

8b OPTIMIZE

8b.1	Introduction	2
8b.1.1	Noise Curtailment vs. Layout Curtailment	2
8b.1.2	The GUI tree-structure.....	2
8b.1.3	Presentation of results	9
8b.1.4	Storing results	11
8b.2	Optimization decisions	12
8b.2.1	The noise model	12
8b.2.2	Noise receptors.....	13
8b.2.3	Wind resource model.....	13
8b.2.4	Strategy decisions	14
8b.3	Optimization algorithm	15
8b.3.1	Noise curtailment optimization algorithm.....	15
8b.3.2	Turbine shutdowns	15
8b.3.3	Operation mode curtailment	15
8b.4	References	15

8b.1 Introduction

Wind farms must comply with noise regulations, and two approaches are being used to ensure compliant noise immission levels at noise receptors emitted by wind turbines: control the turbine position (Cao et al. 2020) or control the turbine operation modes (Nyborg et al. 2023). When wind turbines are already installed or the planned positions are decided upon, the remaining option is, therefore, curtailing the operation modes of the turbines. The curtailment of wind turbine modes comes with reduced noise emission but also reduced energy production (Steurer et al. 2017). The purpose of noise curtailment optimization in the context of wind farm planning is to satisfy acoustic constraints while maximizing the usual benefits, e.g., energy production or profit.

The Noise Curtailment Optimizer (NCO) adds such functionality to the Optimizer module in windPRO to the Layout Optimizer. The objective of the NCO is to suggest a curtailment strategy for wind farms to comply with noise receptor thresholds around the wind farm with the lowest production loss possible. If a noise curtailment is insufficient to comply with defined noise regulations, the tool can also propose to shut turbines down for specific conditions as a last resort.

The NCO facility in windPRO was developed as part of the Decowind project, supported by the Danish Innovation Fund.

8b.1.1 Noise Curtailment vs. Layout Optimizer

The Noise Curtailment Optimizer is designed to resemble the Layout optimizer, and a lot of the structure of the optimizer will look and feel similar. In both cases the objective is to maximize production output of a wind farm, but the degrees of freedom are different. The Layout Optimizer reaches its objective by moving the turbines within a set of constraints, while the NCO does the same through changing the operation mode on the turbines. The constraints of the NCO are controlled by the noise code it must comply with and the possibilities the turbine type offers. For these reasons, the GUI must diverge from that of the Layout Optimizer as described in the following. The result of the NCO is not a new layout but a Noise Curtailment Matrix for each turbine.

8b.1.2 The GUI tree-structure

The GUI of the Noise Curtailment Optimizer uses a tree structure like that of the Layout Optimizer with three levels: Site, Layout and Strategy (Figure 1).

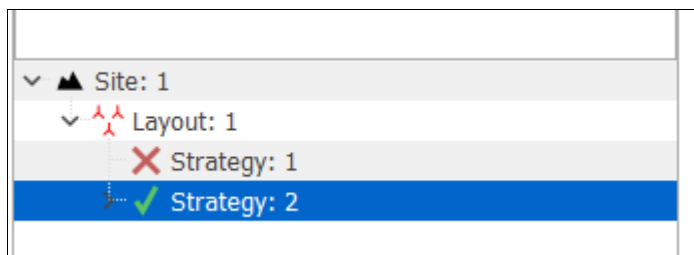


Figure 1: The three hierarchy levels of the GUI tree: Site, Layout, and Strategy.

When the NCO is opened for the first time, a first Site will be available and set with default settings for the country of the project. The optimizer allows creating several sites, where each site can contain several layouts, and a layout can have several strategies. Each hierarchy level can be expanded or collapsed and if highlighted, the options for the level become visible to the right.

New levels can be added, deleted or copied. Sites can be cloned by right-clicking on the Site level:

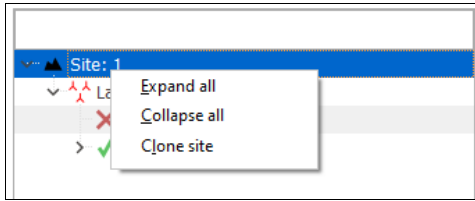


Figure 2: Option to expand, collapse and clone sites.

There are some restrictions to the upper levels in the structure once lower levels have been added. These restrictions can be lifted if the lower levels are removed. It is for example not possible to change the noise model once a Strategy has been added but removing all strategies reenables noise model changes.

8b.1.2.1 Site

The Site level sets up fundamental decisions regarding the noise model and wind resource model. In principle, the Site will include all the basic conditions of the location and would, ideally not need to be changed when testing different options. There may be a need or an interest in changing fundamental conditions, such as the selection of noise receptors, parameters in the noise model or details in the wind model. For such variations, separate sites can be made. Selecting a Site in the left column enables the Setup & Run field on the right.

