The Role of GeoSpatial Visual Analytics and Virtual Organizations in the Search for Solutions to Complex Public Policy Problems

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1.0 Introduction

Public policy problems often require decision-makers to consider the geographic consequences of alternative solutions. Such problems, which range from local siting decisions related to the provision of salutary as well as noxious public services to the global impact of climate change, often contain aspects that cannot be quantified or measured in ways that allow them to be incorporated into computer-based representations. This class of problems, referred to as wicked or ill-defined (Rittel and Weber, 1973), are often addressed by groups of people who are assembled to bring together varied types of expertise. The intent is that each group member will contribute different kinds of knowledge and different perspectives during policy deliberations.

Despite the widespread use of boards, panels, and committees to address critical problems facing society, the development of GIS tools that support group use remain underdeveloped. This lack of advancement is particularly notable in the domain of multi-criteria decision-support. The purpose of this paper is to develop constructs to guide the development of such tools and to define an architecture to support their use by virtual organizations that are enabled by an underlying cyberinfrastructure (CI). The development and use of CI has taken place in several cognate disciplines and it has emerged in a fashion that loosely parallels that of the web—its origins lie in the need to support work by far-flung groups of researchers who are conducting state-of-the-science work in particle physics. These research groups create massive amounts of experimental data that are transmitted between continents for analysis with distributed tools. This same infrastructure can be used by virtual organizations (defined below) to address geographical public policy problems. The work described in this paper builds directly from the experiences of the authors in the areas of spatial decision support systems, geovisualization, evolutionary algorithms, multi-criteria problem solving, group decision-making, and CI.

2.0 Multi-Criteria Optimization

Complex policy problems do not reduce to a form that enables them to be addressed using a single criterion. Instead, such problems are formulated to consider multiple aspects that can be evaluated by decision-makers. During the past 10 years, several approaches to multi-criteria optimization have been advanced. Some employ a method, called scalarization, to re-map several criteria to a single weighted variable that can be optimized (Malczewski, 1999; Feick and Hall, 2002; 2004; Jankowski, 1995). Other approaches use evolutionary algorithms (EA) to generate a large number of solutions that can be evaluated (Krzanowski and Raper, 2001; Bennett *et al*., 2004; Xiao *et al*., 2002;

2007). The EA approach is advantageous because it provides decision-makers not only with a collection of Pareto-optimal trade-off solutions, but also (importantly) provides them with near-optimal results. Such solutions are often useful because they may, in fact, be "best" when non-quantitative criteria are brought into decision-making processes. Significant challenges remain, however, with the application of EA-based multi-criteria optimization techniques in group settings. As discussed below, virtual organizations can facilitate the difficult processes of consensus building and team-based evaluation. Geospatial visual analytics can be used to help in the ideation phase and to help decision-makers cope with the complexity of evaluating hundreds or thousands of alternative solutions.

3.0 Virtual Organizations and Group Tools

Computer-based tools that support group-oriented business decisions have been in development for decades. These computer-supported cooperative work (CSCW) tools can be used in a variety of contexts, but most are designed for group meetings that occur with participants in the same time and place. This has also served as the focus of a majority of the GIS work that has been done in this general area (Jankowski and Nyerges, 2001a; Balram and Dragicevic, 2006). With the emergence of CI, however, the lofty goal of meeting synchronously, at the same time in *different* places, is not only feasible, it is a growing expectation. CI supports the secure transmission of information across high performance networks. CI also provides the capability to coordinate and use flexible configurations of distributed computational resources that can be employed to produce computer solutions to computationally complex optimization problems in minutes, rather than hours. This distinction is important since it allows the use of such tools during the time that is normally taken to conduct a meeting. Evolutionary algorithms and the analytical tools, simulations, and data used for multi-criteria optimization problems can often be decomposed to enable distributed parallelism (Xiao and Armstrong, 2003). Analyses of the computational characteristics of geographical problems can be guided through the use of theoretical constructs developed by Wang and Armstrong (2008).

