Environment and Planning B: Planning and Design 1994, volume 21, pages 323-340

Integration of GIS-based suitability analysis and multicriteria evaluation in a spatial decision support system for route selection

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Received 15 September 1992; in revised form 13 August 1993

Abstract. Land suitability mapping techniques and geographic information systems (GIS) have been used in the last decade to assist planners in route selection problems. These techniques, though robust in translating physical constraints into feasible alternatives for route location, are weak in incorporating the decisionmaker's preferences, and, hence, are of limited use for decision support. The decisionmaking process that follows a route location study can be supported by multicriteria evaluation techniques that incorporate decisionmakers' preferences. This paper presents an approach to integrating a GIS-based land suitability analysis and multicriteria evaluation in a spatial decision support system for route selection. The design and implementation of the system are presented together with an example of system application to a study of the route selection for a water transmission supply line.

1 Introduction

In the last twenty years, planning has become increasingly complex because of the plethora of environmental laws and regulations as well as a greater public awareness of zoning and environmental issues. Site and route planning, in particular, must reflect both the economic realities of a least-cost project and the conflicting environmental and social requirements. In response, the field of planning has evolved to meet the new demands. This evolution is exhibited, in large part, by an abundance of decision support techniques which are designed to include the various criteria for the decision as well as the decisionmakers' priorities. However, in a practical sense, these decision support techniques have traditionally lacked the capability to take into account the physical constraints placed on the decision by the geographic characteristics of the study area.

Land suitability mapping techniques were developed to allow planners to use various physical criteria for facility site selection. With the advent of GIS, land suitability mapping was automated, making the process quicker and more responsive to planners' needs. A major flaw in land suitability mapping, the inability to incorporate the decisionmaker's preferences, makes this process an intermediate one; the results of land suitability mapping are often superseded by the results of the decision analysis. Costly and time consuming errors may occur if a decision analysis results in a decision which is incompatible with physical constraints. Conversely, land suitability mapping may result in an optimal choice of sites and routes which is unacceptable to decisionmakers because of social, political, or economic priorities. Integrating the social, political, and economic priorities and decisionmaker's preferences addressed in decision analysis with the physical constraints addressed in land suitability mapping would provide results that are not only environmentally feasible but also acceptable to decisionmakers. Few methods have been developed which integrate GIS-based land suitability mapping with decision analysis. The purpose in this paper is to present an approach which integrates GIS with multicriteria evaluation into a spatial decision support system for route selection.

The rest of this paper proceeds as follows. In the next section the current approach to site selection based on GIS-automated suitability mapping is presented. This is followed by a brief description of multicriteria evaluation for decisionmaking support. Section 3 outlines the proposed methodology for integrating GIS-based suitability analysis with multicriteria evaluation. The design and application of a spatial decision support system for the route selection of a pipeline in King County, Washington State are presented in section 4.

2 Current approaches to the route selection problem

Traditionally, simple land suitability studies have been used to identify possible routes. First, the physical criteria for the study are identified. Physical criteria usually include zoning, land use, ownership, and soils, to name a few. These criteria are depicted on transparent maps which are overlaid, and the routes with the most desirable features are identified. This approach was suggested by McHarg (1969), among others, as an alternative to an economic cost-benefit analysis which ignored the costs and benefits of the effect of the project on natural and social environments, which are often not measured in economic terms.

Land suitability mapping can be performed at a number of different measurement scales. The lowest, the nominal scale, is best represented by the Gestalt method (Hopkins, 1977), in which the study area is implicitly subdivided into homogeneous regions and classified according to their suitability for various land uses. This method requires the planner to be very familiar with the study area—a rare occurrence. Furthermore, the implicit nature of the method makes the results difficult to convey to the public and to the decisionmakers. More sophisticated methods, at higher scales of measurement, involve the ordinal combination of factor maps to determine suitability (Hopkins, 1977). The results are represented in shades of gray, from light to dark. This method is, however, burdened with methodological problems. First, it is mathematically incorrect to perform addition at the ordinal scale, and second, the measurement of factors at the ordinal scale is subjective. The subjectivity can be avoided if qualitative factors can be represented by quantitative attributes measurable on an interval/ratio scale.

Although the methods described by Hopkins utilize manual overlays, the process is easily computerized. Because the map layers are essentially themes, a GIS can be used to perform the map overlays.

2.1 Geographic information systems and land suitability mapping

With the advent of GIS and its capability to overlay digital maps, land suitability studies became more sophisticated. An early example of GIS in site planning was a study by Sperry and Smail (1985) in which a GIS was used in the environmental assessment of a high-level nuclear waste repository. The GIS used was raster based, and relatively primitive compared with current technology, but the authors developed a database which was used for a variety of environmental planning tasks. Of particular importance in reference to this study was the development of an environmental constraint coverage which represented the constraints created by various environmental conditions within the study area, weighted according to their relative importance to the planning process. This map was then used to site facilities and to identify areas of environmental concern for special management.

Another similar study was done by Buckley and Hendrix (1985). In this study, a raster-based GIS was used for the assessment of site suitability for the land application of liquid waste. Spatial criteria were identified and scores were calculated for each criterion. The criteria were not, however, weighted. An evaluation matrix was formed and the scores were totaled for each area. The final scores were then used to rank the areas according to their achievement of the criteria.

A study by Moreno and Seigel (1988) was significant in terms of expanding the applications of GIS in decisionmaking. The study was an impact analysis for the siting of a highway corridor in Colorado. Although the purpose of the study was environmental assessment, many of the techniques used in multicriteria evaluation were employed. In the analysis, a modified delphi process was used to identify criteria and weights. In the delphi process, a group of individuals each identified and weighted the criteria. The results were compiled and sent back to the individuals to determine if any of them wanted to change their criteria or weights, on the basis of the results of the compilation. This process was repeated until a consensus was reached. Composite-factor maps were created, reflecting the criteria chosen. Each factor was assigned a numerical weight reflecting its relative importance in the siting decision. A weighted overlay was used to combine the factor maps into a composite map for each criteria. Finally, the criteria maps were combined to find suitable corridors which then were analyzed in the second phase, the environmental assessment. In this phase, standard query language was used to identify possible impacts resulting from the proposed project. The first phase of the analysis by Moreno et al (1988) encompassed the early steps in the methodology presented in the next section of this paper.

