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Sustainable Transportation Decision-Making Process with the Implementation of a Raster-Based SDSS

- A Texas Urban Triangle (TUT) Case -

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ABSTRACT: Urban planning involves many different disciplines. In order for the related stakeholders to have better understanding and acceptable outcomes, planners are required to present a methodology that would properly reflect people's interest. In order to justify the demand and distribute people's interest, planners actively utilized the suitability analysis. Accordingly, a suitability analysis to find the optimal route for high-speed rail was performed in this paper. With ArcGIS and geographic data sets, simple map algebra could be used. The final product of this research was a map indicating the suitable routes for high-speed rail using the shortest path analysis.

KEYWORDS: Suitability Analysis, Shortest Path, AHP, Delphi Panel, Factor Classification

키워드: 지리정보시스템, 메가리전, 공간정보의사결정모형, 종합평가법, 요소분석

1. Introduction

Urban planning involves many different disciplines. From the most popular subject, land use planning to the most complicated procedure, policy-making process, planners are required to perform diverse roles. In many cases, planners need to present or suggest a decision-making process that will satisfy the general public in a rational way. This is particularly true for a new transportation investment. For example, a new transit system would have diverse impact on the land uses, land prices, accessibility, and so forth. In order for the related stakeholders to have a better understanding and acceptable outcome, planners are strongly required to present a methodology that would reflect people's interest as much as possible.

The suitability analysis is one of the oldest forms of decision-making support system in the field of planning. In order to justify the demands and appropriately distribute people's interest, planners actively utilized suitability analysis. Emerging technologies, such as the Geographic Information System (GIS) and personal communication technology accelerated such movements. GIS implemented decision-making support system is a particularly good way to handle a situation like the above. Significant improvements in geographic data availability made the planners have more inputs and thus, obtain more complicated, but much more diversified and improved outcomes.

In this extent, this study outlines how to successfully address a sustainable outcome in transportation decision-making process. In specific, the study addresses sustainable transportation in the Texas Urban Triangle (TUT) at a regional scale. Its aim is to determine the most suitable corridor for a new transport infrastructure by employing a spatial decision support system (SDSS). The basic research questions asked are spatial in nature, so accordingly GIS is the primary method of data analysis. The overall modeling approach devotes to

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answer the following question: how to adequately model the transportation corridors to meet the demands and to sustain the living environment at the same time?

2. DSS, SDSS, and GIS

2.1 Decision Support Systems

Decision support systems (DSS) in general refer to all types of decision helping systems and academic areas, such as statistics, economics, and operations research have long utilized DSS. Recently, with the advancement of personal computers, other disciplines, such as information science, psychology, and urban planning also implement different types of DSS to acquire optimal solutions (Ascough et al., 2002; Druzdzel., Flynn, 2002; Malczewski, 2006). There is no single DSS application. Nor is the DSS field homogenous (Arnott., Pervan, 2005). Each DSS type identifies different philosophy, system structure, and execution environment. Marginal controversy still remains and user's understanding on DSS slightly varies to some degree. However, the general consensus on DSS is: 1) com–munication–driven; 2) data–driven; 3) document–driven; 4) knowledge–driven; 5) model–driven; and 6)web–based systems (Druzdzel., Flynn, 2002; Eom, 2001; Power, 2007).

Of those different types, spatial decision support systems (SDSS) share the qualities of being model–driven and knowledge–driven (Ascough et al., 2002; Eom, 2001; Malczewski, 2006; Power, 2007) because its overall process to produce the final decision is closer to that of a model, rather than communication or a document. SDSS are intended to resolve issues under spatial domain. The characteristics of an SDSS allow facilitating a research process that is iterative, integrative and participative (Malczewski, 2006; Nyerges., Jankowski, 2012; Power, 2007). As the nature of SDSS stands on spatial planning aids, its application implies a certain type of spatial interactions. Consequently, GIS have been one of the key interface tools of SDSS allowing a more interactive decision–making environment (Spatial Decision Support Consortium, 2008). Urban decisions have particularly enjoyed the expanded applications of SDSS. There have been a large number of studies utilizing an SDSS in development decisions and many of them tried to improve and revise the practical aspect of SDSS (Ascough et al., 2002; Crossland et al., 1995; Kim et al.,; Malczewski, 2006).

