An Integrated Approach for Exploring Opportunities and Vulnerabilities of Complex Territorial Systems

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Abstract. Dealing with territorial transformations assessment means addressing the challenge represented by the inherent complexity and multidimensionality of these systems. This requires an integrated approach for the evaluation in order to obtain concise final judgments. Moreover, when dealing with territorial systems, the analysis of the geographical patterns of the elements under investigation plays a fundamental role. The paper thus proposes an innovative approach for the analysis of a complex territorial system based on the integration of Geographic Information Systems (GIS) and a specific Multicriteria Analysis technique, named Analytic Network Process (ANP). In particular, starting from a real case related to a mountain area in Northern Italy, the present paper explores the potentialities of spatial Multicriteria analysis for supporting strategic planning and sustainability assessment procedures.

Keywords: Scenario analysis, Multicriteria Analysis, Spatial Decision Support Systems, Analytic Network Process.

1 Introduction

Territorial transformation projects are affected by high levels of uncertainty and refer to long-term perspectives. In this context, a very useful role is played by scenario analysis which supports the decision-making process for the definition and assessment of future development strategies for a certain area [1]. In particular, scenario analysis attempts to develop and judge a set of hypothetical policy or development alternatives for a complex decision-making system, in order to generate a rational frame of reference for evaluating different options [2]. Scenarios studies have usually an experimental nature and play an important role in the field of spatial planning and analysis [3].

The use of scenario analysis in decision-making processes related to spatial planning is based on the assumption that the future is not predetermined, but it consists in the product of causal chains of events that are determined from exogenous or endogenous elements of the spatial system [1]. Planning actions aim to guide these events in order to achieve political objectives.

An important problem arising when assessing territorial systems refers to their complexity which requires an integrated and systemic approach for the evaluation.

B. Murgante et al. (Eds.): ICCSA 2014, Part III, LNCS 8581, pp. 667–681, 2014.

Following this reasoning, there is a need for quantitative methods that are able to synthesize the full range of aspects involved in the transformation, from the impacts on the environmental system to the effects in terms of mobility and accessibility, from the social and economic consequences of a certain strategy to the outcomes with reference to landscape and cultural heritage.

In the current debate regarding sustainability assessment and integrated approaches, spatial Multicriteria Analysis [4] plays a fundamental role by solving semi-structured spatial problems through the integration of Geographic Information Systems (GIS) and Multicriteria Decision Aiding (MCDA) techniques.

From the methodological point of view, the present application proposes the integration between GIS and a specific MCDA technique named Analytic Network Process (ANP; Saaty 2005), which represents the evolution of the Analytic Hierarchy Process (AHP; Saaty 1980). Since the incorporation of the AHP calculation block in the IDRISI 3.2 software package, it has become much easier to apply this technique to solve spatial problems. Applications of the ANP, which is particularly suitable for dealing with complex decision problems that are characterized by interrelationships among the elements at stake, are instead scarce.

The purpose of the paper is thus to investigate the potentialities of the ANP-GIS integration and to present the innovative methodological framework with reference to a case study dealing with the identification of future opportunities and vulnerabilities in a mountain area in Northern Italy. Moreover, the research also explores the potentialities of a decision support process which makes use of a panel of experts for the implementation of the evaluation model.

2 Scenario Analysis and Spatial Decision Support Systems

2.1 State of the Art

Scenario analysis has been developed as a scientific tool for supporting policy-making processes under uncertainty conditions. According to Kahn and Wiener [5], a scenario can be defined as a possible, often hypothetical, sequence of events constructed in an internally consistent way for the purpose of focusing attention on casual processes and decision points.

Following this first definition, several attempts were made in the scientific literature for better clarifying the concept of scenario. Warfield [6] defined the scenario as "a narrative description of a possible state of affairs or development over time. It can be very useful to communicate speculative thoughts about future developments to elicit discussion and feedback, and to stimulate the imagination. Scenarios generally are based on quantitative expert information, but may include qualitative information as well".

Ratcliffe [7] states that "the principal objective of scenario analysis is to enable decision-makers to detect and explore the full range of alternative futures so as to clarify present actions and subsequent consequences".

