A GEOGRAPHIC VISUALIZATION APPROACH TO MULTI-CRITERIA DECISION-MAKING

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ABSTRACT

Geographers are increasingly adopting visualization methods for exploring spatial data and generating hypotheses. Data exploration is not limited to the examination of original attribute data, but can be applied at different stages of geographic information processing. Multi-criteria evaluation is a simple yet powerful data processing technique for decision support using geographic information systems. This paper discusses the benefits of a geographic visualization approach to multi-criteria decision-making. In particular, an interactive, spatially enabled implementation of the analytic hierarchy process will be described. The effectiveness of this method will be demonstrated using a case study of assessing population health status for health regions in Ontario.

KEY WORDS: Geographic Visualization, Interactive Mapping, Spatial Decision Support Systems, Multi-Criteria Evaluation, Analytic Hierarchy Process, Population Health Indicators

1. INTRODUCTION

In a recent keynote lecture, Shneiderman (2004) presented guidelines for information visualization in the geographical domain, and discussed existing tools and applications with, and without, a geographic visualization component. Geographic visualization is associated with the use of highly interactive maps in a private, research setting with the aim of revealing unknowns from geographic data (MacEachren 1994). In this approach to generating hypotheses, geographic phenomena are usually explored on the basis of their original attributes. In this paper, we argue that geographic visualization can also be applied throughout geographic information processing. To demonstrate the visual exploration of processed data, we use the example of multi-criteria evaluation (MCE) within geographic information systems (GIS). MCE is a simple yet powerful decision support technique that combines feature attributes to produce a priority ranking of decision alternatives. When applied to spatial decision problems, geographic visualization can be used throughout the evaluation process by displaying ad-hoc results of the user’s preference settings and adapting those displays to changes in the parameters of the MCE process.

In section 2, we will provide background information on GIS-based MCE and its relation to geographic visualization. Section 3 describes an interactive, map-centred implementation of the analytic hierarchy process (AHP), a widely used MCE method. In section 4, we present a case study of evaluating the health status of the population in Ontario using the interactive spatial AHP tool. We conclude the paper with a discussion of the geographic visualization approach to multi-criteria decision-making and an outlook on future research.

2. GIS-BASED MULTI-CRITERIA EVALUATION

Multi-criteria evaluation was introduced to GIS some 15 years ago with a series of papers describing various MCE methods that were implemented in GIS software and applied to a number of decision problems. Malczewski (1999) provides an account of the methods used, including Boolean operators and simple additive weighting. A slightly more complex MCE method is the analytic hierarchy process (Saaty 1980), which was transferred to a GIS environment by Banai (1993) and Eastman (1997). The common procedure of GIS-based MCE is to determine decision alternatives and decision criteria, establish the performance of alternatives in those criteria, and aggregate the performance values to a single evaluation score for each alternative in order to create a preference ranking.

Geographic visualization has been defined by MacEachren and Monmonier (1992) as the “purposeful exploration, search for pattern, and development of questions and hypotheses” based on spatial data. MacEachren (1994) associates the visualization function of maps with the private activity of revealing unknowns in a highly interactive human-map environment. The visualization function has been contrasted with the communication function of maps. Along the same lines, Slocum et al. (2005) define spatial data exploration as using interactive graphics that permit users to examine different representations of spatial data dynamically. Methods for spatial data exploration summarized by Slocum et al. (2005) include data standardization, varying the symbolization, highlighting data subsets through focusing or brushing, providing multiple connected displays, and animated data representations.

While other authors emphasize the exploration of spatial phenomena through geographic visualization, in this paper we argue that visualization can also help understanding geographic information processing. In various GIS procedures, we are interested in understanding the processing of geographic datasets and the underlying scientific models. For example, in MCE, attribute values are
processed according to user preferences. We propose to make various settings in a MCE process interactive and use geographic visualization principles to explore the underlying decision-making process.

The use of interactive maps to explore spatial patterns of variables and spatial trends over time has been a focus of cartographic research for about a decade, leading to a number of prototypical software tools. One of these is CommonGIS, in which a particular focus has been on combining visualization with decision support methods. Jankowski et al. (2001) presented a prototype tool that allowed decision-makers to explore and structure spatial decision problems using interactive maps. Andrrienko and Andrrienko (2001) developed “utility signs” for visual comparison and decision support. Rinner and Malczewski (2002) proposed an exploratory approach to spatial decision strategies based on the ordered weighted averaging (OWA) method. Those methods are now integrated in CommonGIS making it a suitable platform for additional spatial decision support tools.

