Development of an Indicator of Objective Aesthetic Impact of Wind Farms. Application to Three Wind Farms.

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Abstract: Wind energy represents one of the most important renewable resources. Although wind farms are represented as environmentally friendly projects, they frequently encounter public resistance. One of the main criticisms of wind farm construction projects is directed at their aesthetic impact. This work develops an indicator to assess the magnitude of the objective aesthetic impact caused by the installation of the wind farm. The indicator combines measures of 'visibility', 'colour', 'fractality' and 'continuity' which can be taken from photographs. Value functions are constructed for each variable and incorporated into the indicator, which has been applied to three wind farms. Analysis of the results suggests that the indicator is an appropriate objective measure of aesthetic impact of wind farms.

Key–Words: Indicator, Objective Aesthetic Impact, Wind Farm, Landscape
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1 Introduction

The last few decades have been characterised by an increasing demand for "Renewable Energy" which has a low, or negligible, environmental impact. Wind power is an important contributor to the renewable energy mix. Over the last ten years, global installed generating capacity has recorded a consistent growth of over 20% per year [1]. Although wind farms are often represented as environmentally friendly projects, they frequently encounter public resistance due to the poor integration of the turbines into the landscape [2]; often over 100 meters tall and of a highly artificial appearance the generators are criticised for their aesthetics [3].

Large scale developments such as wind farm construction projects require a visual impact assessment, which has now become a statutory requirement of Environmental Impact Assessment (EIA). Thus there is a need to establish a tool to analyse and evaluate the aesthetic impact generated by wind farm projects.

Work reported on the analysis and evaluation of the aesthetic impact of wind farms on a landscape shows that visual perception of a wind farm is influenced by different factors, of which physical attributes such as visibility and colour may be determined objectively [4, 5, 6, 7, 8] . However, the majority of the studies have analysed each attribute individually without consideration of the collective effect of the components.

One way to evaluate the landscape and its components is by means of quantifiable indicators [9]. Numerical evaluation of an impact is desirable for comparative purposes and because of the straightforwardness with which it can be used in EIA. Often however, indicators become too complicated, or too specific to be useful in practice. The aim of this work is to develop a user-friendly indicator to quantify the objective, collective, aesthetic impact generated by the construction of a wind farm on a given landscape.

This work is a continuation of a paper presented at the *X International Congress of Project Engineering* [10], which introduces the concepts and the steps necessary to develop an indicator to evaluate the visual impact of wind farm projects. Aesthetic impact of a wind farm is affected by the 'visibility', the 'colour', the 'fractality' of the turbines, and the layout of the farm ('continuity'). It is suggested that the effect of each variable on visual impact can be described by value functions determined by expert opinion. The final indicator combines these functions in a weighted sum.

This work presents the value functions for the impacts due to visibility, colour, fractality and continuity. The Indicator of Objective Aesthetic Impact of

Wind Farms (hereafter referred to as OAI_{WF}) is constructed thereof and subsequently used to assess the aesthetic impact of three different wind farms.

2 Aesthetic Impact

Aesthetic impact of an object on a landscape comprises both an objective part which includes physical characteristics of the object, and a subjective part which involves human perception of the object. For example a larger turbine will have a greater impact than a smaller one (objective component). This difference however, may be perceived differently by an external observer, compared to the local resident who may find the turbine unacceptable regardless of its size. Considering human perceptions thus introduces a subjective component. The purpose of this investigation is to study objective visual impact. Hence, it will not seek to establish whether the impact is approved of or not by the viewer population, rather it will present a method to determine the size of the impact, its magnitude[11].

One way to quantify objective aesthetic impact is through the use of indicators. Two conventional methods exist for the development of an indicator of environmental impact, the expert approach and the public preference approach [12, 13, 14]. The first method requires the contribution of skilled and trained experts in the field of environmental sustainability, whereas the second relies primarily on the subjective judgement of the participants affected by the project. The expert paradigm seeks to devise ways of measuring physical attributes of the landscape to reflect visual quality. This approach is widely used in the literature, particularly for landscape planning and management [13]. In this work, we will apply an expert-based methodology to develop an indicator of objective visual impact of wind farms.

3 Development of OAI_{WF}

Visibility, colour, fractality and continuity will affect OAI_{WF} differently, and each will generate a separate impact. A change in the visibility of the landscape will generate an impact due to visibility, I_v. Similarly, changes in colour, fractality and continuity will generate impacts I_{cl}, I_f and I_{ct} respectively.