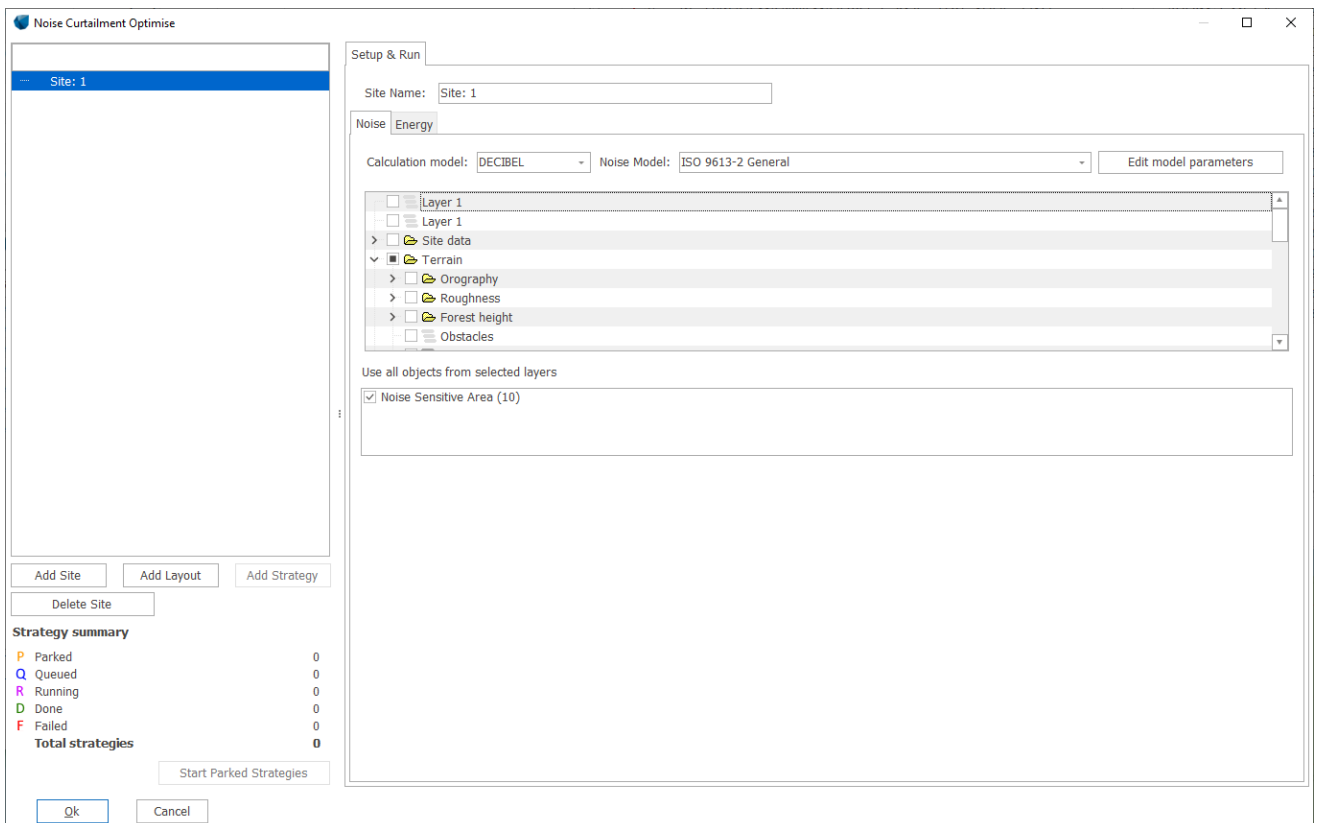


Figure 3: On the Site level, three components of the optimization are selected: the noise receptors, the noise model, and the wind resource.

Noise receptors: On the *Noise* tab, the relevant receptors are selected by pointing out the layer in which the receptors are located. As default all receptors in a layer are selected, but by removing the check in *Use all objects from selected layers*, specific objects can be pointed out.

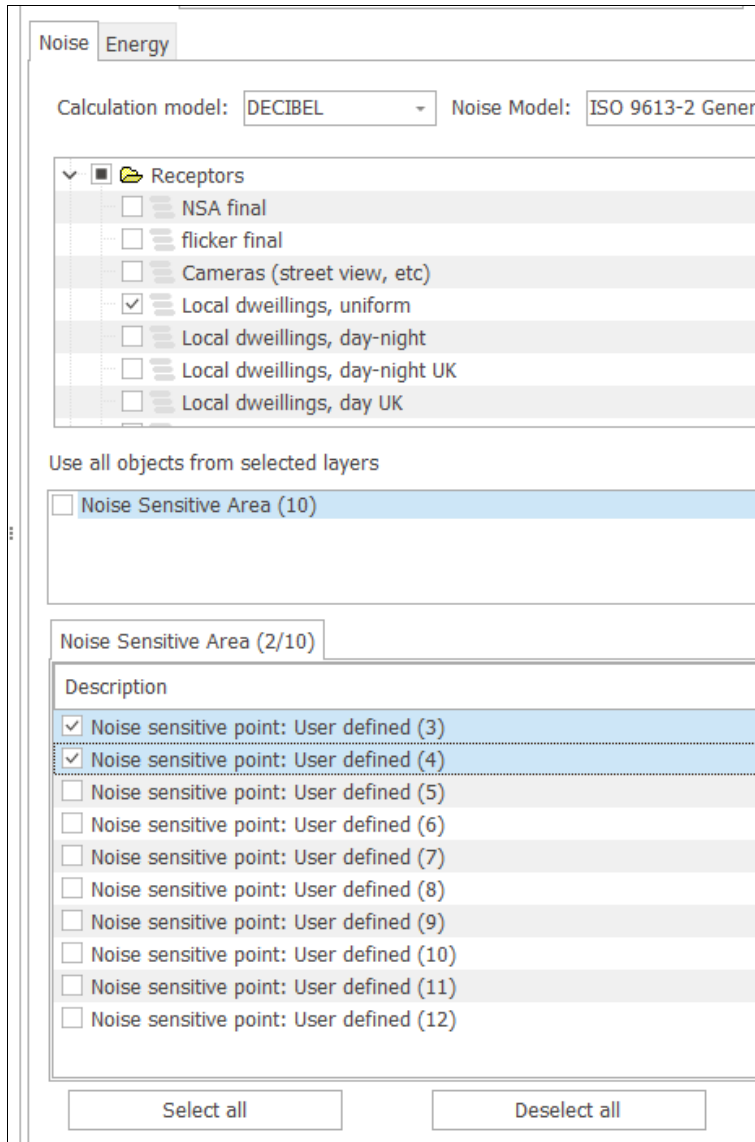


Figure 4: Noise model configuration.

It is important that the noise receptors selected match the noise model used, see section 8b.2.2.

Noise model: The NCO gives access to both Decibel and *NORD2000* from the *Noise* tab. To access either requires a license for the module. The *Noise model* selection box provides quick access to one of the preset models in either Decibel or *NORD2000*. The *Edit model parameters* button gives access to view or modify the parameters in the noise model. *DECIBEL* and *NORD2000* are described in detail in section 6 of the windPRO Environmental manual. The model parameter details are also described in section 6 with additional information in section 8b.2.1 where the optimizer provides additional or reduced options.

If a model needs to be customized, it is recommended to select the *ISO 9613-2 General* model from *DECIBEL* or *General* from *NORD2000*.

It is not possible to use different noise models at the same site. The questions of how to combine multiple models, e.g. one noise model for existing turbines and one noise model for new turbines, has not been answered yet.

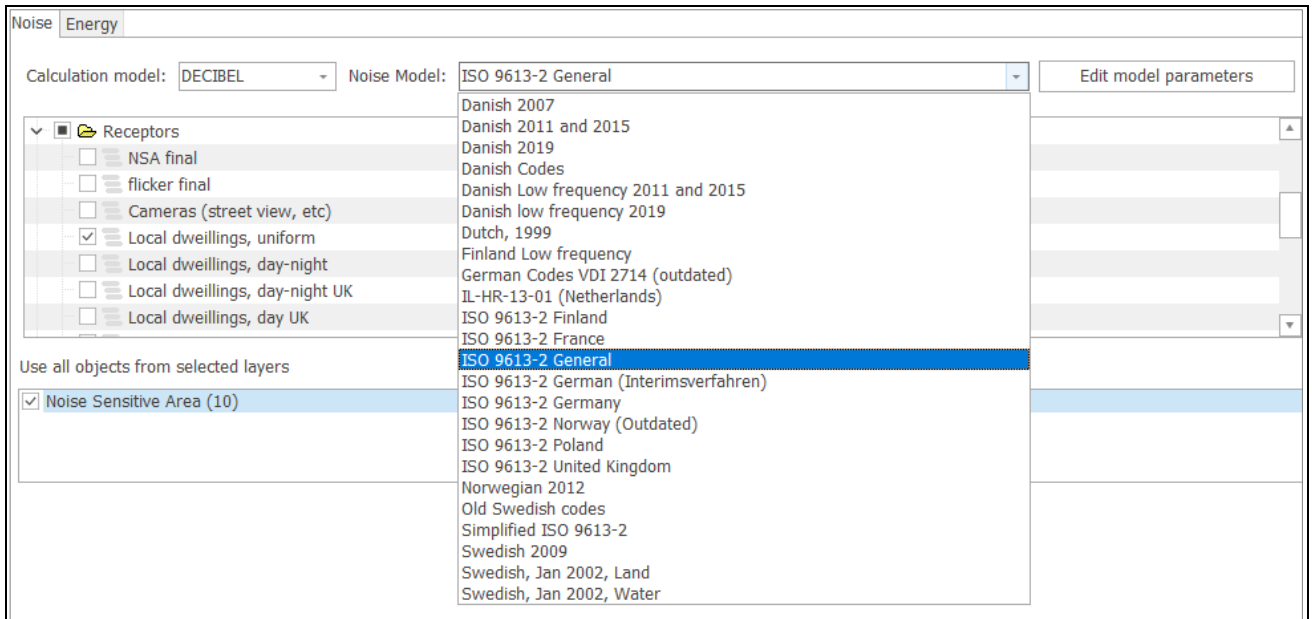


Figure 5: Noise regulation specification selection.

