A GIS-MULTICRITERIA BASED MODEL FOR IDENTIFYING THE OPTIMAL LOCATION OF ROAD INFRASTRUCTURES

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Abstract

Construction of road infrastructures usually produce very relevant landscape changes generating complex environmental, ecological, social, and economic issues. The optimal location of these infrastructures during the planning and design stages becomes a priority to minimize the impacts on the landscape. In this regard, GIS combined with multicriteria decision making, can support a wide range of spatial analysis that can be used to support location studies in which participatory steps could be also integrated. This study deals with the creation of a GIS-multicriteria based model to identify the optimal location of road infrastructures taking in consideration the main environmental, social, economic, technical and operational aspects of the road construction. A particular focus is kept on the analysis of ecological fragmentation caused by the road networks and by urban settlements. The methodology, applied to an Italian case-study, relies on the implementation of spatial indicators concerning the various criteria included in the model. The indicators are hierarchically combined in a final landscape sensitivity index using AHP (Analytical Hierarchy Process), a widely-used multicriteria technique. This index is then used in a least-cost path analysis to identify a corridor composed by three level of land suitability to be considered in the subsequent design step. Results confirm how the approach could support the initial planning and design stages of road infrastructure projects integrating the main environmental, social, economic, technical and operational factors. Specific participatory steps could also be developed thanks to the multicriteria approach to involve more stakeholders and local population in order to improve the selection of the assessment criteria and the calculation of their relative weights and related scenarios.

Key words: GIS, multicriteria decision analysis, decision support systems, road infrastructures, landscape modelling

Introduction

The construction of a road, especially if characterized by high traffic capacity, is a complex work in which many economic, environmental, and political aspects strongly influence the planning, design and construction process. As a consequence, a continuous activity of choices optimization becomes essential in order to identify shared solutions for addressing a sustainable landscape planning and management.

S-MCDA (Spatial Multi-Criteria Decision Analysis) combines Geographic Information Systems (GIS) and Multi-Criteria Decision Aiding (MCDA) to support the decision-making process by addressing the challenges represented by making spatial decisions (MALCZEWSKI, 2006; De MONTIS, LAI, 2009). Among the different MCDA methods, the AHP (Analytical Hierarchy Process) (SAATY, 1988, 1980) helps one to capture both qualitative and quantitative aspects of decisions and provides a powerful yet simple way of weighting selection criteria, consequently reducing bias in decision making (ANTOGNELLI, VIZZARI, 2016; VIZZARI, MODICA, 2013). For these reasons, AHP-based S-MCDA methods have been widely applied in complex landscape analysis, where landscapes of various sizes can be explored using multiple spatial indicators, calculated at the various hierarchical levels (ANTOGNELLI, VIZZARI, 2017; VIZZARI, 2011), also using web-based interfaces (MODICA et al., 2016). Such methods have been already used for identifying the optimal location of linear infrastructures (COUTINHO-RODRIGUES et al., 2011; LÓPEZ, MONZÓN, 2010; NERI et al., 2010) often including a GIS least-cost path analysis (BAGLI et al., 2011; EFFAT, HASSAN, 2013; KESHKAMAT et al., 2009) where suitability or sensitivity indices are used to identify the path or the landscape corridors characterized by the best compromise considering the various evaluation criteria.

In this context, the objective of this research concerns the development of a methodology, based on an AHP S-MCDA model, to identify the optimal location of road infrastructures taking in consideration the main environmental, social, economic, technical and operational aspects of the road construction. A particular focus is kept on the analysis of ecological fragmentation caused by the road networks and by urban settlements. The approach focuses on landscape areas in where the fragile natural habitats, the peculiar orographic conformation and the current ecological issues make problematic both the strengthening of existing transport networks and the construction of new infrastructures.

Materials and methods

The study area, located in central Italy, includes the four municipalities involved in a road project called "Pedemontana Fabriano-Muccia". This road layout, which has a length of 34.28 km and connects the two homonymous towns, is a part of a more extensive new infrastructural plan called "Quadrilatero Marche-Umbria". This plan has included a series of road interventions in order to improve the connection of the Adriatic side of the Italian peninsula with the more internal areas of Marche and Umbria. The "Pedemontana" Fabriano-Muccia, on which the attention has been focused, constitutes a transversal intermediate axis that transversally connect the two new main highway routes (Fig. 1).

