Consensus-building in a Multi-Participant Spatial Decision Support System

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Abstract: *Geographic Information Systems (GIS) are widely used in local and regional planning for managing, integrating and visualizing spatial data sets. However, beyond basic levels of decision support, GIS remain largely external artifacts to the decision-making process. This suggests that despite increased analytic sophistication, most GIS software is more suited to providing limited outputs (maps, tables, etc.) than as a tool to support, at anything other than a superficial level, tactical or strategic decision-making processes. To improve the usefulness of GIS as a decision support tool, two needs are apparent. First, decision-makers require methods that allow them easily to select alternatives most closely aligned with their priorities across a number of relevant criteria. Second, it is necessary to recognize explicitly that most decision-making processes involve multiple participants. Since problem solving is often characterized by multiple and conflicting objectives, methods that contribute toward consensus building are required. This paper describes a prototype Spatial Decision Support System (SDSS) that satisfies these needs through a tight-coupling of GIS functionality and Multiple Criteria Analysis (MCA) techniques. The potential benefits of adopting this approach and future extensions to the prototype are discussed in light of a land use-planning example.*

Introduction

Geographic Information Systems (GIS) have gained increasing acceptance as important tools for the organization, manipulation and display of data pertinent to many urban and regional planning activities. Much of the success of GIS implementation in the planning field has been in the areas of task automation, spatial data creation and enhanced map and tabular report production. Particularly significant are the capabilities of GIS to integrate large volumes of spatial and non-spatial data and enhance problem understanding through visualization of data in map form. However, at the strategic or policy-making level of decision-making, the contributions of GIS still appear to be quite limited. At this level, planning activity centres upon resolving complex and ill-structured problems characterized by multiple objectives, multiple considerations, numerous participants, and a host of uncertainties (Janssen and Rietveld, 1990, 129). Frequently, conflict exists between planning objectives and the vested interests of groups involved in the planning process. It is argued in this paper, that an integration of GIS and Multiple Criteria Analysis (MCA) allows conflict to be reduced by providing mechanisms for revealing participants' preferences, exploring compromise alternatives and for building consensus. This paper provides an illustration of the potential of this approach through a discussion of the design and operation of a prototype SDSS intended to assist decision-making in a land use planning context.

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GIS and Decision-making in Planning

Much of the use of GIS in planning assumes use of a rational mode of decision-making, which entails a linear process initiated with the identification of a problem, followed by a comprehensive search for alternatives and concluded with the selection of the optimal alternative as indicated by the gathered information (Batty, 1993, 59). This process is typically characterized by recursive feedback loops in the decision process, where evaluation and selection criteria are refined and steps repeated as a result of refinements. However, these loops are generally non-systematic and informal. Under bounded rationality, uncertainties and resource constraints in the decision environment cause decision-makers to adopt a satisficing mode of behaviour such that the search for solutions concludes once an option that meets or exceeds their context-specific aspiration levels of participants is encountered (Malczewski and Ogryczak, 1996, 73).

Central to both of these models is the premise that larger volumes of accurate information will lead to better decision results (Campbell, 1991, 264). This is a premise that the GIS industry reinforces explicitly in its promotional approaches and implicitly through the continued emphasis of software and hardware development on the technical aspects of producing faster methods of manipulating larger and more diverse quantities of data. This perspective appears to be most applicable to operational decision problems that are primarily problems of plan implementation or regulatory enforcement. Much of the success that GIS have enjoyed in the planning context has been in the area of automating and assisting with frequently occurring, routine and clearly defined tasks, such as the processing of zone change applications or conducting spatial queries of housing stock or demographic databases.

