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Abstract. Due to the negative impact on the environment of traditional power-generating methods, especially coal and oil-fired power stations wind power has increased in popularity. Achieving the goal set by the EU due to the implementation of the Kyoto protocol will require further expansion, and in order to facilitate this process around the Baltic Sea. A project – Wind Energy in the Baltic Sea Region - financed by EU / INTERREG III B was initiated in order to develop methods and tools to support spatial planning in relation to wind energy. The aim of the current study is to develop multi-criteria evaluations, which can provide tools for analysing the complex trade-offs between choice alternatives with different environmental and socio-economic impacts. The weaknesses of the Boolean logic have been recognised in recent years and a fuzzy logic approach is applied in the system design. The developed methodology is based on data form Northern Jutland, but later on this kind of multi-criteria will be used in the in Finland and Estonia.

1 Introduction

An increase in public awareness regarding the negative impact on the environment of traditional power-generating methods, especially coal and oil-fired power stations, has created a demand for developing and using environmentally friendly renewable energy. Wind power is a popular and safe form of renewable energy, and in Europe, the demand for wind energy is increasing. Achieving the goal set by the EU due to the implementation of the Kyoto protocol will require further expansion, and in order to facilitate this process around the Baltic Sea a project – *Wind Energy in the Baltic Sea Region* - financed by EU / INTERREG III B was launched in January 2003. One aim of this project is to develop methods and tools to support spatial planning in relation to wind energy. An important outcome of the project will be identify best practices in wind energy planning and disseminate these methods to Member States with no or little experiences with wind energy.

Planning and environmental restrictions and conflicts inevitably accompany the extension of wind energy. Parallel to this, land-use planning has become increasingly complex. The principles of sustainable development confront land planners with a paradox of two apparently contradictory objectives: nature conservation and economic development (van Lier, 1998). Considering wind energy the situation is even more paradoxical. Furthermore, the Aarhus Convention (UNECE, 1998) emphasises the active involvement of the public in land-use planning, and various lobby groups promote their points of view. NIMBY (Not In My Back Yard) controversies illustrate the difficulties that often arise when a development project has significant impact on the surrounding environment (Couclelis and Monmonnier, 1995). In this new situation, planners face a double challenge. First, they must design projects and plans that maintain an ecological equilibrium but nevertheless contribute to economic growth. Second, they must be mediators trying to avoid opposition and reduce objections (Joerin et al., 2001). Therefore, environmental planning of today calls for a multiple criteria decision-support system.

Geographical information systems have been a powerful supporting tool for spatial planning during the last decades, and a lot of advanced methods and techniques have been developed. However, most often, deterministic overlay and buffer functions are used in site location studies. When handling multiple conflicting criteria this is kind of geoprocessing is of limited use (Janssen and Rietveld (1990) and another approach is needed. Multi-criteria evaluations techniques, which can provide tools for analysing the complex trade-offs between choice alternatives with different environmental and socio-economic impacts, will be used in the current study.

This purpose of the paper is to develop methods to identify the best sites for new wind farm development by using the fuzzy logic and multi-criteria analysis. The paper is divided in to 5 parts. After the introduction we describe the objectives and background for the project. Third, we focus on the methods used in the decision support system and describe the GIS implementation. Fourth, I illustrates the use of the multi-criteria decision support system in Northern Jutland County. Finally, I have some concluding remarks and suggestions for follow-up activities.

2 Project objectives and background

Climate change is one of the greatest environmental, social and economic threats facing our planet. During the last century, the Earth's average surface temperature rose by around 0.6°C. Evidence is getting stronger that most of the global warming that has occurred over the last 50 years is attributable to human activities. Human activities that contribute to climate change include in particular the burning of fossil fuels and deforestation, both of which cause emissions of carbon dioxide (CO_2), the main gas responsible for climate change. In order to bring climate change to a halt, global greenhouse gas emissions must be reduced significantly

The Conference on Environment and Development (Earth Summit) in Rio de Janeiro in 1992, (United Nations, 1992a) and Agenda 21 (United Nations, 1992b) was the first international collaborative efforts to examine the consequences of environmental impacts due to past and present anthropogenic activities. The latest to promote the use of renewable energy sources was the Conference of the Parties, Third Session, Kyoto, December 1997. Internationally, the EU has put strong efforts in order get the so-called Kyoto Protocol ratified by the International Community. United States has long ago decided not to ratify the protocol, but the Kyoto Protocol is now in operation by Russia's ratification just before the end of year 2004.

