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A new criteria to classify orographic complexity for wind energy yield assessment

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Abstract. The assessment of orographic complexity is a central factor when determining the wind- and energy potential for proposed wind energy projects. Orographic complexity is particularly important for evaluating the suitability of flow models, as it can influence the limits of applicability of different models and methods. The criteria currently used in Technical Guideline 6, Revision 11 to assess orographic complexity is based on the method of IEC 61400-1, Ed.3, where complexity is characterized by the variations of the terrain topography from a plane, the radius of observation of which depends, among other things, on the hub height taken as a basis. However, it has been shown that this methodology does not meet the technical requirements for use in wind and yield potential assessments and, moreover, does not correspond to the subjective assessments of experts. In order to close these gaps, we present in this article a new pragmatical methodology for assessing terrain complexity, which was developed and validated within the framework of the FGW Expert Committee on Wind Potential (FGW FAWP). Additional aspects, such as variations in terrain, explicit design for wind and energy potential analysis, similarity between sites considered (e.g., location of wind measurement and location of proposed wind turbine), and consideration of terrain slope, were included. The application of this procedure allows an objective assessment of the terrain complexity and thus helps to define more precisely the limits of transferability of wind conditions using flow models.

1. Motivation

Assessment of orographic complexity is a criteria for suitability of wind data sources in a wind study since [1] and [2], therefore since more than 10 years. Both guidelines use the complexity criteria as defined in [3] which is binary, meaning the result of a complexity check is either “complex” or “not complex”. Based on the result both guidelines mainly define a maximum distance between a wind data source and a newly planned WTG that is allowed.

Over the years it turned out that this complexity criteria does not always deliver optimal results that fit the assessment of expert reviewers on the complexity in the context of a wind resource assessment. This is not surprising, as the purpose of the complexity criteria in [3] is different. It is designed for determination of additional loads due to ambient turbulence in the context of site suitability which does not necessarily mean it is as well suited for estimating the complexity of flow in wind resource assessment. Another drawback is the binarity of the criteria. The latter has been modified in [4], where several stages of complexity have been introduced as possible results and also the criteria itself has been modified. The suitability of this new criteria was tested by the “Fachausschuss Windpotenzial” (FAWP) in 2021 and no improvement in regards of wind resource assessment was seen.

As a consequence, the FAWP decided to establish a working group that should examine the options to improve orographic complexity assessment in the means of wind resource assessment. In a first step, the working group collected the requirements for a complexity criteria, the actual degree of fulfilment using the [3] criteria and the degree of difficulty to fulfil the requirements with a new criteria. The

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result was that very few requirements are fulfilled at the present state, but many can be fulfilled with low effort by developing new criteria (see table below).

Table 1: New criteria for assessment of topographic complexity

Criteria	Actual fulfilment (0-not at all, 2-completely fulfilled)	Importance (0-unimportant, 2-very important)	Reachability (0-easy, 2-complex)
Designed for wind resource assessment	0.0	1.8	1.0
Project domain considered (typically about 40x40 km)	0.0	1.4	0.4
Assessment of similarity of sites	0.2	2.0	0.6
Company-specific validation	0.6	1.6	1.4
Public validation	0.4	1.4	1.8
General suitability for wind (public available)	0.0	1.4	0.8
Applicable with reasonable effort	1.8	1.8	1.0
Consideration of wind directional distribution	1.2	2.0	1.0
Consideration of terrain elevation variations	1.4	1.8	0.0
Consideration of terrain slopes	1.4	1.8	0.2
Good reproduction of wind experts' assessment of orographically simple and difficult sites	0.8	1.8	1.6
Applicability for model class distinction (WAsP => CFD)	0.2	1.0	1.8
Independency on hub height	0.0	1.4	0.6
Smooth (at least not binary) criteria	0.2	2.0	0.6

2. Survey and results

A survey was carried out in spring 2022 to get the opinion of wind consultants and members of the FGW committee on the complexity and the subjective difficulty to transfer wind resources for 30 selected sites around the world. Each site contained 2 positions A and B, the objective was to transfer observed wind conditions from A to B. The sites covered a broad bandwidth of complexity, from very simple, flat terrain to alpine sites. The members of the FAWP were invited to participate on the survey. The following questions were asked:

1. On a scale from 1 to 10, rate the complexity only of position A.
2. On a scale from 1 to 10, rate the complexity only of position B.
3. For the previous 2 questions, in which radius the terrain was considered?
4. On a scale from 1 to 10, rate the comparability of the two positions in regards of orography.
5. On a scale from 1 to 10, rate the expected representativity of the wind conditions at position A for the wind conditions at position B.
6. What is the maximum distance between A and B where you would not consider an additional uncertainty penalty in situations that you rank similar in regards of the orographic situation?
7. From what distance between A and B a wind study is not possible any more in situations that you rank similar in regards of the orographic situation?
8. What is the additional uncertainty penalty (in % on AEP) that should be considered when the latter distance is reached?

Depending on the site and the question, between 15 and 19 replies were collected. The evaluation showed a remarkably accordance of the different consulting companies that participated although it is expected that the assessment of complexity is very subjective. Table in Appendix 9.1 shows the overall results of the survey.

doi: 10.5281/zenodo.10078649

Next, we examined in detail how the ratings of orographic complexity and similarity relate to the distances in question 6 and 7. Even considering only the complexity, a surprisingly strong linear correlation emerged. Further, it makes virtually no difference whether the summary is based on the mean value or the maximum of the complexity of the two individual sites. The following two graphs show the correlation between complexity mean A and B and distance from question 6 (left graph) and including the similarity by 40 % (right graph):

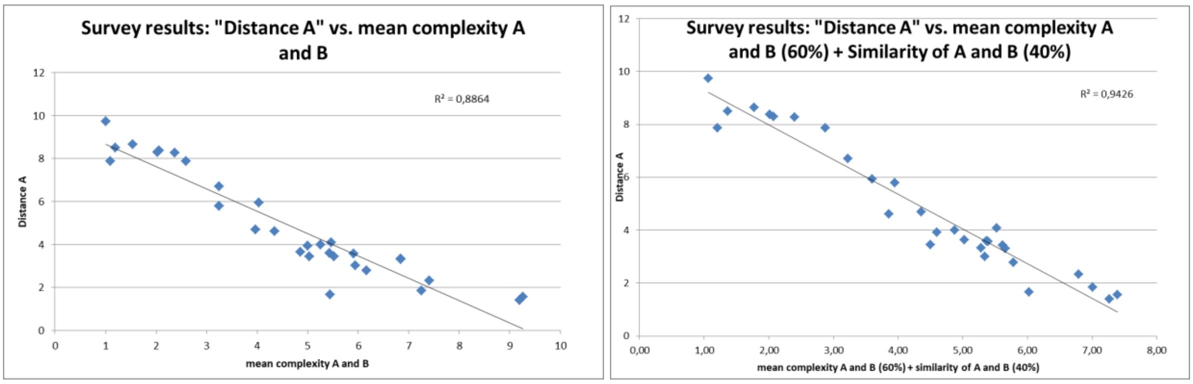

Figure 1: Left: Correlation between complexity mean A and B and "distance A" (according to survey)
Right: Correlation between a combined measure of mean complexity A and B and the similarity between A and B, and the "distance A" (according to survey)

The results are similar when evaluating the distance from question 7, only with higher distance numbers.

