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Geovisual analytics for spatial decision support: Setting the research agenda

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This article summarizes the results of the workshop on Visualization, Analytics & Spatial Decision Support, which took place at the GIScience conference in September 2006. The discussions at the workshop and analysis of the state of the art have revealed a need in concerted cross-disciplinary efforts to achieve substantial progress in supporting space-related decision making. The size and complexity of real-life problems together with their ill-defined nature call for a true synergy between the power of computational techniques and the human capabilities to analyze, envision, reason, and deliberate. Existing methods and tools are yet far from enabling this synergy. Appropriate methods can only appear as a result of a focused research based on the achievements in the fields of geovisualization and information visualization, human-computer interaction, geographic information science, operations research, data mining and machine learning, decision science, cognitive science, and other disciplines. The name 'Geovisual Analytics for Spatial Decision Support' suggested for this new research direction emphasizes the importance of visualization and interactive visual interfaces and the link with the emerging research discipline of Visual Analytics. This article, as well as the whole special issue, is meant to attract the attention of scientists with relevant expertise and interests to the major challenges requiring multidisciplinary efforts and to promote the establishment of a dedicated research community where an appropriate range of competences is combined with an appropriate breadth of thinking.

Keywords: Geovisual analytics; Spatial decision support; Research agenda

1. Introduction

On 20 September 2006, a workshop on Visualization, Analytics & Spatial Decision Support took place at the GIScience conference in Münster, Germany. The aim of the

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workshop was to bring together researchers from relevant fields to discuss the state of the art in visually enabled spatial decision support, identify major problems, and define directions for future research. The workshop attracted more than 60 participants and had a very interactive, discursive character. This article summarizes the outcomes of the discussions and introduces the current special issue of IJGIS, which contains extended versions of selected contributions by workshop participants.

Spatial decision support means computerized assistance to people in the development, evaluation, and selection of proper policies, plans, scenarios, projects, or interventions where the problems have a geographic or spatial component. This refers to both long-term decision-making (e.g. planning for sustainable places, mitigating hazards, infrastructure management, and strategic business planning) and short-term time-critical decisions such as emergency response and resource logistics. The spatial (and often spatio-temporal) character together with the need to integrate heterogeneous information makes such decision problems challenging for people and demanding with respect to technologies and tools. Existing tools (in particular GIS, which are most commonly used as spatial decision aids) are often incapable of coping with the size and complexity of real-life problems, which forces the users to reduce the problems in order to adapt them to the capabilities of the tools.

The reason for the inadequacy of the current tools is not the deficiency of computer performance or memory size but the fact that most spatial decision problems are inherently ill-defined, and hence cannot be fully converted into a form suitable for automatic processing. The way to overcoming this weakness is, in principle, clear: complement the power of computational methods with human background knowledge, flexible thinking, imagination, and capacity for insight. However, current tools hardly allow this, as they have not been designed for such use. A new generation of tools is needed: tools enabling a truly synergetic work of humans and computers where each side applies its unique abilities in the best possible way.

Visualization and interactive visual interfaces, as an effective way to provide material for human's analysis and reasoning, are essential for supporting the involvement of humans in problem-solving. However, a simple combination of visualization with computational analysis and modelling is not sufficient for facilitating the mutual reinforcement of the abilities of humans and computers. New methods are needed, and such methods can only result from a focused cross-disciplinary research based on the achievements in the fields of geovisualization and information visualization, human–computer interaction, geographic information science, operations research, data mining and machine-learning, decision science, cognitive science, and other disciplines, so that a synergy of approaches and technologies could lay a basis for a synergy between humans and computers in solving complex decision problems.

Presently, the research on visualization and computational support for space-related problem-solving and decision-making have been mostly developing in separation, which can be easily noted, in particular, from the presentations at the workshop. Therefore, concerted efforts are required for establishing the new research area and building a research community where an appropriate range of competences is combined with an appropriate breadth of thinking.

We suggest the name 'Geovisual Analytics for Spatial Decision Support' for the cross-disciplinary research that looks for ways to provide computer support to solving space-related decision problems through enhancing human capabilities to analyse, envision, reason, and deliberate. The name emphasizes the link with the emerging research discipline of Visual Analytics (Thomas and Cook 2005). Geovisual Analytics for Spatial Decision Support can be viewed as a sub-area of Visual Analytics with its specific focus on space and time posing specific research problems and calling for special approaches to solving more generic research problems of Visual Analytics.

Three aspects distinguish Geovisual Analytics for Spatial Decision Support from Visual Analytics in general. They are: (1) complex nature of geographic and temporal spaces, (2) multiple actors, and (3) tacit criteria and knowledge. Before discussing these aspects in more detail, let us consider a few examples of spatial decision problems. Although the examples may seem quite commonplace to a typical reader of IJGIS, one should bear in mind that, despite the ordinariness of these problems, they are not yet adequately solved by means of GIS or other existing technologies but can at best be tackled after a substantial reduction in size and complexity. It is the goal of Geovisual Analytics to find a way out of this forced simplification.

