Route/Site Selection of Urban Transportation Facilities: An Integrated GIS/MCDM Approach

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Abstract: Route/site selection is the process of finding locations that meet desired conditions set by the selection criteria. In such a process, manipulation of spatial data and satisfaction of multiple criteria are essential to the success of decision-making. Because of the complexity of the problems a number of tools must be deployed to arrive at the proper solution. Expert systems, geographic information systems and multi-criteria decision making techniques have been systematically used for decades to support such projects. This paper discusses the most recent developments of this field. A hierarchical decision tree model is prepared to join the diverse engineering, economical, institutional and social perspectives as well as the environmental objectives. A comprehensive example of the route/site selection process of a metro-rail network project is also presented.

Keywords: Route/site selection, GIS, expert systems, multi-criteria decision making

1 Introduction

Building a new urban transportation facility is a major, long-term investment for owners and investors. Route/site selection of such a capital project (e.g. a corridor rapid transit project like a metro-rail system) is considered a crucial action made by owners/investors that significantly affects their profit and loss. Decisions related to the locations of the facilities (e.g. metro-rail routes, stations, depots, etc.) influence economies of the metropolitan area and strongly impact on the lifestyle of the whole residential community.

Any public transportation infrastructure development project should begin with the recognition of an existing or projected need to meet the present and the growing demand in the future. This problem triggers the series of actions starting with searching out and screening of geographic areas and specific locations. Routes/sites that satisfy the screening criteria are subjected to detailed evaluation.

In general, the screening criteria include multiple measures, such as engineering, economic, institutional, social, and environmental factors.

The goal in a route/site selection project is to find the best location with desired conditions that satisfy predetermined selection criteria. As shown in Figure 1, route/site selection typically involves two main phases: (*i*) site screening (i.e., identification of a small number of candidate sites from a broad geographic area and a range of selection factors) and (*ii*) site evaluation (i.e., in-depth examination of each candidate site to find the most suitable one) [1]. The selection process attempts to optimize a number of objectives in determining the suitability of a particular route/site for a defined transit facility. Such optimization often involves a multitude of factors, sometime contradicting. Some of the important factors that add to the difficulty of the proper choice include the existence of numerous possible options within a sought territory, multiple objectives, intangible objectives, diversity of interest groups, lack of quantitative measures of the factors' impact, uncertainties regarding impact timing and magnitude, uncertainties regarding government influence on the selection process through legislations, uncertainties regarding possible delays of permitting and construction [6].

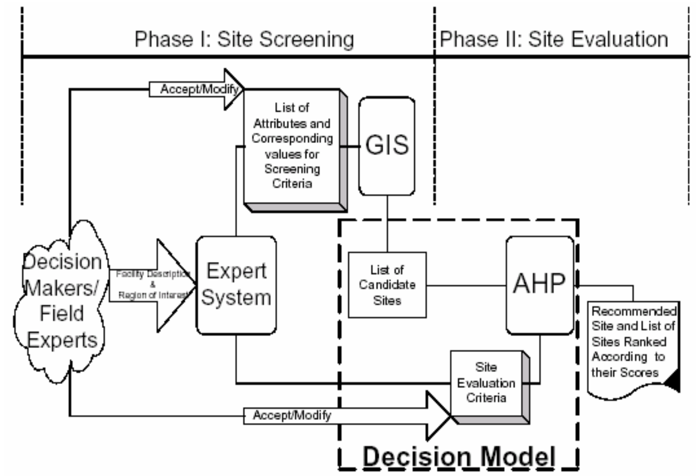

Figure 1
Framework for screening and evaluation [1, p.76]

Geographic Information Systems (GIS), Multi-Criteria Decision Making methods (MCDM), and Expert Systems (ES) have extensively been used in solving site selection problems for the last two decades. However, each of these techniques has its own limitations in addressing spatial data, which is indispensable when one is dealing with spatial decision problems such as a route or a site selection problem. For example, the traditional MCDM techniques have been non-spatial. However, in a real life situation it can hardly be assumed that the entire study area is spatially homogenous, because the evaluation criteria used to vary across space. A modified approach has kept spreading in practice, in which the three tools are combined as is seen in Figure 1 in a manner so that the shortcoming of one tool is complemented by the strength of another. An ES is used to assist the decision makers in determine values for the screening criteria of the site screening phase, building the decision model and assigning weights to the attributes used as evaluation criteria for the site evaluation phase. A GIS system is utilized to perform the spatial analysis required in the screening phase of candidate sites. A MCDM procedure is used for the evaluations, usually the Analytic Hierarchy Process (AHP) method [10], to identify the most suitable site in the second phase.