CI has been developed to support the creation of virtual organizations. A virtual organization (VO) is a network-enabled workgroup that can be flexibly formed to focus on a particular interdisciplinary and collaborative research task or ongoing set of tasks. A VO creates and enforces rules that define its membership and the rights of members to access Grid resources (Foster *et al*., 2001). Members can be added and deleted as appropriate and a VO can also be either terminated or put into hiatus.

For example, policy decisions involving "linked human-environment interaction and models in sustainability science, might require expertise in climatology, hydrology, GIScience, computer science, economics, sociology, agriculture, and industrial ecology. Though sufficiently high levels of expertise in each of these areas might be co-located in a single place at a few locations in the world, it is far more likely that scientific expertise will be geographically distributed, perhaps on different continents" (Armstrong, et al., 2005). CI-based virtual organizations supported by geospatial visual analytics provides a mechanism to drive synchorochronous (same place and time) and asynchorochronous collaboration (different places and times).

4.0 GeoSpatial Visual Analytics

Building on earlier work by DiBiase and MacEachren, Armstrong and Densham (2008) defined three intersecting "spaces" in which maps are used during decision making (Figure 1). The private realm conforms to individual map creation and analysis. Public spaces are for sharing results with others. The evaluative realm is where group deliberation occurs. In any process of iterative "generate and evaluate" decision-making style (Figure 2), the evaluative space is where political processes assume the greatest prominence. When geospatial visual analytics are implemented for distributed group decision support, we can envision the result metaphorically— the map becomes a virtual campfire about which group members gather for discussion and evaluation.

In order to move work in this area forward, a collection of tools needs to be specified and constructed. These visual analytical tools work in coordination with the process of generating and evaluating alternative solutions to complex policy problems. We contend that these tools can be used with mapped representations to inform decision-making processes and support discussion among members of virtual organizations. As part of a deliberation, group members must be able to move back and forth between the public, private and evaluative realms.

The following classes of tools are needed to:

1. Assist in the elicitation of criteria
2. Exclude or lock out infeasible combinations of criteria values
3. Provide information about individual solutions
4. Display criteria values on maps
5. Support the comparison between two solutions or among small groups of solutions
6. Find regions where pairs or groups of solutions are the same or similar
7. Compute summary and variability measures of the characteristics of collections of solutions
8. Find solutions that are similar to a selected one in one or more dimensions
9. Combine, splice and blend solutions as a way to reach compromise

These tools can be classified according to the number of solutions to which they are applied (one or more), as well as the kind of space (private, public, evaluative) and the stage of decision making in which they are used.

Some of these tools can be constructed from meta-data about solutions. In other cases, information about the geographical characteristics of solutions can be manipulated through map algebra-like logic in this multi-criteria domain. Map algebra tends to be applied to areal data (cells and polygons) so extensions may need to be implemented for linear (network) and point-formatted elements of solutions (see Armstrong and Densham, 2008).

Decision-making can take place in several spatiotemporal contexts. In same time, same place contexts, each decision-maker could generate and champion a large number of solutions with little likelihood of consensus emerging. Limitations are enforced by the duration of interaction that can take place (e.g., a one hour meeting) and the amount of "air time" allocated to individuals either in "chunks" (e.g., a three minute egg timer) or in total for a meeting (e.g., nine minutes total air time). An alternative approach is to allocate a fixed amount of "currency" that forms a decision-making budget, like poker chips, that can be expended during discussions. Points/money would be allocated among options to illustrate relative preferences. Working with the amount of currency expended by individuals to back different solutions would provide a way to weight the strength of preferences among solutions in the evaluative realm.

5.0 Putting It Together: Geospatial Visual Analytic Portals (GVAP)

Many of today's most challenging problems are inherently ill-structured and geographic. As illustrated above, the evaluation of such problems is complex and places significant demands on human and computational resources. In this work, we argue for a problem-solving environment (PSE) that provides decision-makers with a set of computer based analysis tools, visualization capabilities and access to heterogeneous computing resources. Such environments "allow users to define and modify problems, choose solution strategies, visualize and analyze results, and record and coordinate extended problem-solving tasks." (Armstrong, et al., 2005). This flexibility is particularly important when VOs are employed since each member may have a different background (including education and work experience), and familiarity with computer tools (including map creation and interpretation).

