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Spatial Multi-Criteria Decision Analysis Tool Suite for Consensus-Based Siting of Renewable Energy Structures

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Expansion of renewable energy development causes concerns which traditional land-use planning may have limited capacity to address adequately. The complexity and multiplicity of scales, criteria and actors involved in decision-making processes requires a holistic approach that captures the variety in stakeholder interests. Reaching consensus across interests ensures democratic and cost-effective decision-making processes. The Consensus-based Siting (ConSite) tool suite was developed for optimal siting of onshore wind-power plants and routing of high-voltage power lines considering stakeholder interests. ConSite is based on the operational steps of spatial multi-criteria decision analysis using a bottom-up holistic approach. Its spatially explicit graphical user interface allows for a high level of stakeholder involvement and includes inherent capabilities of scenario modelling. ConSite thereby helps to structure decision problems, balance conflicting interests and identify relevant decision strategies based on risk assessment and trade-off analysis. ConSite

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visualises the spatial consequences of implementing various decision strategies and balancing site-specific conflict levels with energy production potential.

Keywords: GIS; SMCDA; optimisation; spatial planning; renewable energy siting.

Introduction

Renewable energy is an essential measure for climate change mitigation. Hence, a rapid and large-scale development of renewable energy technology is pivotal to substitute carbon-based energy sources. However, as new renewable energy technologies continue to be deployed, it is increasingly important to acknowledge the effects these technologies may have on the natural environment and society. Although there is considerable support for renewable energy development, its expansion also causes several concerns, which traditional land-use planning may have limited capacity to address adequately. The negative impacts of renewable energy production on the environment and societies often become one of the main issues when new renewable energy structures (e.g. wind-power plants and high-voltage power lines) are planned, often leading to prolonged consent application processes (IPCC, 2011; Wolsink, 2012). Such conflicting issues may cause financial problems for the energy industry and for society as a whole (Cole, 2011) and reduce the predictability of the spatial planning and consenting processes. Therefore, there is a clear need for new, comprehensive and inclusive decision-making processes to avoid negative impacts during the planning phase (May, 2017). Conceptually, this requires a structured, iterative process of 'robust decision-making' (Lempert and Collins, 2007; Rist *et al.*, 2013) to reduce uncertainty and to increase trust in the consenting decisions. The complexity and multiplicity of scales, criteria and actors involved in decision-making processes, however, requires a holistic approach that captures the variety in stakeholder views and perspectives (technological, socio-economic and environmental). Implementing a place-based social-ecological-technical system concept (Ostrom, 2009; McGinnis and Ostrom, 2014) allows us to consider the intricate linkages between environmental impacts, landscape and resource utilisation and the complexity of social acceptance of renewable energy development (McLachlan, 2009) and the inherent environmental, aesthetic and socio-economic dimensions (Enevoldsen and Sovacool, 2016). In short, there is a need for an improved planning and decision support tool that ensures democratic and cost-effective processes securing qualified decision-making (Wolsink, 2007; Mateo, 2012).

Siting of wind-power plants, and the accompanying routing of high-voltage power lines, is a spatially explicit process based on multiple criteria (Fargione *et al.*, 2012; Araneo *et al.*, 2015) preferably derived through stakeholder involvement (Thygesen and Agarwal, 2014). Commonly included criteria for siting or routing are: connectivity to the electricity transmission grid and the identification of suitable corridors for power-line routing (Luthi and Prassler, 2011; McWilliam *et al.*, 2012), turbine noise propagation and turbine/power line visibility in the landscape (Pedersen *et al.*, 2009; Molnarova *et al.*, 2012), property values (Zangl *et al.*, 2008) and hotspots for birdlife (e.g. Bright *et al.*, 2008; Tellería, 2008; Carrete *et al.*, 2012; Liechti *et al.*, 2013). Such exercises to support decision-making are predominately performed using Geographical Information Systems (GIS) and/or engineering tools specifically designed for the purpose. In regional planning, however, environmental and societal concerns of renewable energy development and transmission lines need somehow to be offset against technological and socio-economic benefits within a spatial context. Spatial multi-criteria decision analysis (SMCDA) tools can help to identify suitable development areas and render feedback on the conflict potential and its inherent conflict levels. Several decision-support systems have been developed using GIS, employing both expert-based (Voivontas *et al.*, 1998; Aydin *et al.*, 2010; van Haaren and Fthenakis, 2011) and participatory approaches (Baban and Parry, 2001; Ramirez-Rosado *et al.*, 2008; Gorsevski *et al.*, 2013; Tsoutsos *et al.*, 2015). GIS-based tools for multi-criteria analysis enable planners and decision-makers to prioritise among alternative strategies, thereby avoiding potential conflicts and enabling a more inclusive and transparent planning process (Simao *et al.*, 2009; Ciaccia *et al.*, 2010). Currently, most of these tools lack, however, the flexibility to vary their criteria sets. Although relevant criteria sets can be justified, these may simultaneously vary by country or region. Using a fixed set of criteria may hamper the stakeholder dialogue processes if some criteria are missing or considered irrelevant. Although regulations define minimum requirements for criteria inclusion and restriction areas (e.g. protected areas and urban areas), relevant criteria need to be identified and weighed by relevant stakeholders to enhance transparency and to reduce conflict levels.

SMCDA is an established approach to tackle complex and inclusive decision-making processes with a rich body of literature (Malczewski, 2006a; Afshari and Yusuff, 2012; Malczewski and Rinner, 2015; Schafer and Gallemore, 2016). The development of multi-criteria decision theory was from its beginning characterised by the methodological principle of multi-criteria decision-making. Although multi-criteria problems sometimes are presented as a classical optimisation problem, the conception of an 'optimal' solution is recognised as having limitations. One limitation is that most criteria considered in decision-making are of non-linear nature (Piegat and Sałabun, 2012). Another limitation is that it is impossible to optimise all criteria at the same time. Instead, decision theory teaches us to look for 'compromise solutions' — thus finding the balance between conflicting incommensurable values and dimensions (Munda, 2004). The notion 'optimal' siting, nevertheless, commonly appears in SMCDA papers but should be interpreted as 'suitable' sites that render least level of conflict and highest levels of consensus, and which thereby represent the 'optimal compromise'. What really matters in a multi-criteria framework is the actual democratic process towards consensus since the problem structuring will determine the ultimate result (Munda, 2004). A high level of stakeholder involvement facilitates the SMCDA planning process from the initial problem structuring and throughout the entire decision-making process up to the final decision. Involving stakeholders is important to reach a justifiable decision through a systematic, participatory, transparent and documented process. Moreover, active participation further provides support for the generation and comparison of spatially explicit alternatives. The definition of 'stakeholder' may diverge because it may be difficult to define what constitutes a legitimate stake (Reed *et al.*, 2009). In this paper, we follow the definition of Gorsevski *et al.* (2013) and consider any individual or group of individuals that are affected by and/or involved in a technical development as primary stakeholder candidates (also called 'agents').