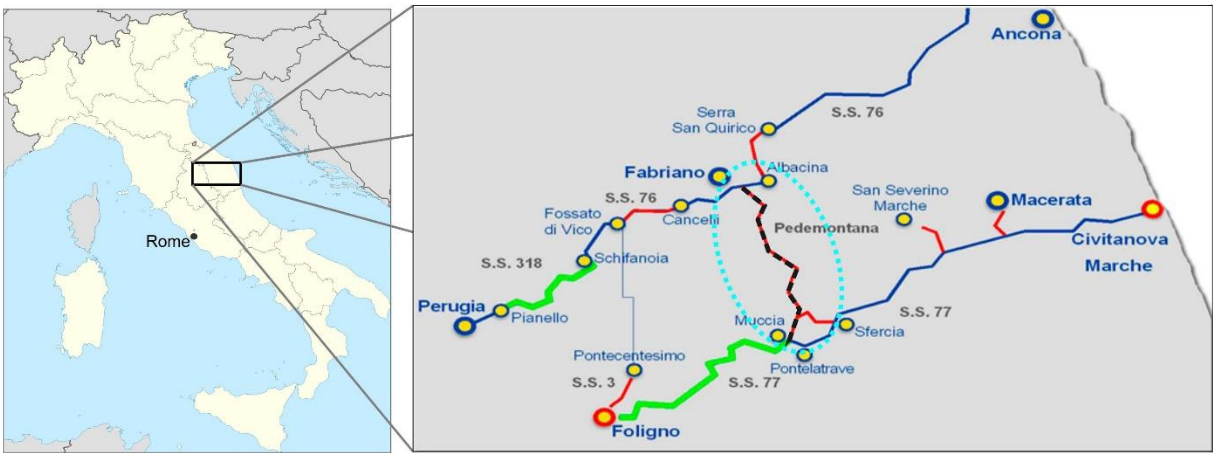

Fig. 1. Location of the study area and general layout of the "Quadrilatero Marche-Umbria" project
(the "Pedemontana" road is highlighted by a dotted ellipse).
Source: (ANAS, 2010).

The proposed methodology is based on AHP S-MCDA approaches by which the best design solution is identified on the basis of a number of significant interacting factors (in this case geo-morphological, ecological, socio-cultural, spatial fragmentation). The general aim is to set up a GIS-based spatial decision support system capable of achieving the most acceptable compromise between the different objectives. The methodological steps are as follows: a) Building the geo-information framework and GIS implementation; b) Structuring the AHP-based model; c) Sensitivity indices calculation; d) Identification of the optimal road path and of a wider landscape corridor.

Building the geo-information framework and GIS implementation

Considering the objectives of the research, all the relevant, available geo-information related to the selected assessment factors were included in four corresponding thematic groups: Geo-morphological components (morphology, geology); Ecological components (national parks, regional parks, SIC, SPAs, biodiversity of endangered species); Socio-cultural components (historical-cultural elements); Spatial fragmentation (infrastructures and settlements).

Structuring the AHP-based model

AHP is based on the principles of decomposition, comparative judgments and synthesis (SAATY, 1980, 2006) applied in breaking down the decision-making model into a series of elements (objectives, attributes and alternatives) that must then be organized hierarchically (hierarchical structuring). AHP supports the acquisition of relative weights in situations where a ranking of decision alternatives or evaluation criteria is desired and helps also to formalize public participation in decision-making processes integrating stakeholders' preferences (ANANDA, HERATH, 2003; MENDOZA et al., 1999; KOSCHKE et al., 2012) and experts' knowledge (see, e.g., VIZZARI, MODICA, 2013; KOSCHKE et al., 2012; TALEAI et al., 2014). The use of a Pairwise Comparison Matrix (PCM) to obtain a ratio scale of measurement for both tangible and intangible factors is the most recognized advantage of the AHP. In fact, PCM effectively makes it possible to overcome human difficulty in simultaneously evaluating the importance of all the factors included in the evaluation. From PCM, an absolute scale of relative values (importance) can be obtained through their principal eigenvectors and, if necessary, by normalizing those by dividing each value by the sum of all the values. The hierarchical model and the related spatial indices on which develop the AHP were defined (Fig. 2).