According to Godet [8], "scenarios should aim to detect the key variables that emerge from the relationship between the many different factors describing a particular system, especially those relating to the particular actors and their strategies". Moreover, Schwartz [9] highlights that scenarios "provide a context for thinking clearly about the otherwise impossible complex array of factors that affect any decision; give a common language to decision-makers for talking about these factors and encourage them to think about a series of 'what-if' stories; help lift the 'blinkers' that limit creativity and resourcefulness; and lead to organisations thinking strategically and continuously learning about key decisions and priorities".

The purpose of scenario analysis is not just about constructing scenarios, but it is about informing decision-makers and influencing and enhancing, decision-making, thus creating a learning process.

The methodological base of scenario building, as with all future studies, is broad, diverse and comprises a wide range of approaches and techniques. It has been noticed that the integrated use of scenario analysis and Multicriteria Analysis can efficiently support decision-making process [10, 11].

With specific reference to the context of spatial planning, many applications exist in the literature related the use of Spatial Decision Support Systems (SDSS) in the domain of scenario analysis. In order to better contextualize our study and highlight its innovation with respect to the state of the art, Table 1 syntheses the main scientific papers, highlight the field of application, the objective of the analysis and the methodology applied. As it is possible to see from Table 1, the sphere of the researches is very vast, including application for environmental risk analysis and energy planning. The principal aim the studies is the creation of a suitability map with the projection of effects produced by the considered scenarios.

Table 1. Examples of applications of (SDSS) for scenario analysis in land use planning and management

Author	Field of application	Objective of the evaluation	Methodology
Volk et al. [12]	Management of water resources	Analysis of different land use scenarios from the point of view of the ecological and socio-economic effects.	FLUMAGIS (GIS-based integrated ecological-economic model)
Duzgun et al. [13]	Evaluation of seismic vulnerability	Map of the seismic vulnerability index of an urban area with 3D visualizations	MC-SDSS (Multicriteria-Spatial Decision Support Systems) where the MCA module is based on a set of indicators obtained by means of a series of questionnaires to DM and key actors
Zerger e Wealands [14]	Hydrogeological risk management	Map of the effects of different potential risk scenarios	Integration between GIS and hydrodynamic models

Table 1. (*Continued*)

Scholten et al. [15]	Hydrogeological risk management	Ranking of alternative management scenarios	SDSS developed through the IDRISI software
Brody et al. [16]	Management of energy resources	Suitability map for the identification of the best sites for the production of oil and gas in Texas (USA)	MC-SDSS based on a set of statistical indicators
Volk et al. [17]	Management of landscape and river basins	Critical review of different SDSS approaches	FLUMAGIS Elbe-DSS CatchMODS MedAction
Ballas et al. [18]	Evaluation of public policies	Analysis of the effects of different scenarios for the city of Leeds s	SDSS based on micro-simulations for the generation of predictions of census data (Micro-MaPPAS)
Grueau e Rodriguez, [19]	Environmental planning and management	Evaluation of the environmental effects of different land use scenarios	Integration of multi-agents models with GIS
Rutledge et al. [20]	Regional planning	Evaluation of different land use scenarios in New Zealand	MC-SDSS based on a set of spatial indicators developed through the software GEONAMICA
Danese et al [21]	Geomorphological and geostatistical analysis	Macroseismic damage effects in urban areas	Integrated Geological, Geomorphological and Geostatistical Analysis

2.2 Spatial Multicriteria Analysis: Methodological Background

Scenario analysis plays a crucial role particularly in the field of sustainability assessments and territorial transformation processes, both at the urban and rural scale. These contexts give rise to complex decision problems due to the presence of different and often conflicting objectives to be pursued, the public/private nature of the goods under investigation, the existence of several values (historical, naturalistic, cultural, economic, etc.) and the presence of different actors (public government representatives, architects, architectural historians, citizens, developers and owners).

Moreover, when dealing with territorial transformation processes, an undeniable important role is played by the spatial distribution of the characteristics and consequences of each option under analysis.

The availability of analytical frameworks able to support the process is thus getting more and more important.

Within this context, a fundamental support may be provided by spatial Multicriteria Analysis [4] which combines Geographic Information Systems and Multicriteria Decision Aiding in order to provide a collection of methods and tools for transforming and integrating geographic data (map criteria) and Decision Maker's preferences and uncertainties (value judgments) to obtain information for decision-making and an overall assessment of the decision alternatives.

Spatial Multicriteria Analysis is an increasingly popular tool in decision-making processes and in policy making, thanks to its significant new capabilities in the use of spatial or geospatial information. In recent years there has thus been a growing interest towards the development and application of spatial Multicriteria Analysis across many scientific fields for solving different decision problem typologies [22], thanks to the ability of this integrated approach to both generate alternatives during the strategic planning phase and to compare them during the evaluation phase.