Beyond basic map production and data assembly, fewer examples can be found of direct use of GIS to support the resolution of more complex and higher level strategic decision problems, such as the creation of a long term development plan. This complexity arises from three main sources. First, it is uncommon for decision-making to be conducted by a single individual - rather it is more likely to involve a number of individuals and/or groups working, to a greater or lesser degree, together (Vlek et al, 1993, 45). These participants may differ in their underlying objectives, their perception of the significant problem areas, as well as their relative influence and authority in the decision-making forum. Consequently, planning decision problems are typified by the creation and evaluation of multiple, sometimes contradictory, potential solution strategies.

Second, many planning and development issues are multifaceted and involve the introduction of change to one or more relevant socio-cultural, economic and environmental dimensions. The magnitude, nature and spatial extent of these changes can differ substantially within and between the courses of action or alternatives available to decision-makers to choose from.

Third, and most importantly, these less frequently encountered decision problems tend to be poorly defined. Decision-makers are not able to indicate clearly exactly what the nature of the problem is, what their objectives are, or what standards of measurement can be used to judge the acceptability of a solution choice (Densham, 1991, 403). The multiplicity of decision-makers, alternatives and dimensions mentioned above only accentuates these difficulties. Given this multiple objective/multiple participant context, decision-making does not focus on the rational pursuit of an optimal or even a satisficing alternative. Rather, an interactionist mode of decision-making is adopted to recognize directly the importance of bargaining and negotiation in resolving strategic decision problems (Radford, 1988, 40). In this context decision-making is seen to be a non-linear and fully recursive process that is initiated by a negotiated agreement on the nature of the ill-defined problem under study, the assumptions underlying the collection of data, and the generation of choice alternatives.

Information, including that generated from GIS, is used in a justifying manner by decision-makers first, to clarify, iteratively, and bound the problem and, second, to support their own preferred strategy role (Campbell, 1991, 265). In this context, Obermeyer and Pinto (1994, 173) note that the "belief in the ability of GIS to minimize conflict rests on an implicit assumption that the participants in the decision-making process will agree on the relative importance of the facts (data) and that all participants will construe those facts identically." In part, this belief is a manifestation of the deterministic analysis methods inherent to most commercial GIS - the most frequently cited example being overlay procedures which assume that all of the data sets being combined are of equal importance to the decision-maker(s) (Carver, 1991, 326; Janssen and Rietveld, 1990, 132). The validity of this assumption is questionable since decision-makers' objectives and priorities both vary in importance and evolve throughout the decision-making process as participants refine their understanding of the decision problem and the interactions between different criteria. Within this dynamic decision environment, conflict frequently occurs between objectives, evaluation criteria and participants.

Integrating GIS and MCA for Decision Support

In response to the shortcomings noted above, interest is being focused in the literature on integrating MCA techniques and GIS. MCA methods complement GIS in a number of ways, the most significant being the mechanisms MCA has for exposing the preferences and objectives of multiple decision-makers. Based on this capability, MCA can provide decision-makers with a structured environment for exploring the intensity and sources of conflict, generating compromise alternatives and ranking alternatives according to their attractiveness (Janssen and Reitveld, 1990, 129). Further, MCA methods are well-suited to interactionist decision-making as they are flexible, interactive, and transparent - thereby contributing to problem clarification and accountability (Carver, 1991, 326). These attributes are critical since the resolution of ill-structured, multiple-party planning problems is judged as often on the quality of the decision-making process as the validity of the outcome (Campbell, 1991, 256).

Surveys of the MCA literature can be found in Voogd (1983), Vincke (1992) and Olsen (1996), among others. The discussion in this paper is restricted to discrete compensatory methods. This class of MCA techniques is appropriate to planning issues as it focuses on problems with a finite number of choice alternatives and also permits inter-criteria tradeoffs to be made. Hence, high scores that an alternative has on some criteria can compensate for low scores on other criteria, subject to the priorities, or weights, that a decision-maker assigns to each criterion (Jankowski, 1995, 256).

