Deconstructed and Inverted Multi-Criteria Evaluation for On-The-Fly Scenario Development and Decision-Making

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Abstract

We propose a variation of the conventional spatial multi-criteria evaluation workflow for suitability analysis that allows efficient on-the fly scenario development for decision-making. Our approach proposes to reconstruct the conventional MCE workflow in order to exclude computationally expensive geoprocessing from the iterative scenario development. We then introduce a procedure that replaces costly iterations of spatial operations with one off-line preprocessing step followed by iterations of much less computationally expensive database queries. We illustrate our approach for deconstructed and inverted multi-criteria analysis with a case study aiming at selecting suitable sites for wind turbines in the Swiss alps.

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1 Introduction

Spatial multi-criteria evaluation (MCE) is a formalized procedure for spatial decision problems [7], and represents one of the key applications of GIS. MCE applications include land suitability evaluation [4] or selecting suitable sites for wind farms [6]. Many of these applications have contributed to the GIScience theory by introducing computational techniques for improving the MCE workflow, proposing optimization approaches, performing sensitivity studies, handling uncertainties, as well as visualizing multi-faceted MCE results [3, 8, 2].

MCE is typically data-rich and computationally expensive, which can make it impractical for decision-making processes requiring iterative scenario development. Therefore we propose a variation of the conventional MCE that specifically aims at optimizing the workflow in such

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a way that decision makers can exploit the full depth of MCE results for efficient on-the fly scenario development. We achieve this by (a) proposing a deconstructed and rearranged MCE workflow where computationally expensive steps can be precomputed and hence excluded from the interactive and iterative scenario development, and (b) proposing a procedure for inverse criteria evaluation that reduces the computational costs for adjusting MCE criteria in scenario development to a feasible minimum. The work emerges from an applied research project on selecting suitable sites for wind turbines in the Swiss Alps.

Conventional MCE typically follows a standardized workflow (Figure 1): selecting the criteria (e.g. "not within a given distance to power lines"), defining a model for translating them into spatial relations (line buffer with radius b_l), parameterizing the criteria ($b_l < 110m$), computing the respective spatial operations, standardizing and weighting the value scores (0 or 1 for not-suitable/suitable), aggregating the value scores (overlay operation), and finally interpret and validate the results, e.g. using sensitivity analysis [8]. There are several types of spatial criteria in MCE. Many criteria valuate locations by spatial properties, e.g. slope or soil type. This paper, however, focuses on criteria that valuate locations by properties of their neighborhoods. This is typically done with some form of a distance relation expressed by a buffer, e.g. "within 200m of a main road". The latter type of criteria can then further be separated into selection ("suitable locations must be within 200m of a main road") and exclusion criteria ("suitable location must not be within 150m of a power line").

MCE is primarily a planning and decision-making tool, so not surprisingly, participatory concepts are increasingly used [5, 9]. The input of decision makers is also required when potentially conflicting interests have to be balanced in multi-objective evaluation [8]. At the same time, MCE is typically data-rich, which means it requires time-consuming computing and produces a wealth of data. These two aspects both hinder interactive decision-making [4]. The adjustment of a single parameter of a neighborhood criterion (e.g. increasing the exclusion distance to power lines from 110m to 150m) may trigger costly recomputing of spatial buffers and overlay operations. Under such conditions, efficient on-the-fly scenario development for decision-making is challenging.

The overarching objective of our work is developing a MCE workflow for neighborhood criteria that allows for fast and simple on-the-fly scenario development for interactive planning sessions with decision makers or for on-line decision-making tools. This leads to the following research question: How can the conventional MCE workflow be modified such that adjusting criteria parameters does not require computationally expensive spatial operations?

2 Deconstructed and inverted MCE (di-MCE)

We propose a variation of the classic MCE workflow based on two key ideas. First, we deconstruct the MCE procedure into its constituent operations and re-assemble them in such a way that fast and efficient scenario development becomes feasible. For those operations that have to be repeated frequently in scenario development, we propose secondly a procedure that inverts the perspective of the spatial criteria evaluation. Costly spatial operations are precomputed and for the scenario development phase replaced by more efficient SQL queries. We subsequently refer to *deconstructed and inverted MCE*, in short *di-MCE*.

