INTEGRATIVE DATA STRUCTURES FOR COLLABORATIVE MODELING AND VISUALISATION IN SPATIAL DECISION SUPPORT SYSTEMS

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Summary

Spatial decision support systems, in which group members individually and collectively pursue solutions to ill-structured problems, have a unique set of analytical and cartographic visualization requirements. This article describes an approach to supporting group decision-making activities. The focus is on the domain of facility location problems and this article describes a set of map types that depict the elemental structure of location selection scenarios. These map types are designed to support the process of summarizing alternatives and for making comparisons among them. The derivation of these map types and their alternative forms are described and examples are presented. In each case, the maps are created through the use of a specific set of data

structures that capture the salient elements of each solution and enable the computation of summary maps.

1. Introduction

Plan-making routinely involves a broad community of actors that may include the public, particular stakeholder coalitions, and interest groups that respond in different ways to specific issues. With the increasing use of computer-based tools to support the generation and evaluation of alternative planning scenarios, tension based on competing analyses by stakeholders can arise. The resolution of such tension can be realized through the development of computer-based tools that are specifically designed to support participative decision-making processes.

Such tools, however, may prove to be inaccessible to some parties who wish to influence plan- making. Furthermore, the design, implementation and application of such tools is complicated because stakeholders typically hold different views of a problem and, as a consequence, they may have considerably different perspectives on the way questions should be defined and addressed. For example, if a proposed residential development project would impact a wetland, considerable tension could arise between, for instance, developers and environmental advocates with each stakeholder supporting or attacking different aspects of the proposal. A problem such as this is referred to as ill-structured because it contains aspects that defy the most strenuous attempts of model developers to capture all its relevant characteristics in a computer representation. Maps play an important role in communicating information about many aspects of planning, especially when computer technologies are applied to ill-structured problems. However, methods to compare maps of alternative planning strategies and to resolve a divergence of views on what constitutes a good solution are not widely available. The purpose of this article is to present a conceptual framework and a set of illustrations that describe the types of cartographic displays required to support participative planning by multiple stakeholders in a decision support environment. A set of prototypical examples from location selection problems is used to illustrate the discussion. For related issues, see *Introduction to Spatial Decision Support Systems.*

2. Context

Computer-based systems that are explicitly referred to as decision support systems (DSSs) have been built since the early 1970s. These systems were a response to the need articulated by decision makers for flexible tools that could help to address the complex problems facing corporations. DSSs are explicitly designed to address ill-structured problems: typically strategic in nature rather than routine, an organization often has not faced similar problems before and, therefore, no body of knowledge exists on how best to address them. Consequently, ill-structured problems are recognized as being dynamic rather than static, having elements that cannot be fully defined, incommensurable variables, and often decision makers are not clear what their objectives are, which characteristics of a solution might be desirable, or even how best to proceed.

To address ill-structured problems, decision makers need DSSs that are "systems to think with": flexible tools that have a number of desirable characteristics: first, a powerful and easy to use interface; second, a system architecture that enables users to combine data and analytical models in flexible and novel ways; third, well-structured models that help users to understand how variables interact and, thus, can be used to explore the solution space—the range of feasible options; and fourth, the accommodation of users with different cognitive and decision-making styles, who will wish to use the system in different ways to address the same problem.

Consequently, the system architecture must be flexible enough to respond to changing user needs by rapidly assimilating new capabilities, as they are required. Finally, because users will be exploring the solution space, learning about the problem and its structure as they do so, a DSS must support a process of problem solving that is both interactive and recursive. Interaction and recursion enable users a particular avenue of investigation and then to backtrack and try others, possibly synthesizing elements from various avenues in the search for a resolution strategy for the problem. The nature of ill-structured problems means that rather than being solved completely, a resolution strategy is developed for a given problem that adapts to its evolution through time, as more is learnt about it.