Wind resource model: On the *Energy* tab, the wind resource model is selected. The wind resource model is used to calculate the production loss inflicted by curtailments. The wind resource model can be based on time series data or a wind resource map. A wind resource map is a precalculated map for the area that provides Weibull parameters and direction frequencies in each grid cell. Wind resource maps are described in detail in section 3 of the manual. For the NCO a wind resource map in either .rsf, .wrg or .siteres format can be used. It is required that it covers the location of all wind turbines in the calculation as well as any reference points (for the Wind speed inside Wind farm model). A very easy and simple access to a wind resource map is the *GASP* data which are freely available world-wide from windPRO. A wind resource map can be used if the only two dimensions used in the optimization are wind speed and wind direction.

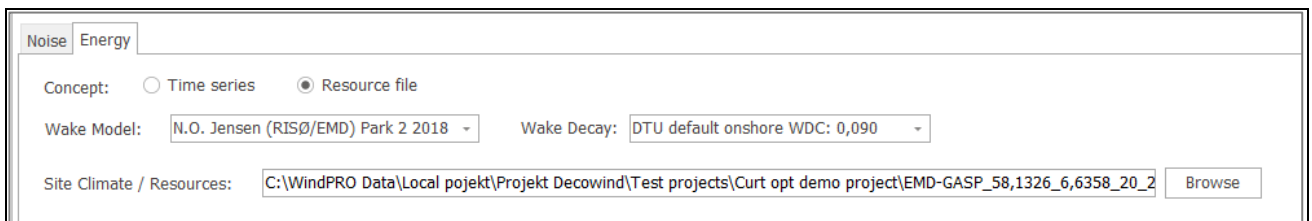


Figure 6: Resource and wake model specification.

The *Time series* option sets up a time domain model as described in the *Chapter 3 Energy*. This includes a Scaler and a time series and is entirely identical to the model in the *PARK* module. A full description of the Scaler and selection of time series data can be found in *Chapter 3 Energy*.

The time series model has the advantage, compared to a wind resource map, that it is not limited to wind speed and direction. The time domain nature of the model means that the time dimension can be used in the optimization, i.e. calculation of day and night curtailments. If the time series includes temperature and humidity data, it is possible to include these dimensions as well. If these dimensions are needed, but not available in the time series used by the Scaler, time series with those data can be pointed out separately at the bottom of the field. As the objective is to calculate and minimize curtailment losses, precision on the absolute wind speed is not required and downscaled mesoscale data is an easy and suitable option for a time series wind model.

Noise
Energy

Concept: Time series Resource file

Wake Model: N.O. Jensen (RISØ/EMD) Park 2 2018 Wake Decay: DTU default onshore WDC: 0,090

Scaler: Demo Setup

Select meteo objects to scale from.

Name	Data type	Use in scaling	Sample rate [min]	Duration (enab...)	Recovery (enab...)	First	Last
✓ EMD-WRF Europe+ (ERA5)_N58,126396_E006,620087 (9)	Meso						
> 10,00m -		<input checked="" type="checkbox"/>	60,0	5,0	100,0	01/01/2018 01	01/01/2023 00
> 25,00m -		<input checked="" type="checkbox"/>	60,0	5,0	100,0	01/01/2018 01	01/01/2023 00
> 50,00m -		<input checked="" type="checkbox"/>	60,0	5,0	100,0	01/01/2018 01	01/01/2023 00
> 75,00m -		<input checked="" type="checkbox"/>	60,0	5,0	100,0	01/01/2018 01	01/01/2023 00
> 100,00m -		<input checked="" type="checkbox"/>	60,0	5,0	100,0	01/01/2018 01	01/01/2023 00
> 150,00m -		<input checked="" type="checkbox"/>	60,0	5,0	100,0	01/01/2018 01	01/01/2023 00
> 200,00m -		<input checked="" type="checkbox"/>	60,0	5,0	100,0	01/01/2018 01	01/01/2023 00
> 300,00m -		<input checked="" type="checkbox"/>	60,0	5,0	100,0	01/01/2018 01	01/01/2023 00

Horizontal interpolation between selected meteo objects

Take nearest Distance weighted at geostroph wind Distance weighted after scaling

Interval

Use all Use period - latest Use last years Offset time series 0 years

Temperature

Meteo object EMD-WRF Europe+ (ERA5)_N58,126396_E006,620087 (9).10,00m - Default: 20,0 °C

Scaler Default: 20,0 °C

Relative humidity

Meteo object EMD-WRF Europe+ (ERA5)_N58,126396_E006,620087 (9).2,00m - Default: 50,0 %

Fixed 50,0 %

Figure 7: Energy tab setup with Time series data.

Finally, a wake model must be selected. The wind resource at each turbine is highly influenced by wake loss and changes in operation mode changes the thrust curve of turbines and therefore also the wind resource experienced by turbines downwind. In the present version of the NCO only the *PARK2* model is available. It can be selected with either default onshore or default offshore (low turbulence) wake decay constant.

8b.1.2.2 Layout

On the Layout level, the wind farm is selected. Several different layouts can be tested on the same site as it is often required to try different turbine types or layout configurations.

The layout is selected by selecting the layer(s) with the wind turbines. All wind turbines selected are included in the layout optimization. It is required that the turbines must have noise data and power curves defined as modes in either a *PowerMatrix* or as a *Power & Noise Pair* (see Chapter 2 *BASIS*). Existing turbines can also be included in the optimization. If they are not to be curtailed, simply edit the Existing WTG object to use a fixed noise mode and power curve instead of using *PowerMatrix* or a *Power & Noise pairing*.

By default, all wind turbines in a layer are selected, but a more specific selection can be made by removing the hatching from *Use all objects from selected layers* and picking the turbines from the list below.

