1-1-1995

Toward the development of a conceptual framework for GIS-based collaborative spatial decision-making

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1 Introduction

GIS software has been designed to support a single-user approach to spatial problem-solving. Though this approach has many significant advantages and many successful systems have been implemented during the past two decades, experience shows that many spatial problems are not always addressed by individual actors. This is especially true when complex, ill-structured interdisciplinary problems are faced. These types of problems, which in the business world may have strategic significance and in the public sector normally have a policy component, are often addressed by groups of people in a collaborative setting. These groups are formed because single individuals normally lack the breadth of experience required to solve complex, interdisciplinary problems. Because of this mis-match between current systems and the styles of problem-solving that are favored in both the public and private sectors, GIS software often cannot be used to its full potential. Several problems must be overcome before GIS can effectively support collaborative spatial decision-making (CSDM). The purpose of this paper is to develop a conceptual framework to guide the development of software environments that can be used by groups of decision-makers to address ill-structured spatial problems.

Significant technological impediments must be overcome before CSDM environments routinely can be applied to ill-structured spatial problems. In some cases, normal advances in technology may prove sufficient. For example, improvements in networking are proceeding at a rate that is likely to be sufficient to support CSDM activities. On other fronts, however, advances in software that are specifically designed for CSDM environments must be made. In addition to these technical impediments, work is required to study the behavior of groups as they apply the technology in various problem settings.

2 Data Requirements

CSDM environments must ensure that individual users will be able to access a broad array of data and modeling capabilities. Efficient access to data could cause a significant bottleneck for several reasons.

- Because several individuals will require simultaneous access to different data, network bandwidth must be sufficient to move large GIS databases. DeWitt and Gray [DG1992] page 97, for example, report that if a terabyte database is moved at a megabyte per second, over 12 days and nights are required to complete operations such as a restore. An additional complication can occur if multiple simultaneous requests to the same data are made.

- In many GIS models, raw layers are operated on using a set of “map algebra” operations [T1990] that each result in new layers that, in turn, may be subjected to additional analyses. These activities will serve to increase the volume of disk storage required to support these group activities.

- In some instances, different representations of the input data may be stored and made accessible to system users. Consider for example, an application that deals with network analyses; if a TIGER file containing road network descriptions and a small-scale locally-produced network are available for the same area, and if different analyses are conducted using the different versions of the network, it is likely that different results will be obtained. These differences would need to be resolved, often by introducing additional steps into the
decision-making process; simply to ignore these differences, particularly where they are substantial, could derail the whole process.

To overcome these problems with data and data access, it is likely that work in distributed databases can be adapted to the requirements of CSDM. For example, transaction processing in traditional distributed databases requires concurrency controls and crash recovery mechanisms [SKS1991]. Additional research is required to determine if there are unique requirements created by distributed geographical databases when they are used in a CSDM environment.

3 User Interfaces

Groups will often be comprised of individuals that not only bring different disciplinary perspective to a problem-solving process, but it is also very likely that individuals will have substantially different levels of experience with both computing and the use of GIS software. Consequently, the user interface of CSDM software is a key issue in its adoption and use in applied contexts.

To illustrate the difficulty involved, consider a sequence of actions, described by Armstrong and Densham [AD1994], that are typically required when locational analysis software is used to help decision makers solve location-selection problems:

1. Select the particular set of thematic data to be used with the geometric and topological data to generate a location set.
2. Ensure the integrity of the spatial data.
3. Generate interaction data.
4. Select an objective function.
5. Solve the location-allocation model.
6. Evaluate the statistical characteristics of the location set.
7. Display the solution in map form.

In this case, it is clear that there is a set of actions that are often accomplished in a deterministic sequence. These repetitive sequences are often required in other GIS-based analyses and careful study of the kinds of tasks that are required at different stages of decision-making is essential to the development of user interfaces that will support the demands of CSDM environments. Three interrelated problems can be identified:

- even when GIS capabilities are available to answer a question, they cannot be sequenced in a way desired by a user;
- when these capabilities can be sequenced, a sequence may not be supported by commands in the interface; and,
- because users usually are not trained in the use of GIS software, they may not understand how the system can be used to answer their questions. This problem is exacerbated as the number of capabilities available to users increases.