In the next section an overview of the most recent developments of the field is presented building upon the excellent works of Keshkamat [7], Keshkamat et al. [8], and Sharifi et al. [11, 12, 13] on the subject.

2 The integrated use of GIS and Spatial Multi-Criteria Evaluation

Recent advances in geo-information technology through various remote sensing techniques has offered appropriate technology for data collection from the earth's surface, information extraction, data management, and visualization, however, it lacks well-developed, analytic capabilities to support decision-making processes. Spatial Multiple Criteria Evaluation (SMCE) is based on multiple attribute decision analysis techniques and combines multi-criteria evaluation methods and spatio-temporal analysis performed in a GIS environment [9, 12]. The performance assessment of an option in one or more criteria at a point in time can be described by a defined set of maps. Therefore, the spatial decision problem can be visualized as a two or three dimensional table of maps, or map of tables as displayed in Figure 2, which has to be transformed into one final ranking of alternatives [11]. SMCE partially implements Herwijnen's model of spatial multi-criteria analysis [2]. In the SMCE, the decision alternatives, a_i, are the three series of maps, and the criteria, c_j, are the pixels (basic units for which information is explicitly recorded) or polygons in the maps. The model in Figure 3 shows that not only an aggregation of effects (function f), but also a spatial aggregation (function g) is necessary to arrive at a ranking of alternatives. Such spatial aggregation is first applied to attribute maps, after which the aggregate effects are evaluated and ranked. Different paths lead to different results in the ranking of the alternatives. The distinguishing feature of Path 1 and Path 2 is the order in which aggregation takes place. Most computer applications of SMCE follow the aggregation of effects of Path 2 (the first step is aggregation across criteria, the second step is aggregation across spatial units) [12, p. 2]. Thus, Spatial Multi-Criteria Decision Analysis (SMCA) is a process that combines and transforms geographical data (the input) into a decision (the output). This process consists of procedures that involve the utilization of geographical data, the decision maker's preferences and the manipulation of data and preferences according to specified decision rules. For ranking of the alternatives, the evaluation table of maps has to be transformed into one final ranking of alternatives. The ranking of the alternatives could be different, since the decision makers, i.e. the groups of stakeholders, may have conflicting interests as they represent dissimilar perspectives.

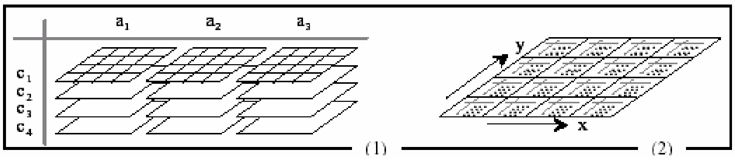

Figure 2
Two interpretations of a decision problem: (1) table of maps, (2) map of tables [13, p. 2]

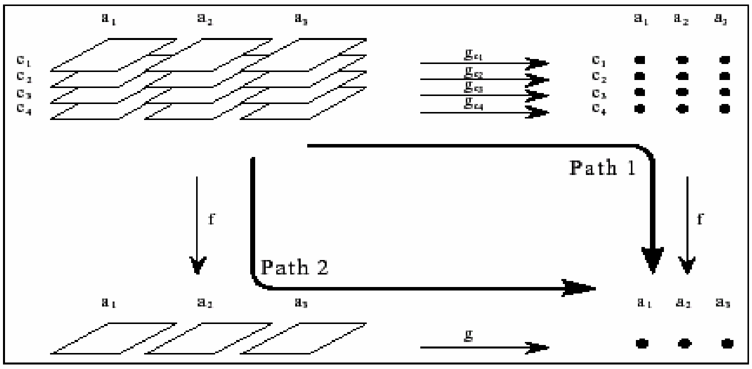

Figure 3
Two possible pathways of spatial multi-criteria evaluation [13, p. 2]

According to Keeney [5], two major approaches can be distinguished in MCDM: (*i*) the alternative-focused and (*ii*) the value-focused approach. The alternative-focused approach starts with development of alternative options, specification of values and criteria, then, it follows the evaluation and recommendation of an option. The value-focused approach considers the values as the fundamental component in decision analysis. Therefore, first, it concentrates on the specification of values (value structure), then, it develops the values feasible options and evaluates them with respect to the predefined value and criteria structure. This implies that the decision alternatives should be generated in a way that values specified for a decision situation are best met. Hence, the order of thinking is focused on what is desired, rather than the evaluation.