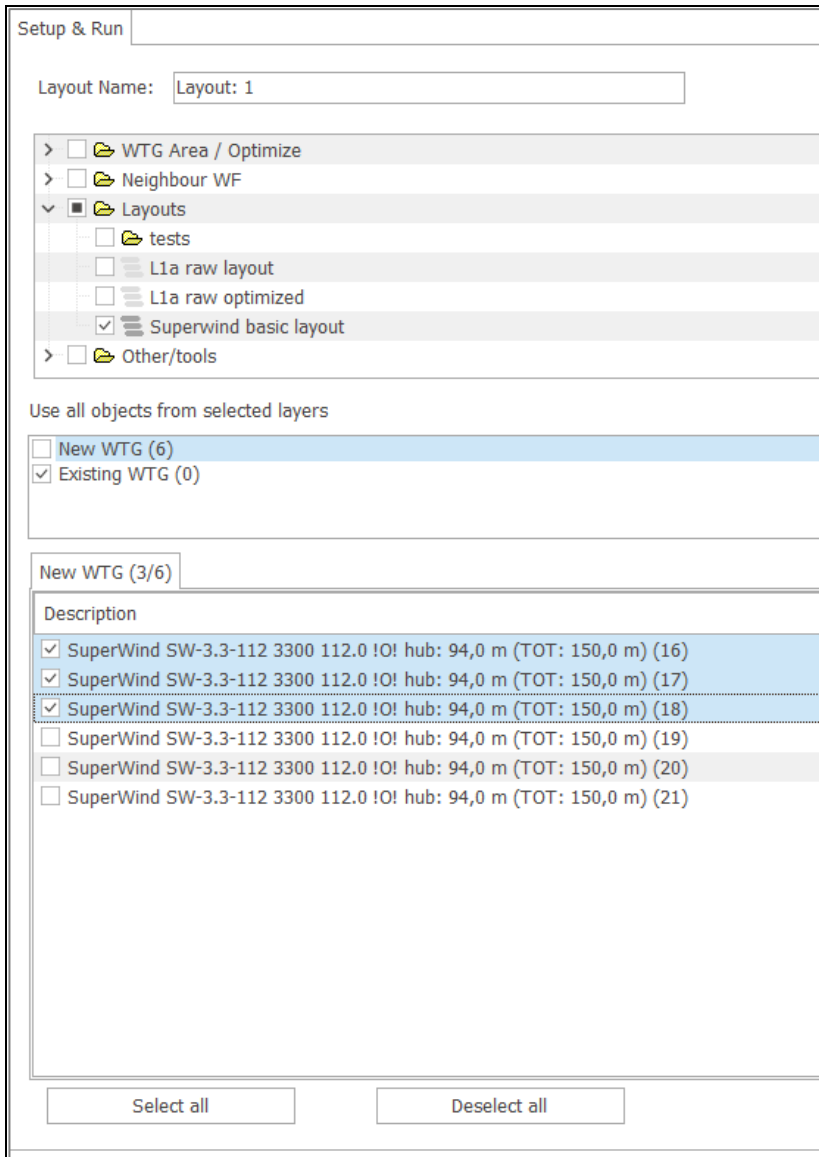


Figure 8: Selecting the WTGs to be considered in the curtailment optimizer.

8b.1.2.3 Strategy

The strategy window displays which dimensions are available for optimization, containing single or sets of curtailment strategies, where each strategy is a plan for how you want to run your optimization. It is a requirement that the binning file allows for the dimensions. This is set in the *Noise Matrix Analyzer*, a description of defining the binning file be found in the manual section 2.

It is also necessary for the model to calculate along a range of values in order to perform an optimization. If, for example, the noise model is set up with fixed time period (or none at all), it is not possible to include the time component in the optimization. In that case, the *Time bin* will then be greyed out. However, it is possible to calculate along a range of wind speeds, but not optimize along wind speed dimension. In that case, the optimizer determines the specific single noise mode for each turbine that will comply for all wind speeds in the range.

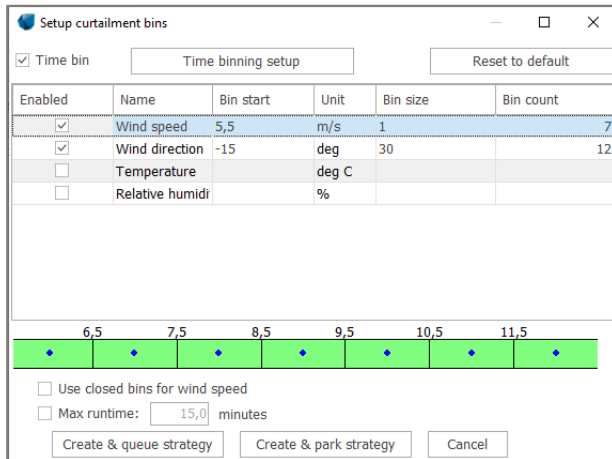


Figure 9: Defining the bins of the considered variables that can have an effect on the noise propagation.

Check the dimensions along which the optimization should be done (Figure 9): In each bin line are listed the binning of each dimension. This information is taken from the binning file. It can be changed at this point and that will override the binning file. It is recommended to use the same binning as in the noise model, but it is not a requirement. If the turbine being optimized allows for a less granular binning than what needs to be tested, it can be inserted here. In case the bins are not matching, the test must comply everywhere inside the optimization bin.

The time binning setup has its own entry (Figure 10). If the time dimension is used, it should match the binning in the noise model. It must be ensured that the time periods are correct. The curtailment losses are calculated according to the period definition, but *Penalty* and *Days per year* are not used information. It is possible to set the time binning as default if you know you will always use the same time periods. The *Reset to default* button reverts the settings to that of the binning file but will respect your new time default.

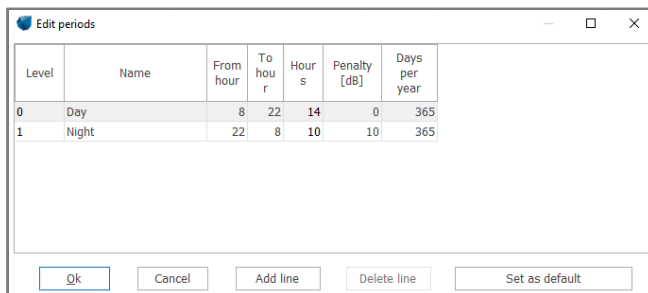


Figure 10: The time binning specification. It is possible to include more than two periods.

Clicking on a dimension line triggers a bar at the bottom of the window. These are the bins that are considered in the optimization. For these bins the optimal strategies will be calculated and saved in the curtailment matrix. The dots inside the bins are the values that are tested in the noise model. In the above example, the first bin on wind speed is from 5.5 m/s to 6.5 m/s and the last bin is from 11.5 m/s to 12.5 m/s.

For the wind speed dimension, it is possible to use open or closed bins (Figure 11). The open status means that for any wind speed below the lowest wind speed optimized, the settings for the lowest optimized wind speed will be used. Correspondingly, for any wind speed above the highest wind speed optimized, the modes for the highest wind speed optimized will be used. In the above example, for wind speeds higher than 12.5 m/s, the noise mode settings of 12 m/s bin will be repeated. The open bin status does not result in extra lines being written in the curtailment database, but a flag is set to repeat the information outside the optimized interval. Checking the *Use closed bins for wind speed* box means that no curtailment is done outside the optimized interval. Essentially, as there is no noise threshold at those wind speeds, the turbines do not need to comply with noise regulations.

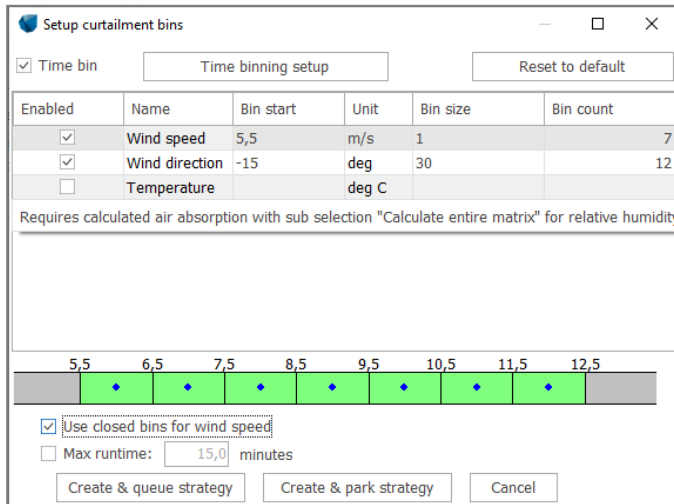


Figure 11: Curtailment bin setup with closed wind speed bins.

