

Coordinated Views for Informed Spatial Decision Making

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Abstract

There exists a range of computational methods for supporting multi-criteria decision-making. We argue that a combination of these methods with visualisation tools promotes more conscious use of the results of the computations and, hence, contribute to making sound, well-substantiated decisions. Multiple complementary displays enable a comprehensive analysis of potential decisions. We suggest several coordination mechanisms as particularly suitable for combining the computational and visual tools for decision support. The combined use of the tools is illustrated by examples.

1. Introduction

In this paper, we consider the use of coordinated displays for multi-criteria decision making in a spatial context. The most widely accepted generalisation of the decision-making process was introduced by Simon [25], who divided the process into three major phases: intelligence, design, and choice. The intelligence phase involves data collection, integration, pre-processing, and exploration with the aim to identify the problems or opportunities. During the design phase, one looks for a set of possible solutions to the problem(s) identified in the intelligence phase and analyses the options thus found. During the choice phase, the options are evaluated and analysed in relation to others, and a particular option or a set of options is selected. Typically, a decision-maker must account for multiple, often conflicting, evaluation criteria, and the final decision results from an explicit or implicit trade-off. At any point in the decision-making process, it may be necessary to loop back to an earlier phase.

Malczewski [20] mentions the software tools that can support the decision process at the different stages. Techniques of exploratory data analysis, or EDA, play a major role in the intelligence phase. For determining the set of alternatives in the design phase, formal models are

typically used. The phase of choice is supported by an array of computational methods developed within the research field called multi-criteria decision-making, or MCDM.

The concept of EDA emerged in statistics. John Tukey [28] introduced it as a counterbalance to the traditional statistical techniques of checking a priori selected hypotheses. The goal of EDA is to survey previously unknown data and to arrive at plausible hypotheses concerning relationships, patterns, and trends hidden inside the data volumes. Techniques of EDA are mostly based on data visualisation, that is, graphical representation of data that can help in revealing important traits and relationships [7]. A high degree of user interactivity is a general requirement to graphical displays used for exploratory data analysis. A taxonomy of techniques for interactive manipulation of graphical displays can be found in [4].

It is commonly recognised that comprehensive data investigation requires multiple complementary displays exposing various aspects of the data. Multiple views need to be linked so that the information contained in individual views can be integrated into a coherent image of the data as a whole [5]. The most common method of linking is the identical marking of corresponding parts of multiple displays, for example, with the same colour or some other form of highlighting. Usually highlighting is applied to objects interactively selected by the user in one of the displays. This technique originates from the so-called “scatterplot brushing” operation suggested by Newton [22] and is often traditionally called “brushing”. An overview of currently existing methods for display linking is proposed in [24].

Over the past decade, the notion of EDA has spread from statistics to cartography. Cartographers have recognised the demand for new software supporting the use of interactive, dynamically alterable thematic maps and facilitating “visual thinking” about spatially referenced data [18] [19]. Linking of a map display with various kinds of statistical graphs was suggested as a

primary instrument of the exploratory analysis of spatially referenced data [21] [17] [26] [8] [9].

We argue that linked displays may be supportive not only during the intelligence phase of the decision-making process but also in the stage of choice. They can aptly complement and enhance the existing mathematics-based, computational MCDM support techniques.

Surveys of the existing MCDM methods can be found in [10] and [27]. For supporting decision making in a spatial context, for example, for choosing locations, most researchers suggest integration of the MCDM support methods with geographical information systems (GIS) [14] [6] [12] [20]. A GIS is used as a source of data for the MCDM methods and a means of displaying the results. For example, in the prototype described in [13], evaluation scores assigned to spatially distributed options by one of the MCDM methods are shown on a map by circles of differing sizes. We find, however, that this kind of interaction is very limited and insufficient for making informed, well substantiated decisions in a spatial context.

