SPATIAL DECISION SUPPORT SYSTEMS: A RESEARCH AGENDA

Paul J. Densham,
National Center for Geographic Information and Analysis
and
Department of Geography,
State University of New York at Buffalo,
Buffalo, NY 14260
GEOPJD@UBVMS.BITNET

and

Michael F. Goodchild,
National Center for Geographic Information and Analysis
and
Department of Geography,
University of California at Santa Barbara,
Santa Barbara, CA 93106
GOOD%TOPDOG.UCSB.EDU@SBITP.BITNET

ABSTRACT

Definitions of geographic information systems often focus on the capture, storage, manipulation, analysis and display of spatial data - implying that geographic information systems implicitly are designed to support spatial decision-making. For many spatial problems, however, geographic information systems do not support decision-making effectively: analytical modelling capabilities are lacking and system designs are not flexible enough to accommodate variations in either the context or the process of spatial decision-making. One response to these needs is the development of spatial decision support systems. We draw a distinction between geographic information systems and spatial decision support systems in terms of system design, the types of problem to which each can be applied, and the decision-making processes supported. We classify the impediments to both the design and implementation of spatial decision support systems and outline a research agenda to address these problems.

INTRODUCTION

Definitions of geographic information systems (GIS) place varying degrees of emphasis on the functions of capturing, storing, manipulating, analyzing and displaying spatial data. Implicit in many of these definitions is that GIS are designed to support spatial decision-making. We contend, however, that for many complex spatial problems GIS do not support decision-making effectively. Current GIS lack analytical modelling capabilities; indeed, "Virtually all GIS developments thus far have resulted in 'data retrieval and sifting' engines; modelling work has not yet been brought together with this technically accomplished sub-structure" (Rhind, 1988). Furthermore, current GIS designs are unable to accommodate variations in either the context or the process of spatial decision-making.

To support spatial decision-making effectively, a system design strategy that explicitly accommodates both the context and the chosen process of spatial decision-making is required. Spatial decision support systems (SDSS) are being developed in response to these needs. Such systems can be viewed as spatial analogues of decision support systems developed in operational research and management science to address business problems.

Our objectives are twofold: first, we draw a distinction between GIS and SDSS in terms of system design, the types of problem to which each can be applied, and the decision-making processes supported; second, we examine the impediments to both the design and implementation of SDSS and outline a research agenda to address these problems.

SPATIAL PROBLEMS AND DECISION-MAKING

A Classification Scheme for Spatial Problems

One classification scheme for spatial problems is based on the degree of structure that a problem exhibits. The fundamental variables and relationships of a well-structured problem are easy to identify, to measure and, consequently, to represent in a mathematical model. Semi or ill-structured problems (Gorry and Morton, 1971; Alter, 1980; Hopkins, 1984), often defined as complex, have aspects that are essentially qualitative in nature and require value judgements to be made; in addition, the decision-maker may be unable, or unwilling, to articulate clearly both the objectives of the analysis and their preferences for characteristics of the solution. Furthermore, the psychological literature shows that people have a range of decision-making strategies; that they place differing emphases on variables and relationships; and that they will select and use information in a variety of ways before making a decision. The decision-making process applied to ill-structured spatial problems must reflect these inherent difficulties and inter-personal differences.

Decision-makers have turned to analysts and analytical modelling techniques to enhance their decision-making capabilities when faced with complex spatial problems. The decision-making process adopted, however, often has been unsatisfactory (Densham and Rushton, 1988): many mathematical models, including hybrid formulations, fail to capture the important dimensions of spatial problems; those problem dimensions actually modelled have been selected by analysts, rather than decision-makers; consequently, the variables selected and the level of resolution and the geographic extent of their coverage have been inappropriate; and, finally, solutions have been deemed unsatisfactory when evaluated on the quality of the decision-making process that generated them. It is in this environment that GIS have been promulgated as spatial problem-solving tools.