Please note that the wind speeds being displayed are the wind speeds from the noise model. These may be converted to hub height wind speed for the noise curtailment matrix.

It is possible to set a max runtime, but it is generally not recommended. An optimization stopped before it is done may not comply with the noise thresholds. However, if the calculation is suspected to be very long, it can be used as an emergency stop.

Create & queue strategy will start the optimization immediately. *Create & park* will leave the optimization parked, to be run as a batch run later. More details and considerations about strategy can be found in section 8b.2.4.

8b.1.3 Presentation of results

When a strategy is started, the NCO will run through the algorithm described in section 8b.3 to find in each bin the operation mode that will comply with noise threshold with the minimal loss of yield. A counter indicates the optimization progress.

The outcome of the optimization can either be an “✗” for failed or a “✓” for done. A failed calculation does not deliver a result but will tell you through an error message what went wrong. Usually, it would be an inconsistency between noise model requirements and noise receptor settings (e.g. no low frequency thresholds in the receptor when the noise model is set to calculate low frequency noise). The resulting strategy line can be unfolded and will then list all the wind turbines in the optimization. Each turbine curtailment plan can be inspected by clicking on it (Figure 12).

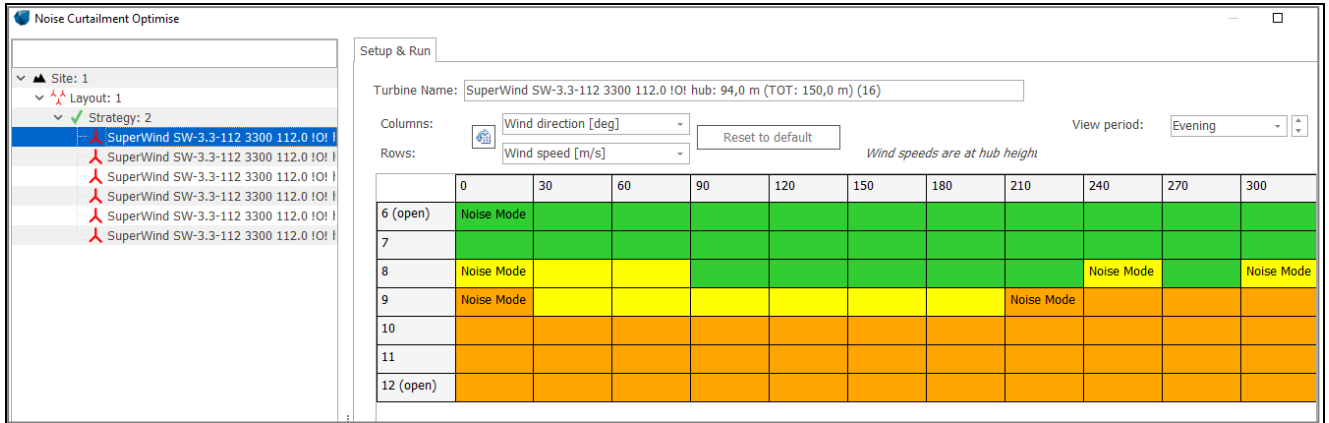


Figure 12: Resulting strategies after the NCO is completed.

The *Setup & Run* pane can display two dimensions at the time. In the above example, wind directions are in the columns and wind speed is in the rows. If additional dimensions are included in the optimization, they can be displayed instead. If time is an active dimension, *View period* can be used to select which period to display.

The colors correspond to the operation modes of the wind turbine and the upper left corner in each bin group will display the name of the operation mode. In the example above (Figure 12), brown bins indicate the operation mode “Noise Mode 2”.

If a bin contains sub-bins in different dimensions (e.g. temperature), the label will indicate the most restrictive mode among the sub-bins and it will also decide the color. This view is consistent with the presentation in *DECIBEL* and *NORD2000* curtailment presentations with the exception that the range of modes is not displayed here. If the strategy used open bins, this is remarked for the highest and lowest wind speed used. These will be the modes the turbine will operate in at higher and lower wind speed (Figure 12).

If the strategy used closed bins, an extra wind speed bin is added above and below highest and lowest wind speed with unreduced operation mode (example in Figure 13).

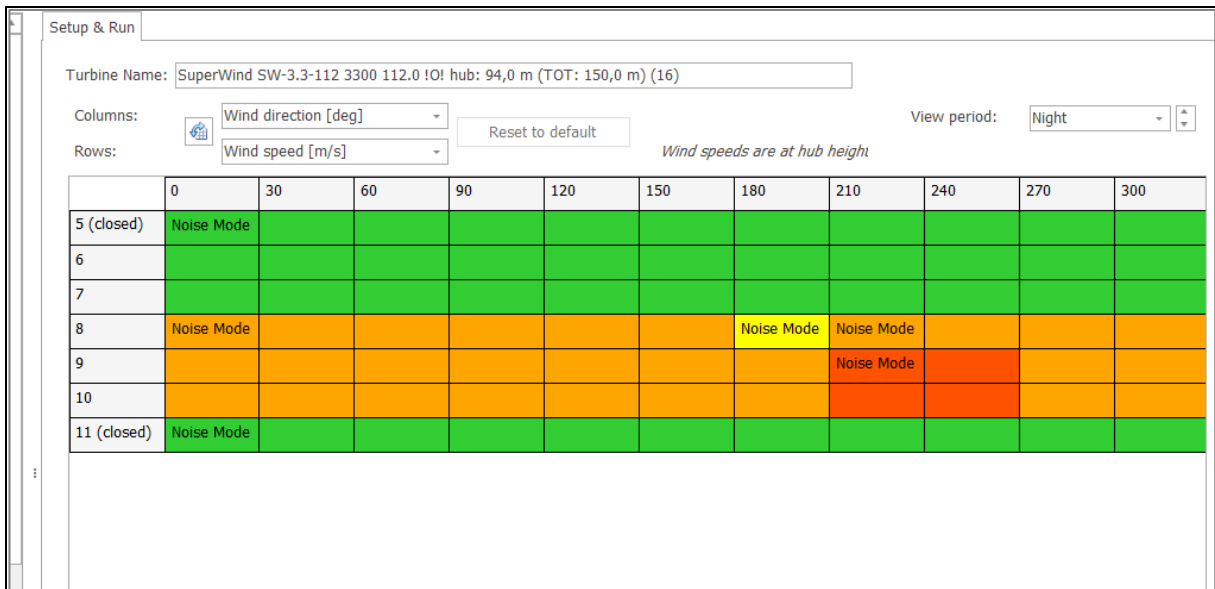
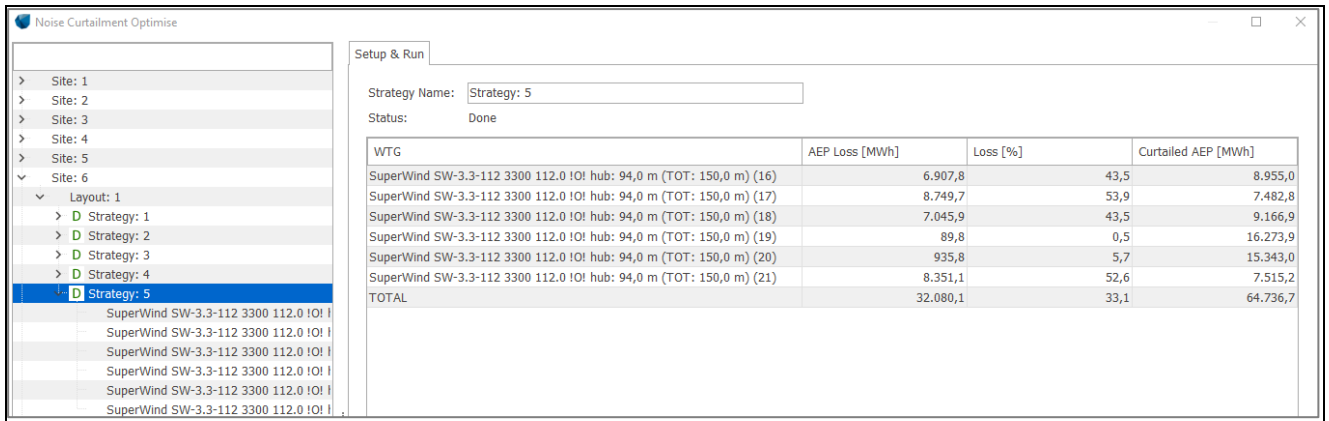