2. Examples of spatial decision problems

2.1 *Example 1*

Let us start with a 'simple' example of selection of a house for living, or a site for company's office, or a locale for a congress or a sports championship, or a place for the treatment of toxic wastes. This class of problems, known as 'site selection', has become a classical case where the combination of the GIS technology with the methods of multi-criteria decision analysis (MCDA) (Malczewski 1999) works fairly well. However, a closer look at how such problems are usually solved may disclose that a large part of relevant information is often left aside in order to make a problem manageable. Thus, a good choice of a house requires paying attention to the relationships between a building that one may find desirable and be able to afford, and spatial and temporal conditions in which the building is situated, including traffic patterns, socio-demographic make-up of the neighbourhood, proximity to and quality of services, and future growth of the neighbourhood, to name but a few. The cognitive difficulty of accounting for all relevant aspects forces the decision-makers into the use of a 'reduced processing strategy', in which only a few criteria are taken into account, for example price, overall house quality, and the quality of schools in the area. This may not be extremely harmful when it comes to selecting a new house, but it may well be when it comes to more crucial endeavors.

Would the availability of data and tools for processing such data and presenting their meaning both visually and numerically sway one to adopt a full processing strategy and deal with existing problems in more rigorous and open ways? If so, what kind of tools would be needed, and how should they be integrated to afford an effective conveyance of meaning?

2.2 *Example 2*

Many domains require planning of various actions distributed in geographical space and *time*. The examples include:

- retail outlet location decisions: where, when, and what outlet should be opened, closed, or modified; what should be the size and profile of each outlet;
- groundwater management: how much water can be taken from each well in different time periods; when and where to restrict the water withdrawals;

- forest management: where and when to harvest the wood (and how much), where and when to plant new trees, and thin out the plantations; what species to plant where.

Such applications require the examination of numerous possible variants of spatio-temporal distribution of actions (termed *scenarios* from here onwards) and dealing with complex, heterogeneous information involving geographical space, time, characteristics of places (infrastructure, demography, environment, land use, climate, etc.), properties of time moments and intervals (seasons, periods of different agricultural activities, etc.), attributes of the actions (character, scope, expenses, gains, etc.), interests of different stakeholders, as well as various related phenomena such as market trends.

A range of computational methods have been developed to deal with the complexity of real-world decision-making problems, such as the three examples noted above. For instance, simulation and optimization models and tools are devised and applied to generation and evaluation of possible scenarios. However, the choice of the scenario to follow cannot be fully automated as it usually depends on multiple criteria, and not all of them can be easily quantified for automatic processing. In particular, important criteria related to properties of the spatial and/or temporal distribution of actions are usually hard to express numerically, and the quality of a scenario can only be judged by a human analyst on the basis of their domain expertise and knowledge of the study area. Thus, the analyst may prefer an even distribution of small enterprises in some regions and focused interventions in specific places in other regions. All such preferences cannot be specified in advance and translated into routines for automatic evaluation, since they usually result from investigating the possible variants of the distribution. For this purpose, the analyst needs the scenarios and the related information appropriately presented, for example, on a map.

Since it is physically impossible for an analyst to review all possible scenarios, computational support is absolutely necessary. The support may involve, for example, clustering of scenarios by similarity and generalization of the resulting groups of scenarios so that the analyst can explore and evaluate the categories of scenarios by means of an appropriate interactive visual interface.

Furthermore, effective problem-solving requires the user to actively *guide* the work of the computational models in order to overcome the computer's inability to incorporate intangible knowledge and criteria. Such an approach improves the quality of the generated solution variants and simultaneously reduces the breadth and/or depth of the search, and hence saves the computation time and user's efforts on examining the model's output, which becomes substantially smaller. Hence, the user should be able to interact with the computational models and get immediate feedback in an appropriate form. Interactive visual interfaces play an essential role here. This sort of synergy between computational and visual methods of analysis is key to supporting this class of problems effectively.

2.3 *Example 3*

Quite different from the previous two examples is decision-making in time-critical applications, in particular, in emergency situations. Imagine, for example, the problem of planning the evacuation of people from a disaster-affected zone (assuming that the decision about the evacuation, which is in its own right a very difficult problem, has been already made). A planner needs to know the geography of the place, in particular, the roads and their characteristics, where people live, how many people are in the area (a more complex issue than knowing the recorded population), what transportation means can be used, and where they are at the current moment. They need to find suitable places for shelters, define meeting points and evacuation routes, and schedule the transportation. Particular care must be taken of casualties and particularly vulnerable people such as the elderly, disabled, hospital patients, or prisoners, who may need additional help, special transport, special destinations, and/or other special measures. The routes chosen must be as safe as possible, and the evacuation must be scheduled so as to minimize the harm to the people. For casualties and seriously sick people (e.g. those needing life-support measures), the time of evacuation and the right choice of the destinations are extremely critical. However, delays are also harmful to all other people because of increasing the risk to people's lives or the damage to their health. For example, if there is a release of a toxic substance, the level of contamination increases with the time spent in the affected zone.

When the plan is ready, and the evacuation is under way, rapid changes in situation require one to check whether the plan is still valid and consider adapting the plan to the new situation or even complete re-planning. The changes that require quick reaction include new casualties appearing, a road becoming impassable, fuel shortages, a destination becoming unreachable, a vehicle being damaged, some routes taking more time than initially estimated, or delays in meeting the schedule for any other reasons.