Even taking into account complexity only, the coefficient of determination is remarkably high (0.89). This value can be increased again noticeably to 0.94 by adding similarity. These results conclude to the following:

1. The orographic complexity as estimated only by experience of the participating experts has a strong correlation to their estimate on how far a transfer of wind conditions is still possible.
2. This strong correlation becomes even higher when including the estimate of orographic similarity between sites A and B.

This means that objective, technical criteria that reproduce the experts' assessments of complexity and similarity well are also well suited for determining maximum distances for transferring wind conditions from A to B. It also means that including similarity will deliver better results than considering complexity only.

3. Testing procedure, identification and optimization of suitable indicators

3.1 Utilized software SAGA GIS

The open-source software "System for Automated Geoscientific Analyses" (short SAGA) [5] is primarily used for the physical-geographical calculation and presentation of geographic data, which is mostly available based on raster data.

SAGA originally arose from many small, specialized programs for various geoscientific calculations, which were combined into one program. SAGA is mainly developed at the Department of Geography at the University of Hamburg. The indicators described in chapter 3.3.1 to 3.3.7, that were used to measure terrain complexity, were supplied by and executed in the software SAGA [5].

doi: 10.5281/zenodo.10078649

3.2 Step wise process of reviewing tools to measure terrain complexity

The analysis for each tool consists of comparing the given indices from the SAGA tools with the values of the previous survey. A tool with a specific set of parameters only passed a step if the results were promising. If not, a new tool or new parameters were used for the investigation.

1. Each tool was first checked for five to ten locations.
2. The tool was used to calculate the results for all locations.
3. Only if the overall result for all locations were showing a very promising correlation between the indices and the terrain complexity the results were relayed to the "Complexity Working Group".

3.3 Reviewed tools to measure terrain complexity

3.3.1 Wind Effect (Windward / Leeward Index) [6]

The "Wind Effect (Windward / Leeward Index)" [6, 7] (short Wind Effect) is a parameter used to assess the impact of wind on a particular area. This index provides valuable insights into the wind exposure and sheltering conditions across the landscape.

To calculate the Wind Effect, a dimensionless index is considered, meaning it does not have any units of measurement. The index is derived by comparing the windward and leeward conditions of a location, all regarding the specified wind direction.

Values below 1 indicate wind-shadowed areas, where the terrain or landforms act as barriers and provide protection from the wind. These areas experience reduced wind exposure and may have relatively calm conditions.

Conversely, values above 1 indicate areas exposed to the wind. These locations are more susceptible to wind effects, including higher wind speeds and increased turbulence. The index value reflects the degree of exposure to wind for a given area in relation to the specified wind direction.

Fundamentally the index was used in combination with the main wind directions. On basis of accessible reanalysis data with the best spatial resolution, typically EMDWRF, ERA5 and MERRA2, a wind rose for each location was created. These wind roses where subdivided into 30-degree segments and were displaying the amount of energy in each 30-degree segment. The segment with the highest amount of energy was chosen as the main wind direction.

For the calculation, the Wind Effect tool considered the terrain in a radius of 20 km around each reviewed position. This tool passed all three steps of analysis.

3.3.2 Wind Exposition Index

The "Wind Exposition Index" is basically the Wind Effect from 3.3.1, but now it is not calculated for one wind direction, but for all directions. This is implemented through an angular step which can be set freely. The average of the Wind Effect for every angular step creates the Wind Exposition Index. Similar to the Wind Effect, this index is dimensionless. Values below 1 indicate areas sheltered from the wind, while values above 1 indicate areas exposed to wind.

In this case, an angular step of 30-degree was selected and a radius of 20 km terrain was considered. Further this tool passed all three steps of analysis.

3.3.3 Frequency based weighted Wind Effect (Windward / Leeward Index)

This Index is a mixture of the Wind Effect 3.3.1 and the Wind Exposition Index 3.3.2. It considers all wind directions, like the Wind Exposition Index, but is not weighting all directions the same. It combines the Wind Effect for each 30-degree segment with the percentage of each segment of the total amount of wind energy. This way the new index can consider the whole terrain, but different to the Wind Exposition Index not every wind direction has the same share in building the final index.

In this calculation the terrain was considered in a radius of 20 km. Only the first two steps of analysis were passed.

3.3.4 Topographic Position Index (TPI)

The "Topographic Position Index" [8–10] (TPI) is a method used in geography to classify and analyze terrain based on its elevation characteristics. It provides a quantitative measure of the relative position of a point within its local neighborhood, aiding in the characterization of landforms and landscape features.

The TPI calculation is performed for each data point in the terrain, resulting in a grid with TPI values assigned to each location. This grid provides a comprehensive representation of the topographic position.

To calculate the TPI, first a specific data point in the terrain was considered. Next, the elevations of the surrounding points within a defined neighborhood or window were examined. This neighborhood can vary in size, depending on the specific application and study area.

Once the elevation values of the neighboring points are gained, they were compared to the elevation of the central point. The TPI is determined by evaluating whether the central point is higher or lower in elevation than its surrounding points.

If the central point is located at a higher elevation than its neighbors, the TPI value will be positive. This indicates that the point is situated on a ridge or hilltop. On the other hand, if the central point is at a lower elevation than its neighbors, the TPI value will be negative. This suggests that the point is situated in a valley or depression.

In cases where the central point is on relatively flat terrain or a continuous slope, the TPI value will be near zero.

In this case the TPI were calculated for radii of 1 km, 3 km, 5 km, and 10 km. All with an inversed distance weighting to a power of 2. While all different parameters passed step one and two in the analysis, only 5 km were considered to pass step three, because it provided the highest correlation.

3.3.5 Multi-Scale Topographic Position Index (TPI)

In this implementation of the TPI into the “Multi-Scale Topographic position Index (TPI)” [8–11], the TPI is computed at various scales and combined into a unified grid. The hierarchical integration process begins by considering the standardized TPI values at the largest scale. Subsequently, standardized values from smaller scales are added to the grid, but only if the absolute values from the smaller scale surpass those of the larger scale.

In this case the Multi-Scale Topographic Position Index (TPI) were used with a maximum scale of 5 km and a minimum scale of 50 m. In between these ranges five different scalings are calculated according to the pattern explained above. This tool passed the first two steps of the analysis.

3.3.6 Terrain Ruggedness Index (TRI)

The "Terrain Ruggedness Index" [12] (short TRI) is a metric commonly used in geography to quantify the roughness or ruggedness of a given terrain. This index provides valuable information about the variability and complexity of the landscape.

To calculate the TRI, the elevation values of the terrain must be considered. The index is computed by examining the differences in elevation between neighboring cells within the terrain dataset. By

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measuring and aggregating these height differences, a numerical value that represents the ruggedness of the terrain is obtained.

The calculation of the TRI involves several steps. First, a specific area or region within the terrain was identified. Then, the elevation values of the neighboring cells surrounding each location within that area were determined.

Next, the elevation of each central cell was compared with the elevations of its neighboring cells. The differences in elevation are quantified and aggregated to generate a measure of ruggedness. The resulting TRI value provides an indication of the roughness of the terrain at a given location.