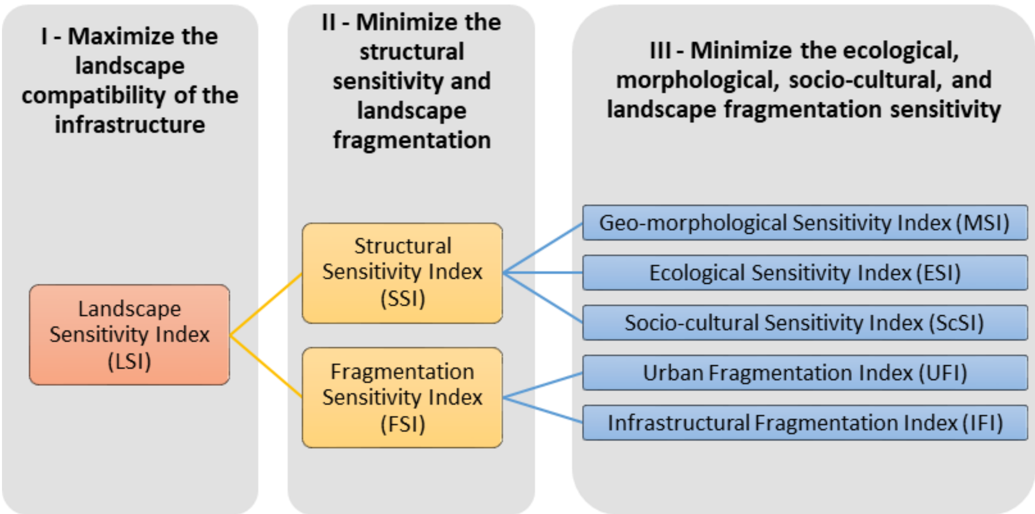

Fig. 2. General objectives, hierarchical model and related spatial indices used in the research.
Source: Own study.

Landscape sensitivity indices calculation

The collected geo-information is used to produce five synthetic spatial indexes (geo-morphological sensitivity, ecological sensitivity, socio-cultural sensitivity, urban and infrastructural fragmentation sensitivity) that improve the interpretability of the spatial variability of the thematic levels, facilitate their comparison and subsequently allow their aggregation using AHP methodologies. Such indices are calculated from cartographic and statistical data whose variability has been expressed using a scale between 0 and 5, where zero represents the lowest sensitivity level and 5 the highest. This step, normally included in AHP S-MCDA approaches, allowed to normalize all the evaluation factors considered on a common and continuous scale of sensitivity to facilitate the comparison and integration between different information.

The geo-morphological sensitivity index (MSI) expresses the sensitivity of the landscape to the insertion of new road layouts, evaluating both the ability of the slopes to host the infrastructure and the potential impact of the same on already structurally compromised areas. The MSI is calculated considering the classes of acclivity and the degree of potential instability related to the underlying geology.

The ecological sensitivity index (ESI) expresses the response of the ecological systems to the inclusion of new road infrastructures considering both the ability to rebalance ecosystems consequently of human driven change and the naturalistic value of the areas. The index is determined through the calculation of the Territorial Biopotential Capacity (INGEGNOLI, 2015; INGEGNOLI, GIGLIO, 1999) and is combined with the local degree of biodiversity derived from national biodiversity maps (AMADEI et al., 2004; BOITANI, 2002) and the presence of protected natural areas.

The socio-cultural sensitivity index (ScSI) combines the connection demand (depending on the distribution of population centers and their size) and the protection of historical-cultural elements of values. ISsc is determined by relating aspects related to population density and the presence of historical-architectural values on the territory, evaluating on the one hand the susceptibility of areas with high population density to be connected by roads, on the other the potential impact of new infrastructures in areas with a high concentration of historical and architectural elements.

Fragmentation indices measure the degree of fragmentation caused by the linear development of settlements (UFI – Urban Fragmentation Index) and by the presence of the road network (IFI – Infrastructural Fragmentation Index) whose elements are characterized by different levels of occlusivity. These indices arise from an adaptation of the homonymous indices developed in previous researches (De Montis et al., 2018, 2017;Romano, 2002). Such fragmentation indices are usually calculated referring to a basic area unit (municipalities, provinces, landscape units, etc.). In the present study, in order to locally quantify the fragmentation levels associated with infrastructures and urbanized areas, the two indices were calculated using a square mesh of 1 km per side.

