Transit Station Area Land Use/ Site Assessment with Multiple Criteria: An Integrated GIS-Expert System Prototype

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Abstract

This article is intended to assist decision-makers confronted with the problem of determining the suitability of a site with a proposed light rail transit (LRT) stop as a transit supportive (re)development by exploring a prototype, integrated Geographic Information System (GIS) and decision-support system. An inclusive concept of a hierarchy is presented in which the multiple, diverse dimensions of the land-use/site assessment problem—from goal, criteria, to alternatives—can be embedded in deciding suitability of a site as a transit-supportive development.

Framed as a multicriteria procedure, and integrated with a GIS, the decision-support system provides the flexibility to account not only for the configurational or physical features of the built environment and the patterns of growth (or decline) of the population and employment in the region, but also the socioeconomic, demographic, and trip-making characteristics of the targeted population. The joint effects of the population (demand) characteristics and the features of the built environment of land use/trans-

portation (supply) are reflected in the scores of the site assessment. Furthermore, the prototype facilitates decision making by deriving the relative importance of the multiple "supply" and "demand" factors strategically and adaptively vis-a-vis the site-specific constraints and opportunities. Finally, criteria-weighted land-use suitability scores are computed and displayed to indicate the suitability of the site as a transit-supportive development. The multicriteria part of this prototype is implemented with a C++ program as an interactive, expert decision-support system integrated with a GIS.

Introduction

Spatial systems analysis and the planning of land use and transportation have been increasingly aided by GIS. GIS-based approaches surmount the limitation of the locational or allocational models (e.g., Urban Transportation Modeling System or standard urban simulation models) by providing physical or configurational features of the built environment as spatial data used in the analysis of land use and transportation. The configuration and "grain" of land use, the physical form or layout of the road network (e.g., grid versus curvilinear), street width, block length, continuity and compatibility of the circulation or movement systems—both vehicular and pedestrian—open space organization, building setbacks, layout of streets, parking areas, and sidewalks are among the factors considered in the suitability of a transit-oriented development (TOD) site (see also Calthorpe 1993; Ewing et al. 1997; Bernick and Cervero 1997). Consideration of land use and movement (vehicular and pedestrian) as systems with both functional and spatial (physical) properties are facilitated by GIS (see also Wegener 1998; Spiekermann and Wegener 1998).

The recent use of simulation models in combination with GIS is a new direction in analyzing the joint effects of land use and transportation, both highway and transit (e.g., see Landis and Zhang 1998). The facility to address the joint effects of land-use and transportation improvements at a development site is a strength of a combined GIS-simulation approach. The reliance on previous, historical patterns encounters a limitation of prediction with simulation methods (regression) in the absence of precedence or with structural transformation.

A plausible alternative to deductive, statistical simulation techniques are inductive, multicriteria methods. The Analytic Hierarchy Process (AHP) is one

multicriteria method (Saaty 1987, 1996) that is increasingly used in conjunction with a GIS. Combined multicriteria-GIS methods with AHP are used diversely, ranging from evaluation of group decision making and route selection to the site-suitability evaluation of investment decisions and, most recently, in TOD site suitability (Jankowski and Richard 1994; Malczewski 1996; Lin et al. 1997; Banai 1993, 1998). The increasing popularity of AHP is attributed to its methodological flexibility in situations involving factor diversity, mixed-tangible and intangible criteria, uncertainty, and limited information (Banai 1989). Above all, it allows for a process of interpreting both tangible and intangible data directly and inductively—rather than inferring indirectly and deductively—while providing a robust scientific framework to gauge the consistency and efficacy of the interpretation (see Saaty 1986, 1996).

In this article AHP is integrated seamlessly with a commonly used GIS software (ArcView, ESRI, Inc., Redlands, California), and developed as a prototype GIS-Expert System to aid transit station area land use/site assessment. The multicriteria part of this prototype is implemented with a C++ program as an interactive, expert decision-support system, which is integrated with a GIS. The hierarchical structure of AHP is used as an approach to a transit station area site assessment. The aim of this approach is to account not only for the configurational or physical features of the built environment (“supply”), which are conducive to transit use, but also the socioeconomic and trip-making characteristics of the targeted population (“demand”) of transit users. The joint effects of the population and the built environment of land use/transportation are reflected in the site assessment scores of the transit station area. This concept is in contrast to or supplements previous ones in which characteristically only the supply side of TODs is considered with multiple criteria or guidelines (e.g., Calthorpe 1993), however, with the demand side treated exogenously (as a given).

An Integrated GIS-Expert System Prototype for Transit Station Area Land Use/Site Assessment

The AHP is a rational method in which the analytic and synthetic operations are performed in a number of distinct steps. First, and most important, the struc-

tural property of AHP (hierarchy) should be used to frame the problem. In general, the hierarchy levels range from the abstract to concrete elements; that is, from goals, strategies, actions, to decisions, choices, alternatives, and outcomes.