As environmental or societal concerns often cause opposition against the construction of renewable energy facilities at a specific site (IPCC, 2011; Wolsink, 2012), we developed the Consensus-based Siting (ConSite) SMCDA tool suite to map and assess the spatial consequences of planning decisions based on stakeholders' valuation and acceptance of multiple criteria. ConSite supports integrated assessments instead of isolated sectorial environmental and societal impact assessments. Thereby it provides a decision-support planning tool suite that ensures a holistic, democratic and transparent assessment of technological, socio-economic and environmental perspectives. In this paper, we present the ConSite SMCDA tool suite which is based on current developments in SMCDA for renewable energy development (Pohekar and Ramachandran, 2004; Mateo, 2012) and current developments within stakeholder analysis (Reed *et al.*, 2009) and decision theory (Bottero *et al.*, 2015). ConSite was developed with Model Builder in ArcGIS 10.3 (ESRI, 2015). ConSite is exemplified for the socially acceptable, environmental friendly and cost-effective routing of high-voltage power lines and siting of onshore wind-power plants in central Norway. ConSite helps decision-makers and planners to dynamically identify suitable areas for development and aid decisions taken with respect to both transparency and re-examination. This demonstrates that the ConSite tool suite can help to operationalise Environmental Impact Assessments (EIA) and Strategic Environmental Assessments (SEA).

Methodological Framework

The ConSite SMCDA process is a step-by-step process that enables problem structuring, decision problem formulation and identification of relevant drivers, thematic content and associated criteria, criteria valuation and their relative importance represented as weights. ConSite combines spatial MCDA, dialogue theory and decision theory into one methodological framework adapted for GIS. The methodological framework consists of six sequential and iterative steps — all with a high level of stakeholder involvement — towards a final compromise output (Fig. 1). The output is an inverted suitability map (hereafter called 'conflict' map as it gives an aggregated measure on the spatial distribution of conflicting interests) visualising where the technological development can be best located within the social-ecological-technical conflict landscape (Ostrom, 2009; McGinnis and Ostrom, 2014). A unique 'optimal' solution does not exist, but the most suitable solution should be grounded on stakeholder inputs and one that minimises conflict and maximises consensus. Feedback loops enable continuous improvements of the model and allows transdisciplinary co-learning to take place (Ferretti and Montibeller, 2016). While these modelling steps are being presented slightly

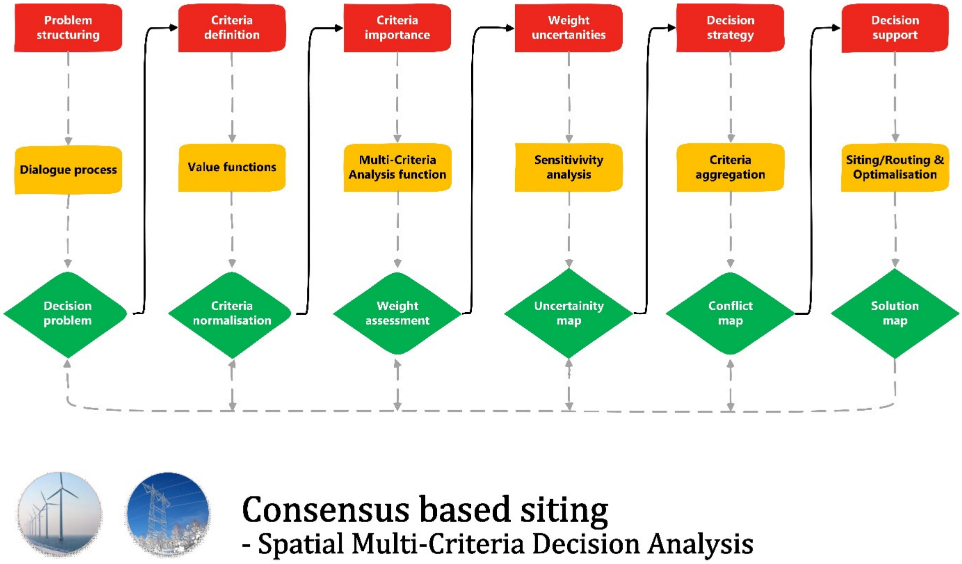

Fig. 1. (Color online) The ConSite SMCDA workflow. Stakeholder interaction throughout the SMCDA process is illustrated with solid arrows. If consensus is not reached at any step, the dialogue is looped back to one of the previous steps in order to seek new consensus (grey arrows). The red boxes signify the six steps in the ConSite SMCDA model. The yellow boxes signify the inherent methodological approaches of each step, and the green boxes signify the outcomes of each step.

different in the SMCDA literature (Hongoh *et al.*, 2011; Gbanie *et al.*, 2013; Ferretti and Montibeller, 2016), our diagram emphasises ConSite as a cyclic evaluation process facilitating a flexible and adaptive SMCDA. The main difference between ConSite and many other SMCDA tools is how ConSite facilitates a high level of stakeholder involvement throughout the entire process (but see Simao *et al.*, 2009). Stakeholders should be involved as active participants with agency. They should not merely be regarded as passive recipients of information, but as local experts with knowledge worthy of inclusion in all steps in the SMCDA. We are convinced that such involvement will give stakeholders ownership and validity to each of the step-wise outputs and the final solution map.