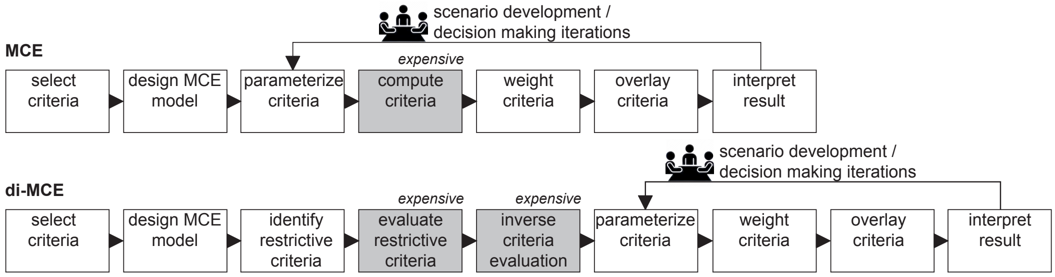

Figure 1 Comparison of conventional MCE with di-MCE. In the conventional case, the iteration loop for scenario development includes adjusting criteria parameters and recomputing the criteria, which can be costly and impractical. di-MCE, instead, suggests re-assembling the workflow such that computationally expensive steps are excluded and outside the decision-making iteration loop.

Deconstructing MCE. The idea of deconstructing[1] the MCE workflow lies in disaggregating the data analysis process into its constituent steps and excluding the computationally expensive steps from the iterative scenario development phase. In our experience, most MCE studies feature some criteria that are more spatially restricting than others and most often also non-negotiable. These could, for example, be a maximal slope or a minimal wind speed for positioning a wind turbine. We hence propose analyzing the complete set of criteria and isolating those that most reduce the resulting suitable space. Instead of including the entire set of criteria into the scenario development iterations, we propose precomputing such *restrictive criteria* and thereby excluding them from scenario development (Figure 1). Note that in *di-MCE* the computationally expensive evaluation of restrictive criteria is excluded from the iterative scenario development loop. This results in two MCE phases, where the first (off-line) phase results in the intermediate result of the *potentially suitable space* (S_{pot}). Ideally, S_{pot} only covers a small fraction of the entire study area (Figure 2). For S_{pot} we then propose an inverse criteria evaluation approach, where the computationally expensive steps can again be precomputed, and separated from the interactive and iterative decision-making.

Inverse criteria evaluation. Neighborhood criteria in conventional MCE typically focus on the spatial features that support or limit the suitability of the solution space. That means, suitability criteria are implemented using buffers that *expand from* supporting or limiting features (note the direction of the arrows in the left Figure 2). We propose inverting the perspective and focusing instead on S_{pot} identified in the previous step, and then evaluating spatial relations *directed towards* the supporting or limiting features (now note the opposite direction of the arrows in the right Figure 2).

Allowing for this inverse perspective, we tessellate the S_{pot} and for each tessellated unit compute a nearest neighbor distance d to the nearest feature of every remaining criterion. Note that for simplicity we chose a regular raster data structure for tessellating S_{pot}, resulting in candidate cells c_i. However, our approach also works for irregularly tessellated spaces, e.g., based on land-use parcels. This step translates the topological relation (“within buffer of width b”) into a numeric attribute of a candidate cell. Again, for simplicity, we focus so far on simple distance relations to supporting or limiting features, acknowledging that more complex distance functions could be used.

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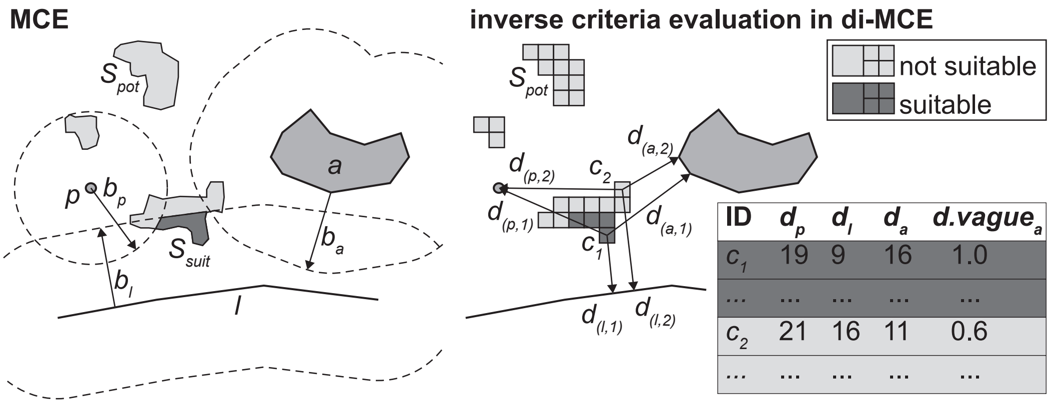
[1] The term deconstructed is inspired from cookery, proposing the deconstruction of classics, e.g. as in “Deconstructed Pavlova”, the antipodean pastry classic.