In a typical AHP hierarchy, the goal, criteria, subcriteria (if any), and alternatives are represented as various factors in distinct levels in a descending order. The factors at each lower level are compared (pairwise) with respect to the factors at each higher level of the hierarchy. First, the relative importance of the criteria (for goal) is determined, followed next by the importance of subcriteria (for criteria), and finally by the relative importance of the alternatives (for subcriteria), which are represented at the lowest level of the hierarchy. Once the relative weights of the factors at all the levels of the hierarchy are determined, a weighted summation procedure is used in which the scores of the alternatives as aggregate (overall) weights of all the factors are given. A hierarchy for transit-oriented land-use suitability is shown in Figure 1.

At the kernel of AHP is a systematic, analytic procedure for determining the relative importance of factors through their paired comparisons. Homogenous factors are compared in reciprocal matrices by using this AHP scale of absolute numbers (1–9):

- 1 = Equal importance
- 3 = Moderate importance of one over another
- 5 = Essential or strong importance
- 7 = Very strong importance
- 9 = Extreme importance
- 2, 4, 6, and 8 = As intermediate values between two adjacent judgments

An example of such a reciprocal matrix ($a_{ji}=1/a_{ij}$) from the suitability criteria used in the next section is:

$$A = \begin{matrix} & \begin{matrix} A_1 & A_2 & A_3 \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ A_3 \end{matrix} & \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix} \end{matrix}$$

Figure 1. (a) Planned metropolitan region LRT lines (adapted from Memphis Area Transit Plan 1997); (b) station area focus; (c) a hierarchy for TOD land-use suitability

The rows and columns of this matrix are identically labeled by a set of factors A_1, A_2, A_3 ; thus, all the diagonal elements are 1 ($a_{ii} = 1$). Various methods, from the simple to more elaborate, may be used to compute the relative weight or importance of factors. The robust method of estimation in AHP, however, is the eigenvector solution (see Saaty 1996), which derives the relative weights of the factors on a ratio scale (0–1).

In the process of the paired comparison of factors or elements, the consistency of judgments is gauged.¹ An upper limit of 10 percent is considered a good measure of consistency (Saaty 1980). When exceeded, the estimates of the relative weights may be revised to improve consistency. Thus, consistency is gauged, particularly when violated in multicriteria evaluation in the face of limited information, data imperfection, uncertainty, and factor diversity.

The paired comparison method as an approach to relative measurement is particularly desirable when relative merit is all that can be expected, in the absence of standards. However, when certain desirable thresholds, if not fixed standards, exist, alternatives may be rated by means of absolute measurement. A rating intensity scale is developed and then used to rate alternatives, denoted in this study by land-use units. Both relative and absolute measurements are accommodated in the prototype presented here. The AHP is implemented with a C program and integrated with ArcView GIS.

An Application Example of the Integrated GIS-Expert System Prototype

A recently planned LRT station to be located in the medical district of Memphis, Tennessee, is the focus of suitability analysis of station area land uses (Figure 1a). This site is a major employment center in the metropolitan region. The area provides housing, ranging in both mix and density. An assessment of the suitability of this site as a TOD with respect to the station area land uses is of interest here.

The land-use suitability problem is framed hierarchically (Figure 1c). The assessment criteria, distinguished by supply and demand factors, the subcriteria (used for the ratings of the land uses), and the land-use units, comprise the levels of this hierarchy. The land-use units are mapped thematically (public,

commercial, residential, and vacant) and buffered (GIS) by various distance from the LRT station. (For an elaboration of the significance of such a land-use classification, see Calthorpe 1993.) Tax assessor GIS parcel data (1998) provided the principal source of information for land-use classification. The differentiation of distance from the station (from $\frac{1}{4}$, $\frac{1}{2}$, to 1 mile) aims to capture the corresponding effects on the suitability scores of land-use units. In addition, the aggregate scores of land-use units expressed proportionally (0 to 100%) indicate the potential suitability of this site compared to desirable threshold(s) for a TOD.

The assessment criteria on the demand side include four factors: (1) auto ownership (AutOwn), (2) population change (PopChange), (3) trip origin-destination (Origin/Dest), and (4) household income (HHInc). These factors are used as a measure of socioeconomic, demographic, trip-making, site-specific characteristics of the targeted population. Census tract and block (GIS) data (1990) and trip origin-destination data by traffic analysis zones (MINUTP) provide information for the site ratings (see also Figure 1b). The ratings intensity scales of the criteria are shown in Table 1.

