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Practice report

Multicriteria analysis to compare the impact of alternative road corridors: a case study in northern Italy

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The analysis and comparison of a set of project alternatives implies balancing the different impact types so as to reach an evaluation of the merit of each alternative. Multicriteria analysis (MCA) proved to be useful for this kind of assessment by providing a framework to integrate the available information about the impacts with the values and preferences of stakeholders and decision-makers. This paper presents a case study in which MCA was applied to achieve a suitability ranking of the alternative land corridors that were proposed to host a road development within an alpine valley in northern Italy.

Keywords: multicriteria analysis; sensitivity analysis; road corridor

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CONSIDERATION OF DIFFERENT alternatives is one of the fundamental requirements of environmental impact assessment (EIA). The analysis and comparison of sets of project alternatives implies balancing up the different impact types so as to reach an evaluation of the merit of each alternative, and eventually a suitability ranking. This calls for a framework to integrate the available information about the impacts with the values and preferences of the decision-makers, to examine the overall implications of the alternatives. Multicriteria analysis (MCA) offers suitable support for this kind of assessment, and for this reason has become useful within EIA (Janssen, 2001; Caggiati and Ragazzoni, 2000; Bonte *et al*, 1998).

MCA techniques support the solution of a decision problem by evaluating the alternatives from different perspectives and by analysing their robustness with respect to uncertainty. A characteristic feature of multicriteria approaches is that the evaluation is based on a number of explicitly formulated criteria, that is, ‘standard of judging’, that provide indications of the performance of the different alternatives. Such criteria, considerably different in nature, are expressed by appropriate units of measurement. In EIA, the evaluation criteria typically consist of different types of impact caused by the project under analysis. Such impacts need to be contrasted and aggregated into concise assessments to allow a comparison of the alternatives.

This paper presents a case study on the EIA of alternative corridors for a road development. A geographic information system (GIS) was used to

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Figure 1. Location of the study area

compute the impacts of the different alternatives on a set of environmental components. Subsequently, MCA was applied to aggregate the impact scores and achieve a ranking of the proposed alternatives. Finally, the robustness of the results was tested using to sensitivity analysis techniques. The case study is represented by the construction of a new motorway within an alpine valley in northern Italy. Further analyses on this case study may be found in Geneletti (in press; 2003; 2002) and Geneletti *et al* (2003a; 2003b).

Case study

The study area is located within the Autonomous Province of Trento, in northern Italy, and includes part of the wide valley of the Adige river and its surrounding peaks (see Figures 1 and 2). It covers about 300 km^2, extending from the northern outskirts of the town of Trento to the beginning of the Non valley. The area is characterised by alpine geomorphology and the elevation ranges from 200 m up to 2000 m.

As shown by the land-cover map represented in Figure 2, the cultivated areas include most of the valley floors and part of the lower slopes. They are almost exclusively composed of vineyards and apple orchards. Urban settlements and industrial plants, and a few remnants of natural areas occupy the rest of the valley floor.

The area has a strong economy, based on agriculture and tourism. The Non valley is famous for its apple production, whereas the Adige valley, and especially the Piana Rotaliana alluvial cone, is a well-known wine area, producing vintage of high quality.

The Non valley suffers from traffic congestion at its junction with the Adige valley. The present passage through a narrow gorge is winding and unsuitable for heavy traffic. Traffic problems are also reported in several villages in the Adige valley, and especially near the town of Trento. For these reasons, the local authorities have decided to strengthen the existing road network by developing a new connection between the town of Trento and the beginning of the Non valley.

At the time this research started, no alternatives had officially been proposed. However, a number of possible alignments for the whole route, or just for sectors of it, were drafted in earlier studies. On the basis of those documents, five different corridors were reconstructed and analysed to provide an assessment of their suitability (see Figure 3). Therefore, this study did not aim to evaluate the final project blueprints, but rather to provide a preliminary comparison of the proposed land corridors within which the road is to be designed.

Impact computation

The area to be crossed by the road is characterised by a very intensive land use. Urban settlements, infrastructure, agriculture, and natural areas all compete for space. To complicate matters even further, geomorphologic constraints reduce the areas suitable for new construction. Therefore, placing a new motorway within such a landscape is a complex task. As the main concern of the project relates to the amount of land used, this study has focused on the space required for the road. Space requirement refers to the direct impact caused by the presence of the road and its verges, that is, by the conversion of the original land cover and land use into an artificial surface.

Five different environmental components potentially affected by the space requirement were considered: vegetation; wildlife habitat; landscape; land production; and geomorphology. For each of these components, a value map was generated.

Vegetation The vegetation of the study area was evaluated according to its naturalness (that is, the

Five different environmental components potentially affected by the space requirement were considered: vegetation; wildlife habitat; landscape; land production; and geomorphology: for each of these components, a value map was generated

degree to which a vegetation type is free from bio-physical disturbance caused by human activities) and to the disturbance introduced by management, following the approaches proposed in de Amicis *et al*, (1999), Minghetti (1999), and Andreis (1996). The resulting value map ranges from zero (artificial vegetation types) to five (undisturbed vegetation types).

Habitat The suitability of the study area as a habitat for two representative animal species (roe deer and capercaillie) were estimated using a model based on the application of GIS spatial functions and expert knowledge (Patrono, 1998; Perco, 1990). The resulting value map ranges from zero (unsuitable for both species) to ten (most suitable for both species).

Land production Data on annual income derived from the main cultivation types and coppice woodlands were used to reclassify the land-cover map into a land-production map, expressed in euro/year.