We see two major problems. First, besides the geographical space, a decision maker needs to see how the solution found by a MCDM algorithm is positioned in the attribute space and where it is with respect to the remaining options. On this basis, the decision maker can check whether this solution corresponds to her/his expectations and whether the trade-off involved is admissible. Otherwise, the decision maker would have to blindly accept the output of a “black box”, while bearing the full responsibility for the decision to be made. Second, the decision maker needs to test the robustness of the solution with respect to minor changes of input parameters. For example, some MCDM support methods ask the user to specify so-called weights for the decision criteria to express the relative importance of the criteria. If changing the weight of some criterion from 0.33 to 0.35 results in the MCDM method proposing a different solution, this means that the previous solution might not be really optimal. In such a case, careful consideration of options with close ranking is necessary, probably, with the involvement of additional criteria. For testing a solution for sensitivity, the decision maker needs the decision support software to be highly interactive and dynamically reacting to user’s actions. Such a degree of user interactivity and reactivity is not achieved in the known GIS-MCDM combinations.

In the remainder of the paper, we describe our solution to these two problems based on an active involvement of multiple coordinated views. All the techniques described are implemented in the software system CommonGIS designed to support exploratory data analysis and decision-making in a spatial context.

2. Spatial decision support in CommonGIS

2.1. CommonGIS overview

CommonGIS offers an array of data visualisation techniques facilitating exploratory analysis of spatially referenced data, including highly interactive maps [2] and various statistical graphs: dot plot, frequency histogram, scatter plot, scatterplot matrix, parallel coordinate plot, etc. Besides the tools for EDA, CommonGIS offers a range of spatial decision support facilities. Some of them are described in [3].

Multiple displays in CommonGIS can be simultaneously present on the screen providing an opportunity to view data from various perspectives. All the displays are dynamically linked in many different ways. The most general way is simultaneous highlighting of corresponding objects. All displays synchronously react to changing conditions in the dynamic query device [1] by removing objects that do not satisfy the current conditions. When there is a map with object classification, the classes can be propagated to all non-cartographic data displays, and the graphical elements in these displays will be painted in the corresponding class colours. Object colouring dynamically changes in response to interactive altering of the classification.

A full enumeration of display linking methods supported in CommonGIS is beyond the scope of this paper. While any of them may be useful for spatial decision-making, we would like to consider in more detail a method we regard as particularly suitable for supporting the choice phase of the decision-making process. The method involves so-called dynamic attributes produced by interactive computational tools. For example, there is a tool for assessing the degree of similarity of objects to a selected object with respect to their characteristics expressed by values of attributes. The tool generates a new attribute with values representing the distance of each object to the selected object in the multidimensional attribute space. The computation may use different distance metrics, and the user may switch from one metrics to another. As a result, the distances are immediately recomputed, and the values of the attribute change. Respectively, when some graphical display represents this attribute, it updates itself to reflect the new values. When multiple displays represent the same dynamic attribute, they change in parallel.

The idea of dynamic attributes represented on various displays, including maps, can be used for appropriate integration of computational MCDM support methods with visualisation tools, which is necessary for informed decision-making, in particular, in a spatial context. For this purpose, a MCDM method needs to be realised as an interactive tool allowing the user to alter its input parameters and dynamically re-computing the results after

each change. The results take the form of a dynamic attribute, which may be represented on any display. In this way, the degree of reactivity required for a solution sensitivity analysis is achieved.

Let us now illustrate on a few examples how visualisation tools may be combined with computation-based MCDM support methods to support informed decision-making.

2.2. Example decision problem

As an example, we use a real-world decision problem of ranking Idaho counties according to the need for funding the primary health care services. The problem is considered in detail in [13]; here we give a short summary.

Due to numerous geographic and access barriers, the delivery of primary health care services throughout the state of Idaho is complicated. Idaho has one of the lowest physician-to-population ratios in the nation. Recruiting health professionals to Idaho's remote areas and to regions in the state with substantial portions of low-income/undeserved persons is a constant challenge. The decision problem is how to distribute limited funds in order to help the state counties attract health care professionals through repaying their education loans.