1. *Scoping the problem*

The first step of the ConSite workflow is to define and structure the decision problem. For this purpose, we have recognised and adapted a participatory dialogue process in ConSite based on the Adaptive Environmental Assessment and Management (AEAM) methodology (Holling, 1978). This included the formalisation of a representative group of stakeholders that would be affected by the actual renewable energy construction project (Thomassen *et al.*, 2012a, 2012b). While stakeholder involvement can be organised in many different ways according to the context and the inherent needs, if implemented early in the planning and decision process, participatory dialogue can avoid potential conflicts and increase the public transparency. To optimise the dialogue process, it is important to balance competing interests and, from that, decide who should be involved and how they can contribute. Durham *et al.* (2014) recommend that dialogue processes address why (i.e. defining the outcomes desired from the engagement process; weighing the criteria to assess agreement and disagreement), who (i.e. identifying the stakeholders necessary for a robust outcome), when (i.e. engagement levels necessary at certain times in the process, also to secure robust outcomes) and how (i.e. finding the best dialogue form to build trust and obtain robust outcomes) to engage stakeholders in order to ensure inclusiveness and enhance legitimacy and societal relevance.

From the prior assessment, invited stakeholders will during one or several dialogue seminar(s) structure the decision problem and identify relevant criteria pertaining to the decision process. The identified criteria (e.g. distance to settlements, visibility in the landscape, migratory corridors, biodiversity hotspots, terrain conditions for construction) are defined during the dialogue seminars. In such cases in which criteria could be interpreted in various ways (e.g. visual impact or biodiversity hotspots), stakeholders were asked to provide spatially explicit proxies for these (e.g. line-of-sight visibility or diversity of bird species). Input criteria values can often be derived from peer-reviewed literature describing legal requirements, best practices, expert judgements and/or layman judgements. To ensure that each stakeholder is heard, an additional (anonymised) survey can provide all with the opportunity to adjust and set criteria values after the dialogue seminars. Such surveys also provide the opportunity to derive statistical information (e.g. median, range) from the feedback to map the level of agreement and disagreement among stakeholders as part of a sensitivity analysis.

2. *Normalisation of multiple criteria proxies*
Involved criteria are often multiple and incommensurable because they have different objectives measured along qualitative, quantitative, discrete or continuous measurement scales. To make the different criteria proxies comparable along a common measurement scale, they must be normalised using a value function. Value functions enable stakeholders to set thresholds regarding their degree of acceptance, or lack thereof, in the original units. Value functions were used to normalise all criteria proxy values relative to the stakeholder's degree-of-acceptance into a continuous scale from 0 (low acceptance) to 1 (high acceptance). ConSite allows for the utilisation of different value functions (linear, binary, sigmoid and parabolic) based on fuzzy logic theory (Zadeh, 1965; Klir and Yuan, 1996). The involved criteria should as far as possible also be made comparable at a common spatial scale and resolution. Normalising and comparing criteria proxies mapped at unequal spatial scale and resolutions may blur and deteriorate the final consensus (solution) map.

3. *Multiple criteria weighing*
After the normalisation procedure of the criteria proxy values, the relative weight of every normalised criterion is determined by the stakeholders. Malczewski (1999) outlines four main methods for assigning weights to criteria: (1) ranking methods, in which every criterion under consideration is ranked in the order of the decision-maker's preferences; (2) rating methods, which require the estimation of weights on the basis of a predefined scale; (3) pairwise comparison methods, which involve pairwise comparison to create a ratio matrix and (4) trade-off analysis methods, which make use of direct trade-off assessments between pairs of alternatives. ConSite applies the two latter methods to determine the relative importance (weights) of the individual criteria and to aggregate the different criteria into a 'conflict' map (inverted suitability map). Pairwise comparison used to create a ratio matrix or used in a trade-off analysis has the advantages of providing an organised structure for group discussions and helping the stakeholders to focus on areas of agreement and disagreement when setting criterion weights (Drobne and Lisec, 2009). The analytical hierarchical processes (AHP) decision-making procedure (Saaty, 1987) is used to derive ratio scales from both discrete and continuous paired

comparisons, and it is a method applicable also for qualitative data, although it may be difficult to subjectively scale a concrete quantitative number for pairwise comparisons without losing some degree of accuracy (Mateo, 2012). Despite this, the way AHP handles multiple qualitative and quantitative criteria has favoured its use as a decision-making method and it has therefore been widely used in renewable energy siting projects (e.g. Al-Shabeeb *et al.*, 2016). AHP is particularly recognised for its justification of decisions in terms of transparency and re-examination (Mateo, 2012).

4. *Spatial sensitivity analysis*

Depending on the level of disagreement among stakeholders and the inherent quality of the background geographical data, uncertainty arises regarding how well the aggregated conflict map depicts the reality and degree of consensus for the given decision problem. The background data quality will in principle have the same impact for all stakeholders and may be limited by the maps available to the decision-makers. As part of the scoping process, selection criteria should be defined for spatial data to be included, and at which spatial resolution, in the further process. Variation in opinions concerning criteria normalisation and weighing by stakeholders will however be important to visualise in the SMDCA. Various forms of spatial sensitivity analysis have been developed (Chen *et al.*, 2013; Ligmann-Zielinska and Jankowski, 2014), but are generally not a common practice in SMCDA-based siting studies (Crosetto *et al.*, 2000; Ligmann-Zielinska and Jankowski, 2008; Lilburne and Tarantola, 2009; Benke and Pelizaro, 2010; Chen *et al.*, 2011). The simplest and far most frequent implementation of sensitivity analysis is based on the variation of criteria proxy normalisation values and weights to see whether, and how, this significantly modifies the resulting outcome map (Montserrat and Joaquín, 2014). ConSite currently supports only this type of spatial sensitivity analysis.

5. *Criteria aggregation and trade-off analysis*

The next stage is to aggregate the various criteria (by some authors called the evaluation or combination stage). There is a great diversity of methods on how to combine spatial multi-criteria data, but these are usually variants of Boolean overlay operations, weighted linear combination (WLC) (Voogd, 1983) and ordered weighted averaging (OWA) (Yager, 1988). The simplest method is the traditional overlay techniques using Boolean operators. Aggregating conflict areas using the Boolean operators AND and OR implies risk-aversive and risk-taking decision alternatives but without any continuity between them (binary decision alternatives). In addition, AND and OR implies no trade-off.

WLC is an aggregation method that seeks to overcome the lack of sensitivity in traditional Boolean overlay techniques. The WLC aggregation method multiplies each normalised criteria map by its criteria weight and then sums the results

(Comber *et al.*, 2010). Instead of the hard Boolean decision of assigning absolute low conflict or high conflict to a location for a given criterion, WLC scales the criteria to a particular common range where suitable and unsuitable areas are continuous measures (Sposito *et al.*, 2013). Therefore, WLC is more often used in decision-making processes than the Boolean approaches (Jiang and Eastman, 2000). There are, however, some issues associated with multi-criteria evaluation analyses using WLC approaches. WLC lacks proper capabilities to evaluate decision risk, due to the assumed linearity of scale transformations of criteria and additivity of weight averaging (Malczewski, 2000; Jiang and Eastman, 2000).