Defining "Geographic Information Systems"

Many definitions of GIS have been advanced, including "a spatial data handling system" (Marble et al, 1983); an "internally referenced, automated, spatial information system" (Berry, 1986); "a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world" (Burrough, 1986); and "an information technology which stores, analyzes, and displays both spatial and non-spatial data" (Parker, 1988). Cowen (1988) classifies definitions of GIS into four basic approaches, based upon the underlying focus: the process-oriented approach, the application approach, the toolbox approach, and the database approach. The explicit role of analytical modelling in all these definitions, however, is limited. Indeed, Cowen (1988) defines the function of a GIS as the "ability to automatically synthesize existing layers of geographic data and to update a database of spatial entities"; while Parker (1988) states:

> "GIS analytical operations can be broken into two classes, primary and compound. Primary operations include basic GIS functions like area and distance measurement, buffer generation, reclassification, and various Boolean operations. These have been referred to as a spatial data handling 'primitives' (Berry, 1986) or GIS 'tools' (Dangermond, 1986). They are the building blocks out of which compound procedures are developed."

Clearly, neither the role of analytical modelling techniques nor the decision-making process supported have been of primary concern in defining GIS. If GIS are to provide effective decision-making support in solving complex spatial problems, they must integrate analytical techniques and enable decision-makers to use their chosen decision-making processes. We believe that this integration of GIS and geographic information analysis (GIA) is best achieved within the framework of spatial decision support systems.

SPATIAL DECISION SUPPORT SYSTEMS

Semi-structured problems often are addressed by selecting viable solutions from among a set of competing alternatives. The goal of a SDSS is to help decision-makers generate and evaluate these alternative solutions. Thus, the decision-making process is iterative, integrative and participative: it is iterative because the decision-maker generates and evaluates a set of alternative solutions, gaining insights which are input to, and used to define, further analyses; integration occurs because decision-makers, who hold expert knowledge that must be incorporated into the analysis with the quantitative data in the models, evaluate alternatives across a broad range of pertinent criteria, making value judgements that materially affect the final outcome; and, finally, this participation by decision-makers returns control over the decision-making process to them, enhancing the quality of that process.

Decision Support Systems

Spatial decision support systems have evolved in a manner which parallels that of decision support systems in the business data-processing community. During the 1960s and 1970s, business decision-makers sought better analytical modelling capabilities and more interaction with solution processes, features lacking in the management information systems (MIS) of the period. A new literature, initiated by Gorry and Morton's (1971) paper, has documented the development of decision support systems (DSS), resulting in a substantial body of theory and a large number of applications (see Keen and Morton, 1978; Alter, 1980; Bonczek, Holsapple and Whinston, 1981; Ginzberg and Stohr, 1981; Sprague and Carlson, 1982; Bennett, 1983; House, 1983). DSS provide a framework for integrating analytical modelling capabilities, database management systems and graphical display capabilities to improve decision-making processes.

Differentiating GIS and SDSS

Geoffrion (1983) identifies six distinguishing characteristics of DSS:

1) "They are used to tackle ill or semi-structured problems - these occur when the problem, the decision-maker's objectives, or both, cannot be fully and coherently specified.

2) They are designed to be easy to use, the often very sophisticated computer technology is accessed through a user-friendly front end.

3) They are designed to enable the user to make full use of all the data and models that are available, so interfacing routines and data base management systems are important elements.

4) The user develops a solution procedure using the models as decision aids to generate a series of alternatives.

5) They are designed for flexibility of use and ease of adaptation to the evolving needs of the user.

6) They are developed interactively and recursively to provide a multiple-pass approach which contrasts with the more traditional serial approach - involving clearly defined phases through which the system progresses."

In the geographic literature, the terms DSS and SDSS appear with increasing frequency. Cowen (1988) defines a geographic information system "as a decision support system involving the integration of spatially referenced data in a problem-solving environment." This definition, however, is too vague to capture the emphasis on analytical modelling and decision-making processes explicit in the DSS

literature, and generalizes the scope of SDSS to all computer-based, spatial problem-solving.

The characteristics Geoffrion identifies can be used both to define SDSS and to distinguish SDSS from GIS. To effectively support decision-making for complex spatial problems, a SDSS normally is implemented for a limited problem domain; it integrates a variety of spatial and non-spatial data; it facilitates the use of analytical and statistical modelling; a graphical interface conveys information to decision-makers; and the system both adapts to the decision-maker's style of problem-solving and is easily modified to include new capabilities (Keen, 1980).