Another study by Moreno (1991) reflects the refinement of the above analysis resulting from years of work using GIS applications. In this study, a comprehensive database with a raster-based GIS, a vector-based GIS, and satellite imagery processing software were used to identify possible corridors for the southwest intertie project (SWIP)—a proposed 710 mile power transmission line connecting an existing Idaho Power Company substation in southern Idaho with a new substation near Ely, Nevada. Innovations from previous techniques include using the networking capabilities of the vector-based GIS to identify the paths of least resistance between the two endpoints, on the basis of terrain, and physical and environmental constraints, and using the imagery software to assist in locating possible corridors. The database compiled, via the same methods described in the 1988 study (Moreno et al, 1988), was then used more extensively in environmental decisionmaking for impact types, impact analysis, and impact mitigation. Recently, Harris et al (1992) reported a powerline siting study that included forty various land use suitability factors.

In all three studies a final decision analysis was done outside of the GIS. The methodology presented in section 3 of this paper is meant to illustrate that the composite coverages can be used not only for identifying feasible alternatives, as described in the literature, but also for the decisionmaking process, by utilizing multicriteria evaluation, a commonly used decision analysis technique.

2.2 Multicriteria evaluation for decisionmaking support

Decision analysis has become a necessity in the face of an increasingly complex and risk-prone decisionmaking environment. There is a greater demand for natural resources, yet there are stricter laws protecting the environment. In addition, social and political issues have gained prominence in decisionmaking over the years (Jankowski, 1989).

Multicriteria evaluation (MCE) is a suitable type of decision analysis for land use issues because of its simplicity, its treatment of multiple objectives, and its capability to handle many different types of criteria. MCE is especially useful in reflecting the preferences of decisionmakers and in allowing *sensitivity analysis*, which enables decisionmakers to test the validity of the weights used and the ranking of the alternatives.

MCE techniques can be classified according to the type of data used in criterion scores: *quantitative*, *qualitative*, and *mixed* data. Qualitative techniques accept only ordinal data, whereas quantitative techniques deal only with ratio or interval data. Mixed-data techniques accept quantitative and qualitative data.

The assumption made in this paper is that data extracted from a GIS-based land suitability analysis will be quantitative, therefore a quantitative technique is appropriate for the multicriteria evaluation of the alternatives. Surveys of qualitative and mixed-data techniques can be found in Jankowski (1989), Nijkamp et al (1990), and Voogd (1983).

All of the quantitative techniques have two steps in common: the formulation of an *effectiveness matrix* consisting of standardized scores, and formation of a *weight vector*, consisting of priority weights corresponding to the criteria. The effectiveness matrix, **E**, and weight vector, $\boldsymbol{w}$, take the following forms:

$$\boldsymbol{E} = \begin{bmatrix} e_{11} & \cdots & e_{1I} \\ \vdots & & \vdots \\ e_{J1} & \cdots & e_{JI} \end{bmatrix},$$

$$\boldsymbol{w} = (w_1, w_2, ..., w_j), \qquad \text{and} \sum_{j=1}^{J} w_j = 1 .$$

where e is the effectiveness score; I is the set of alternatives; J is the set of criteria. Two of the most common quantitative MCE methods are based on a weighted summation approach and pairwise comparison of the alternatives. The basic form of the weighted summation technique can be depicted in this matrix notation:

$$\begin{bmatrix} s_1 \\ \vdots \\ s_I \end{bmatrix} = \begin{bmatrix} e_{11} & \cdots & e_{1I} \\ \vdots & & \vdots \\ e_{J1} & \cdots & e_{JI} \end{bmatrix} \times \begin{bmatrix} w_1 \\ \vdots \\ w_J \end{bmatrix},$$

where s_I is the appraisal score for alternative I.

The assumptions behind the technique are that the weights are quantitative, the effectiveness scores are determined on a ratio scale, and data are aggregated by addition. The most frequently violated assumption is the second one. It is sometimes impossible to measure all the relevant criteria on a ratio scale. Another potential disadvantage occurs when the weighting of criteria is not linear, making the linear aggregation of data difficult. The advantage of this method is its simplicity. However, that simplicity not only limits the evaluation of the alternatives, but also limits sensitivity analysis. In this technique the primary avenue for sensitivity analysis is in changing the weights to see if the ranking of alternatives is affected (Voogd, 1983).

The *concordance analysis*, which is the most common technique based on pairwise comparison, determines the ranking of alternatives by means of pairwise comparison. The comparison is based on calculations of the concordance measure, which represents the degree of dominance of alternative i over alternative i', and the discordance measure, which represents the degree of dominance of alternative i' over alternative i (Voogd, 1983). The calculation of concordance and discordance measures is carried out in concordance analysis for every pair of alternatives.

On the basis of these measures, the differences between alternatives are quantified and a final score is calculated for every alternative. From this score the alternatives can ranked from best to worst.

In the concordance measure, only preference weights are taken into account in order to quantify the dominance of alternative i over alternative i'. In the discordance measure, weighted criterion scores are used in order to quantify the dominance of alternative i' over alternative i. The concordance measure is based on the concordance set, the subset of all criteria for which alternative i is not worse than the competing alternative i'. The discordance measure is based on the discordance set, the subset of all criteria for which alternative i is worse than alternative i' (Nijkamp and Van Delft, 1977). The concordance index can be formulated as:

$$c_{ii'} = \sum_{j \in c_{ii'}} w_j \ ,$$

where w is the weight associated with those criteria contained in the concordance set.

The concordance index reflects the relative importance of the criteria for which alternative i is dominant over alternative i', by summing the weights associated with criteria contained in the concordance set. The discordance index is:

$$d_{ii'} = \max_{j \in d_{ii'}} \frac{|e_{ji} - e_{ji'}|}{d_j^{\max}} \ ,$$

$$d_j^{\max} = \max_{(1 \leqslant i,\, i' \leqslant I)} |e_{ji} - e_{ji'}| \ ,$$

where $d_j^{\max}$ is the maximum difference between the various outcomes of criterion j. The index, $d_{ii'}$, represents the pairwise outcomes of all criteria belonging to the discordance set of alternatives i and i' (Nijkamp and Van Delft, 1977).