As Voogd (1983, 28) notes, the general operating principles of most MCA methods are relatively simple and are based upon different methods for manipulating two matrices to produce a ranking of the alternatives under consideration. Below, the evaluation matrix, *C,* contains the set of alternatives (*I*) that are available for decision-makers to choose from and the set of attributes, or criteria (*J*), that describe the relevant characteristics of each alternative. Typically, criteria scores are standardized on a 0 to 1 scale to permit comparisons and tradeoffs between criteria measured in different units. The priority matrix *W* contains the weighting values that each decision-maker assigns to criteria to indicate their relative importance in determining the attractiveness of alternatives.

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1I} \\ \vdots & & \vdots \\ c_{1j} & \cdots & c_{IJ} \end{bmatrix} \qquad W = \begin{bmatrix} w_{11} & \cdots & w_{1K} \\ \vdots & & \vdots \\ w_{j1} & \cdots & w_{JK} \end{bmatrix} \quad (1)$$

where c_{ij} = score of alternative *i* for criterion *j*
w_{jk} = weight of criterion *j* for decision-maker *k*
and $\sum_{j=1}^{J} w_j = 1$

A number of different techniques have been developed for generating criteria weights and for calculating appraisal scores or ranks using the evaluation and priority matrices. In the latter instance, one of the most widely used techniques is the simple utility-based method of weighted summation which calculates the appraisal score of each alternative as the sum of its criteria scores times the corresponding weighting values. Other, more sophisticated, methods such as those based on the concepts of outranking (each alternative is scored according to its degree of dominance over all other alternatives and the extent to which all other alternatives dominate it) and multi-dimensional scaling (each alternative is scored relative to how far it is from a hypothetical 'ideal point') have been applied to planning problems as well. (Voogd, 1983; Nijkamp et al, 1990).

Two approaches to the integration of MCA and GIS can be identified in the literature and are used in commercial software. The first approach focuses on adding MCA to the general set of tools found in full-featured, general purpose GIS. This is done either by linking standalone GIS and MCA packages together through file exchange (loose-coupling) or by incorporating MCA techniques directly within the GIS menu structures (tight-coupling) (Jankowski, 1995, 264). With this latter 'toolbox' approach, of which IDRISI and SPANS are two commercial GIS examples, a technically skilled GIS user is usually required to act as an intermediary between the information system and the decision-makers, many of whom may have only minimal GIS knowledge, interest and general computing experience (Carver, 1991, 337).

Heywood et. al. (1994, 633) note some decision-makers may be uncomfortable with a decision-making process that is dependent upon the need to enlist an intermediary to translate their individual preferences into terms understandable by a computer software 'black box'. Adoption of this approach requires the decision maker to surrender a certain amount of control over the methods used to arrive at a decision. Consequently, more efforts are being directed toward the second approach to GIS and MCA integration, namely the tightly-coupled implementation of MCA and GIS functionality within a user-friendly, domain-specific SDSS environment.

The benefits of constructing focused SDSS rather than relying on general purpose GIS for decision support tasks have been noted elsewhere (Hall et. al., 1997) and are not repeated here. However, it can be argued that both loose and tight-coupling approaches are necessary to facilitate better GIS-based decision support - the first approach to ensure that the data sets created by general purpose GIS actually reflect the needs that the SDSS addresses, while the second approach may be more suitable for supporting strategic decision-making.

Multi-party Decision-making: The Example of *Tour*Plan SDSS

The potential of a decision support tool based on GIS inputs and MCA-based decision processing can be illustrated through a description of *Tour*Plan, a prototype SDSS designed to assist multi-party land use planning and development decision-making. While *Tour*Plan was designed to focus on a specific problem domain, namely site selection and impact evaluation for tourism planning in small island states (SIS), the design and application principles are also relevant to other land use planning contexts.