There are ten evaluation criteria (attributes) to be taken into account in making the decision about the distribution of the funds:

1. <i>Estimated Number of Unaccounted Primary Care Visits</i> . This criterion serves as an indicator of unmet demand for primary care medical services due to the unavailability of providers within the 15-mile travel distance constraint.
2. <i>Burden on On-Call Providers</i> . Expresses the number of hours on call for each provider.
3. <i>Availability of Obstetrical Care</i> . It is expressed by the number of providers offering obstetrical delivery services in each county.
4. <i>Availability of Emergency Medical Services</i> . The criterion values are calculated dividing the sum of ambulances and quick response units by the number of population in each county
5. <i>Percent of Population Receiving Medicaid / Medicare</i> . It is the percent of population in each county who utilize Medicaid or Medicare medical insurance.
6. <i>Low Birth Weight Rate</i> . It is the percent of low weight births per each county averaged from a multi-year interval.
7. <i>Poverty Rate of Population</i> . The criterion values are based on census poverty rates by county.
8. <i>Proximity of a Hospital to the Population</i> . The criterion values are calculated based on the nationally

accepted standard for the maximum travel distance of 35 miles to a hospital in rural areas. The number of individuals residing outside each hospital influence zone (35-mile radius) is calculated for each county.

9. <i>Emergency Room Visits</i> . The criterion values are based on annually collected hospital emergency room visit data.
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10. <i>Fertility Rate</i> . County wide average fertility rates.
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2.3. General notes about numeric MCDM support methods

Most MCDM support methods require decision criteria to be represented as numeric attributes. In order to use a qualitative attribute as a decision criterion, one needs to specify an order of preference among its values and encode the values by numbers, for example, 1, 2, 3,

Two different types of criteria are possible: benefit criteria and cost criteria. If higher attribute values make an option better (more appropriate), this attribute is a benefit criterion. If higher attribute values are less desirable (less appropriate) than lower ones, this is a cost criterion.

Criteria may have different relative importance for a decision maker. The relative importance of criteria can be specified, for example, through so-called weights of the criteria. The weights are real numbers between 0 and 1. The sum of the weights of all criteria used in the decision-making process must be equal to 1. The weight 0 means that the corresponding criterion is of no importance for the decision maker. There are also MCDM support methods which do not make use of criteria weights, as, for example, the Feasible Goals method considered below.

2.4. Trade-off analysis using Feasible Goals method

The Feasible Goals Method [15][16], or FGM, uses a mathematical model to compute from a given set of options with their characteristics so-called non-dominated frontiers, or efficiency frontiers, of the space of feasible solutions. A reasonable strategy is to select one of the alternatives positioned on these frontiers or close to them, since the options lying inside are dominated and, hence, not optimal. If the number of decision criteria is relatively small, the frontiers can be visually represented on graphs called "decision maps" (these should not be mixed with conventional maps). A decision map for three criteria is shown in Figure 1.

In this display, the X-axis corresponds to the attribute "Fertility rate" and the Y-axis to "Low-weight birth rate". The coloured regions represent the spaces of feasible

alternatives depending on the values of the third attribute, “Poverty rate”. The largest, outer region corresponds to the lowest values of the poverty rate, specifically, below 13.7 (the minimum value in the dataset is 7.09). The second largest region nested inside the first one shows the feasible decision space when the poverty rate values are from 13.7 up to 15.3. The next region corresponds to the poverty rate from 15.3 up to 16.9, and so on. One may observe that, with increasing the values of the criterion “Poverty rate”, the space of feasible alternatives shrinks. Respectively, with increasing the poverty rate values, the values of the other two criteria that can be potentially attained decrease.

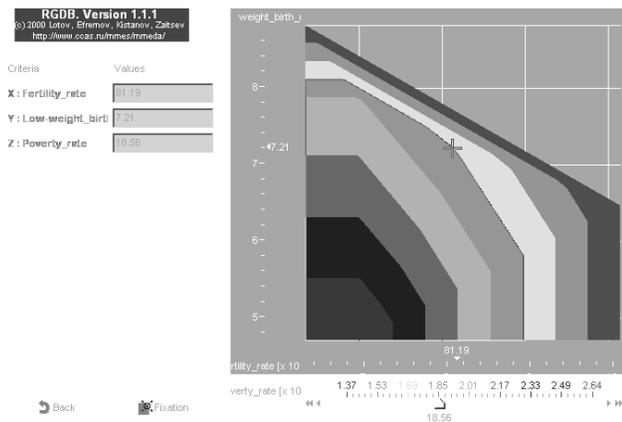


Figure 1. A decision map for three criteria.