The EU has agreed upon a so-called burden sharing agreement among its Member States, and according to this agreement some countries have to reduce their emission of greenhouse gasses dramatically. Parallel to this the EU has set up several similar programmes all aiming at treble renewable energy sources, reducing carbon dioxide emission levels and promoting collaborative efforts to substitute the equivalent of 15% energy demand in the EU with renewable energy sources.

The current situation in the Baltic Sea Region concerning wind energy shows huge differences between the various countries. Denmark has been a pioneer in modern wind energy, and today more than 15 % of the Danish electricity production originates from wind energy. However, Germany and recently Sweden have also given high priority to the development of the wind energy sector. Finland as well as the new Member States Poland, Estonia, Latvia and Lithuania are all beginners in this field. Wind power is a popular and safe form of renewable energy there is generally a strong focus on wind energy around the Baltic Sea Region. Although wind energy is a real renewable energy source, planning and environmental restrictions and conflicts inevitably accompany the extension of wind energy. Not at least the negative visual effects of today's huge wind turbines have to be considered. An obvious answer on these challenges could be a spatial decision support system with multi-criteria capabilities.

A decision is a choice between alternatives. For natural resources decisions, GIS can be a powerful tool base for evaluation of choice alternatives based on spatially related criteria (Carver, 1991). Traditionally, overlaying and buffering have been used in site location studies, but when handling multiple conflicting criteria this kind of vector-based geoprocessing is of limited use. Janssen and Rietveld (1990) argue that overlays are difficult to handle when there are many underlying variables. Next, the overlay procedure does not take into account that the different variables are not of equal importance. Finally, it is difficult to handle threshold values, and a transformation of a continuous variable to a nominal basis will inevitable lead to substantial losses of information.

Present analytical functions and conventional spatial analysis and modelling techniques are based on Boolean logic, which implicitly assumes that objects in a spatial database and their attributes can be uniquely defined. In the land-use evaluation process with Boolean classification all land units with values that exceed the given threshold may be defined as the class or set of land units, which are to be rejected for new development. The weaknesses of the Boolean logic have been recognized in recent years. As an alternative to Boolean logic, fuzzy set theory has been proposed as a new logical foundation.

3 Methods

Decision-making on environmental issues is often a process characterised by complexity, uncertainty, multiple and sometimes conflicting management objectives, as well as integration of numerous and different data types. A decision is a choice between alternative actions, hypotheses, locations, and so on (Eastman *et al.* 1993), and a decision support system should aid and strengthen the process of choice (Sauter, 1997). A decision is therefore derived from an assessment of suitability, the degree, which a location belongs to the suitable or not suitable set. Generally, the not suitable set is assumed to be the complement of the suitable set. Most decision-making processes consider multiple criteria to assess the degree of suitability each location bears to the allocation under consideration. Therefore, suitability is generally not Boolean in character, but expresses varying degrees of set membership.

3.1 Multi-criteria decision support

Two types of criteria support the decision-making: *constraints* and *factors*. These criteria represent conditions possible to be quantified and contribute for the decision-making (Eastman et al., 1993). The constraints are based on the Boolean criteria (true/false), which limit the analyses to specific regions. The factors are criteria, which define some degree of suitability for all the geographic regions. They define areas or alternatives according to a continuous measure of suitability, enhancing or diminishing the importance of an alternative under consideration in the geographic space resulting after the exclusion of the areas defined by the restrictions. The factors indicate continuous degrees of fuzzy membership in the range between one and zero, whereas the Boolean factor criteria can be considered as a special case of fuzzy sets.

Decision norm is the procedure through which the selected criteria, factors and restrictions are aggregated. The aggregation process demands the factors to be standardised to a same scale. Standardisation is a process of conversion of the original values into values adequate to the purpose aimed, by applying the pre-established criteria through pertinence to the area set for the purpose of setting up a new wind farm. This normalisation process is essentially identical to the process introduced by the fuzzy logic, which states that a set of values expressed in a given scale is converted into another comparable to it, expressed in a normalised scale. The result expresses a relative degree of belonging to a set, ranging from 0.0 to 1.0, indicating a continuous growth from not belonging up to total belonging. Two approaches can be considered

- *Boolean intersection* operation on Boolean constraint maps. It is a logical AND, where only locations that are characterized as suitable (value 1) on all maps will be suitable in the result.
- *Weighted linear combination* (WLC) assesses the suitability of grid cells by weighting and combining factor maps. WLC multiplies cell values in standardized factor maps by the corresponding factor weight, and then adds weighted values across images. Due to conditions on the weights (all

positive or zero, sum equal to one), the resulting cell values are in the same range as those of the factor maps.

