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Bridging decision-making process and environmental needs in corridor planning

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Abstract

Purpose – The aim of this paper is to clarify the spatial multi-criteria workflow for stakeholders and decision makers, for which feedback rankings are vital to the success of the transportation planning.

Design/methodology/approach – The experimental approach was designed to integrate in a novel fashion both analytical hierarchy process (AHP) and multi-criteria decision making (MCDM) within a geospatial information system (GIS) framework to deliver visual and objective tabular results useful to estimate environmental costs of the alignments generated. The method enables ranking, prioritization, selection, and refinement of preferred alternatives. The Interstate-269, the newly planned bypass of Memphis-TN, for which a recent environmental impact study (EIS) was completed, was selected as the experiment test-bed.

Findings – The results indicate that the approach can automate the delivery of feasible alignments that closely approximate those generated by traditional approaches. Furthermore, via integration of local planning and ancillary spatial data, the method provided alignment results that avoided areas where local opposition was noted in the EIS. This enhanced method based on remote sensing and spatial information technologies delivers low or high-predicted environmental costs per feature criteria and cumulative predicted costs while preserving local values and plans.

Practical implications – The method is highly transferable and limited solely by the availability of sources of geospatial data and coordination with stakeholders. The approach was implemented to derive results similar to traditional approaches with benefits in time, costs, and quality of solutions.

Originality/value – A novel adaptation of MCDM and AHD within a spatial decision-making framework is presented. The paper suggests a clarification of multi-criteria workflow to design and select least-environmental-cost corridors. The case study application provides a starting point to develop practical tools that delivers environmental benefits through a collaborative process capturing stakeholder values and decision maker opinions.

Keywords Decision making, Geographic information systems, Analytical hierarchy process

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Introduction

Geographic Information Systems (GIS) are capable of handling massive amounts of data, as shown in Clevenger *et al.* (2002), O'Hara *et al.* (2000) and Singleton and Lehmkuhl (1999). The integration of economic and ecological information in a spatial context is a valuable approach for strategic policy development and decision making (Hill *et al.*, 2005). When coupled with physical or economic models, a GIS may be employed to transform and manipulate spatial and attribute data as needed to express values for evaluation criteria, e.g. the cost of different alternatives, the population exposure to different levels of health risk, and the distribution of road network concentrations in different areas of a city. Because the social-economic and biophysical implication as well, transportation corridor planning is a multidisciplinary task, which involves collaborative decision making among stakeholders who often have conflicting values and objectives. Transportation projects are normally lengthy and include many data-driven processes from early planning through the Environmental Impact Assessment (EIA) process and beyond.

One of the targets set for transportation projects is sustainability, which involves environmental, socio economic and risk assessment. Stakeholders who typically assess these areas normally have opposite opinions and expectations that, according Thabrew *et al.* (2009) increase the complexity of multi-stakeholder interaction in environmental decision making. Evaluating the best corridor alignments is a complex process that involves many decision makers and stakeholders. The amount and the complexity of the data are time-limiting factors for effective use in an EIA study without compromise the project. Gallis *et al.* (2008) emphasized that nowadays projects consider more variables than the projects taken in the past decades. Fortunately, GIS have been successfully employed by transportation practitioners to address the issues of data and decision-making complexity. Integrating current and future transportation scenarios with future planned development, as presented in long-term plans, plays a vital role in accessing the benefits, costs, efficiencies, and impacts of planned transportation improvements as well as the performance of the planned system with improvements. These issues have challenged researchers to overcome traditional approaches with innovative methods on behalf of transportation planning (Spellerberg, 1998; Stefanakis and Kavouras, 2002; Mongkut and Saengkhao, 2003; Huang *et al.*, 2003). In Sharifi *et al.* (2006) the efficiency of transportation corridor was predicted based on a GIS-Multi-Criteria Decision Making (MCDM) balanced solution of economic, engineering, environmental, institutional and social objectives during the planning phase.

The complexity of the data as well as the need to capture diverging values and opinions implies that an objective and collaborative approach would deliver benefits by providing methods to generate various scenarios. The scenarios should be produced under differing ranking strategies using different intra-factor and inter-factor criteria, as seen in O'Hara *et al.* (2000). In this context, Saaty (1995) explained how a MCDM-based GIS could lever the efficiency of transportation planning. MCDM enables the application and modeling of stakeholder preferences and offers the opportunity to improve the coordination and collaboration among planning organizations, resources agencies, transportation practitioners, and affected citizens.

MCDM has provided positive results in terms of transportation planning from the past 15 years. However, at least two big pictures still remain to be explored:

(1) an automated "decision-making" framework for easily integrating varying stakeholder values and conflicting opinions to generate results that may be considered in a spatial information; and

(2) a strategic way to introduce the multi-criteria workflow and needs to stakeholders and experts, which feedback rankings are vital to the success of the transportation planning.