In emergency situations, analysts and decision-makers do not have time to consider all possible variants of problem solutions in detail or to search for an optimal variant. The cost of an error, however, may be very high. In addition to the lack of time for analysis, time pressure and associated stress can cause people to overlook or forget something important. Therefore, decision-support systems must provide support for distributed, shared memory along with efficient and intelligent computational and knowledge management tools that alert participants to key decision points, provide reminders about and access to relevant prior information, and present and rate available options. Furthermore, as noted above, decision-making in emergency situations is a dynamic process in which key parameters change quickly. Hence, tools must do more than display the end results of a database query or of alternatives designed by computational analysis; they must support the whole process in such a way that human expertise and system capabilities are iteratively applied and mutually reinforcing. Maps and related visualization tools are obviously fundamental here.

These examples clarify what is meant by space-related decision problems (or, more concisely, spatial decision problems), which need to be supported by visual analytics methods and tools. Note that spatial decision problems are often also time-related. Let us now explain the meaning of the three aspects, complex nature of geographic space, multiple actors, and tacit criteria, which make Geovisual Analytics for Spatial Decision Support a valid research area.

3. Specific features of spatial decision problems

3.1 *Complex nature of geographic space*

The structure and properties of geographic space (or, more generally, physical space) differ radically from those of abstract (mathematically defined) spaces, which are usually dealt with in analysing general types of data and information. There is a wealth of literature discussing 'what is special about spatial' (e.g. Anselin 1989, Goodchild 2003); we shall briefly mention just a few aspects. One of the most important differences is the heterogeneity of physical spaces. Thus, in geographic space, oceans and seas are very different from continents and islands, mountains are very different from valleys, forests differ from deserts, coasts differ from inland regions, cities differ from rural areas, countries differ from each other, etc. It is very important to realize that solving spatial problems involves taking into account not only the metric properties of the space and topological relations between objects in the space but also the heterogeneity of the space. Moreover, even the metric properties of physical spaces are quite different from the metric properties of abstract spaces. Thus, distances in geographic space are not the same as Euclidean distances on a plane or in an abstract three-dimensional space; furthermore, distances are often defined in a problem-specific manner. Among the specific characteristics of geographical space, there is also the multitude of objects, phenomena, and events occurring in a physical space at different points in time that need to be considered in solving space–time-related problems.

The definition of the research agenda for Visual Analytics provides convincing justification for the importance of using visual representations and visual interfaces in analysis and reasoning (Thomas and Cook 2005). Visual representations are even more important where geographical or physical space is involved. The heterogeneity of the space and the variety of properties and relationships in it cannot be adequately represented for fully automatic processing. At the same time, an isomorphic visual representation, such as a map or an orthophoto, allows a human analyst or decision-maker to perceive spatial relationships and patterns directly. Furthermore, the map or photo portrays coasts, rivers, relief, state boundaries, cities, roads, etc. and in this way not only exhibits the heterogeneity of the space but establishes the geographic context within which decisions can be made. The analyst or decision-maker can grasp this information and relate it to their background knowledge about the properties of different parts of the space and take the variation of the properties into account.

However, one should not conclude that a faithful representation of geographic space, like in Google Earth and similar applications, is all that is needed to support spatial problem-solving and decision-making. Unfortunately, there is a common and growing conception that geovisualization and the geospatial information science as a whole has been or may be taken over by Google Earth, which is, in essence, a 3D viewer of geospatial data equipped with the capabilities to rotate the globe, zoom in and out, fly over terrain, annotate points of interest, and hyperlink additional geospatial data.

Google Earth technology fuses imagery, terrain, and GIS data to deliver them to their users by means of a client–server architecture, where a Web browser is the client that accesses the data viewing and navigational services on the Google Earth server. Google Earth, however, is not an analytical environment in the sense of quantitative data analysis intelligently integrated with data-visualization methods. Basically, Google Earth and similar virtual globes allow the user to view landscape and its observable features. This is insufficient to lend an effective decision support to problems such as emergency management, planning for sustainable growth, or infrastructure project selection. An effective decision support in any of these and other complex spatial decision problems will require techniques and tools that help to articulate a decision goal, discern information from the multitude of data through both data analysis and visualization, create plausible scenarios representing possible courses of action, compute and visualize their impacts, test the stability of scenarios, and prioritize them to help select the right course of action.

The research agenda for Geovisual Analytics for Spatial Decision Support must include the development of methods and technologies that, while sharing the flexibility of Web-based services, will go beyond the geodata viewing capabilities of Google Earth and other virtual globes, and offer analytical-visual support for human reasoning in various types of decision situations.

3.2 *Multiple actors with different roles*

In various decision-making processes, not necessarily space-related, it is common that several persons with *different roles* are involved. Thus, people who make decisions are often administrators or politicians who have limited time and/or qualification to assemble information, analyse problems, find possible solution options, and evaluate them. This work is done, depending on the complexity of the problem and the expertise required, by one or more analysts, who then need to present the results of their analyses to decision-makers in a summary form. A decision-maker often wants only a few clear and easily comparable options to make the final choice. However, in order to make an informed decision, they need to understand, first, where the options come from and why these particular options were selected from the whole space of possibilities and, second, what are the trade-offs associated with choosing each of the options. This raises the importance of effective *communication* of information, where visual representations can be extremely valuable (Tufte 1997), and of 'what-if' testing and comparison of options, where interactive visual interfaces are required.