In particular, spatial Multicriteria Analysis is most commonly applied to land suitability analysis in the urban/regional planning, hydrology and water management and environment/ecology fields and is usually based on a loose coupling approach and on a value focused thinking framework [22].

Within these fields an emerging trend seems to focus on the application of spatial Multicriteria Analysis for scenarios generation and evaluation, thanks to the ability of combining both qualitative and quantitative data representing the spatial consequences of different future courses of actions.

From the methodological point of view, the steps needed for the development of a spatial Multicriteria Analysis to specifically support planning and decision-making processes are summarized in Figure 1.

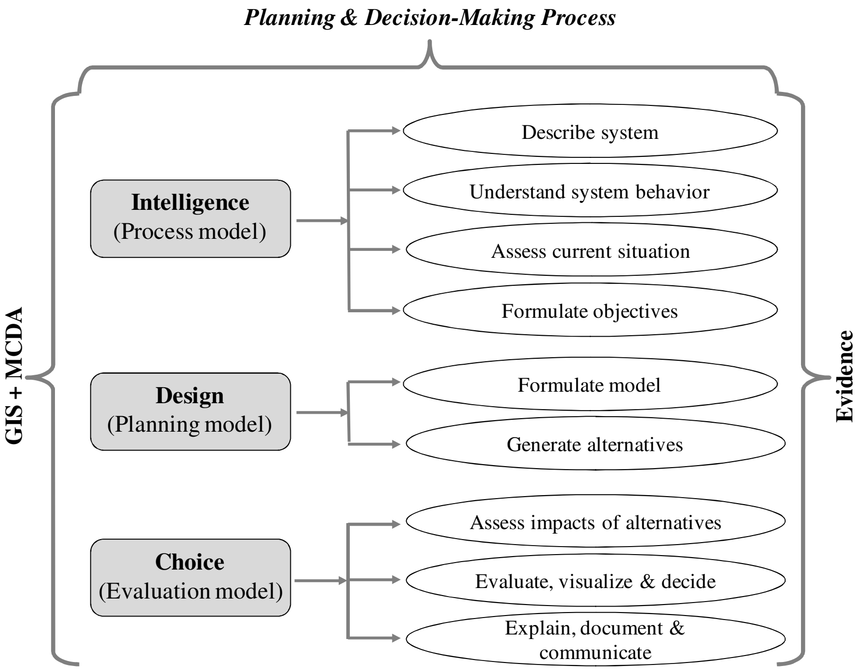


Fig. 1. Framework for planning and decision-making process (Source: adapted from [23])

In this model, there is a flow of activities from intelligence to design to choice phase, as well as steps in each phase.

In particular, the intelligence phase refers to the examination of the environment in order to identify problems or opportunity situations and includes the structuring of the problem, during which the system under consideration is defined and the objectives to pursue are explored. One or more criteria, or attributes, are then selected to describe the degree of achievement of each objective.

The design phase involves the development and analysis of possible courses of action. During the choice phase alternatives are evaluated and a selection of specific courses of action is performed; furthermore, detailed analyses, such as the sensitivity analysis, are deemed appropriate in order to obtain useful recommendations.

Finally, evidence is defined as the total set of data, information, and knowledge at disposal of the planner, Decision Makers and analysts.

3 Application

3.1 Presentation of the Case

The case study considered in the application refers to a small town in Northern Italy named Ormea[1]. The town has a population of 1750 inhabitants and is located in the Alpine territory of the Piedmont Region, on the border with the Liguria Region and with France (Figure 2).

In the past, the city used to be very important from the point of view of the industrial activities concerning the production of wool and paper. Moreover, thanks to the presence of the railway line, the town was an important tourism centre with tourists coming from many European countries.

Nowadays, due to the phenomenon of the abandon of mountain areas, many economic activities have been relocated; also the tourism sector is suffering and the trends of the presences has been decreasing since the last decades. As a result, the town is experiencing a deep crisis and new strategies for the development of the area are needed.

The objective of the paper is to support the creation of future development scenarios for the area, with particular reference to the analysis of the opportunities and the risk characterizing the town under investigation.