3. AN INTERACTIVE AHP IMPLEMENTATION

We have developed an interactive, spatial variant of the analytic hierarchy process (AHP; Saaty 1980) that combines the advantages of this MCE method with the benefits of geographic visualization. The method is implemented as a calculation function within the CommonGIS environment and as such takes its input from a feature attribute table. Users can develop a decision scenario by selecting attributes as decision criteria, establishing a hierarchy of these criteria, and determining the relative importance of criteria by weighting. A standardised score and ordered ranking of the decision alternatives is computed instantly as two additional columns in the attribute table. The preference settings for the AHP method can be modified at any time during a session, and the effects will be visualized immediately. Visualization tools allow for the simultaneous observation of geographic space, criterion space, and decision space; it is within the latter that preference settings for the AHP process are defined.

The AHP method is characterised by the phases of (1) decomposition of a decision problem into a hierarchy of goals, objectives, and criteria; (2) judgement of relative importance weights between the attributes; and (3) synthesis to overall evaluation scores. Decomposing a decision support problem in the AHP requires framing it in an attribute hierarchy, rooted at a single attribute representing the overall score for a decision alternative. The root node is then composed of a number of attributes, and these attributes may in turn be subdivided further. The establishment of such a hierarchy reduces the cognitive load of importance weighting to only those criteria that fall under the same group attribute, instead of comparing all possible attributes at once.

For the weighting process, Saaty (1980) proposed the pairwise comparison approach to further reduce the number of elements involved in a preference judgement. In the pairwise comparison matrix, two elements are compared at a time using a scale that ranges from “overwhelmingly more important” (9:1) to “equally important” (1:1), and their inverses (down to 1:9). Based on the criterion weights derived from the pairwise comparison matrix, scores for group attributes in the hierarchy are calculated as a weighted average of elements in the group, and the final evaluation score for each decision alternative is attained by iterating this process from the leaves upwards to the root of the hierarchy.

While group attributes get derived scores, the leaf attributes at the bottom of the hierarchy get their scores from the table attributes for the decision alternatives. Converting the numeric data for an attribute to commensurate scores is done through standardisation, for which several different techniques are available, including score range transformation and proportional transformation (Malczewski 1999). Figure 1 outlines a hierarchy of group and table attributes with importance weights attached to each of them by sub-hierarchies, and the calculation of the overall evaluation score by bottom-up iteration of the hierarchy.

Our implementation of the AHP includes these three stages as separate tabs in a calculation window. The user can create new group attributes and organise the hierarchy using the “Hierarchy” tab. Weighting among group attributes is done in the “Criterion Weights” tab, where the user has access to a pairwise comparison matrix. Also in this tab a parallel coordinate plot displays decision alternatives (as vertical lines) and their scores at each table attribute, as well as the overall ranking and score, giving an instant visual representation of the current weighting scheme and its results. Finally, the parameters for different standardisation schemes may be
modified in the “Standardisation” tab. The parallel coordinate plot is a built-in function of CommonGIS (Andrienko and Andrienko 2001) while our implementation of the pairwise comparison matrix was inspired by Divisek and Meyersiek (2001).

Settings and parameters for the three stages may be modified at any time, and the updated results are displayed on the map and on the parallel coordinate plot immediately, giving the user instant visual feedback. The user is not chained to a particular order of operations; for example, the user may determine a weighting scheme for a group of attributes in the “Criterion Weights” tab, then assign the group’s parent attribute to a new location in the “Hierarchy” tab, and finally change the standardisation method for one of the attributes in the group. In addition, the weighting scheme and hierarchy can be saved so the careful consideration going into the AHP configuration can be re-used later.

4. CASE STUDY

A case study of public health indicators from the Canadian Community Health Survey (Statistics Canada 2004) is used to illustrate the interactive, spatial AHP method. The objective of the case study is to determine the overall health status of the 37 public health units in the Province of Ontario, Canada. Based on this information, decisions about increasing or re-allocating funds could be made. This application is meant to provide a realistic example of the benefits of geographic visualisation for exploring decision problems rather than achieving a comprehensive evaluation of population health status in Ontario.

Decision alternatives for the case study are Ontario public health units, roughly county-sized administrative regions. As they vary greatly in population, percentage values were used for the attributes instead of raw counts. Health determinants are used to estimate overall population health in lieu of using actual health indicators. For demonstration of the method, the case study is limited to using four categories of non-medical health determinants: Health behaviours (drinking and smoking), living and working conditions (such as employment and income), personal resources (life stress) and environmental factors (second-hand smoke).