A condition for the acceptance of a proposed alternative is fulfillment of *threshold values*:

$$c_{ii'} \geqslant \eta, \qquad d_{ii'} \leqslant \mu \ ,$$

where η and μ are determined outside of the analysis by the user.

Finally, the appraisal score, s_i, for each alternative can be calculated by means of the following (Voogd, 1983):

$$s_j = \sum_{\substack{i' = 1 \\ i' \neq i}} z_{ii'} - \sum_{\substack{i = 1 \\ i \neq i'}} z_{ii'}$$

$$z_{ii'} = \begin{cases} 0 \text{ when } c_{ii'} < \eta \text{ and } d_{ii'} > \mu \ , \\ 1 \text{ when } c_{ii'} \geqslant \eta \text{ and } d_{ii'} \leqslant \mu \ . \end{cases}$$

The alternative with the highest s_i receives the highest rank.

The assumptions made in the concordance analysis are that:
(1) threshold values can easily be determined;
(2) the values of $c_{ii'}$, $d_{ii'}$, and the scaling parameter are defined by the user;
(3) criterion weights are quantitative;
(4) effectiveness scores are derived from at least the interval scale; and
(5) an alternative that is not dominated by any other alternative, and dominates another alternative, dominates all alternatives (Nijkamp and Van Delft, 1977).

There are definitie advantages and disadvantages of this type of technique. First, the pairwise comparison between alternatives provides a much more elegant evaluation of the relative performance of a given alternative. The analysis is much more thorough, as every alternative is matched against every other alternative, rather than the performance of the alternative being stated in terms of an average achievement. The threshold values give the analyst some control over what minimum standards are to be enforced. However, the concordance analysis technique is sufficiently complex that only users familiar with this technique will understand the mechanics of the analysis. This makes the control of threshold values essentially meaningless, as a person unfamiliar with the technique is likely to choose an arbitrary value with no reasoning behind it. To the 'uninitiated', concordance analysis is a 'black box' approach that miraculously decides which alternative is best. Therefore, even though concordance analysis techniques make better use of available information than the weighted summation techniques, it may not necessarily be better for decision support.

Both the weighted summation and the pairwise comparison approaches define general classes of quantitative evaluation techniques. Variations on the weighted summation approach include the goals achievement method (Hill, 1968) and part/whole percentaging (Nagel, 1989; Nagel and Long, 1989). Techniques based on pairwise comparison include ELECTRE, ORESTE, PROMETHEE (Teghem et al, 1989), and analytical hierarchy process (Saaty, 1980).

3 Methodology for integrating land suitability analysis with multicriteria evaluation

The linking of GIS-based land suitability analysis and MCE in an integrated GIS-MCE decision support system involves a number of steps (see figure 1). These steps represent a proposed model of multiple criteria decisionmaking with GIS. First, a set of decision criteria is formulated. The decision criteria may be quantitative and qualitative and they may concern physical, economic, and social aspects of the decision problem. Next, a set of feasible solutions is generated in the GIS. The feasibility of the alternatives is determined upon the satisfaction of the set of minimal physical (that is, engineering) and qualitative constraints imposed upon the decision criteria. Spatial analysis operations such as overlay, buffer, and proximity are used to create a composite coverage, and standard logical operators available in the GIS database query language are used to derive sites (route corridors) satisfying the minimal physical and qualitative constraints. The sites that satisfy the minimal constraints (threshold values) constitute the feasible solutions. The solution alternatives are then overlaid with the criterion coverages. The result of this step is an output coverage containing the original attribute data of the alternatives and the criterion attribute data. Next, the alternatives, represented by their attribute data, are extracted from GIS in the form of an ASCII file and are input into the MCE software where the decisionmaker can attach a relative preference measure to every criterion in the analysis. Then the alternatives are ranked, based on the criterion scores extracted from the GIS and criterion weights assigned by the decisionmaker. Finally, a sensitivity analysis can be performed within the MCE software to determine the vulnerability of the analysis to changes in decisionmakers' preferences. The results of the evaluation, made up of the ranking of alternatives, are exported into the GIS and displayed for visualization.

The proposed model of multiple criteria decisionmaking with GIS is iterative as depicted by the feedback loops in figure 1. The first feedback loop connecting the last step of the process (visualization of results in GIS) with the first step (formulation of decision alternatives) represents the case in which the decision criteria are the subject to change. This situation may arise in decisionmaking problems characterized by the lack of consensus among the group of decisionmakers (that is, group members cannot agree upon the common set of decision criteria) and uncertainty regarding the role and importance of various decision criteria in generating the alternatives. The second feedback loop connecting the last step with the second step (generation of feasible alternatives) represents the case in which the threshold values imposed upon the decision criteria are changed. These two feedback loops underscore the potentially iterative character of the generation of alternatives. The third feedback loop depicted in figure 1 represents the situation where the decisionmaker wishes to repeat the evaluation of the alternatives after changing the criterion priorities.

The premise of the presented approach is that the integration of land suitability analysis and multicriteria evaluation within the GIS would ensure that the often crucial physical elements, such as geophysical or environmental criteria, are not neglected, and would make the decisionmaker more aware of the physical environment surrounding possible sites. In addition, many city, county, state, and federal agencies are developing GIS databases, making this method increasingly accessible.

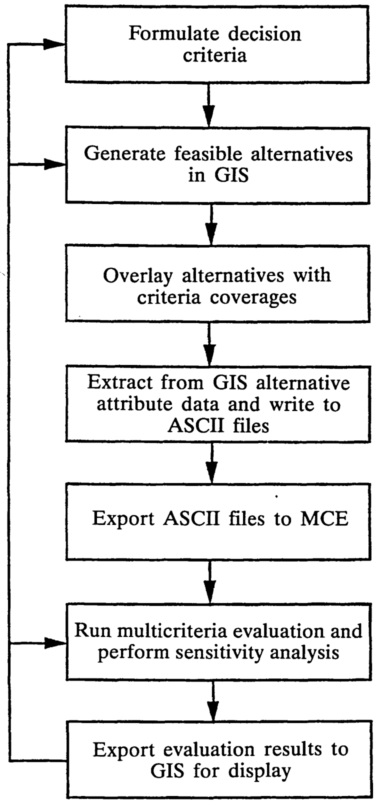

Figure 1. Procedure flowchart for linking suitability analysis with multicriteria evaluation.