Because the interface is the point of mediation between the system's capabilities, individual users and the group, the design of an effective interface requires an understanding of the tasks that user and the group must accomplish along with the structure of the system's underlying capabilities. If a mismatch occurs among these, users will not be able to use the system as they wish. A growing body of knowledge exists about how users can use GIS to solve problems in a wide range of application domains. To increase the ease of use of CSDM environments, such knowledge must be distilled, made available to group members and used to help design the user interface. Such knowledge, for example, could be used to highlight an appropriate sequence of actions for a user to take based on their current problem-solving style. The choice of parameters and weightings, however, would be input by the user to allow them to apply their individual criteria to the problem under investigation.

4 Group Modeling

A hallmark of complex ill-structured problems is that different stakeholders will often have completely different ideas about how such problems can best be solved. In many instances, there are disagreements about the relevant factors that should be included in an analysis. Moreover, even when an agreement can be reached about the factors that should be included, further disagreement can occur about the relative weighting of these factors. This problem is especially pervasive when GIS-based analyses are used since they often use a weighted-layer approach to handling interactions among factors to be included in a decision. Unfortunately, there are many ways that different factors can be combined and many methods are available for accomplishing this task [H1977]. Methods must be developed to allow group members to come to some agreement about the factors to be included in analyses and the relative weights that are applied to them.

5 Computational Bottlenecks

Many GIS operations are computationally burdensome. Analytical operations such as intervisibility, overlay, buffering and some forms of interpolation are especially difficult to perform in near-real-time using conventional RISC workstations. The computational burden experienced by a single user will be translated into very large amounts of computation that will have to be accomplished in group decision-making settings in which members are able to meet for only a limited duration of time. For example, groups may decide to meet for an afternoon to generate and evaluate alternative scenarios to a problem. If each scenario requires, say, 30 minutes to create, then during the course of an afternoon meeting, only a limited number of options might be considered.

It is likely, however, given a networked collection of workstations that, at any given time, some decision-makers will be considering their next step, or that they will be evaluating an intermediate or end-product (a map). In such cases, there will be available spare cycles that could be "harvested" by other group members. This requires, of course, the development of parallel implementations of GIS operations that are coarse-grained and "network-friendly". These algorithms can be implemented using parallel coordination languages such as PVM or Linda.

In previous research, Armstrong, Pavlik and Marciano [AM1994a]; [APM1994a]; [APM1994b] have demonstrated
the effectiveness of MIMD-parallel versions of interpolation and spatial statistical analyses. Ding, Densham and Armstrong [DDA1992] have examined the use of Transputers to implement coarse-grained approaches to finding shortest paths over a network. Ding and Densham [DD1994a]; [DD1994b] have also examined the use of Transputers for rendering terrain and performing triangulation. Rokos and Armstrong [RA1993] have used a collection of networked workstations and Linda to implement a parallel version of a spatial autocorrelation algorithm. In each of these cases, a coarse-grained approach to parallelism yielded substantial improvements in performance. Other work, however, has also shown that for some problems, SIMD architectures seem to be attractive alternatives [MFI1992]; [AM1994b]; [B1991]. Intuitively, we might establish that grid-based computations are well suited to SIMD machines, but that may not always hold. Additional research is required to determine which architectures are best suited to particular approaches and also if there are general classes of problems that might be identified that are well-suited to a specific architecture.