One of widely utilized forms in SDSS is a combination of GIS and multi–criteria decision analysis (MCDA). The common purpose of MCDA is to evaluate and select an optimal solution based on multiple criteria defined by users (Brucker et al., 2011; Graymore et al., 2009; Kiker et al., 2005). Optimization methods, such as the analytic hierarchy process (AHP), Delphi panel discussion, and multi–attribute utility/value theories (MAUT/MAVT) are the synthesis of MCDA to prioritize in–formation and evaluate alternatives (Belton., Stewart, 2002; Kiker et al., 2005; Yoe, 2002). There are two dominant features in spatial MCDA. One is the GIS component and the other is MCDA analysis, all of which are the foundations of SDSS (Ascough et al., 2002; Greene et al., 2011). The main challenge in the latest SDSS research is not in the development of more sophisticated MCDA methods. More important is in the support of structure and design of the system. Improving the process that is supportive to generate new alternatives and is also capable of evaluating the goodness of outputs makes a major contribution to advanced spatial–MCDA.

There are two main reasons for a rapid increase in GIS–MCDA research, and the first is a wide recognition of decision analysis as an essential element in GIS science (Graymore et al., 2009). The second reason is its lower cost and greater ease of use in operation systems (Malczewski, 2006). The major advantage of incorporating MCDA into GIS is in its value judgments capability – users' preferences with respect to evaluation criteria and/or alternatives (Graymore et al., 2009; Kim et al., 2014; Malczewski, 2006). In order for the model to produce reliable products, it is often required to have experts' advice at the beginning, and the Delphi panel discussion is a fine form that will enhance the process of expert interaction during the entire SDSS process. GIS–MCDA provides a framework to identify problems, organize elements, understand relationships in input components, and stimulate communication among users (Malczewski, 1999; Ramsey, 2009). In other words, GIS–based MCDA have a possibility to incorporate user and expert participation into its overall decision–making environment. Theoretically, this perspective is sustained as the MCDA side of GIS–MCDA providing a structure of merging participants' inputs into the decision–making process, and the GIS side enables a

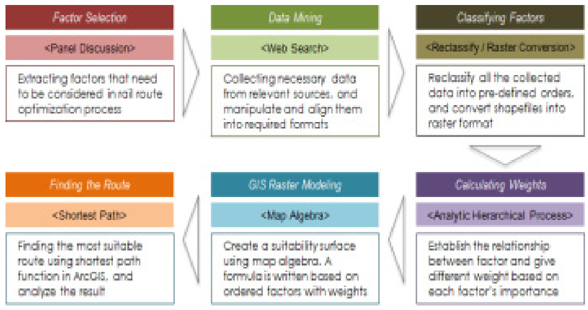

Figure 1. SDSS Process

graphical interface illustrating visual results of participation.

2.2 SDSS Process

In general, suitability analysis using GIS involves 6 different steps. First, the analysts need to define what factors affect most when determining potential sites for the required facility. Among various different ways, the Delphi Panel Discussion is a popular approach to handle this step. After establishing the factors, relevant data sets are collected and manipulated. Third, the collected data sets are converted into a raster grid, and further reclassified into a uniformed scale. The next step involves the articulation of the relationship between the factors. This relationship is usually represented by the numerical values and thus, can be calculated in several ways including statistical approaches. Subsequently, the analysts need to implement above findings to the GIS modeling. In order to perform such process, a raster-based modeling is often implemented. Finally, the shortest route is extracted based on each pixel's suitability score. Figure 1 illustrates the overall process of SDSS.