The geo-morphological, ecological, and socio-cultural sensitivity indices, according the AHP model, were aggregated in a Structural Sensitivity Index (SSI) by a weighted linear combination. To this purpose, weights were calculated through PCMs filled with the support of five landscape experts. Similarly, the two fragmentation indices (UFI, IFI), considering their equal importance, were aggregated in an overall Fragmentation Sensitivity Index (FSI) using a simple average. A subsequent weighted aggregation of the two previous indexes produced a final Overall Sensitivity Index (OSI) able to estimate the overall sensitivity of the landscape to the inclusion of new road infrastructure works considering, in an interrelated manner, all the included geo-morphological, ecological, socio-cultural, and fragmentation factors.

Identification of the optimal road path and of a wider landscape corridor

This step was aimed to the identification of the best path and of those areas characterized by the greater suitability to the insertion of the road infrastructure. To achieve this objective, a least-cost path analysis (LONGLEY et al., 2005) was developed where the LSI was used as a cost measure to identify both the optimal path connecting the two end-points defined by the project and several adjacent areas useful for localization optimization purposes. Indeed, LSI can be considered as a kind of impedance surface since higher overall landscape sensitivity corresponds to higher pass-through impedances related to higher "landscape costs" generated by the road construction. Using LSI as a cost surface and excluding a 250 m buffer around each settlement, an accumulative cost distance (using a LSI "accumulative cost" function) was calculated by which it was possible to identify both the path with minimum impedance (using a GIS "least-cost path" function) and a wider corridor composed by three levels of overall sensitivity. These levels are based on the minimum overall sensitivity associated to the least cost path according to three classes (Table 1). The three corresponding buffers define a landscape corridor useful for finding local alternatives to the theoretical optimal path.

Table 1. Classes of accumulated cost used to define the three buffers composing the road corridor.

Class	Lower limit	Upper limit
I	Ms	Ms + 0.25%
II	Ms + 0.25%	Ms + 0.5%
III	Ms + 0.5%	Ms + 1%

Key: Ms Accumulated cost of the least-cost path.

Source: Own study.

Results and discussion

The areas with the highest landscape sensitivity are located along the mountain belts that extend longitudinally in the study area, while in the low hilly and plains areas the degree of landscape sensitivity decreases and results around average values (Fig. 3). The mid-low and low levels of sensitivity are found in the central valley areas and in the eastern portion of the study area. These trends, considering the weights calculated using the AHP approach, reflects to a greater extent the ecological sensitivity and the geo-morphological sensitivity of the study area. The higher levels of fragmentation, and therefore less sensitive to the insertion of infrastructures, are found, as expected, in correspondence with the main road axes and the larger and more elongated settlements. On the contrary, the higher levels of sensitivity to fragmentation are observed in the less populated areas and those in which the density of the road infrastructures becomes lower.

The least-cost path can be considered as the most suitable route that, according to the multicriteria model, defines the optimal location of the new road infrastructure (Fig. 3). Evidently, the accuracy of the path location is closely linked to the scale, nature, and quality of the data used as well as to the completeness of the information introduced in the evaluation process. The areas belonging to "buffer 1" represents the most suitable context for the insertion of possible variations of the new road axis with respect to minimum impact path. The other buffers within the road corridor are characterized by higher levels of sensitivity, but nevertheless contained. Within these areas, limited portions of the road layout may be located, but introducing appropriate measures aimed at identifying any critical issues present and mitigating the impacts locally determined on the landscape components by the infrastructure.

By comparing the corridor identified in this study and the path identified in the "Pedemontana" project, substantial differences emerge. In general, it can be observed that the optimal path has, in some sections, a greater tortuosity than the design track. This tortuosity can be possibly reduced with appropriate variations to be developed within the buffers identified in the research.