In the context of route/site selection of urban transportation facilities the value-focused approach has many advantages over the other [13]. To implement this, for an urban transportation project like a metro-rail system is, a top-down decision analysis process is proposed to define the goal, the objectives and their related indicators for the facilities. This hierarchical decision tree model is presented in Figure 4. In the decision making phase, a consulting team, technical committee members, designers, investors, local authority officials and public representatives are involved as the basis for development and evaluation of the project. The various elements of this criteria structure are briefly described as follows:

Goal and Objectives: The goal of this framework is to identify an effective public mass transportation system for a metropolitan area integrated with an efficient land use so that it meets the present and long-term socio-economic and environmental requirements of the residents of the marked territory. This goal can be achieved if the following objectives are met:

Economic Objective: Economic objective seeks to maximize feasible economic return on investment from the system. A number of criterion is used to measure how well an option performs on each indicator, e.g., benefit/cost ratio, first year return, internal rate of return, net present value, construction cost and operation cost, as well as minimizing land/real estate acquisition (expropriation of property), intensification of existing land use and maximizing the potential of the location.

Engineering Objective: This objective looks at three main concerns that are the efficiency of the system, the construction issues and the effective use of the network for work and non-work travels. The criteria used to measure the extent to which such achievements are met by the transit route or facility options are the following:

• Efficiency is measured by examining the minimum number of transfer, (whereby an alternative with excessive transfer will score low for this criteria) A transit option which contributes to a reduction in travel time compared to time spent on the roads and provides a close-to-optimal convenience for pedestrian access and links to other local and commuter transportation modes, and, also an effective connection of housing jobs, retail centers, recreation areas is beneficial and will score high.

• From the construction perspective, alternatives that have rail routes passing through high demand areas like high-density built-up areas, commercial, industrial and institutional areas, will score high for this criterion. This aspect, however, particularly when it is accompanied by poor geological conditions at a route/site option, conflicts with a low construction cost requirement. To build metro-line stations, the commonly used construction modes are: open-cast construction (just below grade, building pit is beveled or secured by walls, requires large construction areas, more flexibility in design); bored-piled and cover-slab construction with or without inner shell (bored-piled wall, generates column free space, reduces surface interruption);