Following Jiang and Eastman (2000) the suitability s at the k^{th} pixel can be determined by a weighted linear combination

$$S^k = \sum w_i x^k_i \qquad (1)$$

Where w_i is the weight, and x^k_i is the value of criteria i in the k^{th} pixel. The weights w_1, ….. w_n reflect the relative importance of each criteria. Clearly, real world planning problems involves a considerable degree of uncertainty concerning the quantitative values of the weights The criteria weights, w_i must add up to 1.0 for WLC to work properly.

3.2 Uncertainty and fuzziness

Measurement uncertainty is that which resides in the data. This error is often assumed to be random with a normal distribution and can be handled by identifying levels of risk based on standard deviations, and accepting a certain risk in the decision. Human conceptual uncertainty stems from difficulties in setting precise (numerical) thresholds. For instance, if we identify tall as more than 2 meter, does that make 2.01 meter "tall" and 1.99 meter "not tall"? This type of uncertainty can be resolved by applying continuous classifications based on fuzzy logic. Finally we have decision rule specification uncertainty. A decision rule might be biased towards one single factor, which was not intended by the decision maker. To resolve this the robustness of the decision rule should be evaluated carefully. Incorporating risk and uncertainty in the decision-making is sometimes referred to as going from a hard to a soft decision (Gumbricht and McCarthy, 2003).

Thus the problem of dealing with imprecision and uncertainty is a part of human experience, but until Zadeh (1965) introduced the theory of fuzzy sets there was no strict mathematical method to handle impression and uncertainty. Zadeh (1965) published his work *Fuzzy Sets*, which described the mathematics of fuzzy set theory. This theory, which was a generalisation of classic set theory, allowed the membership functions to operate over the range of real numbers [0, 1]. The main characteristic of fuzziness is the grouping of individuals into classes that do not have sharply defined boundaries. Thus fuzzy sets are useful whenever we have to describe ambiguity, vagueness and ambivalence in models of empirical phenomena.

Fuzzy memberships differ from probabilities primarily in interpretation. Probability theory assumes that only one class or set is present and expresses the degree to which its presence is likely as a probability. The class with the highest probability is interpreted as the actual class. Fuzzy set theory accepts that multiple classes or sets can be present at one place and time and express the degree to which each class or set is present as a membership value. A vector of fuzzy memberships is maintained and classes or sets with non-zero memberships are interpreted as present to some degree.

A fuzzy subset, **A** of **Z**, is defined by a function $\mu_\mathbf{A}$

$$\mathbf{A} = \{ z, \mu_\mathbf{A}(z) \} \quad \text{for each } z \in \mathbf{Z}. \qquad (2)$$

The relation $\mu_\mathbf{A}(z)$ is called a fuzzy membership function (MF^F) defining the grade of membership the object z in **A** and $z \in \mathbf{Z}$ indicates that z is an object contained in **Z**. For all **A**, $\mu_\mathbf{A}(z)$ takes on the values between and including 0 and 1.

A fuzzy membership function is thus an expression defining the grade of membership of z in **A** – i.e. a function that maps the fuzzy subset **A** into a membership value. Various types of fuzzy membership functions have been defined (fig. 2). The first point (b1) marks the location where the membership function begins to rise above 0. The second point ($b_1 + d_1$) indicates where it reaches 1. The third point ($b_2 - d_2$) indicates the location where the membership grade begins to drop again below 1, while the fourth point (b_2) marks where it returns to 0.