The boundaries of the coloured regions, in turn, represent the relationships between the criteria “Fertility rate” and “Low-weight birth rate” (for each particular value range of the third criterion). It may be seen that attaining higher values of one of the criteria can only be achieved by sacrificing the other criterion. Hence, the decision map represents the possible trade-offs among the criteria.

The “decision map” visualisation technique may be extended to represent four or five criteria. In the first case, several decision maps corresponding to representative values of the fourth criterion are shown in a row. In the second case, a matrix of decision maps is displayed.

Having explored the feasible decision space and the possible trade-offs, the user may identify the goal within this space she/he wishes to attain, that is, a particular combination of values of the attributes. For this purpose, the user needs to click on the corresponding position on the decision map. In the example presented in Figure 1, the user decided that sufficient conditions for giving funding are the poverty rate being around 18.56, the low-weight birth rate being about 7.2, and the fertility rate being about 81.2. The cross marks the corresponding position on the decision map. The choice of this particular position was affected by the shapes of the efficiency

frontiers, that is, the boundaries of the coloured regions on the graph. It may be seen from the picture that, for the selected poverty rate value, moving the cross farther up (i.e. increasing the value of the low-weight birth rate) would lead to a dramatic decrease for the criterion “Fertility rate”, since it is only possible to move along the boundary. At the same time, increasing the poverty rate value is only possible at the cost of moving to one of the inner frontiers, where no appropriate combination of fertility and low-weight birth rates can be attained.

After the desired goal has been indicated, the FGM tool finds among the available options the options being the closest to the goal. The result is represented on the map, as is shown in Figure 2. The counties with the characteristics close to the user-specified goal are marked by thick boundaries. The bar charts inside the boundaries show the differences between the characteristics of these counties and the goal. A bar chart contains a bar for each attribute. The height of the bar is proportional to the difference of the value of this attribute and the desired value. Upward-oriented bars represent values higher than the desired values of the respective criteria, and downward-oriented bars represent values lower than the desired values. When a value is equal or very close to the desired value, the corresponding bar has zero height and, hence, does not appear. More information about this method of representing and comparing decision options can be found in [3].

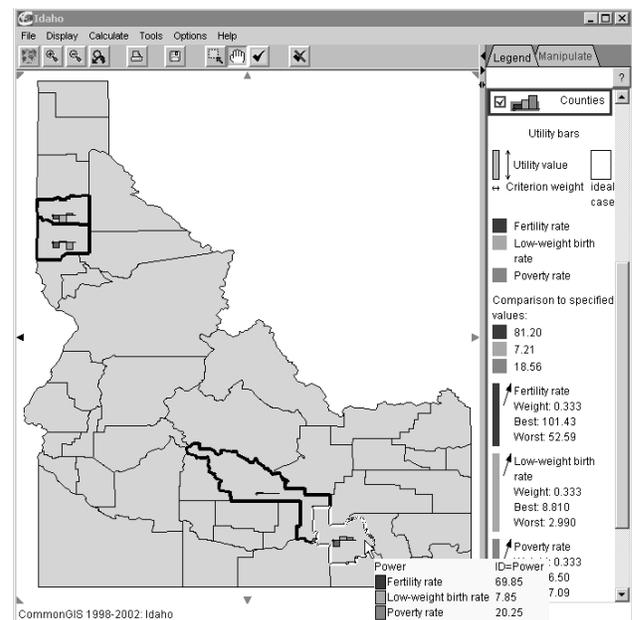


Figure 2. The map shows the options (Idaho counties) close by their characteristics to the goal defined by the user on the decision map from Figure 1. These three counties are suitable candidates for receiving funding, with respect to the criteria “Fertility rate”, “Low-weight birth rate”, and “Poverty rate”.

It should be noted that the options close to the goal are not only shown on the map but also highlighted in all displays currently present on the screen. This provides an opportunity to analyse various characteristics of these options and compare them with other options.