For example, consider population change (differentiated by decline, stable, and growth) as a measure of site suitability. The ratings intensity scale is determined by three paired comparisons. The following assumptions are used: A site with both stability and growth in population is considered as moderately more important (3) and as strongly more important (5), respectively, than one with a decline in population. Also, a site with growth in population is given a nearly stronger weight (4) than one with a stable population. The relative weights are shown in the last column of the table. The Origin/Dest criterion assesses this site as a major activity (medical) center—an indicator of (employment) density on the demand side. Density (residential) is considered as well on the supply side. The relative weights of the subcriteria for the remaining, demand-side factors are similarly determined, with the assumptions of the paired comparisons indicated by AHP numerical scale (1 through 9).

The assessment criteria on the demand side are considered equally important in this illustration (Figure 2). However, by means of paired comparisons,

Table 1
Deriving Ratings Intensity Scales for Demand-Side Factors

<i>AutOwn</i>	<i>Low</i>	<i>Average</i>	<i>High</i>	<i>Weight</i>	<i>PopChange</i>	<i>Decline</i>	<i>Stable</i>	<i>Growth</i>	<i>Weight</i>
Low	1	3	5	0.637	Decline	1	1/3	1/5	0.100
Average	1/3	1	3	0.258	Stable	3	1	1/4	0.226
High	1/5	1/3	1	0.105	Growth	5	4	1	0.674

<i>HHInc</i>	<i>Low</i>	<i>Average</i>	<i>High</i>	<i>Weight</i>	<i>Origin/Dest</i>	<i>Major</i>	<i>Minor</i>	<i>Weight</i>
Low	1	3	5	0.637	Major	1	5	0.833
Average	1/3	1	3	0.258	Minor	1/5	1	0.167
High	1/5	1/3	1	0.105				

the relative importance of the criteria can be derived. For example, the assessment criteria on the supply side vary in relative importance. These include road network (RoadNet), land-use mix (MixUse), proximity to LRT station (ProxStat), and housing density (Density) in ascending priority order (Figure 1c). For a discussion of these criteria as well as the significance of their relative weights, see Banai (1998). Once the relative importance of the criteria and the ratings intensity scales are determined, the alternatives expressed by land-use units are assessed. Figure 3 presents examples in which school and housing are assessed with both the supply- and demand-side criteria.

The suitability scores that reflect the effects of supply and demand criteria factors jointly are shown in Figure 4. In aggregate, the three land-use classes indicate a high suitability, with the highest score—public land use—at the critical quarter-mile-zone distance from the station. Commercial and residential uses score proportionately to public land use, suggesting the potential functional significance of this zone as a “balanced” transit-oriented site. The public land-use scores decline with distance from the LRT station. However, their relative weights indicate the significance of public land use even in zones beyond the quarter-mile, in what Calthorpe (1993) calls “secondary areas” of a TOD. The site examined here has initially met the planning criteria for station spacing and location within a major activity center. This site meets the criteria for a TOD as well, as the outcome of this preliminary analysis suggests. If stations in locations along the vari-

Figure 2. Submenus of AHP in ArcView GIS with examples of dialog boxes for deriving weights of the criteria and ratings intensity scales used in evaluating land-use units

ous planned LRT lines (Figure 1a) are similarly scrutinized, they could lend further credence to the planning criteria for route alignment and station spacing, with the indication of whether a station area's land uses are supportive of employment and shopping activities or of places in which to live, or both.

Land-use suitability scores are presented in aggregate (Figure 4). As shown in the dialog box in Figure 3, however, finer classification, as well as evaluation at the parcel level is accommodated by the integrated GIS-Expert System prototype.

A GIS-Expert System Integration

C++ is a general-purpose programming language that provides flexible and efficient facilities for defining new constructs specific to an application

Figure 3. Use of the Alternatives submenu of AHP to assess land-use units

domain (Strostrup 1997). It is widely used for application development. C++ provides powerful support with libraries and documentation for implementing the AHP. Some flavors of C++, such as Microsoft Visual C++ version 6.0, provide support for Windows programming.²

Since C++ is an object-oriented programming language similar to ArcView GIS (i.e., with Avenue scripts, ERS 1998), it provides an effective coupling of AHP with GIS in a single package. Once the user interacts with the AHP, the results can be stored, updated, and retrieved in a GIS. The implementation of AHP is carried out using Microsoft Visual C++ version 6.0 on Windows NT 4.0.

Software Architecture

ArcView GIS provides the driver software that invokes the user interface written in C++ (Figure 5). AHP is created as a basic menu in ArcView (ESRI,

Figure 4. Land-use suitability ratings for an urban TOD by distance from LRT station (composite scores with supply and demand criteria)

version 3.0). The submenus of the AHP include Pairwise Comparison, Ratings, Alternatives, and Join. These menus help the user determine relative weights of the suitability factors, relative importance of subfactors using a ratings intensity scale, and the total suitability score for a land-use unit. A brief overview of the AHP submenus is presented below.