3.1 System design and implementation

The design of the spatial decision support system for route selection integrates GIS and MCE software through a transparent file-sharing with a hierarchical, menu-organized user interface (figure 2). The design follows the *loose coupling strategy* in which GIS and MCE software are linked via a file exchange mechanism and independent GIS and MCE user interfaces (Fedra, 1993; Nyerges, 1993). A similar approach was used in GIS and MCE integrations described by Carver (1991) and Janssen and Retvield (1990). The generation of feasible alternatives in the GIS module, the transfer of attribute files representing the alternatives into the MCE module, and the evaluation of the alternatives are run by a user from the common user interface. The user interface is invoked with a batch file that opens the main menu, presenting the user with the choice of performing GIS analysis in PC-ARC/INFO® 3.4D (commercial GIS software from ESRI Inc., Redlands, CA), evaluating the alternatives in BEST CHOICE (commercial multicriteria evaluation program from Decision Aids, Inc., Champaign, IL), or returning back to the DOS prompt:

1. GIS ANALYSIS IN PC-ARC/INFO
2. MC EVALUATION IN BEST CHOICE
3. QUIT

ENTER MENU CHOICE (1/2):

The flowcharts depicting the hierarchical structure of the main menu are presented in figures 3 and 4, respectively. The choice of option 1 results in the opening of the GIS Analysis menu:

THE MCE-GIS SPATIAL DECISION SUPPORT SYSTEM
MAP VIEW
GIS ANALYSIS
CREATE MCE FILES
RESELECT FEATURES
HELP
MAIN MENU

The user can view maps in the ARCPLOT module of PC-ARC/INFO®, perform GIS analysis using buffer and various overlay operations, create files for multicriteria evaluation, and select coverage attributes (features) that will be used as evaluation criteria. Selecting HELP activates the series of screens describing the use and functionality of the commands MAP VIEW, GIS ANALYSIS, CREATE MCE FILES, and RESELECT FEATURES available from the menu window. The selection of option 2 (MC EVALUATION IN BEST CHOICE) from the main menu brings up a menu window with four choices:

A. IMPORT GIS FILE TO BEST CHOICE
B. EVALUATE LOTUS FILE IN BEST CHOICE
C. IMPORT RESULTS TO GIS DATABASE
D. MAIN MENU

ENTER MENU CHOICE (A/B/C):

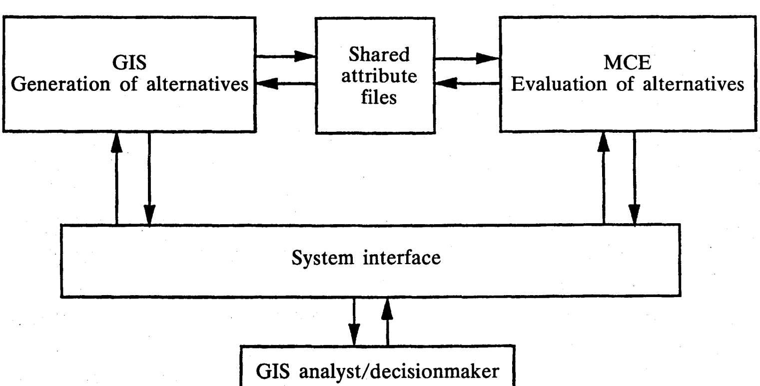

Figure 2. The architecture for an integrated GIS-MCE spatial decision support system.

The user can import PC-ARC/INFO files into the multicriteria evaluation software BEST CHOICE, run the evaluation of the alternatives, import the evaluation results into PC-ARC/INFO and display them on the map, or return to the main menu.

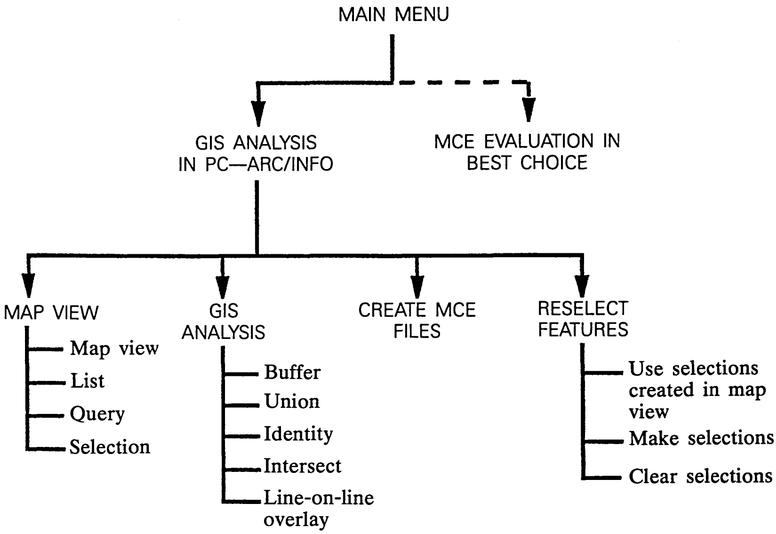

Figure 3. Flowchart of GIS ANALYSIS menus.

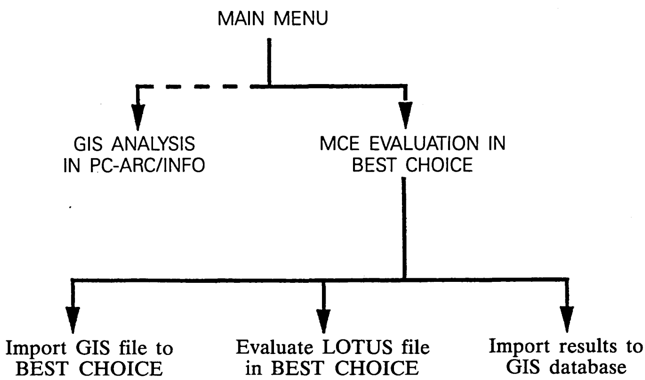

Figure 4. Flowchart of MCE Evaluation menus.