A PSE that is designed specifically for multi-criteria evaluation of policy problems and that uses geospatial visual analytics can be implemented as a type of portal. This web-service based approach hides implementation details and allows users to access high level tools that enable problem solving. In this paper we draw upon our past work in EA-based multicriteria evaluation, CI, and geovisualization to illustrate how such a web-based geospatial visual analytic portal can be developed to address complex geographic problems.

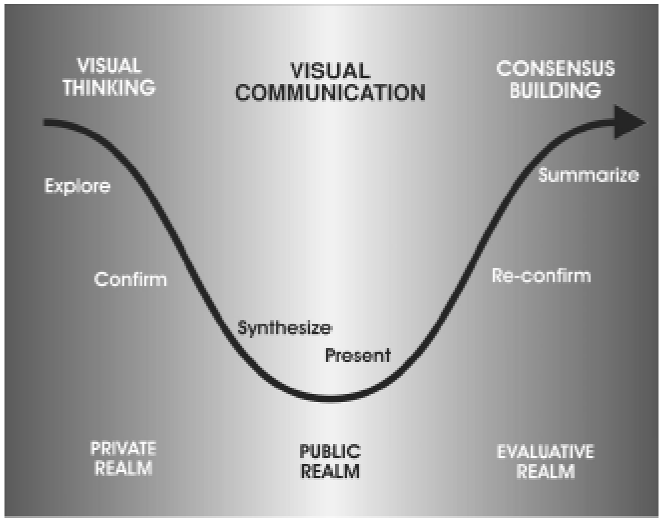

Figure 1. The three spaces in which map are used during decision-making (Source: Armstrong and Densham, 2008).

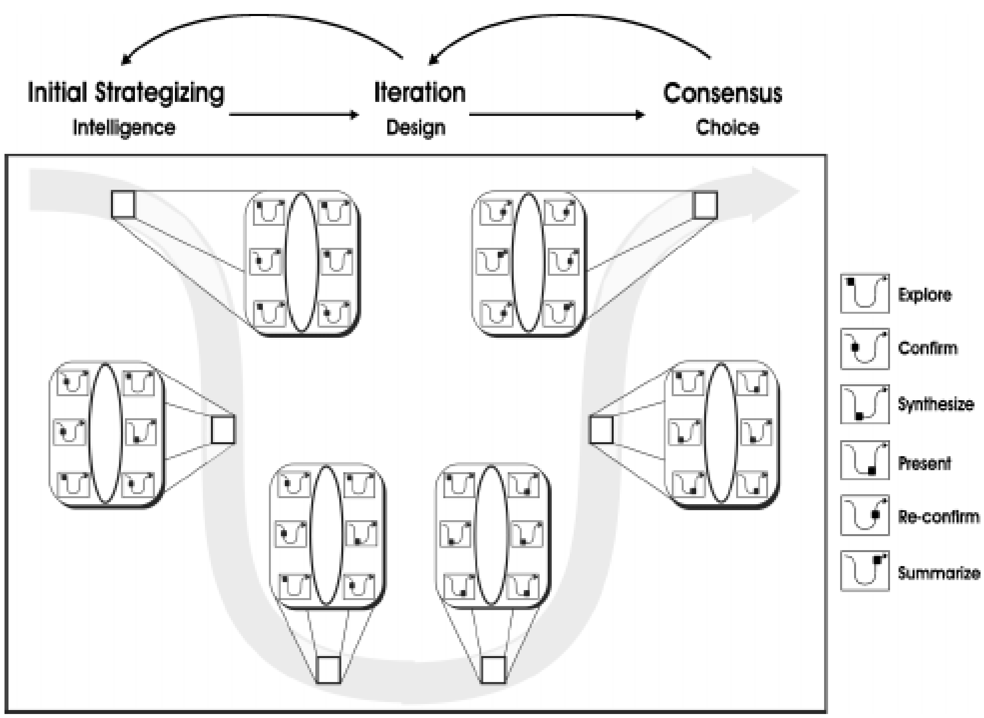

Figure 2. A schematic diagram of a generate and evaluate decision process based on the decision-making approach described by Herbert Simon. (Source: Armstrong and Densham, 2008).

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