ID	d_p	d_l	d_a	$d.vague_a$
c_1	19	9	16	1.0
...	...	...	...	...
c_2	21	16	11	0.6
...	...	...	...	...

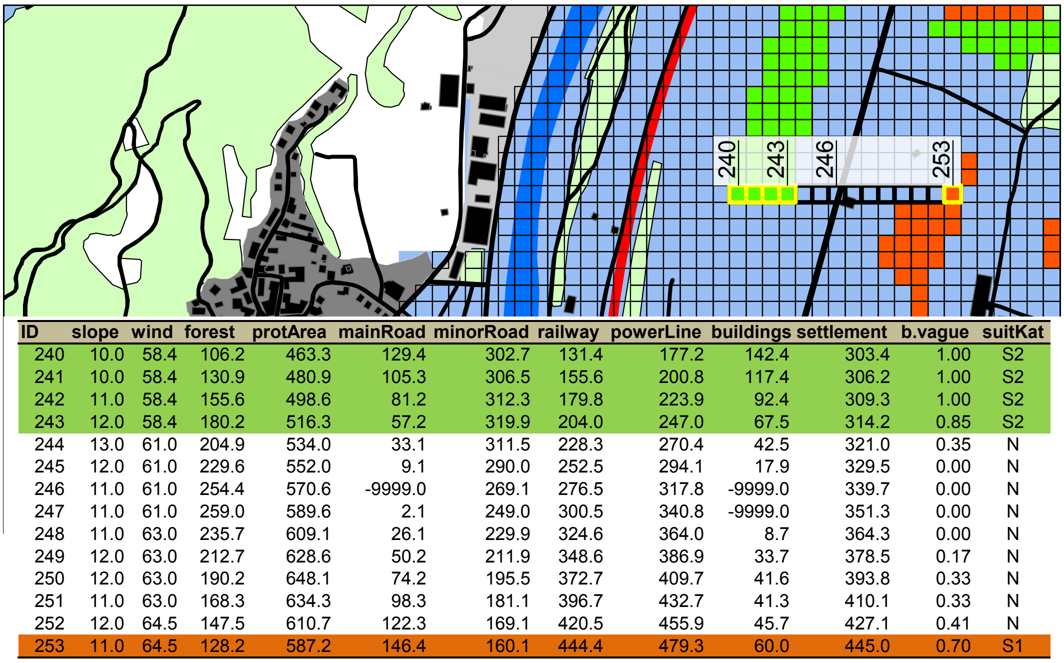
Figure 2 Conventional MCE adds distance buffers to points (p), lines (l), and areal features (a) with buffer parameters b_p, b_l, and b_a, resulting in the overall suitable area S_{suit} (dark grey). di-MCE precomputes distances ($d_{(p,n)}$, $d_{(l,n)}$, and $d_{(a,n)}$) from S_{pot} – tesselated into candidate cells c_i – to the nearest point, line, or area. In the example, c_1 is suitable, but c_2 is not. Crisp buffers can be dissolved into vague criteria.

Combining all computed distances for all spatial units of S_{pot} results in the cell attribute table (CAT). In unfavorable criteria constellations, this transformation can be computationally expensive. However, the distances have to be computed only once, which can be done in advance. The inversion transforms the structure of intermediate MCE results. The spatial criteria do no longer come in the form of buffer vector data or raster cost-surfaces, but as numeric data in a table. This in turn means, that adjusting parameters does not require costly recomputing of geoprocessing operations (such as buffer, overlay, or map algebra operations) but only adjusting SQL queries on attribute tables. In short, we precompute the computationally expensive spatial operations for all candidate cells and then make use of SQL queries for the final site selection in the iterative scenario development – the dark grey cells in Figure 2. Going back to Figure 1 the deconstruction idea becomes evident again. The computationally expensive calculation of the distances is precomputed and hence excluded from the scenario development. Hence, the parametrization of all negotiable criteria can happen *after* the costly spatial processing.