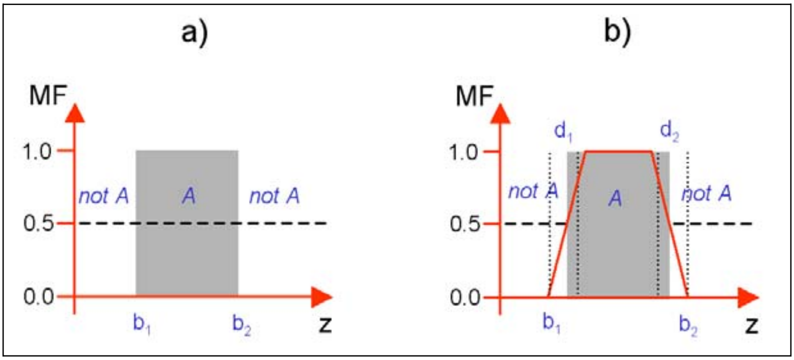

Figure 2. Selected membership functions

It seems reasonable to place the transition zones so the crossover points of fuzzy sets lie at the boundaries of the corresponding Boolean set (Burrough & McDonnell, 1998). The width of the transition zones d_1 and d_2 are rather difficult to choose. Concerning land-use, only the lower boundary has practical importance. Mathematically, the left side of the quite simple fuzzy membership function at figure 2.b can be expressed by the following three equations:

$$MF^F(z) = 0 \qquad \text{for } z < b_1 \qquad (3)$$

$$MF^F(z) = \frac{z - b_1}{d_1} \qquad \text{for } b_1 \leq z \leq b_1 + d_1 \qquad (4)$$

$$MF^{F}(z) = 1 \qquad \text{for } z > b_1 + d_1 \qquad (5)$$

The traditional Boolean membership function is represented by figure 2.a. In essence, the procedure considers each of the variables to be a statement of the degree to which a location belongs to a vulnerable set (as opposed to a non-vulnerable set) based on that quality. These sets, however, do not have crisp boundaries.

For example, it might be clear that the noise from a wind turbine of 60 dB or more is unquestionably annoying, whereas a noise of 20 dB or less is clearly not a problem. However, there may be no crisp boundary that can distinguish these two sets. Rather, one might only be able to say that as noise increases from 20 dB, the noise is becoming more and more annoying. In this case one can define the degree of membership (known as the "possibility") of a location in the set called "at risk", by scaling values such that those of 60 db or greater have a membership of 0.0 while those of 40 dB or lower have a membership value of 1.0. Between these two extremes, values would be scaled according to one of a range of possible membership functions. This process of rescaling variables into fuzzy set is known as "fuzzification".

3.3 Site selection criteria

The site selection criteria were developed by interviewing spatial planners in the Baltic Sea region. First the criteria should represent national and regional legislation related to wind turbine development. Second, the criteria should incorporate local conditions such as infrastructure and site characteristics. Third, the criteria must take into account local restrictions like master plans and zoning ordinances. Finally, the concrete project will depend on the economic viability must be considered by taking into account the available wind resources.

The resultant criteria are presented in table 1 in decreasing order of relative importance.

Constraints		**Data source**
Protected nature		AIS
EU Habitat		AIS
EU Bird protection		AIS
Ramsar areas		AIS

Factors	**b1; d1**	**Weight**	**Data source**
Proximity to coast	100; 3000		TOP10DK
Proximity to forests	300; 500		AIS
Proximity to streams	150; 500		AIS
Proximity to lakes	150; 500		AIS
Proximity to settlements	500; 1000		TOP10DK
Proximity to roads	150; 300		TOP10DK
Proximity to power lines	200; 500		North Jutland County
Proximity to airports	5000; 7500		TOP10DK
Proximity natural gas lines	300; 500		North Jutland County
Proximity to radio masts	1000; 1500		TOP10DK
Proximity to churches	300; 500		TOP10DK
Proximity to mounds	100; 250		AIS
Wind potential (W/m^2)	250; 400		Risoe

Table 1. Wind farm site selection criteria

3.4 GIS implementation

ArcGIS Spatial Analyst 9 has been the primary software tool for implementation - and particularly the Raster Calculator. The various steps in the calculation are illustrated in figure 3. Most data is available in vector format. Only the wind resource map is in raster format with a cell size of 250 m. We decided to use a common cell size of 50 m. After deciding the cell size, converting vector data sets to grids was the next step to be performed. The wind resource map needed to be resampled to change the cell size. The other layers needed more complex operations to be performed on them such as reclassification for the constraints and distance calculations for the factors. The constraints are classified using a traditional Boolean classification method. Once the distance layers were generated, the next step was to standardise the values using a fuzzy classification. By applying the following formula in the Raster Calculator the standardised grids were generated for all factor layers. The variables b1 and d1 are explained in figure 2.b.

```
Con( [grid layer] < b1,
     0.0,
     Con( [grid layer] > d1,                    (6)
          1.0, ([grid layer] – b1) / d1
        )
   )
```