3.2 Structuring of the Decision Problem

Starting from the overall objective of the analysis, which is the definition of the opportunities and risks of the territory of Ormea, a comprehensive set of evaluation

[1] The material used to illustrate the case study application is based on the thesis work performed by Elisa Piolatto at the Architectural and Landscape Heritage post-graduates specialization school of the Polytechnic University of Turin (Italy).

Fig. 2. The location of the area under investigation

criteria that reflect all the concerns relevant to the decision problem has been identified according to a value focused thinking approach, which assumes the values as fundamental elements in the decision analysis and, based on the values and criteria structure, develops and evaluates feasible options [24].

Due to the presence of different interrelated factors and to the intrinsic spatial nature of the problem, the method of the Analytic Network Process (ANP, [25]) has been coupled with Geographic Information Systems (GIS). The ANP represents the evolution of the Analytic Hierarchy Process (AHP, [26]) in order to take into account interactions and feedbacks among the decision elements. According to the ANP, the problem structuring phase involves identifying groups (or clusters) constituted by various elements (nodes) that influence the decision. All the elements in the network can be related in different ways since the network can incur feedbacks and complex inter-relationships within and between clusters, thus providing a more accurate modeling of complex settings.

In the present application the model has been developed according to the complex network structure [25]. The problem has thus been divided four five clusters (namely, natural system, historical and cultural heritage, economic aspects, territorial system) that have been organized according to the categories of Opportunities and Risks. In this case, the opportunities and the risks have been considered, respectively, as positive and negative aspects of the transformation in the long time period, for which it is difficult to make any prevision

According to the ANP methodology, once the network has been identified, it is necessary to represent the influences among the elements [25].

Moreover, a raster map was linked to each criterion, within which each pixel has a suitability value. These maps were derived from basic raster GIS operations (map overlay, buffering, distance mapping, spatial queries, etc.).

Table 2 presents the criteria identified for the analysis while Figure 3 represents as an example the Opportunities subnetwork of the ANP model.

Table 2. The ANP model for the problem under investigation

O/R	Cluster	Elements	Description
OPPORTUNITIES	Natural system	Naturalness index	This index allows the evaluation of the environmental quality of the territory, according to the physical and structural features of the vegetation
		Natural elements	Specific natural elements, such as caverns
		Viewpoints	Viewpoints identified by the Landscape Plan of the area
		Protected areas	Areas that have been identified as Sites of Community Importance (SCIs) and Special Protection Areas (SPAs)
	Historical and cultural heritage	Historical monuments	Archaeological sites and historical monuments such as castles, towers, churches, industrial archaeology buildings, etc.
		Historical settlements	Important settlements identified in historical sources
		Cultural events	Cultural events such as feasts, religious events, etc.
	Economic aspects	Accommodation structures	Hotels, bed & breakfast, mountain dews, etc.
		Sport pathways	The elements is related to the paths destined to the practice of trekking and other sport activities
		Sport facilities	Facilities for climbing, sport fishing, skiing, hand gliding, etc.
		Picnic areas	Areas for the temporal stop of tourists
	Territorial systems	Accessibility	Infrastructural roads for arriving at Ormea from Piedmont, Liguria and France
		Local roads	Local roads for reaching the different parts of the town of Ormea
RISKS	Natural system	Hydrogeological risk	Areas which are characterized by an high level of hydrogeological risk (water bodies, areas subjected to avalanches and landslides)
	Historical and cultural heritage	Abandoned historical pathways	This elements is related to the presence of pathways that used to be employed for the transhumance or for reaching seasonal settlements
		Tracks of ancient cultivations and productive activities	The element concerns the presence of ancient rural activities that nowadays are disappearing (for example, terraces, mill runs, etc.)

	Economic aspects	Power lines	Network infrastructure for the transportation of the electric energy
		Quarries	Presence of quarries for the extraction of the marble
		Abandoned industrial areas	Former productive areas which now are abandoned (for example, the building of the paper mill)
		Distribution of the population	This elements concerns the different distribution of the population in the centre of Ormea and in the small outlying suburb hamlet
	Territorial systems	Slope	This element is related to the slope of the ground which constitutes an obstacle for the accessibility
		Soil consumption	The element concerns the progressive soil consumption, comparing the actual situation with the situation registered in the historical maps