The limited export-based economies of most SIS have led them to rely increasingly on international tourism as a means of generating foreign exchange earnings. Correspondingly, concerns regarding the negative impacts of allocating scarce land resources to tourism functions have intensified in recent years. In particular, there has been increased recognition of the need for comprehensive, yet adaptive, long-range planning structures to avoid problems of ecosystem destruction, alienation of the host population, and piecemeal evolution of incongruous built environments. Further, given the importance of tourism development to the economic, social and environmental character of SIS, this planning context is characterized by a significant variety of interests including but not limited to the development industry, environmentalists, various government ministries and the public at large. Methods are required for reconciling conflicts in the priorities and objectives between and within these interest groups.

*Tour*Plan shares a generic design architecture with two other GIS-based decision support tools, one named *Access*Plan developed to deal with planning health facility locations and resource allocation, and the other named *Edu*Plan, which was developed to support school location planning and to evaluate school performance in satisfying operating objectives. As described in Hall et. al. (1997), the generic architecture of these tools is designed to support decision-making for users with a wide variety of skill sets, objectives, and problem contexts. Analyses are structured around the concept of developing scenarios, or alternate views of the future, in which one or more decision participants can explore policy problems, key assumptions, and develop alternative solution strategies. Much of the following discussion focuses on two ‘assistants’ (referred to as ‘wizards’ in Microsoft products) used by *Tour*Plan to guide users through complex procedures and to manage their access to the spatial modelling and analysis routines used by the software. The first of these assistants is a GIS-based tool for identifying sites suitable for tourism development while the second features a complementary MCA module for evaluating sets of choice alternatives.

Since dedicating land to tourism functions such as accommodation, attractions and supporting businesses can have significant and largely irreversible socio-economic and, in some cases, ecological impacts, it is paramount that these land uses are located properly. This problem is addressed by *Tour*Plan’s **site selection assistant** that permits scenarios of alternate tourism land use patterns to be developed. At a minimum, three spatial data layers are required for site selection: 1) a census-based small area layer (for example, enumeration areas (EA)) polygon layer to which census data can be linked; 2) a point or polygon layer describing the location of tourism facilities, such as hotels, guest houses, etc. and the land parcels they are situated on; and 3) a land use layer. Land use can be accommodated either in raster form (single layer) or in vector format (generalized land use polygons in one or multiple layers or multiple cadastral mapsheets of individual land parcels with attached information). Data layers representing zoning status, important natural habitats (marine and terrestrial), roadways, points of historic or cultural significance, and so on are desirable although not required.

A simple example of allocating additional land parcels to tourist accommodation allows the multi-participant nature of Tour*Plan* and the benefits of tight coupling of GIS and MCA to be explained. A site selection scenario is initiated by entering the names of the up to ten participants who will participate in the site selection process. A participant can be an individual or a group of individuals acting together (e.g. community group, business association). In this example, two participants having divergent viewpoints, namely a “developer” and a “conservationist”, are used.

Within a given scenario, all users must agree only on the delineation of a study area and the data sets (spatial and non-spatial) that will be used to select sites, as participants must use the same data layers in the site selection process. The study area used for this example is the Electoral District of West Bay on Grand Cayman, Cayman Islands. The base data layers (both spatial and attribute) used were provided by various Government Departments from the Cayman Islands and supplemented with field data by the authors. The decision to focus on West Bay District was based on a spatial analysis, within *Tour*Plan, of employment data from the most recent Cayman census (1989) that was linked to the EA map layer, the availability of vacant land parcels potentially suitable for tourism development and the proximity of the district to the capital, George Town. Other factors, including infrastructure availability or population densities could have indicated a different study area to focus on within Grand Cayman.