Spatial decision support systems (SDSSs) have evolved from geographic information systems (GISs) in much the same way as DSSs were built upon the data organization and sifting capabilities of management information systems. The academic literature on SDSSs has existed since the early 1980s and borrows heavily from those on GISs and DSSs. In addition to the characteristics of DSSs identified above, a SDSS requires the capabilities to: input and structure spatial data; represent the often complex spatial relations that characterize detailed digital spatial datasets; apply methods of spatial and geographical analysis to the data held in the system; and to generate maps and other spatial outputs that help users to visualize and understand the elements of their problem and the ramifications of particular resolution strategies. This article focuses on this last capability. (See also ***Web-Based Spatial Decision Support: Technical Foundation and Applications.)***

2.1. A SDSS Architecture

A common architecture for SDSSs is depicted in Figure 1. The user interacts with system components via the user interface. Ideally, the architecture behind the interface should be transparent to the user—the system should appear to be a seamless entity with no boundaries between data management, analytical, and reporting capabilities. Where such boundaries are apparent, the user will have to devote time and effort to "thinking about how the system works" rather than "using the system to think with." The architecture contains database and modelbase management systems and display and report generators. A modelbase management system (MBMS) is similar in concept to a database management system (DBMS), except that it stores computational units (atoms) that can be selected, extracted, and sequenced to yield models and algorithms—much as a database contains items of data that can be selected, extracted, and sequenced to answer queries. A MBMS offers a number of benefits, including the quick construction of new models and algorithms either from existing atoms or with the addition of one or more new atoms to the modelbase.

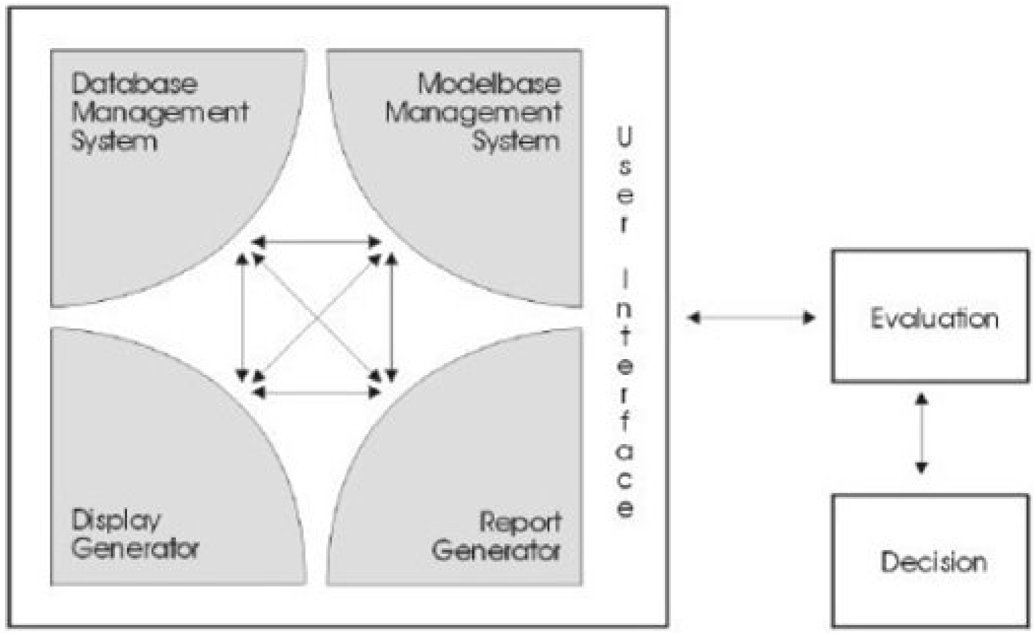

Figure 1. Architecture for an SDSS. Users work with the system components, through the user interface, to generate scenarios that are evaluated against a range of criteria.

2.2. Location Selection Problems

Although SDSSs have been used to address a wide range of ill-structured spatial problems, location selection problems are the domain of interest for this article. Given the importance of location in helping to determine the viability of many forms of economic activity, many GIS vendors include some location selection tools in their commercial products and numerous SDSSs have been built to address ill-structured location selection problems. (See also ***Spatial Decision Support for Housing Location and Residential Mobility.)***

Grocery retailers in the UK can be placed into one of three groups: "multiples," the large national and regional chains of supermarkets; "affiliates," independently owned stores that are allied with a large wholesale organization that produces "own brand" groceries; and "independents," stores that are often owner-operated, local in nature, and buy their product range from local wholesalers—the quintessential corner shop. All three groups have faced major changes in the social, economic, and legislative environments within they operate since the early 1970s. In general, there has been increasing competition from non-traditional grocery outlets, while the multiples, in particular, have undergone a process of consolidation that has eliminated both large and small players, and have been forced to compete for market share rather than enter new markets. The response of each of the multiples to these pressures reflects their unique brand image and has a major location selection element.

In a battle for market share, no supermarket operates in isolation from others in its own or competing chains. Thus, at a strategic level, each multiple must determine:

- how many supermarkets it should operate;
- where it should locate them; and
- which product lines and services should be offered at each location.