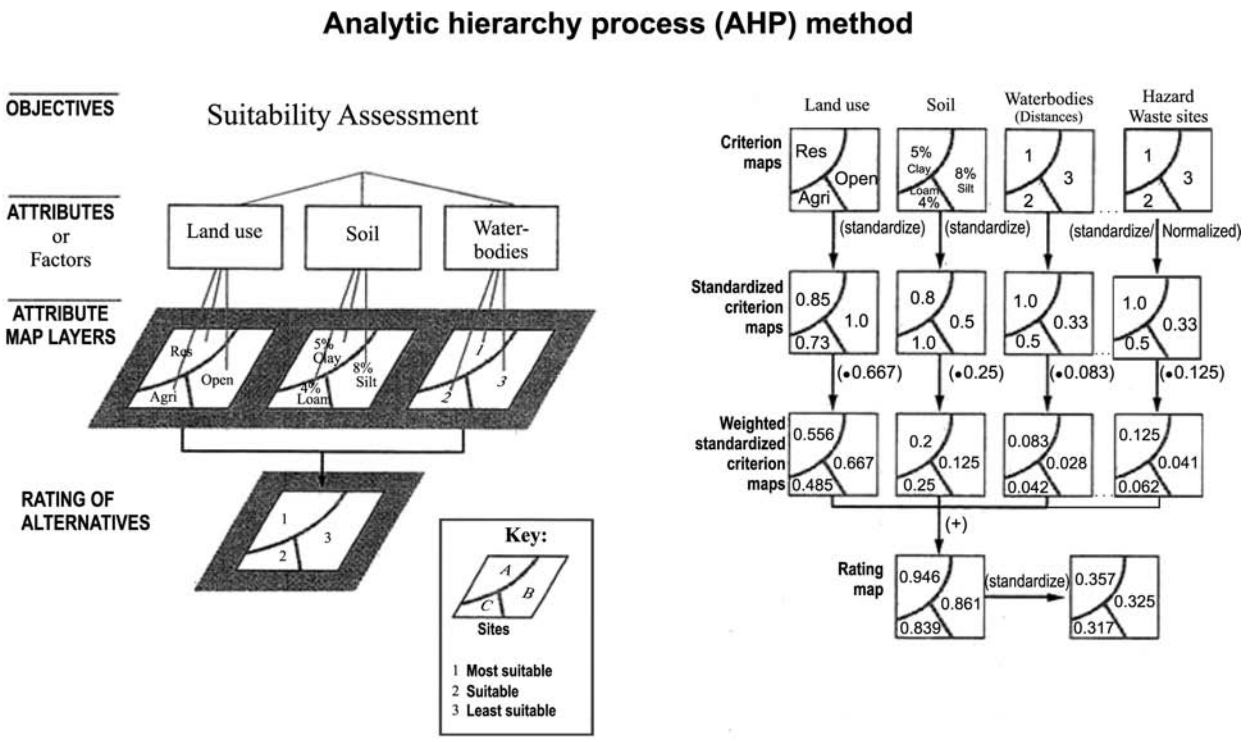
This paper presents practical approaches based on an adaptation of Saaty's Analytical Hierarchy Process (AHP) as a preprocessor to MCDM. The hierarchy scheme is developed in two levels, where single scenarios are computed in the first level and then combined into a multi-layer scenario as the second level. Intra-factor and inter-factor rankings are used to generate weights to compute the scenarios through GIS map algebra. Scenarios presented utilized data and experimental results of a research project studying the proposed I-269 bypassing the metropolitan Memphis, TN. It demonstrates the integrated use of MCDM with GIS technology in a manner that supports effective early planning, feasibility, and environmental analyses for transportation projects. In addition, the roles of experts, stakeholders and transportation practitioners associated with the project and their input and feedback to the process are highlighted as a vital bridge that connects transportation decision making and environmental impacts screening and analysis in transportation corridor planning.

An overview of MCDM for transportation practitioners

MCDM is a systematic methodology to generate, rank, compare, and select multiple conflicting alternatives using disparate data sources and attributes. The applicability of MCDM is being extended to many different fields including GIS. Spellerberg (1998) presented a long collection of environmental studies based on MCDM methods and Malczewski (1999) reported the positive results of MCMA in spatial decision support systems thought criterion weighting, decision rules, and sensitivity spatial analysis. Within the domain of transportation roadway planning, alternative alignment generation and the selection of a preferred alignment alternative, multiple criteria evaluation methods have been historically developed to support selecting the best alternative from a set of competing options (Sharifi *et al.*, 2006).