OWA can be recognised as a modification of the WLC formula by introducing two different kinds of weights: the criteria weights (also used in WLC) and the order weights. The criterion weights are assigned to the evaluation criteria to indicate their relative importance. The criteria weights (w_j) are applied uniformly: all locations (e.g. pixels) on the jth criterion map are assigned the same weight of w_j. The order weights are associated with the criterion values on the location-by-location basis. They are assigned to the ith location's attribute value in decreasing order without considering from which criterion map the value comes (Malczewski, 2006c). The OWA procedure includes the following steps (Comber *et al.*, 2010):

(1) Each criterion is weighted for its relative importance.
(2) An intermediate layer is derived from each criteria map, and the weighted values at each location (pixel) are evaluated and ranked from lowest to highest values.
(3) The order weights are then applied in the following way: the first order weight is applied to the highest value; the second order weight is applied to the next highest value and so on.

OWA has been used in many different GIS applications (Comber *et al.*, 2010; Ahn and Yager, 2014) and provides considerable refinement of the Boolean and WLC approaches. Both WLC and OWA allow for trade-off between different criteria by weighing the normalised criteria according to their relative importance. A low conflict value defined by one criterion with a high weight may be equivalent to a high conflict value in another criterion with a lower weight — thus the former may be compensated by the latter. This capability of compensating a low score for one criterion with a high score for another criterion is known as *trade-off* or *substitutability* (Jiang and Eastman, 2000). Trade-offs between criteria depend on, and are controlled by, the weights that are assigned to them. Still, it is important to point out that also OWA has its limitations one should be aware of. Even though a single user may make a conscious risk decision, trade-offs (i.e. balancing a high-conflict criterion with a low-conflict criterion using weights) can lead to overlooking critical factors and mislead decision-making. This can be overcome by a thorough deliberative process in which the input from stakeholders is combined, evaluated and — if necessary — adjusted. Although the individual-based OWA is bound to overlook some critical factors, participation of different users in a deliberative process enhances the chance that all critical factors will be included in the assessment.

For ConSite, we have implemented both the WLC and OWA for criteria aggregation, risk assessment and trade-off analysis. The introduction of the order weights makes OWA a better aggregation approach than WLC in managing decision risk. The order weights control the degree of risk-aversion or risk-taking one is willing to take, i.e. the position along the first axis in Fig. 2. Risk and trade-off are the two dimensions that define the decision strategy space (as illustrated in the right part of Fig. 2). The Boolean approach (not included in ConSite, but here visualised by grey dots) represents an extreme risk aversion (binary rejection) and extreme risk taking (binary acceptance) as portrayed in Fig. 2. WLC (medium risk and maximum trade-off) is in position 1, whereas positions 2–7 represent different

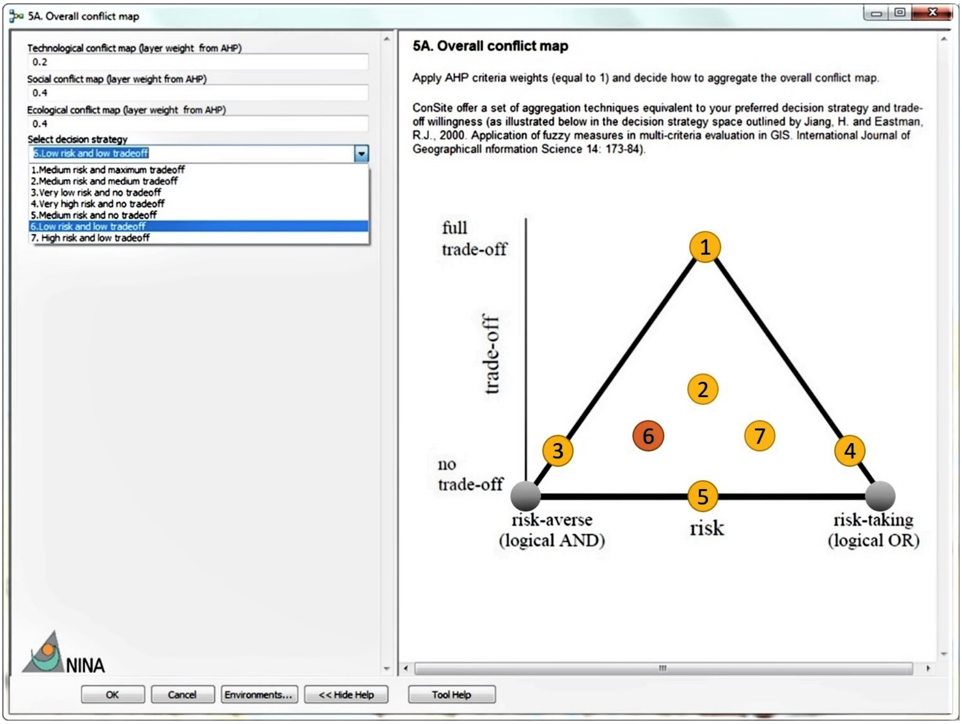

Fig. 2. (Color online) Criteria aggregation using AHP, OWA and a low risk and high trade-off decision strategy to obtain the conflict map (illustration after Jiang and Eastman, 2000).

OWA-based decision strategies. Position 6 (red dot) represents decision strategy number 6 (low risk and low trade-off).

6. *Siting/routing optimisation*
The ConSite SMCDA suite has currently two modules: ConSite Power-line and ConSite Wind. While these two modules are relatively similar, albeit with potentially different criteria, they have specific methodology for, respectively, routing (i.e. line segments) and siting (i.e. polygons).

Based on the aggregated conflict maps, ConSite Power-line utilises a standard least-cost path (LCP) algorithm (Chang, 2016). An LCP algorithm finds the 'cheapest' path from one point to another over a cost surface (equivalent to our conflict map). The cost surface is a raster map where each cell value defines how "expensive" it is to pass through that cell (Bagli *et al.*, 2011). By generating an accumulated cost surface based on the conflict map, the LCP algorithm identifies the line between two points with the lowest accumulated level of conflict. ConSite Power-line uses LCP analysis to calculate suitable power-line routing and identify project corridor(s) for further impact assessments and detailed planning between predefined locations (e.g. existing transformer and connector stations). ConSite Power-line currently only supports WLC for criteria aggregation, risk assessment and trade-off analysis.