All the weighted grid layers were added together in the Raster Calculator to a final suitability surface. Multiplication of the standardised layers with their associated weights was carried out during the addition process. This way of working will ease later recalculations with other weights. The final grid layer has values between 0 and 1 and illustrates the suitability for new wind farm development based on the criteria as well as the weights chosen.

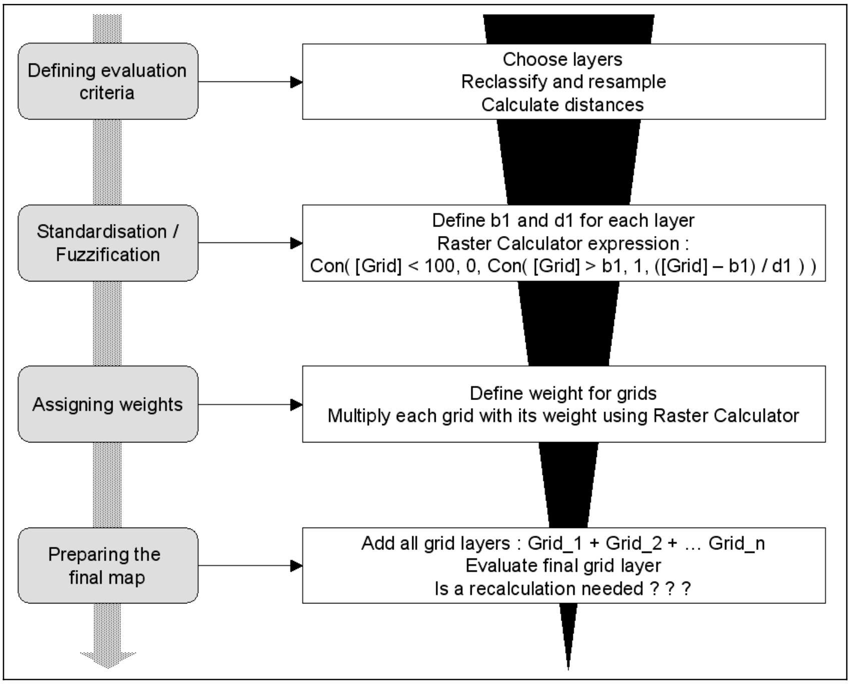

Figure 3. Implementation in ArcGIS Spatial Analyst

4 Application and results

The data layers used in the analysis (see table 1) were identified by analysing current practises in the countries around the Baltic Sea. The study area covers Northern Jutland in Denmark. The main data source for the current project has been the Danish Area Information System produced in the late nineties (Ministry of Environment & Energy (2000). This database in scale 1: 25.000 is freely available, but it is not updated regularly and mainly the layers related to national and EU legislation. Additionally, selected layers from the National topographic database (TOP10DK) of scale 1:10.000 have been used. Besides these national databases the Northern Jutland County administration has provided data, which was needed but not generally available from various national sources.

The criteria values (b1 and d1 in equation 3 – 5) are for current development project defined on a minor stakeholder analysis among the project partners. However, these values may vary among different countries due to variations in their national legislation.