3. Methodology

3.1 Study Boundary and Data Management

The study area is set to the route between Austin and San Antonio, and 6 factors are implemented as inputs. First, population density is in a combined format of the U.S. Census 2010 in block group level and TIGER Shape File. Second, floodplain and hydrology were used to represent environmental measures. Road network data are also selected to see how the route relates to the transportation network and Slope indicates engineering and construction limitations and the datasets are in the Digital Elevation Model (DEM) format. Finally, Geology is selected to recognize the vibration problem in the route. The cell size is set to 30m x 30m and this is the prevalent resolution for the chosen input datasets.

3.2 Analysis

3.2.1 Factor Selection

Factors that need to be considered when performing a suitability analysis vary across the study purpose, and require different methodologies in factor selection. In general, the Delphi Panel Discussion is a broadly accepted method to determine the necessary factors. It requires many inputs from the experts and thus, generally demands significant time and costs. Therefore, this study adopted some of the existing factors extracted based on the Delphi Panel Discussion in the previous studies (Kim et al., 2014).

The Texas Urban Triangle (TUT) research team organized a panel consists of 25 different experts with various back-grounds. The result is 42 different indices that would be defined as the sustainability indicators. Among those 42, this study implemented 6 factors, and they are 1) population density; 2) roads; 3) floodplain; 4) hydrology; 5) geology; and 6) slope. Population density is a ratio and interval variable, whereas floodplain, geology, roads, and hydrology are closer to present or not-present type with a different hierarchy and thus, ordinal items. Since the cost of moving people would be enormous, density must be dealt within the study horizon. Hydrology and floodplain are measures to consider any impacts on the water resource environments. Hydrology relates to water quality aspect and floodplain is connected to the potential natural disaster. Slope indicates engineering specification. Any vertical slope of the land above 2% grade is not suitable for high-speed rail con-struction. Road type is an important measure since it is virtually impossible to remove or replace highways. Finally, geology indicates the vibration and operation issues. Clay or sands are not stable for the rail operation.

3.2.2 Factor Classification

Once necessary factors are set, the next step is classifying them with an order. By setting up the standard for each factor with desired hierarchy, *'reclassify'* feature in the *'spatial analyst'* extension of ArcGIS could be used. The general rule is the less the score, the better for the suitability, and all

Table 1. Factor Reclassification

Factor	Description / classification	Score	Factor	Description / classification	Score
Pop. Density	The lesser the density, the better for a rail route		Roads	Rail depends on the type of roads that will cross	
	classification	Score		classification	Score
	0~0.5	1		Local streets	1
	0.51~3.0	2		County RD	2
	3.1~10.0	3		FM roads	3
	10.1~30.0	4		State HW	4
	30.1~	5		IS/US HW	5
Flood	The lesser the impact of flood the better for maintenance		Hydro	Rail depends on the type of hydrology it will cross	
	classification	Score		classification	Score
	500YR	1		Internittent	1
	100YR	2		Minor Stream	2
	1% annual −	3		Major Stream	3
	1% annual	4		Water Bodies	4
	1% annual +	5		Dam	5
Slope	Slope above 2% is nor suitable for construction		Geology	Geology relates to vibration and operation	
	classification	Score		classification	Score
	0~1.0%	1		Limestone	1
	1.1~2.0%	2		Stone	2
	2.1%~	5		Gravel	3
				Clay	4
				sand	5

the score is set to 1–5 scale implying that 5 being the least suitable. Population density was calculated with the total number of population and area of block groups. The areas were calculated with *'calculate geometry'* feature, and one new field, density was added in the attribute table. Roads, hydrology, geology, and floodplain were categorized into their types. Slope was calculated in percentages using *'spatial analyst'* extension. Table 1 indicates the selected factors and their classifications.