The ConSite Wind module helps to identify suitable areas for wind-power development. First, it computes a conflict map based on a preferred trade-off/risk decision strategy and from this derives a conflict zone map (with inherent conflict statistics). Thereafter, the ConSite Wind module optimises siting and design layout of a wind-power plant based on the maximum allowed conflict level, calculated annual turbine power output (MWh) from local wind resources and preferred wind-power plant size (number of turbines and inter-turbine distance) (for details, see Hanssen *et al.*, 2018). ConSite assumes rectangular wind-power plant sites calculated using the Minimum Bounding Geometry tool in ArcGIS 10.3 (ESRI, 2015) to delineate the areas satisfying the requirements given by the criteria. ConSite Wind supports both AHP, WLC and OWA methodology for criteria aggregation, risk assessment and trade-off analysis.

Implementation Examples for the Siting of Renewable Energy Structures

Routing of high-voltage power lines

As an example of routing optimisation, we present an application of ConSite Power-line to validate the construction of a high-voltage power-line routing project. With 'validate' we here mean a comparison of the post-construction modelled power-line routing to the constructed power-line routing. We used a subset of the same criteria as those used in the actual EIA made prior to the construction of the existing power line (Table 1). In total, 18 stakeholders who were involved in the EIA process (developers and consultants, national authorities (energy, environment, cultural heritage), regional and local authorities, NGOs (farmers' association, tourism, reindeer management)) and seven experts,

Table 1. Criteria included in the ConSite Power-line routing exemplar.

Criteria	Criteria value		Criteria weight	Domain weight
	Least acceptable	Most acceptable		
Distance from:				
- Cabins	500 m	1 km	20%	Socio-economics 40%
- Tracks	500 m	1 km		
Distance from cultural heritage sites	200 m	500 m	10%	
Distance from cultural landscapes	300 m	2 km	15%	
Distance to densely populated areas	100 m	120 m	10%	
Distance to buildings	75 m	150 m	20%	
Distance to domestic reindeer:				
- Breeding areas	700 m	1 km	10%	
- Tracking routes	300 m	700 m		
- Winter pastures	300 m	700 m		
- Reindeer infrastructure	300 m	700 m		
Visual impact of power lines:				
- Rural homes	200 homes	0 homes	15%	
- Urban homes	200 homes	0 homes		
Power line environmental stress:				
- Ice load	20 kg/m cable	0 kg/m cable	20%	Technology 20%
- Wind load	50 m/s	0 m/s		
Distance from existing roads, railways and power lines	100 m	40 m	40%	
Ground conditions relevant for pylons:				
- Exclude bogs, mires, water bodies	Binary YES/NO		40%	
- Exclude stone avalanche areas	Binary YES/NO			

Table 1. (*Continued*)

Criteria	Criteria value		Criteria weight	Domain weight
	Least acceptable	Most acceptable		
- Exclude snow avalanche areas	Binary YES/NO			
- Exclude quick clay areas	Binary YES/NO			
Terrain steepness	30°	0°		
Distance to protected nature areas:				
- Nature reserves	500 m	1 km	20%	Ecology 40%
- National parks	300 m	875 m		
- Protected landscapes	500 m	1 km		
- Protected water courses	100 m	150 m		
Distance from wilderness areas	5 km	>5 km	20%	
Distance from important bird sites:				
- Nesting sites for gallinaceous birds	200 m	300 m	20%	
- Nesting sites for raptors	750 m	1 km		
- Leks of gallinaceous birds	300 m	500 m		
- Resting sites for redlisted birds	500 m	1 km		
- Wetlands (wading birds)	500 m	1 km		
Distance to wild reindeer:				
- Breeding areas	700 m	1 km	40%	
- Tracking routes	500 m	700 m		
- Seasonal grazing areas	500 m	1 km		

altogether representing a wide expertise on societal, ecological and technical issues relating to routing of power lines, were invited to two dialogue seminars. The participants defined relevant themes (e.g. cultural landscapes), sub-themes (e.g. distance to national important cultural landscapes), criteria (e.g. avoid infrastructure close to the cultural landscape) and criteria threshold values (e.g. >120 m away from existing infrastructure). As a final step, the different criteria were given a weight of importance compared with the other criteria (more details are described in Thomassen *et al.*, 2012a, 2012b). The power line modelled in ConSite collocated relatively well with the existing power line (Fig. 3) (Hanssen *et al.*, 2014). The modelled power line deviated from the constructed power line