Figure 13: Resulting strategies with closed bins.



WTG	AEP Loss [MWh]	Loss [%]	Curtailed AEP [MWh]
SuperWind SW-3.3-112 3300 112.0 !0! hub: 94,0 m (TOT: 150,0 m) (16)	6.907,8	43,5	8.955,0
SuperWind SW-3.3-112 3300 112.0 !0! hub: 94,0 m (TOT: 150,0 m) (17)	8.749,7	53,9	7.482,8
SuperWind SW-3.3-112 3300 112.0 !0! hub: 94,0 m (TOT: 150,0 m) (18)	7.045,9	43,5	9.166,9
SuperWind SW-3.3-112 3300 112.0 !0! hub: 94,0 m (TOT: 150,0 m) (19)	89,8	0,5	16.273,9
SuperWind SW-3.3-112 3300 112.0 !0! hub: 94,0 m (TOT: 150,0 m) (20)	935,8	5,7	15.343,0
SuperWind SW-3.3-112 3300 112.0 !0! hub: 94,0 m (TOT: 150,0 m) (21)	8.351,1	52,6	7.515,2
TOTAL	32.080,1	33,1	64.736,7

Figure 14: Result overview of energy production losses per WTG.

The curtailment loss is presented in an overview when clicking on a curtailment strategy (Figure 14). The AEP losses are shown in MWh, together with the losses expressed in percent. The loss is relative to the production of the default (highest) operation mode, according to the defined wind model.

At bottom of the page are placed two export user options, *Write curtailment strategy to WTGs* and *Create noise calculation based on strategy* (Figure 15).

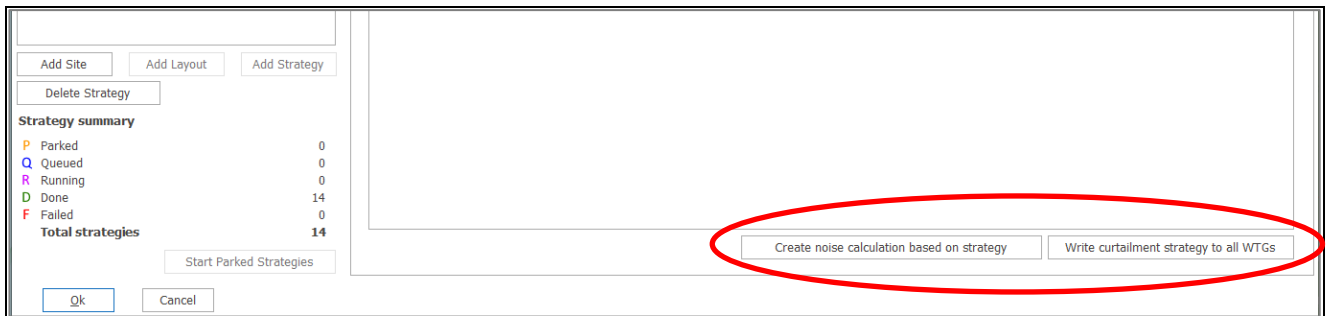


Figure 15: Steps to proceed with a selected strategy: Create noise calculation and write curtailment strategy.

Write curtailment strategy to WTGs will write the curtailment databases to the WTG object. Only when this button has been pressed can the strategy be used outside the optimizer (e.g in PARK). If there already exists a curtailment database for any of the turbines, this will be overwritten with a warning.

Create noise calculation based on strategy will create a *DECIBEL* or a *NORD2000* calculation identical to the settings used in the optimizer. This means the same noise model, the same wind turbines and the same noise receptors. To use the optimized curtailment strategy in the *DECIBEL* or *NORD2000* calculation, please remember to click on the *Write curtailment strategy to WTGs* button first.

The *DECIBEL* or *NORD2000* calculation just created needs to be run before it can be printed or results from it saved. A noise calculation created in this manner will not have noise maps selected, but they can be added by opening the calculation properties. Please note that noise maps based on very granular optimizations can be slow to calculate and it is possible to get a lot of maps if all possible situations must be presented.

8b.1.4 Storing results

When the NCO is closed, the work done is saved, but results are only exported to the rest of windPRO when the export buttons are pressed in the results presentation, see section 8b.1.3. The NCO thereby functions as a self-contained laboratory for finding the best operational strategy for the wind farm. The NCO may hold many different curtailment strategies for the same wind farm, although only one of these may be saved to the same turbine at the time.

8b.2 Optimization decisions

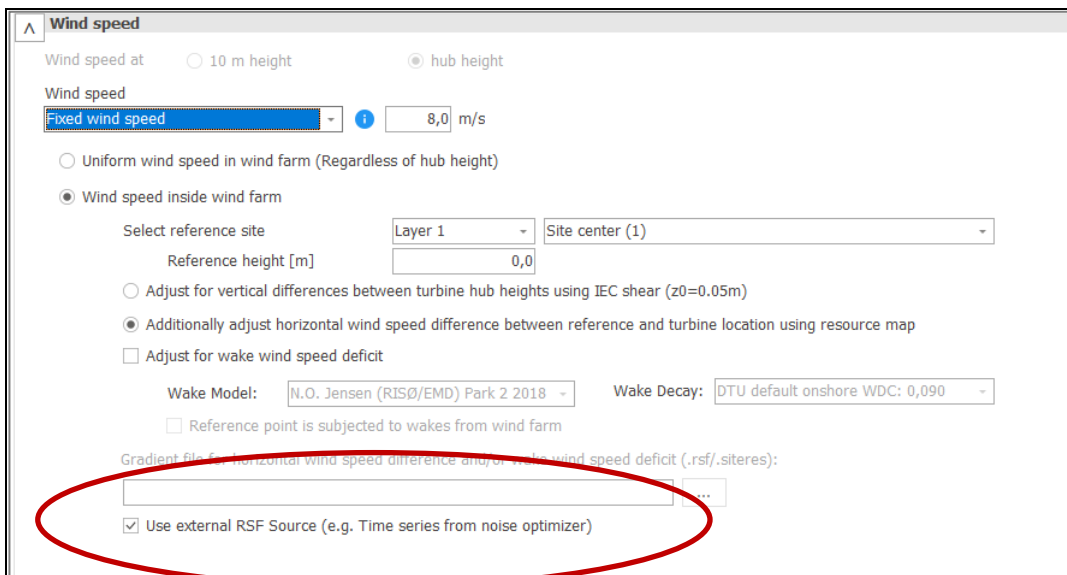
8b.2.1 The noise model

Selection of a suitable noise model is key to a successful noise optimization. The principle for the noise models in windPRO is that of a sandbox. While some of the models are rigid or even based on customized components to comply with noise codes in specific countries, other models have some degree of flexibility. For both the DECIBEL model, with the ISO 9613-2 and for the NORD2000 model it is possible to go all in on flexibility and design your own noise model.