3.2.3 Factor Relationship

Of those previously mentioned research steps, establishing a relationship between the factors is the critical part of the entire research. The way researcher deals with this step can make a significant difference in the final result. Similar to factor selection, there are several different ways to articulate the relationship. Some of them are based on statistical method, such as confirmatory factor analysis and principal component analysis, and some of them are based on relatively straightforward judgment with a few mathematical procedures. The most popular example would be the Analytic Hierarchical Process (AHP).

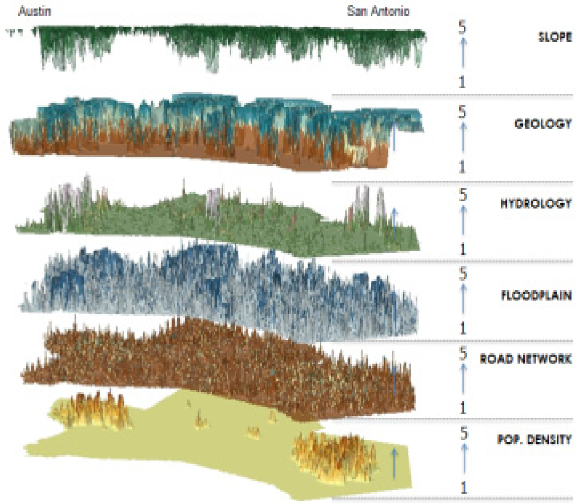

Figure 2. Factor Visual Examination

AHP is a widely utilized method in decision-making process, and ArcGIS even supports an extension for AHP to be run in its operational environment. Once the decision for the initial input is made based on participants' consensus, the standardized factor weights can be calculated with a simple excel sheet. The initial input is the relative importance between the factors. For example, if we value population density twice more than hydrology because the impact and required cost of moving people is expected to be much higher than building a bridge, then the initial input (ratio) between population density and hydrology becomes 2:1. Similar procedures were adapted to other factors. Once this basic numbers are set, then we could follow the general procedures in the AHP.

Table 2 is the final result of factor weight using AHP. The Consistency Ratio indicates that the calculated weight has 2% error in its scale consistency and is less than 5% significance level. In other words, the result could be assumed to be a reliable construct. Eigen vectors are the coefficients (factor weights). As can be seen, Population Density, Slope, and Roads came out to be the highest weighted factors affecting the final suitability. This is because those factors are set to have more importance than the others, and also because more weights are given to the construction costs than any other possible considerations.

Table 2. AHP Resluts and Factor Weights

	Density	Slope	Roads	Hydrology	Floodplain	Geology	SUM
Density	1.00	1.50	2.00	5.00	5.00	3.00	17.50
Slope	0.67	1.00	3.00	5.00	4.00	3.50	17.17
Roads	0.50	0.33	1.00	5.00	4.50	3.50	14.83
Hydrology	0.20	0.20	0.20	1.00	2.00	0.29	3.89
Floodplain	0.20	0.25	0.22	0.50	1.00	0.25	2.42
Geology	0.33	0.29	0.29	3.50	4.00	1.00	9.41
SUM	2.9	3.57	6.71	20.00	20.50	11.54	65.22

	Density	Slope	Roads	Hydrology	Floodplain	Geology	Eigen Vector	%
Density	0.34	0.42	0.30	0.25	0.24	0.26	0.31	31.00%
Slope	0.23	0.28	0.45	0.25	0.20	0.30	0.28	28.00%
Roads	0.17	0.09	0.15	0.25	0.22	0.30	0.20	20.00%
Hydrology	0.07	0.06	0.03	0.05	0.10	0.03	0.05	5.00%
Floodplain	0.07	0.07	0.03	0.03	0.05	0.02	0.04	4.00%
Geology	0.11	0.08	0.04	0.18	0.20	0.09	0.12	12.00%
SUM	1.04	1.02	0.99	1.15	0.96	0.8	1.00	100.00%

(λ_{max} = 4.07 / Consistency Index (CI) = 0.02 / Consistency Ratio (CR) = 0.02– 〉 2%(5%)

3.3 Shortest Path

3.3.1 Suitability Surface

Based on the previous steps, a suitability surface indicating suitability scores for high-speed rail route is created. Figure 3 gives the fundamental idea of how suitability surface is created. Since all the maps (factor maps) are in a raster format, meaning that they are composed of 30m x 30m cells, the final suitability map would also be in a raster format with same cell size.