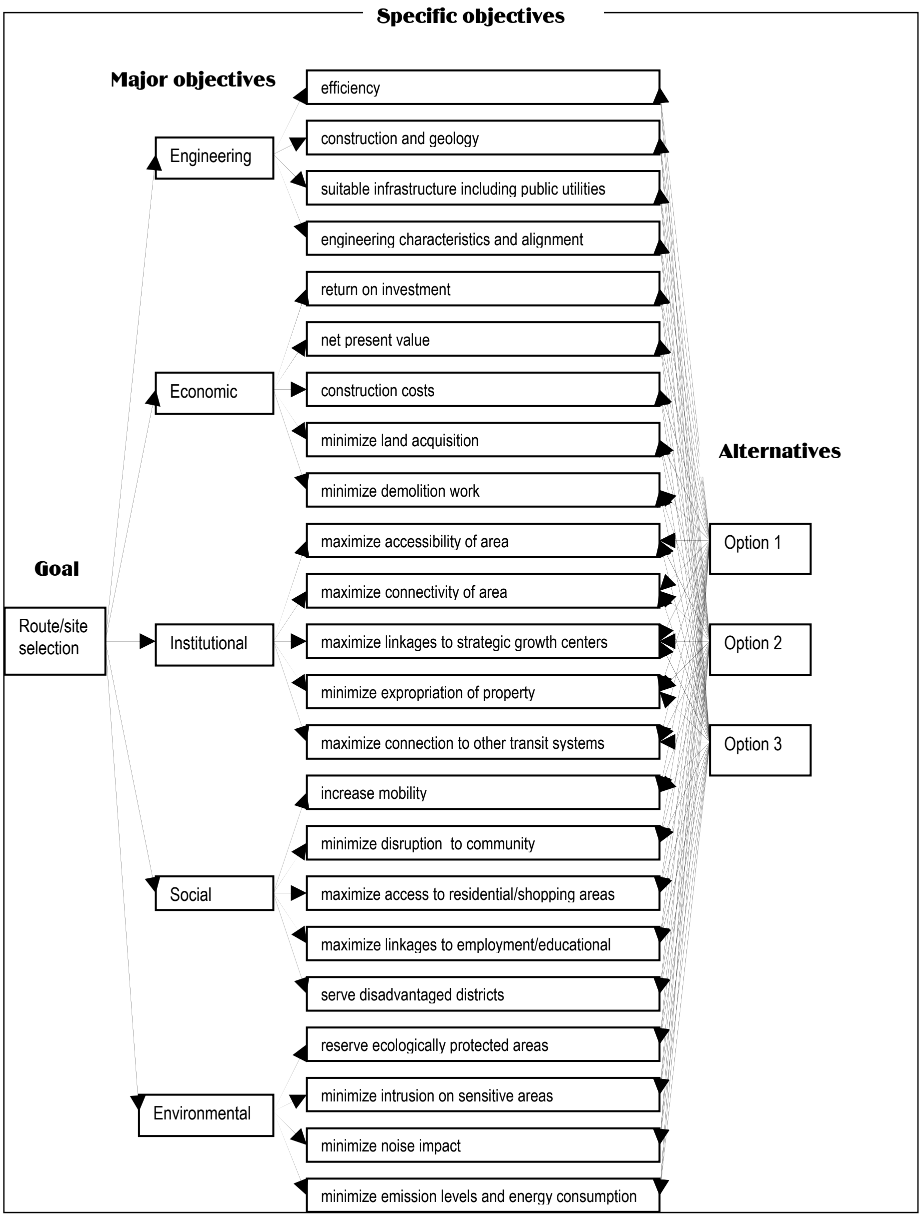

Figure 4
Hierarchy of goals, objectives, criteria and indicators

diaphragm wall and cover-slab construction (excavation after diaphragm and cover-slab are constructed, multi-story basement structure, structure growths from top to downwards); mine tunneling construction (extremely deep situation, use of shot crete but cracks and leakages are not avoidable).

• Engineering characteristics and alignment are evaluated with respect to the measures/attributes constituting the geological environment (including soil mechanics, intrusive rock structure, stratification, etc.); hydro-geological conditions (including underground water-level, chances of inrush, perviousness, locations of permeable or impermeable layers, chemical and physical characteristics of underground water and their effects on the built-in architectural structures) and geotechnics (rock boundaries, response surfaces, geographic configuration). Special focus should be given to safety. Therefore, the recognition and control of risk factors are of utmost importance (water intrusion, gas explosion, earth quake).

• Infrastructure involves the careful examination/analysis of overground building up, the suitability of the existing public utility network capability and the required overground organization to be made before the construction works are started.

Institutional Objective: This objective measures the match between the transit system and spatial policies of the government/urban municipality, e.g. to maximize interconnectivity to existing public transport systems; to maximize linkages to strategic growth centers (as designated/proposed in local plans), to provide good linkages among urban centers and suburban railway networks, airports, long-distance bus stations, park and ride lots as well as to minimize land acquisition.

Social Objective: Establishment of a transit system should increase social mobility by way of easy access to existing and future settlements. This can be measured by forecasting the passenger/km reduction for residential to employment areas, and residential to educational institutions. Based on plans and ideas of future settlements, employment and educational institutions, efficiency of the land use objective should be achieved by maximizing access between residential areas and shopping, service and recreational centers. Such systems would serve highly populated areas and particularly disadvantaged areas (low cost settlements); would increase access to tourism attraction areas; minimize disruption to neighborhood communities; and maximize linkages to major employment areas/centers.

Environmental Objective: The designed transit project should minimize intrusion and damage to the environment. Protected areas must be excluded from the set of the potential options. The expected accomplishments are: a reduction in energy consumption, minimal emission levels, minimal intrusion into environmentally sensitive and reserved areas, minimal noise impact to sensitive land use (such as hospitals, residential buildings and schools) during site construction.

Criteria and Indicators: To further support the design and evaluation of a metro-rail network, the major objectives are further broken down into specific objectives with their corresponding indicators (sub-criteria). These indicators are then used to measure the performance of each alternative route/site option on each objective.

A proper governmental/metropolitan council's transportation policy should comply with the criteria structure shown by Figure 4. In contrast to the conventional approaches of predetermining route/site alternatives and then assessing their impacts subsequently, this integrated GIS/MCDM approach utilizes an opposite strategy. Determine first the proper, but at least promising locations of such facilities (the sites of the metro stations), along which the appropriate route options can be defined.