<table>
<thead>
<tr>
<th>First-Level Group Attributes</th>
<th>Second-Level Group Attributes</th>
<th>Third-Level Data Attributes</th>
<th>Weight (within lowest grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health Behaviours</td>
<td>Drinking</td>
<td>People reporting having 5 or more drinks, 12 or more times a year (MULT_DRNKS)</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Smoking</td>
<td>Current smokers, both occasional and daily (CURR_SMOKE)</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Current smokers who started smoking between the ages of 5 and 14 (SMKINIT_5)</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Current smokers who started smoking between the ages of 15 and 19 (SMKINIT_15)</td>
<td>9%</td>
</tr>
<tr>
<td>Living and Working Conditions</td>
<td>Physical Activity</td>
<td>People reporting active or moderately active recreational lifestyles (PHYS_ACTIV)</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Education</td>
<td>25-29-year-olds with a high school diploma (HS_DIPLOMA)</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Labour Force</td>
<td>Unemployment rate for people aged 15 and over (UNEMP)</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Long-term unemployment rate (UNEMP_LONG)</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td>Income</td>
<td>Households spending 30% or more of total income on shelter expenses (INCM_SHLTR)</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Population in low-income households (INCM_HHLD)</td>
<td>25%</td>
</tr>
<tr>
<td>Personal Resources</td>
<td>Life Stress</td>
<td>Some Stress (STRESS_SOM),</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quite a lot (STRESS_LOT)</td>
<td>75%</td>
</tr>
<tr>
<td>Environmental Factors</td>
<td>Exposure to Second-hand Smoke</td>
<td>Exposure to Second-hand Smoke (SCHAND_SMK).</td>
<td>100%</td>
</tr>
</tbody>
</table>

A hierarchy was built based on the given grouping of variables in the Statistics Canada (2004) dataset, and weights were determined between the elements of each group. The hierarchy is composed of three levels grouped under the Evaluation Score. The first level is composed of the high-level attributes representing the four major categories listed above. The first two categories are further broken down into second-level group attributes, which are in turn composed of the actual data attributes at the third level. The full hierarchy is shown in Table 1.
The result of this AHP configuration is a ranking of the Ontario’s public health units, displayed as a choropleth map in Figure 2, with high scores (top ranks) shown as dark areas and low scores (bottom ranks) shown as light areas. This entire map updates dynamically during the course of setting up the AHP, and some interesting patterns appear in this map. The areas with the lowest scores are located in Northern Ontario, and the highest scores occur in Central Ontario. The two most North-Westerly units have higher scores than their surroundings, as does the Ottawa health unit in the East, while the Toronto and Peel units have lower scores than their surroundings. The parallel coordinate plot inside the “Criterion Weights” tab (also in Figure 2) becomes very useful in investigating these differences. For example, the Halton and Peel regions are adjacent, yet the former has a much higher score than the latter. On the parallel coordinate plot we see the regions have similar scores in smoking, drinking, education and household income, but Peel has higher unemployment while Halton has much higher rates of physical activity.

5. DISCUSSION AND CONCLUSIONS

By reviewing different decision strategies in terms of the importance weights given to decision criteria, we found that the interactive manipulation of the map of evaluation scores, the dot plot of evaluation scores, and the settings of the AHP method greatly helped understanding the original dataset as well as the (preliminary) results of the MCE process. Not only does AHP help to structure a complex evaluation problem, but the geographic visualization approach also supported the identification of outliers, comparison of decision outcomes, and exploration of different decision strategies. For example, in the above case study the analyst could modify the symbolization of the results map to compare the evaluation scores of all public health units to a selected unit; decrease the weight of the unemployment indicator until Peel improves its rank above Halton region; or change the AHP hierarchy by creating a single group attribute for both, personal resources and environmental factors, to reduce the influence of each of these health determinants.

The geographic visualization approach also addresses general criticism of MCE concerning the production of different results by different MCE methods, and the difficulty of choosing the “right” method for a specific decision problem. Our approach allows for a visual sensitivity analysis of decision rule settings in which the effects of small changes in the settings can be explored on interactive maps. Using the linked displays of geographic space, criterion space (parallel coordinate plot), and decision space (AHP hierarchy and weights), analysts are supported in understanding the factors that influence the outcome of the MCE process and either adjust the analysis to additional knowledge they may have, or adjust their implicit assumptions on the decision problem to the findings of the decision-making process.

In terms of future research, we plan to extend the existing interactive spatial AHP implementation with additional functionality. It would be highly beneficial to combine the power of the AHP as a weight-determining method with some other MCE methods, such as the ordered weighted averaging. Ideally, both calculation windows could be open at the same time and dynamically linked, permitting the user to change settings in one window and have the results instantly appear in the other. We will also conduct user experiments to examine the usability and flexibility of the geographic visualization approach to multi-criteria decision-making. Expert interviews with urban geographers and planners are being designed to this end.

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