The user interface was developed entirely in simple macro language (SML) which is a part of PC-ARC/INFO software. SML was used to program the interface menu files and the macro files which automate the menu commands. A Pascal program was written to facilitate the conversion of attribute data from the PC-ARC/INFO format into the LOTUS 1-2-3® format. The BEST CHOICE multicriteria evaluation program is a large LOTUS 1-2-3® macro, and files that are imported into the program should be in the LOTUS 1-2-3® format.

The GIS-MCE spatial decision support system can be used either for the generation and evaluation of alternative route locations or for repeated evaluations of the alternatives already existing in the database, by means of different sets of decisionmaker priorities. The first mode of using the system, described more extensively in the next section, involves the following steps.

(1) GIS land suitability analysis. The objective of this step is to generate the feasible alternatives.
(2) Updating the GIS database. The objective of this step is to prepare the database for multicriteria evaluation by adding the evaluation criteria.
(3) Extracting the GIS attribute data and writing to ASCII files. This step includes the following tasks: select the coverage data to be extracted; extract the specific items to be used as decision criteria; and write the information to one or more ASCII files.
(4) Multicriteria evaluation. The following tasks are involved: convert the data to the BEST CHOICE format; perform a multicriteria evaluation of the alternatives; and perform a sensitivity analysis to examine the robustness of the results of evaluation ranking,
(5) Viewing the evaluation results. The following tasks are included in this step: extract, sort, and write to an ASCII file the ranking results; import the ASCII file to an existing dBase file; join the ranking in the dBase file to a PC-ARC/INFO® coverage depicting the alternatives; view the ranking of the alternatives in the ARCPLOT module of PC-ARC/INFO.
This last mode of using the system may be attractive to a decisionmaker who wants to evaluate decision alternatives himself or herself but who is unfamiliar with GIS operations and wants to rely on a GIS specialist for the generation of the alternatives. This mode, also discussed in the next section, is implemented by repeated evaluations with different sets of criterion weights.

The software requirements of the GIS-MCE spatial decision support system include: PC-ARC/INFO 3.4D, LOTUS 1-2-3 release 2.2 or higher, and the LOTUS version of the BEST CHOICE software. The hardware requirements are: an IBM compatible 386 microcomputer with a math coprocessor, VGA display, 2 Mb of RAM, and at least 30 Mb of hard disk space.

4 System application

The GIS—MCE spatial decision support system was applied to verify a route selection study for a water transmission supply line which is to provide water for the city of Seattle and environs. The study area is southwest of Duvall, near Seattle, Washington, encompassing 22 miles^2 (figure 5). The project area spans the Snoqualmie River

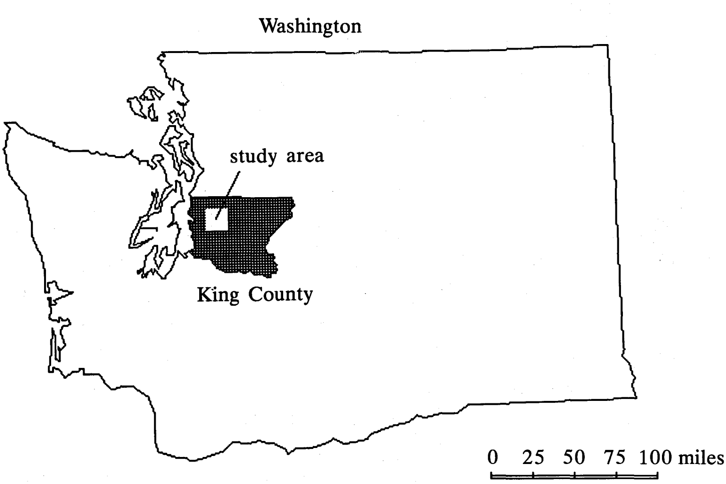

Figure 5. Study area in King County, Washington.

valley southwest of Duvall, and, regardless of which alternative is chosen, must cross the Snoqualmie River, which discharges into the Puget Sound. The Tolt Eastside Supply Line Number 2 (TESSL No. 2) pipeline is being built in three phases (see figure 6). The first two phases are nearly complete. The third phase is the project under consideration in this study.

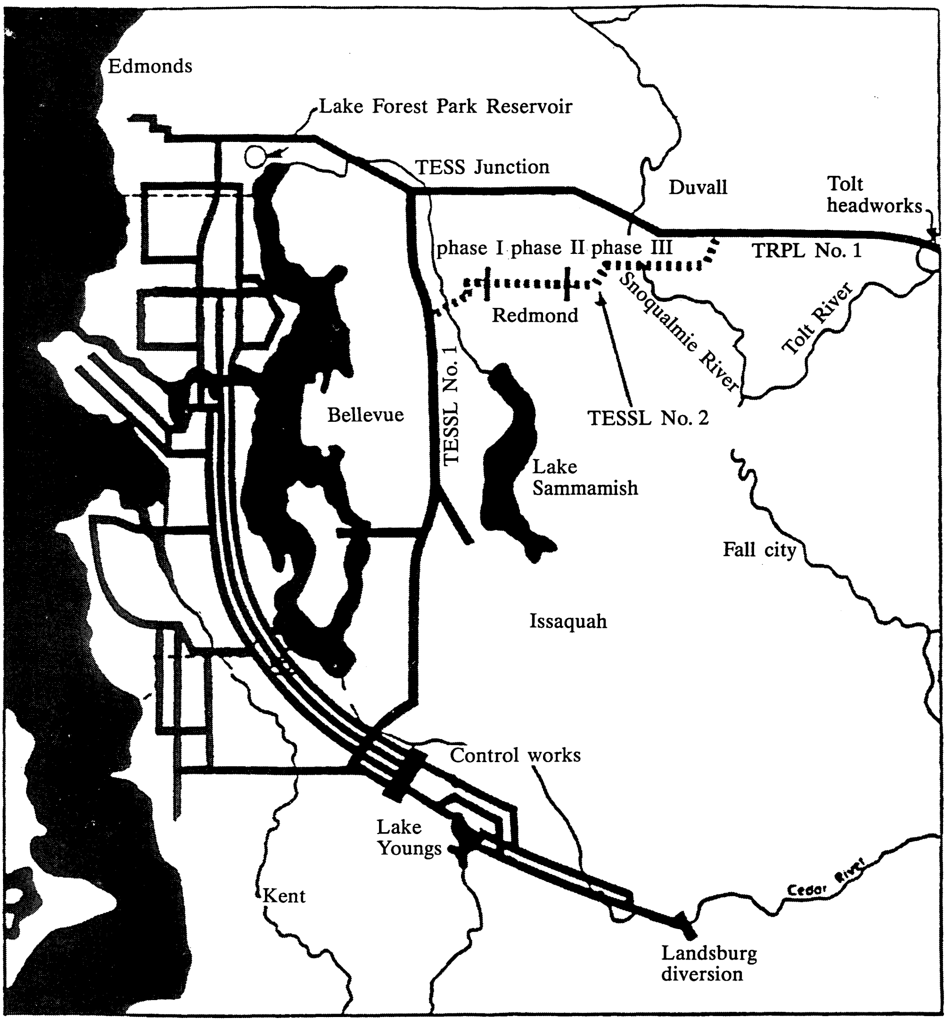

Figure 6. Puget Sound area and the location of TESSL No. 2 pipeline.