3 Route/Site Selection of a Planned Metro-Rail Network through GIS and Spatial Multi-Criteria Evaluation

This section presents an application of how a combined GIS-SMCE (as a Path 2 analysis) system can assist the design of alternative solutions for urban transit zone locations in a given metropolitan area. As is usual in many countries, spatially referenced data (with geometric positions and attribute data) are rarely available in a direct way. Therefore, the author has chosen a built-in database from the ILWIS (Integrated Land and Water Information System) library [4], which has been developed by the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands. ILWIS is a Windows-based remote sensing and GIS software which integrates image, vector and thematic data in one powerful package on the desktop. In this study, Release 3.4 is applied (as an open source software as of July 1, 2007) which contains a strong SMCA module [3].

3.1 Study Area

The study area is Cochabamba city, a fast growing center located in the Andean region of Bolivia with a fast growing population of approximately 550000. The city is located at an elevation of about 2600 meters above sea level in a large valley on the alluvial fans at the foot of steep mountains. The city's northeastern side area is occasionally subjected to landslides, soil erosion and heavy flashfloods. Hence from a perspective of urban development, the improvement of its transport infrastructure is of utmost importance, however, topographical and geological attributes do form quite serious considerations in building a metro-rail system.

3.2 Geographic Data

Spatial data includes field collected data and GIS datasets (which consist of data derived by remote sensing from satellite imagery and/or field measurements) Attribute data are partly based on actual measurements, but, for the most part, are elicited from judgments, and, thus, they are fictive. To display geographic data (spatial and attribute data) on screen or in a printout, digitized vector maps (point, segment and polygon maps) and raster maps are used in a conveniently chosen visual representation form. Each map should contain the same coordinate system and georeference. In a raster map, spatial data are organized in pixels (grid cells). Pixels in a raster map all have the same dimensions. A particular pixel is uniquely determined by its geographic coordinates expressed in Latitudes (parallels) and Longitudes (meridians). With the help of a map projection, geographic coordinates are then converted into a metric coordinate system, measuring the X and Y directions in meters (UTM). This way a very high degree of accuracy is reached.

3.3 Description of Data Sets

The geographic area of the planned metro-rail project (network system) is given by the polygon map "Cityblock" and is shown in Figure 5. (The skewness of the chart is due to the north-pole orientation of the map.) This map has a total of 1408 blocks (polygons). To each of these polygons an identifier code is assigned. Block attributes are the geometric area in square meters; the prevailing land use type, i.e. residential (city blocks used primarily for housing), commercial (city blocks containing malls, supermarkets, shops, banks, hotels, etc.), institutional (such as schools, universities, hospitals, museums, governmental offices), industrial (buildings dedicated to industrial activities, storages), recreational (including protected areas, parks, sport fields), existing transport facilities (railway stations, bus stations, taxi services, public parking lots), airport, water (including lakes and rivers) and vacant (blocks that are not used for any urban activity); the codes of city districts; and population (number of persons living or using a city block).

3.4 Identifying Assessment Objectives/Criteria

As a simplified illustration of the site selection problem, that is to find the potential locations for metro-rail stations, consider the central part of the city only. This dependent polygon map "Center" has 137 blocks and its location is shown by the shaded area that is added to the layer "Cityblock" as it is depicted in Figure 6. Its block attributes include the following specific objectives (with their computed or estimated numerical data) for each polygon:

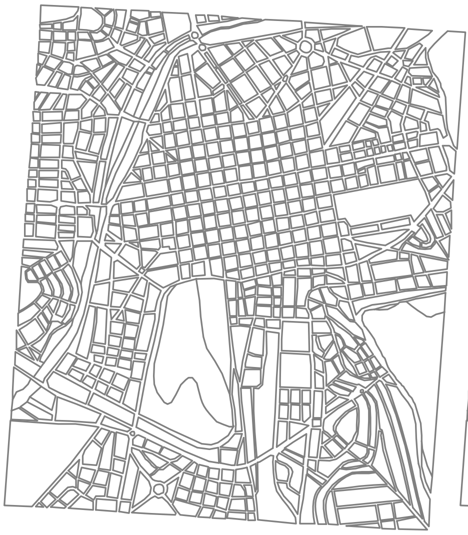

Figure 5
Polygon map "Cityblock"

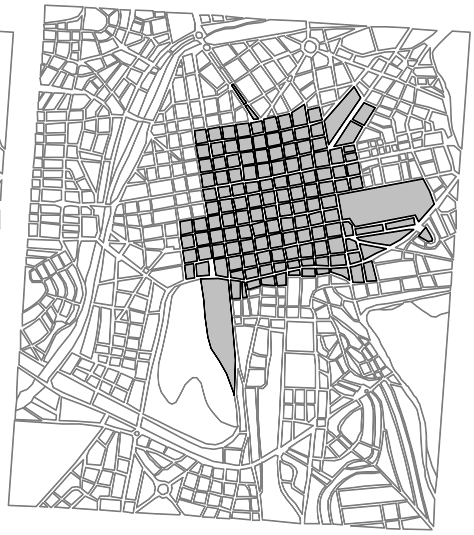

Figure 6
The embedded polygon map "Center"

C_1 = engineering characteristics and geological soil structure (rocks) [% scale],

C_2 = ecological suitability [% scale],

C_3 = connectivity index [m] (converted to an inverse interval scale),

C_4 = population density [number of people/area-hectare], and

C_5 = projected construction costs [mi$].