When the user redefines the goal, i.e. alters the desired values of the attributes, the FGM tool performs a new search for the closest options and sends the new set of the desired values and the new set of options to the geographic map display. The map is automatically updated to represent the new result. For example, the map in Figure 3 represents the result of increasing the desired value of the criterion “Low-weight birth rate” to 7.95 at the cost of decreasing the values of the fertility and poverty rates to 72.9 and 17.03, respectively. Three of the earlier selected options have remained in the set of the options approximating the goal while one option has been replaced. Note that the bar charts now represent the result of comparison with the new set of the desired values.

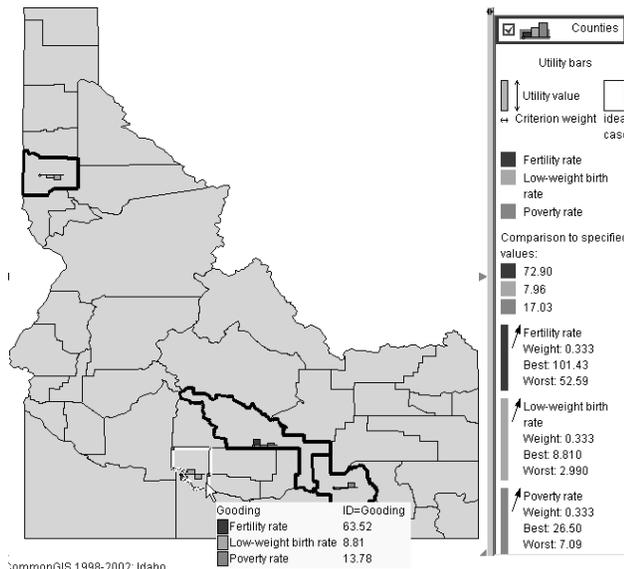


Figure 3. In order to probe the robustness of the solution presented in Figure 2, the user has slightly altered the goal. Three of the four initially selected options have remained in the new set of the recommended options.

This example shows that the link between the geographical map display and the FGM tool can be effectively used for testing the robustness of the outcomes of the FGM, which is usually hard to do in a GIS-MCDM combination. Like in a typical GIS-MCDM combination, a geographical map in CommonGIS shows positions of the recommended solutions in the geographical space. At the same time, the decision map display used by the FGM tool allows the user to see the space of feasible alternatives and the positions of the solutions in this space. The link between all displays in the system through highlighting provides good opportunities for comparing

characteristics of the recommended options with those of the others. Hence, MCDM results can be comprehensively and conveniently analysed in both geographical and attribute spaces.

Although the mathematical model underlying the feasible goal method can take into account any number of decision criteria, the decision map visualisation technique is limited to up to five criteria. This limitation can be compensated by applying the FGM tool to different combinations of criteria and comparing the results.

There is a group of MCDM support methods that aggregate values of multiple attributes characterising each decision option into a single evaluation score reflecting the degree of appropriateness of this option. These methods typically pose no limitations on the number of the criteria involved. Several methods of this kind are realised in CommonGIS as interactive computation tools producing dynamic attributes. All the methods explicitly involve criteria weighting.

2.5. Dynamic ranking of decision options

Figure 4 shows the user interface for specifying types (cost or benefit) and weights of decision criteria in CommonGIS.

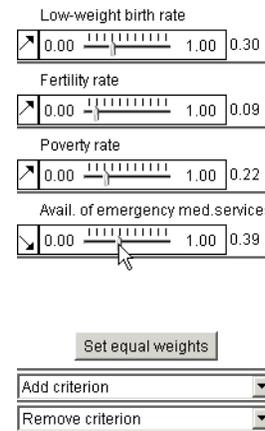


Figure 4. The user interface for specifying types and weights of decision criteria in CommonGIS.

Below each criterion name there is a slider allowing the user to select/adjust the criterion weight within the value range (0, 1). The adjustment of one weight causes all other weights to automatically change values proportionally to their values before the adjustment in order to keep the sum of weights equal to 1. Through the weights the user expresses the relative importance of criteria. The North-East pointing arrow, on the left of each weight slider, indicates a benefit criterion, the South-East pointing arrow corresponds to a cost criterion. The user can easily change the directionality of criteria with a mouse click.