Besides analysts and decision-makers, decision processes often involve various stakeholders, i.e. people or organizations that can be somehow affected by the decisions made. It is usual that stakeholders have differing interests, and any solution option may be beneficial to some of them and disadvantageous for others. It is important to find such solutions where the interests of the stakeholders are balanced in a rational way. This requires involvement of the stakeholders in the analysis process, where effective communication of relevant information from the analysts to the stakeholders plays a crucial role as well as the possibility for the stakeholders to evaluate proposed options from the perspective of their interests (of course, all this may not apply to time-critical situations such as emergency evacuation). Like a decision-maker, a stakeholder would need an easily understandable presentation of information and easily usable interaction facilities; however, a stakeholder may need a more detailed view of the options and background information or even a tailored visualization that helps them to figure out the consequences of each solution.

Furthermore, stakeholders may wish or be expected to contribute to the process of problem analysis, generation of solution options, and evaluation of the options using their background knowledge, preferences, and value-driven evaluation criteria. Hence, adequate support is required for stakeholder–analyst interaction. The supporting software should help the analysts obtain early input from the stakeholders about decision criteria, information sources, options, etc. and provide mechanisms to present results of analysts' work to the stakeholders and obtain their feedback, often as part of an iterative process. It should also help the stakeholders understand the nature of the problem including the key relationships involved, facilitate their understanding of data and information, and guide them in the process of analysis and evaluation.

Hence, a decision process may involve multiple heterogeneous actors with different roles, interests, levels of knowledge of the problem domain and the territory, and experiences in using visualization and analytical tools. It is also important to emphasize that this is a process that is likely to take an extended period of time and to be iterative; thus the methods and tools must support a process characterized by extended, asynchronous, systematic, multi-person, varied, and complex work.

As an implication, Geovisual Analytics for Spatial Decision Support needs to pay attention to the following issues:

- collaboration: how interactive visual interfaces (in particular, map interfaces, which are essential for spatial problems) can enable many actors to work together in the same room, between rooms, between offices, between countries, or even between cultures;
- communication: how interactive visual interfaces can facilitate effective transfer of spatially related information, knowledge, evidence, judgements, considerations, etc. from one actor to another;
- flexibility: how to make the interfaces adaptable to the needs and skills of different actors.

3.3 *Tacit criteria and knowledge*

In presenting the examples, we have mentioned that some important criteria for evaluating options and making decisions cannot be easily quantified to enable automatic processing, in particular, criteria related to properties of spatial and/or temporal distribution. Moreover, some criteria may be even harder to verbalize or externalize. In addition, decision-makers often have their reasons to keep certain criteria implicit, and computer support that requires an absolute transparency from them is unlikely to be fully embraced. Since tacit criteria are habitual and unavoidable in decision processes (Nevo and Wand 2005, Saaty 2005), it is necessary to allow a human analyst or decision-maker to apply such criteria in assessing the suitability of each option. For this purpose, they need to *see* the situation and the options and to interact with decision parameters in a flexible way.

Not only decision criteria but also much of conceptual knowledge and expertise required for solving spatial problems are very difficult to capture in algorithms and programs for automated analysis and evaluation. This concerns first of all knowledge related to space and time: properties of various parts of space, spatial and spatio-temporal phenomena and events, spatial and temporal relations, and variation of decision criteria over space and time. Computers are currently much weaker than humans in reasoning about space and time. Hence, it is reasonable to utilize and enhance these abilities of humans as much as possible. In current practices, people employ GIS or other software tools for doing some preliminary work and then apply their tacit knowledge and criteria to the outputs in order to derive final conclusions or make final choices. Geovisual Analytics for Spatial Decision Support should suggest and enable a better strategy so that tacit knowledge can be used throughout the whole process of problem-solving to make it more effective and efficient.

Another related issue is the widely known fact that decision-making is not always a rational process but is often affected by human emotions and preconceived opinions. In such situations, people tend to use decision-support tools mainly to justify the choices they have already made. While it is not realistic to preclude such unintended uses of tools, it may be reasonable to investigate the possibility of creating geovisual interfaces that can stimulate users' willingness to open their minds, set aside prejudices, and consider various decision options.

4. Goals of geovisual analytics for spatial decision support

Summarizing the previous discussion, we define Geovisual Analytics for Spatial Decision Support as the research area that looks for ways to provide computer support to solving space-related decision problems through enhancing human capabilities to analyse, envision, reason, and deliberate. It addresses all phases of the decision-making process (Simon 1960): analysis of the problem situation (intelligence), finding or building the possible solution options and evaluation of the options (design), and selection of an appropriate option (choice). It addresses the needs of various actors involved in spatial decision processes: analysts, stakeholders, and decision-makers. Visualization and interactive visual interfaces are of primary importance, as they can effectively provide material for human analysis and reasoning. At the same time, the size and complexity of real-life problems necessitate the use of computational tools. The challenge is to achieve a real synergy of human and computer in solving spatial problems.

Geovisual Analytics for Spatial Decision Support is a multidisciplinary field that is built on the basis of research in the areas of geovisualization and spatial decision support as well as Geographical Information Science and other disciplines developing methods for computational analysis of spatial and geographical information, in particular, data mining and statistics. Geovisual Analytics for Spatial Decision Support should also incorporate relevant knowledge and experiences from information visualization, human–computer interaction, computer-supported cooperative work, decision sciences, cognitive sciences, and operations research, in particular, mathematical programming and multiple criteria decision analysis. Developments in text and image analysis may also be relevant.

The goals of Geovisual Analytics for Spatial Decision Support are consistent with the goals of Visual Analytics (Thomas and Cook 2005) as a more generic research field. Within this broader research area, Geovisual Analytics for Spatial Decision Support pays special attention to handling the complexities of the geographical or, more generally, physical space, to supporting the work of multiple actors with diverse roles, expertise, capabilities, and interests, and to integrating innovative computational technologies into the established human practices of decision-making.