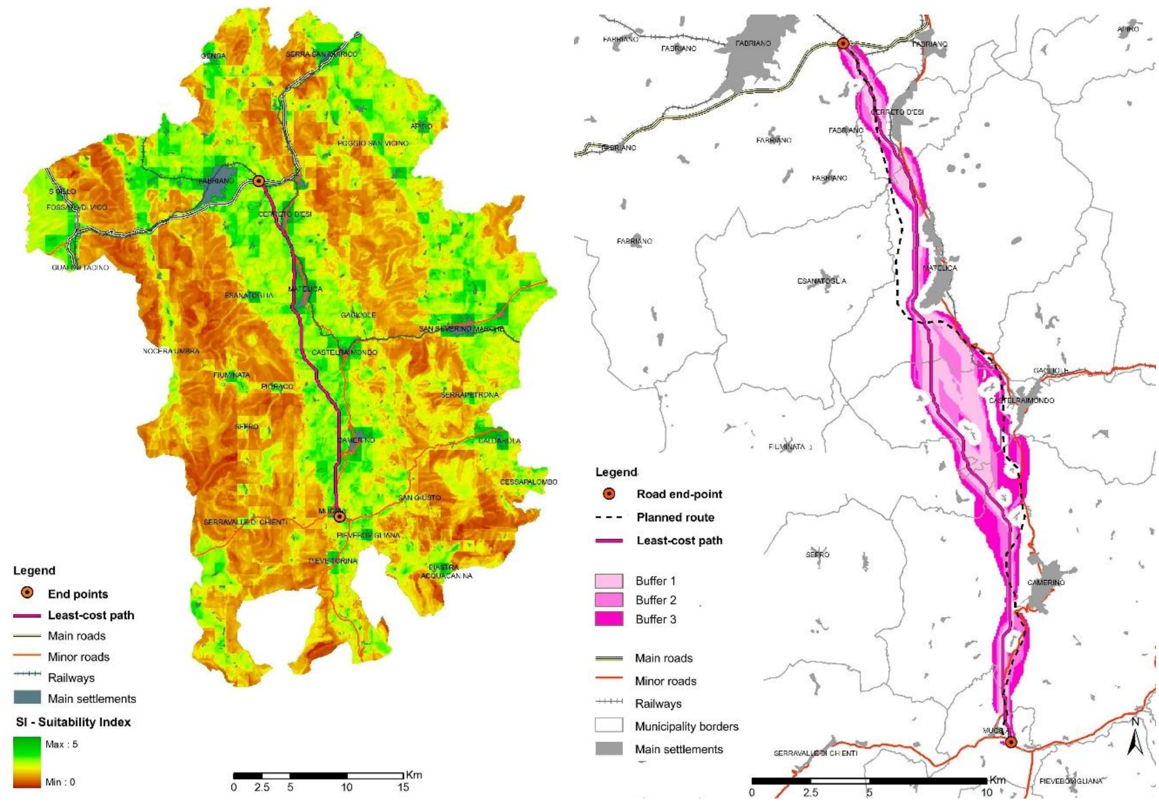

Fig. 3. Final Landscape Sensitivity Index (LSI) and least-cost path (*left*). Least-cost path and landscape corridor (*right*). *Source: Own study.*

Conclusions

The methodology, based on GIS-multicriteria methods, is aimed to define the best allocation in the landscape of new road infrastructures, with a particular focus on the ecological sustainability of the works in terms of conservation of vegetation resources, wildlife and protection of habitat from fragmentation. The methodology could provide a support to the planning processes of territorial development, with particular reference to the strategic assessments of infrastructural interventions. The GIS model, if adequately configured, can constitute a useable, practical tool for simplifying the activities of technicians called upon to express judgments about technical and landscape opportunities for the construction of infrastructural works. The versatility of multicriteria techniques will allow the introduction of additional assessment factors that will become available or could be derived within GIS environment as, by example, the viewshed analysis very useful to minimize the aesthetical impact of the infrastructure not considered yet in this application. A transdisciplinary approach inclusive of public opinion will be very important for future, similar applications. To this aim and to involve a wider group of local people, the implementation of a web AHP interface could be effective for a more e-participatory multicriteria application. This participation can become a key step in improving the selection of the more relevant assessment criteria and for locally exploring the reliability of the spatial indices included in the model. In addition, the e-participation can give the possibility to have a number of pairwise comparison matrices filled without a direct interaction between stakeholders because, as highlighted by SMITH et al. (2013), the influence of specific groups can potentially bias decisions if not put into the larger perspective.

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