A higher TRI value indicates a more rugged terrain, characterized by significant variations in elevation and the presence of steep slopes or abrupt changes in topography. Conversely, a lower TRI value suggests a smoother and more gently sloping terrain with fewer pronounced elevation differences.

The neighboring cells considered were in this case within a radius of 1.25 m, 2.5 km, 5 km, 7.5 km and 10 km around each reviewed position. The TRI passed only step one and two in the analysis.

3.3.7 Standard deviation

Furthermore, we also reviewed the standard deviation from grade elevation of each location in perspective the overall elevation from DEM in a radius of 2.5 km. This approach did not pass the first step of analysis.

3.3.8 Ruggedness Index (RIX)

The Ruggedness Index (RIX) is a measure of the steepness or ruggedness of the terrain around a site, defined as the percentage fraction of the terrain within a certain distance from a specific site which is steeper than some critical slope. This index was proposed as a coarse measure of the extent of flow separation and thereby the extent to which the terrain violates the requirements of linearized flow models.

3.3.9 IEC 61400-1 Ed. 4 indices (TVI, TSI)

The IEC 61400-1 Ed. 4 [4] proposes that the complexity of a site is characterized by the slope of the terrain and variations of the terrain topography from a plane that is best fitted to the terrain. IEC 61400-1 Ed. 4 [4] proposes to assess the complexity of the terrain by means of a terrain variation index (TVI) and terrain slope index (TSI). Each indicator aggregates the slope respectively the terrain variation along twelve 30° wide sectors (weighted by their energy content), for a certain radius around the turbine position. The indices are calculated for radii as a function of the hub height:
($5 \times z_{hub}$, $10 \times z_{hub}$ and $20 \times z_{hub}$).

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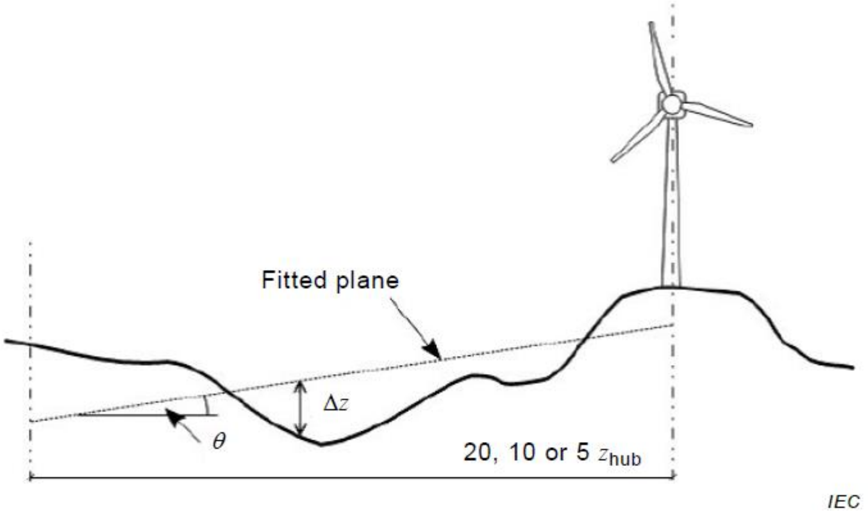

Figure 2: Terrain variation Δz and terrain slope Θ [4]

The IEC 61400-1 [4] further proposes a terrain complexity categorization based on the highest category TSI or TVI for any of the circle areas.

Table 2: Threshold values of the terrain complexity categories L, M and H [4]

Radius of circle area	Sector amplitude of fitted plane	Threshold values (lower limit)					
		Terrain slope index (TSI)			Terrain variation index (TVI)		
		L	M	H	L	M	H
5 z_{hub}	360°	10°	15°	20°	2 %	4 %	6 %
5 z_{hub}	30°						
10 z_{hub}							
20 z_{hub}							

In order to use this proposed procedure to assess the complexity of the terrain for the purpose of this case study, some adjustments had to be made:

- The virtual "hub height" has been set (for every site) to 200m - this led to the assessment of the TVI and TSI in the radius of 1000 m, 2000 m and 4000 m.
- Instead of the classes (L, M and H) the raw TVI and TSI values for 1000 m, 2000 m and 4000 m has been used as a measure to define orographic complexity of each of the sites.
- The twelve sectors have been weighted equally (as no energy content was available)
- The index representing the complexity of a site is derived based on the maximum index (TVI and TSI) for any of the circle areas of 1000 m, 2000 m and 4000 m radius, thus the complexity is derived from the most complex circle area.

Those adjusted indices were called TVI Max and TSI Max [4] and were calculated for each of the sites "Position A" and "Position B".

4. Identification and optimisation of suitable indicators

The survey has shown a clear (linear) dependency of the proposed maximum distances for the transfer of wind resource (Questions 6 and 7) from a measure (=an index) that combines the complexity of the terrain of the sites A and B and the similarity of the two sites.

In other words, if the single results from the survey for complexity (scale from 1-10) and for the similarity of sites A and B could be re-produced using objective indicators based on numerical assessment of the terrain, the respective maximum distances for the transfer of wind resource in the context of a resource assessment could be assessed with objective measures.

Therefore, the FGW working group has developed a testing procedure to examine the suitability of multiple terrain indicators to reproduce the results of the survey in terms of complexity and similarity of sites.

After that, research has been made to identify various indicators which are used explicitly in the wind energy industry and also in other industries. Every of the identified indicators was tested in the developed testing procedure. Indicators with promising ability to reproduce the survey results were then optimized by change of the parameters, in order to improve the reproduction.

The identification and optimization of suitable indicators is based on a correlation analysis between the indicators used and the survey results. Not only presented complexity indicators were considered, but also relevant parameters of the individual complexity indicators were varied in order to optimize the correlation. The first step was to correlate the results from the various complexity indicators with the survey results. The two relevant parameters examined are the orographic similarity of the respective paired sites and the absolute orographic complexity for the respective paired sites. After the results were normalized so that a direct comparison was possible, promising complexity indicators were identified and subsequently optimized. Appendix 9.2 describes the testing and optimization procedure in detail.

5. Optimization procedure

Indicators that were found to be generally suitable to reproduce the survey results were further assessed for their potential for optimization. Many of the indicators use parameters that can be changed in order to adapt the sensitivity of the indicator to terrain variations. The parameters of the indicators were changed to improve the correlation to the survey results. An example of such an optimization is shown in the next chapter.

5.1 Optimizing the complexity correlation based on an example (here: RIX-values)

In the following figure the correlation of the complexity according to the survey and the standard RIX values for the investigated sites is shown. In principle, the RIX complexity indicator seems to be suitable, but it can be seen from the figure that the RIX value is too low for sites that were already assessed as moderately complex by the survey participants.