OAI_{WF} should enable comparison between impacts generated by different types of farms on different types of landscape. Consequently, each I_v, I_{cl}, I_f and I_{ct}, will be a function of the contrast between the farm and the surrounding landscape.

Photographs were taken of different wind farms with varying contrasts in visbility, colour, fractality and continuity, and the ratios were calculated. The calculation procedures for each variable are shown in the following section. Minimum and maximum ratios were assigned impact values of 0 (no impact) and 1 (total impact) respectively. The photographs and their respective results were presented to a panel of ten experts, who were asked to evaluate the visual impact induced by each variable on a scale of 0 to 1. Subsequently, individual value functions were created for each I_v, I_{cl}, I_f and I_{ct}.

3.1 Impact due to Visibility, I_v

The concept of visibility refers to the degree to which it is possible to see within a certain territory, through a certain medium [15]. Introduction of a wind farm into a landscape will decrease the amount of visible area, thereby obstructing the view of the background.

Ratios were calculated for five different photographs by comparing the area occupied by the farm (S_{fa}) to the area taken up by the initial background landscape (S_{ba}). The calculations were done using Photoshop. The area of the farm is the sum of the areas of the individual turbines. The area of a turbine was calculated as the area of the mast together with the area of the ellipse formed by the rotation of the blades. The expert evaluation showed that I_v can be described as (Figure 1):

$$I_v = \begin{cases} 0.184x & for 0 < x \leq 0.7 \\ -0.003x^2 + 0.114x + 0.051 & for 0.7 < x \leq 12.3 \\ 1 & for 12.3 < x \leq 20 \end{cases} \quad (1)$$

where I_v is the aesthetic impact due to the visibility of the wind farm, S_{fa} is the area occupied by the turbines in view, S_{ba} is the area of the photograph, and x=100 · ($\frac{S_{fa}}{S_{ba}}$)

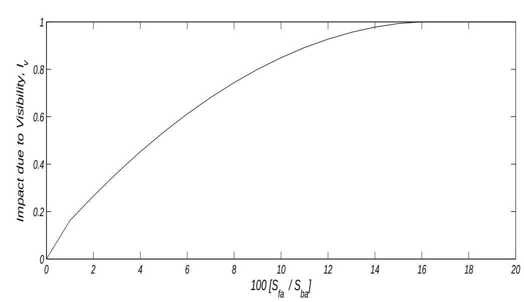


Figure 1: Value function I_v as given by the experts.

When there are no turbines in the landscape, the impact perceived is zero. Visual impact increases with the number of turbines and reaches a maximum value of unity when the farm makes up 15% of the view.

3.2 Impact due to Colour, I_{cl}

Differences in hue, saturation and brightness can generate contrasts in colour and affect aesthetic impact [8, 15]. These differences are calculated using the CIELAB colour formulae [16], which generate CIELAB points. For each turbine and each background, mean values of the three characterising parameters (L, a, b parameters) were obtained using Photoshop. CIELAB points were calculated for nine combinations of turbine colour and background colour, and assessed with respect to aesthetic impact. The resulting value function is (Figure 2):

$$I_{cl} = \begin{cases} 0 & for 0 < x \leq 5 \\ -(\frac{356}{10^9})x^2 + (\frac{12}{10^4})x - (\frac{56}{10^4}) & for 5 < x \leq 1563 \\ 1 & for 1563 < x \leq 1700 \end{cases} \quad (2)$$

where I_{cl} is the aesthetic impact due to colour and x is CIELAB points.

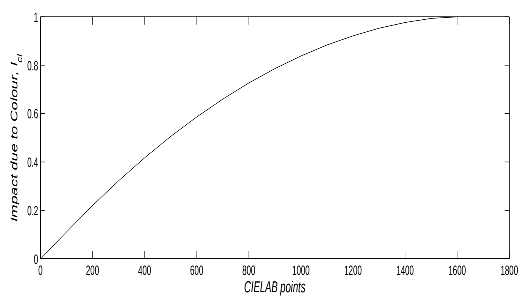


Figure 2: Value function I_{cl} as given by the experts.

The larger the colour differences, the greater the impact.