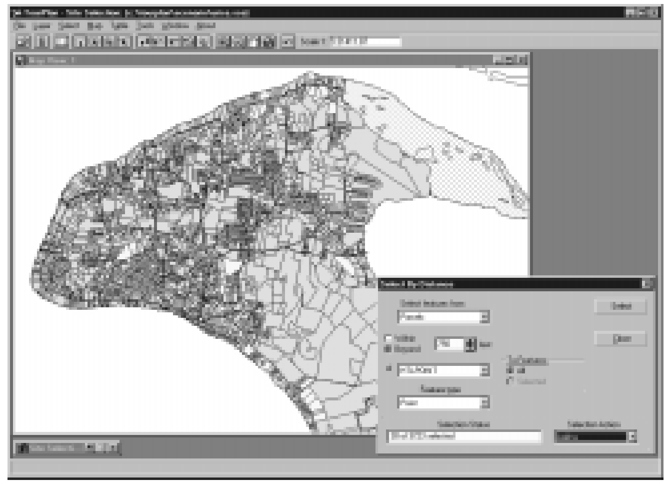

Figure 1: Selection of parcels by distance criteria

Seventeen cadastral map sheets consisting of 3723 parcels fell within the prescribed West Bay study area. From this global set of potentially developable sites for additional tourist accommodation, each of the two participants used logical Structured Query Language (SQL) and spatial queries available from *Tour*Plan’s set of site selection tools to refine a set of suitable development sites meeting their respective objectives and criteria.

Using the criteria listed in Table 1, the developer identified 19 potential sites for a 100 room hotel while the conservationist identified 69 candidate locations where several smaller guest homes could be constructed. *Tour*Plan saves all selection operations to user-specific meta data files, thereby providing a mechanism for participants to log and, at a later date, to recall and refine their rationale for conducting particular operations.

To a limited extent, the interactive and flexible procedures utilized by the site selection assistant can contribute toward conflict resolution and consensus building among multiple participants. Visual comparison and debate is fostered by displaying

Developer’s Selection Criteria
1. site size between 2 and 10 acres (building regulations and budget constraints)
2. zoned beach residential, tourism/hotel or medium density
3. more than 750 feet from existing hotels (servicing & attractions concerns)
4. within 1000 feet of sandy coastline
Conservationist’s Selection Criteria
1. site size between 1.7 and 6 acres
2. greater than 1500 feet from significant terrestrial and marine (reefs) habitats
3. more than 1500 feet from inland lakes
4. within 2000 feet of any existing hotel / tourism facility (clustering)

Table 1: Selection Criteria

static bitmaps of other participants selections alongside of a map window that displays the choice set of the "active" user currently making selections. Further, it is possible to display quickly throughout a site selection process the candidate sites that have been identified by any, none, all, or a specific participant. Finally, as individuals redefine their perception of the objective at hand and its possible outcomes, additional scenarios built upon revised objectives or assumptions can also be constructed.

Even in this simple example, GIS-based functionality is not sufficient on its own to determine which site(s) are collectively appropriate for tourism development. The selected sites represent only a list of feasible candidate possibilities, according to two different perspectives and two sets of selection criteria. Without progressively restricting the logical and distance-based screening thresholds listed in Table 1, it is not easy to determine which sites suit each party best. Expanding this procedure across several participants is particularly difficult in most, if not all, commercially available GIS software. *Tour*Plan's **MCA assistant** was programmed specifically to make this problem not only tractable, but also easy to use by non-expert computer users. Similar to the site selection assistant, the MCA assistant supports multiple participants (evaluators) concurrently and records all evaluations in scenario-like decision-making "sessions" for future recall and/or modification. In this example, participants are limited to the developer and conservationist, although other participants such as planning, engineering, and tourism staff can be added at this stage as evaluators of the suitability of either or both sets of potential sites. There are essentially seven basic steps for evaluators to proceed through in an MCA session. It is important to note that this is not necessarily a linear, nonrecursive process since participants are likely to repeat and refine certain steps (e.g. criteria weighting) in response to the results of their own actions or those of other participants. The steps are:

1. Select an MCA technique.
2. Create the evaluation matrix containing the set of feasible alternatives.
3. Add the participants who will be conducting the evaluation procedure.
4. Determine each participant's criteria weightings.
5. Calculate the rank of each alternative for each participant.
6. Display evaluation results in a database browser and a GIS map window.
7. Print outputs as required.