In GIS applications of MCDM, factors (as streams and water bodies, slope, conservation and urbanized areas) are extracted from layers (as hydrology, elevation, land cover, urban zoning, among other datasets). Criteria are then selected per factor and their respective rankings are allocated according to different priorities. The GIS-based MCDM enables spatial analysis using a combination of factors and rankings, which forces the system to produce desired and balanced outcomes. Figure 1 illustrates how MCDM works in a GIS using map algebra.

In practice, a GIS-based multi-criteria decision framework for transportation planning requires more than simple input of factors. MCDM is currently a well-known subject, however, its best integration within transportation-GIS practitioners still remains a challenge. Despite the corridor planning have been mostly designed in digital way, high resolution imagery as well as other layers of information are normally employed as simple background on manual heads-up digitizing process. Results are good in general but not the efficiency of the method.



Analytic hierarchy process (AHP) method

(a)
AHP procedure

(b)
GIS-based rating of alternatives

Source: (b) modified from Malczewski (1999)

Figure 1.
(a) Illustration of Analytic Hierarchy Process method of MCDM based on land cover themes; (b) GIS-based rating of alternatives

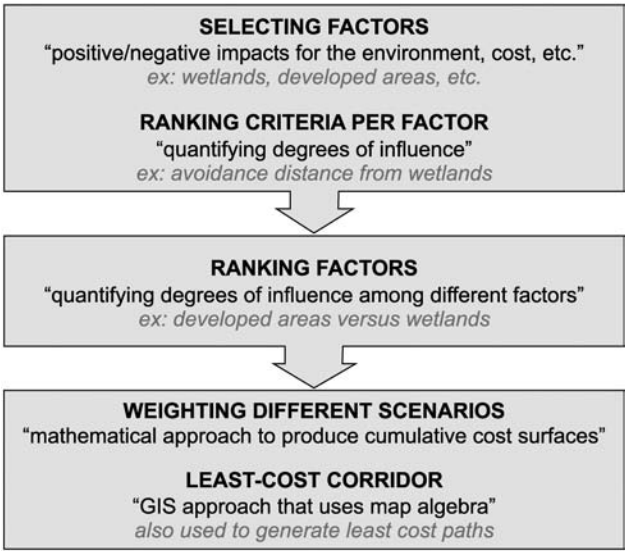


Figure 2.
The basic steps required to design the least-cost corridor using a spatial AHP-MCDM implementation

Prior to the effective use of AHP-MCDM on transportation planning, the GIS-transportation practitioners and stakeholders must to know how the proposed method works. The flowchart in Figure 2 contains the basics steps necessary to understand the process, from the selection of factors and criteria to the computation of the cumulative cost surfaces used to generate a set of least cost-path alignments (based upon different scenarios).

The study area and background

Interstate 69 is a 1,600-mile long corridor proposed to connect Canada to Mexico across the USA. The overall project is divided into 32 Segments of Independent Utility (SIU) for studies purposes. SIU-9 ranges from Millington-TN down to Hernando-MS crossing the metropolitan area of Memphis-TN, reusing some existing roads such as I-55. However, a new I-269 bypassing the Metropolitan Memphis-TN to the east has been approved through an EIS process and is entering construction phases (Figure 3).

The I-269 bypass serves as the research testbed of the Streamlining Environmental and Planning Processes (SEPP) project of National Consortium for Remote Sensing in Transportation (NCRST). In this research project, a recently completed Final Environmental Impact Statement (FEIS) provides a baseline of results delivered by tradition approaches that are being rigorously compared to results developed through new and innovative applications of commercial remote sensing and spatial information (CRS&SI) technologies. The methodology presented for implementation of MCDM for corridor decision making provides clear indications that the effective use of factors mined from best-available Federal, State and local spatial information databases combined with appropriate rankings in a decision making framework can deliver results that closely resemble traditional methods, but are supported by rational and objective processes that are traceable, repeatable, and readily adapted to consider adjustments to criteria as well as inclusion of additional factors.

