showing the *Setup* tab.
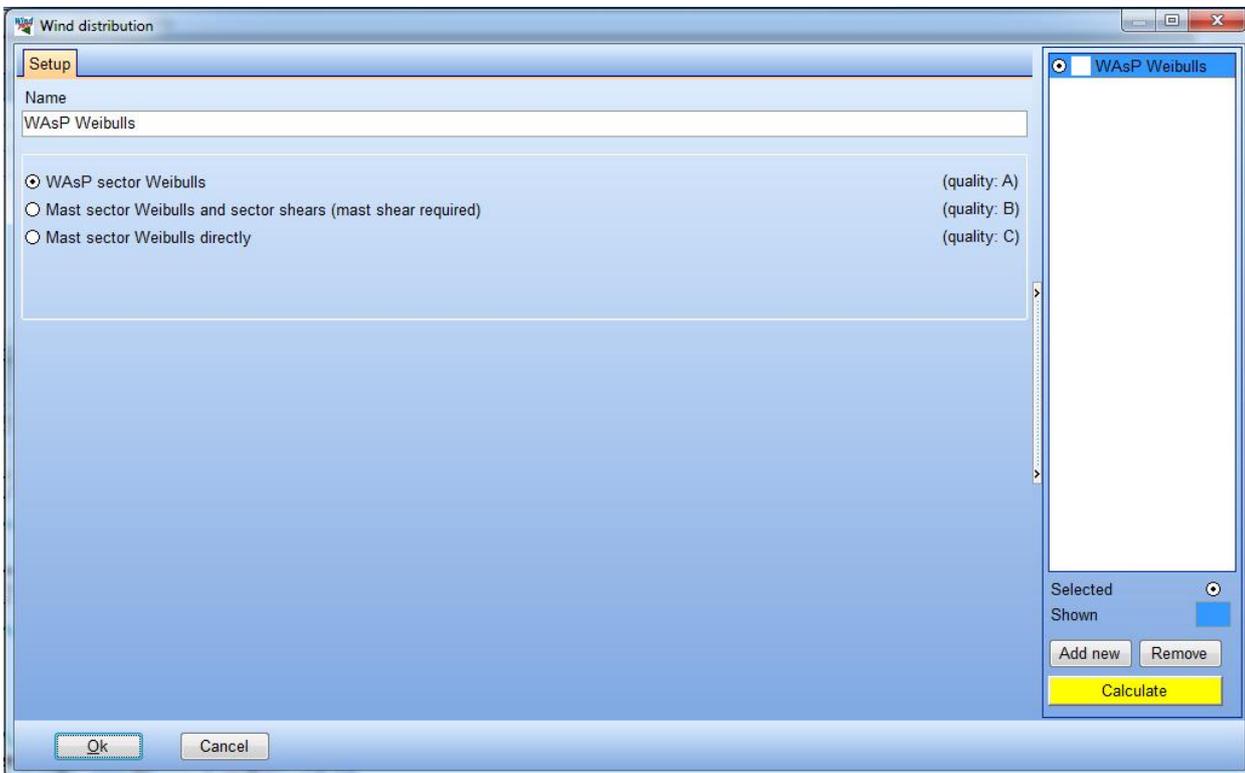

Figure 45. Setup tab of the Wind distribution check.

In most cases a WAsP calculation has been run and using these results predicted at each WTG will then be the default option.

The *Results (Table)* summarizes the results for all relevant wind speed bins for each WTG. Bins are highlighted if the frequency within that bin exceeds the IEC limit. If the overall exceedance for the WTG is evaluated to be critical the highlighting is red or if it is only evaluated to be *Caution* highlighting is orange.

First row for each WTG shows the frequencies of occurrence in each bin predicted for the WTG. Second row shows the IEC limit, i.e. the frequencies of the relevant IEC class. If the sub-levels are expanded the sector-wise frequencies for the predicted WTG climate are presented.
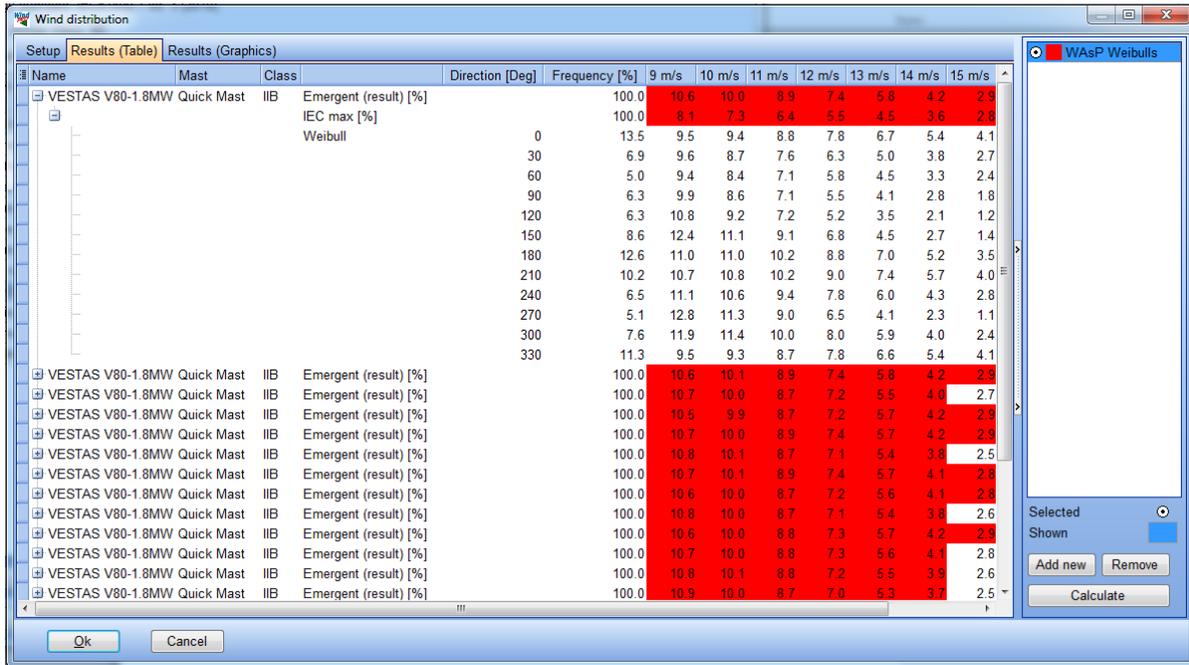
Figure 46. Results (Table) tab of the Wind distribution check.

On the *Results (Graphics)* tab the WTG probability density function (frequencies of occurrence in each wind speed bin) is graphically compared to that for the IEC class. The IEC wind speed check interval is highlighted by the blue vertical lines, and any exceedance is highlighted by a light red box covering the exceeded interval. Results for *Next* or *Previous* WTG and are viewed using the *WTG selection* buttons to the lower left.
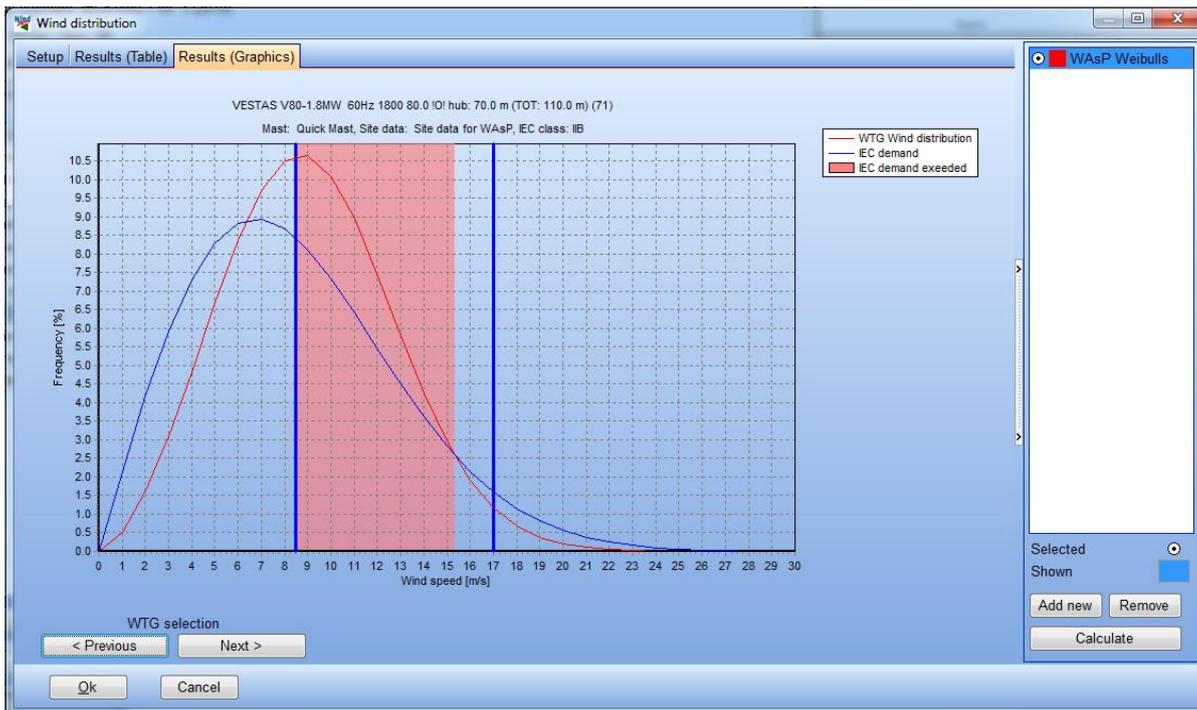
Figure 47. Results (Graphics) tab for the Wind distribution check.

13.3.4.3 Calculation options

There are only few calculation options for the Wind distribution check with the most common one being the WAsP sector Weibulls. The two other options should only be used where the mast position is truly representative for the WTG positions.

It is well known that the WAsP model has limitations in very steep or complex terrain where it may over-estimate the terrain speed-up factor considerably. If the mast position is representative of the WTGs this should not pose a major problem.

WAsP sector Weibulls

With this setup the check calculates the so-called Emergent wind speed distribution using the WAsP nomenclature. Each of the sector-wise Weibull distributions is weighted by the frequency of the sector and added to form the omni-directional distribution of wind speeds, referred to as Emergent distribution. The resulting distribution is generally not a Weibull itself and hence may exhibit bi- or multi-modality (i.e. multiple maxima). Finally, the Emergent distribution is compared against the IEC design limit for the wind speed bins required by the IEC standard.

Mast sector Weibulls and sector shears (mast shear required)

Basing the vertical extrapolation on shear measured on the mast relies on the assumption that wind shear is constant with height, which is certainly not the case in areas with strong terrain speed-up effects. It also relies on the assumption that horizontal variations of the wind distribution are negligible.

If no WAsP calculation/license is available this calculation option may be used if the mast position is considered to be representative of the WTG positions. The calculation will use the fitted sector-wise Weibull parameters for the main height of each mast. The Weibull A parameter for each sector is then scaled from mast main height to WTG hub height using the corresponding sector shear exponents estimated for the mast shear heights. Finally the Emergent distribution is formed by summing the scaled sector Weibull parameters weighting them by the sector frequencies.

Mast Weibulls directly

In this option the Emergent distribution is calculated directly from the mast sector-wise Weibull parameters. This is only advisable if the mast is representative for the WTG positions both in terms horizontal variations and in terms elevation above ground (i.e. mast main height ≈ hub height).

13.3.5 Flow inclination

The Flow inclination check predicts the flow inclination in each sector and identifies the sector with highest absolute (positive or negative) flow inclination for each WTG. The resulting flow inclinations are compared against the IEC design limit for each WTG.

13.3.5.1 Description and limit

The IEC design limit for the Flow inclination check are flow inclinations of +8° and -8° for the worst direction. Thus, flow inclinations above +8° or below -8° exceed this limit.

The IEC standard mentions that the slope the smallest of the terrain fits (5xHH) required in the Terrain complexity check may be used as an estimate of the flow inclination. We allow this option in SITE COMPLIANCE, and note that generally the resulting estimates are not too different from more advanced estimates obtained using WEng.

13.3.5.2 Setup, Calculation and Results

The following text describes the workflow in setting up, calculating and reviewing the results of a typical Flow inclination calculation. Setup of this check is quite simple with only two options as illustrated in the figure below showing the *Setup* tab.
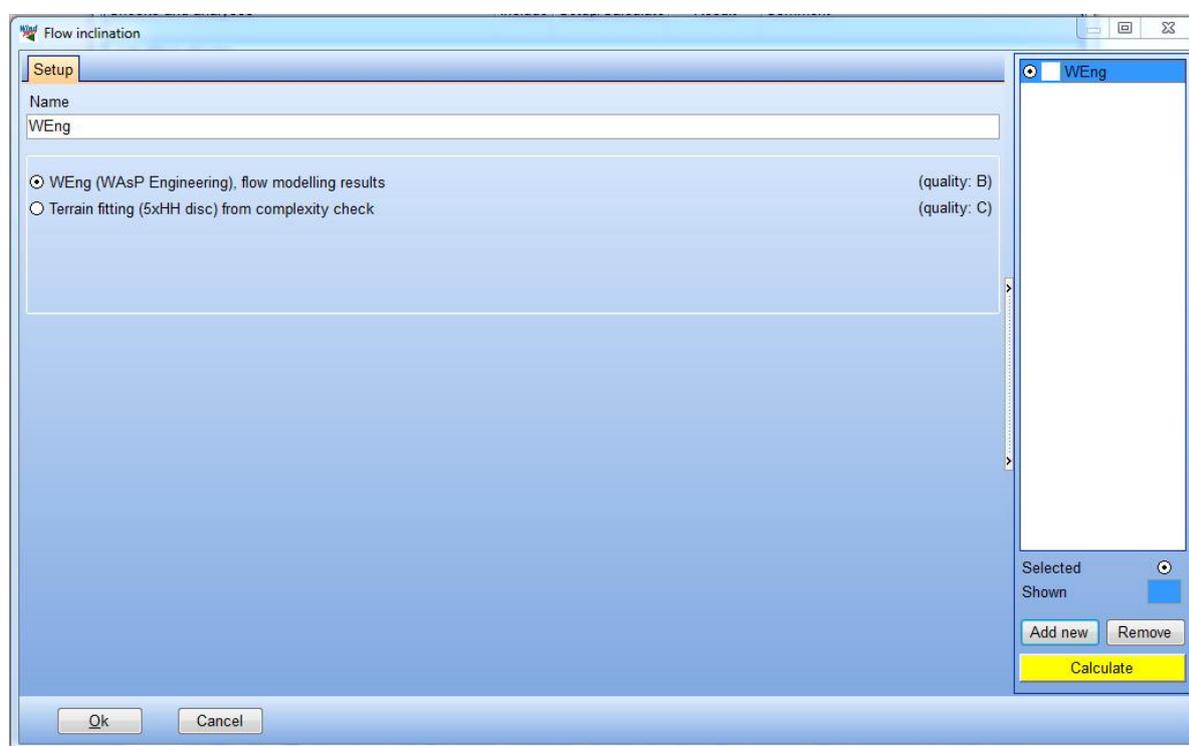
Figure 48. Setup tab of the Flow Inclination check.

In cases where a WEng license is available and the WEng calculation has been run, the WEng flow inclination estimate for each WTG is the default option.

The *Results (Table)* summarizes the result, i.e. the maximum flow inclination for each WTG and the direction (sector median) in which it occurs. If the table is expanded the flow inclination for each sector is shown. The expansion with sector-values is not available for the calculation *Terrain fitting (5xHH) from complexity check*, as sector-wise results are not available from that calculation.
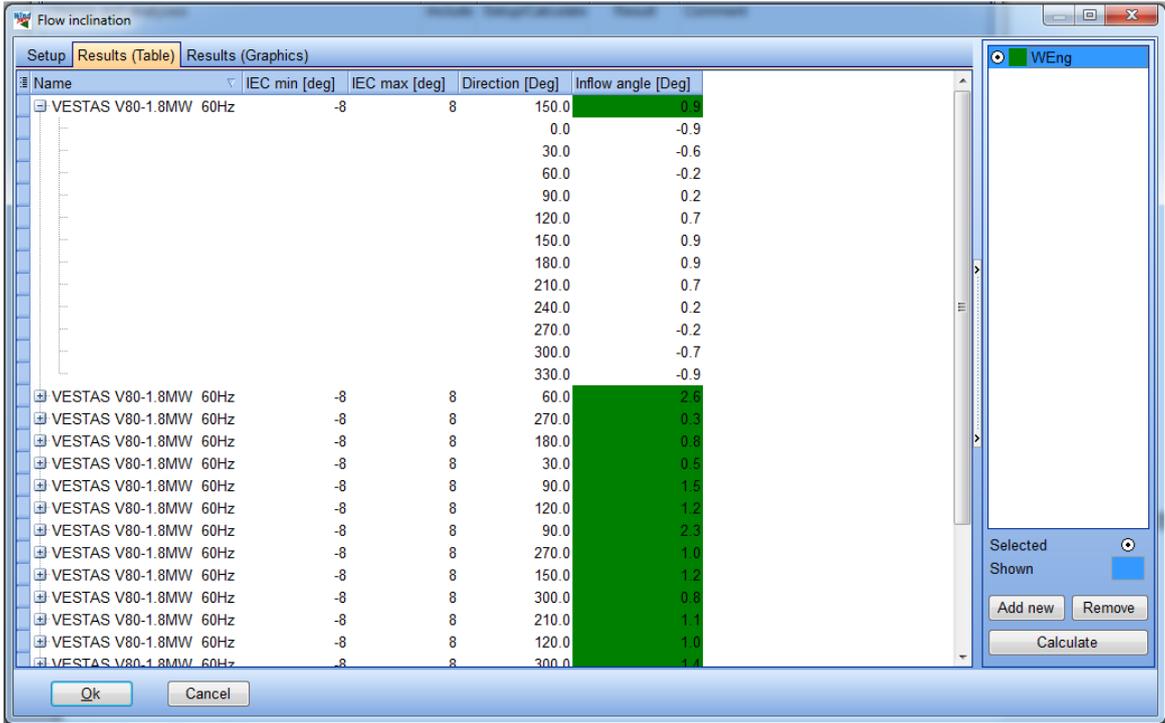
Figure 49. Results (Table) tab of the Flow inclination check.