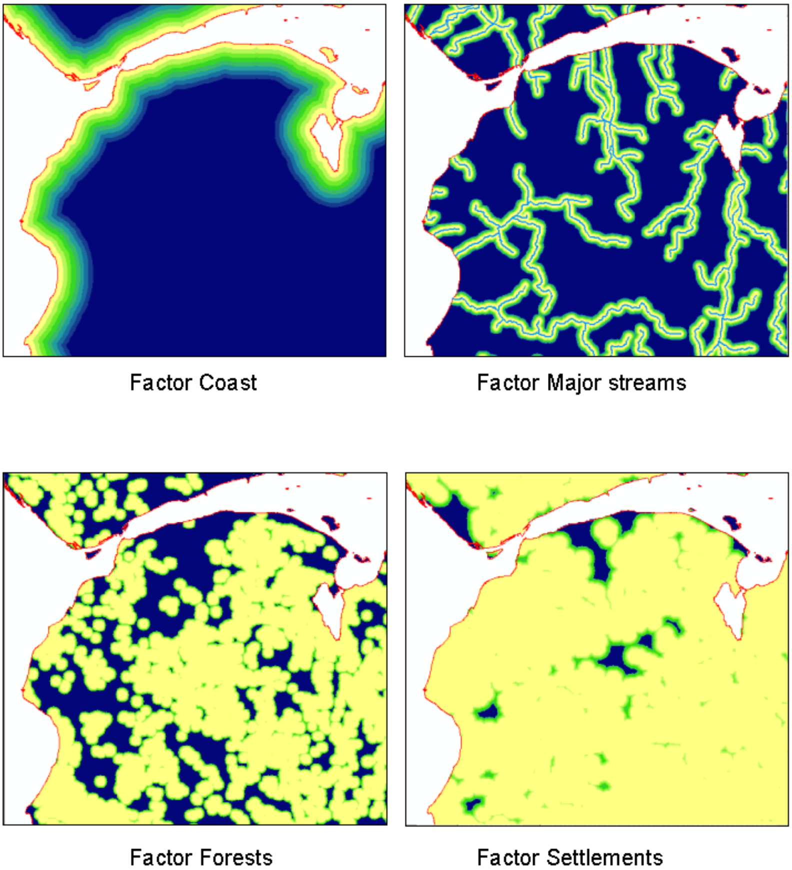

Figure 4. Fuzzy standardised maps for selected factors cover part of Northern Jutland.

After having provided necessarily data layers to include in the multi-criteria analysis, the selected layers were processed as described in paragraph 3.4. Figure 4 illustrates examples on standardised factor maps. The blue areas correspond to high values (i.e. suitable areas for wind turbines), whereas the yellow areas represent lower values (i.e. areas which not suitable for new wind turbines). The layers contain values between 0 and 1, where 0 represents unsuitable locations and 1 represents ideal locations. Weighting the various layers is perhaps the most critical part of the in decision support systems. On the other hand it is not an easy task to set up appropriate weights among many grid layers. For development and test purposes, we believe that assigning weights based on some common sense are sufficient.

Figure 5. Final suitability map.

Figure 5 shows the “final” map based on the data layers, the criteria, and the assigned weights. The light yellow areas indicate suitable locations for new wind farm development. Obviously, there is not much room for new wind farm development I that part of Northern Jutland. Denmark has already a lot of wind turbines, and most new wind farms will be located offshore and based on huge 2 – 4 MW turbines. Nevertheless, the developed spatial multi-criteria decision support system can be very helpful for identifying suitable locations for new wind farms in for example Finland, Poland and the three Baltic countries.

5 Concluding remarks

Decision-making concerning new wind farms is an important issue in environmental and spatial planning. Due to the increasing threats of climate change / global warming, there has been growing interests for renewable energy – and particularly wind energy. Although wind energy is a clean technology without any emissions to the surroundings, the location of new wind turbines is often discussed a lot among the public in neighbourhood around a proposed new wind farm. This does not mean that people generally are against wind energy, but the modern huge 2 – 4 MW wind turbines are noisy, cast shadows and have significant visual effect in the landscape. Therefore, the location of new turbines must be based on thorough analyses.

The current paper has described how to use fuzzy based multi-criteria analysis for the evaluation of new wind farms. This system is able to handle the complexity, uncertainty, multiple and sometimes conflicting management objectives, which is characteristic for environmental planning generally. Additionally, the developed system is capable to support the integration of numerous and different data types. By using other combinations of weights various scenario building is possible. This flexible approach makes it useful as a planning tool as it provides the operator with the freedom to use their individual expertise in the decision making process. The output maps can be used easily to assist in making informed decisions. Additional relevant layers of information, such as stake holder opinion, could be quantified and easily integrated into the GIS and, consequently, be taken into consideration when locating new wind farms.

The methodology will be used in the case study areas during 2005, and we will continue the development by making the tools more user friendly – perhaps by using the Model Builder and Phyton programming language in ArcGIS Spatial Analyst (ESRI, 2004). Additionally we will try to apply this kind of tools in the public participation phase of the master plan development. The subsequent work can be followed at our project homepage http://www.windenergy-in-the-bsr.net/.

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