In the region there are numerous wetlands, streams, and steep slopes which complicate the site selection. All the pipelines discussed are serviced by the Seattle Water Department (SWD), the regional supplier of water for more than 1 million people in an area covering much of King County, Washington. SWD directly supplies customers within and near the Seattle city limits, and sells water wholesale to thirty-one separate water purveyors outside the direct service area. The present sources of water are the Cedar River and the South Fork Tolt River, supplying roughly 70% and 30%, respectively, of the 174 million gallons per day (659460 m^3) average annual daily consumption, according to the 1988 site-selection study for TESSL No. 2 phase III (SWD, 1988).

In the fall of 1987, Tolt River Pipeline Number 1 (TRPL No. 1) failed in a 66 inch diameter section east of Woodinville. Before a major rehabilitation of TRPL No. 1 (a 25-year-old pipeline) can be achieved, a parallel pipeline must be built. This requires the building of TESSL No. 2 phase III, the project under consideration, which will extend eastward from TESSL No. 2 phase II, and connect to TRPL No. 1 beyond the damaged section, several miles east of the Snoqualmie River (SWD, 1988). SWD and CH_2M Hill (a consultancy firm) used a weighted summation method for the site selection of phases I and II of TESSL No. 2 (SWD, 1987). The weights were derived by means of the rating method, on the basis of preferences stated by a citizens advisory committee, therefore the criteria scores had to be standardized prior to application of the weights by converting them to percentages.

The route selection for phase III of TESSL No. 2 was via a direct qualitative evaluation method. There were mixed data, but quantitative data were only considered at the ordinal scale. The criteria scores were considered on a scale of high, medium, and low achievement or impact (SWD, 1988). This method does not easily lend itself to analysis with the GIS, nor does it adequately consider the impacts of the alternative routes.

4.1 Data for the study

The data used in this study were obtained from a variety of sources (table 1). The map coverages, LandHaz, ErosionHaz, SeismicHaz, WetlandArea, and Streams were obtained from the King County Environmental Division, Resource Planning. The coverages were developed with the pc ARC/INFO® software at the scale of 1:24000. The Roads, Pipes, and Railroads coverages used to determine the public right-of-way were obtained from USGS in DLG (digital line graph) format at the scale of 1:24000. The coverage RightOfWay was obtained by buffering the Roads, Pipes, and Railroads coverages via a buffer item called SETBACK. The values in the SETBACK item were obtained from King County Assessors Maps, which state the setback from the centerline of any public right-of-way.

Table 1. Data coverages and sources (all data have units of feet).

Coverage	Theme	Source	Scale
LandHaz	Landslide hazard areas	King County Environmental Division Resource Planning	1:24000
ErosionHaz	Erosion hazard areas	King Co. Env. Div., Resource Planning	1:24000
SeismicHaz	Seismic hazard areas	King Co. Env. Div., Resource Planning	1:24000
WetlandArea	Wetland Areas	King Co. Env. Div., Resource Planning	1:24000
Streams	Streams	King Co. Env. Div., Resource Planning	1:24000
Roads	Roads	USGS	1:24000
Pipes	Pipelines, electrical transmission lines	USGS	1:24000
Railroads	Railroads	USGS	1:24000
AltPipes	Alternative pipe routes	SWD, 1988	1:24000
RightOfWay	Public right-of-way	King County Public Works, Department/USGS	1:24000

4.1.1 *Decision alternatives*

The alternative routes were provided by SWD (1988) and by CH_2M Hill. They were identified by the engineers at SWD and CH_2M Hill on the basis of technical and geographical constraints (figure 7). The routes have a common beginnning point at the end of TESSL No. 2 phase II, and a common end point, an extension of TRPL No. 1, several miles east of the Snoqualmie River. The nomenclature of the routes was determined by SWD. The nomenclature changed when the second site selection study for phase III was commenced. The 'north route', alternative 6, is referred to as N1 in this study to maintain consistency.

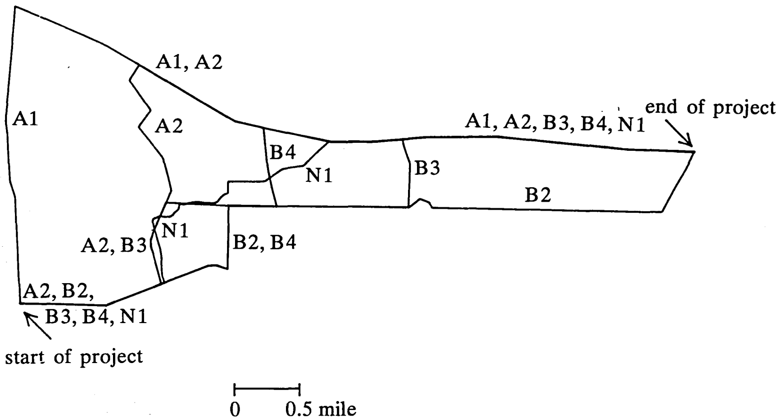

Figure 7. Alternative routes for the phase III of TESSL No. 2 pipeline (source: SWD, 1988).

4.1.2 *Decision criteria*

To illustrate the developed methodology, it was necessary to build a model of a site selection study, including realistic decision criteria. The criteria used in this study were obtained from the TESSL No. 2 phase III site selection study (SWD, 1988). Some of the possible candidate criteria were either considered irrelevant by the decisionmakers, or were impossible to obtain without an extensive staff. The remaining criteria are summarized in table 2, and are described in detail below.