3.3 The Climatology Coefficient β^*

Visibility and colour will depend on the atmospheric conditions of the area between the object and the observer [15]. Thus, the impact due to visibility and colour must be corrected by the atmospheric coefficient β^*. For calculation of the atmospheric coefficient, see [10].

3.4 Impact due to Fractality, I_f

Fractality is quantified by the fractal dimension, D. As nature builds many of its patterns from fractals, the fractal dimension can be used to identify the naturalness of a pattern [17]. Thus man-made structures such as wind turbines against natural backgrounds will generate an impact I_f which can be represented by contrasts in fractal values.

This investigation will use the box counting method [18] to calculate D. Using Photoshop, the contour of the wind farm and of the main topographic line (usually the skyline) are extracted from the photograph ([10]). This information is then fed into the program ’fdc Linux’ [19], and D is calculated from $N(d) = 1/d^D$, where $N(d)$ is the number of boxes of linear size d necessary to cover a data set of points distributed in a two-dimensional plane.

The ratio ’fractal dimension of the farm versus fractal dimension of the skyline’ was calculated for five photographs and I_f was generated (Figure 3):

$$I_f = \begin{cases} 0 & for x = 0 \\ 1 & for 0 < x \leq 0.7 \\ -0.3^{-1}x + 0.3^{-1} & for 0.7 \leq x \leq 1 \\ -2.04x^2 + 6.94x - 4.9 & for 1 \leq x \leq 1.7 \\ 1 & for 1.7 \leq x \leq 2 \end{cases} \quad (3)$$

where I_f is the aesthetic impact due to fractality, $x = \frac{D_{fa}}{D_{fb}}$, D_{fa} and D_{ba} are the fractal dimensions of the farm and of the background respectively.

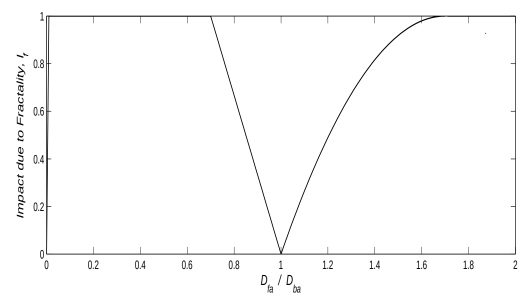


Figure 3: Value function I_f as given by the experts.

Assuming that a background is geometrically planar ($D_b = 2$), impact will reach a maximum when a straight line is introduced into the scene. This value remains constant as more turbines, and thus more lines, are incorporated into the landscape up to the point where adding further turbines will start to convert a group of lines into a plane. At this point ($D_f/D_b = 0.7$), the impact starts decreasing and becomes zero when D_f reaches the value of 2 and the fractal ratio is unity. The remainder of the value function shows impact increasing as more planes are created on top of a planar background. As three-dimensionality is approached, the impact generated by the contrast against a planar background is once again at its highest.

3.5 Impact due to Continuity, I_{ct}

Continuity refers to the silhouette enveloping a group of objects and is measured in terms of the number of ”turns” in the silhouette. An envelope can turn depending on the layout of the turbines and on the line defining the topography of the area, making the farm appear more or less continuous with respect to the background. A difference between the number of turns of the wind farm envelope and the number of turns of the background envelope will affect impact perception [17, 20]. The number of layers of turbines in a farm too, will exert an effect. This relationship can be represented by:

$$I_{ct} = f(\sum_{j=1}^{N}(\frac{2^{N-j}}{2^N - 1}) \cdot (1.05^{|t_{wf} - t_{tl}|_j})) \quad (4)$$

where I_{ct} is the aesthetic impact due to continuity, N is the number of layers and j is the number describing the position of the layer.

In a similar manner to visibility, colour and fractality, a value function was obtained for continuity (Figure 4):

$$I_{ct} = \begin{cases} -4x^2 + 12x - 8 & for 1 \leq x \leq 1.5 \\ 1 & for 1.5 \leq x \leq 3 \end{cases} \quad (5)$$

where $x = \sum_{j=1}^{N}(\frac{2^{N-j}}{2^N-1}) \cdot (1.05^{|t_{wf}-t_{tl}|_j})$

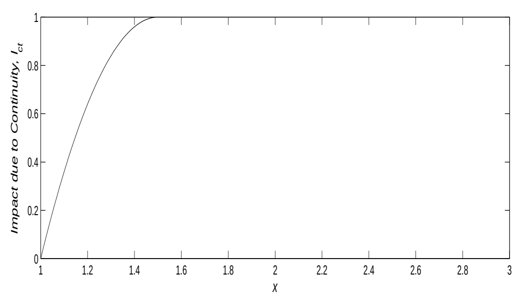


Figure 4: Value function I_{ct} as given by the experts.