On the *Results (Graphics)* tab the results (i.e. max flow inclination) are summarized for all WTGs. IEC design limits at ±8° are shown as the horizontal blue lines.
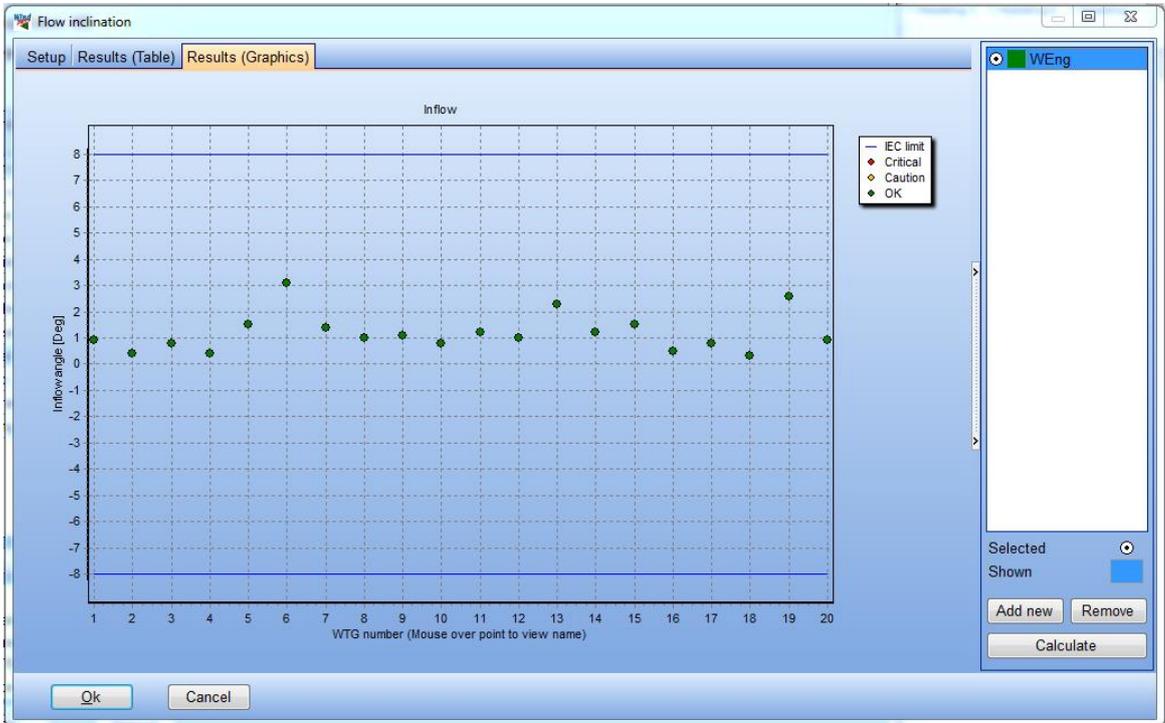

Figure 50. Results (Graphics) tab for the Flow inclination check.

13.3.5.3 Calculation Options
The following describes the calculation options for the Flow inclination check.

WEng (WAsP Engineering), flow modelling results

WEng is a broadly accepted and used flow model suited for engineering calculations like flow inclination. The advanced setup of the WEng calculation determines the number of sectors in the WEng calculation with a default of 12 sectors. A finer resolution of the inflow angle estimate may be obtained by increasing the number of sectors in the WEng calculation. As a linearized flow model WEng has a tendency to over-estimate inflow angles in steep and complex terrain.

Terrain fitting (5xHH disc) from complexity check

See the section 13.3.1 describing the Terrain complexity check for further details of the terrain fit. Again it is important to stress that this option is mentioned as acceptable in the IEC standard.

13.3.6 Wind shear

13.3.6.1 Description and limit

The Wind shear check evaluates the vertical wind shear or in other words the vertical variation of wind speed across the rotor for each WTG position. Wind shear is quantified by means the wind shear power law exponent, α.

The IEC design limits for wind shear is an average wind shear above 0 but less than 0.2 for all design classes.

The IEC standard is not clear regarding "the average shear" as it may refer to the shear exponent of the omni-directional mean wind profile or to the average of the sector-wise shear exponents. Since the shear calculation is non-linear (it is based on a log-log fit), these two estimates generally differ but not drastically so. In Section 11.3 of the Standard [1] it is mentioned that the shear must be estimated for at least 30° direction sectors. In SITE COMPLIANCE the shear average is taken to be the weighted average shear of the sector-wise shear exponents. A reason for this is that it enables more detailed adjustments to the sector-wise shear estimates. This interpretation of "average shear" is consistent with the approach adopted in the Risø/DTU WAT tool [15].

13.3.6.2 Setup, Calculation and Results

There are five options to select between for the Wind shear check, as illustrated in the *Setup* tab below. The two upper options seek to combine mast measurements of shear with flow predictions to improve the estimation. The next two options are based purely on flow modelling results and the last option is based purely on measurements.
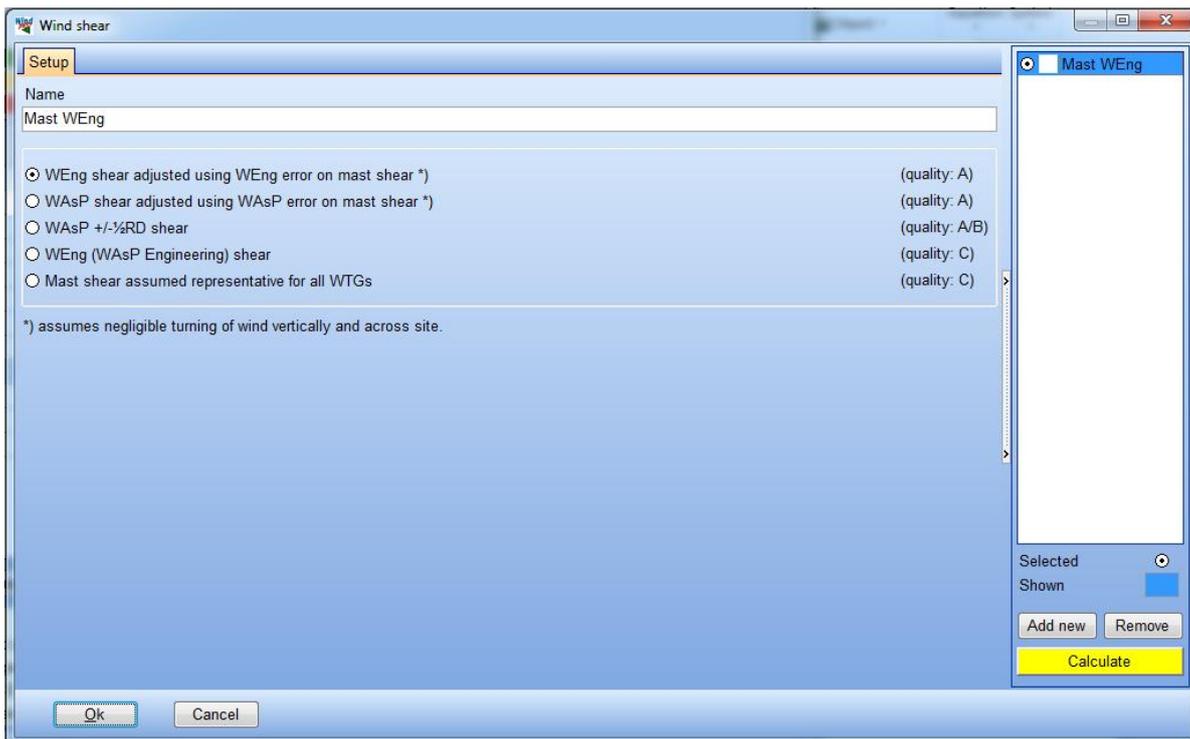
Figure 51. Setup tab of the Wind shear check.

The *Results (Table)* tab for Wind shear shows the IEC high and low design limits and the wind shear estimate for each WTG. If the table is expanded for a particular WTG the sector-wise shear estimates and their frequency are presented.
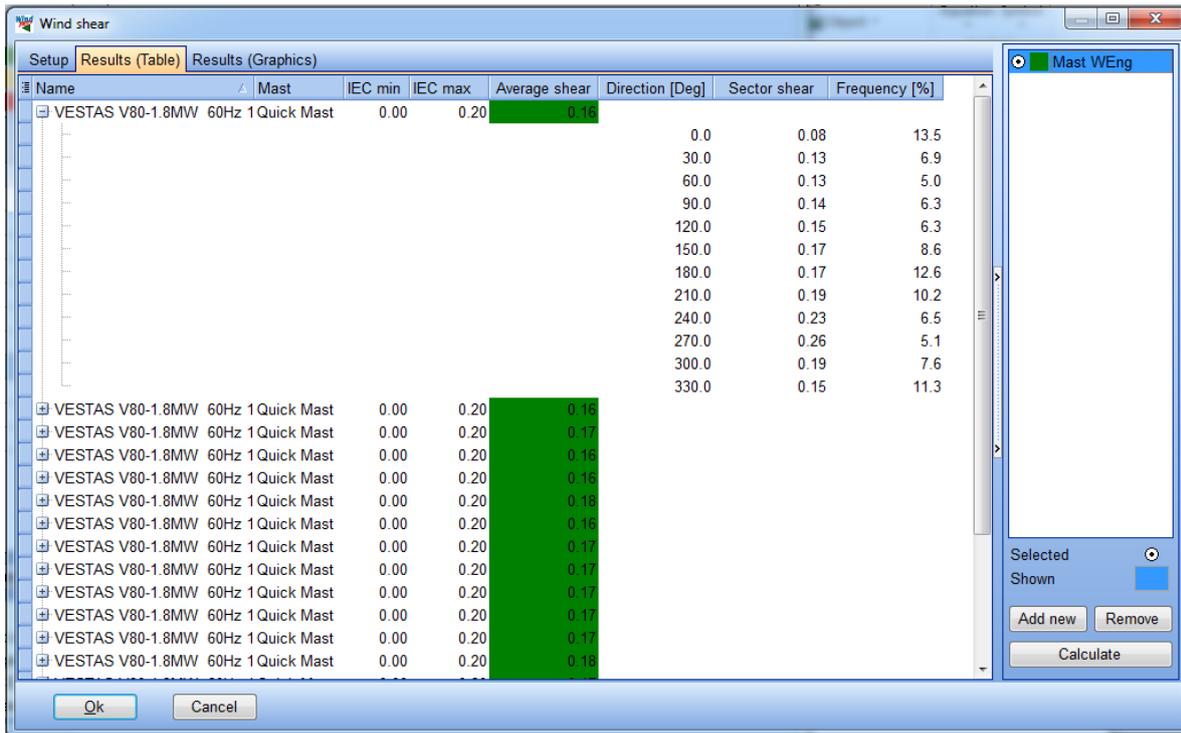
Figure 52. Results (Table) tab of the Wind shear check.

Finally the *Results (Graphics)* presents the easy overview of all the WTG results with the IEC limits highlighted as blue lines.
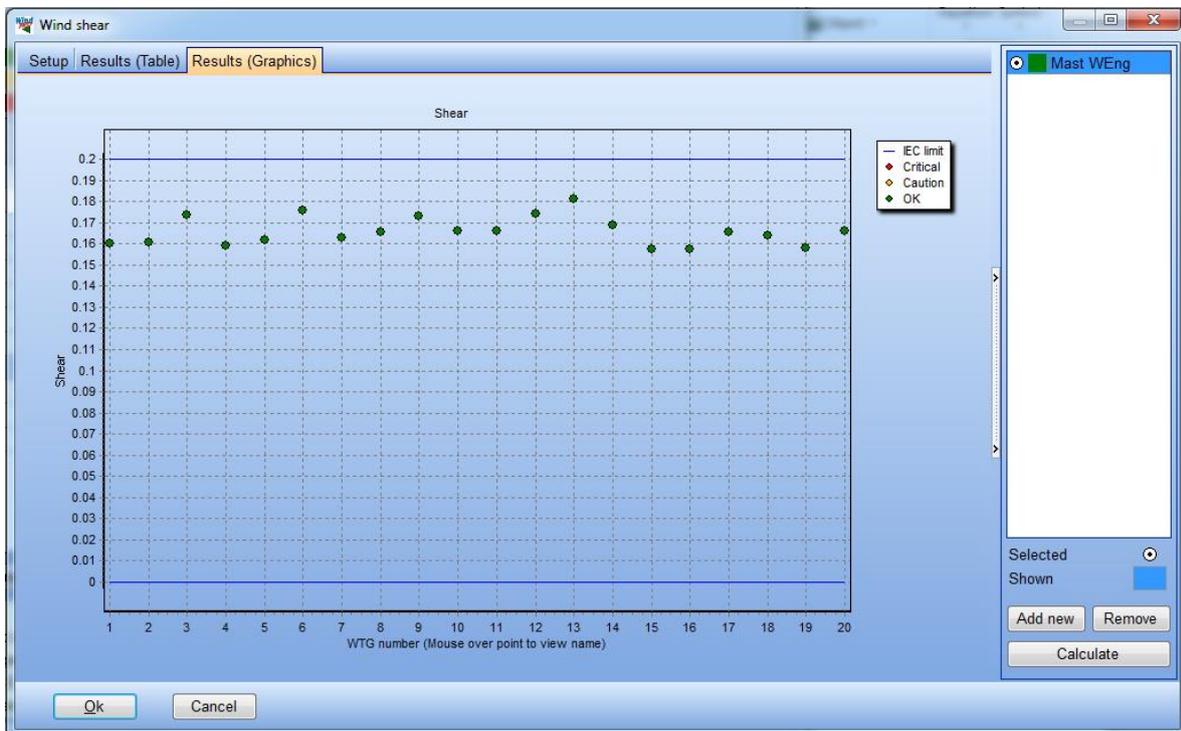
Figure 53. Results (Graphics) tab for the Wind shear check.

13.3.6.3 Calculation Options

The following text describes the detailed calculation options of the Wind shear check and their main assumptions. The figure below shows the options.

Figure 54. Calculation options in the Wind shear check.

WEng shear adjusted using WEng error on mast shear

The sector-wise shear estimates based directly on WEng results are usually quite biased to the low side as WEng assumes neutral stability. This bias may be estimated for each sector of the mast and applied as a correction to the WEng shear estimated for each sector at the WTG positions. After applying the bias-correction the corrected sector-wise shear exponents are averaged using the sector frequencies for the turbine position to obtain the final average shear estimate.

This method seeks to combine the best from measurements with the best from the flow modelling. Measurements accurately represent the shear at a single position, namely the mast, but may not be representative for the site as such. Flow modelling has its strength in resolving the relative variation of shear across the site although generally with a constant bias which may be considerable.

The method relies on the assumption that wind does not turn significantly across the site or vertically,. i.e. flow conditions in one sector at the mast are assumed not to have turned significantly when they reach the WTG positions. The larger the sector width the better this assumption is. Turning across a site and vertically is usually much less than the 30° of standard sectors, however, in very complex terrain turning may be very significant. It also important to validate that all direction sensors used on a mast are consistent because such errors might mess up this calculation option considerably.

WAsP shear adjusted using WAsP error on mast shear

This method is similar to the adjusted WEng method described above. The only difference is that the relative variation of shear is extracted from the results of WAsP flow modelling. The WAsP profile is quite different from the WEng profile as WAsP has built-in stability model that has a very strong effect on the predicted profiles.

WAsP +/-½RD shear

The default setup of the WAsP calculation includes modelling of wind conditions at HH (hub height), but also at HH+½RD and H-½RD, where RD is the rotor diameter. Having the flow conditions modelled at these three heights allows the estimation of the wind shear across the rotor for each sector and hence definition of the "average shear".

The quality of this calculation option depends on how well the WAsP profile has been validated and adapted for the site. The quality may be high if WAsP stability settings have been adjusted appropriately and the WAsP profile matches well with the observed profile at the mast position.

In tropical and mid-latitudes the WAsP profile using default stability settings has a tendency to over-estimate wind shear. The reason is that WAsP defaults are calibrated using the measurements from Northern Europe.

WEng (WAsP engineering) shear

Flow results from WAsP Engineering include the derivatives of the flow field and bases the calculation of wind shear on these derivatives. Hence the estimated shear represents the hub height exactly. However, as WEng assumes neutral stability the wind shear is usually under-estimated significantly using WEng results. This method is not generally recommended. It is included to allow comparison with the more suitable estimation methods as it is not common to see that WEng shear is used directly.

Mast shear assumed representative for all WTGs

This calculation is only recommended only if the mast is representative for all the WTG positions and for the WTG hub height, both in terms of terrain and roughness conditions.

13.3.7 Air density

13.3.7.1 Description and limit

The IEC standard requires an assessment of the air density at hub height.

The IEC design assumption for air density is 1.225 kg/m^3. Hence, air densities lower than this limit results in less loading on the WTG and vice versa.

In principle the IEC standard requires the air density to be averaged only for wind speeds greater than the wind speed at rated power of the WTG. This adds a significant complexity to calculation of this check. However, a number of test cases have shown that the difference between the annual mean air density and that averaged for wind speeds above U_{rated} is usually within 1-2%. Considering the other uncertainties that affect air density estimates this small difference is not considered significant. In addition it is common practice among turbine manufacturers to use the annual mean air density instead. This practice has also been adopted in the SITE COMPLIANCE module.

The model adjustments of temperature (and pressure) from mast height amsl (above mean sea level) to WTG HH amsl are based on the ISO standard atmosphere as mentioned in the IEC standard.