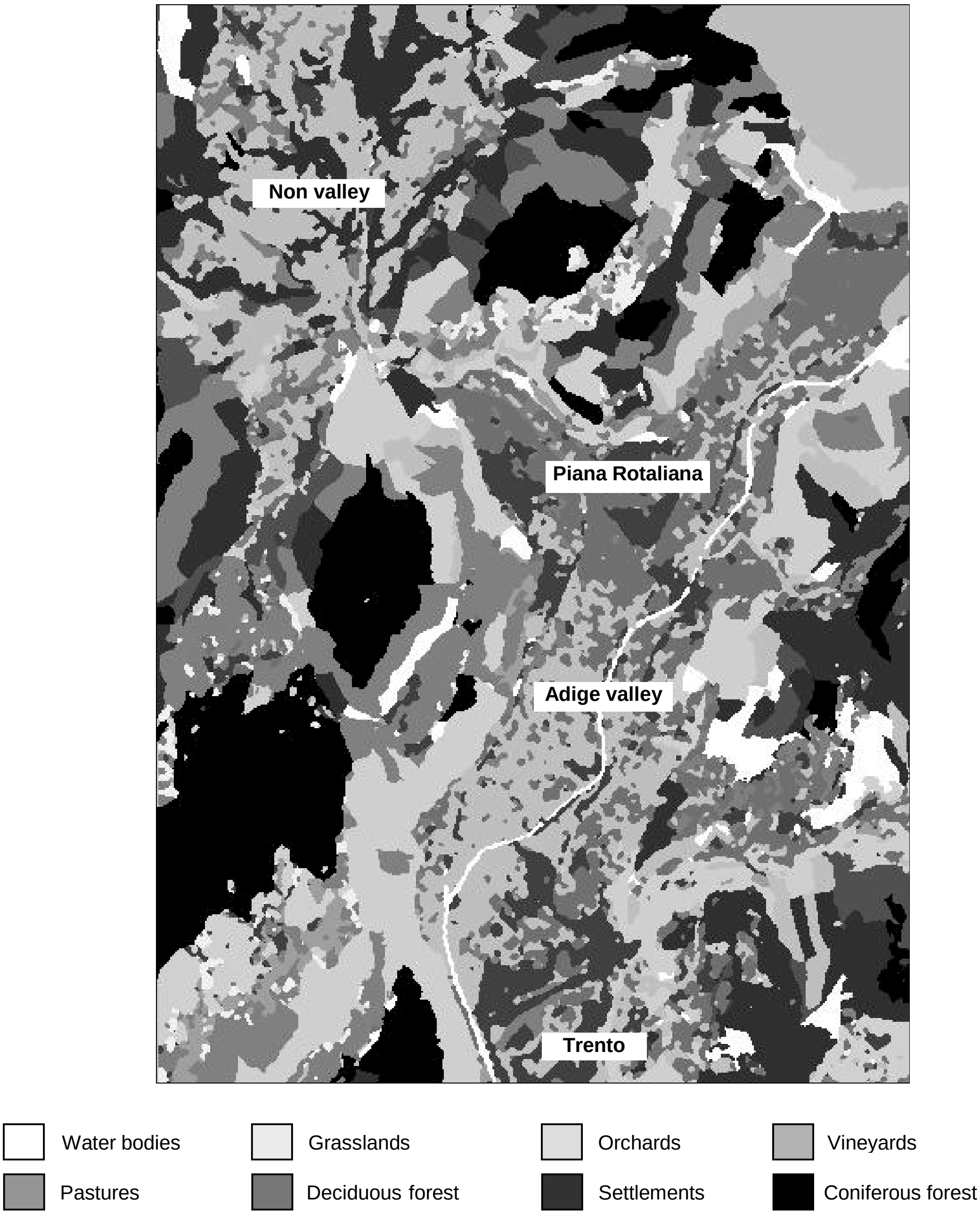

Figure 2. Land-cover map of the study area

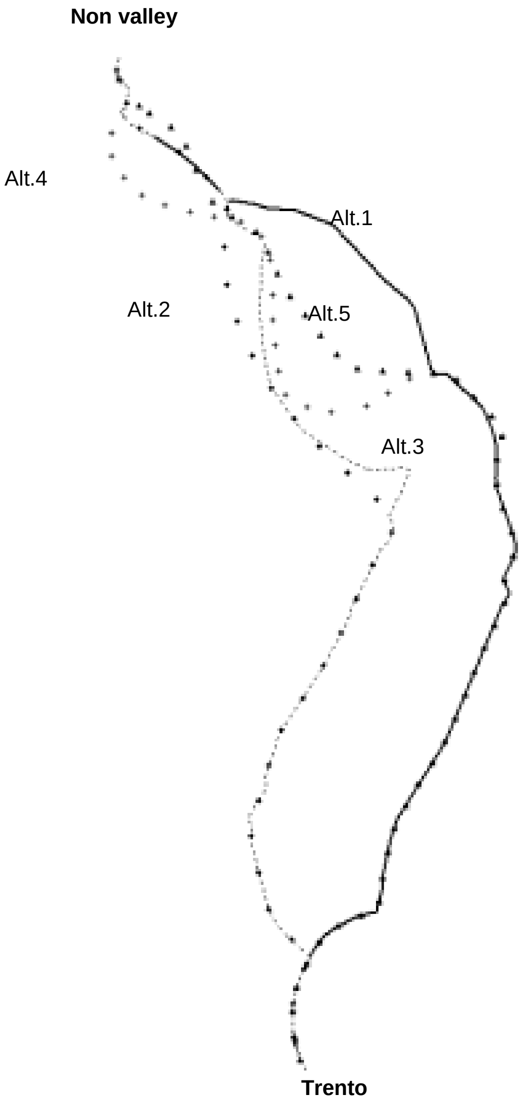

Figure 3. Road alignments

Landscape The visibility of every location within the study area was assessed by calculating a viewshed[1] from five selected points. The five maps thus obtained were combined into a final value map ranging from zero (pixels not visible from any of the viewpoints) to five (pixel visible from the five viewpoints).