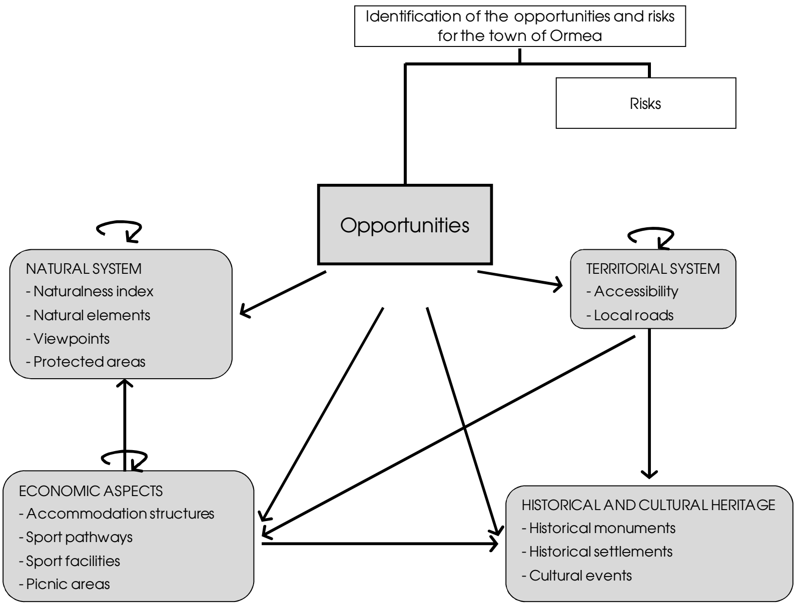


Fig. 3. The Opportunities subnetwork

3.3 Standardizing the Criteria Maps

For decision analysis the values and classes of all the maps associated with each considered criteria should be converted into a common scale. Such a transformation is commonly referred to as standardization [27].

Through standardization the original factor scores (each expressed in its own unit of measurement) are converted into dimensionless scores in the 0 (worst situation) or 1 (best situation) range.

In the present study standardization was performed by means of a focus group of both experts in different fields (economic evaluation, environmental engineering, and landscape ecology) and real stakeholders coming from the Ormea municipality. The training of a panel of experts allows to overcome some difficulties and biases which characterize the decision processes based on a single expert. In the present application, a close attention was devoted to the formation of a group of experts having a balanced background composition.

Through the active participation of all the experts and stakeholders the control points used for the standardization of each criterion have thus been discussed and decided during the aforementioned focus group.

With the aim of providing an illustrative example, Figure 4 shows the initial raw map (Fig.4a), the intermediary source map (Fig.4b), the standardization function (Fig.4c) and the standardized map (Fig.4d) for the factor “panoramic viewpoints” under the Opportunities sub-network.