ARCHITECTURES FOR SDSS

Sprague (1980) presents a development framework for DSS that is readily transferred to the spatial domain. He differentiates between DSS toolboxes, DSS generators and specific DSS. The DSS toolbox is used to construct the DSS generator - a sophisticated applications generator that is used to quickly develop prototype implementations, or specific DSS. Working within this framework, Armstrong et al (1986) develop an architecture for a SDSS generator - an integrated set of flexible capabilities implemented as a set of linked software modules. There are four key modules present in this architecture: a database management system; analysis procedures; display and report generators; and a user interface. To the programmer, the modularity of the system facilitates software engineering; to the SDSS user, however, the system appears to be a seamless entity.

A RESEARCH AGENDA

Designers of geoprocessing systems have begun to adopt the SDSS approach (Densham and Armstrong, 1987; Gould, 1989) but there remain many impediments to the widespread adoption of this approach. The remainder of this paper is devoted to examining some of the impediments affecting each of the four major modules of a SDSS. We suggest avenues for research that hold the promise of ameliorating the effects of these problems.

Database Management

The database management systems underpinning many GIS are designed to support cartographic display and spatial query. In contrast, the database of an SDSS must support cartographic display, spatial query and analytical modelling by integrating three types of data: locational, topological and thematic. Moreover, such a database must provide the ability to construct and exploit complex spatial relations between all three types of data at a variety of scales and levels of aggregation.

The database management systems found in many GIS use the relational data model, despite its fundamental problems in spatial applications (Marble and Calkins, 1987). Alternative data models, such as the extended network model have proved effective in applications of DSS (Bonczek, Holsapple and Whinston, 1984); Armstrong and Densham

(1990) use this model to support location-allocation modelling, cartographic display and spatial query. We advocate investigating the suitability of other data models for use in SDSS.

The techniques of object-oriented programming (OOP; Egenhofer and Frank, 1987) hold a great deal of potential for developing SDSS database management systems, supporting complex spatial relations between data items, in an easily extendible, modifiable and reusable manner.

Analytical Modelling

One approach to incorporating analytical models in geoprocessing systems is to develop libraries of analytical sub-routines (Dixon, Openshaw and Wymer, 1987). This approach permits large numbers of models to be made accessible very quickly, because existing codes can be patched into a system, but it is wasteful in terms of replicated code.

Generating solutions to analytical models often involves using an algorithm, which consists of a series of discrete steps. Heuristic location-allocation algorithms, for example, use steps to calculate the value of the objective function, to determine the effect of moving a facility location to a site not in the current solution, and to update the current solution after a facility is relocated. These steps are the "atomic" elements of such algorithms, combining them in different groups and sequences permits different algorithms to be solved. There is a similar degree of commonality in the steps used in algorithms for solving many types of spatial and non-spatial analytical models, both among algorithms applied to similar models and between algorithms applied to different types of model.

Disaggregating algorithms into their atomic elements necessitates developing "formulae" for their recombination. Such formulae could be part of a model-base management system (MBMS; Konsynski and Sprague, 1986) which, when asked to employ a particular algorithm, combines the atomic elements - discrete modules of code - into the necessary sequence. This view of a MBMS fits very well with OOP techniques; if each atom is regarded as an object, then both the required data structures and the code needed to manipulate them and do the processing can be encapsulated in each object. Messages passed from the MBMS can sequence objects in the appropriate way, indicate the data to process and communicate results to the user.

The MBMS approach offers several advantages: first, considerable reductions in storage could be realized compared with sub-routine libraries; second, the implementation of new algorithms can be achieved simply by developing a new formula - in some cases, new atoms also may be added to the model-base - so the researcher can rapidly develop and assess the suitability, effectiveness and computational efficiency of new algorithms; third, updating the model-base is easy because individual atoms can be replaced by improved versions without changing others.

To develop sophisticated model-base management systems for SDSS generators, the wide range of algorithms used in GIA must be examined. Researchers will need to develop a taxonomy of the uses to which each of these algorithms is put, and the atomic elements from which each is built. This taxonomy will guide the process of designing, implementing and developing model-base management systems; it also may provide considerable insight into the nature of GIA. We may recognize underlying similarities between models and algorithms, subsequently developing unifying frameworks - such as the unified linear model in location-allocation modelling (Hillsman, 1984).