Geomorphology The landforms of the study area were assessed in terms of their scientific value and their degree of preservation, according to the methodology proposed in Rivas *et al* (1996; 1995). The resulting map ranges from zero (scarcely significant and poorly preserved landform) to ten (most significant and best preserved landform).

The five value maps are shown in Figure 4. Since the maps are expressed in different value ranges, only an ordinal scale was used.

To compute the impact of the different alternatives on the five environmental components, each of the value maps was overlaid on a map indicating the space required by the five alternatives (Geneletti *et al*, 2003a). Subsequently, for each environmental component, an impact score was computed by summing the value of the cells lying within the space buffer.

The impact on land production is expressed in a monetary unit because that was used in the relevant value map. Since all other value maps were expressed in a dimensionless score range (see description above), the unit of the relevant impacts was termed "weighted hectares". This is because the impact scores represent the surface of the impacted area (expressed in hectares) multiplied by the relevance of this area.

The computation of the impact scores allowed the generation of the impact matrix shown in Table 1. This matrix represents the starting point of the multicriteria analysis.

Multicriteria analysis

Introduction

This sub-section describes the main operational steps required to carry out an MCA for decision problems. Complete overviews and examples of applications of MCA for environmental management and land-use planning, can be found in Lahdelma *et al* (2000), Beinat and Nijkamp (1998), Janssen (1992), Nijkamp *et al* (1990).

The typical flowchart of an MCA procedure is shown in Figure 5. The starting point is the evaluation matrix, which contains the possible alternatives and the criteria against which they will be evaluated. Each cell of the matrix is filled with a score representing the performance of the corresponding alternative with respect to the relevant criterion.

To be able to relate these scores to the degree of 'desirability' of the alternatives under analysis, they need to be transformed from their original units into a value scale. This is the role of the value assessment

Table 1. Impact matrix

	Unit	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Vegetation	weighted ha	117	146	94	102	133
Habitat	weighted ha	210	225	278	221	223
Land production	euro/ha*year	16802	10427	14587	13221	17442
Landscape	weighted ha	710	533	534	566	705
Geomorphology	weighted ha	394	373	310	358	440

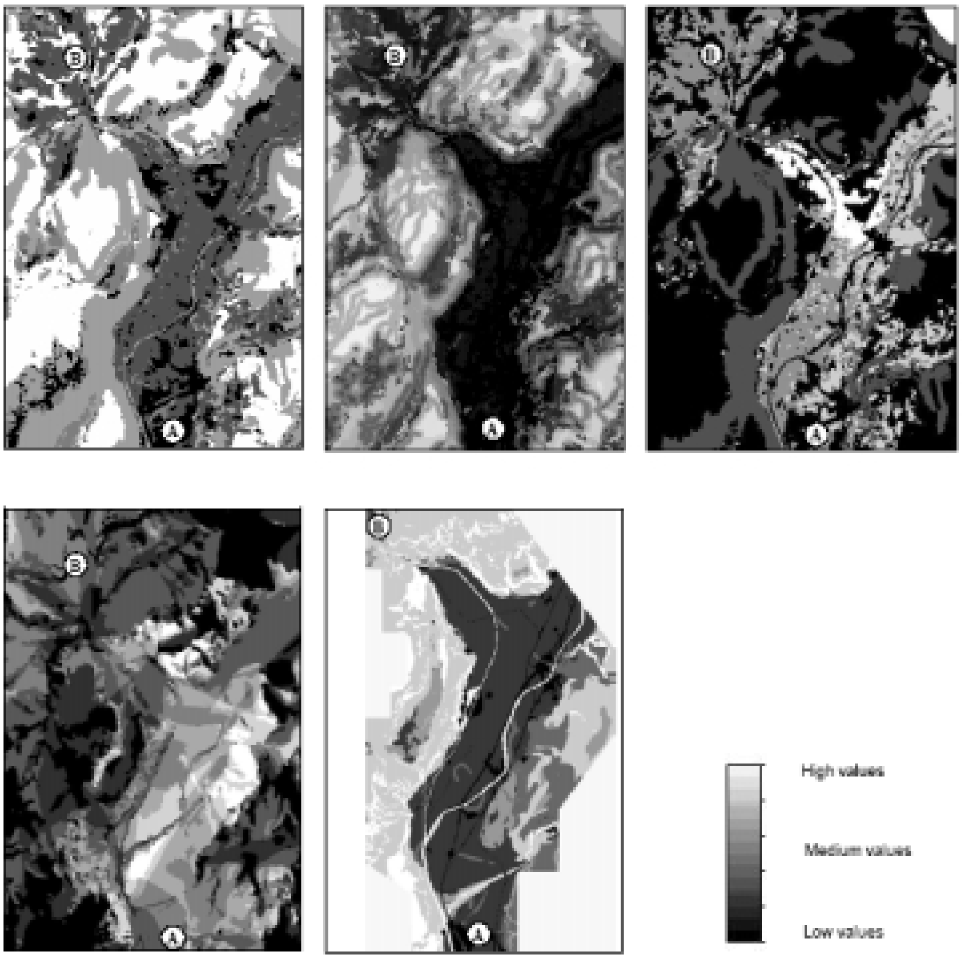

Figure 4. Value maps
Notes: From top-left to bottom-right: vegetation, habitat, land production, landscape, and geomorphology A and B indicate the locations to be connected by the road

(or 'standardisation'), through which the criterion scores lose their dimension and become an expression of the achievement of the evaluation objectives. As a result, all the scores are transformed into a given value range (for instance, between 0 and 1). This operation is performed by generating a value function, that is, a curve that expresses the relationship between the criterion scores and the corresponding value scores.