Figure 4 shows the impact due to continuity increasing with the difference between the number of turns of the envelope of the wind farm and the number of turns of the topographic lines. When x approaches 1.5, the continuity impact reaches a maximum value of unity.

3.6 The Indicator OAI_{WF}

The global indicator OAI_{WF} combines the above value functions in a weighted sum (Equation 6):

$$OAI_{WF} = \beta^*(0.64 \cdot I_v + 0.19 \cdot I_{cl}) + 0.09 \cdot I_f + 0.08 \cdot I_{ct} \quad (6)$$

The weights are given by expert judgement in a Delphi procedure [21, 22] and analysed by means of the Analytical Hierarchy Process (AHP). Greatest importance was attributed to visibility, which was considered more than three times as important as the second most important attribute, colour. Fractality and continuity were assigned smaller weights, but were still significant.

4 Application of the Indicator to Three Wind Farms

OAI_{WF} was applied to study the objective aesthetic impact of three different wind farms, Wind Farm A, Wind Farm B and Wind Farm C.

Wind Farm A is one of the main wind farms in the region of Tarifa (Spain). This particular wind farm consists of 50 turbines rated at 150 kilowatts situated in an environmentally protected natural park in a mountainous area, such that its accessibility is restricted to a main road, a rural road and one scenic view-point. The wind turbines differ in design, with most turbines exhibiting truss towers as opposed to the tubular towers used for farms B and C.

Wind farm B consists of 25 turbines of 21MW capacity and is located on a rocky and agricultural Valencian landscape (Spain). Four views of the farm were identified; three from three different fields nearby and one from a road leading into the town.

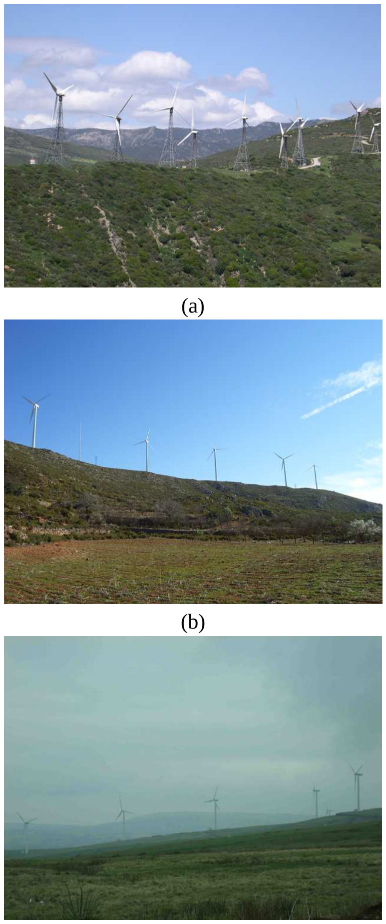
Finally, Wind Farm C has been built on a field in Cardiff (Wales), in the vicinity of two villages, and consists of 20 turbines, with 9MW capacity.

Figure 5 shows photographs of the three farms.

4.1 Analysis for I_v, I_{cl}, I_f, I_{ct}, β^* and Results

The analysis is carried out for close-up views of the wind farm, as a worst case scenario. A close-up view of a wind farm is one for which the area required to enclose the farm takes up more than 33% of the actual view (Law of Land Planning and Landscape Protection, Valencia, Spain). At each close-up view, highly frequented locations which offer maximum visibility of the farm are identified, and panoramic photographs are taken of the entire expanse of the wind farm. For each Wind Farm A, B and C, a total of five, seven, and four photographs respectively were analysed for visibility; five, four and four respectively for colour; four, six and four respectively for fractality and five, seven and four respectively for continuity.

The average values for visibility, colour, fractality and continuity of the farms and of the background



(a)

(b)

(c)

Figure 5: Photographs of (a) Wind Farm A, (b) Wind Farm B and (c) Wind Farm C.

views were calculated from the photographs. The corresponding ratios were computed and translated into values of I_v, I_{cl}, I_f and I_{ct}. The climatology coefficient β^* was calculated for each farm, using atmospheric data obtained from the Spanish an UK Meteorological Offices websites. The resulting values are presented in Table 1.