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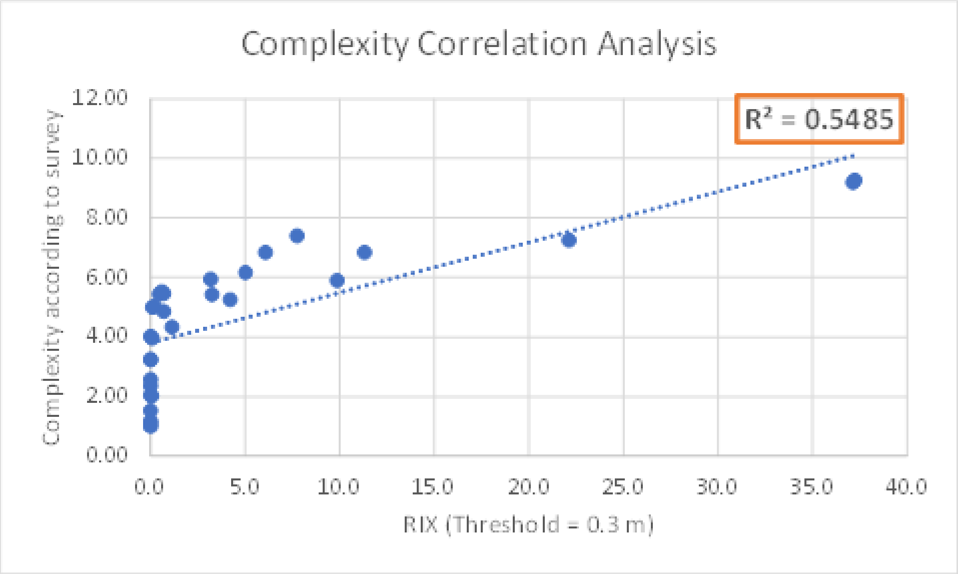

Figure 3: Correlation to survey results with the "original" definition of RIX (threshold 0.3 m)

Among others, the RIX threshold (default: 0.3 m) is a key parameter to modify the RIX's sensitivity. Therefore, this parameter was adjusted to optimize the correlation coefficient R².

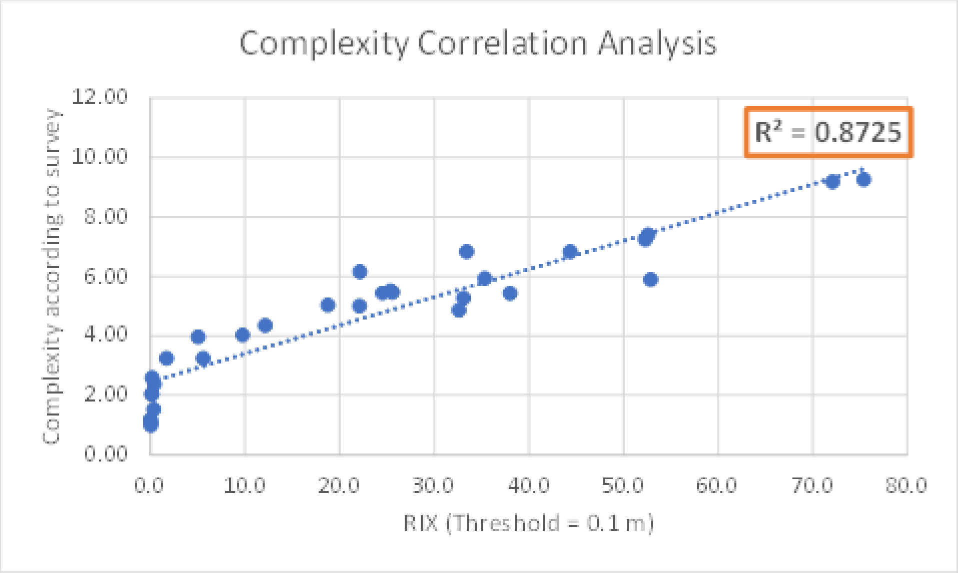

Figure 4: Correlation to survey results with the "adjusted" definition of RIX (threshold 0.1 m)

By reducing the threshold further, the maximum correlation coefficient R² was found to be 0.033 m, as shown in the next figure.

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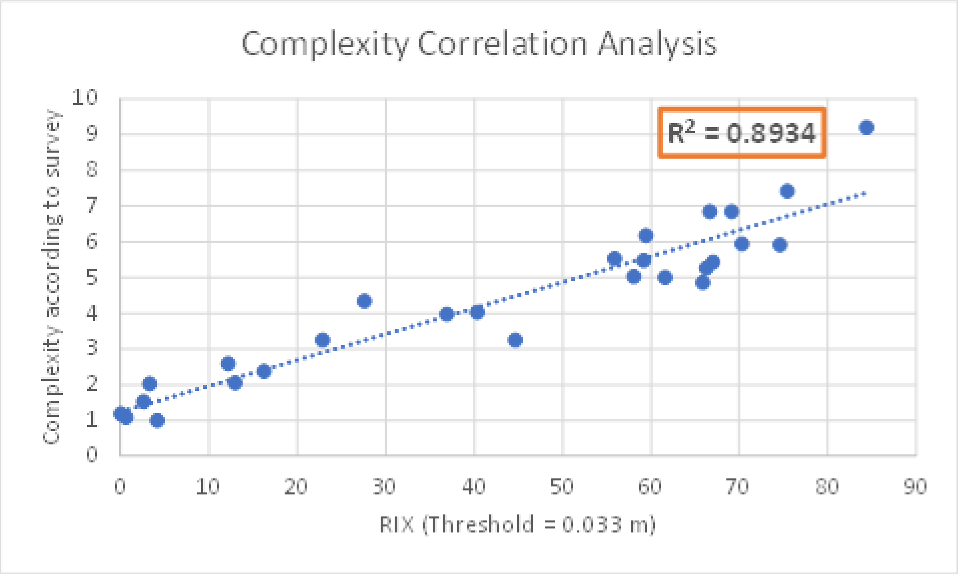

Figure 5: Correlation to survey results with the finally optimized definition of RIX (threshold 0.033 m)

5.2 Best indicator to assess complexity of a site

From different variations of the complexity indicators under consideration (see 3.3), RIX calculations with a radius r = 3500 m and a threshold of th = 0.033 showed the best correlation in terms of the absolute orographic complexity with the survey results. The RIX with the adjusted parameters were therefore used to represent the complexity of a site in the further part of the work.

5.3 Optimizing the orographic similarity correlation

In analogy to the optimization of the correlation of the RIX values and the survey results (as described in the previous chapter), the correlation coefficient R^2 of the orographic similarity and the survey results of all paired sites was also optimized, as far as possible.

The indicators that showed promising behaviour to reproduce the survey results for the similarity between two sites (in descending order) were the (i) (Delta of) topographic position index, (ii) the simple difference in elevation between the two sites and (iii) the (delta of) RIX.

The optimization process (to maximize the correlation between the index and the survey results for similarity) lead for the TPI and the Delta Rix to the need to apply further mathematical functions (like log10 or sqrt) to the indicators. The application of those functions for the sole reason to maximize correlation to the survey results was not deemed constructive. Furthermore, the need to calculate two different kind of indicators for complexity and similarity was also not deemed to fulfil the requirement of easy usage of the indicator.

On the other hand, the survey has shown, that similarity of two sites plays a large role for the assessment of the suitability and accurateness of flow models to transfer wind resources from one to another site.

Therefore, under consideration of all aspects, the “measure” of the simple difference in elevation between two sites is proposed as an indicator for the similarity of two sites, defined later as $|\Delta h|$ It later came out that the performance of this approach, in combination with the chosen orography indicator performed almost as good as the best – and much more complicated – similarity indicator.