The complexity of determining a strategy as the social, economic, and legislative environments evolve, suggests that it can be considered an ill-structured problem. One approach is to reduce these questions to a series of issues, for which information can be collected, that help to inform strategy development:

- Given the brand identity of the chain, how many consumers frequent existing supermarkets and how many might be attracted to any proposed supermarket location?
- For proposed new sites—what is the cost, what is the current use and form of any existing structure, and what planning regulations are in force?
- How accessible is each current supermarket to its customers and to what degree does its site's attributes match its operator's needs? For example, is a site it on a major street, how large is the car park, and what are the adjacent land-uses?
- What products do customers buy from existing supermarkets and will this be the same for proposed locations?

Three of these four issues essentially focus on location and interaction amongst consumers and suppliers. To support its users, a SDSS must provide a representation of space that facilitates investigation of these issues. A vector representation of space is often used in which nodes depict the locations of consumers and suppliers and the paths through space amongst these locations are captured as links. With this representation, a wide range of well-developed modeling and cartographic approaches can be used to investigate the questions and issues identified above.

3. Map Types and Map Use

As a decision support tool, maps serve as more than the formal cartographic representation of a set of ideas. Maps are a basic token of exchange among participants in the planning process: they not only communicate the form and structure of a scenario, they are also an interface to its underlying data, models, and criteria. In a location selection context, such maps are constructed from the contents of a set of data structures that support locational analysis operations. The contents of these data structures are themselves derived from the decision support system's database and the knowledge of its users. To explore and modify a scenario, however, users must be able to interact with the data, models, and criteria that underlie that scenario. Consequently, while a map may be thought of as a scenario by a user, to a SDSS designer a scenario consists of: a set of user inputs and analytical operations; the contents of the analytical data structures and their linkages back to the database; and maps and other forms of graphical display. (See ***Interacting with GIS: From Paper Cartography to Virtual Environments.)***