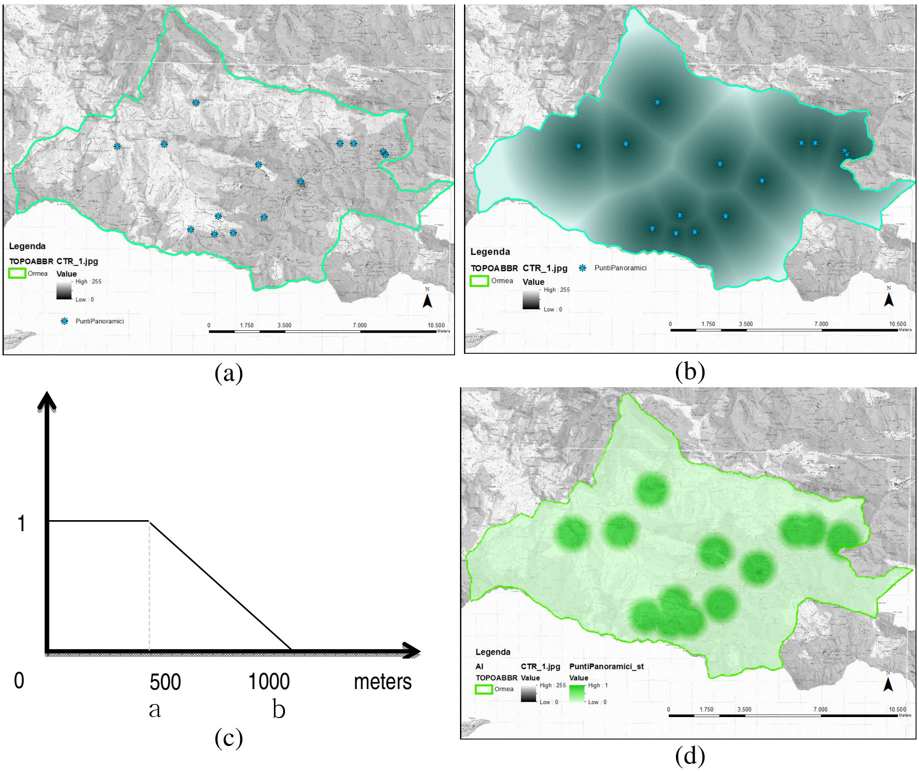


Fig. 4. The initial raw map (Fig.4a), the intermediary source map (Fig.4b), the standardization function (Fig.4c) and the standardized map (Fig.4d) for the factor “panoramic viewpoints”

In particular, control point *a* and control point *b* in Figure 4c are the points that govern the shape of the standardization function. In this case, the first control point (*a*) indicates the value where the membership function starts to decrease. This is due to the fact that during the focus group the experts and the stakeholders agreed that after 500 meters the perceived utility of being near to a panoramic viewpoint starts to decrease. The second control point (*b*) in this case indicates the point at which the function reaches membership 0, since the focus group result was that a distance greater than 1000 meters is not worth being covered to reach a panoramic viewpoint.

The same kind of reasoning has been repeated for all the considered factors inside the Opportunities and Vulnerabilities sub-networks.

3.4 Weighing and Aggregation

Once all the maps have been standardized in the 0-1 range, the next step of the decision process consisted in weighing all the factors according to the pair-wise comparison approach underpinning the Analytic Network Process methodology. The different experts thus worked together in order to achieve a consensus with reference not only to the standardization of each factor map but also to the weighing of the elements involved in the decision. According to the ANP methodology, the comparison and evaluation phase is based on the pair-wise comparison of the elements under consideration which can be divided into two levels: the comparison between clusters which is more general and strategic and the comparison between nodes which is more specific and detailed.

In paired comparisons, the smaller element is used as the unit, and the larger element becomes a multiple of that unit with respect to the common property or criterion for which the comparisons are made. A ratio scale of 1–9, that is, the Saaty's fundamental scale, is used to compare any two elements. The main eigenvector of each pair-wise comparison matrix represents the synthesis of the numerical judgements established at each level of the network [26].

As an example, Figure 5 shows the graphical representation of the following question asked to the panel of experts and stakeholders during the focus group: *with reference to the valorisation of the area under analysis, which of the following aspects can better enhance the opportunities of the territory? And how much more?*

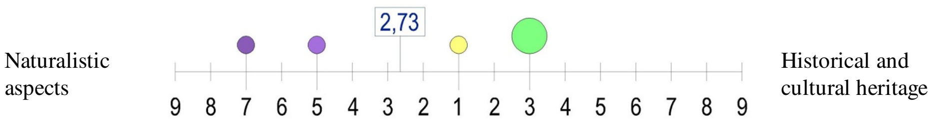


Fig. 5. Graphical representation of one of the pair-wise questions asked during the focus group. In case of disagreement, the dimension of the circles in the picture is proportional to the number of votes obtained by each value.

The results of the collaborative procedure for weighing all the elements are summarised in Table 3. In particular, the final priorities showed in Table 3 are those obtained from the progressive formation of the unweighted supermatrix, the weighted supermatrix and the limit supermatrix on which the ANP development is based [26].