5.4 Normalization and combination of indicators for complexity and similarity

In order to achieve a direct comparison to the survey results, in the next step the indicators were normalized to the same scale as the survey results (from 1-10). Then, in analogy to the assessment of the survey results, a simple combination of the indicator for complexity and similarity was done by the

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method of weighted average. The weighted average of the measure for complexity and the measure for similarity (for every of the 30 sites) was then compared with the results from the survey for the maximum distances for the transfer of wind resource (refer to Questions 6 and 7). For better understanding the maximum distance from question 6 (maximum distance for the transfer of wind resource without uncertainty penalty is called “yellow line”, also called “limit A” and the maximum distance from question 7 (no transfer of wind resource possible anymore) is called “red line” or “limit B”.

The comparison was done in a y-x plot and a linear relationship (linear regression) was expressed between the value of the (combined) indicator (complexity and similarity, weighted average) and the value of the yellow and red line based on the survey (y-Axis = yellow resp. Red line of survey, x-Axis = value of combined indicator that is to be assessed).

Then, the weight of complexity and similarity respectively was adjusted in a way, that the combined measure achieved the highest correlation to the yellow line (“Distance A”) and red line (“Distance B”) distance from the survey. The coefficient of determination was used as a measure for the ability of a certain (combined) indicator to re-produce the survey results. An example of the result of such a test can be found in Figure 6.

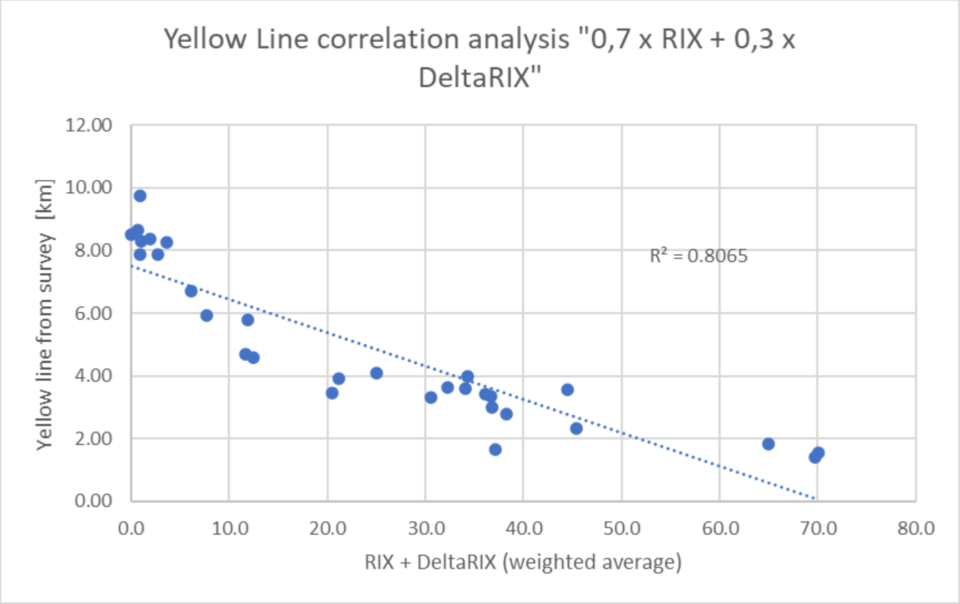

Figure 6: Example of correlation analysis using combination of complexity and similarity indicators (each point represents the results for one of the 30 pairs from the survey)

6. Results

After all possible complexity indicators are evaluated and optimized in terms of absolute orographic complexity and orographic similarity, the final representativeness measure was developed.

From the above steps, a correlation-optimized weighting of complexity (RIX) and absolute difference in terrain elevation |Δh| was performed against the yellow and red line distance. Both values were used dimensionless (a RIX of 35 % is 35; a difference in elevation of 40 m is 40) with the following result:

$$Representativeness\ measure\ T-RIX = 0.9 \cdot mean(RIX) + 0.1 \cdot |\Delta h|$$

The relatively low weight of 10 % for the measure for similarity is somehow in contradiction with the weight of the similarity of 40 % based on the survey results (to optimize for correlation with yellow and red line). The reason for the lower weight is due to the lower quality of correlation for the measure for similarity.

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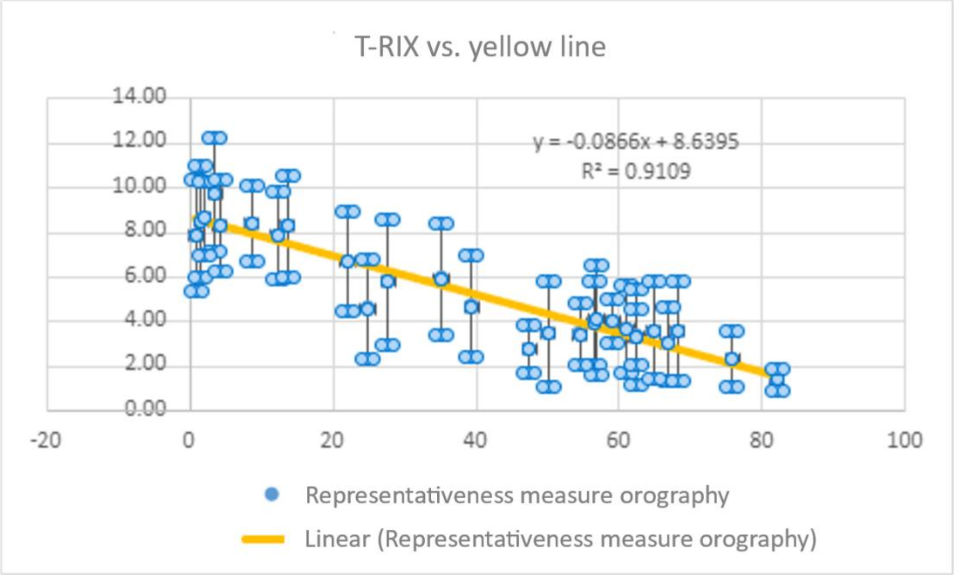

Figure 7: Representativeness measure of T-RIX vs. yellow line

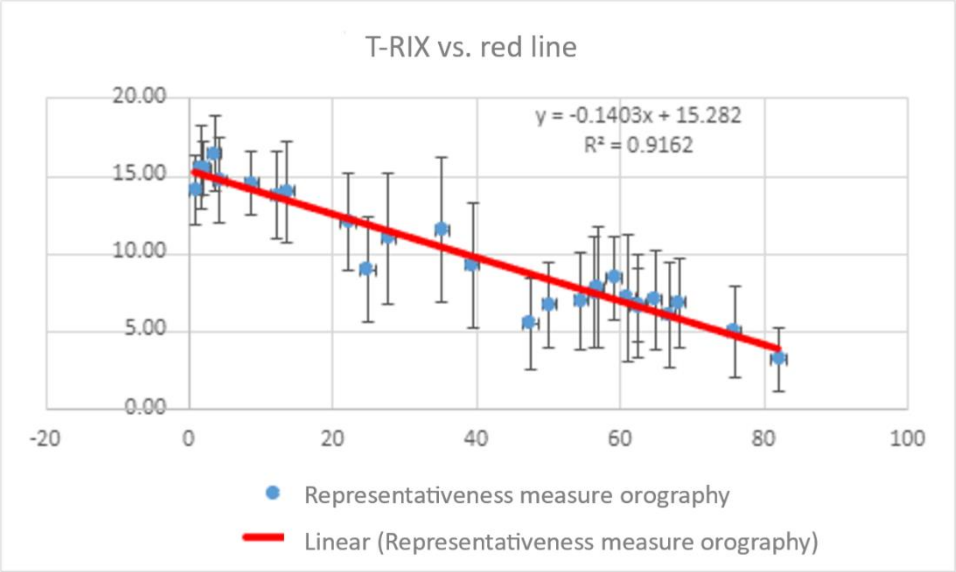

Figure 8: Representativeness measure of T-RIX vs. red line

6.1 Investigation of the influence of the wind direction distribution

In the further elaboration of the representativeness measure, the influence of the wind direction distribution was examined. For this purpose, the wind direction distributions for all 30 sites were extracted from available data sources and weighted accordingly with the available sectoral RIX values per site. The result of this evaluation showed that for the vast majority of sites the influence on the representativeness measure can be considered small. Even from the low standard deviation of the sectoral RIX values, it can be deduced that complex sites are obviously rated very similarly in all directions in the vast majority of cases.