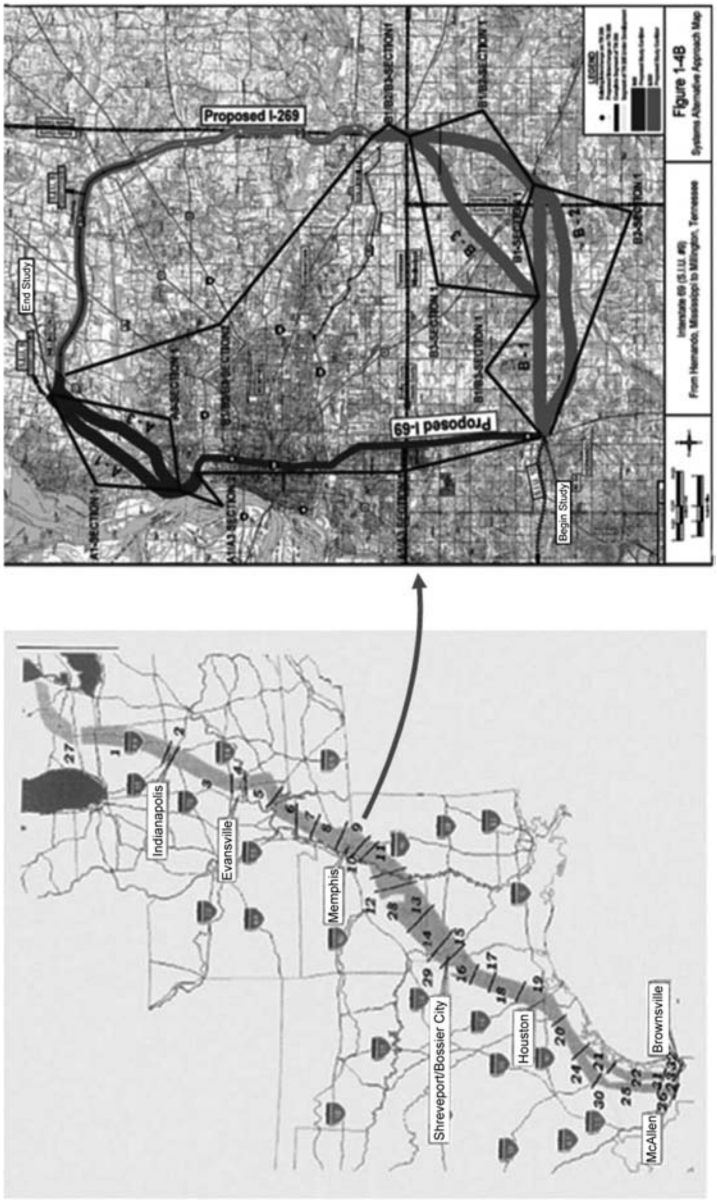


Figure 3.
The proposed I-69 corridor (left) and the respective study area located along the border of Mississippi and Tennessee, which illustrates the original and the bypass proposed alignments (right)

This study is part of SEPP project of NCRST titled “Validating commercial remote sensing and spatial information technologies” (www.ncrste.msstate.edu/), which is sponsored by the US Department of Transportation – Research and Innovative Technology Application (DOT-RITA).

The analytycal hierarchy process

AHP is as a multi-hierarchy-layer comparison method for MCDM. AHP employs mathematic decision analysis to determine the priorities of various alternatives using pairwise comparison of different decision elements with reference to a common criterion. “It can be used to make direct resource allocation, benefit/cost analysis, resolve conflicts, design and optimize systems” (Saaty, 1994).

In practice, different levels of the hierarchical process involve different elements. Initially, factors are introduced and certain criteria are considered. The criteria are ranked and then single scenarios are produced. Following the generation of single scenarios, different scenarios arising from the use of different factor/criteria, are ranked according to documented stakeholder values and preferences. Each single-factor scenario result in a cost surface depicting the values associated with factor criteria. Scenarios cost surfaces are then combined to form a multi-factor-scenario that in turn results in the calculation of a cumulative cost surface unique to each multi-factor scenario. The AHP method is flexible in general and can be adopted to solve multi-hierarchy levels. This paper presents the use of two hierarchy levels to arrive at a set of multi-factor scenarios, the results of which are presented in the following sections.

Hierarchy level one: single scenarios

In this study, a reduced number of factors are used to reach the proposed objective. As a practical GIS exercise, this problem addresses the automated capabilities of early planning for transportation practitioners and decision makers. The factors selected transcend the bio-physical scenario. Maps derived from urban planning are also considered. Factors and criteria employed (Table I) are hypothetical, gathered from experimentation results and literature reviews. Rankings range from 1 (low impact) to 9 (high impact), as recommended by Saaty (1995). The application is flexible and extensible such that any other factor containing spatial information can be easily included in this procedure.

Focusing on the regional scale for planning, the scenarios were created based on the appropriate use of best-available Federal, State and local geographical data. As a bypass project, the desired I-269 should maintain a certain distance from the Metropolitan Memphis area, which in practice is a balancing act aimed at minimizing community impacts all the while having integration with surrounding road networks and communities. This criterion is the most important among the other scenarios during the definition of a macro area to site the corridor. In addition, the existing and future urban developments are also considered in the equation.