Graphical Display And Report Generation

GIS normally provide high-resolution cartographic displays. In a SDSS, this capability must be augmented with other kinds of graphical displays. These must include both general forms, such as two and three-dimensional scatter plots and graphs, and those specialized forms used to represent the output from statistical analyses and varying types of analytical models.

In addition to providing these capabilities, a SDSS should enable its user to interact graphically with the MBMS. By this, we mean that the user should be able to adjust model parameters by interacting with a graphical display. For example, the initial solution for a location-allocation model can be selected by using a mouse to click on locations on a map rather than by typing in a list of node identifiers. Taking this interaction a stage further, the user could carry out visual interactive modelling (Hurion, 1986), where the system user and the selected analytical models carry out a dialogue via a graphical display. Thus, the user is able to intervene and manipulate the model during the solution process. The visualization of the solution process itself, and of the changes taking place in the modelled system, will require a lot of research into human factors, cognition, and the design of new kinds of graphical display. SDSS will require very different user interfaces to those commonly available.

User Interfaces

The user interfaces of many geoprocessing systems are modelled on those of business systems. Command lines, system prompts, obtuse commands, and jargon abound. The move to graphical interfaces for operating systems provides an opportunity for system designers to rectify many of these shortcomings, rather than simply incorporating them in overlapping windows and pull-down menus. A move towards more interactive modelling, with two-way communication taking place via a graphical display, will necessitate the development of intuitive interfaces. The use of icons to represent system capabilities is one way to proceed, but the cultural specificity of icons has not been adequately researched.

Expert Knowledge. We noted above that decision-makers often have turned to expert analysts to help them solve complex spatial problems. To provide effective decision support, a SDSS should incorporate knowledge used by expert analysts to guide the formulation of the problem, the articulation of the desired characteristics of the solution, and the design and execution of a solution process (Armstrong et al, 1989). The elicitation and incorporation of this knowledge is a major avenue for research.

Three kinds of knowledge need to be considered: environmental, procedural and structural. Environmental knowledge describes the fabric of the problem. Procedural knowledge is derived from the problem-domain and is used to help design a solution process and determine the values of model parameters. Finally, structural knowledge is exploited during analysis to solve problems efficiently, using a minimum of computation. In assisting a decision-maker, expert analysts variously synthesize these three types of knowledge with their own procedures during the different stages of solving a problem. Designers of SDSS must determine what these procedures are, when they are used with the three kinds of knowledge, and how to represent them within the system.

CONCLUSIONS

The development of SDSS requires many issues to be addressed, drawing upon current and future research findings in many disciplines. Areas that will require particularly concentrated research include: the development of DBMS that can support cartographic display, spatial query and analytical modelling at a variety of spatial scales and geographical extents for a large number of variables; MBMS that provide users with flexible modelling and analysis capabilities that are extended easily; graphical user interfaces that enable users to interact with systems in an intuitive way; and the elicitation and representation of expert knowledge which the user can draw upon for guidance at all stages of the decision-making process. If GIS are to evolve into SDSS, system designers will have to address these issues and also ensure that their systems are capable of supporting different cognitive styles of decision-making in a variety of decision-making environments and contexts.

ACKNOWLEDGEMENT

We wish to thank Michael D. Gould for his insightful comments and suggestions. This paper is a contribution to Initiative 6 (Spatial Decision Support Systems) of the National Center for Geographic Information and Analysis.

REFERENCES

Alter, S.L. 1977, A taxonomy of decision support systems, Sloan Management Review, Vol. 19, pp. 39-56.

Alter, S.L. 1980, Decision Support Systems: Current Practice and Continuing Challenges, Addison-Wesley, Reading

Armstrong, M.P., S. De, P.J. Densham, P. Lolonis, G. Rushton and V.K. Tewari 1989, A knowledge-based approach for supporting locational decision-making, Department of Geography, The University of Iowa, Iowa City, Iowa 52242

Armstrong, M.P. and P.J. Densham 1990, Database organization alternatives for spatial decision support systems, Forthcoming, International Journal of Geographical Information Systems

Armstrong, M.P., P.J. Densham and G. Rushton 1986, Architecture for a microcomputer-based decision support system, Proceedings, the Second International Symposium on Spatial Data Handling, International Geographical Union, Williamsville, New York, pp. 120-131.