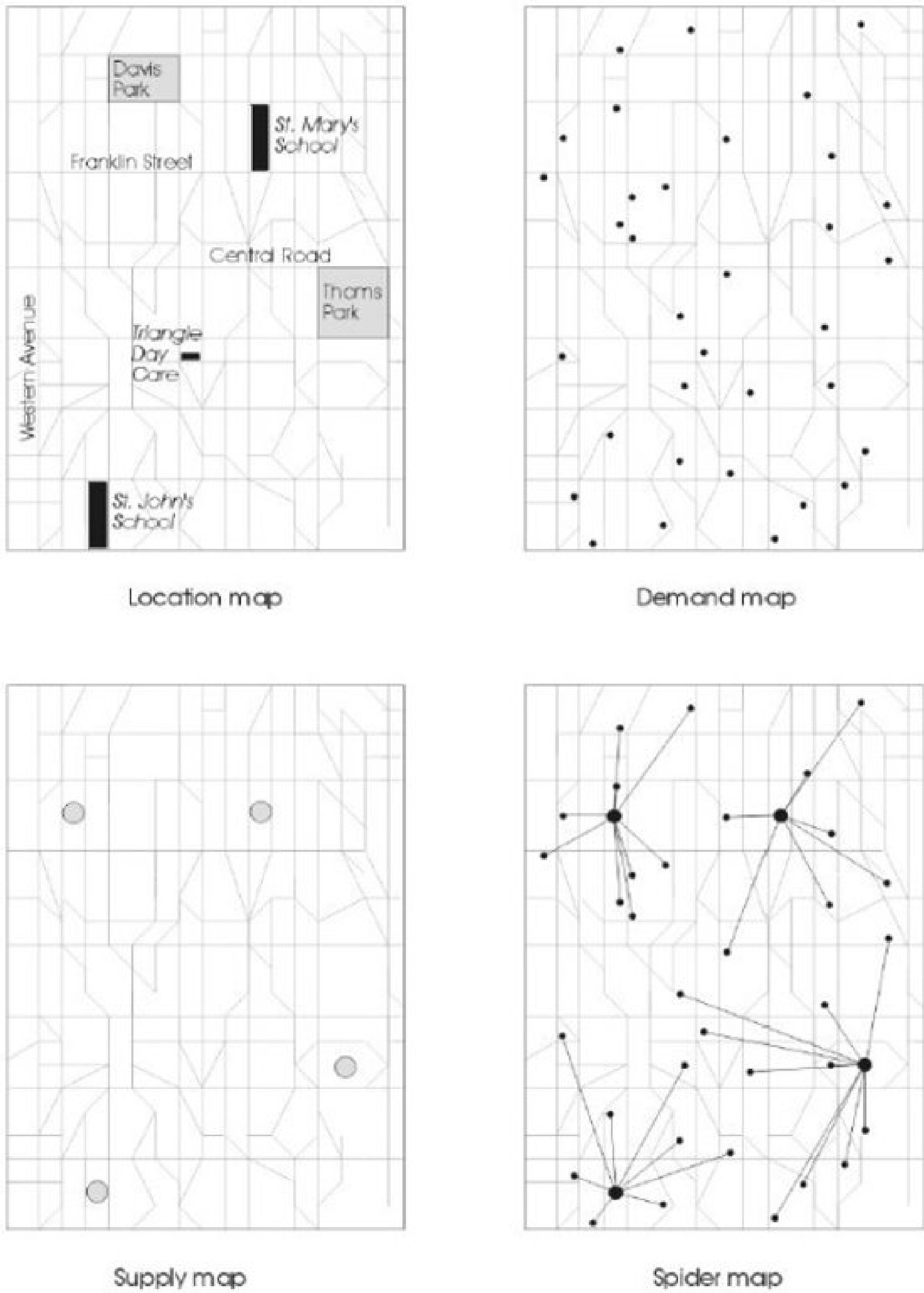

Figure 2. Four types of scenario maps: location, demand, supply, and spider. "Location maps" depict the geographical context of a decision, including highways and political jurisdictions. "Supply maps" identify the locations of facilities from which goods and services are available. "Demand maps" depict the spatial arrangement of demand for goods and services. "Spider maps" relate supply to demand.

Several types of maps can serve as exchange tokens during group decision-making. Amongst these are "scenario maps" (see Figure 2) that have been designed explicitly to support locational decision- making depicting the characteristics of individual scenarios.

A scenario is developed from a set of decision alternatives. These alternatives are normally based on a set of criteria that are used in decision making. In a spatial context, the realization of a scenario can be visualized as a map. Thus, when scenario maps are used to explore ill-structured location selection problems, an individual often uses them privately, during the process of generating a scenario. Supply maps, for example, may enable a decision maker to identify an under-served area; this problem would then be addressed in subsequent scenarios, leading to the generation of further maps. When assembled into a collection, these maps can convey the form and substance of scenario-based plan development to other participants in the decision process.

As users of a SDSS generate additional scenarios, they typically want to compare the structure and characteristics of these scenarios. However, making comparisons among numerous, similar scenarios is a difficult task. Consequently, three additional map types, described in greater detail in Section 5, have been developed for this purpose.

- "Facility frequency maps" accumulate the locations of facilities selected to provide goods or services across two or more scenarios.
- "Allocation consistency maps" identify robust combinations of demand and supply linkages—those situations where facility locations are selected in two or more scenarios.
- "Network consistency maps" are used to identify routes amongst demand and supply locations that occur across scenarios—such routes may require special attention because of weight restrictions on bridges, inappropriate speed limits on roads, and hazards that may need to be removed or at least ameliorated.

For each task that must be completed during problem solving, SDSS environments must provide users with appropriate types of maps that are created from several underlying data structures.

Historically, cartographers have provided appropriate, and often detailed, geometrical representations of space. Such representations are typically held in purpose-designed cartographic data structures that have benefited from many years of development and refinement. In a GIS context, these data structures accommodate, and support the display and analysis of, the spatial primitives from which most databases are constructed. (See ***Cartographic Generalization: Interface Issues*** **and** ***Spatio-Temporal Information Systems.)*** Spatial analysts, however, have pursued a different path and have constructed models around highly abstracted representations of spatial relationships. In some cases, traditional geographical representations are discarded altogether and only an abstracted form of topology is retained. An origin-destination matrix, for example, provides only a measure of the intervening distance between places; the geometry of the actual paths used is, at best, implicit. Though well suited to analysis, the level of abstraction of these representations makes their display difficult even though they often are derived from detailed cartographic information.

These analytical data structures also fail to reflect the broader representational context within which the results derived from their contents are evaluated and applied. This can be seen in the stand- alone nature of many custom-written modeling tools that lack integrated visualization capabilities. The developers of these tools have paid little attention to the identification and definition of the geographic primitives and objects that underlie their algorithms and models. Consequently, analytical objects normally differ from display (cartographic) objects in their structure, content, and function. This variation has, in part, led to an asymmetry: the display of cartographic objects must reflect the current status of analytical objects (for example, which nodes are facilities) but it is difficult to relate cartographic objects to analytical objects typically carrying little or no geometrical information and often only abstracted topological information.