5. Major research problems and directions

As a result of the discussions that took place during and after the workshop on Visualization, Analytics, and Spatial Decision Support, several research issues requiring multidisciplinary effort have been identified. These issues are briefly presented below.

5.1 *Develop a typology of spatial decision problems*

The three examples of spatial decision problems introduced in section 2 are quite different and seem to represent distinct problem classes. References to such problem classes can be found in the literature, for example, in Malczewski (2006):

- land suitability evaluation;
- plan/scenario evaluation;
- site search/selection;
- resources allocation;
- transportation/vehicle routing/scheduling;
- impact assessment;
- location–allocation.

However, this typology seems to be empirical and arbitrary rather than systematic and comprehensive. It is necessary to put it on a solid scientific basis. A first question here is what are the key parameters that define problem types and how do they relate to each other? Some candidates include: spatial extent of territory about which a decision is being made (local, regional, global); temporal extent (time-critical versus long-term, one-time decision versus long-term sequence of linked decisions); domain (private, government, industry; planning, management, location–allocation; command and control, public participatory); complexity (which restaurant to pick, whether to evacuate New Orleans); and number of decision-makers (individual, small team, public). Once categories of decision-making are understood, a key question is: Do different types of problems require different kinds of geovisual support? If so, what are the relevant differences that influence the choice of approaches and methods? Is it productive to develop separate methdologies for different phases of problem-solving including intelligence, design, and choice?

5.2 *Support spatial decision-making as a process*

It is necessary to investigate what kind of support would be appropriate for each phase in the process of spatial problem-solving and decision-making. However, it is important to support the process as a whole rather than each phase separately. It should be borne in mind that the partition of the process into phases is mainly a theoretical model while there is no strict separation in practice. For example, when analysing a problem (intelligence), an analyst may simultaneously find possible solution options (design), immediately evaluate them and prune inadequate variants (choice). Even the simplistic theoretical model assumes that returns to earlier phases are possible. Hence, geovisual analytics tools for spatial decision support should allow easy and intuitive transitions between different kinds of activities and seamless flow of information and knowledge.

5.3 *Support exploration of the problem and solution options*

In the phase of intelligence, geovisual analytics methods could be helpful in the search for appropriate data and information and bringing together data of various types: spatial, temporal, statistical, qualitative, and multimedia. Yet the most obvious and the most important role of geovisual analytics in this phase is to support exploration and analysis of problem-relevant information, which is heterogeneous, complex, and often quite sizeable. Special attention needs to be paid to the properties of physical (geographical) space and time. Exploration and analysis of space- and time-related information is also a part of the design phase, when the analyst needs to explore the universe of possible options, which may be quite numerous and/or have a complex spatio-temporal structure, like scenarios in example 2 or transportation schedules in example 3. Furthermore, evaluation and comparison of options in the phase of choice also requires dealing with heterogeneous information having spatial and temporal components.

Using the current state of the art in geovisualization (Dykes *et al.* 2005) as the basis, geovisual analytics requires advances in several areas to support exploration and analysis of information during all phases of spatial decision-making. We list the required advances below.

5.3.1 Scalability. Geovisual analytics methods and tools must be scalable with respect to the amount of data, dimensionality, number of data sources and heterogeneity of information, data quality and resolution, and characteristics of various displays and environments such as size, resolution, interaction possibilities, immersiveness, etc.

To cope with the problems of data size and dimensionality, synergetic links need to be established between the geovisualization and data mining (Hand *et al.* 2001, Han and Kamber 2006) and database technologies (Ramakrishnan and Gehrke 2003). The paper by Guo in this issue describes how data mining together with interactive visual techniques helps in the discovery of spatial patterns guiding the development of proper decision strategies. Bertolotto *et al.*, also in this issue, combine data mining with visualization to analyse huge spatio-temporal data.

New solutions are required for user interaction with data displays. Current approaches in geovisualization and information visualization assume that data are loaded in the computer memory. In particular, brushing between two or more parallel views is based on fast access to individual data items. This mechanism may not work well enough in the case when data do not fit in the computer memory and have to be presented in an aggregated and generalized form. Even assuming that advances in database technology will soon enable very fast access to data stored out of memory, it will still be not trivial to link parallel views where data are aggregated and summarized in different ways.

5.3.2 Interoperability. While the issue of tool interoperability is not strictly specific to Geovisual Analytics for Spatial Decision Support, it is undoubtedly very relevant: a generic system including all necessary tools and methods is not a realistic idea because of the complex nature of spatial decision problems. Since the use of multiple tools of diverse origins is inevitable, it is necessary to develop theoretical and methodological foundations for making such tools interoperable. The interoperability problem has many aspects from the basic connection of machines on a shared network, through the sharing of data, to the fusion of perspectives (Andrienko *et al.* 2005). At present, perhaps the most pressing problem is that of consistency of the 'world view', a concept that covers all assumptions made in relation to semantics, semiotics, user interactions, and so on.

5.3.3 Visualization of complex spatio-temporal constructs. Many kinds of spatial decision problems require construction and analysis of action plans where actions refer to different positions, regions, or paths in space and to different moments or intervals in time. Spatial development scenarios (example 2) and transportation schedules (example 3) fall into this category. Analysts need methods and tools for reviewing and comparing such complex spatio-temporal constructs; however, no good solutions currently exist. The problem becomes especially challenging with the increasing number of constructs to be analysed.