Berry, J.K. 1986, Learning computer-assisted map analysis, Journal of Forestry, pp. 39-43.

Bonczek, R.H., C.W. Holsapple, and A.B. Whinston 1981, Foundations of Decision Support Systems, Academic Press, New York

Bonczek, R.H., C.W. Holsapple, and A.B. Whinston 1984, Micro Database Management: Practical Techniques for Application Development, Academic Press, New York

Burrough, P.A. 1986, Principles of Geographical Information Systems for Land Resources Assessment, Oxford University Press, Oxford

Cowen, D.J. 1988, GIS versus CAD versus DBMS: what are the differences? Photogrammetric Engineering and Remote Sensing, Vol. 54, pp. 1551-1555.

Dangermond, J. 1986, The software toolbox approach to meeting the user's needs for GIS analysis, Proceedings of the Geographic Information Systems Workshop, American Society for Photogrammetry and Remote Sensing, Atlanta

Densham, P.J. and M.P. Armstrong 1987, A spatial decision support system for locational planning: design, implementation and operation, Proceedings, Auto Carto 8, pp. 112-121.

Densham, P.J. and G. Rushton 1988, Decision support systems for locational planning, in R. Golledge and H. Timmermans eds., Behavioural Modelling in Geography and Planning, Croom-Helm, London, pp. 56-90.

Dixon, J.F., S. Openshaw and C. Wymer 1987, A Proposal and Specification for a Geographical Analysis Sub-routine Library, Northern Regional Research Laboratory, Research Report 3, Department of Geography, University of Newcastle, Newcastle upon Tyne.

Egenhofer, M.J. and A.U. Frank 1987, Object-oriented databases: database requirements for GIS, Proceedings, International Geographic Information Systems Symposium, NASA, Vol. II, pp. 189-211.

Geoffrion, A.M. 1983, Can OR/MS evolve fast enough? Interfaces, Vol. 13, pp. 10-25.

Ginzberg, M.J. and E.A. Stohr 1981, Decision support systems: issues and perspectives, in M.J. Ginzberg, W. Reitman and E.A. Stohr eds., Decision Support Systems, North-Holland, New York

Gorry, G.A. and M.S. Morton 1971, A framework for management information systems, Sloan Management Review, Vol. 13, pp. 56-70.

Gould, M.D. 1989, The value of spatial decision support systems for oil and chemical spill response, Forthcoming, Proceedings of the 12th Applied Geography Conference, Binghampton, New York

Hopkins, L. 1984, Evaluation of methods for exploring ill-defined problems, Environment and Planning B, Vol. 11, pp. 339-48.

House, W.C. 1983, ed. Decision Support Systems, Petrocelli, New York

Hurion, R.D. 1986, Visual interactive modelling, European Journal of Operational Research, Vol. 23, pp. 281-287.

Keen, P.G.W. 1980, Adaptive design for decision support systems. Data Base, Vol. 12, pp. 15-25.

Keen, P.G.W. and M.S. Morton 1978, Decision Support Systems: An Organizational Perspective, Addison-Wesley, New York

Konsynski, B. and R.H. Sprague 1986, Future research directions in model management, Decision Support Systems, Vol. 2, pp. 103-109.

Mantey, P.E. and E.D. Carlson 1980, Integrated geographic data bases: the GADS experience, in A. Blaser ed. Data Base Techniques for Pictorial Applications, Springer Verlag, Berlin, pp. 173-98.

Parker, H.D. 1988, The unique qualities of a geographic information system: a commentary, Photogrammetric Engineering and Remote Sensing, Vol. 54, pp. 1547-1549.

Rhind, D. 1988, A GIS research agenda, International Journal of Geographic Information Systems, Vol. 2, pp. 23-28.

Sprague, R.H. 1980, A framework for the development of decision support systems, Management Information Sciences Quarterly, Vol. 4, pp. 1-26.

Sprague, R.H. and E.D. Carlson 1982, Building Effective Decision Support Systems, Prentice-Hall, Englewood Cliffs