Relative humidity is not an input as it only has a minor effect on air density. This is illustrated in the plot below. For relative humidity to have an effect on air density exceeding 2%, the mean air temperature must exceed 35°C and the mean humidity be close to 100% - it is worth noting that the highest annual mean temperature worldwide is 34°C (in Dalol, Ethiopia[3]). Hence, in most typical locations the effect of relative humidity is well below 1%. In addition including the effect of humidity decreases air density and hence the aerodynamic loads. Thus, excluding relative humidity is a very slightly conservative assumption in regards to wind turbine loads.

---

[3] http://www.weatherexplained.com/Vol-1/Record-Setting-Weather.html#b
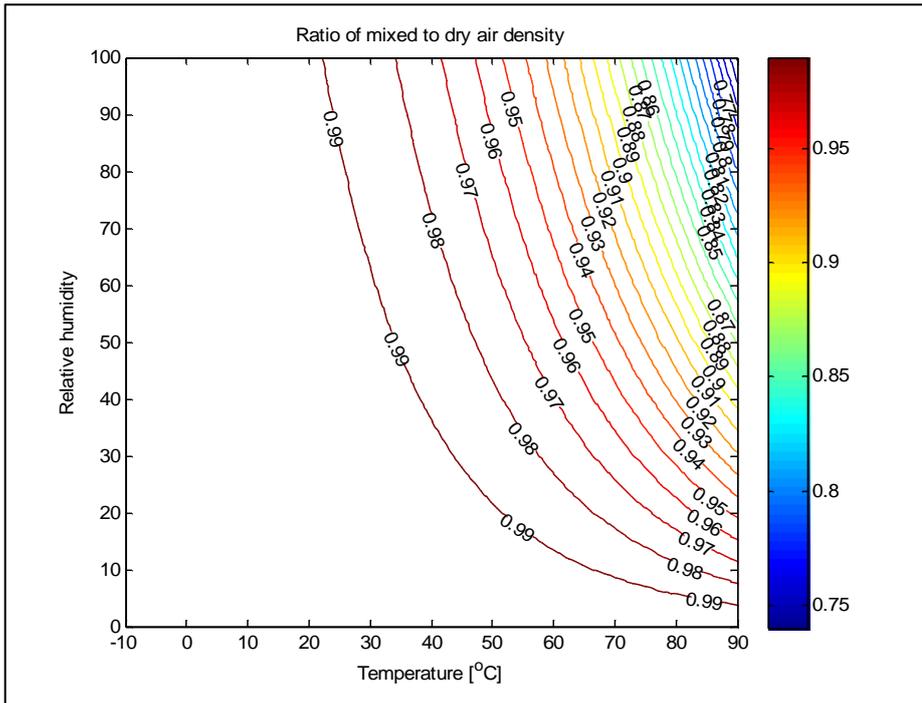
Figure 55. Plot showing the relative effect on air density of varying mean temperature and relative humidity.

13.3.7.2 Setup, Calculation and Results

The *Setup* tab for the Air density check requires only the choice of the input data. If a site mast is available with temperature (and pressure, but not required) this option can be chosen. If there are more site masts with temperature, just one has to be chosen. Alternatively, if a mast e.g. SYNOP or METAR data downloaded using the online data option in a Meteo Data Object with temperature (and pressure) was defined as a *Climate mast* in the general SITE COMPLIANCE setup this too may be selected.

If there are no on-site measurements of temperature (and pressure), climate statistics from the Global Historical Climatological Network (GHCN) may be chosen. By default this option will choose the nearest station. Sometimes a more distant station may be more appropriate if its elevation above sea level is more representative of the site under study. To review and choose other stations click the *Climate database* button.
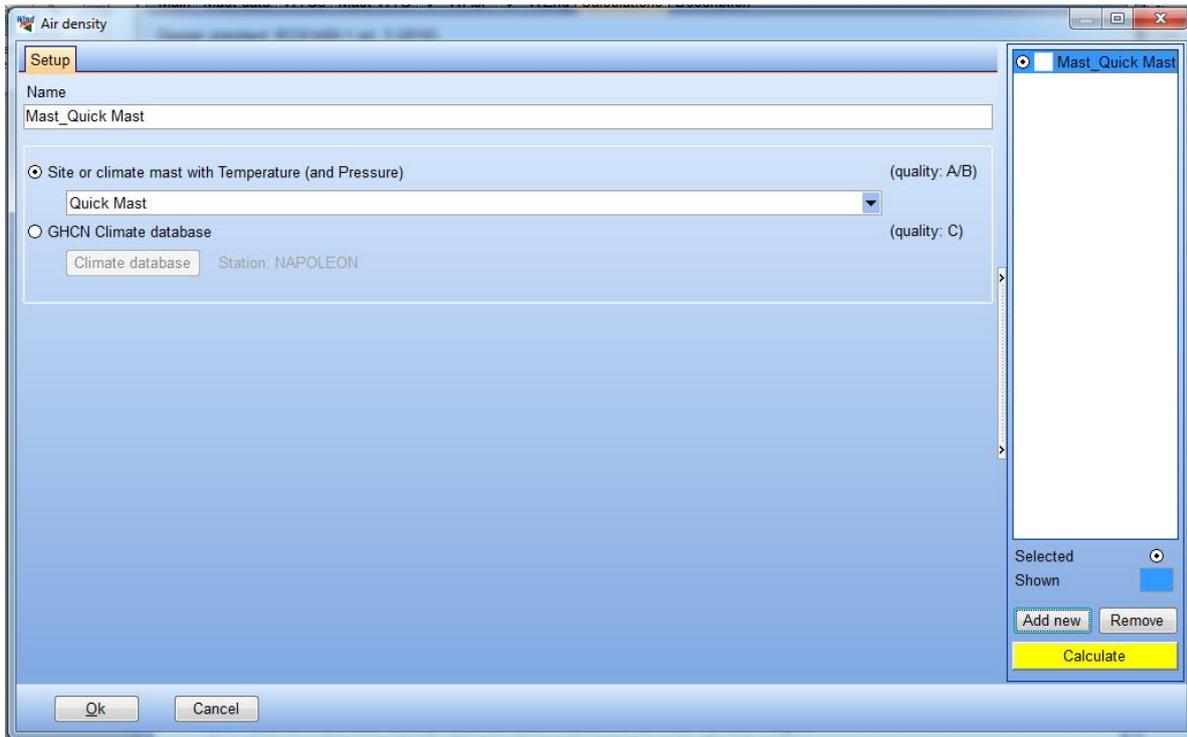
Figure 56. Setup tab of the Air density check.

Once the calculation is run by clicking the yellow "Calculate" button, the results tabs are generated. The tab *Base data* summarizes the selected masts annual mean data and the measuring height above sea level. Below that all the relevant atmospheric model parameters are listed and at the end the air density calculated directly for the mast data is shown.
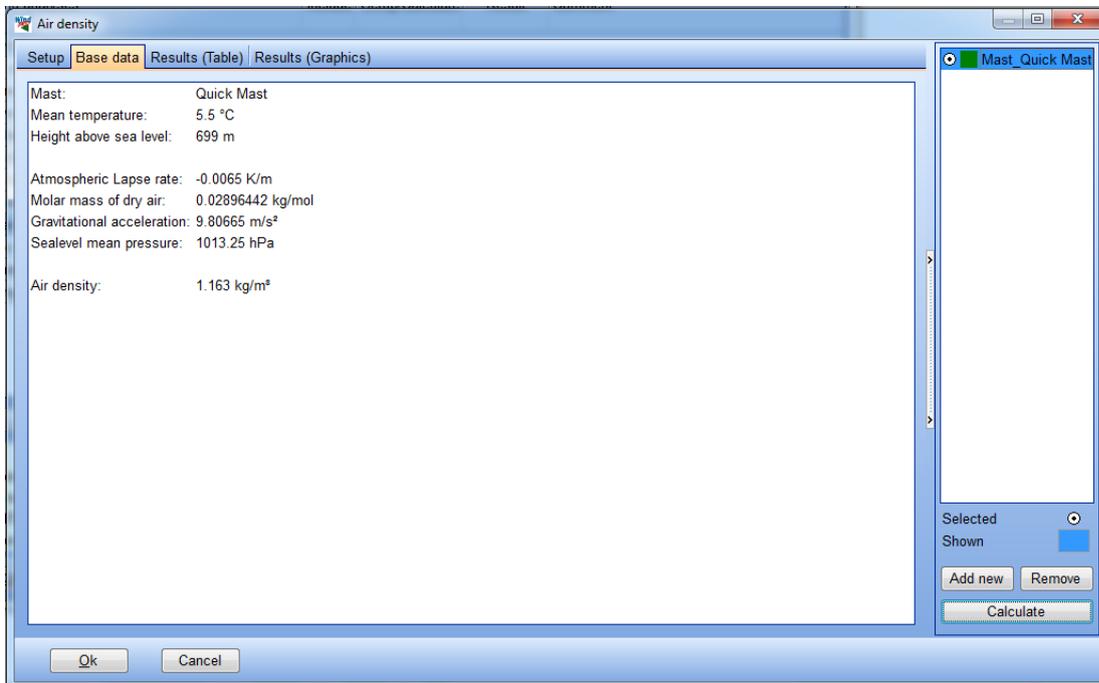
Figure 57. Base data tab of the Air density check.

The *Results (Table)* tab shows the resulting annual mean air density for each WTG. A column shows the height difference to the mast used and another lists the predicted annual mean temperatures and pressures.
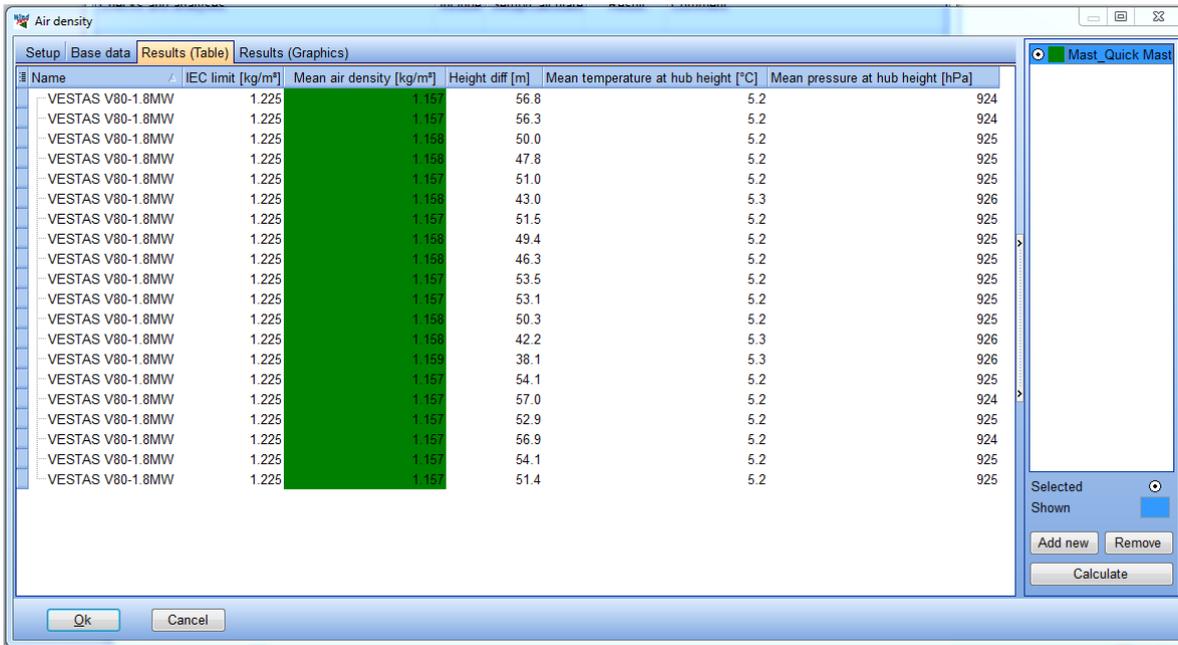
Figure 58. Results (Table) tab of the Air density check.

Finally the tab *Results (Graphics)* provides the now familiar overview plot of all the WTG results and the IEC design limit.
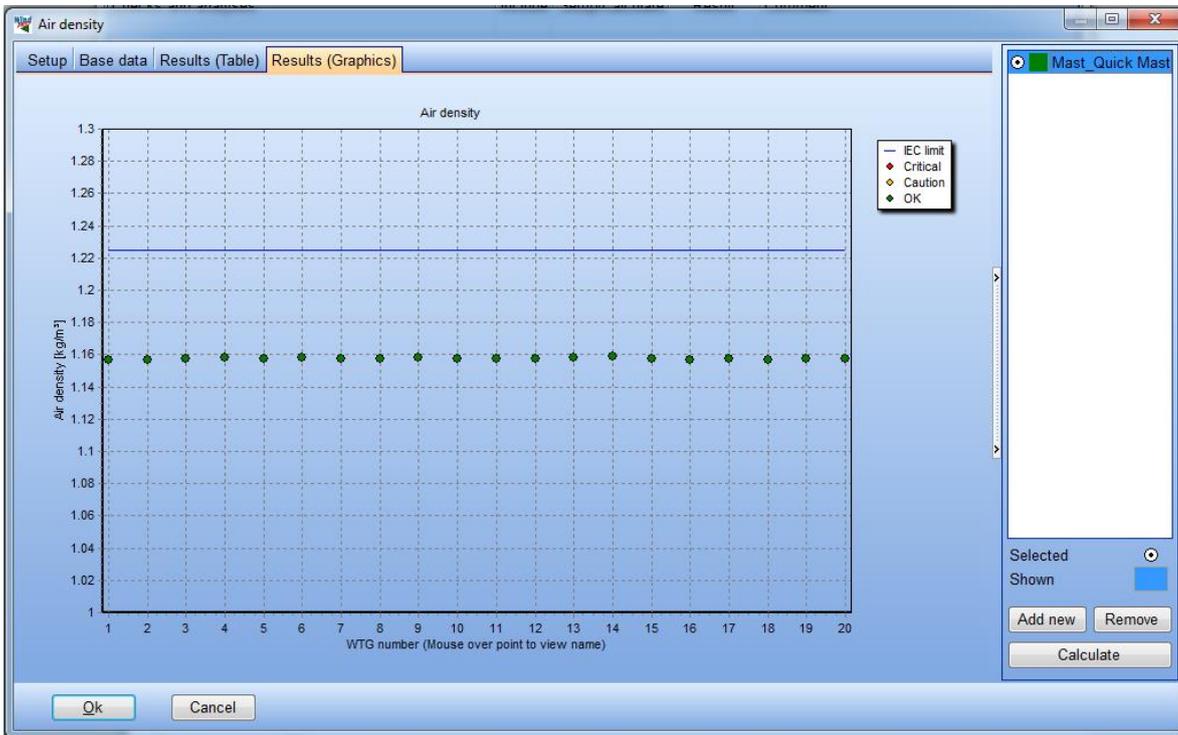
Figure 59. Results (Graphics) tab of the Air density check.

13.3.7.3 Calculation Options

For both calculation options the same extrapolation model is used; it corrects the mean temperature using the standard temperature lapse rate of -0.0065 K/m from measuring height to WTG hub height. If pressure measurements are available too these are corrected using the temperature difference as input and the

hydrostatic equation. If no pressure data are available the sea level pressure is corrected to WTG HH using the standard atmosphere model.

Site or climate mast with Temperature (and Pressure)

If temperature (and pressure) data are available for a site mast the air density calculation may be based on these. As described above

GHCN Climate database

GHCN is a database[4] maintained by the US institution NOAA (National Oceanic And Atmospheric Administration). The database contains historic climate statistics for a large number of stations worldwide.

---

[4] http://www.ncdc.noaa.gov/ghcnm/

13.4 Calculations - Other checks

The IEC standard [1] lists a number of so-called *Other environmental conditions* to be assessed and compared with the design assumptions for the WTG. In addition *Earthquake conditions* must be evaluated to assess if further actions in this regard are needed for the site. The list below summarizes these additional site parameters mentioned in the IEC standard.

- **Earthquake conditions (seismic hazard)**
- **Normal and extreme temperature ranges**
- **Lightning**
- Icing, hail and snow
- Humidity
- Solar radiation
- Chemically-active substances
- Salinity

In SITE COMPLIANCE we have only included some of these additional parameters, those highlighted in bold above. The selection was based on a combination the possibility of allowing a meaningful estimation method and data source and the risk that the parameter is critical for a site.

13.4.1 Seismic hazard

13.4.1.1 Description and limit

The IEC standard requires a site estimate of the peak ground acceleration (PGA) with a recurrence period of 475 years for the site area. This recurrence level is equivalent to an annual risk of exceedance of 0.2%. There is no explicit IEC limit for PGA, hence the general hazard levels of GSHAP have been adopted in SITE COMPLIANCE. "Low hazard" results in *OK*, "Moderate hazard" in *Caution*, and "High" and "Very high hazard" results in *Critical*, emphacizing the need for futher and detailed investigation of seismic loads.

For the PGA site estimate SITE COMPLIANCE uses a database which results from the UN funded Global Seismic Hazard Assessment program (GSHAP). GSHAP database is compiled from several regional and national sub-projects and summarizes the PGA in m/s^2 at a resolution of 0.1° by 0.1°. The GSHAP data is available via the ETHZ or GeoForschungsZentrum Potsdam homepages. The figure below illustrates the global GSHAP seismic hazard map.