Figure 4 illustrates the suitability surface based on the previous steps. As the cell becomes more suitable, meaning that a cell has small number in terms of suitability scores; the color of a cell becomes redder. On the other hand, as the cell becomes less suitable, a cell with higher scores, the color becomes bluer. As seen in Figure 4, cells around the major cities are in blue color and this is because higher population densities. Since population density, slope, and roads impose a relatively greater factor weight, this result seems reasonable.

3.3.2 Shortest Paths

After this suitability surface process, the shortest path between the two cities could be extracted. Because the station decision involves a different set of decision indicators, the study assumed to have stations on both cities' airports. Therefore, the departure and arrival points are set to the

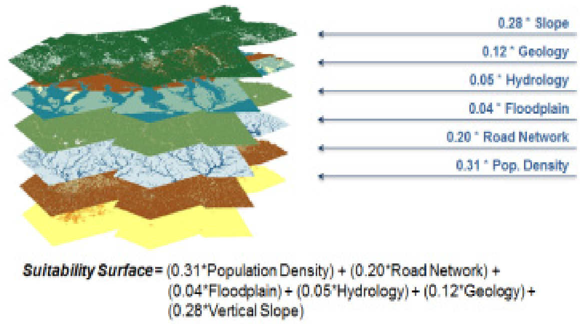

Figure 3. Suitability Surface Equation

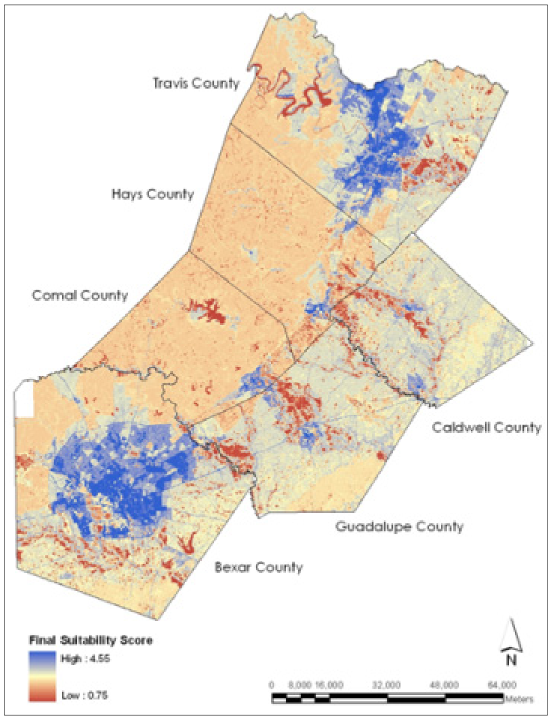

Figure 4. Suitability Surface

Austin-Bergstrom Airport and San Antonio International Airport.

By using 'Cost Distance' and 'Shortest Path' functions in 'Spatial Analyst' extension, the most suitable route is extracted based on cell values. Figure 5 illustrates two possible routes of high-speed rail between two cities. Red route indicates that all factors being equally treated, meaning no factor weights, whereas green route is the final result of this entire process with factor weights and map algebra.