Figure 5. Software architecture

Pairwise Comparison. A new dialog box is created with a drop-down list box. On selecting the OK button, a “child” dialog window is created with edit boxes in which the user can specify the criteria names. Once the OK button is pressed, a series of pairwise comparison dialog boxes appears sequentially in which the user can compare one criterion with another. Finally, the Consistency Index is shown. The user can either save the pairwise comparison or discard the changes depending on the Consistency Index.

Ratings. A new dialog box appears with an option of selecting an existing Ratings file or creating New Ratings. If the user requests a New Ratings scale, the steps in the pairwise comparison are repeated for subfactors of the criteria shown. If the user selects an existing Ratings file, a summary of all the factors and weights of their subfactors is shown. Again, the user has the option of saving the Ratings carried out or discarding the changes.

Alternatives. In order for the user to access the Alternatives option, Ratings must have been carried out first and the results must be stored in a Ratings file. The Ratings file must be provided to compute Alternatives.

Join. The Join script provides a file dialog box in which the user can select the Alternatives file. Once the user selects the file, the Avenue script automatically updates the tables in GIS with the weights of the alternatives obtained from the previous step. These features are shown in Figure 6.

Figure 6. Abstract navigation features

Conclusions

Standard urban simulation models and statistical techniques provide greater facility to cope with the spatial/locational features of land-use and transportation systems than their physical/configurational features. Recent integration of locational or allocational models with GIS is a step in the direction of greater accountability to site- rather than zonal-level impacts of land-use and transportation systems. The site-specific physical/configurational features of land-use/transportation systems, however, defy conventional methods of analysis and evaluation. Configurational features of the built environment—land use, open space organization, street layout and the like—require methods that facilitate analysis and synthesis of form and function, empirical observation, and policy prescription. The integration of AHP as a multicriteria method with GIS offers the ability to interpret site-specific, sociospatial data directly and inductively, rather than to infer indirectly and deductively.

The AHP method supports an inductive-reasoning logic to consider the particulars specific to a site, city, or region in the light of general concepts, principles, and criteria for a TOD, station siting, or route alignment. The

method aids decision-makers in deriving or modifying the weights of the criteria to reflect the conditions specific to a locality. The method is synthetic; that is, it allows for observation, empirical evidence, experience, and interpretation in problem framing and decision making. For example, the criteria for site suitability can be based not only on the (empirical) observation of areas with population growth (or decline), but also on the interpretation of their (transit-induced) economic development potential as well as the experience of growth management and regional policy. Similarly, the availability of parking, multi-modal connectivity, land prices, and distance to major trip attractions can be explicitly scrutinized as criteria (or subcriteria) in site-suitability analysis. The procedure suggested in this article, however, remains the same in deference to the criteria used in a site-specific problem formulation.

The integrated GIS-Expert System prototype described here illustrates the use of the structural property of AHP to account for both the supply and demand factors as multiple criteria for a transit station area land-use/site assessment. This approach is in contrast to “checklist” methods or guidelines commonly used to assess desirable supply-side features of TODs. However, combined with the demand-side factors, they provide criteria for further site-specific assessment of their relative importance as well as ratings of transit area land use by AHP. Finally, both the popularity of AHP as a multicriteria method and the (ArcView) GIS are considered as factors with equal importance to further application, dissemination, and research and development of the integrated GIS-Expert System prototype.

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Endnotes

1. Consider an example of a perfectly consistent set of preferences: an apple (i) is moderately (3) preferred to an orange (j), which is twice as much preferred to a grapefruit (k); the apple is strongly (6) preferred to grapefruit. Denote the relative weights

by a_{ij} , a_{jk} , a_{ik} , respectively. With consistency $a_{ij} \cdot a_{jk} = a_{ik}$, and the largest characteristic value of $A=(a_{ij})$, the matrix of ratio estimates, denoted by $\lambda_{\max}$ equals n , the number of factors or elements compared in A . However, with inconsistency ($a_{ij} \cdot a_{jk} \neq a_{ik}$), $\lambda_{\max} > n$. In general, then, $\lambda_{\max} \geq n$ (Saaty 1980), a property that is used to obtain a measure of deviation from consistency, with an index CI :

$$CI = (\lambda_{\max} - n)/(n - 1)$$

The value of CI is compared with its average value for a randomly generated reciprocal matrix of the same size as A . The comparison indicates whether the paired comparisons are performed consistently or randomly.

2. Microsoft Visual C++ provides built-in classes in the form of Microsoft Foundation Classes (MFCs) like `CDialog` and `CFileDialog`, which facilitate user interface with timely development of new applications (Microsoft Visual C++, version 6.0).

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