The PGA mapped in GSHAP refers to standard soil conditions which is rock (rock/firm soil in US/Canada). As a consequence very special local conditions which differ significantly from this like a deep and soft sedimentary setting may amplify ground motions significantly making conditions more severe than mapped in GSHAP. Nevertheless, GSHAP is considered a reliable source of seismic hazard (in terms of PGA) as it compiles numerous local and regional studies thus, made by local experts and authorities.
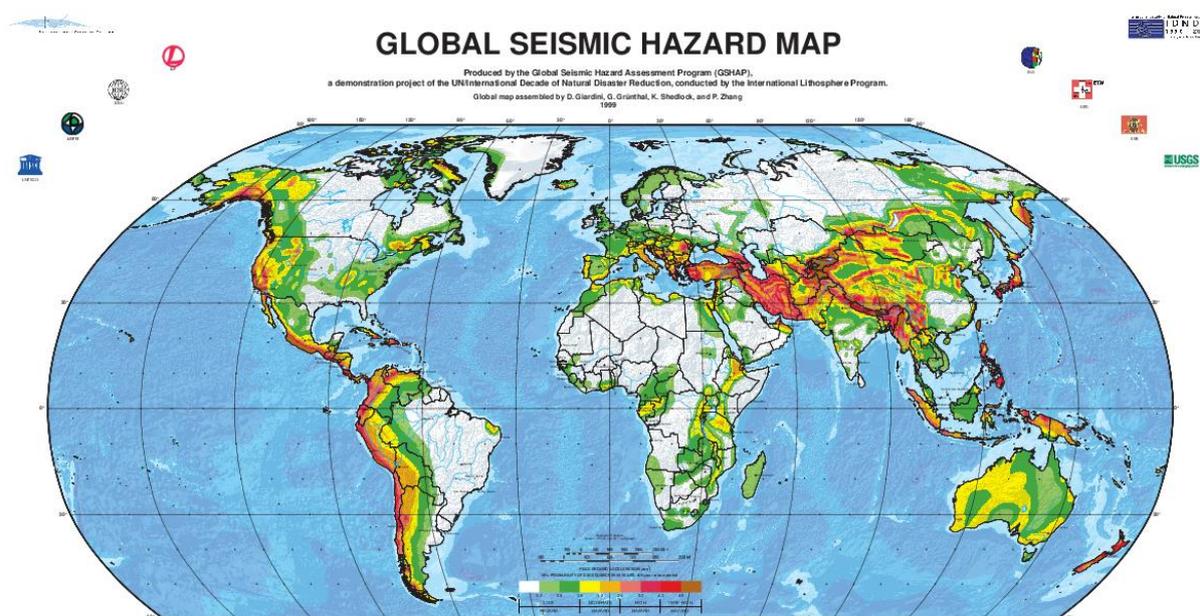
Figure 60. GSHAP seismic hazard map showing global variation of PGA. From [16].

13.4.1.2 Setup, Calculation and Results

No inputs are required in the Seismic hazard calculation, as only the GSHAP database is available.
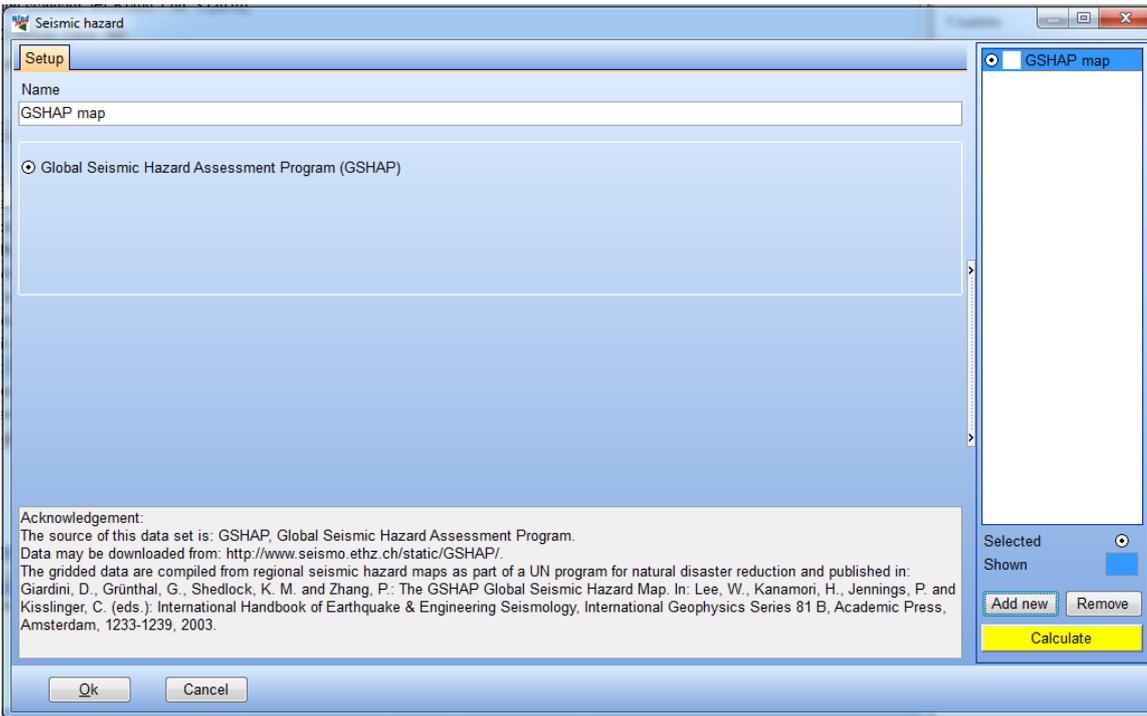
Figure 61. Setup tab of the Seismic hazard check.

The *Results (Table)* tab summarizes the site estimated seismic hazard in terms of the PGA level in m/s². It also gives the expected hazard level.
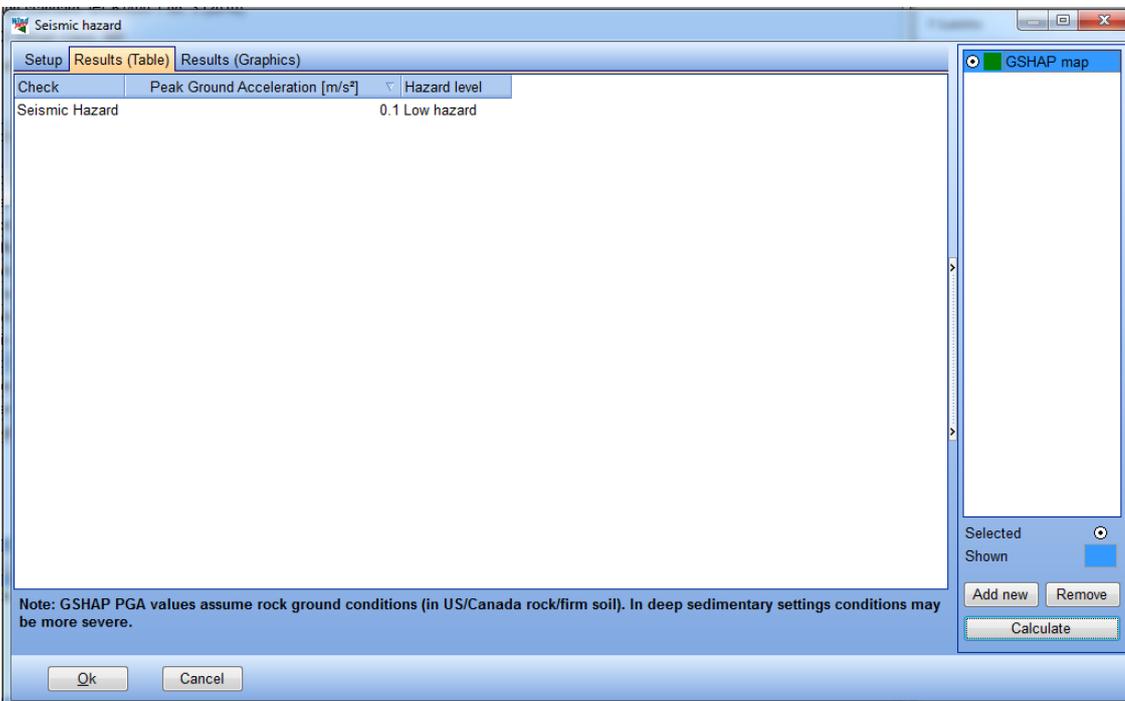
Figure 62. Results (Table) tab of the Seismic hazard check.

The last tab in the Seismic hazard check provides a map of the seismic hazard in an area of approximately 1000km by 1000km around the site. Note that as GSHAP is compiled of several national and regional projects variations in PGA may not allways be 100% smooth across national borders as is seen for the US Canada border in the case illlustrated below.
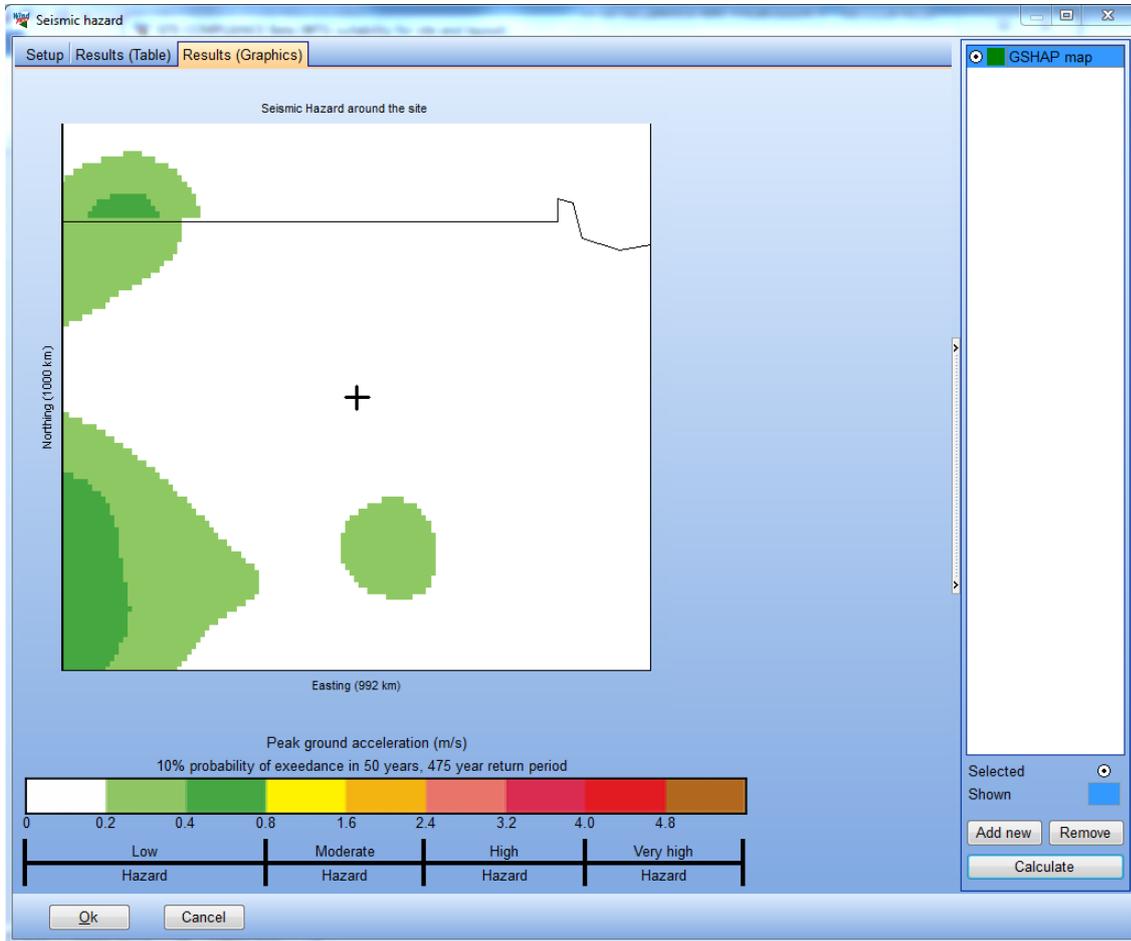
Figure 63. Results (Graphics) tab of the Seismic hazard check.

13.4.2 Temperature range

13.4.2.1 Description and limit

Wind turbines are designed for operation within a certain range of temperatures, the operational or *Normal range*. A wind turbine may survive temperatures beyond the operational range, but will cease operation in order to do so. If temperatures exceed the so-called *Extreme range* or survival range components within the wind turbine may suffer permanent damage.

The *Normal range* for the IEC standard class WTGs is: -10°C to +40°C.
The *Extreme range* for the IEC standard class WTGs is: -20°C to +50°C.

Most manufacturers produce high- or low-temperature versions of their WTG models with extended normal and extreme ranges for specific markets. Such models are categorized as Class S WTGs. The temperature range is typically extended by around 10°C at the high or low end of the ranges noted above in Class S versions. Calculations for customized Class S temperature ranges are supported by SITE COMPLIANCE and described below.

13.4.2.2 Setup, Calculation and Results

On the *Setup* tab of the Temperature range check there are two setup groups; *Select data and fit* and *Temperature design limits*. In the former group a mast with temperature measurements must be selected. In the latter group the fit option must be selected as either *Full gaussian* or *Tail gaussian*, deciding whether to fit the full the range of measurements or just the high and low tails, respectively. If the *Tail gaussian* option is selected the tail fraction may adjusted. By default the highest and lowest 10% of the samples are fitted in this option.
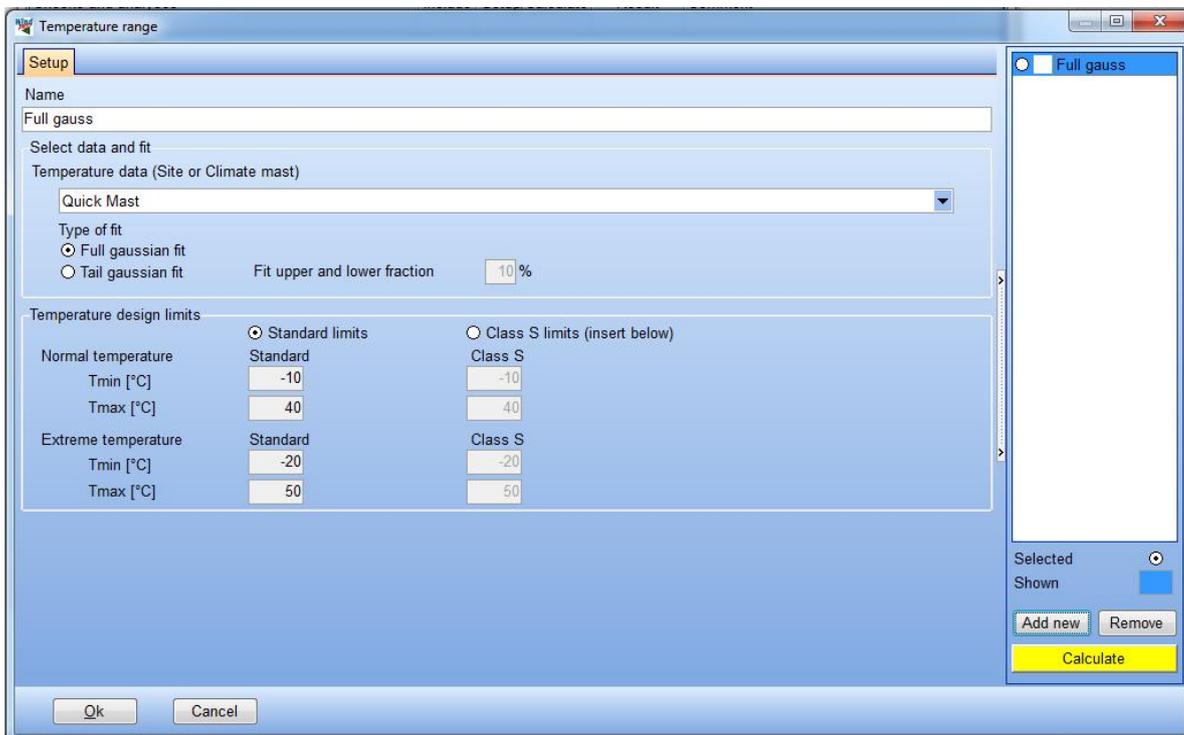
Figure 64. Setup tab of the Temperature range check.

Once the calculation has been performed by clicking the yellow "Calculate" button, the results tabs appear. The *Base data* tab summarizes the chosen temperature measurements and the mast details as well as the mean WTG HH above sea level which is used to estimate a single result for entire site.
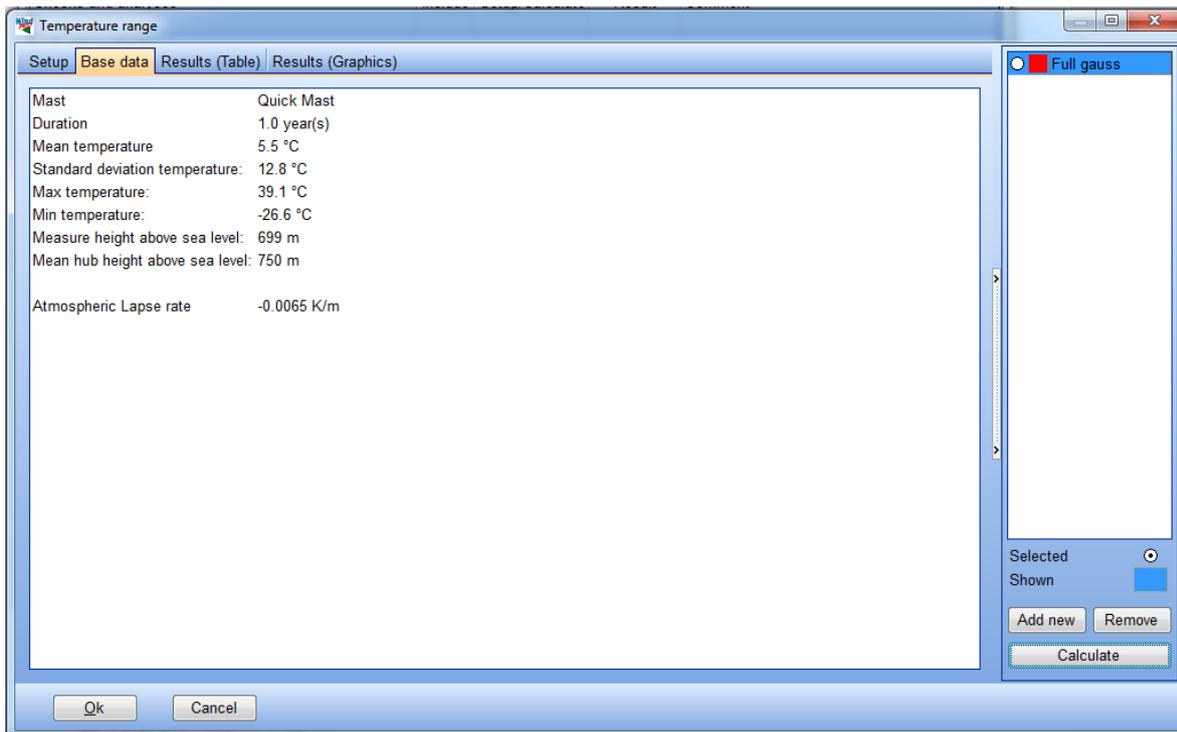
Figure 65. Base data tab of the Temperature range check.