To increase credibility and complexity to produce refined results, some other environmental scenarios are also included. At a regional scale corridor selection, most of the data came from National raster and vector datasets, corresponding to a medium scale map (1:25,000-1:100,000). Wetlands and forest areas are considered natural conservation features due to the potential impact in the wildlife and natural

Factor	Criteria: ranking	Source
Developed areas	Desired distance (corridor) from MPO urban limits: 0-2 km: 9 | 2-4 km: 7 | 4-6 km: 1 | 6-10 km: 3 | >10 km: 8	NLCD + Memphis MPO
	Avoidance distance from existing and future developments: 0-1 km: 9 | 1-2 km: 6 | 2-3 km: 3 | > 3 km: 1	Desoto County long-term plan
Hydrograph	Avoidance distance to water (streams and water bodies): 0-25m: 9 | 25-50m: 7 | 50-100m: 5 | 100-150m: 4 | 150-200m: 3 | 200-300m: 2 | > 300m: 1	NHD
Wetlands	Avoidance distance: 0-50m: 9 | 50-100m: 7 | 100-150m: 5 | 150-200m: 4 | 200-300m: 2 | > 300m: 1	NLCD
Forest	Avoidance distance: 0-50m: 9 | 50-100m: 7 | 100-150m: 5 | 150-200m: 4 | 200-300m: 2 | > 300m: 1	NLCD
Agriculture	Avoidance distance: 0-25m: 9 | 25-100m: 6 | 100-300m: 2 | > 300m: 1	NCLD
Slope	Preferable slope classes: 0-5%: 1 | 5-10%: 4 | 10-15%: 5 | 15-20%: 7 | >20%: 9	NED (10m)
Existing roads	Desired reuse of major roads: 0-25m: 1 | 25-50m: 3 | 50-100m: 6 | > 300m: 9	BTS

Table I. Factor, criteria and ranking used to produce the single scenarios

environment. These areas were detected from National Land Cover Data (NLCD) and scored high. The same analogy is applied to primary agriculture fields due to the importance to the regional economy.

This study is not focused on traditional engineering processes. The primary focus from a terrain perspective is slope and hydrograph. Significant cost savings occur when the analysis techniques provide alignments that are void of significant slopes and multiple stream and/or wetland systems, therefore, slope and hydrograph scenarios are added in the process. The slope map was produced using the National elevation Dataset (NED), and the avoidance distance to water was produced based on National Hydrograph Dataset (NHD). Figure 4 shows the individual scenarios for the overall study area as well as I-269, which is a visual reference to understand the idea of project.

Hierarchy level two: cumulative cost surface

In this level the single scenarios as previously computed are combined into a unique scenario using the GIS map algebra technique. Because the input rankings can vary in range from different sources and large amounts, the mathematical normalization is required to assure unbiased results. Then, prior to other processes, each single scenario is considered as raster data and the ranking values reclassified according to correspondent weight resulted from the intra-scenario comparison. Figure 5 illustrates the combination of a few layers to compose the cumulative cost surface using map algebra technique.

This level requires the inter-factor ranking, which quantifies degree of influence among different scenarios toward the environmental impact. Rankings were based on