Many GIS algorithms contain several embedded types of computation, so it may turn out that there is no one single architecture that can be proved to be demonstrably superior to others. In such cases, the use of heterogeneous approaches to computation may prove to have important advantages over monolithic approaches [FS1993]. Armstrong [A1994b] for example has described a framework for implementing a heterogeneous approach to GIS map algebra analyses. Densham and Armstrong [DA1994] have also developed an approach to heterogeneous processing for computationally complex heuristic algorithms that are used to solve location-selection problems. Additional work on the development of heterogeneous environments must be conducted. CSDM however, appears to be a promising test bed since there is a wide variety of computation required to develop scenarios in these cases.

6 Group Displays

As individuals search for solutions to ill-structured problems, they typically engage in a process of exploratory analyses in which they generate and evaluate a range of alternative solutions to a problem. In such cases, it is important for them to be able to visualize differences between alternatives and therefore maps that are designed to facilitate this process have been developed [ADLR1992]. When groups of individuals engage in the process of exploration, a very large number of alternatives may be generated. It is important, therefore, that tools be developed to allow group members to see how similar or different their approach is from the remainder of the group. Such tools can be exceedingly useful in the process of attempting to reach a consensus on a difficult-to-solve problem.

7 User Conflicts

Because CSDM environments are intended to be used to arrive at solutions to ill-structured public policy problems, it is expected that group members will bring distinctly different perspectives to the process of decision-making. Moreover, each of these different stakeholders will have different criteria that they wish to bring to the fore in the problem-solving process and, consequently, support for variable types of weighting strategies must be supported by the CSDM environment. Nunamaker et al. [N1991] have described several tools that can be used to expedite the decision-making process. Electronic questionnaires can be used to determine the degree to which disagreements exist among group members. Questionnaire responses can be placed in a group matrix to enable individuals to place their response in a broader context. The results of these group matrices are useful for promoting discussion about different positions adopted by stakeholders. If a person holds a position that is contrary to other group members, they may decide to adopt a consensus view when the result of the group matrix is made available to them. Several methods have been advanced to circumvent bottlenecks in deliberative processes supported by other types of computing technology. These techniques involve majority and plurality voting, group matrices in which individuals can stipulate a criteria to be considered and then see how their views correspond with other group members by seeing how many others selected the same criteria.

8 The Role of Agents in CSDM

Because of the complexity of tasks that must be completed by inexperienced users in CSDM environments, provisions will have to be made for providing assistance in many situations encountered by individuals working alone and in group situations. In many cases, GIS-based analyses require the user to concatenate a long string of operations to perform suitability analyses; in others, complex analytical models must be selected, invoked, parameterized and interpreted. Neither set of actions is intuitive.

Software agents are emerging as an important computing paradigm. A key feature of an agent is that they go outside the originating computer in search of resources on the network. Moreover, agents typically have embodied in them a collection of knowledge that is specific to a particular problem domain. For example, the most successful agents developed to date are those that manage e-mail for users who may require that certain types of mail be "filtered" from their input stream, and that other mail be brought to their immediate attention.

In CSDM environments, agents might be made available to perform routine data management tasks (e.g. file access) as well as to provide advice on the performance of selected analytical tasks. In the process of conducting an analysis using locational modeling software, for example, a series of operations must be performed before others can be completed: the optimization component of the problem cannot be accomplished until the user has conducted a shortest path analysis through the network and has processed these paths into a set of data structures that the optimization software uses to improve its performance.

9 Conclusions

The development of CSDM environments that can be used by groups of individuals from diverse backgrounds to address ill-structured geographical problems presents a host of challenging research opportunities that touch on many existing branches of research in GIS. In some cases, these opportunities are direct extensions of work already underway. In other cases, entirely new lines of inquiry must be established. Specific attention must be placed on research that supports the implementation of group modeling and interaction. This will require the development of new user interface protocols, new types of maps to convey agreement about alternatives generated by group members, and basic
research into overcoming the computational complexity of group-based GIS analyses.

10 Acknowledgments

This paper is a contribution to Initiative 17 (Collaborative Spatial Decision-Making) of the National Center for Geographic Information and Analysis which is supported by the National Science Foundation (SES-88-10917).

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