The *Results (Table)* lists the chosen limits for the normal and extreme temperature ranges. In the table the column labelled "hours < Tmin [h/year]" shows the estimated hours below the normal and extreme low limits. The column labelled "hours > Tmax [h/year]" shows the hours above the normal and extreme high limits. The total result is the estimated sum of hours outside the two ranges shown in the rightmost column.
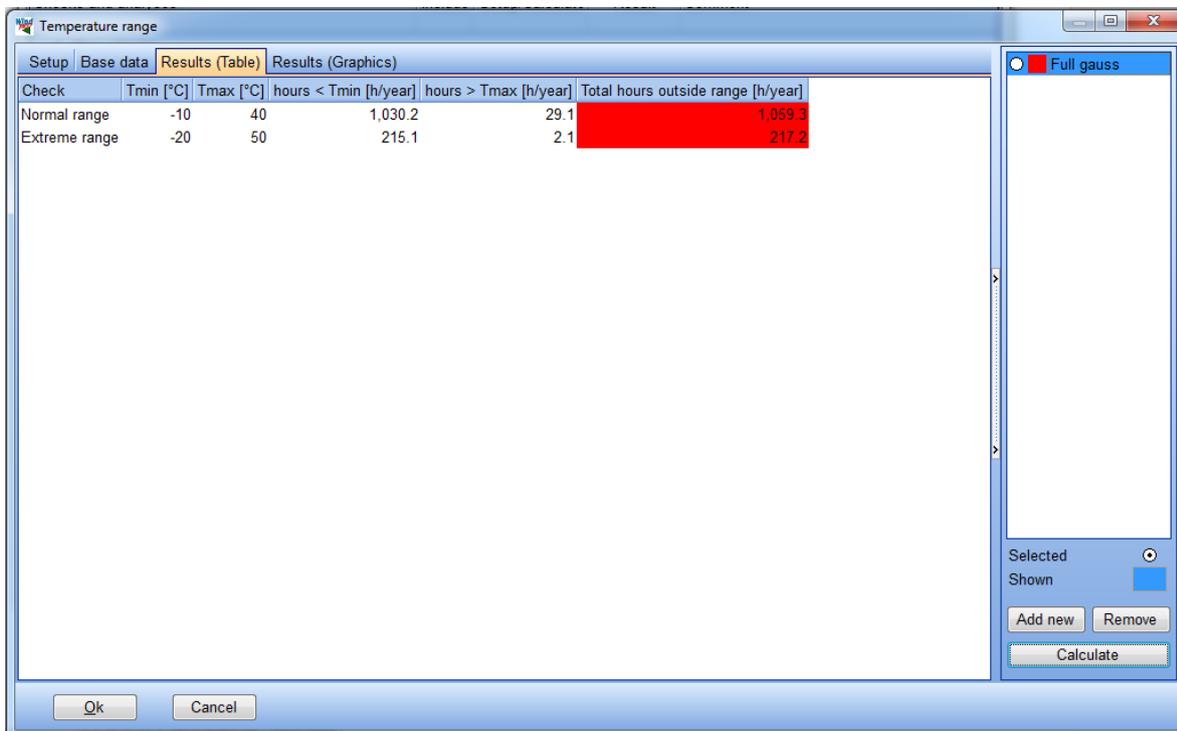
Figure 66. Results (Table) tab of the Temperature range check.

On the *Results (Graphics)* tab, the measurements and the fits are presented. In the upper (larger) plot the cumulative sample distribution is shown with the normal and extreme ranges indicated using the vertical red lines. If the Full Gaussian fit was chosen in the setup this fit is also illustrated in the plot as the blue curve.

The two lower plots illustrate the upper and lower quartiles (25%) of the samples, respectively. The frequency of occurrence axis (y-axis) has been transformed to illustrate directly the hours below (left graph) or above (right graph) the temperatures on the x-axis. The fit(s) are also illustrated in both these plots. The hours below or above the normal and extreme limits may be read directly at the y-axis besides the crossing points where the fit(s) cross the vertical red lines.
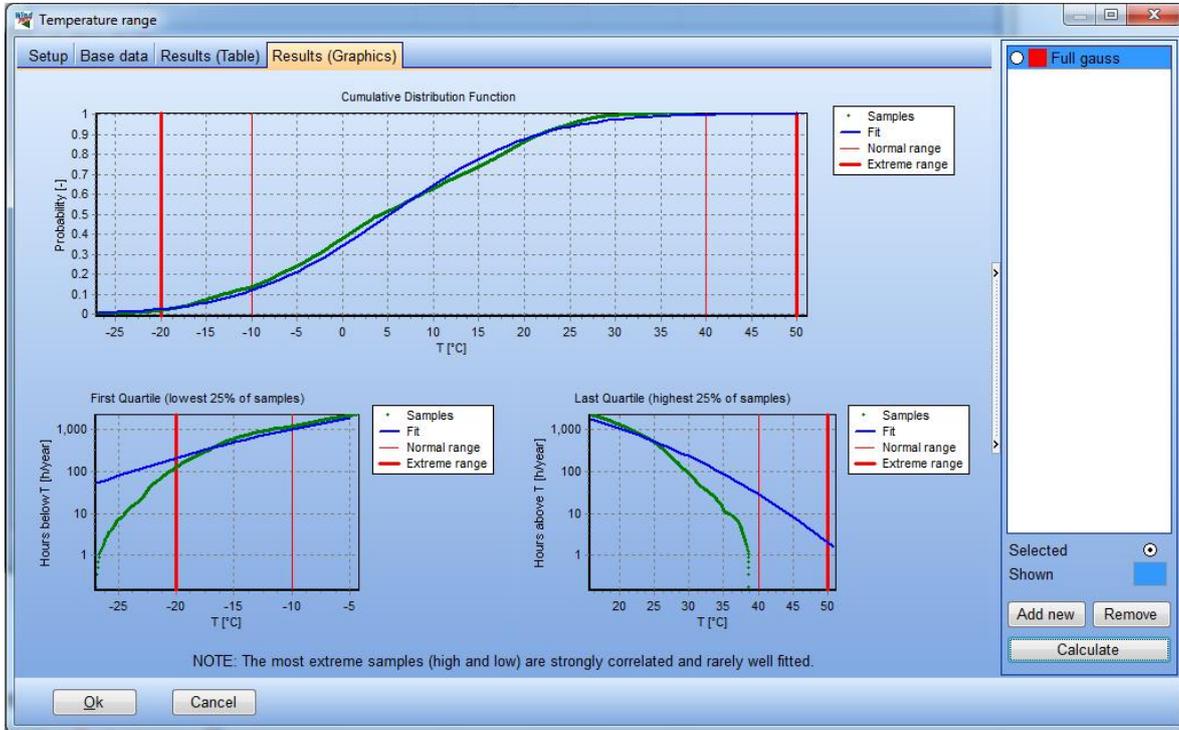
Figure 67. Results (Graphics) tab of the Temperature check.

13.4.2.2 Calculation options

The calculation options of the Temperature range check are described in the following.

Select data and fit

A Site or Climate mast with temperature data may be chosen in the setup as illustrated below. The SYNOP stations are often a good alternative if no on-site data are available. Users should make sure that the mast elevation above sea level is properly defined in the properties of the Meteo object as this may strongly influence the results. Usually the the mast evelation may be read from the header lines of the data files in the Meteo object.
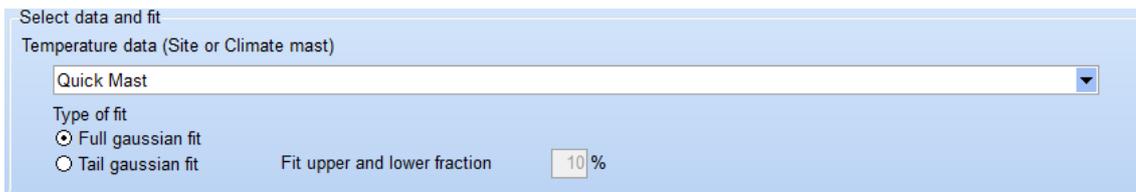
Figure 68. Setup details of data source and fit for Temperature range check.

Full Gaussian fit

Selecting this option fits the full sample distribution using a Gaussian relationship, which has the same mean and standard deviation as the samples. This method is very robust but for many sites the fit is not always satisfactory which is clearly visible from the graphs.

Tail Gaussian fit

This option fits separate Gaussian distributions to the low tail and to the high tail ranges with the default "tail range" set to fit the lowest 10% and the highest 10% of the samples. The fits are performed using the so-called Normal probability plots of the ordered samples against the theoretical Gaussian quantiles, but only fitting the relevant tail range.

Temperature design limits

The figure below illustrates the setup of the *Temperature design limits*.

Figure 69. Setup of Temperature design limits in the Temperature range check.

Standard limits

The default option *Standard limits* is used for standard class WTGs or in initial screenings of the Temperature range check. Note that some manufacturers such as Vestas have extended the temperature range on all their standard WTG models to e.g. -20°C for the *Normal range* minimum temperature. Such models should be calculated using *Class S limits* for temperature range although the WTG model is not a special high- or low-temperature version.

Class S limits

The *Class S limits* option should be selected and *Normal* and *Extreme* temperature ranges adjusted appropriately if the WTG model in question is known to be a low- or high-temperature version. This option is also appropriate if perhaps a Temperature range calculation was initially performed for the standard limits, but resulted in a Critical exceedance. In such cases it is necessary to explore which temperature limits would then be needed/acceptable. Usually, the special high- or low-temperature versions have *Normal* and *Extreme* limits which are extended by 10°C or 20°C, to e.g. -30°C and -40°C for a low-temperature version.

13.4.3 Lightning rate

13.4.3.1 Description and limit

The estimation of Lightning rate in SITE COMPLIANCE is based on a data base established by the NASA Global Hydrology and Climate Center (GHCC) [17]. Data were collected using two kinds of satellite detectors LIS (Lightning Imaging Sensor) and OTD (Optical Transient Detector).

The IEC standard does not specify a specific limit for the lightning rate.

13.4.2.2 Setup, Calculation and Results

No alternatives are available in the setup of the Lightning rate check.
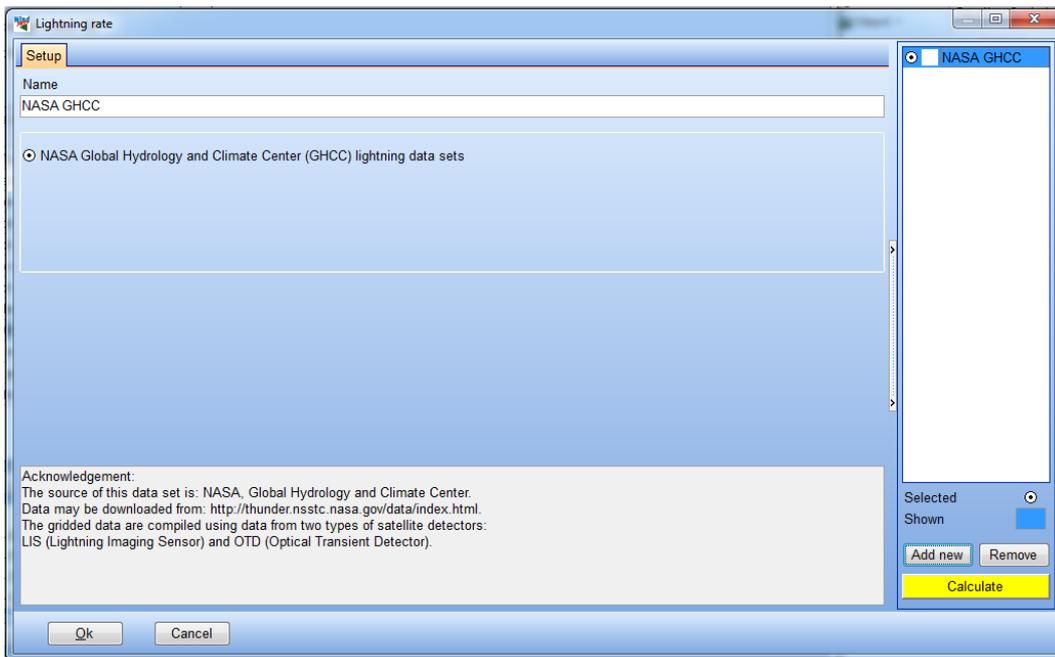
Figure 70. Setup tab of the Lightning rate check.

The Results (Table) provides the expected lightning rate for the site.
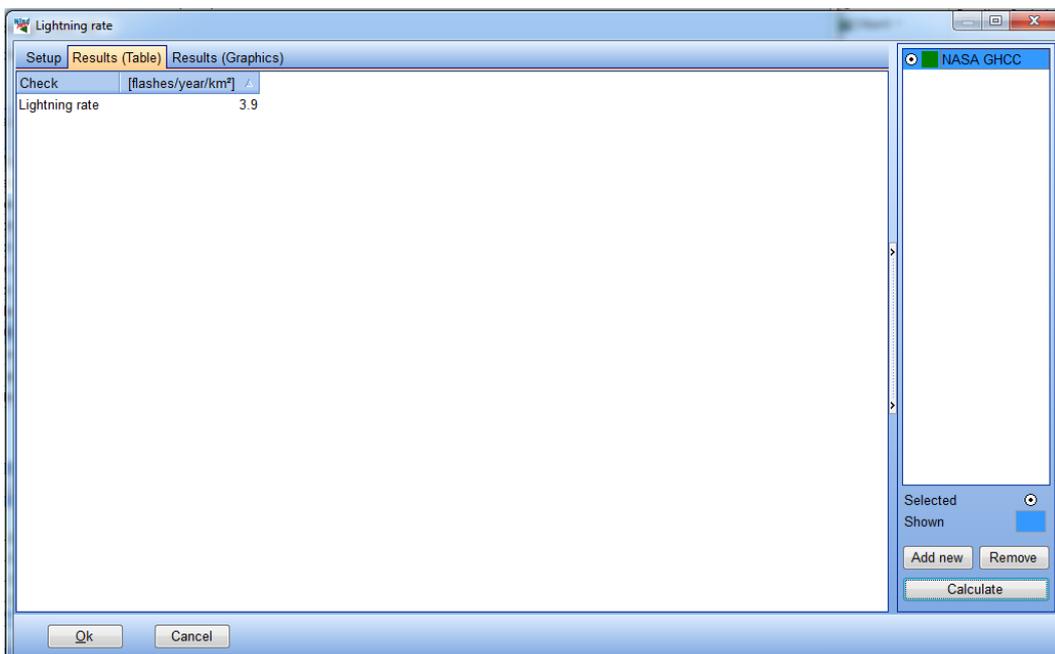
Figure 71. Results (Table) tab of the Lightning rate check.
The last tab *Results (Graphics)* illustrates the lightning rate in a ca. 1000km by 1000km square centered on the site.
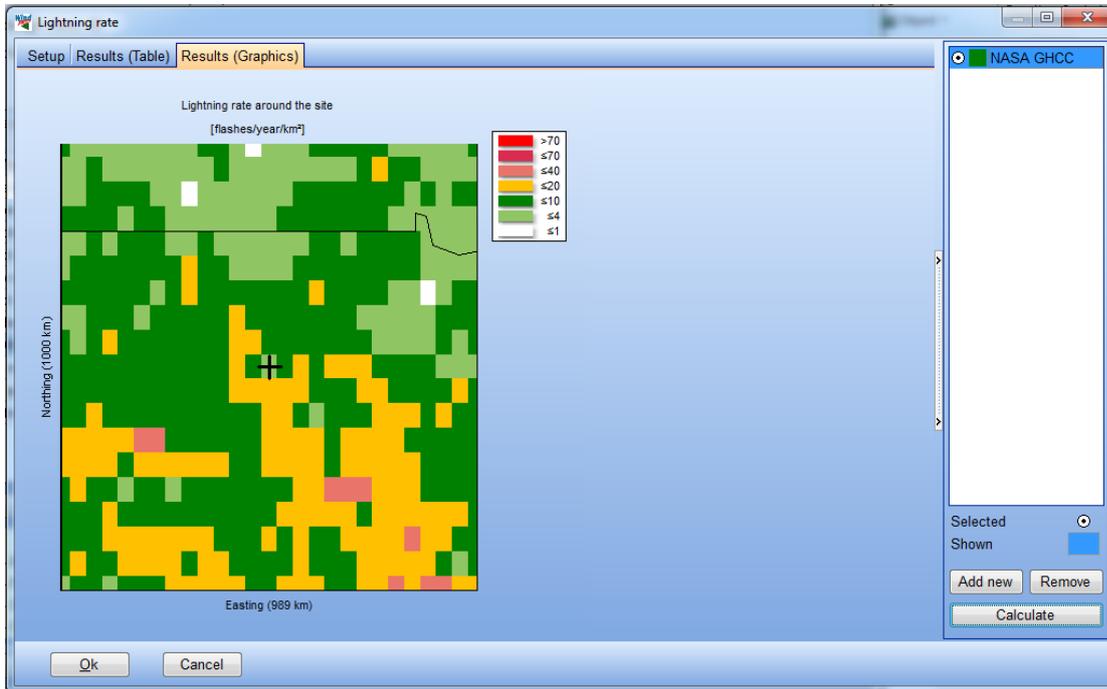
Figure 72. Results (Graphics) tab of the Lightning rate check.