The inversion furthermore allows for an efficient inclusion of multi-criteria trade-offs and vagueness. First, the balancing of objectives, even conflicting objectives, can be implemented into CAT queries, using sophisticated SQL functions combining multiple attributes. The nearest neighbor distance values in the CAT secondly allow also for a straightforward inclusion of vagueness into criteria evaluation. Membership functions can be applied to nearest neighbor distances, dissolving unrealistically crisp buffer boundaries into gradual memberships.

3 Case study: Positioning wind turbines

We illustrate our approach with the very research project that highlighted to us the shortcomings of conventional MCE. The study aimed at finding suitable areas for positioning wind turbines in a region of the Swiss alps. The criteria covered technical requirements (maximal slope, accessibility for construction), economic requirements (e.g. minimal wind speed of 4.5 $\frac{m}{s}$), and a set of regulatory requirements given through a federal guideline [1]. A subset of the approximately 50 criteria and their parameterization for two types of wind turbines T_1 and T_2 is given in Table 1. Note that most criteria are of the neighborhood type.



ID	slope	wind	forest	protArea	mainRoad	minorRoad	railway	powerLine	buildings	settlement	b.vague	suitKat
240	10.0	58.4	106.2	463.3	129.4	302.7	131.4	177.2	142.4	303.4	1.00	S2
241	10.0	58.4	130.9	480.9	105.3	306.5	155.6	200.8	117.4	306.2	1.00	S2
242	11.0	58.4	155.6	498.6	81.2	312.3	179.8	223.9	92.4	309.3	1.00	S2
243	12.0	58.4	180.2	516.3	57.2	319.9	204.0	247.0	67.5	314.2	0.85	S2
244	13.0	61.0	204.9	534.0	33.1	311.5	228.3	270.4	42.5	321.0	0.35	N
245	12.0	61.0	229.6	552.0	9.1	290.0	252.5	294.1	17.9	329.5	0.00	N
246	11.0	61.0	254.4	570.6	-9999.0	269.1	276.5	317.8	-9999.0	339.7	0.00	N
247	11.0	61.0	259.0	589.6	2.1	249.0	300.5	340.8	-9999.0	351.3	0.00	N
248	11.0	63.0	235.7	609.1	26.1	229.9	324.6	364.0	8.7	364.3	0.00	N
249	12.0	63.0	212.7	628.6	50.2	211.9	348.6	386.9	33.7	378.5	0.17	N
250	12.0	63.0	190.2	648.1	74.2	195.5	372.7	409.7	41.6	393.8	0.33	N
251	11.0	63.0	168.3	634.3	98.3	181.1	396.7	432.7	41.3	410.1	0.33	N
252	12.0	64.5	147.5	610.7	122.3	169.1	420.5	455.9	45.7	427.1	0.41	N
253	11.0	64.5	128.2	587.2	146.4	160.1	444.4	479.3	60.0	445.0	0.70	S1

Figure 3 Excerpt from the results of the wind turbine project. The map features a number of spatial layers required for evaluating the suitability criteria, e.g. streets (black), railways (red), settlement areas (grey), and buildings (black). For a small horizontal transect of cells c_{240} to c_{253} the computed nearest neighbor distances d_{nn} are displayed in the cell attribute table below. Note, -9999.0 as in c_{246} codes the case when the candidate cell touches the feature (e.g. mainRoad).

Table 1 Eight out of approx. 50 criteria for positioning two types of wind turbines T_1 and T_2.

Criterion	T_1	T_2	Criterion	T_1	T_2
forest	not within	not within	mainRoad	$d > 17$	$d > 33$
protArea	not within	not within	minorRoad	$d > 17$	$d > 33$
buildings	$d > 50$	$d > 50$	railway	$d > 17$	$d > 33$
settlement	$d > 100$	$d > 100$	powerLine	$d > 110$	$d > 190$

The available wind field, a slope threshold and an accessibility criterion were identified as restricting criteria and consequently used for computing the *potentially suitable space* (S_{pot}). The map in Figure 3 illustrates a small space depicting a subset of all criteria (streets, railways, settlement areas, building, forest) as well as the precomputed *potentially suitable space* (S_{pot}). In correspondence with Figure 2 (S_{pot}) was tesselated into $25m * 25m$ cells, the blue layer in the background indicates the areas with enough wind. Finally, the overall suitable area S_{suit} is depicted with orange and green cells (suitability categories S1 and S2).