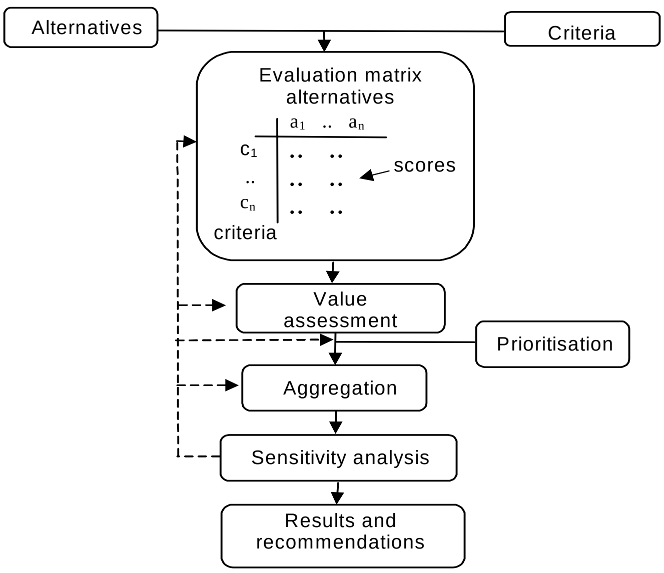

Figure 5. Operational flow of MCA
Note: Dotted lines refer to feedback mechanisms

The different evaluation criteria are usually characterised by different importance levels, which need to be included into the evaluation. These are obtained by assigning a weight to each criterion (prioritisation). A weight can be defined as a value assigned to a criterion that indicates its importance relative to the other criteria under consideration (Malczewski, 1999). (A survey of the methods developed to support the weight assignment can be found in van Herwijnen (1999) and Beinat (1997).) Then the aggregation can be performed. This is done by using a decision rule that dictates how best to order the alternatives, on the basis of the data on the alternatives (criterion scores), and on the preferences of the decision-makers (criterion assessment and weights).

The last step in the procedure is the sensitivity analysis. This aims to determine the robustness of the ranking with respect to the uncertainties in the assigned weights, value functions and scores, and to changes in the aggregation method. The information available to the decision-makers is often uncertain and imprecise, because of measurement and conceptual errors. Sensitivity analysis considers how, and how much, such errors affect the final result of the evaluation.

The following sub-sections describe the application of MCA to the impact matrix previously generated to compare the performance of the five alternatives and provide indications of their relative suitability. For this purpose, the DEFINITE Decision Support System (Janssen *et al*, 2001) was used.

Value assessment and prioritisation

The first step of the MCA was the value assessment procedure, through which the impact scores are made comparable. The computed impact scores were normalised by using the value function:

$$S = -r/max + 1 \qquad (1)$$

where

S = *normalised* score;
r = raw score;
max = highest raw score of the relevant impact.

This approach is called 'maximum standardisation' and was adopted for the following reasons:

- It constructs a linear relationship between the impact scores and the perceived significance of the impacts. This means that the same increase of an impact score is equally valued all over the range of possible scores (for instance, an increase in the impact on vegetation from 200 to 300 'weighted hectares' is considered as significant as an increase from 300 to 400). This was thought suitable for this case study because no information was available about critical impact thresholds.
- The ratio between the value scores of two alternatives is the same as the ratio of their original raw scores. This means that the relative differences among the impacts of different alternatives are kept.

Figure 6 shows an example of the value function constructed for the vegetation impact. As can be seen, the highest values were assigned to the best-performing alternatives, that is, to the alternatives with the lowest impact. In particular, the value zero was assigned to the highest impacting alternative, whereas the value one would have been assigned only if an alternative caused no impact at all. The results of the value assessment were summarised in the standardised impact matrix (see Appendix 1).

The next step consists of assigning a weight to each impact type. The weight assignment should reflect the relative importance of the impacts with respect to each other. In particular, weights relate to the change in the overall alternative performance that occurs when each of the impact types is moved from its minimum to its maximum score, all other things being equal. Unfortunately, a weight-set whose suitability can be supported by analytical and objective data does not exist.