In the course of the aggregation to calculate the values of the composite attributes, among these criteria, C_2 represents a spatial constraint that determines areas which are not at all suitable (these areas will get a value of 0 for that pixel in the final output); C_1, C_3 and C_4 are criteria representing spatial benefits that contribute positively to the output (the higher the values are, the better they are with respect to those criteria) and C_5 represents a spatial cost factor that contributes negatively to the output (the lower the value is, the better it is with respect to that criterion).

3.5 Processing of Raster Datasets

The raster layers were derived by applying an appropriate GIS raster processing method to the vector maps. The vector maps contain the data sets required for the SMCE. ILWIS requires all raster overlays to have the same pixel size. In this study, a pixel size of 20.00 meter was chosen to rasterize all vector layers.

3.6 Weighting of Criteria

Weights of the major objectives of the hierarchical decision model of Figure 4 were determined by a group of experts formed of five transportation engineers, three mechanical engineers and two economists using the pairwise comparison matrix of the AHP. In real life problems, obviously, more groups of stakeholders must be requested. Our results, therefore, will not represent the positions involved organizations and civil members take and are only indicative. Still, we attempted to illustrate the deviations rising to the surface in the views of the different stakeholders' groups through evaluation. The inconsistency measures, μ_i, of the pairwise comparison matrices generated by the committee' members were varying between 0.023 and 0.042.

3.7 Spatial Multi-Criteria Assessment

For the major objectives, their embraced factors and constraints together with their attached weights a criteria tree was built in ILWIS for three different project policies (equal vision, engineering vision, economic vision). In such an application of SMCA, each criterion is represented by a map. Due to the different units of measurement, standardization of all criteria should be carried out using an appropriate method ("Attribute", "Goal", or "Maximum") depending on the given factor and data characteristics. As a result, all the input maps are normalized to utility values between 0 (not suitable) and 1 (highly suitable). The completed criteria tree constructed in ILWIS is exhibited in Figure 7 for the engineering vision. In this study we selected only one specific objective from each set of the five sets of the major objectives as it is readily apparent from Figure 4.

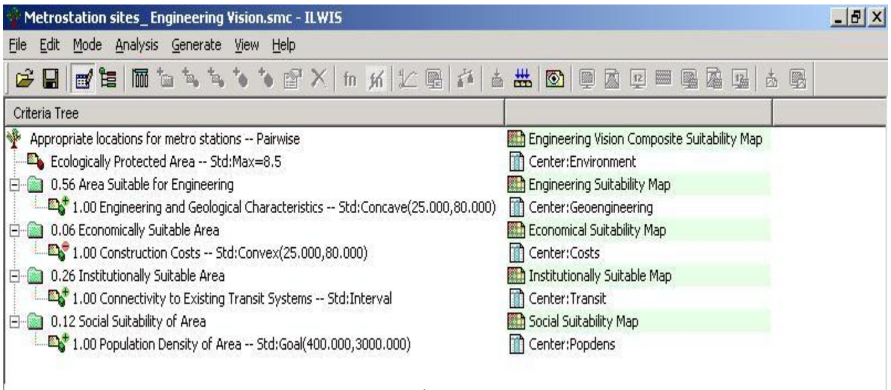

Figure 7
ILWIS screenshot of the criteria tree for identifying suitable locations

This process resulted in output maps for the policy visions, showing the suitable locations of metro-rail stations in the inner part of the city. As an example, the suitability maps of the single objectives (criteria) and the composite suitability map for this metro-rail station problem are shown in Figure 8 for the engineering vision. In these raster maps, areas of low suitability (valued 0 or close to 0) are symbolized by the color red, while areas of highest suitability (valued 1 or close to 1) by the color green. For color interpretation the reader is referred to the web version of this paper. The pixel information catalog contains the utility values in numerical terms for every pixel. We remark that the pixel information is invariant within a particular polygon (city block), since the functionality of these blocks can be regarded to be homogenous.