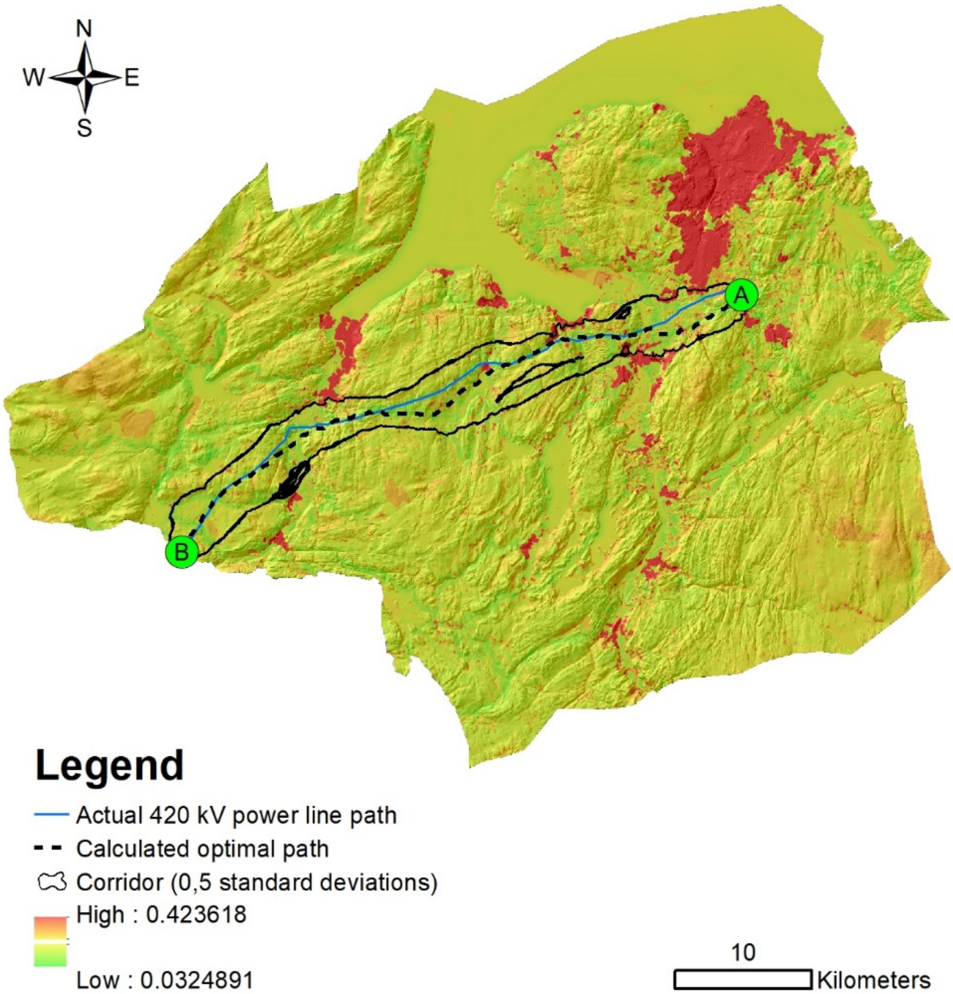

Fig. 3. (Color online) The conflict map based on an aggregation of social, technological and ecological criteria maps and the result of processing a least cost path algorithm from A to B. The calculated corridor (black polygon) and optimal power-line path (dotted line) is compared to the existing power-line path (blue line).

from 0.1 km to 0.85 km; with an average deviation of 0.46 km and median deviation of 0.2 km (first and third quartile is 0.1 km and 0.85 km, respectively).

Siting of wind-power plants

There exist extensive plans for wind-power development in Norway. However, it is not entirely problem-free to develop wind-power plants, as they may come into conflict with environmental, societal and other interests. Currently, there is no national SEA for onshore wind-power development in Norway upon which to base a national plan for (politically decided) areas for development (May, 2011; Thygesen and Agarwal, 2014). Regional plans for wind-power development, however, in part comply to SEA requirements as set out in the EU SEA Directive which Norway signed (May, 2011). A national plan is being developed at the moment, however not strictly following the guidance of the EU SEA Directive. However, county governments are to draw up regional plans to ensure holistic and long-term wind-power development in their region according to the national Planning and Building Act. These regional plans provide guidelines for appropriate planning and site selection of wind-power plants within the county or region. The regional plans focus on identifying and characterising the potential for

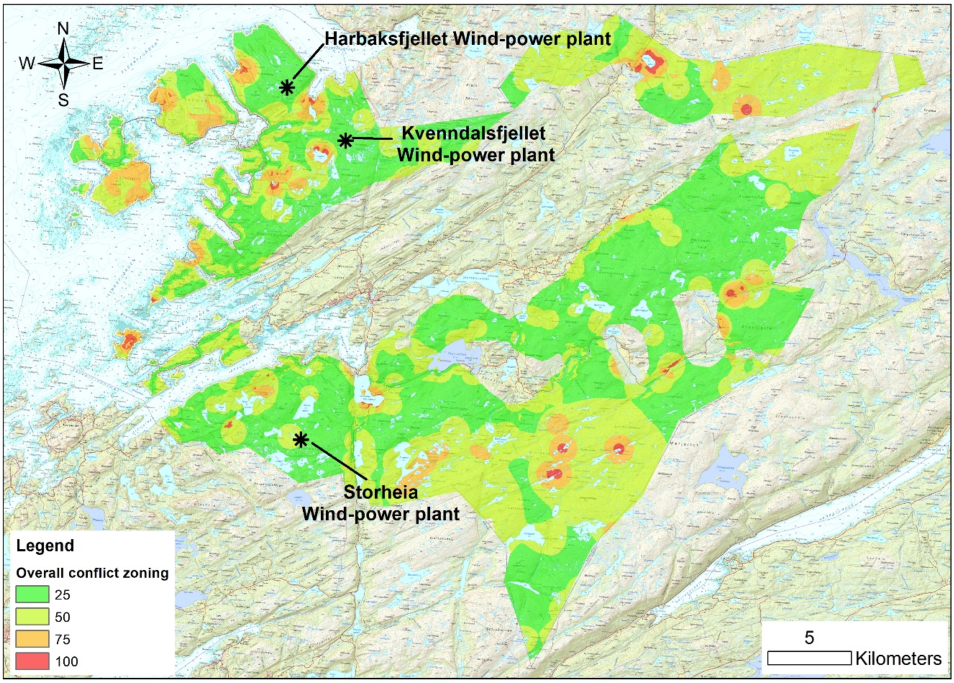

Fig. 4. (Color online) Conflict levels in the Åfjord municipality case study area (based on a low risk and low trade-off decision strategy), in areas with sufficient wind resources, derived from socio-economic, technological and ecological criteria maps. The Harbakfjellet wind-power plant (outlined in red) has a low conflict level and hence a high suitability, based on the applied criteria in this example. Wind-power plants under planning and concession evaluation are outlined in black.

conflicts and aid the identification of suitable sites for wind power in the region with least societal and environmental conflict per kWh. We applied a selection of relevant criteria derived from the regional plans and valuated and weighted the criteria for a case study example in the Åfjord municipality on the Fosen peninsula, Central Norway, where extensive wind-power development is planned. Within Åfjord municipality, three wind-power plants were consented to be constructed before 2020. Based on the criteria applied in this example, the consented Harbakfjellet (108 MW, 324 GWh), Kvenndalsfjellet (101 MW, 302 GWh) and Storheia (288 MW, 864 GWh) wind-power plants were all delineated as suitable areas using the ConSite Wind module because of these areas' lower level of conflict (Fig. 4). Offsetting the level of conflict to the expected energy production potential at each site, Harbakfjellet wind-power plant came out as being the best site within Åfjord municipality (Fig. 5). This corresponds very well with the given concession at Harbakfjellet.