5.3.4 Linking exploration with validation. Traditionally, geovisualization and information visualization focus on developing methods and tools to support discovery of patterns and relationships in data. However, it is known that visual displays are not always productive; moreover, they may be misleading when used improperly. In decision-making, it is of crucial importance that decisions are based on valid premises. Therefore, it is necessary to find ways for linking exploratory visualization with validation of patterns and relationships detected in data by means of visualization (Chen 2005). How can visualization tools enable and, possibly, even prompt immediate testing of what appears as pattern in data?

There is a need to integrate visual and computational methods currently applied to support decision-making with statistical methods providing formal validation capabilities. While there have been efforts to integrate visual and statistical analysis methods (e.g. Anselin 2000, Carr *et al.* 2005), the focus has been on supporting exploratory spatial data analysis separately from considering the role of such analysis in decision-making.

5.3.5 Support of knowledge capture and manipulation. What analysts get from viewing visual information displays is impressions, images, and ideas that appear in their minds. How can such impressions and ideas be put in a form suitable for later reviewing, communicating to others, and use in further analysis and in the subsequent phases of the decision process? In particular, how can spatial and spatio-temporal patterns and relations discovered in data be represented in an explicit, preferably visual, form? How do we support knowledge synthesis when such fragmentary discoveries are combined into a more complete picture of the whole? Progress has been made recently on capturing and representing situated geographical knowledge (Gahegan and Pike 2006). This work, however, is just a first step toward addressing a difficult problem, and the ideas have yet to be extended from the context of supporting scientific research to that of supporting decision-making.

5.4 *Support consideration of heterogeneous information*

Most current support for spatial decision-making, whether visual, computational, or both, focuses on single kinds of input information. Typical examples are exploratory spatial systems that emphasize analysis of multivariate numerical data, MCDA tools that focus on capture and analysis of human-provided ratings of criteria, and GIS-based decision tools that focus on map algebra-based overlay and related analysis operations. But many real-world decision situations require collection, organization, and analysis of much more heterogeneous kinds of information. Consider, for example, the director of an emergency response centre charged with making decisions about preparation for and response to a hurricane event who must cope with maps and numerical data from hurricane forecast models, text-based situation reports from the field, real-time video depicting traffic and/or impacts at road intersections around town, cell-phone-derived images showing the location of stranded travellers, and more. Enabling the use of rapidly changing, heterogeneous information for time-critical decisions is a fundamental challenge that integration of geovisual analytics with computational spatial decision-making tools needs to address.

5.5 *Support rational choice*

A number of mathematical theories and computational techniques have been devised to optimize the choice from multiple alternatives taking into account multiple criteria (Figueira *et al.* 2005). However, formal methods alone are not sufficient for supporting decision-making because of the existence of tacit criteria and knowledge, which cannot be translated into numbers, formulas, or rules. This problem is recognized in the research area of multiple-criteria decision analysis (MCDA), where theories and techniques are specially devised for handling it. One example is the Analytic Hierarchy Process (AHP), which is based on pairwise comparisons of alternatives and criteria by the decision-maker. Generally, MCDA researchers acknowledge the importance of a fruitful dialogue between a computer system for decision support and the decision-maker, where the system provides the decision-maker with relevant information about reasonable alternatives and, in turn, obtains useful information about the preferences of the decision-maker. In such a dialogue, graphical representations may be of great use. While modern MCDA software often includes such graphical displays as trees, plots, and bar charts, a recent survey of the state of the art (Figueira *et al.* 2005) shows that the MCDA research community is much more focused on mathematics than on visual or other interfaces that make methods accessible to and usable by the decision-makers and other stakeholders.

MCDA per se does not specifically deal with spatial decision problems. The choice in spatial decision-making is currently supported through integrating MCDA techniques with GIS capabilities (Malczewski 1999). GIS functions are used, first, to prepare input for MCDA tools in an appropriate form (which means, in particular, to translate spatial information into numbers, characters, or formulas) and second, to represent the output of the MCDA tools on a map. This general framework by itself does not solve the problems related to a large space of possible solution alternatives, complex structure of solutions, and heterogeneity and complexity of information relevant to characterization and evaluation of alternatives. These problems are a worthy target for geovisual analytics approaches, where MCDA methods may be organically incorporated through interactive and dynamic spatial interfaces. The paper by Rinner addresses this issue.

5.6 *Support reasoning, deliberation, and communication*

Decision-making processes frequently involve multiple actors with different roles. Stakeholders and decision-makers often rely upon services of expert analysts. It is important that the way in which an analyst or a group of analysts comes to the suggested variants of solution can be traced and understood. This means that the course of reasoning needs to be documented and presented in a convenient, easily understandable form, such as an argument map (Kirschner *et al.* 2003). There is a need to support analysts in documenting and visualizing their inferences and arguments. This could be useful not only for communicating solution rationale to others but also for the analysts themselves, as they could more easily review and check their own work, detect inconsistencies, unexplored possibilities, etc. Such support would be very beneficial when several analysts, for example, experts from different domains, are involved in problem-solving and need to exchange their ideas and arguments and jointly find solutions.