The map also features a short transect of candidate cells c_{240} to c_{253} for which the table below the map shows a subset of the CAT. Whereas for slope and wind the actual values of the respective field variable are given (which were used for computing (S_{pot}), all other attributes are nearest neighbor distances d_{nn} to supporting or limiting spatial features. The last two columns illustrate the use of vagueness and the final suitability category. The distances in the table can now be directly compared with the criteria parameters in Table 1.

The case study can illustrate the advantages of di-MCE. Consider the criterion "sites for wind turbines must not be within a defined distance to power lines". This parameter is clearly a function of the size of the turbine, Table 1 indicates $d > 110m$ for the smaller type T_1, and $d > 190$ for the larger T_2. Assuming the scenario for a new turbine type of intermediate size, the suitability for each candidate cell can easily be recalculated from the precomputed distance value in the CAT, without costly repetition of spatial operations. The column **b.vague** in Figure 3 finally illustrates the inclusion of vagueness. To this end, the criterion "distance to buildings" has been dissolved into a vagueness value using a membership function (0 for $d_b < 25$, 1 for $d_b > 75$, and a linear function in between).

4 Discussion and conclusions

The goal of our work is re-structuring the MCE workflow in such a way that on-the-fly scenario development becomes feasible. This explicitly does not mean reducing the overall computing load of MCE. Depending on the criteria constellation, the proposed inverse criteria evaluation may even add to the overall computation cost. However, with our deconstructed and re-assembled workflow, the crucial step of adjusting criteria parameters appears in the sequence of operations *after* the costly spatial operations, making iterative scenario development perfectly feasible. Replacing spatial operations on vector or raster data with queries on attribute tables offers the additional benefit of the straightforward integration of vague criteria and the balancing of conflicting objectives. Once the nearest neighbor distances are computed, SQL queries allow for very flexible transformation and combination of multiple criteria.

Our approach is most suited for MCE projects with (i) frequent stakeholder interaction, (ii) a set of criteria with one or two criteria being rather restrictive and non-negotiable, and (iii) a predominant use of distance-based neighborhood criteria. In our wind turbine site selection case study all three preliminaries were given. We argue, however, that the majority of MCE studies comply with at least some of these preliminaries, hence offering at least partially to benefit from the advantages of di-MCE. In the wind turbine case study we only considered simple distance-based nearest neighbor criteria. More complex neighborhood functions could be conceptualized and implemented within di-MCE. We are currently working on more complex neighborhood functions, comparable to focal and zonal map algebra operations (e.g. %-forest cover within distance d around a candidate cell).

References

1 Mattia Cattaneo and Leonhard Zwiauer. Concept windenergy – Federal guidelines for planning windenergy installations. Technical report, Swiss Federal Office for Spatial Development, 2017.

2 Bakhtiar Feizizadeh, Piotr Jankowski, and Thomas Blaschke. A GIS based spatially-explicit sensitivity and uncertainty analysis approach for multi-criteria decision analysis. *Computers & geosciences*, 64:81–95, 2014.

3 Montserrat Gómez-Delgado and Stefano Tarantola. Global sensitivity analysis, GIS and multi-criteria evaluation for a sustainable planning of a hazardous waste disposal site in spain. *Int.J. of Geographical Information Science*, 20(4):449–466, 2006.

4 Isabel Jaisli, Patrick Laube, Sonja Trachsel, Pascal Ochsner, and Sarah Schuhmacher. Suitability evaluation system for the production and sourcing of agricultural commodities. *Computers and Electronics in Agriculture*, 2018.

5 Piotr Jankowski. Towards participatory geographic information systems for community-based environmental decision making. *J. of env. management*, 90(6):1966–1971, 2009.

6 Dionysis Latinopoulos and K Kechagia. A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in greece. *Renewable Energy*, 78:550–560, 2015.

7 Jacek Malczewski. GIS-based multicriteria decision analysis: A survey of the literature. *Int. J. of Geographical Information Science*, 20(7):703–726, 2006.

8 Jacek Malczewski and Claus Rinner. *Multicriteria decision analysis in geographic information science*. Springer, 2016.

9 Beni Rohrbach, Patrick Laube, and Robert Weibel. Comparing multi-criteria evaluation and participatory mapping to projecting land use. *Landscape and Urban Planning*, 176:38–50, 2018.