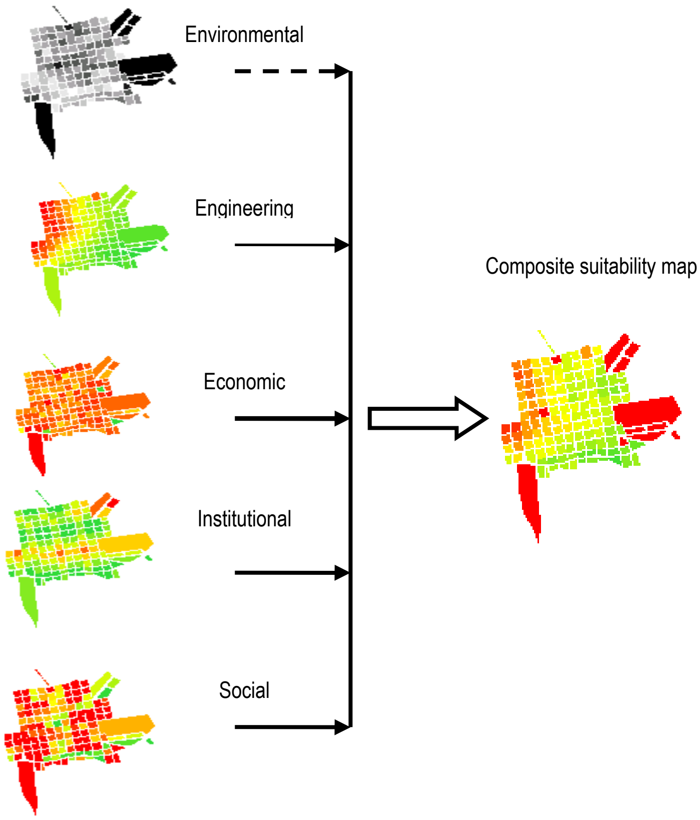

Figure 8
Aggregation of suitability maps of the objectives to an overall composite map

3.8 Designing Alternative Metro-Rail Paths

In this step of the planning process the assessment of proper metro-rail routes are performed. We first extended the processing of our raster datasets to all other city blocks (beyond the blocks contained by the "Center" raster map) and generate the output suitability maps for the polygon map "Cityblock". A careful analysis of the resulted maps for suitable locations of metro-rail stations enabled us to design proper pathways leading between the two major transit zones of the city, in geographical terms, from the origin node (South Railway Station) to the destination node (North Railway Station). These corridors, which span more than one block in the polygon map of the city, are indicated by the shaded areas in Figure 9 for the engineering vision. It was required also to keep ourselves to the technical requirements, i.e. to the track building and vehicle engineering standards and specifications (e.g., feasible length and radius of transition curves, possible slope of the tracks, etc.), when such a corridor was mapped out. As is displayed by gray color in Figure 10, three metro-rail routes for potential metro line alternatives have been established (Blue Line, Red Line and Green Line). By further investigating the values of the multiple factors at different pixels within these three corridors the final locations for the metro stations were fixed. Thus, a rough feasibility plan of this metro network project was completed as it is shown in Figure 10.