A starting-point for developing methods to support capturing and visualizing arguments is to draw upon the state of the art in the field of computer-supported argument visualization (Kirschner *et al.* 2003). At the same time, it is necessary to focus attention on the contemporary Web2.0 applications where people communicate, discuss, and collectively produce content of common value. Perhaps, the most related to the ideas of geovisually supported collaboration are Wikimapia.org and ManyEyes (http://services.alphaworks.ibm.com/manyeyes/home); see also the paper by Heer *et al.* (2007) describing the predecessor of ManyEyes called sense.us. Wikimapia.org allows the users to attach their annotations to regions on a map. These annotations can then be commented on by other Web users. ManyEyes is a site where users can create, share, and comment on interactive visualizations, which include US and World maps and several types of charts and graphs. In this way, ManyEyes enables and promotes collective data analysis and discovery.

Technology is not the sole focus of interest in the collaborative Web2.0 applications; there are also (or, perhaps, even first of all) social, communicational, and behavioural aspects of their use, which need to be understood in order to find proper ways to support collaborative processes in spatial decision-making. In this respect, it is also useful to learn how people collectively create intellectual artefacts in other Web2.0 projects not directly related to maps or visualization, such as Wikipedia. Resulting observations could be a valuable complement to the existing theories of people communication and group work, which are of great relevance to the design of tools for collaborative spatial decision-making as shown in the paper by Hopfer and MacEachren in this issue.

In addition to the exchange of arguments and knowledge between the actors in decision processes, it would be beneficial if stakeholders and decision-makers could not only passively follow the arguments provided by analysts but also participate in 'what-if' testing to understand the consequences of each solution alternative. They would benefit from a 'visual model', in which they can choose any of the options and see the expected outcomes. Decision-makers should also be able to test the solutions for sensitivity to uncertain or subjective information involved and assumptions made. Simple user interfaces and easily understandable visualizations are important for these purposes. It is a challenging research problem to determine how such visual models can be derived from results of problem analysis and option evaluation.

5.7 *Support time-critical decision-making*

In time-critical applications, the feasible alternatives and the information necessary for the choice must be, first, prepared very quickly and, second, presented to the decision-maker so that they could quickly come to the right decision. The general requirements are:

- Reduce the information load on the decision-maker: not only should irrelevant information be excluded, but also the relevant information should be adequately aggregated and generalized, leaving out unnecessary details.
- Use methods of representation that allow quick recognition of the meaning of the information conveyed.
- Increase the clarity of information presentation so that the information can be appropriately understood despite the pressures of time and stress.

- Support knowledge of key information, events, procedures, etc. through externalization in visual artefacts and interfaces that enable quick retrieval of decision-relevant resources.

There is a large body of research that illustrates the role of visual artefacts as a means to offload knowledge in support of memory and cognitive processes (Larkin and Simon 1987, Hutchins 1995). Hence, (geo)visual analytics has a good potential to fulfil these requirements.

5.8 *Support analysis of decision effectiveness and revision of decisions*

There are decision problems where it is not sufficient just to make a decision, but it is necessary to monitor the implementation of the decision and the evolution of the situation in which it takes place. The original decision may prove to be ineffective or no longer applicable because of changes in the situation. This requires the decision to be fully or partly revised. This kind of adaptive real-time decision-making was discussed in the context of example 3, which refers to emergency situations; however, the need for re-assessment and revision of previous decisions may occur not only in time-critical applications. Geovisual analytics solutions are needed for analysing the effectiveness of the current course of action, recognition of the need for revision, and discovering which part of the plan needs to be modified and in what way. Exploratory geovisualization techniques may provide some solutions.

5.9 *Support different actors*

Various actors involved in decision-making have different needs, as discussed above, according to their roles: analyst, consultant, stakeholder, or decision-maker. Besides different needs, actors may also differ in many other respects, including domain and depth of expertise, educational level, computing skills, and experience in using maps, graphics, and information technologies more generally. The differences may be not just personal but implied by their roles. In order to support different actors, it is necessary to identify typical needs for each role and, as much as possible, define a typical profile in terms of the knowledge and skills that may be expected from a person playing this role. This will lay the foundation for task- and user-centred design of geovisual analytics techniques for spatial decision support. Research results and experiences from the areas of human–computer interaction (Jacko and Sears 2002, Dix *et al.* 2003, Shneiderman and Plaisant 2004), computer-supported cooperative work (Palmer, *et al.* 1994, Zhu 2006), and geocollaboration (MacEachren and Brewer 2004, Convertino *et al.* 2005) are of great relevance here.

Supporting different actors in the best possible way involves not only defining adequate information content and choosing appropriate software techniques for visualization and interaction but also using appropriate hardware and technologies. Thus, it may be more natural for high-level managers or politicians, who are expected to make strategic decisions, to analyse and discuss a problem situation and decision options using a wall-size screen and interacting through speech and hand gestures than to do this with a standard workstation. For operational-level decision-makers, who have to make their decisions ‘in the field’, it may be more convenient to use handheld devices or head-mounted displays. Researchers in geovisual analytics for spatial decision support should adapt to and leverage modern advanced technologies related to visualization and interaction and, as mentioned above, consider the scalability of the techniques and tools being developed with respect to characteristics of various displays and environments such as size, resolution, interaction possibilities, and levels of immersion.

