Multicriteria Spatial Decision Support Systems: Overview, Applications, and Future Research Directions

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Abstract: Decision makers historically have indicated that inaccessibility of required geographic data and difficulties in synthesizing various recommendations are primary obstacles to spatial problem solving. Studies have shown that the quality of decisions (i.e., the ability to produce meaningful solutions) can be improved if these obstacles are lessened or removed through an integrated systems approach, such as a spatial decision support system (SDSS). In addition, multicriteria decision making (MCDM) and a wide range of related methodologies offer a variety of techniques and practices to uncover and integrate decision makers' preferences in order to solve "real-world" GIS-based planning and management problems. However, because of conceptual difficulties (i.e., dynamic preference structures and large decision alternative and evaluation criteria sets) involved in formulating and solving spatial decision problems, researchers have developed multicriteria-spatial decision support systems (MC-SDSS). In this paper, we present a general overview of MC-SDSS, briefly review applications of MC-SDSS to a broad range of decision problems, and provide direction for future trends and research in this area.

Keywords: Decision support; Multicriteria; GIS; Information technology; MCDM, Decision analysis.

1. INTRODUCTION

Spatial multicriteria decision problems typically involve a set of geographically-defined alternatives (events) from which a choice of one or more alternatives is made with respect to a given set of evaluation criteria [Jankowski, 1995; Malczewski, 1996]. Spatial multicriteria analysis is vastly different from conventional MCDM techniques due to inclusion of an explicit geographic component. In contrast to conventional MCDM analysis, spatial multicriteria analysis requires information on criterion values and the geographical locations of alternatives in addition to the decision makers' preferences with respect to a set of evaluation criteria. This means analysis results depend not only on the geographical distribution of attributes, but also on the value judgments involved in the decision making process. Therefore, two considerations are of paramount importance for spatial multicriteria decision analysis: (1) the GIS component (e.g., data acquisition, storage, retrieval, manipulation, and analysis capability); and (2) the MCDM analysis component (e.g., aggregation of spatial data and decision makers' preferences into discrete decision alternatives) [Carver, 1991; Jankowski, 1995]. The major elements involved in spatial multicriteria analysis are shown in Figure 1 [Malczewski, 1999].

Figure 1 presents a three-stage hierarchy of intelligence, design, and choice to represent the decision making process [Simon, 1960]. In the intelligence phase, data are acquired, processed, and exploratory data analysis is performed. The design phase usually involves formal modeling/GIS interaction in order to develop a solution set of spatial decision alternatives. The integration of decision analytical techniques and GIS functions is critical for supporting the design phase. The choice phase involves selecting a particular alternative from those available. In this phase, specific decision rules are used to evaluate and rank alternatives. The three stages of decision making do not necessarily follow a linear path from intelligence, to design, and to choice [Malczewski, 1999].

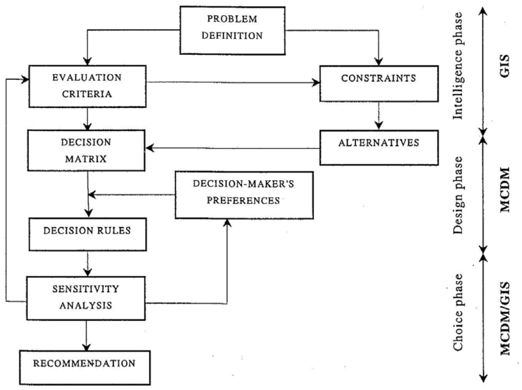

Figure 1. Decision flowchart for spatial multicriteria analysis [Malczewski, 1999].