These noise models are described in detail in *Chapter 6 Environment*. In some places, however, the noise model selection in the Noise Curtailment optimizer (NCO) differs from the setup in the DECIBEL and NORD2000 calculation.

8b.2.1.1 Wind speed options

Whereas the Wind speed inside wind farm (Wiw) model in DECIBEL and NORD2000 are limited to use a predefined wind resource map, it is possible to link to the wind model used to calculate the losses in the optimization. If a resource map is used as wind model Wiw will simply use the same resource map. If the wind model is a time series model, a customized wind resource map (.rsf) is calculated for the specific points in the Wiw calculation (Figure 16). The selected wind resource map is exported through to the DECIBEL or NORD2000 export calculation. This approach ensures consistency and limits the number of wind models required for the calculations.



The screenshot shows the 'Wind speed' configuration window. At the top, there are radio buttons for '10 m height' and 'hub height' (selected). Below that, a dropdown menu is set to 'Fixed wind speed' with a value of '8,0 m/s'. There are two main radio button options: 'Uniform wind speed in wind farm (Regardless of hub height)' and 'Wind speed inside wind farm' (selected). Under 'Wind speed inside wind farm', there are fields for 'Select reference site' (Layer 1), 'Reference height [m]' (0,0), and 'Site center (1)'. There are also checkboxes for 'Adjust for vertical differences between turbine hub heights using IEC shear (z0=0.05m)', 'Additionally adjust horizontal wind speed difference between reference and turbine location using resource map' (selected), and 'Adjust for wake wind speed deficit'. Below these are dropdowns for 'Wake Model' (N.O. Jensen (RISØ/EMD) Park 2 2018) and 'Wake Decay' (DTU default onshore WDC: 0,090). A checkbox for 'Reference point is subjected to wakes from wind farm' is unchecked. At the bottom, there is a text field for 'Gradient file for horizontal wind speed difference and/or wake wind speed deficit (.rsf/.siteres):' and a checkbox for 'Use external RSF Source (e.g. Time series from noise optimizer)' which is checked and circled in red.

Figure 16: Wind speed options.

8b.2.1.2 Frequency options

The A-C weighing test is not included in the optimizer. It is simply a test for the NORD2000 calculation and a failure in this test has no consequences for the calculation.

8b.2.1.3 Wind direction options

If the optimizer is set to calculate noise propagation by wind direction, it is possible to select either a customized set of wind directions or link to the curtailment matrix. The difference may seem insignificant as the default curtailment matrix is identical with the default direction setup, but the idea is to create link to the optimization strategy setup, so the tests are done in the same bins as are optimized. The reverse is possible as well, tests for compliance can be done independently of the optimization strategy. For example, a strategy may only be allowed with 60° bins, but the compliance check must be made with 30° bins. In that case 12 sectors are selected in the noise mode, but only 6 sectors in the strategy.

The *All receptors downwind of all wind turbines* option provides some interesting possibilities. As the noise model will only test for noise compliance in wind directions downwind from the turbines, it is possible to reduce noise

only in those directions. When the wind direction is at an angle from the down wind direction to the tested receptor, there may be no test or a more relaxed test on the turbine as the critical receptor in the new down wind direction has a less critical threshold. In this manner the turbine may actually contribute more noise at the receptor if in a cross wind.

8b.2.1.4 Air absorption options

The air absorption calculation makes use of two parameters that can be used in optimization: Temperature and relative humidity. These parameters will only be used in an optimization if the option *Calculate entire matrix* is selected. The binning is then set up in the strategy. Using the *Range of...* option will only test the range of values for compliance.

8b.2.1.5 Time domain options

The *Fixed / no time dimension* option means that the optimization will only test according to a single time period or that time is just not a parameter. If receptors have more than one time period defined, it will be the indicated period that is used for the optimization, while the other periods are ignored.

Checking *Calculate full matrix resolution* means that each of the time periods defined in the *Time binning setup* is optimized. The optimizer will expect to find the same periods defined in the receptors. If only one period is defined in the receptor, that threshold will be used for all time periods and the result will be the same. If there is more than one period defined in the receptor and the optimization number of periods is different, an error message is triggered.

The L_{den} metric cannot be used in optimizations. It does not appear in the General / ISO-9613-2 General options and the models that use L_{den} are removed from the model list. This includes Dutch 2011, Norwegian 2012 and Norwegian worst case.

8b.2.1.6 Noise reflections

Noise reflections are not included in the noise optimization.

8b.2.2 Noise receptors

In the context of the noise curtailment optimization the primary concern is that the receptors match the noise model, which is the same concern in a *DECIBEL* or *NORD2000* calculation. Mismatching may result in wrong results or error messages. An optimization that considers ambient noise expects to find ambient noise values in the receptors. A low frequency spectrum optimization expects to find a threshold spectrum in the receptors covering the same frequencies. As long as country specific models are being used, you are reasonably safe against such mismatches, but the sandbox nature of the general calculations means that in theory anything can be tested against anything and often that just does not make sense.

As the easiest way to select noise receptors is by selecting a layer with receptors, it is recommended to group receptors with changes in setting in separate layers. Swedish broadband receptors in one layer and a copy with Swedish low frequency receptors in a second layer etc.

Noise receptors are described in more detail in section 5 of the manual.

8b.2.3 Wind resource model

As the objective of the optimizer is to minimize the production loss from the curtailments, the optimizer needs a fast and reliable way to assess the production output in each iteration of the optimization. The concern is not to find the correct absolute production but to arrive at a relative production difference that will be true, also when the production is assessed in a *PARK* calculation.

For an optimization with only wind speed and/or wind direction as optimization dimensions, a wind resource map is a fast and adequate means of assessing the relative production loss. A wind resource map can be produced elsewhere and not necessarily by the acoustic consultants and in many cases a *GASP* map will be adequate enough. *GASP* is available to all windPRO users. To use a wind resource map in the optimizer does not require license to any energy modules except *PARK* and *OPTIMIZE*, nor does it require *WASP*, though either or both may be required to calculate a custom resource map.

If time, temperature and/or humidity are included as optimization parameters, the wind resource map is not enough to calculate the losses. This is where the time series calculation must be used. If the project already includes a time domain wind model, this can simply be reused here. The concept of Scaler and selection of time

series is identical to that used by the rest of windPRO. This means that the concerns about limiting the effective time series to the concurrent part of those time series selected also applies here, but as the concern is relative wind speed, the potential bias from such limitations is less of a problem. The time series model may require *WAsP* if *WAsP* is selected in the scaler. However, there is no need for other windPRO energy modules than *PARK* to run the time series wind model in the NCO.