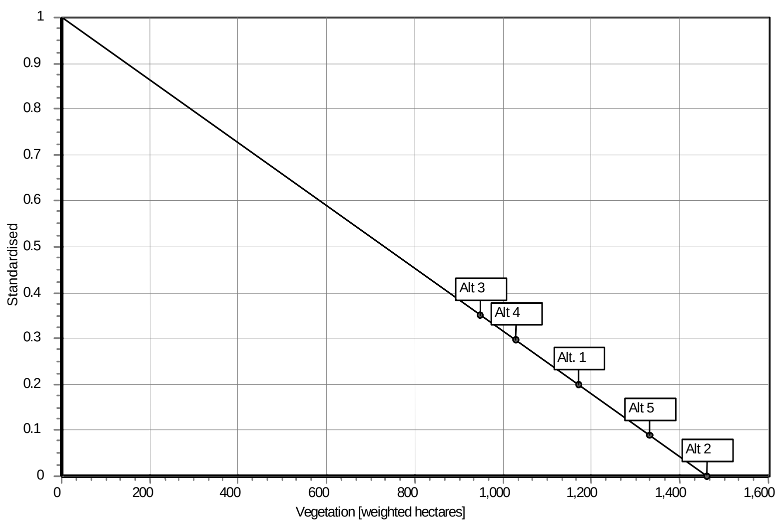

Figure 6. Value function for the impact on vegetation

Weight assignment is a largely subjective operation. Therefore, it is fundamental to involve the decision-makers to make explicit their value systems with respect to the impacts at stake.

In this study, three sets of weights were considered so as to simulate the presence of different perspectives during the decision-making phase:

- Neutral perspective: equal weights are assigned;
- Environmentally-oriented perspective: priority is given to impacts on natural assets, such as vegetation, animal habitat, and landforms;
- Socioeconomically-oriented perspective: priority is given to impacts on economic goods or social values, such as land production.

The pairwise comparison method (Saaty, 1980) was used to support the weight selection. The three sets of weights are shown in Table 2.

Aggregation and preliminary results

The aggregation was performed using the weighted linear combination. This method calculated an overall performance score for each alternative by first multiplying the standardised impact scores by their appropriate weight, and then summing the weighted scores for all impact types (see Appendix 1). Through the weighted linear combination, each alternative was given an overall score ranging from zero to one. The weighted summation was repeated for the three weight sets, leading to the results presented in the three rankings of Figure 7. A comparison of the rankings is shown in Figure 8.

As can be seen, a first general conclusion is that the performances of alternatives 5 and 1 are significantly worse than those of alternatives 4, 3 and 2. On the other hand, the latter three alternatives rank closely in the three scenarios. In particular, alternative 4 dominates the first two scenarios, whereas alternative 2 ranks in the first position in the third scenario, obtaining the best absolute score. Alternative 3 never occupies the first rank, but its score is always very similar to that of the best-performing alternative. Another conclusion that can be drawn is that the scores of alternatives 4 and 3 are very similar in the three scenarios (differences amount to less than 5%), whereas alternative 2 is far less stable, its score varying by 37%.

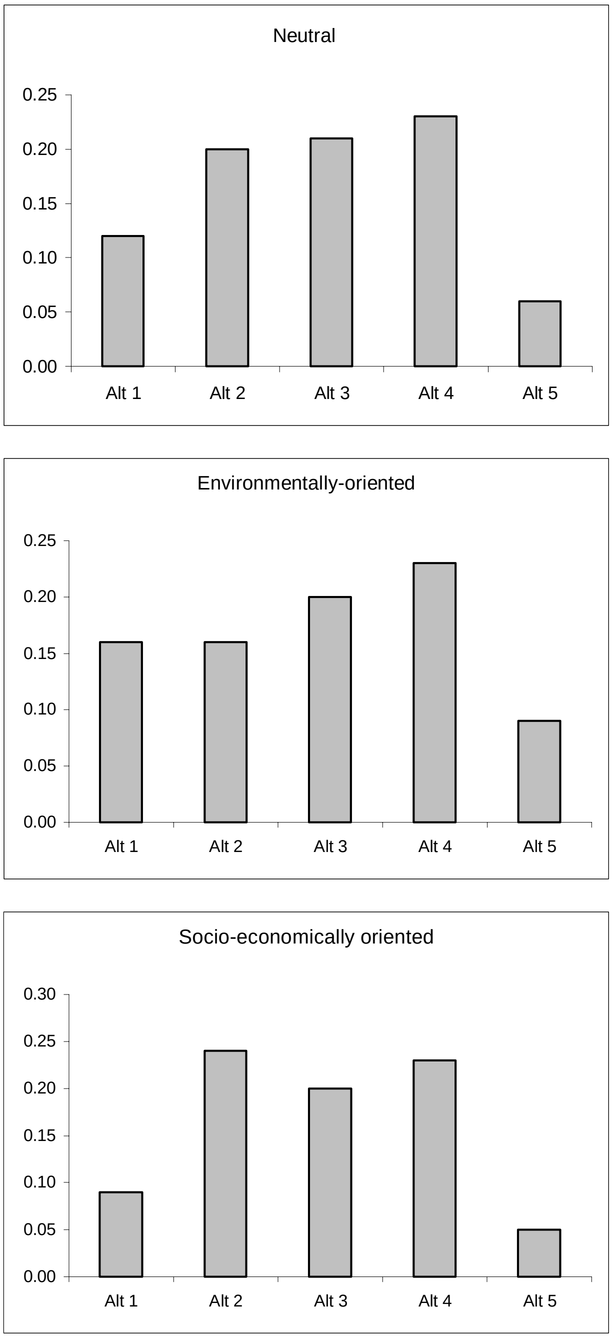

Figure 7. The three rankings of the alternatives

To gain further insight into the behaviour and the relative merit of the alternatives, sensitivity analyses can be carried out. This may help to highlight the differences among the performances of alternatives 4, 3 and 2, and consequently to orient better the decision-makers' choice.