As we already mentioned, values of multiple attributes are aggregated into evaluation scores, which are then used for ranking the options. The results of the computations are represented, together with the initial characteristics of the options, on a parallel coordinate plot [11], as is demonstrated in Figure 5.

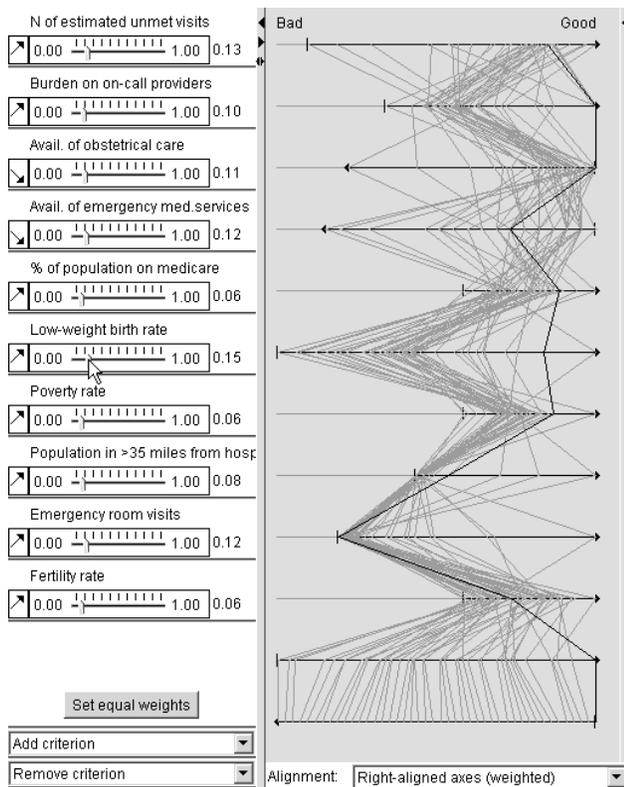


Figure 5. Characteristics of options in terms of multiple criteria are aggregated into evaluation scores. The initial characteristics and the resulting scores are represented on the parallel coordinates. The parallel coordinate plot is transformed so that the axes reflect the weights and types of the criteria.

In our implementation, we customise the general technique of parallel coordinates to the use for decision support. Thus, the axes for benefit and cost criteria have different orientation (indicated by arrows): left to right vs. right to left. With such a solution, the most appropriate values of each attribute are always on the right, and the worst are on the left. This makes it easy to estimate visually how good any specific option is: the closer to the right edge of the plot is a line, the better is the option.

Differences in relative weights of criteria can be (optionally) reflected by variation of lengths of the axes: the more important is a criterion, the longer is the corresponding axis. Due to this transformation, lines of options surpassing others in more important criteria shift visually more to the right (“good”) pole of the plot.

The two axes at the bottom of the plot represent the results of the computation by the selected MCDM support method. The axis second from the bottom represents the aggregated scores, and the next axis shows how the options are ordered (ranked) according to these scores. Note that the axis for the ranks has the inverse (right to left) orientation: better options have smaller rank values.

Any line on the plot can be selected using the mouse. As a result, the corresponding object will be highlighted in all displays. This also helps to see the position of any option among the other options with respect to the initial characteristics and the scores and ranks computed. Thus, in Figure 5 the line of the top-scoring (i.e. the first in rank) option is highlighted. It may be seen that this option has the best values of the attributes “Burden on on-call providers” and “Availability of obstetrical care” and rather good values of other attributes except for the last three ones.

Both the computation procedure and the parallel coordinate plot are sensitive to any changes in the criteria weights. The scores and ranks are immediately recomputed, and the plot immediately redraws itself when a change occurs. This allows the user to investigate how sensitive the result of the multi-criteria evaluation is to minor changes in the criteria weights.

We have already mentioned that the MCDM support methods are realised in CommonGIS as interactive computational tools producing dynamic attributes. Specifically, a MCDM tool generates two attributes: evaluation score and ranking. These dynamic attributes can be represented on various graphical displays, in particular, on maps. When the tool recomputes the scores and ranks after the user altering the criteria weights, the values of the dynamic attributes change. All the displays representing these attributes are notified about the change and update themselves.