Table 3. Final priorities for the elements under analysis

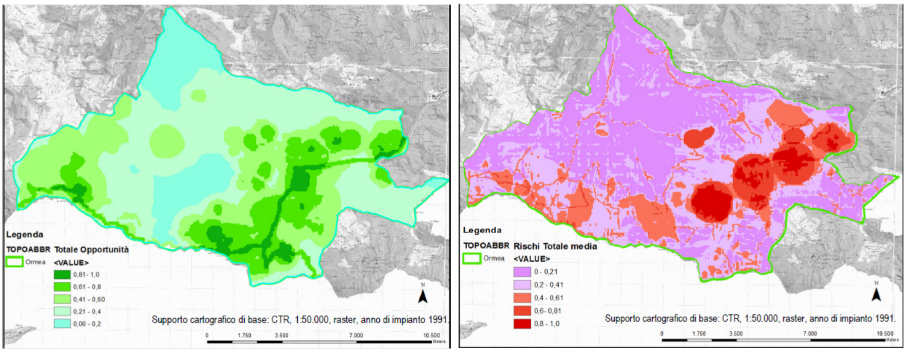
O/V	Cluster	Elements	Final priorities
OPPORTUNITIES	Natural system (0,39)	Naturalness index	0,02
		Natural elements	0,09
		Viewpoints	0,11
		Protected areas	0,17
	Historical and cultural heritage (0,15)	Historical monuments	0,06
		Historical settlements	0,06
		Cultural events	0,02
	Economic aspects (0,39)	Accommodation structures	0,21
		Sport pathways	0,02
		Sport facilities	0,05
		Picnic areas	0,10
	Territorial systems (0,07)	Accessibility	0,06
		Local roads	0,01
VULNERABILITIES	Natural system (0,15)	Hydrogeological risk	0,15
	Historical and cultural heritage (0,21)	Abandoned historical pathways	0,10
		Tracks of ancient cultivations and productive activities	0,11
	Economic aspects (0,56)	Power lines	0,07
		Quarries	0,02
		Abandoned industrial areas	0,35
		Distribution of the population	0,11
	Territorial systems (0,08)	Slope	0,07
		Soil consumption	0,01

In order to obtain the final opportunities and vulnerabilities' maps, a weighted linear combination was used, combining the respective factor maps according to the following formula:

$$S_j = \sum W_I X_I \quad (1)$$

where S_j represents the overall value of pixel j, W_i represents the weight of factor i, and X_i represents the standardized criterion score of factor i.

The results of the proposed study are thus represented by two maps highlighting the spatial distribution of opportunities and vulnerabilities within the area under examination. These maps represent a first synthesis of negative and positive aspects for the region under analysis (Figure 6a and Figure 6b, respectively) and allow to derive



(a) (b)

Fig. 6. Overall distribution of the Opportunities (5a) and Vulnerabilities (5b) for the area under analysis

useful indications with reference to warning spots needing specific mitigation or monitoring measures.

As it is possible to notice from the results of the analysis, the Opportunities and Vulnerabilities seem to concentrate in the South Eastern portion of the area under investigation, where the city centre is located.

The subsequent steps of the study will allow to draw policy recommendations and to support the strategic planning phase in order to foster the opportunities and minimize the vulnerabilities for the region. These results are of crucial importance for the subsequent generation and comparison of valorisation scenarios based on enhancement strategies of the strengths of the region.

4 Conclusions

This paper describes the development of a spatial Multicriteria Analysis to identify future opportunities and vulnerabilities for a specific region. The proposed methodology was illustrated with reference to a mountain area in the North of Italy which represents an environmental system characterized by multiple values.

The obtained results show that spatial Multicriteria Analysis can handle heterogeneous information and provide a significant contribution in the strategic decision-making phase. Moreover, one of the most significant strengths of the adopted methodological approach is represented by the fact that the evaluation is organized in a learning perspective. The decision maker thus gains more awareness with reference to the elements at stake while structuring the model (by means of standardization functions and trade-offs elicitation) and thus learns about the problems throughout the decision process [28].

By identifying opportunities and vulnerabilties for the area under analysis, the adopted approach also allows to foresee different future strategies (scenarios) for the management and valorization of the entire area. Consequently, different policy strategies could then be studied and evaluated in order to select the most sustainable one.

Scenarios can thus assist decision makers in the selection of proper policy solutions which produce robust results under varying conditions, in the assessment of strategies to cope with threats from particular natural and socio-economic conditions, and in risk assessments of various uncertain future developments [29].

With specific reference to the ANP methodology, it is important to highlight that, despite the limitations of a linear aggregation rule with respect to non-compensability issues in sustainability assessments, the approach allows to take interaction effects among the decision elements into account and this is particularly important in environmental decision-making problems, were the different components interact and influence each other.

In conclusion, the integration of decision aiding tools and spatial analysis constitutes a very promising line of research in the context of scenario analysis and sustainability assessments.

Acknowledgments. The paper is the result of the joint work of the three authors. Despite the overall responsibility being equally shared, Marta Bottero is responsible for paragraphs 2.1, 3.1 and 3.2 while Valentina Ferretti is responsible for paragraphs 2.2, 3.3 and 3.4. The abstract, paragraph 1 and the conclusions are the result of the joint work of the three authors. Finally, the authors would like to express a special thanks to Dr. Elisa Piolatto for the work done during her thesis at the Architectural and Landscape Heritage post-graduates specialization school of the Polytechnic University of Turin (Italy).

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