13.5 (Re)calculate all

Once a complete SITE COMPLIANCE calculation has been setup and each included calculation is performed it is time to assess the overall results. In the case shown below design class IIIB is checked for a site. Most checks came out as *OK*, two checks got the result *Caution,* and one check (Wind distribution) ended in the category *Critical*.

To check another design class for the site is very easy and fast in SITE COMPLIANCE. Just go back to the *Main* tab and change the design class to e.g. a higher wind speed class e.g. class IB or IIB instead of IIIB.
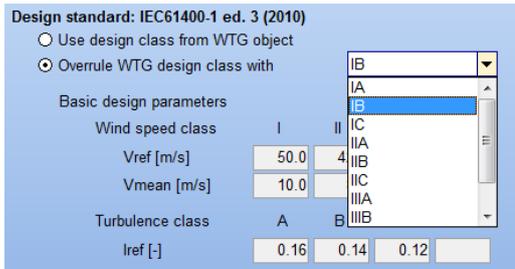
Figure 73. Part of the Main tab where design class is set.

Back on the *Calculations* tab all results will be cleared as one of the basic settings has been changed. To recalculate all included checks simply click the *(Re)calculate all* button. This will recalculate all calculations included for each check and update the visual results accordingly.
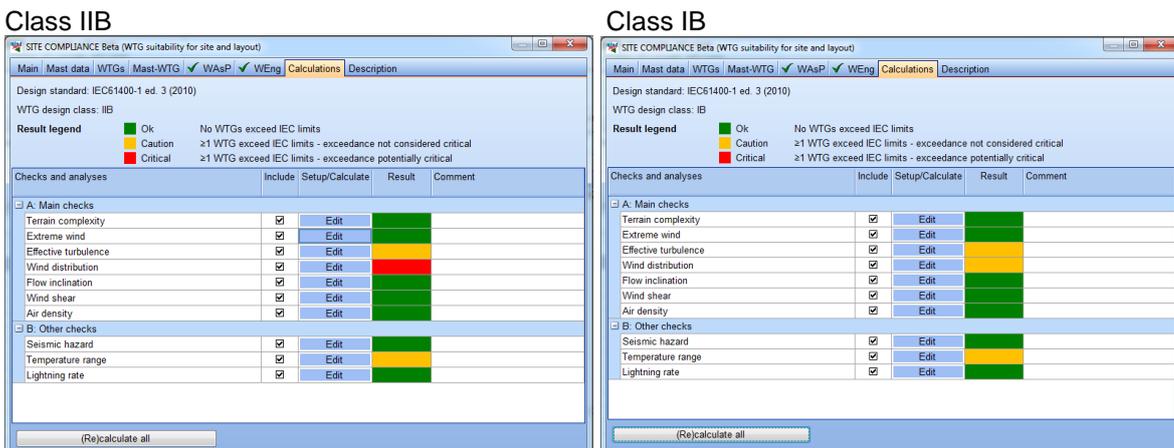
Figure 74. Left: Calculation and overall result for the initial design class IIB. Right: Re-calculation for the design class IB.

Note that SITE COMPLIANCE does not include a full load calculation of the calculated IEC checks for a site as this requires a full aeroelastic model of the WTG, and such details are not released publicly by the turbine manufacturers. As a consequence the complex trade-off between exceeded checks and checks with a buffer cannot fully be modelled. In addition only the manufacturers know the load margins (surplus "strength") in the various WTG components, hence SITE COMPLIANCE does not include this information.

To compensate for the lack of all these aeroelastic details and load margins SITE COMPLIANCE
SITE COMPLIANCE has the yellow category

13.6 Exports and Result-to-file

All result tables inside each of the SITE COMPLIANCE check calculations may be copied and pasted to e.g. Excel. The figure below
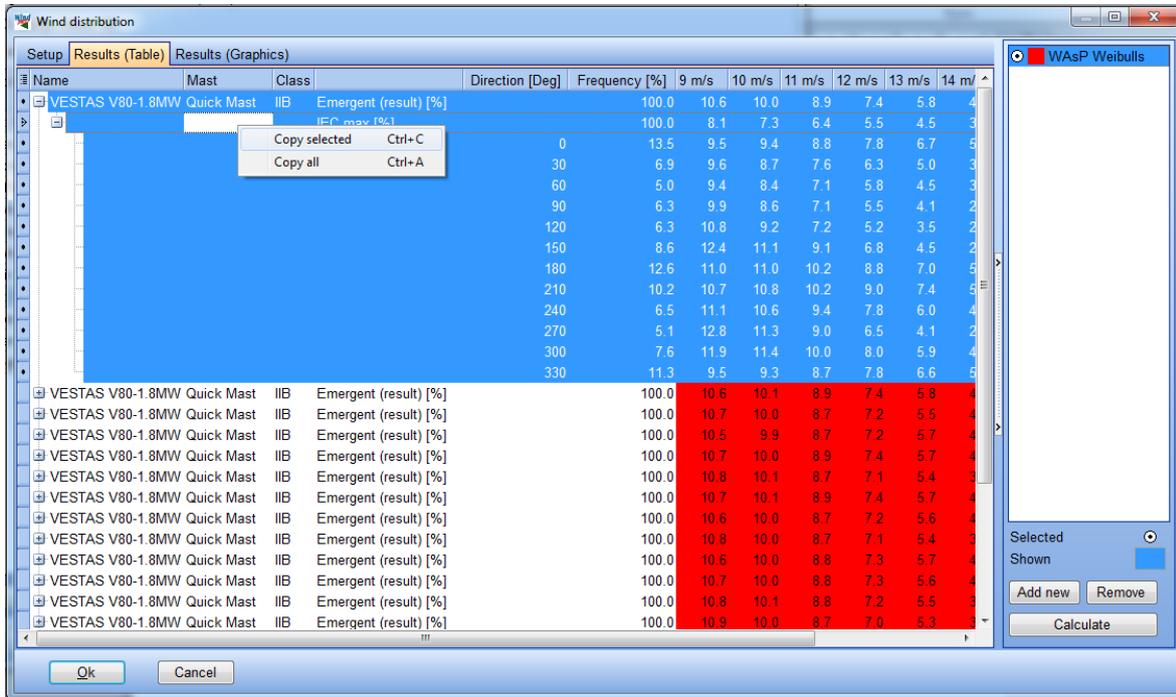
Figure 75. Example of copying data from the results table of a check. Notice the options to copy only the selected part or to copy all of the table including all expandable levels.

Another way of exporting results and data from the module is available once a calculation is completed and closed by clicking OK. The user may right click on the SITE COMPLIANCE calculation and select the Result-to-file option. This action results in a list of the export options available (see below). Two of the available options summarize the flow results of the WAsP and WAsP Engineering calculations (if performed). The other two options are:

1) Summary export of the WTG-wise results of all the calculations and
2) Export of the mast statistics including basic check results at the mast position.

Options 1 and 2 may be used to fill the typical "first check" requirements for climatic site data by required by most manufacturers.

Both exports include information indicating the quality of the measurements and the estimation methods used in the calculation of the checks.
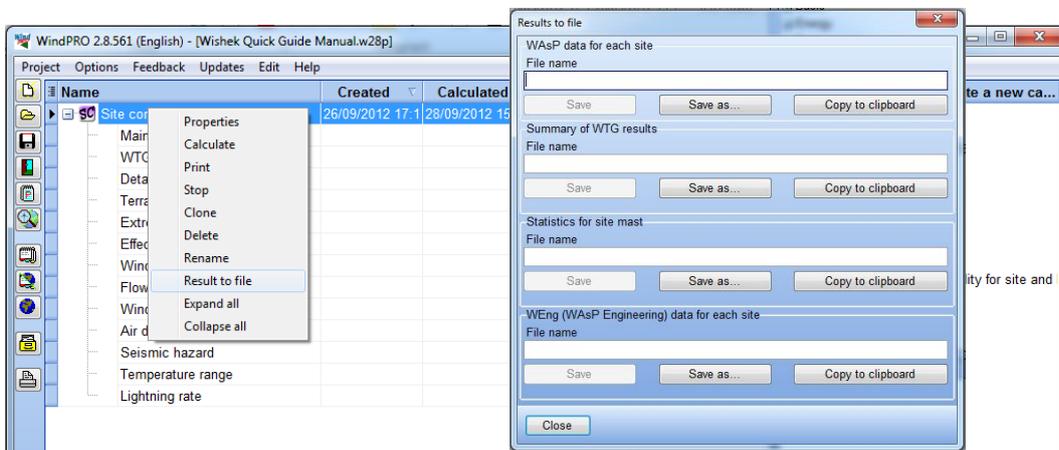
Figure 76. Result-to-file menu is accessed via right clicking on the calculation.

13.7 Reports and printing

13.7.1 Main result

Site compliance Beta - Main result
Calculation: Manual

Summary of data / calculations

Design standard	IEC61400-1 ed. 3 (2010)
Total new WTGs	20
WTG class IB	Overrule all
Hub height	70.0 m
Site masts	1
Quick Mast	40m, 1year(s), 100%recov
WAsP calculation	WAsP 10.2
	Long-term corrected wind statistics
	Defaults used
WEng calculation	Wasp Engineering 3
	Defaults used
Checks performed	7 of 7 Main checks
	3 of 3 Other checks
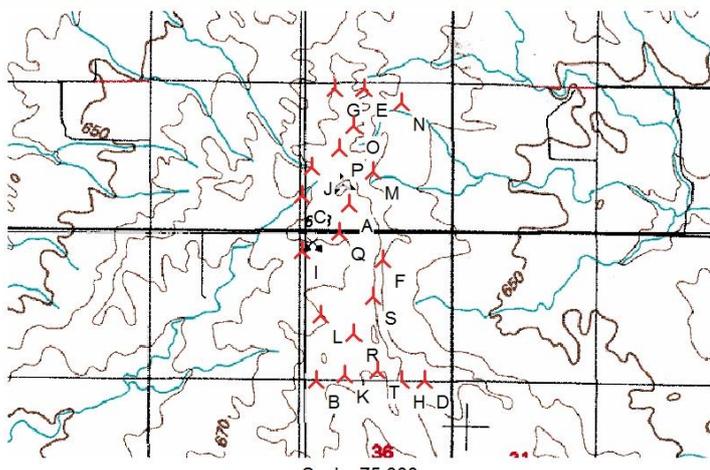
Scale: 75,000

Main result

Main checks

Terrain complexity	OK
Extreme wind	OK
Effective turbulence	*Caution*
Wind distribution	*Caution*
Flow inclination	OK
Wind shear	OK
Air density	OK

Other checks

Seismic hazard	OK
Temperature range	*Caution*
Lightning rate	OK

Result details

			WTG class	Method	Quality	WTG Mean	Max WTG	Min WTG	WTGs OK	WTGs Caution	WTGs Critical
Main checks											
Terrain complexity	ic	[-]		Active DEM		0.00	0.00	0.00	20	*0*	0
Extreme wind	u50y	[m/s]	IB	POT-N	B+A	34.1	35.0	31.9	20	*0*	0
Effective turbulence	σeff(u)*	[-]	IB	Mast	A+A	-	-	-	18	*2*	0
Wind distribution	pdf(u)*	[-]	IB	WAsP Weibulls	A	-	-	-	0	*20*	0
Flow inclination	φmax	[°]		WEng	B	1	3	0	20	*0*	0
Wind shear	α	[-]		Mast WEng	A	0.17	0.18	0.16	20	*0*	0
Air density	ρ	[kg/m³]		Mast	A/B	1.158	1.160	1.157	20	*0*	0
Other checks											
Seismic hazard	PGA	[m/s²]		GSHAP map		0.1	-	-			
Temperature range											
Normal range, hours outside		[h/year]	S	Tail gauss		*106.6*	-	-			
Extreme range, hours outside		[h/year]	S	Tail gauss		*0.9*	-	-			
Lightning rate		[flashes/km²/year]		NASA GHCC		3.9	-	-			

* Parameter checked for a range of windspeeds (u), a single summary value is not possible.

Figure 77. The main page of the report high lights the conclusion of the site assessment and gives an overview of the results on a park level in the table.

13.7.2 WTG results

Site compliance Beta - WTG results
Calculation: Manual

Main checks - WTGs

Criteria	Masts		Site data	
Critical	1	Quick Mast	A	Site data for WAsP
Caution				
OK				

WTG-name	Class	Mast	Site data	Terrain complexity [-]	Extreme wind [m/s]	Effective turbulence [-]	Wind distribution [-]	Flow inclination [°]	Wind shear [-]	Air density [kg/m³]	Total
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (56)	IB	1	A	0.0	34.2	OK	Caution	1	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (57)	IB	1	A	0.0	34.7	OK	Caution	0	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (58)	IB	1	A	0.0	34.0	OK	Caution	1	0.17	1.158	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (59)	IB	1	A	0.0	35.0	OK	Caution	0	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (60)	IB	1	A	0.0	34.7	OK	Caution	1	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (61)	IB	1	A	0.0	33.7	OK	Caution	3	0.18	1.158	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (62)	IB	1	A	0.0	34.2	OK	Caution	1	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (63)	IB	1	A	0.0	34.4	Caution	Caution	1	0.17	1.158	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (64)	IB	1	A	0.0	33.5	OK	Caution	1	0.17	1.158	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (65)	IB	1	A	0.0	34.8	OK	Caution	1	0.17	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (66)	IB	1	A	0.0	34.4	OK	Caution	1	0.17	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (67)	IB	1	A	0.0	33.8	OK	Caution	1	0.17	1.158	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (68)	IB	1	A	0.0	33.4	OK	Caution	2	0.18	1.158	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (69)	IB	1	A	0.0	34.2	OK	Caution	1	0.17	1.159	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (70)	IB	1	A	0.0	34.3	OK	Caution	2	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (71)	IB	1	A	0.0	34.4	OK	Caution	1	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (72)	IB	1	A	0.0	33.9	OK	Caution	1	0.17	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (73)	IB	1	A	0.0	34.3	OK	Caution	0	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (74)	IB	1	A	0.0	33.6	OK	Caution	3	0.16	1.157	Caution
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (75)	IB	1	A	0.0	34.2	Caution	Caution	1	0.17	1.157	Caution

WindPRO is developed by EMD International A/S, Niels Jernesvej 10, DK-9220 Aalborg Ø, Tel. +45 96 35 44 44, Fax +45 96 35 44 46, e-mail: windpro@emd.dk

Figure 78. Second report page summarizing the results of all the main checks (columns) for each WTG (rows).

13.7.3 Details and Assumptions

Site compliance Beta - Details & Assumptions
Calculation: Manual

General details, WTG results

		WTG Mean	Min WTG	Max WTG
u50y (extreme wind)	[m/s]	34.1	31.9	35.0
Mean wind speed	[m/s]	9.0	8.8	9.1
k-parameter ('combined Weibull')	[-]	2.7	2.7	2.7
I15 (mean TI@15 m/s)	[-]	0.11	0.10	0.12

Design parameters IEC classes

		Class IB
Vref (extreme wind)	[m/s]	50.0
Mean wind speed	[m/s]	10.0
k-parameter	[-]	2.0
Iref (mean TI@15m/s)	[-]	0.14

Mast data

Name	Purpose	Main height [m]	Shear heights [m]	Duration [year(s)]	Recovery [%]	Additional signals	Site data
MERRA	Long term reference	50.0		30.3	99.9		
Quick Mast	Site mast	40.0	40.0,30.0,10.0	1.0	100.0	TI,T	Site data for WAsP

WAsP parameters

WAsP 10.2
Default WAsP parameters used
Site data
   Site data for WAsP

WAsP Engineering parameters

Wasp Engineering 3	
Sectors	12
Reduced geostrophic	h=10m, z0=0.05m, u=20m/s
Domain	Buffer: 5000m, Resoluton: 50m, Points N-S: 263, Points E-W: 226
Turbulence model	Kaimal
Site data	Site data for WAsP

Long term correction

Long corrected wind statistics used in WAsP

Figure 79. The Details and assumptions page which summarizes the most important of the general assumptions in the setup of SITE COMPLIANCE.

13.7.4 Detailed results and setup (available for each check)

For each of the checks included and calculated a separate detailed report is available. The detailed report for each check summarizes the selected method, the available methods for that check and the results in a graphical and tabular format. Below is shown the detailed report (two pages) for the Extreme wind check.

Site compliance Beta - Extreme wind
Calculation: Manual

Result: OK

Check setup

Method used	POT-N_WEng	(Quality: B+A)	
Method details			
	Statistical model	POT-N & Gumbel	N = 20, Δt = 4 days
	Propagation model	WEng (sector-wise mast-to-wtg speedup)	
Methods available			
	Statistical model	Propagation model	Additional settings
	POT-N (B)	WEng (sector-wise mast-to-wtg speedup) (A)	Air density correction
	Weibull (C)	WAsP (sector-wise speedup) (B)	Long-term index correction
	Risø (C)	Shear (sector-wise vertical extrapolation only) (C)	k-factor preconditioning
	Eurocode (-)	No model (mast assumed representative) (C)	3s gust estimate
User comment			

IEC limits

IEC class	Max extreme wind (Vref) [m/s]
IB	50.0

Results (Graphics)

u50y

Legend: IEC limit (Vref) ● Critical ● Caution ● OK

Results (Table)

WTG	Class	Mast	Site data object	u50y [m/s]
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (56)	IB	1	A	34.2
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (57)	IB	1	A	34.7
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (58)	IB	1	A	34.0
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (59)	IB	1	A	35.0
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (60)	IB	1	A	34.7
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (61)	IB	1	A	33.7
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (62)	IB	1	A	34.2
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (63)	IB	1	A	34.4
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (64)	IB	1	A	33.5
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (65)	IB	1	A	34.8
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (66)	IB	1	A	34.4
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (67)	IB	1	A	33.8
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (68)	IB	1	A	33.4
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (69)	IB	1	A	34.2

To be continued on next page...

WindPRO is developed by EMD International A/S, Niels Jernesvej 10, DK-9220 Aalborg Ø, Tel. +45 96 35 44 44, Fax +45 96 35 44 46, e-mail: windpro@emd.dk

Figure 80. First page of the Extreme windspeed check.