Due to differences in their underlying principles and assumptions, different MCA techniques can rank a set of alternatives differently. In order to manage this "method uncertainty", Voogd (1983, 199) suggested that more than one MCA technique be available for users to apply and compare in their specific problem domain. Presently, three MCA techniques are incorporated in *Tour*Plan: linear weighted summation, net concordance-discordance and subtractive summation. All three methods can be used for planning problems that can be described adequately by ratio or interval scale evaluation criteria. However, the subtractive summation technique has the important advantage of permitting criteria measured on an ordinal scale to be included also.

For the purposes of this example, the weighted summation method is used. The evaluation matrix was created by filtering the total 88 parcel records selected by either of the two participants from the site selection scenario. Four cardinal evaluation criteria were selected for use in the evaluation. The first criterion, **site area**, is calculated automatically by the software for polygons in the cadastral map sheet layer. The remaining three criteria, namely **distance to coast** (d2coast), **distance to wetlands** habitat (d2wetland) and **distance to tourism accommodation** (d2accomm), were calculated and written to the parcel attribute tables. As part of the standardization process, each user must divide the criteria into "benefit" (high data values are preferred) and "cost" (low data values preferred) types. In this hypothetical scenario, the developer viewed the d2coast criteria as a cost as a site located on or close to a sandy beach is preferred over locations farther inland. In contrast, the conservationist preferred higher d2coast values since intense tourism land uses would then be directed away from fragile coastal environments. Standardized values for cost criteria are then subtracted from 1 to ensure that low values are indicative of poor performance across all criteria while high values are associated with better scores (Voogd, 1983, 79).

Saaty's (1977) eigenvector technique is then used to determine the weighting values for the criteria. For each pair of criteria, a participant determines the importance of the first criterion relative to the second. Relative importance is measured with reference to a scale ranging from 1 (both criteria are of equal importance) to 9 (criterion 1 is extremely more important than criterion 2). These values and their reciprocals are entered into an $n \times n$ matrix from which estimates of a decision-maker's weighting values and level of consistency in expressing those priorities is determined. Group weights are calculated using the geometric mean of the two users' initial 1 to 9-scaled judgment values (Saaty, 1989, 65).