2. MULTICRITERIA SPATIAL DECISION SUPPORT SYSTEMS

Multicriteria-spatial decision support systems (MC-SDSS) can be viewed as a part of a broader field of spatial decision support systems (SDSS) which have been extensively covered in the literature [e.g., Goodchild and Densham, 1990; Craig and Moyer, 1991; Densham, 1991]. The need for using such systems is derived from situations where complex spatial problems are ill- or semi-structured, and decision makers cannot define their problem or fully articulate their objectives. The decision making process adopted to solve semi-structured spatial problems is often perceived as unsatisfactory by decision makers. Densham [1991] lists the distinguishing capabilities and functions of SDSS, which should be capable of: 1) providing mechanisms for the input of spatial data; 2) allowing representation of the spatial relations and structures; 3) including the analytical techniques of spatial and geographical analysis; and 4) providing output in a variety of spatial forms, including maps. Similar to DSS, SDSS typically have three components: a database management system and geographical database, a model-based management system (analytical modeling capabilities and analysis procedures), and a dialogue generation and management system (a user interface with display and report generators). Certain authors [e.g., Goodchild et al., 1992] look at the expert analyst required to operate the system as posing a barrier to decision makers who must translate the problem into a form that can be understood by experts who, in turn must translate their understanding of the problem into a form that can be evaluated and solved. This prevents decision makers from directly interacting with the problem and may prevent them from discovering how intermediate decisions affect final outcomes. MC-SDSS offer a flexible, problem-solving environment where the decision problem can be explored, understood and redefined; trade-offs between multiple and conflicting objectives investigated; and priority actions set. In addition, MC-SDSS should have the ability to support both single-user and group decision-making processes. Systems in this category are termed MC-G(roup)SDSS, and usually provide multiple-user/single-model and multiple-user/multiple-model support [Carver et al., 1996]. MC-GSDSS share common characteristics with group decision support systems (GDSS). Many spatial decision problems are collaborative in nature, therefore, increasing interest in the GDSS concept as applicable to spatial decision making stems from the need to extend SDSS capabilities to support collaborative decisions. To summarize, MC-SDSS tools offer unique capabilities for automating, managing, and analyzing single-user and collaborative spatial decision problems with large sets of feasible alternatives and multiple conflicting and incommensurate evaluation criteria.

A number of frameworks for designing MC-SDSS have been proposed [Diamond and Wright, 1988; Carver, 1991; Eastman et al., 1993; Jankowski et al., 1997]. Despite differences in GIS capabilities and MCDM techniques, the generic or “blanket” framework contains three major components: a user interface, MCDM models (includes tools for generating value structure, preference modeling, and multiattribute or multiobjective decision rules), and geographical data analysis and management (includes DBMS/RDBMS, GIS analytical tools, simulation modeling routines, statistical analysis, etc.). We briefly review these components in the next three sections; Malczewski [1999] describes the components in greater detail.

2.1 User Interface Component

The user interface should support decision makers through all decision-making phases, and is the key to successful use of any decision support system [Sauter, 1997]. It includes all I/O methods by which data are entered and results and information displayed by a MC-SDSS. It enables a dynamically interactive session in a real-time exchange of information between the user and the system [Malczewski, 1999]. Philosophies and guidelines for designing interfaces for SDSS and MC-SDSS are given in Densham and Armstrong [1995], Heywood et al. [1995], Jankowski [1995], and Carver et al. [1996]. Malczewski [1999] lists a number of specific issues for consideration when designing user interfaces:

1. *Accessibility:* This implies that appropriate real-world metaphors are used in developing the graphical environment, and that users unfamiliar with the system can use it intuitively to infer the purpose of a particular screen or graphic object.

2. *Flexibility:* This allows the user to recover from unintended and adverse actions.

3. *Interactiveness:* This refers to the efficiency of information flow from the user to the system, and vice versa.

4. *Ergonomic Layout:* This stresses the effective and efficient communication between the user and the system; several strategies for dealing with the tools contained in the system should be available to the user.

5. *Processing-driven:* This allows users to be aware of the tasks they are carrying out; for example, different colors can be used to show active tools or animation in icons to indicate active processing.

2.2 MCDM Analysis Component

The MCDM component consists of a collection of value or preference structure modeling techniques and associated multicriteria decision models. The value or preference modeling techniques may include criterion weighting techniques as well as the methodology for generating the hierarchical value structure of evaluation criteria [Malczewski, 1999]. Like SDSS, MCDM models implicitly support decision makers in solving semi-structured decision problems. Multicriteria spatial models allow consideration of a number of evaluation criteria (attributes and/or objectives). This implies that usually a multitude of alternative solutions could be recommended for formal analysis by the decision maker. MCDM approaches allow for flexible integration of the attribute/spatial data and decision maker preferences. Thus the spatial modeling techniques become more realistic, more flexible, and more acceptable to the user. MCDM models provide a control mechanism for decision makers, and allow them introduce qualitative and subjective information during the evaluation and solution processes.

2.3 Geographical Data Management and Analysis Component

It is desirable that the geographical data management and analysis component contain a robust set of tools that are available in full-fledged GIS systems. This may include analytical tools for exploratory data analysis such as statistical analysis and mathematical modeling techniques. These techniques can be used to generate data inputs (criterion maps) to multicriteria decision analysis, to design and explore decision alternatives, as well as tools for sensitivity and uncertainty propagation analysis [Malczewski, 1999]. Either loose or tight coupling strategies [Nyerges, 1993; Jankowski, 1995] can be implemented for facilitating the integration of GIS and MCDM techniques (Figure 2). The loose coupling approach combines the capabilities of separate models for GIS functions and MCDM by transferring files through a file exchange mechanism [Jankowski, 1995].