Site compliance Beta - Extreme wind
Calculation: Manual

...continued from previous page

WTG	Class	Mast	Site data object	u50y [m/s]
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (70)	IB	1	A	34.3
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (71)	IB	1	A	34.4
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (72)	IB	1	A	33.9
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (73)	IB	1	A	34.3
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (74)	IB	1	A	33.6
VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (75)	IB	1	A	34.2
				31.9

Gumbel fit

VESTAS V80-1.8MW 60Hz 1800 80.0 !O! hub: 70.0 m (TOT: 110.0 m) (59)

Mast: Quick Mast
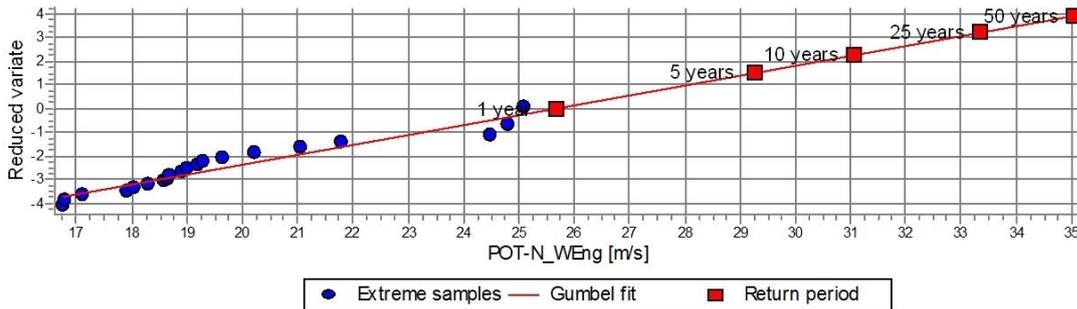
Extracted data

Quick Mast
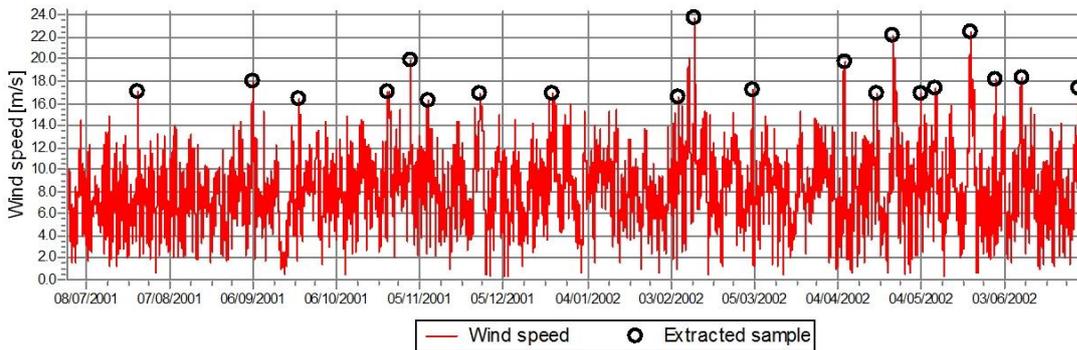
Figure 81. Second page of the Extreme windspeed check.

The remaining checks are reported in a similar way but are not reproduced in this manual.

13.8 References

[1] IEC 61400-1 ed. 3, 2005, Wind turbines – Part 1: Design requirements.

[2] IEC 61400-1 ed. 3, 2010, Amendment 1.

[3] Gumbel, E., 1958, Statistics of Extremes, Columbia University Press.

[4] Abild, J., Andersen, E. Y. and Rosbjerg, D., 1992, The Climate of Extreme Winds at the Great Belt, Denmark, *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 41-4, p. 521-532.

[5] Cook, N., 1982, Towards better estimation of extreme events, *Journal of Wind Engineering and Industrial* Aerodynamics, vol. 9, p. 295-323.

[6] Makkonen, L., 2007, Problems in the extreme value analysis, *Structural Safety*, vol. 30, p. 405-419.

[7] Winklaar, D. (ed.), 1998, *European Wind Turbine Standards II, part I: Load Spectra and Extreme Wind Conditions.*

[8] Bergström, H., 1992, DISTRIBUTION OF EXTREME WIND SPEED, *Wind Energy Report WE 92:3*, Department of Meteorology, Uppsala University.

[9] Larsén, X. G. and Mann, J. 2009, Extreme winds from the NCEP/NCAR reanalysis data. *Wind Energy*, vol 12, p556-573. DOI: 10.1002/we.318.

[10] Svenningsen, L. et al., 2010, An Index-like correction to reduce uncertainty of extreme wind estimates from short-term data, Proceedings of the European Wind Energy Conference.
http://ewec2010proceedings.info/proceedings/index2test.php?page=info2&id=6&id2=326&ordre=19&tr=&searchin=&what=&searchtext=&day=1&top=&fil1=&fil2=&fil2&ord1=&sess=

[11] Unpublished Monte Carlo study of extreme wind estimation presented at Vindkraftnet meeting at Risø/DTU 2010.

[12] Cook, N. J., 1990, The Designer's Guide to Wind Loading of Building Structures, Butterworths. (Book)

[13] Frandsen, S. T., 2007, Turbulence and turbulence generated loading in wind turbine clusters, Risø report R-1188.

[14] Nielsen, M., WAT tool Help file, 2011, Risø/DTU.

[15] Nielsen, M., Jørgensen, H. E. and Frandsen, S. T., 2009, Wind and wake models for IEC 61400-1 site assessment, Proceedings of the European Wind Energy Conference (EWEC 2009).l

[16] Giardini, D., Grünthal, G., Shedlock, K. M. and Zhang, P., 2003, The GSHAP Global Seismic Hazard Map. In: Lee, W., Kanamori, H., Jennings, P. and Kisslinger, C. (eds.): International Handbook of Earthquake & Engineering Seismology, International Geophysics Series 81 B, Academic Press, Amsterdam, 1233-1239.

[17] NASA, Global Hydrology and Climate Center. http://thunder.nsstc.nasa.gov/data/index.html.

[18] Troen, I. and Petersen, E. L., 1989, European Wind Atlas, Risø National Laboratory. (Book)

Appendix I - Gumbel's Theory of Extremes and more

Emil J. Gumbel's model of extremes published in "Statistics of Extremes" [3] in 1958 is the classical standard model for describing the statistics of extreme events. The model is also called Fisher-Tippett Type 1 asymptote or Generalized Extreme Value model (GEV) type 1. The Gumbel model describes the distribution function of annual extremes, i.e. the cumulative probability, G(u), that a yearly maximum wind speed of u is <u>not</u> exceeded and takes the form:

$$G(u) = e^{-e^{-(u-\beta)/\alpha}}$$

Where the parameters β and α, are called mode and dispersion or sometimes location and scale.

There is a simple relation between the Gumbel distribution of annual extremes and the cumulative mean distribution of all wind speeds samples, F(u). The mean distribution, also called the parent distribution, is typically assumed to be Weibull. The simple relation states that the probability that a given extreme wind speed is the largest among N samples is given as the cumulative parent distribution multiplied by itself N times. For large N the exact distribution of annual extremes converges asymptotically to the Gumbel distribution:

$$G(u) = e^{-e^{-(u-\beta)/\alpha}} \approx F(u)^N$$

The error of using the Gumbel asymptote is related to the number of independent samples in a year as well as the k-parameter of the Weibull parent distribution (i.e. the tail behaviour). For lower k-parameters the rate of convergence (i.e. more accurate already for small N) is much faster than for higher k-factors. It is also important to note that all N samples are assumed to be independent, i.e. not correlated. In real life this is not the case for all 10-minute or hourly wind speed samples in a year. The demand for independence leads to considerable complexity. Thus, usually the Gumbel distribution is not estimated from the parent distribution, but rather, directly from extracted extreme samples of the time series and then combining these with theoretical estimates of the cumulative probability of non-exceedance ($P_i \approx G(u_i)$) called "plotting positions". A Gumbel distribution is then fitted to (u_i, P_i) to obtain the Gumbel distribution parameters, α and β.

In the original Gumbel approach the annual maximum samples (u_i) are extracted for each year of an N year time series. These extreme samples are then ranked (i) smallest to largest (i equals 1 to N) and attributed the plotting positions, P_i, the theoretical estimates of the cumulative distribution function, approximating the probability that the annual maximum wind speed u_i is <u>not</u> exceeded. Several formulas for plotting positions have been suggested. The original Gumbel formula is:

$$P_{i,Classic} = \frac{i}{N+1} \approx G(u_i)$$

which in fact was introduced by Weibull (Makkonen, 2004) [6].

An alternative plotting position is due to Hazen (Makkonen, 2004) [6], which is used in the extreme wind plots in for example, most Risø/DTU software (e.g. WAsP Engineering):

$$P_{i,Hazen} = \frac{i-0.5}{N}$$

The extreme wind speed samples, u_i, are then plotted on the x-axis versus a transform of the chosen P-values, called the reduced variate, y:

$$y_i = -\ln(-\ln(P_i))$$

With this transform the Gumbel asymptote takes a very convenient linear form:

$$y = -\ln\left(-\ln\left(G(u)\right)\right) = au+b = \frac{1}{\alpha}u - \frac{\beta}{\alpha}$$

Thus, a linear fit to a plot of (u_i, y_i) provides the parameters of the Gumbel distribution.

The IEC design criterion for extreme wind speed is a 50-year event, where "50" is referred to as the return period. In other words the design criterion is the wind speed that is expected to occur only once in 50 years. The return period is related to the annual risk of exceedance (R) via:

$$R(u_T) = 1 - G(u_T) = \frac{1}{T}$$

Thus, for T=50 years the annual risk of exceedance is R=2%, which is a much more stringent and basic definition of the design criterion than "50 years return period".

Once the Gumbel parameters, α and β, have been obtained from a linear fit to (u_i, y_i) the extreme wind estimate for T=50 years (i.e. R=2%) may be obtained from:

$$u(T) = \alpha y(T) + \beta = \alpha(-\ln\left(-\ln\left(1 - \frac{1}{T}\right)\right)) + \beta$$

Where y(T=50) equals 3.9. Thus, to obtain the estimate of the 50-year wind speed, the linear Gumbel fit of (u_i, y_i) must be extrapolated to y=3.9.

Implicit assumptions in the choice of "plotting positions"
The plotting position associated to each of the extracted extremes is a theoretical estimate of the annual probability that this wind speed is not exceeded. As such this probability also implies an assumption of the return period of the highest of the extracted wind speeds.

For the classical Gumbel plotting position the max wind speed extracted is assumed to have a return period of:

$$T_{max} = \frac{1}{1 - P_{max}} = \frac{1}{1 - \frac{N}{N+1}} = N + 1$$

Using the Hazen plotting positions the same max wind speed is assumed to have the return period:

$$T_{max} = \frac{1}{1 - P_{max}} = \frac{1}{1 - \frac{N-0.5}{N}} = 2N$$

As example with 10 years of data (i.e. N=10) employing the classical Gumbel plotting positions relies on the assumption that the overall maximum wind speed recording has a return period of 11 years. For the Hazen plotting positions the assumed return period is 20 years. A more extreme example is a time series of 25 years. Using the Hazen estimates assumes the max recording to have a return period of 50 years. Thus, it is obvious that the Hazen plotting positions are much less conservative than those of the classical Gumbel method.

Extreme wind speed estimate at return period 1 year
The IEC standard also mentions that the extreme wind speed for T=1 year must be estimated although it is not used directly in the extreme wind check. However, the exact expression above for y(T) is not defined for T=1 year. Instead the most likely extreme to encounter any given year is usually chosen as the most appropriate estimate; this value equals the *mode* of the Gumbel distribution, i.e. the parameter β from the linear fit (which does not exactly equal the mean as the distribution is not symmetric). So we employ the definition of the extreme wind estimate with return period of 1 year as:

$$u(T = 1) \equiv \beta$$

This definition is consistent with the equation derived using a Poisson process (see for example, [4]).

Fitting the Gumbel asymptote
The linear fit to (u_i, y_i) described above represents is the basis of Gumbel's asymptotic model of extremes. However, this linear fit may be performed in various ways. Firstly it is worth noting that the fit is performed on (u_i, y_i), i.e. with the reduced variate as the dependent variable. The reason for this is the implicit assumption in the standard least-squares fitting routine that the dependent variable (here, y) has much higher uncertainty than the independent one (u). The argument is that the wind speeds are measured using high quality equipment whereas y (reduced variate) is a transform of a theoretical estimate of the annual probability of each wind speed not being exceeded, which is associated with considerable uncertainty.

The standard fit is performed using the least-squares method. Monte Carlo simulations (not published) have shown that typically this fit introduces a slight conservative bias.

An alternative fit is done using the Probability Weighted Moments, PWM (Abild, 1992) [4] which only takes the ranked wind speeds as input, and, hence, does not utilize the reduced variate. In this way the PWM fit avoids the main source of method-induced bias. The PWM expressions for the fit parameters to the Gumbel asymptote, scale (α) and location (β) are:

$$\alpha = \frac{2b_1 - b_0}{\ln(2)} \quad \text{and} \quad \beta = b_0 - 0.5772\alpha$$

With estimates of the sample probability weighted moments given as:

$$b_0 = \frac{1}{N}\sum_{i=1}^{N} u_i \quad \text{and} \quad b_1 = \frac{1}{N}\sum_{i=1}^{N}\frac{i-1}{N-1} u_i$$

Monte Carlo simulations (not published) have shown that the PWM fit to the Gumbel asymptote does not introduce a bias in the Gumbel fit. Unfortunately, the PWM fit does not work equally well with all the ways of extracting the extreme samples. It seems that PWM only is only bias-free for the traditional Gumbel approach where only the annual extremes are extracted.

Annual maximum method (AM)

The traditional Gumbel method only extracts the most extreme sample of each year, or from alternatively the most extreme sample of each period of fixed length sub-dividing the time series. Hence, the method is referred to as the Annual Maximum method (AM) or Periodical Maximum method.

The drawback of the AM method is the requirement of relatively long time series for the fit to the Gumbel asymptote to be meaningful. Typically, at least 5-10 years is recommended to constrain the fit parameters reasonably well.

In SITE COMPLIANCE at least 5 years of data are required for the AM method to be available.

Fit
The PWM fit is used with the AM method as it guarantees the least bias in the fitting. Since the PWM fit does not require plotting positions no Gumbel plot is needed. But is used for visual presentation, however.

Peak-Over-Threshold method (POT)

In some applications this method is also referred to as method independent storms. In most applications 5-10 years of on-site measurements are rarely available and within each year there may be more than one significant storm event. Hence a group of extreme wind methods have been developed which utilize more than a single storm from each year. These methods are referred to as Peak-Over-Threshold methods. Storms are typically extracted by defining a high threshold to select only high wind events which exceed this threshold. To ensure that the storm events are statistically independent events a minimum time difference is required between the extracted events, typically a few days. The extracted extreme samples may then be analysed in a way very similar to that of the standard AM Gumbel approach.

Normally, the recommendation for POT methods is given as the number of events to be extracted as 20-50 extremes. This makes the selection of a proper threshold an iterative procedure. As a more efficient way of extracting the extreme samples in SITE COMPLIANCE we have introduced a variation of the POT method which we call POT-N. Instead of defining a threshold the wished number of extremes is defined directly and the program then internally selects the proper threshold to obtain this number of extremes.

As in the AM method the extracted extreme samples are ranked and the "plotting position" (P_i) is attributed to each of the extracted extremes, i.e. the theoretical estimate of the probability of not being exceeded. For POT-N we have decided to use the classical Gumbel plotting positions in SITE COMPLIANCE

Instead of a "storm rate" of just one storm/year as in the AM method the storm rate is λ storms/year in a POT-estimation. Thus, a direct Gumbel fit to the extracted extremes would <u>not</u> yield the distribution of annual extremes, but simply the distribution of the extracted storms. To compensate for this the plotting positions, P_i, may be raised to the λth power provides an estimate of the PDF of the annual extremes (see Cook, 1982 [5]). This transformation is equivalent to a simple shift on the y-axis, i.e. the standard reduced variates are shifted by ln(λ):

$$y_{annual} = y_{storm} - \ln(\lambda)$$

After this transform the POT Gumbel plot is fully equivalent to the AM plot, with $y_{annual} = 3.9$ for T=50 years.

Fit

Our studies have shown that the PWM fit does not work well for the POT method as for the AM, unfortunately. Instead, a linear leat squares fit to the (u,y) is used. The classical Gumbel plotting positions are used as the implicit assumption of return period of the max wind recording seems more sensible than for the Hazen plotting positions.

Weibull parent (EWTS/Bergström) method

The occurrence of high extreme events is closely linked to the tail behaviour of the wind speed distribution. The heavier the tail the more likely are high extreme events to occur. For Weibull distributions commonly adopted in wind energy the shape of the tail is determined by the Weibull shape or k-parameter. A lower k-parameter means a heavier tail and that extreme events are more likely.

This effect has been quantified in the European Wind Turbine Standard (EWTS) that includes a method for extreme wind estimation based on the "Parent"-distribution in this case the Weibull distribution. The method simply assumes a universal number of independent extremes per year (N). The so-called "exact distribution" of the annual maximum is then obtained by raising the Weibull cumulative distribution function to the power of this number, N.

There is an error in the EWTS publication in the number of independent samples which they set to 23037 per year with reference to Bergström (1992) [8]. However, in Bergström (1992) [8] the correct number for 10-minute data is n=2302 independent samples per year, or around every 20th 10-minute sample. For hourly-averaged data the number is 883 or approximately every 10th hourly sample. The error arises due to an exponent of effective frequency which is incorrectly transferred a factor of 10 in EWTS.

The slope and offset of the Gumbel asymptote (for high n) to the "extracted distribution" of annual extremes are given as (Bergström, 1992 [8], EWTS, 1998 [7]):

$$\alpha = \frac{A}{k}[\ln(n)]^{1/k - 1}$$
$$\beta = A[\ln(n)]^{1/k}$$

The difference between the "exact" and Gumbel asymptote is not significant, and working with the Gumbel asymptote allows a fully consistent plotting with the other extreme wind estimation methods.