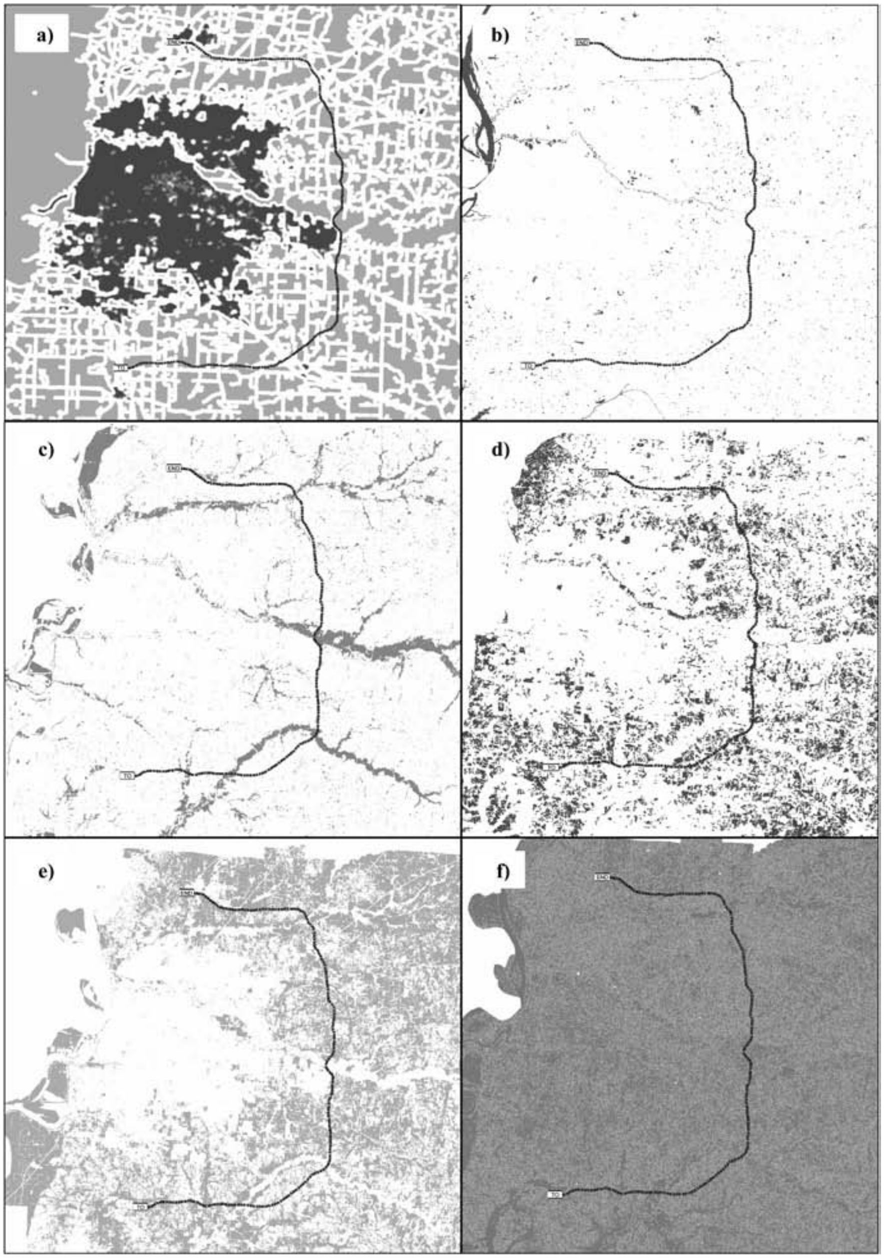
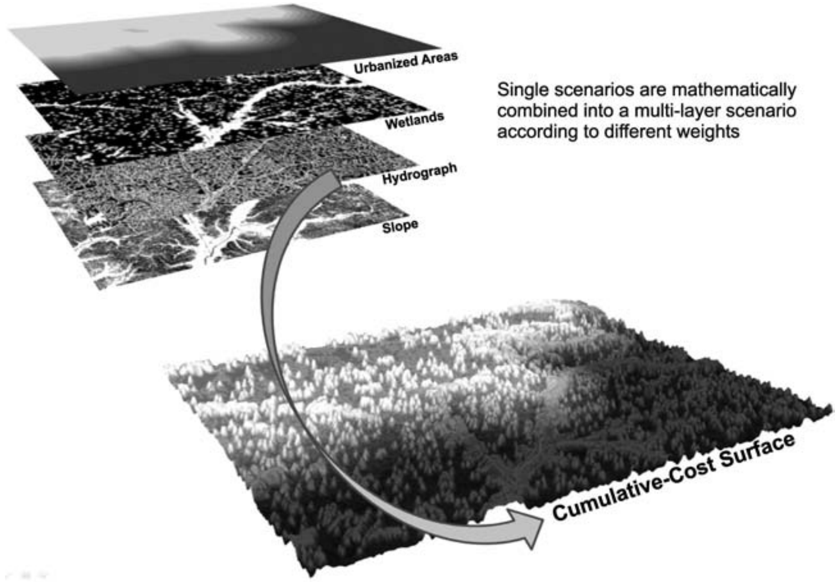


Figure 4.
Single scenarios associated with the study area of the proposed I-269 bypassing the metropolitan area of Memphis-TN

Notes: The darker the area, the higher the avoidance: **(a)** developed areas and the existing roads; **(b)** hydrograph; **(c)** wetlands; **(d)** forest; **(e)** agriculture and; **(f)** slope



Source: Sadasivuni (2009)

Figure 5. Map algebra approach to produce a combined cumulative cost surface from different single scenarios

experimentation results. Table II shows the inter-factor rankings and the respective weights.

Following the major goal of the proposed bypass, distance from developed areas is considered a high priority for the project. In the mean time, moderately high values are given to natural environmental layers as wetlands and forest areas. A moderate to low priority is given to primary agriculture and a low ranking for slope and hydrograph. Additionally, the transportation layer containing the major roads is considered. The existing roads scenario is added into the system at the end with a low value. This forces the computed corridor to follow the existing roads for a low-environmental cost. Figure 6 shows how much each factor contributed to the combined multi-scenario.