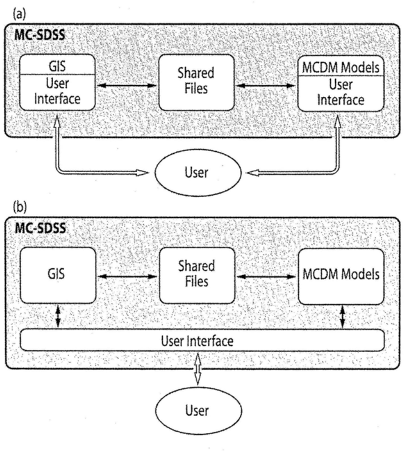

Figure 2. Loose (a) and tight (b) MC-SDSS coupling strategies [Malczewski, 1999].

Data are exported from the GIS software for use within a multicriteria spatial analysis framework. A tightly coupled strategy involves accessing MCDM analysis routines from within GIS software [Jankowski, 1995]. It allows the two components to run simultaneously and to share a common database, therefore, program control remains within the GIS when performing the multicriteria decision analysis. In general, the tight coupling approach requires a high level of knowledge of the GIS in question and considerable programming skills.

3. APPLICATIONS OF MC-SDSS

MC-SDSS have been developed and applied for a variety of situations, including land use planning [Diamond and Wright, 1988], nuclear waste disposal facility location [Carver, 1996], water resource management [Bender and Simonvic, 1995], habitat site development [Jankowski et al., 1997], health care resource allocation [Jankowski and Ewart, 1996], and land suitability analysis [Eastman et al., 1995; Fischer et al., 1996]. A more detailed list of operational MC-SDSS can be found in Malczewski [1999; Table 10.4, pgs. 336-337].

In particular, two systems stand out as examples of viable MC-SDSS tools. The first system, GeoChoicePerspectives, is a GIS-based decision support system for collaborative spatial decision making. The PC-based commercial version consists of three modules: ChoiceExplorer, ChoicePerspectives, and GeoVisual. ChoiceExplorer supports individual decision makers, and provides a toolset to select and prioritize (weight) criteria and to evaluate each alternative via an evaluation score and rank-ordered list. ChoicePerspectives provides collaborative decision support and facilitates participatory decision making and consensus by aggregating the individual perspectives developed by ChoiceExplorer. GeoVisual is an ArcView extension for map presentations and other visual decision making analyses. GeoChoicePerspectives has been successfully used for habitat site selection in the Duwamish Waterway area situated in the state of Washington [Jankowski et al., 1997]. The system has also been used for health care resource allocation [Jankowski and Ewart, 1996] and railway transportation planning. A demo copy of GeoChoicePerspectives can be obtained at http://www.geochoice.com. The second system, Open Spatial Decision Making (OSDM), is an Internet-based MC-SDSS designed to support the selection of suitable sites for radioactive waste disposal by the public in Great Britain [Carver, 1996]. It is user-friendly and does not require prior knowledge of GIS or MCDM methodology. The system has three basic components:

1. A *data viewer* component which permits users to access GIS data and information.

2. A *data selection/criterion weighting* component, which permits users to select and weight a set of constraint and criterion maps and then submit a site search request.

3. A *results display* component, which permits users to view the site search result map.

OSDM has been widely used to demonstrate Internet-based site selection methodology. A detailed discussion and run-time version of the system can be found at
http://www.ccg.leeds.ac.uk/mce/mce-home.html

In summary, the operational MC-SDSS represent many aspects of decision support, including Internet-based, collaborative spatial decision making, decision making under uncertainty, and visualization of multicriteria analysis. In general, the MC-SDSS application frameworks focus on the integration of GIS capabilities and MCDM techniques. The way the two components are integrated depends on: 1) the MCDM models incorporated into the MC-SDSS system (e.g., multiobjective versus multiattribute decision analysis techniques; 2) the decision making philosophy behind the design strategy (e.g., a system for supporting a single-user versus collaborative decision making); and 3) specific types of decision problems (e.g., environmental versus land use planning decision problems).

4. FUTURE TRENDS AND DIRECTIONS

As shown above, multicriteria spatial decision support has already been influenced by the development of the WWW. The Internet provided widespread connectivity between computers; this in turn has facilitated the storage and retrieval of information, including spatial data. In recent years there have been numerous efforts to develop the WWW as a tool for sharing geographic information, through clearinghouses, digital spatial data libraries, etc.; however, much progress is needed before the reality of WWW-based intelligent geographic information management is realized.