Inserting these values into OAI_{WF} (Equation 6), the objective aesthetic impacts of the wind farms are, in order from most impacting to least impacting, 0.58 for Wind Farm A, 0.42 for Wind Farm B and 0.28 for Wind Farm C. The results of these analyses are presented in Table 1.

Wind Farm	β^*	I_v	I_{cl}	I_f	I_{ct}	OAI_{WF}
A (Tarifa, Spain)	0.74	0.91	0.59	0.47	0.37	0.58
B (Valencia, Spain)	0.76	0.53	0.84	0.30	0.22	0.42
C (Cardiff, Wales)	0.55	0.51	0.44	0.43	0.20	0.28

Table 1: β^*, I_v, I_{cl},I_f, I_{ct}, and OAI_{WF} calculated for the three wind farms.

4.2 Discussion of Results

A combination of a high degree of visibility (I_{v_A} = 0.91), moderately high colour contrasts (I_{cl_A} = 0.59), and a sunny climate with low precipitation levels (β^*_{Tarifa} = 0.74), makes Wind Farm A the most impacting of the three sites analysed. Although the farm is located in an environmentally protected, mountainous area and is thus of limited accessibility to observers, the elevated topography of the land and the farm's proximity to nearby, highly frequented roads, make the turbines very noticeable. The farm consists of a large number of truss-tower turbines and so it is not surprising to see that the farm's I_f of 0.47 exceeds that of the other two farms. Further, because of the hilly nature of the landscape, the turbines are placed in a discontinuous manner with respect to the main topographic line of the background. Thus, Farm A's continuity impact (I_{ct_A} = 0.37), is nearly twice that of Wind Farm E, which is located on a flat field.

The turbines at site B have have been made to follow the shape of the skyline. Hence the moderately low continuity impact of this wind farm (I_{ct_B} = 0.22), which combined with reduced values for visibility and fractality (I_{v_B} = 0.53; I_{f_B} = 0.30), contribute to place the overall visual impact of Wind Farm B below that of Wind Farm A. On the other hand, the sunny weather conditions ($\beta^*_{Valencia}$ = 0.76) guarantee a strong contrast between a blue sky and the white shades of the turbines and hence the largest I_{cl} (=0.84) of the three farms. High I_{cl} values are characteristic of older farms, whereas new turbines are painted such that their colour approximates that of the background sky, as is the case of Wind Farm C.

Colour contrast for Wind Farm C is relatively low (I_{cl_E} = 0.44) because the turbines have been painted white to match the colour of the sky, typical of a region prone to precipitation and fog ($\beta^*_{Cardiff}$ = 0.55). Similarly to Wind Farm B, Farm C consists of fewer turbines which are aligned with the background topography. Hence the lower visibility and continuity impacts (I_{v_C} = 0.51; I_{ct_C} = 0.20). The fractal value on the other hand is rather high (I_{f_C} = 0.43), nearing that of farm A. This is because Farm C is situated in a grass field away from any trees or objects that can increase the fractal dimension of the skyline and thereby reduce the fractality ratio.

5 Future Work

In an attempt to develop OAI_{WF} as objectively as possible, the approach taken in this study is analogous to the expert-based approach, widely used in landscape evaluation. Analysis of the indicator results for the three wind farms suggests that visibility, colour, fractality and continuity are representative objective measures of aesthetic impact of wind farms. Nevertheless, even though professional judgements can help assess the landscape, it is ultimately the non-professional public who evaluates it. Hence there is a need for the social validation of the indicator. This is the next step in the development of the indicator, which could also serve to confirm the validity of the indicator variables as representative of public preferences. Further study on subjective judgement is also recommended. Integrating expert knowledge with public evaluative reaction constitutes an important step towards the holistic approach of landscape assessment, which is gaining more strength in landscape evaluation practice [13].

6 Conclusion

In this work we have developed a composite indicator for the objective aesthetic impact of a wind farm located in a defined landscape. The indicator combines measures of visibility, colour, fractality and continuity which can be taken from photographs, and includes weighting functions determined by expert opinion. Application of the indicator to three different wind farms shows that the variables, and hence the indicator, are objective measures of aesthetic impact of wind farms. Improvement of the analysis would require a social validation. Further, a study of the subjective aesthetic impact is necessary to develop a general indicator of aesthetic impact of wind farms.

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