5.10 *Conclusion*

While some of the above-mentioned research challenges have been addressed in the presentations at the workshop and in the papers included in this volume, we are still far from reaching comprehensive solutions. One of the observations that could be made about the workshop is that a small proportion of the contributions dealt with both visualization and decision support. This reflects the general situation, in which there has been limited synthesis and cooperation between the research communities focusing on (geo)visualization and on spatial decision support. To achieve significant advances, both in creating tools and in developing the theory, focused efforts of truly multidisciplinary teams are necessary, where 'visualizers' closely cooperate with 'decision analysts' as well as experts from other related disciplines. That is one of the reasons why the organizers of the workshop, in particular, the Commission on Visualization of the International Cartographic Association, decided to define and popularize the concept of Geovisual Analytics for Spatial Decision Support. This new research direction and the opportunity to re-focus geovisualization research is designed to attract the attention of scientists with relevant expertise and interests and to promote the development of the kind of cross-disciplinary research that is required to move the community forward in addressing the pertinent research issues outlined and discussed here.

6. Structure and contents of the special issue

The paper 'Visual Analytics of Spatial Interaction Patterns for Pandemic Decision Support' by Diansheng Guo addresses the problem of scalability of geovisual analytics tools with respect to the amount of data that needs to be analysed. The author demonstrates how spatial interaction patterns discovered by analysing population movement data can help in finding effective strategies for pandemic mitigation. Since the population movement data are very large and cannot be directly displayed and reviewed, computational (data mining) techniques are applied to synthesize the data and visualize them in such a way that the user can see the relevant patterns. It is interesting that spatial interaction patterns are appropriately exposed by means of a reorderable matrix display rather than a map. This shows that sticking only or mostly to map-based interfaces would be counter-productive for geovisual analytics.

Mike Sips, Jörn Schneidewind, and Daniel A. Keim, the authors of the paper 'Highlighting Space-Time Patterns: Effective Visual Encodings for Interactive Decision Making', integrate computational and visual methods to support the discovery of patterns in large data warehouses and analysis of changes in patterns over time. The authors use multivariate clustering to extract groups of objects with similar values of multiple attributes and apply visualization to investigate the uncertainty of the clusters and their temporal evolution. The analytical tool enables interactive drill-down for examining the sensitivity of the detected patterns to the spatial resolution.

The use of data mining methods is also described in the paper 'Towards a Framework for Mining and Analysing Spatio-temporal Datasets' by Michela Bertolotto, Sergio Di Martino, Filomena Ferrucci, and Tahar Kechadi. The authors present an ongoing work on developing a system for the analysis of large spatio-temporal datasets. Data mining is used for extracting patterns in the form of association rules. Different categories of users can explore these patterns either in a Java3D user interface, which is focused on specifics of the patterns, or in a Google Earth-based interface, which puts the patterns into the geographical context. The system is demonstrated on two application examples with rather different data structures: continuous spatio-temporal fields describing development of a hurricane, and discrete events characterizing highway incidents.

Claus Rinner presents the paper 'A Geographic Visualization Approach to Multi-Criteria Evaluation of Urban Quality of Life' dealing with the use of geovisualization in combination with multi-criteria evaluation methods. The author has undertaken a pilot study to assess the usefulness of interactive visual interfaces in the evaluation of urban quality of life. In the study, users interacted with multi-criteria evaluation models and explored the sensitivity of their results to various settings by means of interactive, highly reactive map displays. The users noticed that the multi-criteria models were somewhat simplistic and incomprehensive, as a consequence of the difficulty of modelling urban quality of life in a quantitative way. This indicates the need for an expert analyst to critically review model results in combination with other relevant geospatial information in order to develop appropriate decision-making strategies. Interactive maps appear to be adequate for this purpose.

Suellen Hopfer and Alan M. MacEachren in the paper 'Leveraging the Potential of Geospatial Annotations for Collaboration: a Communication Theory Perspective' speak about the support of collaboration in space-related problem-solving and decision-making. The authors discuss the role of various forms of geospatial annotations attached to locations on map-based displays in supporting collaborative spatial planning. They consider one of the problems often encountered in group discussions, the collective information sharing bias, when group members tend to pay more attention to commonly known (shared) information at the expense of unique information known to a single member. Hopfer and MacEachren argue that geospatial annotations have a potential to reduce the bias and present their recommendations for the design of geospatial annotation tools for collaboration support. The recommendations are grounded in a relevant theoretical framework and account for informational, social, and psychological aspects of group information sharing.

The paper 'A Spatio-temporal Population Model to Support Risk Assessment and Damage Analysis for Decision Making' by Terhi Ahola, Kirsi Virrantaus, Jukka Matthias Krisp, and Gary Hunter touches upon an important topic of accounting for the temporal variation in data used for spatial decision making. The authors apply an interesting approach where human knowledge (expert judgements), which is utilized by a computational tool for risk assessment, compensates for the lack of exact time-referenced data about the dynamics of the spatial distribution of city population. Despite the simplicity of the knowledge model used, a case study demonstrated a substantial improvement in the quality of the resulting assessment as compared with the case when the temporal variation was not taken into account. It is important that the knowledge base can be easily updated by the user. The authors envision human–machine analytical systems where new knowledge is created through the use of visual tools during the process of analysis and added to the knowledge base for further utilization by both the human and the computer.

The papers in this special issue cover only a subset of the research topics that were identified as important in the discussions at the workshop. This is not surprising for an emerging research field, where an appropriate cross-disciplinary scientific community is yet to be built. We hope that this issue will draw the attention to this field and stimulate further research.

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