Modularization of code is a recent trend likely to affect the world of multicriteria spatial decision support in the next few years. Existing spatial toolsets will be radically affected by current trends toward OpenGIS and interoperability. In order to make GIS interoperable, it will be necessary to establish common standards of meaning, so that concepts in one system can be linked to concepts in another. As data models and database structures become more complex and varied, to better represent the wide diversity of geographic phenomena in our world, metadata will become critical for recognizing, understanding and assessing the range of available data. Currently, standardized metadata has not been designed to describe any data models other than very basic vector and raster structures. Not only does standardized metadata provide the means for recognizing the format and structure of a database for users other than the data creator, it will increasingly provide the means for interoperability of data between different platforms, systems and software packages.

Finally, future multicriteria decision support technologies must be not only spatial but also spatial-temporal. They must address certain key questions: How do we handle large spatial data sets (e.g., remotely-sensed data at a global scale)? What techniques can account for the ways that spatial data influence the type of decision analysis employed (e.g., scale and aggregation effects)? What generic GIS tools are optimal for spatial analysis? In the future it will be necessary to:

1. *Develop methods for handling massive spatial data sets*: As georeferenced data sets become larger, we must develop methods to use, classify, and manipulate the rich information inherent in very large (i.e., global) spatial data bases.

2. *Analyze spatial and space-time data*: We must extend exploratory methods of analyzing spatial data to include space-time data so that we can develop models (decision and otherwise) that better represent reality.

3. *Develop computationally intensive tools and methodologies*: Computationally intensive tools can allow more effective use of large data sets, more sophisticated and extensive simulations of complex spatial phenomena, and the solution of complex location and distribution problems. Potential techniques for inclusion into MC-SDSS include neural nets, fuzzy sets, wavelets, process-based simulation models, artificial intelligence/life, real-time data analysis, numeric optimization techniques and massively parallel algorithms. Many of these techniques have already been incorporated, and should be further evaluated in MC-SDSS environments to determine their usefulness in "real-world" applications. Moreover, our multicriteria spatial decision support tools must be capable of dealing with uncertainty, and coping with multiple sources of varying data quality.

5. SUMMARY AND CONCLUSIONS

Despite the fact that MC-SDSS technology has been successfully applied to "real-world" problem solving, relatively few full-featured MC-SDSS have been developed, implemented, and evaluated. Rapid growth of these systems has occurred in the past decade; however, the field of MC-SDSS is far from maturity. Continued changes in computer hardware and software technology are fundamentally altering the way that decision makers, stakeholders, policy makers, and analysts interact with computers. For example, the possibility of quickly accessing and processing large, spatially distributed databases over high-speed, readily accessible networks offers a tremendous improvement in the way that MC-SDSS are developed and the effectiveness with which they are used. The growing acceptance of graphical, user-friendly operating systems and software has opened the door for more decision makers to take an active role in the use of these systems in spatial decision problem solving. This trend should continue and will probably bring more focus on the formulation of MC-SDSS that are responsive to the needs of the decision makers. This will place a high emphasis on multi-disciplinary team approaches, communications with stakeholders, and appropriately identified issues that are realistic and carry an appropriate recognition of complexities. There are many opportunities for improving MC-SDSS: it would appear that many MC-SDSS tools may be ahead of underlying methodologies, many tools and methodologies may be too complex for potential clients, and that MC-SDSS tools are not always easily accessible. Furthermore, a frequent complaint is that not all objectives of all stakeholders are incorporated in developed MC-SDSS prototypes, i.e., we are not holistic enough in our thinking with regards to considering the multitude of uses, resources, and spatial/temporal scales. In general, MC-SDSS should move decision making toward an equilibrium which reflects an acceptable level of technology, risk /uncertainty, and values of the decision making socio-economic or political-cultural groups.

In conclusion, it is important to see multicriteria spatial analysis as interacting, dynamic parts of the spatial decision support whole. Multicriteria spatial analysis is moving to a more exploratory, interactive emphasis with new decision analysis tools; at the same time GIS is moving to a more expansive view of spatial decision support with exciting new applications. There is increasing emphasis on the study of complex systems through simulation, based in part on the argument that complex systems now dominate the scientific agenda. GIS itself is moving to a greater level of integration with other types of software, and greater modularity. Multicriteria spatial decision support is clearly the appropriate paradigm for the future, precisely because it is such an adaptable and comprehensive concept.

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