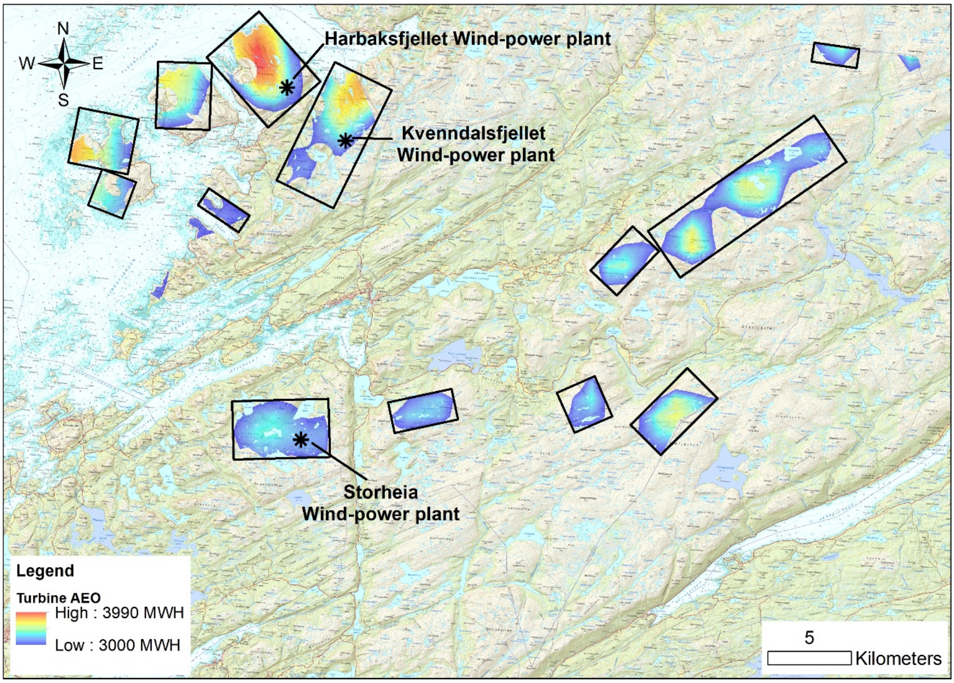

Fig. 5. (Color online) The most suitable areas for wind-power turbine annual energy output (AEO) according to the ConSite tool suite within Åfjord municipality on the Fosen peninsula, Central Norway. Consented wind-power plants are indicated with an asterisk.

Table 2. Criteria included in the ConSite Wind-power siting exemplar.

Criteria	Criteria value		Criteria weight	Domain weight
	Least acceptable	Most acceptable		
Required annual wind resources	4 m/s	Max. wind speed	40%	Technology 20%
Distance to overhead powerlines	150 m	10 km	20%	
Distance to main roads	100 m	300 m	30%	
Topographic heterogeneity	0%	20%	10%	
Distance to cultural heritage sites	200 m	2.5 km	20%	Social 40%
Distance to cultural landscapes	1 km	5 km	10%	
Distance to settlements and cabins	300 m	1.5 km	30%	
Fragmentation of agricultural land and commercial forest land	Binary YES/NO		40%	
Distance to nesting raptors	750 m	1 km	20%	Ecology 40%
Distance to shoreline	100 m	>100 m	24%	
Distance to protected nature areas:				
- Nature reserves	500 m	1 km	27%	
- National parks	500 m	2.5 km		
- Protected landscape areas	1 km	2.5 km		
- Protected water catchment areas	0 m	500 m		
Distance to unprotected wilderness	3 km	5 km	29%	

Discussion

This paper demonstrates how the ConSite SMCDA tool suite can help to build consensus, optimise spatial planning and improve decision-making processes in the pre-construction phase of high-voltage power line and wind-power plant construction projects. ConSite facilitates stakeholder dialogue and is designed to perform a combination of modern multi-criteria evaluation and decision analysis techniques. More specifically this includes criteria standardisation (fuzzy logic value functions), weighting (analytical hierarchy processing), trade-off and risk assessment (WLC and OWA), spatial sensitivity analysis and optimisation techniques for routing and site selection. Because enhanced functionality inherently also increases complexity, it will be important that stakeholders are guided through the dialogue process and will only have to relate to the identification of the decision problem, criteria content and estimation of weights. ConSite is flexible and may be implemented within a range of decision-makers' preferences from different contexts.

Despite scientific advances in SMCDA and Spatial Decision Support Systems during the last decades (Mateo, 2012; Moghadam *et al.*, 2016; Grêt-Regamey *et al.*, 2017), it is our impression that a substantial amount of current spatial decision-making is still based on traditional (and often analogue) land-use planning approaches. SEA and EIA are the most important tools in current spatial decision-making. SEA is a proactive approach at earlier stages of the decision-making process for strategic choice (and siting) of alternative developments. SEA thereby sets the framework for future development consent of projects subject to EIA. Although project-based, EIA should include the assessment of a range of alternatives (including the status quo) such as alternative siting. Both represent a systematic process in which relevant information and stakeholder views are collected, documented and presented in a structured way and regarded as an effective planning tool that helps to improve decision-making (Malczewski, 2006a; Snell and Cowell, 2006). However, the increasing complexity of involved criteria and interests in SEAs and EIAs will probably force decision-makers to use more efficient and intelligent approaches. Our experience from meetings with spatial planners and decision-makers in Norway is that they solely use GIS and spatial data for simple spatial analyses and visualisation purposes. The usage of GIS in combination with SMCDA to improve, qualify and aid spatial decision-making is however still lacking. This is probably a matter of prioritisation, but also an indication that there is a great need for a paradigm shift in the educational programs for future spatial planners and decision-makers. We believe that in the coming decades, we will see many changes to our social-ecological-technical landscapes, not in the least due to urbanisation and renewable energy development at the expense of environmental public goods and services. With the current focus on reaching the United Nations' Sustainable Development Goals to facilitate the 'green transition', there will likely be more leverage for transparent and democratic approaches that are able to address complex spatial planning issues.