Omni-directional or sector-wise
The EWTS/Bergström method requires omni-directional Weibull parameters. In the WAsP context Weibull parameters are sector-wise, which is much more realistic and allows for multimodal omni-directional total distribution (several peaks). However, an omni-directional Weibull distribution called "Combined" may be estimated from the sector-wise Weibulls according to the method in the European Wind Atlas [18].

Fit - is the WAsP Weibull fit appropriate for extreme wind estimation?
The WAsP-type Weibull fit, fits exactly the third moment (energy) and frequency above the mean speed of the table data (no power curve or truncation is applied). Thus, the WAsP fit has a very strong emphasis on the tail behaviour. This is in contrast to ordinary least-squares or maximum-likelihood fits, that fit the wind speeds (and not the energy). These fits tend to fit well around the mean where the highest frequencies of occurrence are, at the cost of reproducing the tail behaviour less well. In conclusion, the WAsP Weibull-fit is in fact better than most other fits at reproducing the right tail behaviour, which is of main importance in extreme wind estimation.

Preconditioning

The Gumbel distribution is an asymptotic distribution. As the number of independent (i.e. not correlated) samples in the pool from which the extremes are extracted, e.g. 1 year, approaches infinity, the Gumbel asymptote becomes exact. The accuracy of the asymptotic assumption depends on the number of independent samples but also on the shape of the parent distribution, i.e. the Weibull distribution. For a k-parameter of 1, the convergence is extremely fast and the asymptote practically exact for just few samples. For higher k-factors the convergence is much slower (see Cook, 1982 [8]).

The deviation of the true annual extreme distribution from the Gumbel asymptote is a slight curvature of the extreme samples when plotting the reduced variate, y, on the y-axis versus wind speed on the x-axis. This curvature will be curved downwards (i.e. concave) and generally results in a conservative fit (over-estimation) which is further exaggerated upon extrapolation to high return periods like 50 years (y=3.9) and higher.

A possible solution is to precondition the data before fitting the slope and offset. The wind speeds are transformed so that the parent distribution becomes a Weibull with a k-parameter of 1 for which the convergence is extremely fast and thus the Gumbel approximation always very good (Cook, 1982 [8]). To achieve this, the wind speeds of the extreme samples are simply raised to the power of k, where k is the parent Weibull distribution. Often k=2 is used as a common assumption in wind energy. In addition using k=2 makes the transformed wind speeds proportional to the dynamic pressure, related to the thrust exerted by the wind. However, the real argument for preconditioning is purely statistical and is illustrated in the graphs below.
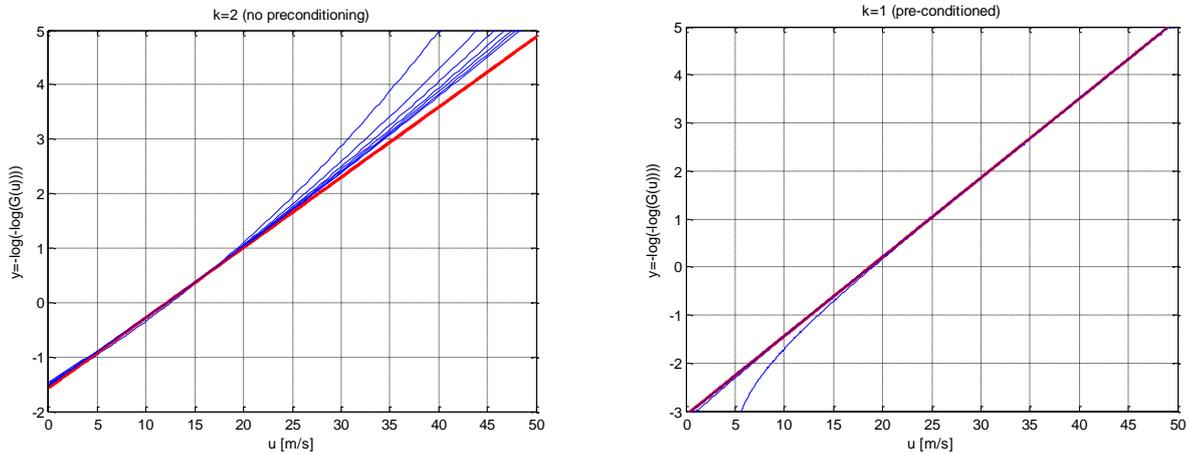
Figure 1. Illustration of the asymptotic nature of the Gumbel model. In the both graphs blue curves show the exact distribution for an annual number of independent samples of $N=10^1$ to 10^7 in steps of 10. Red curves show the Gumbel asymptote assuming N is infinite (hidden behind the blue curves on the right graph).Note that as N increases the blue curves converges to the red. Left graph illustrates the situation for k=2 and the right graph for k=1, which is equivalent to using preconditioning.

Appendix II - Frandsen Effective turbulence model

The following text describes the main assumptions and steps in the implementation of the Frandsen model or Effective turbulence model. Most assumptions are directly specified in the IEC standard [1, 2] or in Frandsens original publication [13].

The Frandsen model [1, 2, 13] defines the so-called effective turbulence as a combination of ambient and wake generated turbulence integrated overall directions in a way that accounts for accumulation of fatigue using material properties. In the edition specified in the IEC61400-1 ed. 3 2010 amendment [2], the effective turbulence is calculated using the 90th percentile of ambient turbulence.

The illustration below gives a simplified overview of the calculation steps of effective turbulence for a WTG.
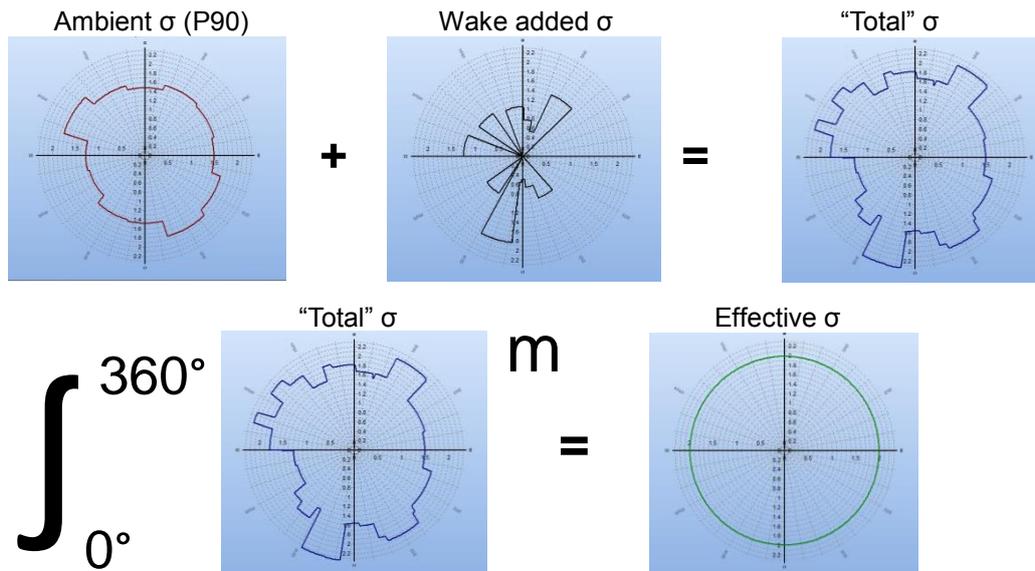

Figure 1. Simplified illustration of the main calculation steps in the Frandsen effective turbulence model. M is the material parameter Wöhler exponent.

For each WTG position in the calculation the Frandsen model needs the following input:

1. $\hat{\sigma}(\theta, u)$ and $\hat{\sigma}_\sigma(\theta, u)$ - Ambient turbulence (mean & st.dev. functions of direction and speed)

2. $W(A_i, k_i)$ & $f(\theta_i)$ - Sector-wise frequencies and Weibull distributions

3. C_T (turbine thrust curve) and park geometry

4. m - Relevant material fatigue property "Wöhler exponent

Input 1 is used to calculate the ambient characteristic turbulence, i.e. the 90th percentile.

Input 2 is used to calculate the directional wind sped distribution conditioned on wind speed.

Input 3 is used to calculate the wake generated contribution to turbulence.

Input 4 is used in the fatigue weighted combination model of single directions to obtain an omnidirectional effective turbulence as a function of wind speed only.

A main decision in SITE COMPLIANCE regarding the implementation of the Frandsen has been working directly with standard deviations of wind speed (σ) instead of turbulence intensity (TI) which is more common. There are several arguments supporting this decision. Firstly, Frandsen's original publication [13, p. 84] states directly that "The model is expressed in terms of standard deviation of wind speed fluctuations rather than turbulence intensity. Secondly, a fundamental assumption in Frandsen's model is that loads are proportional to σ, the standard deviation of wind speed. Thirdly, the variation of σ with wind speed assumed in the IEC design limit ("Normal turbulence model") is linear for (u,σ), but not for (u,TI).

The implementation of Frandsen's model as specified in [1, 2] includes on a number of assumptions and calculation steps. The main assumptions in the SITE COMPLIANCE implementation are (most are directly given in the standard [1, 2]):

- "No reduction of mean wind speed inside the wind farm shall be assumed" (no wake deficit!) [1, 2]
- Only wake from nearest neighbour WTG considered i wakes overlap [1, 2]
- Turbulence structure correction is applied to both σ and σ_σ
- Wakes have a fixed angular width of 22° independent of distance [13, 15]

The main steps in the calculation of effective turbulence (as illustrated in figure 1) are:

- "Total" turbulence (σ_T) is calculated in each direction combining measured 90th percentile of ambient turbulence (σ_C) and calculated wake added turbulence (σ_{wake}) [1, 2] - "^" indicates measured data:

$$\hat{\sigma}_T = \sqrt{\sigma_{wake}^2 + \hat{\sigma}_c^2}$$

where

$$\hat{\sigma}_c = \hat{\sigma} + 1.28\hat{\sigma}_\sigma \quad \text{(90th percentile of ambient turbulence)}$$

and

$$\sigma_{wake} = \begin{cases} 0 & \text{If overall nearest neighbour distance is } > 10RD \\ \dfrac{u}{1.5 + \dfrac{0.8\text{d}/RD}{\sqrt{C_T(u)}}} & \text{In wake affected directions} \\ & \text{d is distance and } C_T \text{ is thrust coefficient} \end{cases}$$

- "Effective turbulence" is calculated from "Total turbulence" raised to the power of m (Wöhler exponent) and integrated (numerically) over all directions weighted by its relative frequency (f):

$$I_{eff.}(u) = \frac{1}{u}\left[\int_0^{2\pi} \hat{\sigma}_T(\theta \mid u)^m f(\theta \mid u)d\theta\right]^{1/m}$$

The Frandsen model requires a "large wind farm correction" when certain conditions are met, but [1, 2] only considers the special case of a regular rectangular layout. In SITE COMPLIANCE a more general sector-wise version of this large wind farm correction has been implemented. For each sector the following evaluation is performed:

- If >5 neighbour WTGs in a sector, the sector is a "large wind farm sector":
  - In direct wake directions σ_T is calculated as above (no correction of ambient level) [1, 2]
  - In non-wake directions (>10RD), ambient σ_c is adjusted using [1, 2]:

$$\sigma_c = \frac{1}{2}(\sqrt{\hat{\sigma}_w^2 + \hat{\sigma}^2} + \hat{\sigma}) + 1.28\hat{\sigma}_\sigma$$

where

$$\hat{\sigma}_w = \frac{0.36u}{1+0.2\sqrt{\dfrac{d_r d_f}{C_T}}} \approx \frac{0.36u}{1+0.2\sqrt{\dfrac{0.5\Delta\theta d_{max}^2}{N_{sec}C_T}}}$$

The latter fraction on the right in the above equation was proposed in [15] as a more generally applicable version of the fraction on the left which is given explicitly in the standard, covering only regular rectangular layouts). The square root argument represents a "thrust versus area". In the fraction on the right the rectangular expression is replaced with an angular expression with the area of an "pie slice" $A = 0.5\Delta\theta d_{max}^2$. N_{sec} is the number of WTGs within the "slice" or sector, d_{max} the radius of the slice and thus distance to the furthest neighbour WTG in the sector.

Calculation of Equivalent effective turbulence (not part of the IEC standard)

This calculation is not part of the IEC standard, but is based on considerations presented in Frandsen's original paper [13]. The Equivalent effective turbulence is used to decide when the calculated Effective turbulence

exceeds the IEC design limit to evaluate if this exceedance is critical or not. The main assumption is the same as in the Frandsen model, but an extra calculation step is added: integrating the effective turbulence over all relevant wind speeds where Frandsens model only integrates over directions. This second integration over wind speeds assumes that the sensitivity of the WTG to wind speed fluctuations is constant for the relevant wind speed range which is a significant extension to the approximation of the Frandsen model and further validation of this approximation is ongoing. The Equivalent effective turbulence is calculated as following:

$$\sigma_{eq} = \left(\int_{u_1}^{u_2} \sigma_{eff.}(u)^m f(u) \, du \right)^{1/m}$$

Where m is Wöhler exponent, $f(u)$ is total frequency of a wind speed bin (omnidirectional) and $\sigma_{eff.}(u)$ is effective turbulence as a function of wind speed bin, i.e. the result from the Frandsen models effective turbulence calculation.

The effective turbulence result for a particular WTG is compared the IEC design limit for the WTG class by calculating the equivalent effective turbulence for the relevant IEC design class (turbulence and frequency values) and for the actual WTG results. These results for the actual WTG result are normalized by the result for the IEC class. If the normalized result (ratio) exceeds 1 the IEC exceedance is considered critical. The integration limits are set to match the IEC check interval.

Appendix III - Critical, Caution & OK limits in SITE COMPLIANCE

The following values are used in the WindPRO SITE COMPLIANCE module to help the user evaluate if an obtained check value is critical or not. They are based on experience from a large number of projects but further validation and improvement are on-going.

General decisions:

For all checks the result of a calculation is green/"Ok" if the result is fully within the IEC limits. If the result for a check exceeds the IEC limit the result will be orange/"Caution" or red/"Critical", depending on the degree of exceedance. Caution is used when the exceedance is not considered critical.

At WTG level:
- A WTG is set to Critical if just one check is Critical, Caution if just one check is Caution, and only Ok if all checks are Ok.

At Park level:
- A check is set to Critical for the park if just one WTG is Critical for the check, it is Caution if just one WTG is Caution and only Ok if all WTGs are Ok.

Assessment of Critical, Caution and Ok for each Site Compliance check:

Terrain complexity (I_c):
IEC limit: (none/see details of terrain check)
- Critical: Never
- Caution: If $I_c > 0$
- Ok: if $I_c = 0$

Wind shear (α):
IEC limits: $0 \leq \alpha \leq 0.2$
- Critical: if $\alpha > 0.3$ or $\alpha < 0$
- Caution: if $0.3 \geq \alpha > 0.2$
- Ok: if $0 \leq \alpha \leq 0.2$

Air density (ρ):
IEC limits: 1.225 kg/m^3 is assumed in design
- Critical: Never
- Caution: $\rho > 1.225$ kg/m^3
- Ok: $\rho \leq 1.225$ kg/m^3

Inflow angle (φ_{max}):
IEC limits: $\varphi \leq 8°$ & $\varphi \geq -8°$
- Critical: $\varphi > 12°$ or $\varphi < -12°$
- Caution: $12° \geq \varphi > 8°$ or $-12° \leq \varphi < -8°$
- Ok: $\varphi \leq 8°$ & $\varphi \geq -8°$

Extreme wind (u_{50y}):
IEC limits: $V_{ref} \geq u_{50y}$
- Critical: $u_{50y} > V_{ref}$ or   gust $> 1.4 \cdot V_{ref}$
- Caution: Never
- Ok: $V_{ref} \geq U_{50y}$ or $1.4 \cdot V_{ref} \geq$ gust

Effective turbulence ($\sigma_{eff.}(u)$):
IEC limits: $\sigma_1(u) > \sigma_{eff.\ WTG}(u)$ for all u
- Critical: $\sigma_{eq,\ WTG}\ \ > \sigma_{eq,\ IEC}$
- Caution: $\sigma_{eq,\ WTG}\ \ < \sigma_{eq,\ IEC}$
- Ok: $\sigma_{eff,\ IEC}(u)\ > \sigma_{eff.\ WTG}(u)$ for all u

$\sigma_{eq,\,xxx}$ is the Equivalent effective turbulence for WTG for IEC design class. See Appendix II for a description of the calculation of this quantity.

Wind distribution (pdf(u)):

    IEC limits: $f_{IEC}(u) > f_{WTG}(u)$ for all u

- Critical: $F_{hi} < 0$ or $(F_{hi} + F_{lo} < 0)$
- Caution: $F_{hi} \geq 0$ & $(F_{hi} + F_{lo} \geq 0)$
- Ok: $f_{IEC}(u) > f_{WTG}(u)$ for all u

         Where:

$$F_{hi} = \int_{0.3V_{ref}}^{0.4V_{ref}} \left(f_{IEC}(u) - f_{WTG}(u) \right) du$$

$$F_{lo} = \int_{0.2V_{ref}}^{0.3V_{ref}} \left(f_{IEC}(u) - f_{WTG}(u) \right) du$$

- The main point here is that exceedances at the lower half of the check interval is not as severe as those in the upper half at higher wind speeds where loads are expected to be higher.

Seismic hazard (PGA):

- Critical: PGA > 2.4
- Caution: 2.4 ≥ PGA > 0.8
- Ok: 0.8 ≥ PGA

Lightning rate:

- Critical: rate > 20
- Caution: 20 ≥ rate > 10
- Ok: 10 ≥ rate

Temperature range (T):

    Normal range

- Critical: h outside > 240h
- Caution: h outside > 24h
- Ok: 24 h ≥ h outside

    Extreme range

- Critical: h outside > 1h
- Caution: 1h ≥ h outside > 0.0 h
- Ok: 0.0 h outside