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Bibliography

Armstrong M.P. (1994). Requirements for the development of GIS-based group decision support systems. *Journal of the American Society for Information Science* **45** (9), 669–677. [This paper sets out a range of criteria to be met, and identifies a set of issues that must be addressed, by developers of GIS-based decision support systems that are designed explicitly for group use.]

Armstrong M.P., Densham P.J., Lolonis P., and Rushton G. (1992). Cartographic displays to support locational decision-making. *Cartography and Geographic Information Systems* **19**(3), 154–164. [A classification of visualization needs during different stages of locational decision-making is developed and a set of map primitives are identified that can be combined flexibly to produce appropriate displays to meet these needs.]

Densham P.J. (1991). Spatial decision support systems, *Geographical Information Systems: Principles and Applications* (eds. D.J. Maguire, M.F. Goodchild and D.W. Rhind), pp. 403–412. London: Longman. [Provides an overview of spatial decision support systems that focuses on system definitions, architectures, and development frameworks.]

Densham P.J. (1994). Integrating GIS and spatial modeling: visual interactive modeling and location selection. *Geographical Systems* **1**(3), 203–219. [Provides an overview of visual interactive modeling and discusses how SDSS design can be modified to enhance user interaction when addressing locational problems.]

Densham P.J. and Rushton G. (1992a). Strategies for solving large location-allocation problems by heuristic methods. *Environment and Planning A* **24**, 289–304. [This paper shows how to use candidate and demand strings with the allocation table to implement heuristic location-allocation algorithms in the Locational Analysis Decision Support System (LADSS).]

Densham P.J. and Rushton G. (1992b). A more efficient heuristic for solving large p-median problems. *Papers in Regional Science* **71**(3), 307–329. [Describes a hybrid algorithm that is designed around distance strings and an allocation table, is more efficient than competing algorithms, and is used in LADSS and commercial GIS software.]

Densham P.J. and Armstrong M.P. (1995). Human-computer interaction aspects of visual-interactive locational analysis, *Cognitive Aspects of Human-Computer Interaction for Geographic Information Systems* (eds. T. Nyerges, D. Mark, R. Laurini and M. Egenhofer), pp. 179–196. Dordrecht: Kluwer. [Shows how distance strings and an allocation table can be used to provide flexible methods of user interaction with locational algorithms and other GIS-based capabilities in SDSSs.]

MacEachren A.M. (1995). *How Maps Work*, 513 pp. London: Guildford Press. [An excellent discussion of the principles of cartography and the use of maps to convey information.]

Peucker T.K. and Chrisman N.R. (1975). Cartographic data structures. *The American Cartographer* **2**(1), 55–89. [A seminal paper that has heavily influenced the subsequent development of digital cartography and GISs.]

Biographical Sketches

Paul J. Densham holds a B.A. in Geography and Economics (University of Keele, 1983), an M.Sc. in Operational Research (University of Birmingham, 1984), and a Ph.D. in Geography (University of Iowa, 1990). He is Reader in Geography and a researcher in the Centre for Advanced Spatial Analysis at University College London (UCL) where he was a Co-Principal Investigator in the *Virtual Reality Centre for the Built Environment.* He was Assistant Professor of Geography at the State University of New York at Buffalo (1988–1993) and a Research Fellow (1988–1996) in the US National Center for Geographic Information and Analysis (NCGIA). He co-led the NCGIA's research initiatives *Spatial Decision Support Systems* and *Collaborative Spatial Decision-Making* and led the investigation *Parallel Computation and GIS*. His research interests and publications focus on spatial decision support systems, locational analysis, GIS, and parallel algorithms for spatial problems.

Marc P. Armstrong has a B.A. in Geography from the State University of New York at Plattsburgh (1974), an M.A. in Geography from the University of North Carolina at Charlotte (1976) and a Ph.D. in Geography from the University of Illinois (1987). He is Professor and Chair of the Department of Geography at The University of Iowa where he also holds an appointment in the Program in the Applied Mathematical and Computational Sciences. Armstrong has served as North American Editor of the *International Journal of Geographical Information Science* and he currently serves on the editorial boards of three journals. His research interests focus on parallel computing using computational grids, spatial decision support systems and geographical visualization.