Results

Within the processing, specific scenarios are created in the first level, combining ranked criteria per factor, as showed in Figure 4. These scenarios are easily

Factor	Ranking	Weights
Developed areas	9	0.3462
Wetlands	5	0.1923
Forest	5	0.1923
Agriculture	3	0.1154
Hydrograph	2	0.0769
Roads	1	0.0385
Slope	1	0.0385

Table II. Factor and ranking used to produce the cumulative cost surface

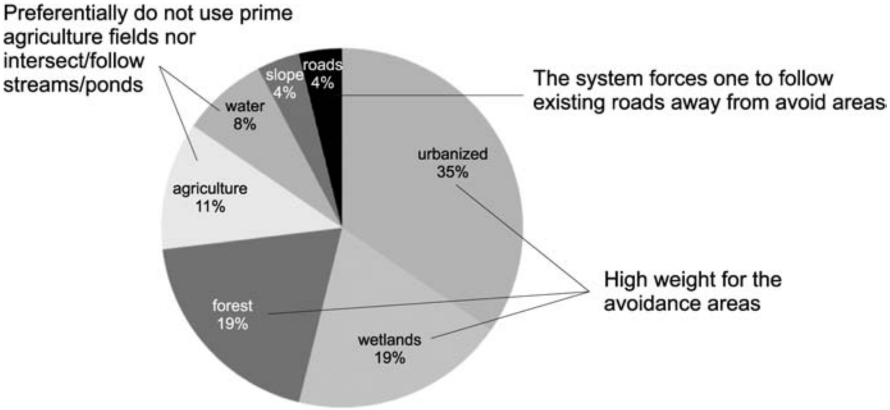


Figure 6.
Combined scenario using inter-factor ranking

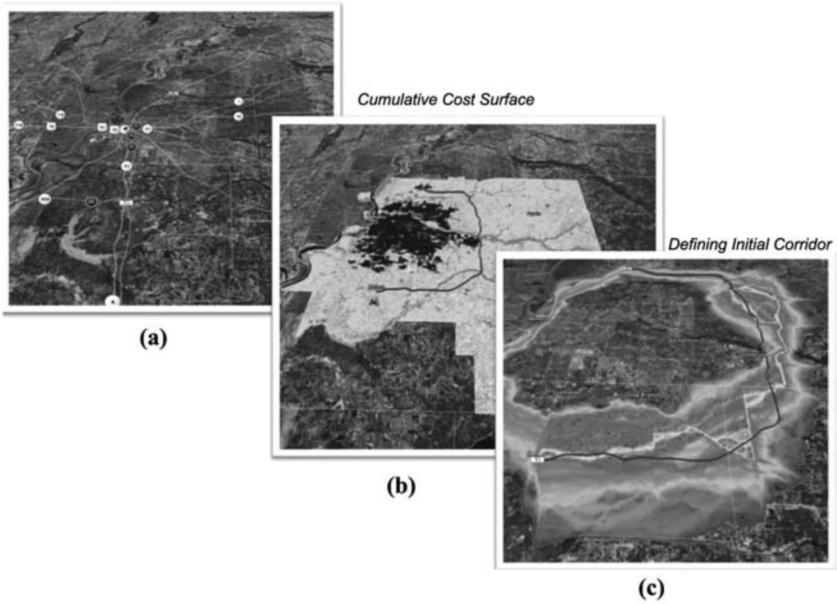
manipulated and correspond to data or areas of interest such as conservation, agriculture, zoning, etc. Depending on the particular relevance toward the project and the ranking, scenarios and their potential to environmental impacts are calculated. With the spatial MCDM approach, all the desired scenarios can be computed together with an appropriate inter-factor ranking. The ranking considers the degree of influence of certain factor compared to others. This study considered the avoidance distance from developed areas as a high impact scenario (higher ranking) to project the initial bypass corridor. In the mean time, other scenarios are also considered under moderate to low ranking, aimed to minimize impacts on conservation and economic areas and also minimize high-cost engineering solution due to rugged terrain and streams.

In short, rankings are used to generate the cumulative cost surface, as illustrated in Figure 6. Then, the cumulative cost surface is used as reference to compute least-environmental-cost corridor, as show in Figure 7. Compared with the final I-269 alignment, the results show close similarity. The final alignment follows the corridor zone and, in some cases, presents extreme accuracy due to the reusing of existing roads (Figure 8).

Discussion and suggestions

An efficient way to understand and organize information prior to MCDM is associating a relative ranking to different factors and the respective criteria. The simple association of relative rankings according to certain degree of influence (Simple Additive Weighting – SAW) has been successfully used in supporting multi-criteria spatial decisions as in Jakimavicius and Burinskienę (2007) and O'Hara *et al.* (2000). Similarly, Furney and Belcher (2008) combined layers from different sources to produce preliminary transportation corridors based on a simple SAW ranking while not considering the ranking normalization nor the long-term land use or zoning. In practice, it does not offer much in terms of innovation, but it saves considerable time when compared to traditional approaches.