6.2 Investigation of the sensitivity

In addition, the influence of the input data on the result of the RIX calculation was investigated. Besides using different tools with different settings to convert raster data into the WAsP *.map format needed for the RIX calculation, the influence of the resolution of the original data as well as the influence of the generated line distances within the WAsP *.map files were analysed, among others. The result of this technical sensitivity analysis showed that the result of the RIX calculation is sensitive to the

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resolution of the source data as well as to the applied line spacing. The application of different tools with different settings showed little influence on the calculation of the RIX values. As a consequence, a determination of the contour line distance to be used for the evaluation to 5 m as well as the resolution of the orography data set to be used as a basis to 50 m is made.

6.3 T-RIX definition

As described above, the correlation between absolute orographic complexity and survey results is influenced by the resolution of height contour lines and the settings used for RIX value calculation. To ensure consistent and replicable outcomes, the following requirements for height contour lines and RIX value calculation settings are defined in the revised version 12 of TR6 [13]:

The RIX values are calculated based on contour lines. The following standards apply:

- The horizontal resolution of the grid cells in the underlying orography dataset used to create the contour line file should not exceed 50 meters.
- The vertical contour line spacing in the file must not exceed 5 meters.

The following RIX settings must be chosen for each location:

- Radius r of the considered circle: 3500 meters
- Threshold regarding maximum slope: 0.033 m/m
- Number of sectors: 12
- Number of sub-sectors: 6

For each location, the average RIX value $\overline{RIX}$ is formed in percent over 12 equally sized sectors, starting at 0° as the sector midpoint:

$$\overline{RIX} = \frac{1}{12}\sum_{i=0}^{12} RIX_i$$

Then, from these average RIX values for each individual location (wind data base $\overline{RIX_{wind\ data\ base}}$ and considered WTG $\overline{RIX_{WTG}}$), the RIX mean value $\overline{RIX_{representative}}$ is calculated for the pair of wind data base location and the considered WTG:

$$\overline{RIX_{representative}} = \frac{1}{2}(\overline{RIX_{wind\ data\ base}} + \overline{RIX_{WTG}})$$

The terrain height difference between the wind data base and the considered WTG $h_{representative}$ is determined without sign based on the terrain height of the wind data base $h_{wind\ data\ base}$ and the considered WTG h_{WTG}:

$$|h_{representative}| = |h_{WTG} - h_{wind\ data\ base}|$$

The representativeness measure T-RIX is calculated dimensionless using the following formula:

$$T\text{-}RIX = 0.9 \cdot \overline{RIX_{representative}} + 0.1 \cdot |h_{representative}|$$

6.4 Application in the TR6 guideline

The application of two empirical formulas defines the limits of transferability of wind conditions using flow models based on this representativeness measure T-RIX. These formulas are derived from the survey results, based on the professional experience of the survey participants.

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$$A = \max\left(-0.087 \cdot T\text{-}RIX + 8.5; 1.5\right)$$

$$B = \max\left(-0.140 \cdot T\text{-}RIX + 15.0; 3.0\right)$$

Limit A defines the distance influenced by complexity within which wind conditions can be transferred using flow models. Limit B defines the distance influenced by complexity within which wind conditions can be transferred using flow models while accounting for additional uncertainties. Energy yield assessments for distances beyond the limit of B are not possible within TR6 rev. 12 [13].

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7. Conclusion and outlook

The assessment of orographic complexity is a central factor when determining the wind- and energy potential for proposed wind energy projects. It is crucial for the right choice of the flow model and for not exceeding its borders to transfer reference data to the sites of planned wind energy turbines.

The existing measures of complexity used in the wind energy industry were originally developed as tools to assess the site suitability of wind turbines and the reliability of measured performance curves and are not tailored to assess the wind and yield potential of newly planned wind turbines. Experience showed that the subjective assessment of the terrain by wind consultants often did not go hand in hand with the complexity measure of IEC 61400-1 Ed.3 [3] used so far. Furthermore, the previous measure showed too little variation in the assessment of orographic complexity.

This became clear from a survey conducted among 19 companies on the assessment of complexity and the resulting maximum possible distance to transfer reference data of an existing wind turbine or of a wind measurement site to a newly planned wind energy project.

For this reason, a working group of the FGW tested a variety of parameters that assessed the orographic complexity on 30 pairs of sites. In an elaborate evaluation process, a new measure for the assessment of orographic complexity was developed, which was able to reproduce the subjective assessment of the experts to a high degree and at the same time can be determined with acceptable effort in the context of wind and energy yield assessments. This measure evaluates the transferability of reference data between two sites based on their mean value of an adjusted RIX value, representing the fraction of the terrain within a certain distance from a specific site which is steeper than a critical slope, as well as on their differences in terrain height and was named T-RIX.

This means that in future both the similarity and the complexity of the sites will determine the limits of transferability. There is no longer, as before, a fixed upper limit for the transferability of data from a met mast or an existing wind turbine due to its orographic properties; instead, the limit is calculated individually for a specific pair of data source and planned turbine location. While the limit A indicates the distance up to which a transfer can be made using flow models without increasing uncertainty, the limit B defines the distance within reference data can be transferred using flow models while accounting for additional uncertainties. If the limit B is exceeded, the processing of a TR6 Rev.12 [13]-compliant wind and energy yield assessment using the available reference data is not possible and a wind measurement must be carried out. From the formulas, depending on the calculated T-RIX values of a site pair (reference site; planned wind turbine), values of limit A range from 1.5 to 8.5 km and for limit B from 3 to 15 km. In contrast, the previously used complexity measure only allowed 2 km for complex sites and only 10 km for non-complex sites. Due to the significantly greater variation and the creation process of the T-RIX, it is assumed that the objective assessment of the limits of the transfer of reference data by a wind model corresponds much better to the available terrain characteristics and the assessment of the wind consultant than was previously the case.