Table 2. The decision criteria.

Group and individual criteria	Method of representation in the database
Total cost	TOTALCOST, an attribute in the FINLINE coverage
Right-of-way acquisition	ROWACRES, an attribute in the RightOfWay coverage
Environmental	
Streams	STRMLEN, an attribute in the Streams coverage
Wetlands	WETACRES, an attribute in the WetlandArea coverage
Reliability	
Accessibility/vulnerability to damage due to traffic	VEH/DAY, an attribute in the Roads coverage
Erosion hazard areas	ERSACRES, an attribute in the ErosionHaz coverage
Seismic hazard areas	SEIACRES, an attribute in the SeismicHaz coverage
Steep slopes	LNDACRES, an attribute in the LandHaz coverage
Length of route	ALTLEN, an attribute in the ALTS coverage

With the exception of public right-of-way, the criteria used are negative, meaning the less the better.

Total cost The total cost of the project was estimated for each route. Construction, right-of-way acquisition, permit costs, engineering, administrative expenses, and related items were included in the estimates.

Reliability The reliability criteria were based on the normal daily volume of traffic on roads which fall with and are parallel to the routes' rights-of-way, and the vulnerability of the alternatives to erosion hazards, landslide hazards, and seismic hazards, measured in acres of hazard areas. The higher the traffic volume and the greater the acreage of hazard areas within a route's rights-of-way, the more vulnerable the route is to damage from vehicle traffic.

Right-of-way acquisition The amount of public right-of-way falling within a route's right-of-way reflects the cost and delay as a result of negotiations with private parties for the purchase of the required right-of-way. The criterion is measured in acres of public right-of-way falling within the right-of-way necessary for the route.

Environmental The environmental impact of the alternatives is based on the area of wetlands and length of stream segments falling within their rights-of-way. The greater the impact to environmentally sensitive areas, the greater the difficulties associated with environmental regulations, permits, mitigation, negative publicity, and so on.

Length of alternative The length of the route affects both its cost and its reliability, as well as the hydraulic efficiency of the pipeline following that route. Therefore, the length must be kept at a minimum, to prevent engineering problems and increased costs.

4.2 Evaluation results

The results of the multicriteria evaluation in BEST CHOICE were interesting in light of the route selection study done for SWD (1988). In that study route B2 was selected as the best alternative. However, the SWD decided to reassess the decision because of increased concerns regarding the reliability of route B2. Another major pipeline had failed, and there was great public pressure to find a route that was safe from failure due to geotechnical influences. The new study recommends that route N1 be selected because of its perceived high reliability rating. The BEST CHOICE analysis was run three times, for three weighting schemes (see table 3). The first run was performed with equal priority weights of 1.0. This is recommended by Nagel (1989) as a way of ascertaining the general trend of the routes' scores prior to

Table 3. Weighting schemes applied in the analysis.

Decision criteria	Criteria weights		
	first run	second run	third run
ROWACRES	1.000	0.133	0.050
ERSACRES	1.000	0.050	0.125
SEIACRES	1.000	0.050	0.125
LNDACRES	1.000	0.050	0.125
WETACRES	1.000	0.045	0.170
STRMLEN	1.000	0.022	0.130
VEH/DAY	1.000	0.050	0.125
ALTLEN	1.000	0.300	0.100
TOTALCOST	1.000	0.300	0.050

performing a true weighted analysis. The results of the first run are given in table 4. They indicated that route N1 was the best choice, with route B3 being the second choice. Route B2 was the fifth choice. After the initial evaluation analysis was performed with equal priority weights the sensitivity analysis was run. BEST CHOICE offers three types of sensitivity analysis—tie values, change scores, and percent changes—all of which were employed to assess the vulnerability of the first-choice route to becoming the second-choice route. Each analysis type is performed on two alternatives at a time. Tie-value analysis calculates the criterion scores or weights that will bring a second-place route up to first place. Change scores are the values calculated in the tie values minus the corresponding raw scores to show the percentage change needed. Percent change is the change scores divided by the raw-score value to show the percentage change needed (Nagel, 1989). The sensitivity analysis indicated that with equal weighting for all criteria, N1 was secure in its position. The minimum-value change needed to bring B3 up to the first position was either a 64% drop in the vehicles per day or a 75% decrease in the weight for the VEH/DAY criteria. Route N1 scored the best in the wetland acreage (WETACRES) criterion. Route A2 scored a very distant third, being three percentage points behind the first choice. The rank of the alternative routes in the first run are given in table 4.

Table 4. Results from the first run.

Route name	A1	A2	B2	B3	B4	N1
Percentage						
ROWACRES	29.39	22.27	6.43	14.45	14.99	12.46
ERSACRES	26.37	16.81	12.29	12.49	14.05	17.99
SEIACRES	16.95	20.86	17.74	16.50	11.60	16.35
LNDACRES	15.94	20.61	15.92	17.38	6.00	24.16
WETACRES	6.36	7.17	33.23	42.41	5.57	5.25
STRMELEN	15.23	19.06	5.68	8.66	11.33	40.04
VEH/DAY	19.42	19.42	10.49	13.93	17.33	19.42
ALTLEN	12.52	14.24	16.02	16.29	19.60	21.32
TOTALCOST	13.96	15.01	16.01	15.50	15.30	24.20
Rank	3	4	5	2	6	1

In the second run, with weights extracted from the phase II study (SWD, 1987), which emphasized cost, length, and public right-of-way acreage, route N1 again came in first, with the B3 route second. Route A1 was a distant third. The sensitivity analysis indicated that routes B3 and N1 were slightly closer in this run than in the first run. N1 was most vulnerable in the cost and length criteria. Route N1 scored much higher than B3 in the reliability and environmental criteria, all requiring large percent changes to push the N1 into second position. Table 5 shows the results of the second run.

The third run, with priority weights based on preferences stated by the citizens advisory committee for the phase III route selection gave the most interesting results. Once again, route N1 was the best choice, with B3 as the second choice and A2 as the third choice (table 6). However, the sensitivity analysis showed that the choice of route N1 was not very robust. A mere 13% increase in the weight for the wetlands acreage criterion would allow B3 to become the first choice. Table 6 summarizes the rank of the routes in the third run.