Table 2. Weight sets

	Neutral perspective	Environmental perspective	Socio-economic perspective
Vegetation	0.20	0.297	0.160
Habitat	0.20	0.297	0.160
Land production	0.20	0.135	0.326
Landscape	0.20	0.066	0.246
Geomorphology	0.20	0.204	0.108

Sensitivity analysis and recommendations

Sensitivity analyses were applied to assess the stability of the obtained rankings with respect to changes in the input factors. In particular, changes in the impact scores and the weights were considered. The sensitivity of the results with respect to the standardisation method was not tested because it would

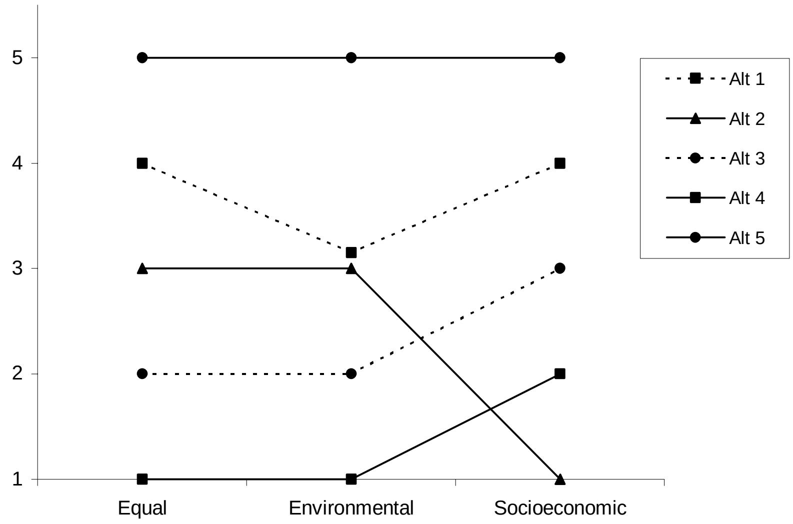

Figure 8. Comparison of the three rankings

require assessments of the relevance of different impact levels and thresholds that were not available in this study.

Analogously, it was decided not to vary the aggregation method because the weighted linear combination offers the advantage of generating quantitative rankings. This means that each alternative is given not only a position in the ranking, but also a performance score. This allows quantification of the relative merits of the different alternatives, making full use of the impact scores generated through the GIS analysis.

'Neutral' ranking The robustness of the ranking obtained with the 'neutral' perspective was analysed with respect to changes in the impact scores. To do this analysis, perturbations were imposed on the impact scores to verify their effect on the overall performance of the alternatives. First, it was necessary to identify an uncertainty range for every impact score. This represents the maximum percentage by which we expect the score to deviate from its original value.

Then, the overall score of each alternative was calculated a large number of times using a random number generator. In this research, a procedure was adopted that generated 1,000 random numbers for each impact score, uniformly distributed within the pre-defined uncertainty ranges. Subsequently, new standardised impact scores and new overall scores were computed for each alternative, generating 1,000 separate rankings. The results can be summarised in a frequency table that shows how many times an alternative ranks in every position.

A 20% uncertainty range was used for all impact scores, since we were not able to count on error estimates specifically related to the different impact types. All the other parameters (for instance, weights and value functions) were kept as in the original analysis. The results are shown in Table 3. Only the frequency of the first three ranks is presented. Note that the values of each row in Table 3 do not necessarily sum up to 1,000 because, when two alternatives drew, they were given the same ranking position, and the next position was not assigned.

As can be seen, alternative 4 ranks in first position in 76% of the rounds. It is interesting to note that, despite the very similar impact scores (see Figure 7), alternative 3 outranks alternative 2.

The subsequent analysis focused on the sensitivity of the ranking with respect to changes in the weights assigned to the different impact types. One way of doing this is to determine the alternative ranking for all possible values of a selected weight. During this procedure the ratios of the remaining weights stay the same as those of the original weights (Janssen *et al*, 2001).

For example, Figure 9 shows the results of this analysis performed on the weight assigned to the impact on habitat. The X-axis represents all the possible values for this weight, that is, from 0.0 to 1.0.

Sensitivity analyses were applied to assess the stability of the obtained rankings with respect to changes in the input factors: in particular, changes in the impact scores and the weights were considered

Table 3. Frequency table of the 'neutral perspective' ranking obtained using a 20% uncertainty range

	1st	2nd	3rd	4th	5th
Alt 4	760	230	10	0	0
Alt 3	200	500	300	0	0
Alt 2	40	270	700	0	0

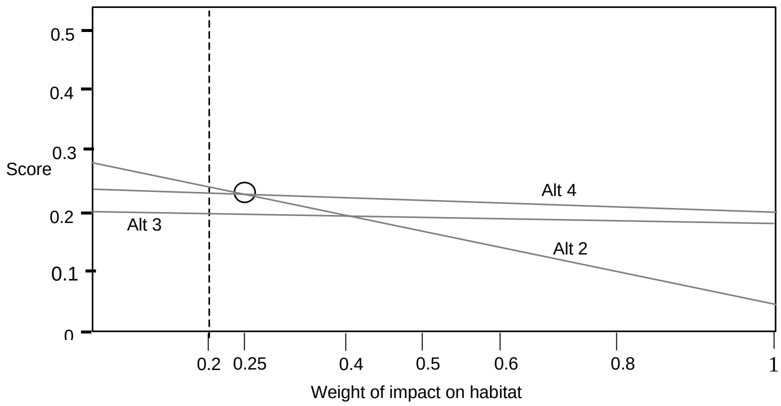

Figure 9. 'Neutral' ranking: diagram of the scores of alternatives 2, 3 and 4 versus the weight assigned to habitat

The Y-axis represents the scores of the alternatives. The three lines represent the trend of the scores of alternatives 2, 3 and 4 with respect to changes in the weight assigned to habitat. The original weight (0.2) is indicated by the vertical dotted line.