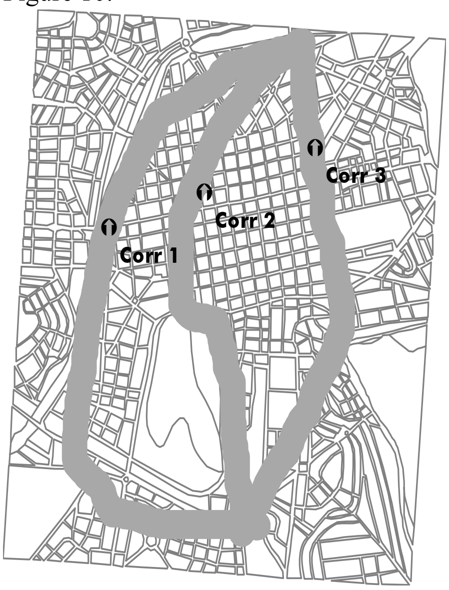

Figure 9
Corridors for the metro-rail routes

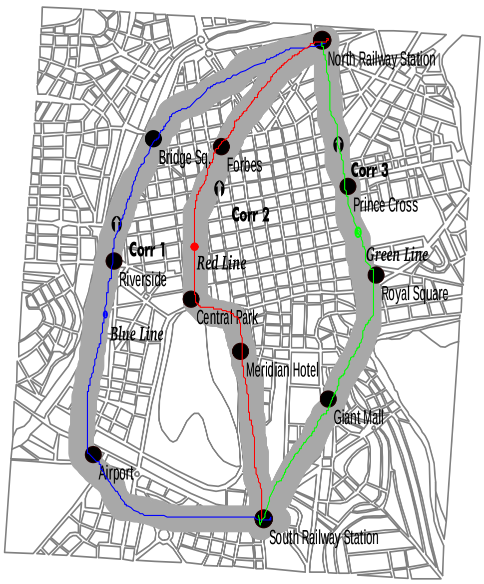

Figure 10
Feasibility plan of the metro-rail network

3.9 Network Analysis via Evaluating Alternative Metro-Rail Routes

Effectiveness and efficiency of both construction and operation of a particular route are mostly determined by the embedded stations along that route. Therefore, it is reasonable to measure the extent to which an average suitability of the stations along a given route contributes to these characteristics. Introducing the mean spatial utility measure of a given metro-rail route as

$$\mathrm{MSU}_i = \frac{\sum_{j=1}^{N} u_j}{N}, \qquad i = 1,2,\ldots,M, \tag{1}$$

where u_j is the utility (suitability index) of the pixel (raster cell) underlying the jth site (metro station) along the ith route, N is the number of the selected sites along the ith route, M is the number of the alternative route options. To form the conventionally used measure in transportation problems called impedance, we should compute the complementary of the value of MSU_i and multiplying it by the total length of the routes [7]. Hence, the impedance of the ith route within the metro network system yields

$$\Omega_i = (1 - \mathrm{MSU}_i) \cdot L_i, \qquad i = 1,2,\ldots,M, \tag{2}$$

where L_i is the length of the ith route option (the length of the ith polyline). The higher the value of the impedance Ω_i is, the greater the costs associated with that route and/or the lower the benefits attained by it. Thus, the best route option is obtained by

$$\Omega^* = \min_i \{\Omega_i\}, \qquad i = 1,2,\ldots,M, \tag{3}$$

The multiple criteria evaluation of the established metro-rail network was carried out based on the performance of each route with respect to the total impedance accumulated by that route. The result of this process for the three competitive metro-rail routes is presented in Table 1 for the engineering vision. This table contains, the route options defined by the respective sequences of nodes (the raster cell code identifiers together with the names of the metro-rail stations and their corresponding utility values/suitability indexes or composite index scores, the length of these lines (obtained by the distance calculation module of ILWIS) and the total impedance of the routes.

Table 1
Effect table of the three metro-rail routes

Route 1 (Blue Line)	**Route 2 (Red Line)**	**Route 3 (Green Line)**
(463) South Railway Station 0.75	(463) South Railway Station 0.75	(463) South Railway Station 0.75
(400) Airport 0.78	(341) Meridian Hotel 0.70	(508) Giant Mall 0.65
(355) Riverside 0.74	(349) Central Park 0.61	(295) Royal Square 0.87
(147) Bridge Square 0.55	(118) Forbes 0.31	(265) Prince Cross 0.80
(181) North Railway Station 0.83	(181) North Railway Station 0.83	(181) North Railway Station 0.83
L_1 = 5801 m	L_2 = 4443 m	L_3 = 4146 m
MSU_1 = 0.73	MSU_2 = 0.64	MSU_3 = 0.78
Ω_1 = 1566.27	Ω_2 = 1599.48	Ω_3 = 912.12
		$\mathbf{\Omega^*}$

The results in Table 1 demonstrate that there is no route option that would entirely dominate over the other options. Observe, for example, that if a route is shorter than another, then, this fact not necessarily means that it represents a better route option. The best option, Route 3 (Green Line), however, outperforms the other two ones both in terms of the total impedance and the length of the line. Therefore, considering the enormous construction costs of the whole metro-rail project, the implementation of the Green Line might be proposed. Perhaps the best conceivable proposal could be to lengthen the track of the Green Line to the airport.

Conclusions

In this paper it was shown how GIS with the value-focused approach of MCDM can support decision makers in the design, evaluation and implementation of spatial decision making processes. The analytical capabilities and the computational functionality of GIS promote to produce policy relevant information to decision makers. Although different stakeholders usually have different priorities to highest level objectives, however, using this approach provides a considerable help in reaching a satisfactory compromise ranking of the objectives for the conflicting interests. To find the appropriate route/site locations of facilities in urban transportation problems is one of the most promising areas of application for such integrated GIS and MCDM approaches as it was demonstrated through this metro-rail system network study.

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