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9. Appendix

9.1 Survey results for 30 sites

Table 3: Survey results for 30 sites

Site	**Complexity A**	Standard deviation	Number of replies	**Complexity B**	Standard deviation	Number of replies	**Considered Radius**	Standard deviation	Number of replies	**Orographic similarity**	Standard deviation	Number of replies	**Representativity of wind conditions**	Standard deviation	Number of replies	**Distance A**	Standard deviation	Number of replies	**Distance B**	Standard deviation	Number of replies	**Uncertainty penalty**	Standard deviation	Number of replies
1	1.00	0.00	19	1.00	0.00	19	7527	5926	19	1.16	0.37	19	3.63	1.64	19	9.74	2.54	19	16.47	2.48	19	5.37	2.11	19
2	5.47	1.12	19	5.58	1.43	19	4401	4364	19	2.95	1.39	19	3.26	1.41	19	3.45	2.40	19	6.73	2.79	19	6.13	2.11	19
3	5.33	0.97	18	5.56	1.20	18	4291	4531	18	6.89	1.64	18	7.28	1.93	18	1.67	1.39	18	3.22	2.31	18	6.12	2.54	17
4	4.44	1.50	18	5.28	1.64	18	4847	4690	18	5.28	1.99	18	5.56	1.69	18	3.64	1.96	18	7.21	4.09	18	7.07	2.97	18
5	5.89	1.41	18	6.00	1.57	18	4931	4697	18	4.44	1.54	18	4.94	1.47	18	3.01	1.63	18	6.08	3.38	18	6.38	2.06	18
6	9.24	0.83	17	9.29	0.69	17	4991	4873	17	4.59	1.50	17	6.47	2.29	17	1.55	0.65	17	3.31	2.13	17	7.13	2.22	16
7	1.19	0.40	16	1.19	0.40	16	8512	10021	16	1.63	0.89	16	3.75	1.65	16	8.51	2.52	16	15.59	2.70	16	5.66	2.26	16
8	6.81	1.83	16	6.88	1.75	16	5199	4750	16	2.94	1.12	16	3.50	1.26	16	3.34	1.25	16	6.72	2.31	16	7.03	2.41	16
9	6.88	1.93	16	7.63	1.75	16	4918	4556	16	6.63	2.19	16	7.63	1.96	16	1.84	1.03	16	3.60	2.00	16	6.70	2.84	15
10	4.94	1.44	16	5.06	1.61	16	4991	4647	16	4.00	1.37	16	4.13	1.41	16	3.93	1.89	16	7.54	3.53	16	6.28	2.21	16
11	6.67	1.35	15	5.67	1.54	15	4905	4738	15	5.20	1.15	15	5.40	1.30	15	2.79	1.08	15	5.51	2.97	15	6.63	2.09	15
12	2.06	1.00	16	2.06	1.00	16	5338	5005	16	1.94	0.85	16	2.69	1.01	16	8.38	1.71	16	14.56	2.06	16	5.66	2.22	16
13	5.27	1.87	15	5.67	1.88	15	5590	5117	15	5.60	1.55	15	7.13	1.51	15	4.09	2.46	15	7.83	3.88	15	7.00	3.11	15
14	5.00	1.15	16	5.06	1.84	16	4730	4705	16	6.50	1.75	16	7.44	1.50	16	3.44	1.38	16	6.97	3.12	16	6.09	2.49	16
15	7.31	1.45	16	7.50	1.46	16	4824	4735	16	5.88	2.13	16	6.63	1.78	16	2.33	1.24	16	4.99	2.89	16	6.37	2.13	15
16	4.31	1.74	16	3.63	1.31	16	4813	4728	16	4.94	1.95	16	5.25	1.77	16	4.69	2.25	16	9.28	3.97	16	6.63	2.21	16
17	2.53	1.01	17	2.65	1.11	17	6413	5205	17	3.29	1.36	17	5.18	2.10	17	7.88	2.00	17	13.79	2.77	17	5.82	2.32	17
18	3.94	1.77	16	4.13	1.78	16	5230	4791	16	2.94	1.24	16	3.50	1.32	16	5.94	2.50	16	11.53	4.65	16	6.25	2.14	16
19	1.06	0.25	16	1.13	0.50	16	6845	5371	16	1.38	0.62	16	3.81	2.29	16	7.88	2.50	16	14.06	2.24	16	5.38	2.38	16
20	2.50	0.89	16	2.25	0.77	16	5678	4758	16	2.44	1.09	16	2.75	1.53	16	8.28	2.25	16	14.05	3.26	16	5.88	2.27	16
21	3.25	1.48	16	3.25	1.29	16	5272	4669	16	3.19	1.83	16	3.69	1.58	16	6.71	2.25	16	12.07	3.17	16	6.13	2.38	16
22	4.19	2.14	16	2.31	1.01	16	5887	4982	16	5.00	2.31	16	6.31	2.12	16	5.79	2.80	16	11.00	4.26	16	6.28	2.29	16
23	6.88	1.82	16	6.81	1.91	16	5876	4789	16	3.88	1.26	16	4.63	1.36	16	3.31	2.13	16	6.63	3.34	16	6.63	2.15	16
24	4.50	1.51	16	4.19	1.64	16	5271	4688	16	3.13	0.81	16	3.88	0.81	16	4.61	2.23	16	9.01	3.33	16	6.31	2.21	16
25	1.40	0.63	15	1.67	0.62	15	6134	5135	15	2.13	0.74	15	2.93	0.96	15	8.65	1.66	15	15.50	1.74	15	5.87	2.22	15
26	9.13	0.96	16	9.25	0.77	16	4699	4708	16	4.38	2.33	16	5.63	2.50	16	1.40	0.52	16	3.23	2.03	16	7.38	2.37	16
27	5.47	1.13	15	5.40	1.72	15	5056	4743	15	5.27	2.19	15	6.00	2.04	15	3.60	2.21	15	7.05	3.23	15	6.43	2.03	15
28	2.00	0.52	16	2.06	0.68	16	6396	5042	16	2.13	1.15	16	2.63	1.45	16	8.29	2.05	16	14.71	2.75	16	6.00	2.21	16
29	4.76	1.82	17	5.76	1.56	17	5765	4667	17	4.29	1.40	17	5.71	1.31	17	4.00	0.98	17	8.44	2.72	17	6.56	2.09	17
30	5.75	1.81	16	6.06	1.69	16	5053	4725	16	4.63	1.63	16	5.88	1.71	16	3.58	2.23	16	6.88	2.90	16	6.66	2.21	16

9.2 Correlation of the indicator with the results of the survey for the complexity

For every pair of the 30 sites (A and B), the average complexity based on the survey (scale from 1-10) was calculated and compared to the average of the indicator of the two sites. The comparison was done in a y-x plot and a linear relationship (linear regression) was expressed between the value of the indicator and the value of the complexity based on the survey (y-Axis = complexity of survey, x-Axis = value of complexity indicator that is to be assessed).

The coefficient of determination was used as a measure for the ability of a certain indicator to reproduce the survey results. An example of the result of such a test can be found in Table 4.