As mentioned earlier, different factor weights will give different routes and thus, the entire process enables a scenario planning with different emphasis on the factors. If there should be a general consensus to a certain types of

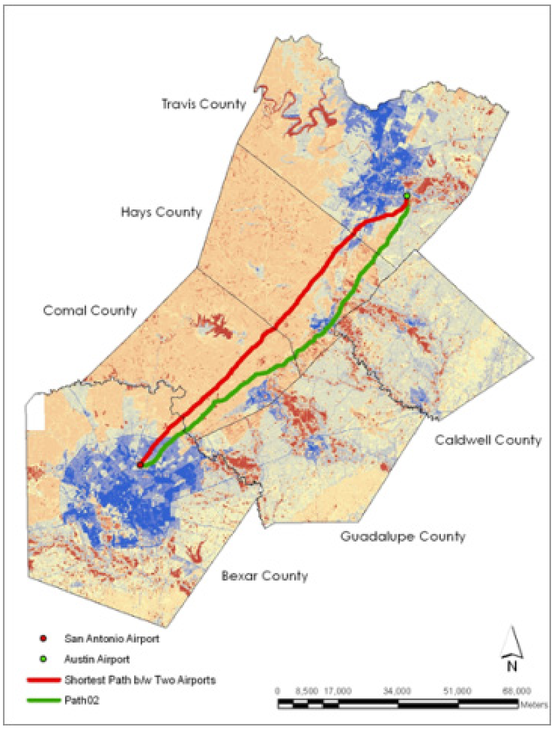

Figure 5. Shortest Path

factors among the participants, the AHP and cost surface steps could incorporate such issues and create the final cost surface map. As mentioned earlier, there are a number of ways to create a sustainable decisions and the gist of such process should be the system of allowing participation from the stakeholders. In this extent, SDSS with geographic datasets and simple statistical approach, such as AHP could create a big difference.

3.3.3 Smoothing

Although this drawn line represents the optimal result based on the inputs, it still is in an unrealistic form. Because the line is drawn by connecting pixels, the form is rather a zigzag than a curve. Therefore, there should be one last process to make the line more realistic. In ArcGIS, there is a function called 'Smooth Line'. This enables a zigzag to become more smooth line. Further, the function can restrain the smoothness by setting up some constraints. For example, a constraint of 2 decimal degrees is used because it is the required horizontal allowance in high-speed rail engineering standards. Figure 6 displays the difference.

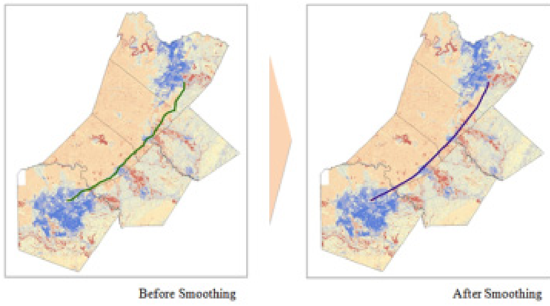

Figure 6. Smoothing Process

4. Conclusions

An SDSS to find the optimal rail route between San Antonio and Austin was performed. By using ArcGIS and geographic data sets, simple map algebra could be used. Further, based on the suitability scores, the shortest path was extracted. This is a quite powerful tool for the planners to justify the rationale, and provide analytical result to the general public. However, there are several possible pitfalls as well.

The first limitation resides in the factor selection. The Delphi Panel is a quite dependable approach to select professionals' opinion. In other words, the result might tend to fluctuate based on some of personal opinions. Second and most importantly, the way the researchers deal with the factor weight would significantly affect the final outcome. AHP provides a mathematical process, but the initial input still relies heavily on the researchers' judgment. Hence, there should be strong theoretical justifications prior to setting up the initial inputs. Finally, there is a chance that data availability might drive the entire research process. IF there is not enough datasets available, the setting up a Delphi discussion to extract the initial inputs becomes meaningless.

Nevertheless, a suitability analysis using GIS still seems a reasonable way to reflect various aspects of the built environment. More progress in data availability would allow the professionals to conduct more sophisticated research. Further, being able to reflect various inputs from the participants makes this process one of a kind. If this research was done in a detailed manner, meaning that the use of confirmatory factor analysis; implementation of more factors; and active utilization of experts' opinion, the final result could become more solid and persuasive. Suitability analysis is one of many possibilities that GIS would bring to the field of urban planning and should be studied further for that reason.

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