The N1 route was strongest in the right-of-way acreage criterion (ROWACRES), largely because of the small amount of weight placed on that criterion relative to the reliability criteria. In fact, N1 had the second lowest amount of public right-of-way within the required right-of-way of the route, but as the quantity was close to the other routes' quantities, and because the right-of-way acreage criterion was given a weight of only 0.05 out of 1.0, N1 was able to overcome this disadvantage. Ironically, route N1 is weakest in the reliability and environmental criteria. A relatively small change in either N1 or B3 in any of those criteria would result in route B3 being the first choice. Although the relative weakness in the environmental criteria is not unexpected, because the raw scores showed that N1 was not in the top three, it is surprising that the results for the reliability criteria were not better, in light of the fact that N1 was chosen by SWD because of its reliability. The results of BEST CHOICE would suggest that B3 and N1 are not very different in terms of their achievement of the reliability criteria. The lack of robustness of N1 or B3 in the third run would indicate that either the other alternatives should be developed, or more criteria should be incorporated into the decisionmaking process. Only a limited number of criteria were used for illustrative purposes, but the results of this research suggest the need for further analysis in this site-selection process. It is significant that in all three runs, route B2 was placed last or second to last, as SWD once considered that route to be a viable choice.

Table 5. Results from the second run.

Route name	A1	A2	B2	B3	B4	N1
Percentage						
ROWACRES	3.92	2.97	0.86	1.93	2.00	1.66
ERSACRES	1.32	0.84	0.61	0.62	0.70	0.90
SEIACRES	0.85	1.04	0.84	0.83	0.58	0.82
LNDACRES	0.80	1.03	0.80	0.87	0.30	1.21
WETACRES	0.29	0.32	1.50	1.91	0.25	0.24
STRMELEN	0.34	0.42	0.12	0.19	0.25	0.88
VEH/DAY	0.97	0.97	0.52	0.70	0.87	0.97
ALTLEN	3.76	4.27	4.80	4.89	5.88	6.40
TOTALCOST	4.19	4.54	4.80	4.65	4.59	7.27
Rank	3	4	6	2	5	1

Table 6. Results from the third run.

Route name	A1	A2	B2	B3	B4	N1
Percentage						
ROWACRES	1.47	1.11	0.32	0.72	0.75	0.62
ERSACRES	3.30	2.10	1.54	1.56	1.76	2.25
SEIACRES	2.12	2.61	2.22	2.06	1.45	2.04
LNDACRES	1.99	2.58	1.99	2.17	0.75	3.02
WETACRES	1.08	1.22	5.65	7.12	0.95	0.89
STRMELEN	1.98	2.48	0.74	1.13	1.47	5.21
VEH/DAY	2.43	2.43	1.31	1.74	2.17	2.43
ALTLEN	1.25	1.42	1.60	1.63	1.96	2.13
TOTALCOST	0.70	0.75	0.80	0.78	0.76	0.21
Rank	4	3	5	2	6	1

4.3 Discussion of the results

Decisions done within a spatial context prevent decisionmakers from losing perspective on the entire set of criteria and focusing on particular criteria which the public perceives as being important, as was apparently the case in the TESSL No. 2 phase III route selection. This would imply that perceiving the results in a spatial context would increase the quality of the decision. An example of this phenomenon can be seen in the results of the analysis. Route B2 was placed last or second to last in all three runs, yet SWD had initially chosen that route for development. The results of the analysis, though abbreviated with fewer criteria than used by SWD in the draft site selection study (SWD, 1988) for TESSL No. 2 phase III, indicate that route B2 was a very poor choice. Had SWD used a more systematic way of decisionmaking, especially when linked to graphic software such as PC-ARC/INFO®, the selection of B2 would have been unlikely, and valuable time and money would have been saved.

The results of the analysis here indicate that once the user has carefully designed the question to be answered, and the criteria to be used to answer that question, the interface between a GIS and MCE can facilitate preliminary and/or final route selection studies. Viewing the results of the evaluation in PC-ARC/INFO® confirms the importance of graphics output in the decision analysis within a spatial context. The results of the sensitivity analysis can either assure the decision-maker that the decision is a robust one, which requires large changes in the weights or criteria to change the results of the analysis, or indicate that further research may be in order, to either identify more alternatives or redefine the problem. These features, made accessible through the use of BEST CHOICE, and facilitated by data extracted from a GIS rather than calculated through nonspatial methods, make the GIS-MCE spatial division support system (SDSS) a viable option for planners who wish to reach a quick decision. The scale at which this analysis was run, 1:24000, is most useful for a preliminary planning study which narrows the field of alternatives. However, if a larger scale were used in the analysis, the level of precision would be increased and, therefore, the quality of the decision reached would be more precise.

5 Conclusion

It is widely accepted that GIS is a tool box capable of providing support for spatial problem-solving and decisionmaking. However, current GIS analysis is based on simple spatial geometric processing operations such as overlay comparison, proximity measures, and buffering. It does not provide optimization, iterative equation solving, and simulation capabilities necessary in planning. Further, GIS does not integrate nonspatial data or decisionmakers' preferences into the decision analysis. Also, GIS land suitability mapping provides a range of suitable solutions, rather than presenting the user with one 'optimum' solution, given the current set of decision criteria. By integration of the multicriteria evaluation software, BEST CHOICE with PC-ARC/INFO®, decisions on site or route selection can be made in a systematic manner, taking into account spatial and nonspatial information, and allowing the user to analyze the information, given one or more sets of priority weights.

Although the GIS-MCE SDSS is an advancement in decision analysis for spatial planning there is a clear need for continued research in this area. Topics for further research include the development of new methods of generating alternatives within the GIS. Development of such methods would further increase the usefulness of the GIS-MCE SDSS, as a major weakness of any decision analysis is the generation of a viable, complete set of alternatives.

Another topic for further research is the extension of links between BEST CHOICE and PC-ARC/INFO® to further increase the exchange of data in the reverse direction from the MCE to the GIS, most likely within a user interface more extensive than the one presented with this study.

Last but not least, integration of other multicriteria decisionmaking techniques, including group decisionmaking multicriteria methods, into the existing system prototype would extend the usefulness of GIS in spatial decision support.

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