By aggregating weighted criteria spatially, ConSite contributes to improved visualisation and transparency of complex planning issues to support consensus-based decision-making. The implementation of OWA in ConSite enables visualising the consequences of various trade-off/risk strategies or weight scenarios. Such functionality will be important for addressing complex and more inclusive decision-making processes, by making the consequences of various planning strategies or stakeholder views spatially evident. In this way, the integration of GIS and MCDA facilitates participation in the decision-making process by allowing stakeholders to explore different aspects of a decision problem and articulate their preferences (Malczewski, 2006b). Stakeholder dialogue may, however, also be perceived to be too challenging, time-consuming and costly. The group dialogue may be characterised by differences in mandates, conformity pressure, dominating personalities and ambiguous responsibilities, which in some, if not most, cases may stall the decision-making process (Ferretti and Montibeller, 2016). This is probably the main reason why stakeholder involvements are not always fully implemented throughout many spatial planning and decision-making processes. It may therefore be important to identify the intra-relationships between the different stakeholders, which could be done in several ways. Among the more established approaches is to use a stakeholder interest-influence matrix (Mendelow, 1981) or constellation analysis (Bruns *et al.*, 2011; Huesca-Perez *et al.*, 2016). These approaches represent a logical process that categorises stakeholders according to their interest and influence (those who have high power and interest, high power and low interest, low power and high interest and low power and low interest). However, relationships between stakeholders are not static but evolve continuously. In addition to identifying what to observe in stakeholder relationships (such as interest and influence), one should recognise the dynamic nature of stakeholder relationships (Missonier and Loufrani-Fedida, 2014). Stakeholder involvement should by no means be restricted to a small circle of influential stakeholder groups (Junker *et al.*, 2007). To address the inherent uncertainty of variability among stakeholder preferences and the uncertainty of applied decision strategies, future development of ConSite should enable mapping these uncertainties using Monte Carlo simulations and variance-based global sensitivity analysis (Feizizadeh *et al.*, 2015) and performing sensitivity analysis for minimising the probability of making errors in decision-making based on fuzzy-modified AHP (Feizizadeh *et al.*, 2015). This could then result in a map visualising the level of disagreement across the landscape, based on the variance in normalisation values and weights. Although the above outline are more ideas for further development rather than implemented functionality, the already established ConSite dialogue approach helps to gather information about and insights into inherent concerns and priorities. This information is used to establish a consensus-based and transparent knowledge platform, which is paramount for obtaining stakeholder consensus and high-quality decision-making (Owen, 2015).

Although ConSite represents a tool suite that can help finding consensus among stakeholders in siting of renewable energy infrastructure, all methodologies inherently have their limitations. ConSite assumes that stakeholders actively participate in the dialogue process and that the constellation of stakeholders is balanced. However, if some sectoral representatives frustrate the dialogue or even refuse to become involved, the ultimate decision may not represent their views, which they thereafter can oppose politically. There should as such also be a societal consensus on whether or not to use a tool suite as ConSite in the first place. This can be realised by the relevant planning authorities by employing it as a standard. Regardless of this, any GIS tool requires that the relevant criteria actually can be mapped and that the extent, accuracy and resolution of the spatial data are deemed sufficient. Criteria that cannot be mapped, either directly or through proxies, cannot be considered. Criteria may function across a range of spatial scales. This necessitates the incorporation of multiple-scale approaches through the involvement of stakeholders at different institutional scales and the consequent setting of threshold values and weights at appropriate biophysical scales (de Groot *et al.*, 2010). Thirdly, associated criteria that are linked to a specific area or regularly appear together repeatedly in space and time may form bundles of associated criteria (Berry *et al.*, 2016). Such bundles of spatially correlated criteria are indicative of the multi-functionality of an area. This, however, also means that multi-functional areas likely result in higher conflict levels due to this collocation which will be of relevance from an SEA/EIA perspective with respect to cumulative effects. ConSite currently associates each criterion to, respectively, the socio-economic, technology and ecology domain and hierarchically aggregates criteria within domains and thereafter across domains. Although not yet implemented, considering criteria bundles may reduce the risk over overseeing specific key criteria, but may also serve the interests of some stakeholders above others, leading to issues in distributive impacts, legitimacy and power asymmetries (Berry *et al.*, 2016). Integrating area multi-functionality or cumulative effects is still quite challenging and requires methods for identifying associations and spatial coincidence of criteria bundles using, for example, multivariate techniques (Berry *et al.*, 2016).

A potential pitfall during the scoping process is the inclusion of both cause and effect criteria, which may inflate a potential conflict due to double counting. For instance, the financial consequences of constructing within highly productive forest sites should preferably not be included; rather constructing at sites of highly productive forest should be set as less acceptable. While financial cost–benefit assessments are currently the most important rationale for decision-making, we think it is better to base decisions on the actual biophysical values rather than on their monetary proxies. Although a number of economic criteria can be spatially represented, beyond fixed prices (e.g. home sale prices, price of land) valuation proxies will have to be used. Monetary valuation has been developed for ecosystem and cultural services (Gómez-Baggethun *et al.*, 2010); however, there are many inherent controversies making a complete representation of economic criteria hard to achieve (Spash and Aslaksen, 2015). Still, applying the ecosystem service framework (de Groot *et al.*, 2010), the benefits humans derive from the natural environment and ecosystems may further strengthen ConSite (for proposed approach, see Hanssen *et al.*, 2018) as it may better visualise the costs and benefits for a variety of public goods and services across the landscape (Geneletti, 2011). This may be of special importance in urban settings in which the pressure on natural features due to anthropogenic development is intense. The ConSite tool suite can thereby contribute to siting of industrial and housing areas or alternatively routing of green corridors in urban areas.

Conclusions

The rapid and large-scale development of renewable energy worldwide places simultaneously more pressure on society and the natural environment. Although there is considerable support for renewable energy development, its expansion also causes several concerns which traditional land-use planning may have limited capacity to address adequately. In regional planning, environmental and societal concerns of renewable energy development and transmission lines need somehow to be offset against technological and socio-economic benefits within a spatial context. SMCDA tools can help to identify suitable development areas and render feedback on the conflict potential and its inherent conflict levels. The ConSite tool suite was developed to support integrated and participatory assessment of renewable energy siting within a spatial context. ConSite build upon active stakeholder dialogue and employs analytical hierarchical processing and ordered weighted assessment algorithms for aggregation and trade-off analysis. ConSite allows for visualising the consequences of various trade-off/risk decision strategies or weight scenarios. In this way, the integration of GIS and MCDA facilitates participation in complex decision-making processes by allowing stakeholders to explore different aspects of a decision problem and to articulate their preferences. ConSite has been applied to the routing of energy transmission lines and the siting of onshore wind-power plants, but can also be modified to aid planning decisions of technical or ecological infrastructures (e.g. aquaculture and ecological corridors).

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