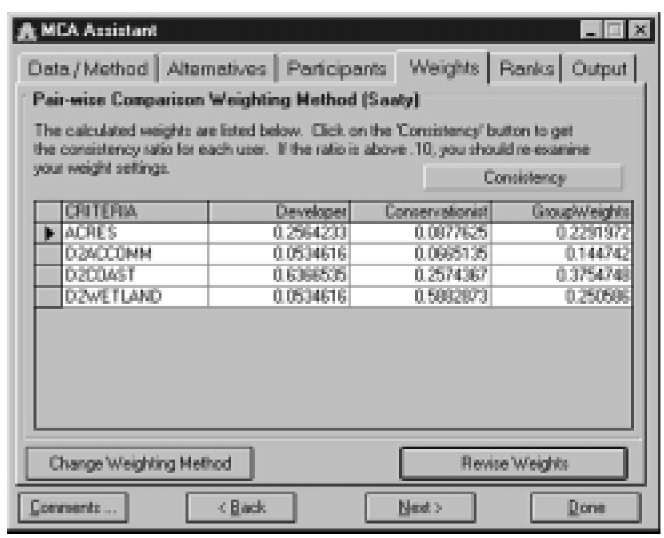

Figure 2: Criteria Weights

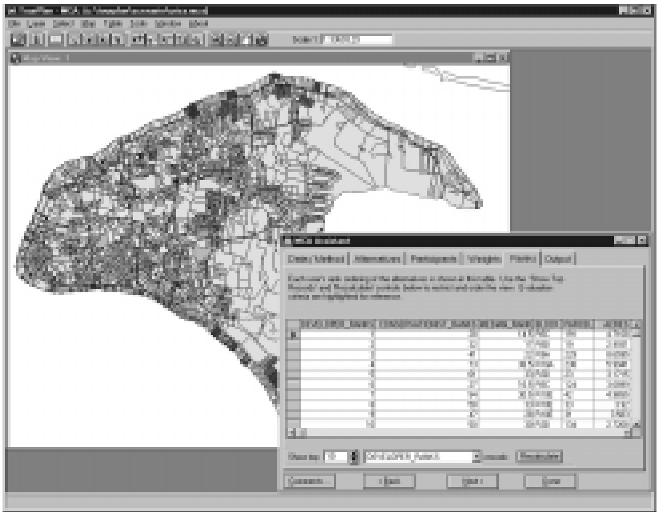

Figure 3: All selected parcels ranked using developer's weights

Appraisal scores and ranks are calculated for each alternative, using the developer, conservationist and "group" weights shown in Figure 2. Exploration of these preference-based suitability rankings is facilitated in several ways in *Tour*Plan. For instance, users can quickly filter and sort the set of feasible alternatives in a database browser according to the top *n* values of a specific criterion or ranking field. Thus, participants can easily determine how the sites that they, or some other participant, had identified in the site selection operation perform relative to different priority sets. To facilitate debate and encourage consensus building, values indicating an alternative's median rank, the number of times that it is ranked within the top *n* by any participant, and its group rank are calculated as well. In the contrived example used in this paper, evaluating the median rank or the frequency in the top *n* is not as useful as it would be in cases where more participants are involved in the decision-making process.

Consensus building, the generation of compromise alternatives, and the redefinition of priorities and perhaps even objectives are encouraged further through map-based visualization of the rankings. Easy-to-use facilities are provided in *Tour*Plan for users to display particular subsets of the entire choice set (e.g. sites selected by specific users, all users, any one user, etc.) and classify these alternatives according to any of the ranking or criteria fields. Hence, users can view their own prioritized selection sets as well as those of other participants.

The map display then serves as a vehicle for reducing conflict and discovering new viable alternatives as the degree of spatial proximity of the participants' moderately-to highly-ranked alternatives is made readily apparent. Therefore, complete consensus is represented by sites that are present in all participants' selection sets and are also ranked more or less equally according to the participants' individual priority. In instances where spatial and priority-based coincidence are not evident, the graphical display of choice selections and corresponding evaluations foster debate and may also highlight the need for individuals to reconsider their weighting assignments and/or choice of evaluation criteria.

Conclusions

GIS provide a powerful and unifying framework for managing the many and diverse spatial data sets required in most planning and development activities. Further, they allow analysts to conduct simple and complex spatial analyses that transform data into visual information in map form. Despite these benefits, GIS have not proven to be as useful for supporting the resolution of ill-defined decision problems, characterized by the presence of multiple interest groups and multiple, sometimes contradictory, objectives. To date, commercial GIS software is primarily able to facilitate without substantial macro programming effort less complex decision support tasks, involving only a single decision objective and a single participant.

Domain-specific information tools, such as the *Tour*Plan SDSS described in this paper, are intended to support decision-making in both the simple (one participant, one decision objective) and complex (multiple participant, multiple objectives) contexts. This is achieved through flexible problem-structuring, based on an integration of geoprocessing technology and MCA methods. Explicit recognition of the interactionist nature of multi-participant decision-making is provided through user-friendly methods which allow participants to develop their own preferred "solutions" to a decision problem within a given scenario file. The same participants or other participants are then able to singly or jointly evaluate the suitability of these solutions with reference to their own evaluative priorities.

Continued work on the *Tour*Plan tool will focus on enhancement of its usefulness to higher-level users (through, for example, addition of an object-oriented scripting language) and decision-makers. In particular, efforts targeted at both high- and low-end users will be directed at improving the generation of alternative sites through fuzzy set-based SQL expression building and distance-based selections and enhancing the evaluation of alternatives through better methods of sensitivity analysis, as well as improving aspects of general usability such as enhanced reporting and map composition capabilities.

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