The MCDM core solution adopted in this study is based on Saaty's Analytic Hierarchy Process (AHP) method instead of the SAW method, which uses pair-wise comparisons and normalization to achieve relative weights. AHP is a robust method



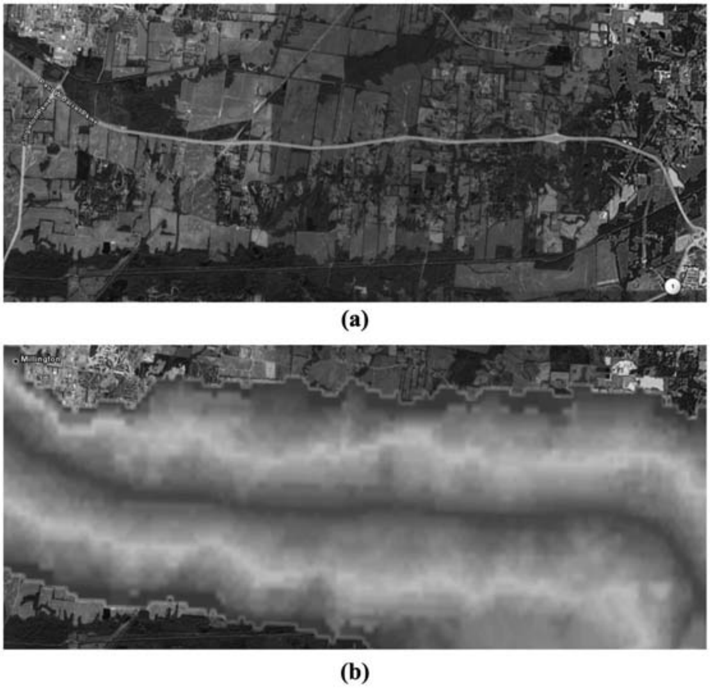
Notes: (a) the overall Memphis I-269 bypass; **(b)** the cumulative cost surface; and **(c)** the computed corridor that assumes minor environmental impact
Source: Google Earth (background image)

Figure 7.
The final data projected using Google Earth application

that uses consistency ratio to control the pair-wising inputs. Mathematical formulations are intentionally not described in this paper. General equations can be seen in Saaty (1994) and their use in practical case study in Sadasivuni *et al.* (2009).

Rescia *et al.* (2005) proposed a SAW decision-making model based on environmental values and impact magnitudes gathered from experts to select the optimum alternative corridor. Impact magnitudes are computed using a complex combination of environmental characteristic given from percentage of surface area occupied by linear engineering project using small sessions. Contrary to this paper, the method used in Rescia *et al.* (2005) proposes a segmented analysis that deals with factors and criteria in a complex way, which in practice could not fit with the real needs and expectations of transportation planning decision makers.

According to Thabrew *et al.* (2009), scientific analyses in multi-stakeholders context have to be more transparent, participatory and stakeholder-based in order to provide useful information to assist responsible direction making. Thus, inputs and outputs have to be strategically simple in a decision-making framework. Unfortunately, the pair-wise comparison approach does not work effectively in practice because transportation practitioners as well as factor/scenario experts typically use ranking comparisons instead of pair-wise ones. The rankings could have different magnitudes per factor, since they depend on expert and stakeholder feedback. Integrating different rankings aiming to find a unique spatial-based solution can become a problem. To overcome this shortcoming, rankings are normalized prior to any advanced GIS processing.



(a)

(b)

Figure 8.

Notes: **(a)** the existent major road; **(b)** the computed least-environmental corridor
Source: Google Earth (background image)

This paper summarizes an efficient method to combine different inputs layers and rankings to compute the least-environmental cost corridor, which provides enhanced capabilities to EIS and pre-NEPA studies. This work is conducted under an environmental, feasibility and early planning points of view. This GIS-based decision making framework can also be adopted for different phases of the transportation project, such as engineering and construction. In this case, the input data and ranking will change according to the goal and the scale of the project. Focusing on streamlining environmental and planning process, the vision and ideas presented in this paper are converging into an effective solution for pre-construction planning in a balanced and rational way that helps to avoid conflicts. Integrating the best available Federal, State and local databases, feedback and goals is vital for a successful transportation project.

Conclusion

As a powerful approach to compute unique solutions based on conflicting interests, the spatial MCDM remains largely unused in practice. Despite the importance of the well-known mathematical approach and GIS capabilities in an automated MCDM framework, we understand the key of the success is well-structured input data. This study reports an exercise where the decision making process is put in practice in a balanced way to find feasible areas to project a transportation corridor. This paper show-cases how different factors, criteria and rankings are used in a spatial decision-making framework, which considers environmental protection and feasibility in early planning. Aiming to reach the decision makers involved in transportation planning, the focus of his paper is the workflow associated with the process instead of the computing process. We believe that access and understanding of the spatial multiple criteria decision process will benefit and add value to the transportation planning process.

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