This representation highlights the reversal points, that is, the weight values that cause a reversal in the rank order of the alternatives. The reversal points occur whenever the lines of two alternatives meet. As indicated by the little circle in Figure 9, a reversal in the first position occurs when a weight bigger than 0.25 is assigned to the impact on habitat. This is because, for weight values smaller than 0.25, alternative 2 outranks alternative 4, whereas the opposite occurs for values larger than 0.25.

This analysis was repeated for all five impact types. Reversals in the first position of the ranking occurred only when using a weight that differed from the original one by at least 20%.

'Environmentally-oriented' ranking The same analyses were repeated for the ranking obtained with the 'environmentally-oriented' perspective. The results of the sensitivity analysis with respect to score variation are summarised in the frequency table (Table 4). This shows that alternatives 4 and 3 firmly occupy the first and the second rank respectively.

As to the sensitivity to change in the weights, the impact on geomorphology proved to be the most critical factor. However, to cause a reversal in the first position, the weight of such an impact type must be changed from the original 0.204 to a value larger than 0.38 (see Figure 10). All other impact types required even larger modifications of their original weight.

'Socioeconomically-oriented' ranking The sensitivity analysis with respect to changes in the impact scores was applied to the 'socioeconomically-oriented' ranking, leading to the results presented in Table 5. Alternative 4 keeps the first position in slightly more than the 70% of the rounds, whereas it is outranked by alternative 3 in about 25% of the rounds. This instability is underlined by the analysis of the score range covered by the three alternatives in the different rounds. This is represented in Figure 11, which clearly depicts that alternative 2 is the best-performing, but also the most unstable, its score covering a broad range. On the other hand, alternative 4 tends to rank in second position, but its performance score is more stable with respect to variations in the impact scores.

Finally, the sensitivity analysis with respect to changes in the weights showed a critical situation. For most of the impact types, a weight difference of the order of 5% is sufficient to induce a reversal in the first position of the ranking (see Figure 12).

In conclusion, all three perspectives agree on the dominance of alternatives 2, 3 and 4 over alternatives 1 and 5. Alternatives 3 and 4 appear quite stable and tend to perform similarly in the three perspectives, whereas alternative 2 is more sensitive to changes in evaluation parameters.

The sensitivity analysis showed that the 'socioeconomically-oriented' ranking is the most unstable. The critical factors in determining the results of such

Table 4. Frequency table of the 'environmentally-oriented' ranking obtained using a 20% uncertainty range

	1st	2nd	3rd	4th	5th
Alt 4	950	50	0	0	0
Alt 3	50	900	40	10	0
Alt 2	0	20	510	470	0

Table 5. Frequency table of the 'socioeconomically-oriented' ranking obtained using a 20% uncertainty range

	1st	2nd	3rd	4th	5th
Alt 4	710	240	50	0	0
Alt 3	260	690	40	0	0
Al 2	30	70	910	470	0

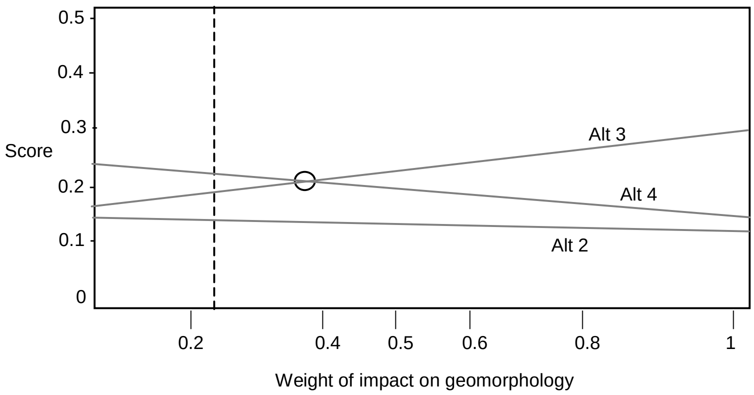

Figure 10. 'Environmentally-oriented' ranking: diagram of the scores of alternatives 2, 3 and 4 versus the weight assigned to geomorphology

a perspective are represented by the weight assigned to the impact on land production and on vegetation. On the other hand, the 'environmentally-oriented' perspective generated a result more stable in terms of its sensitivity to changes both in the impact scores and weights.

Discussion and conclusions

According to Wathern (1988), EIA can be described as:

> "a process for identifying the likely consequences for the biogeophysical environment and for man's health and welfare of implementing particular activities and for conveying this information, at a stage when it can materially affect their decision, to those responsible for sanctioning the proposal."

This definition stresses that the procedure of EIA is not only to study the expected environmental impacts of a development, but also to ensure that the results of such a study can actually influence the decision-making process concerning the approval of the development. In other words, a good EIA must, on the one hand, predict in a reliable way the impact of the project on the different environmental components, and on the other hand, aggregate such predictions into concise judgments that can effectively help decision-makers. MCA can play a key role in the latter by providing a framework to integrate the information generated during the study with the value judgments of the stakeholders involved in the decision process.

Using MCA helps to make use of all the information that has been generated during the study, so as to provide decision-makers with a synthesis and an effective overview. In this way, MCA enhances the transparency of the process through a systematic analysis of the relative merits of the alternatives, and of the consequences of the use of different evaluation parameters and methodologies.