Table 4: Survey results for TVI Max criteria

Criteria: IEC Ed. 4 - TVI Max				**Survey results**
Parameters for indicator: HH150m, Elevation model 50m				Average Complexity
Site No.	TVI Max A	TVI Max B	Average TVI Max A; TVI Max B	
1	0.2	0.0	0.1	1.00
2	1.1	1.1	1.1	5.53
3	1.1	1.0	1.1	5.44
4	0.8	1.1	1.0	4.86
5	0.9	1.1	1.0	5.94
6	3.2	2.9	3.1	9.26
7	0.4	0.0	0.2	1.19
8	1.2	1.9	1.6	6.84
9	2.2	2.4	2.3	7.25
10	1.0	1.0	1.0	5.00
11	1.4	0.9	1.2	6.17
12	0.1	0.2	0.2	2.06
13	1.1	1.0	1.1	5.47
14	0.9	0.8	0.9	5.03
15	1.4	1.8	1.6	7.41
16	0.7	0.3	0.5	3.97
17	0.1	0.2	0.2	2.59
18	0.8	0.7	0.8	4.03
19	0.0	0.0	0.0	1.09
20	0.3	0.2	0.3	2.38
21	0.3	0.2	0.3	3.25
22	0.6	0.1	0.4	3.25
23	1.1	1.0	1.1	6.84
24	0.4	0.3	0.4	4.34
25	0.0	0.1	0.1	1.53
26	3.0	2.6	2.8	9.19
27	1.1	1.1	1.1	5.43
28	0.1	0.1	0.1	2.03
29	0.9	1.7	1.3	5.26
30	1.2	1.5	1.4	5.91

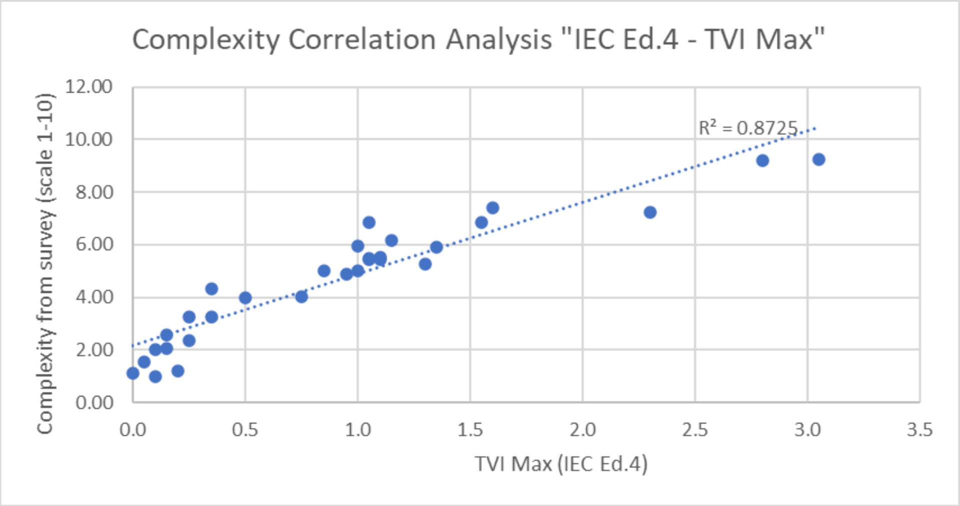

Figure 9: Example of correlation analysis for IEC Ed.4 - TVI Max criteria (each point represents the results for one of the 30 pairs from the survey)

9.3 Correlation of the indicator with the results of the survey for the similarity

For every of the 30 sites (A and B), the similarity of site A and B based on the survey (scale from 1-10) was compared to the indicator of similarity of the two sites. Typically, the indicator for the similarity of two sites was defined as a difference of the indicators for site A and site B which were the same indicators that are used for the complexity. For example, to test the criteria “RIX”, the indicator for similarity was “Delta (RIX Site A; RIX Site B)”.

The comparison was done in a y-x plot and a linear relationship (linear regression) was expressed between the value of the indicator (for similarity of two sites) and the value of the similarity based on the survey (y-Axis = similarity of survey, x-Axis = value of similarity indicator that is to be assessed).

The coefficient of determination was used as a measure for the ability of a certain indicator to reproduce the survey results. An example of the result of such a test can be found in Table 5.

Table 5: Survey results for TPI criteria

Criteria Topographic Position Index (TPI)				**Survery results**
Parameters for indicator: -				
Site No.	Topo position index A	Topo position index B	Delta topo position index	Similarity
1	1.5	1.5	2.75	1.16
2	62.1	62.1	5.04	2.95
3	57.2	57.2	68.38	6.89
4	7.5	7.5	8.98	5.28
5	41.2	41.2	29.37	4.44
6	268.4	268.4	23.08	4.59
7	0.8	0.8	0.16	1.63
8	93.2	93.2	11.12	2.94
9	98.0	98.0	63.20	6.63
10	14.8	14.8	6.74	4.00
11	57.4	57.4	41.56	5.20
12	5.4	5.4	5.08	1.94

Criteria Topographic Position Index (TPI)				**Survery results**
Parameters for indicator: -				
Site No.	Topo position index A	Topo position index B	Delta topo position index	Similarity
13	45.3	45.3	21.00	5.60
14	39.7	39.7	69.42	6.50
15	72.6	72.6	11.54	5.88
16	39.3	39.3	18.98	4.94
17	4.4	4.4	3.69	3.29
18	18.6	18.6	0.28	2.94
19	1.9	1.9	2.49	1.38
20	18.4	18.4	9.67	2.44
21	10.7	10.7	11.07	3.19
22	10.7	10.7	12.37	5.00
23	71.8	71.8	28.23	3.88
24	16.3	16.3	1.66	3.13
25	1.6	1.6	1.71	2.13
26	105.5	105.5	61.07	4.38
27	33.9	33.9	2.79	5.27
28	4.7	4.7	2.06	2.13
29	4.7	4.7	2.06	4.29
30	59.6	59.6	18.03	4.63

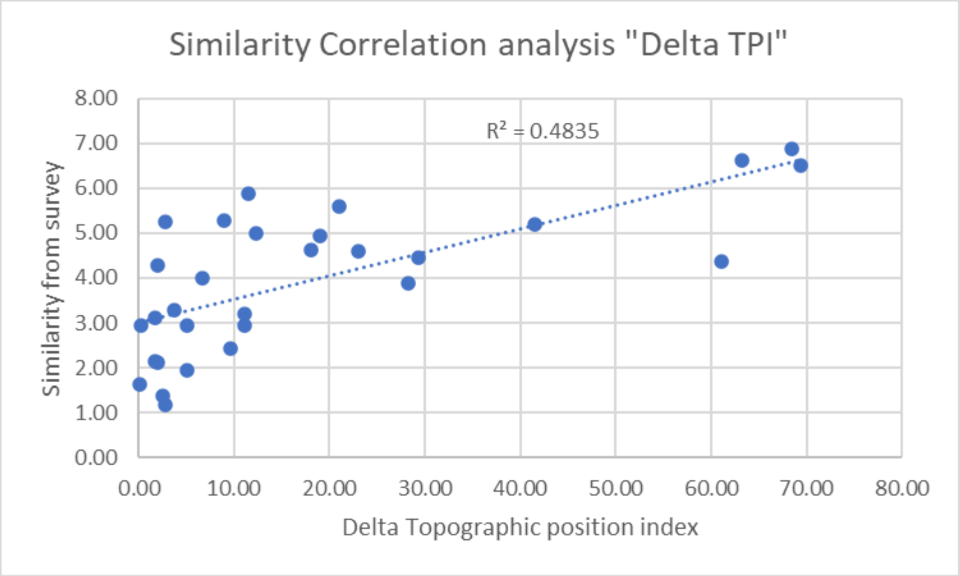

Figure 10: Example of correlation analysis for the similarity of two sites (from survey) with the criteria Delta TPI (each point represents the results for one of the 30 pairs from the survey)