It is the same relaxation of the requirements that explains that only the *PARK2* model can be selected with just two wake decay constant settings. The wake model is needed as a change of the operation mode changes the Ct curve and thereby the wake loss on adjacent turbines. This is the reason some turbines may actually generate more energy when other turbines are curtailed. The precision of the model is, however, not a priority.

The Wind speed inside wind farm model in the noise model can be linked to the wind resource model so only a single model is needed. This will also ensure consistency.

8b.2.4 Strategy decisions

The strategy is a core element of the optimization because it is here you tell the optimizer how you want to optimize your operation. It distinguishes between what is tested and what is optimized. A test means that the noise model will test for compliance and an optimization means that the wind farm will be curtailed in order to comply with the tests.

Often there is a good match between the two. You test specific bins, and you curtail the same bins. In some dimensions, a fixed value is used and so there is no optimization along that bin. But there is a fundamental difference between tests and bins in that a test is done for a specific value and an optimization is done for a bin of a certain range. Sometimes the test is done for the center value but is easy to imagine several tests within a bin (that all have to comply) or bins without a test.

The bar in the strategy view demonstrates this (*Figure 17*). In the example below there is a test for every 1 m/s from 6 to 12 m/s. However, the turbine can only be optimized in 2 m/s intervals and that means that there will be two tests in each optimization bin except for the last bin.

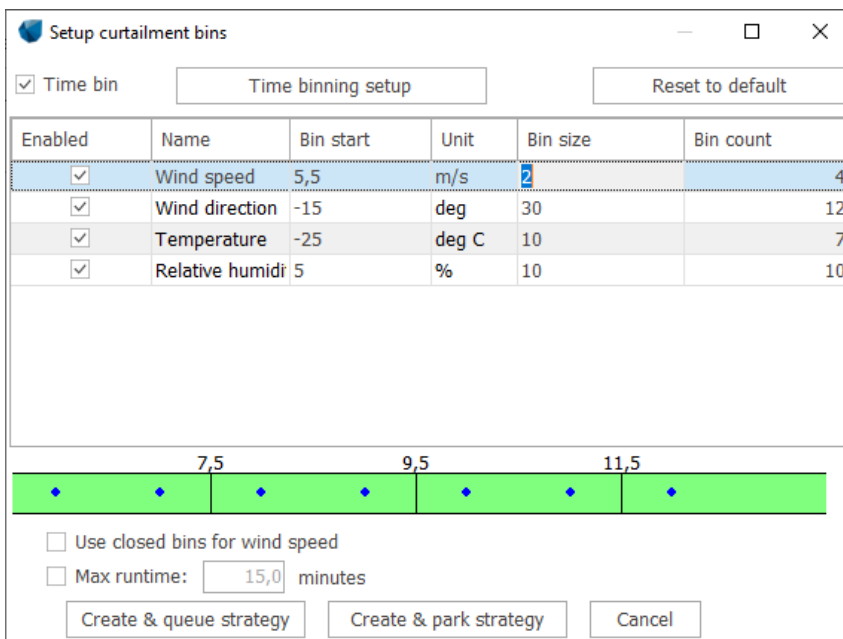


Figure 17: Binning setup decision.

If the noise model uses wind speed as hub height wind speed and all turbines experience the same wind speed at the same time (uniform wind speed), the turbines may be curtailed in the bins listed. Again, in the above example, the turbines may be curtailed in the wind speed bin from 5.5 m/s to 7.5 m/s and the next three intervals.

As this display shows the wind speeds of the noise model, the translation to what happens at the turbine becomes a lot more complicated if the wind speed in the wind farm is not uniform and / or if the wind speed is at 10 m height. In that case, the test wind speeds, and the curtailment bins are translated to the hub height wind speed of every single turbine and the resulting bins may look different from the strategy view

This conversion of wind speed may lead to bins without tests. Here, the NCO distinguishes between untested bins inside the tested range and outside the tested range. Inside the tested range, it is assumed that the turbine cannot run unrestrained just because it is not tested. In this case, the most restrained neighboring bin must be adopted. Outside the tested range the question is settled with the concept of open or closed intervals. Open intervals mean that the turbines must operate in the operation mode(s) of the closest wind speed tested. Closed intervals mean that outside the tested range, there are no restrictions, and the turbine is set free. In the strategy view, this is indicated in the bar and in the curtailment results as a label on the lowest and highest wind speed (for open intervals) and a bookending bin with non-curtailed operation (closed intervals).

Often, the wind model is set up to calculate noise at a fixed wind speed or an unspecified wind speed, such as “Highest noise value” or “95% rated power”. In those cases, wind speed cannot be a dimension, even if the binning file allows it. The operation mode must be valid for all wind speeds, even if only a special case is tested. In the presentation of the curtailments, wind speed is then replaced by a non-wind speed line. The same principle applies for the other dimensions. Fixed values on the parameter means it cannot be an optimization dimension.

8b.3 Optimization algorithm

In contrast to using meta-heuristics to search for optimal strategies, the windPRO noise curtailment optimizer reduces the number of solution evaluations by following a deterministic greedy approach based on relative contributions of WTGs to exceedance levels at noise receptors. This approach limits the number of computations and reduces computation times but can possibly lead to local optima.

8b.3.1 Noise curtailment optimization algorithm

If the highest turbine operation modes lead to noise compliance violations, a strategy is derived for each binned variable and saved in a curtailment strategy matrix. The strategy is computed following a procedure that first identifies whether turbines must be shut down, and then produces a curtailment strategy for all WTGs that are not shut down.

8b.3.2 Turbine shutdowns

To check whether turbines must be shut down completely, all turbines are set to the lowest turbine operation mode and a noise compliance check is performed. While the noise exceeds the allowed noise levels, the turbine with the highest contribution to NSA noise levels is shut down until the park compliance is achieved. Afterwards, all turbine operation modes are reset to the highest operation mode. If the noise compliance for the park with the removed turbines still exceeds permissible noise levels, the operation modes are optimized in the next step.

8b.3.3 Operation mode curtailment

The operation mode curtailment algorithm is a greedy approach. While the noise levels exceed permitted noise levels, the following sub-procedure is: First, the receptor with the highest exceeded is identified. Then, a metric is computed for each turbine that quantifies the relation of produced power per noise exceedance. The turbines are sorted reversely according to that metric, and the turbine with the worst relative power per noise contribution gets downregulated into the next mode. This loop is continued until the noise constraints are not violated any longer for the current bin.

8b.4 References

- [1] Cao, Jiu Fa; Zhu, Wei Jun; Shen, Wen Zhong; Sørensen, Jens Nørkær; Sun, Zhen Ye (2020): Optimizing wind energy conversion efficiency with respect to noise: A study on multi-criteria wind farm layout design. In *Renewable Energy* 159, pp. 468–485. DOI: 10.1016/j.renene.2020.05.084.
- [2] Nyborg, Camilla Marie; Fischer, Andreas; Réthoré, Pierre-Elouan; Feng, Ju (2023): Optimization of wind farm operation with a noise constraint. In *Wind Energ. Sci.* 8 (2), pp. 255–276. DOI: 10.5194/wes-8-255-2023.
- [3] Steurer, Martin; Fahl, Ulrich; Voß, Alfred; Deane, Paul (2017): Curtailment. In : Europe's Energy Transition - Insights for Policy Making: Elsevier, pp. 97–104