As in the case study discussed here, the EIA report usually presents several results obtained by using different perspectives, which typically derive from the presence of different stakeholder groups. Rather than discussing the merits of the different perspectives, the role of MCA is to study the similarity of the results obtained, so as to guide future discussions and analyses only toward the issues that actually prove to play a relevant role in the decision process.

For example, the diagrams of Figures 9, 10 and 12 help in understanding the weight values that represent critical thresholds in terms of changing the evaluation results. Further discussion and analyses could be focused on these critical thresholds, rather than on all possible values. Therefore, through sensitivity analysis, the problematic aspects of the procedure can be highlighted, and, at least in principle, they can be investigated more deeply and improved whenever required to support decision-making.

Another fundamental role of MCA is to underline the robustness of the result of each perspective, and the critical factors that contributed to it. Knowledge of uncertainty factors is bound to increase the awareness of the decision-makers about the merit of the different alternatives, and consequently to orient their strategy better (Geneletti *et al*, 2003b). An

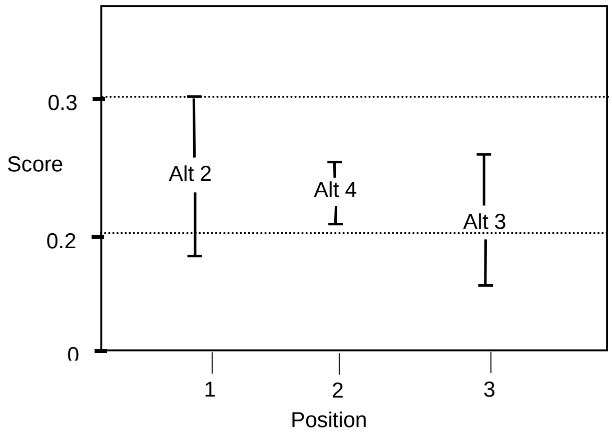

Figure 11. 'Socioeconomically-oriented' ranking: ranges obtained by varying the impact scores by ± 20%

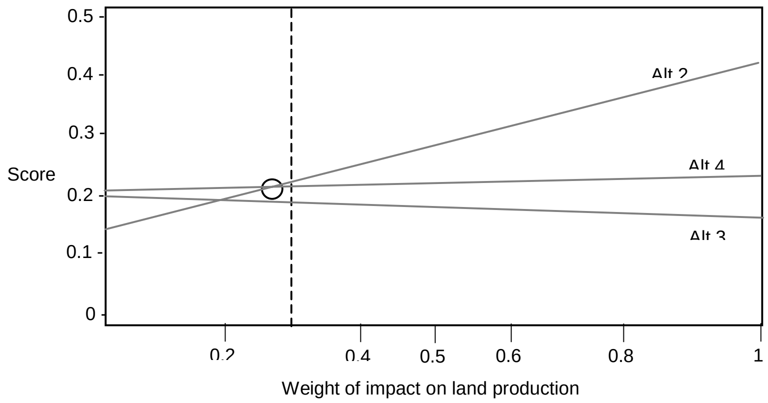

Figure 12. 'Socioeconomically-oriented' ranking: diagram of the scores of alternatives 2, 3 and 4 versus the weight assigned to land production

example is provided by the results illustrated in Figure 11: alternative 2 proved to perform better than alternative 4, but was also much more unstable. The role of MCA is to convey this information to the decision-makers so that they can take a decision according, for instance, to their risk averseness.

Appendix 1. MCA analysis step-by-step

Step 1: Value assessment

The impact matrix (see Table 1) was normalised by transforming the original scores of each row (that is, of each impact type) according to the following linear function:

$S = -r/max + 1$

where

S = normalised score;
r = original score;
max = highest score of the row.

The resulting normalised impact matrix is shown in Table A1.

Table A1. Normalised impact scores

	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Vegetation	0.20	0.00	0.35	0.30	0.09
Habitat	0.24	0.19	0.00	0.21	0.20
Land production	0.04	0.40	0.16	0.24	0.00
Landscape	0.00	0.25	0.25	0.20	0.01
Geomorphology	0.11	0.15	0.30	0.19	0.00

Step 2: Aggregation by weighted summation

The performance of each alternative was computed through weighted summation, that is, the normalised scores were multiplied by the relevant weight, and then summed. This was repeated for the three sets of weights (see Table 2), leading to the results shown in Table A2.

Table A2. Performance scores

	Alt1	Alt 2	Alt 3	Alt 4	Alt 5
Neutral perspective	0.12	0.20	0.21	0.23	0.06
Environmental perspective	0.16	0.16	0.20	0.23	0.09
Socio-economic perspective	0.09	0.24	0.20	0.23	0.05

Step 3: Sensitivity analysis

A ±20% uncertainty factor was applied to the impact scores, leading to the score ranges shown in Table A3. The weighted summation was then repeated 1,000 times by using, each time, a set of scores randomly selected within the identified ranges. The resulting frequency matrices, showing how often each alternative occupied each rank, are shown in Tables 4, 5, 6.

Table A3. Score ranges

	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Vegetation	93–140	116–175	75–112	81–122	106–159
Habitat	168–252	180–270	222–333	176–265	178–267
Land production	13441–20162	8341–12512	11669–17504	10576–15865	13953–20930
Landscape	568–852	426–639	427–640	452–679	564–846
Geo-morphology	315–472	298–447	248–372	286–429	352–528

Notes

1. Viewshed is defined as those parts of the landscape that can be seen from a particular point.

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