In decision-making, it is often necessary to select a subset of appropriate options rather than a single option. For this purpose, it may be convenient to classify options according to the ranks received. For example, in the Idaho problem it might happen that the whole amount of funding available needs to be distributed among three counties which are the most in need. Using the interactive classification tool of CommonGIS, the decision-maker can define the classes so as to separate three options with the topmost ranks from the rest. The decision-maker may wish to introduce more classes. Thus, a class of “conditionally fundable” options may be defined for the case when additional funding becomes available.

The map in Figure 6 represents a classification of the Idaho counties according to the ranks produced by the “Ideal Point” MCDM support method [10] for the ten criteria described in §2.2 with the weights as is shown in Figure 5. The class boundaries are chosen so that the first class includes 3 best options (i.e. with the ranks from 1 to

3), the second class contains 3 next options (with the ranks from 4 to 6), and the third class is formed by the remaining options. The top-scoring option is highlighted (marked with a thick boundary). The same option is highlighted on the parallel coordinate plot in Figure 5.

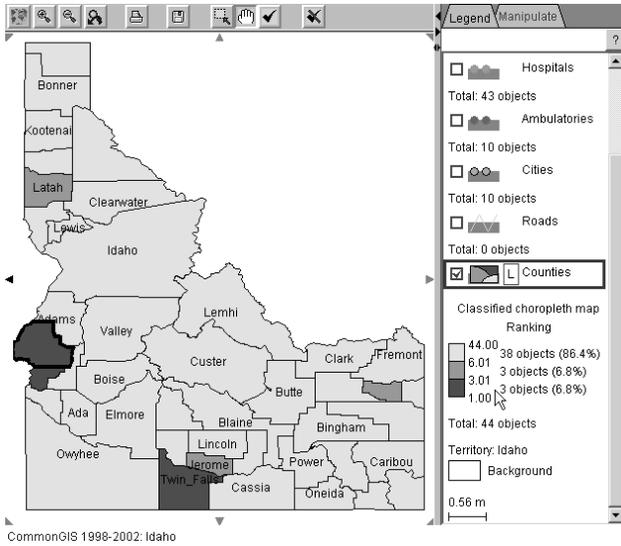


Figure 6. The map represents option ranking computed by the Ideal Point method with the weights of the criteria as is shown in Figure 5. Marked with the thick border is the same option that is highlighted on the parallel coordinate plot in Figure 5.

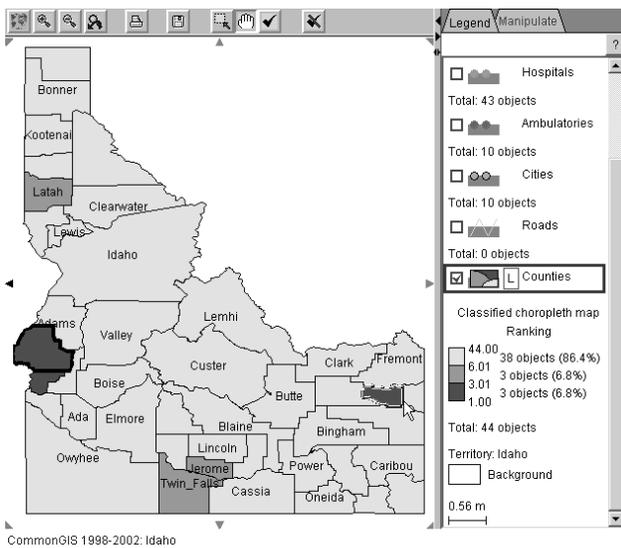


Figure 7. After increasing the weight of the criterion “Population in more than 35 miles from hospitals” to 0.20, the county Twin Falls has moved from the first to the second class, while the county Madison (in the east, pointed with the mouse cursor) has changed from the second to the first class. The classification of the remaining options stays the same.

Let us now alter some of the criteria weights, for example, increase the weight of the criterion “Population in more than 35 miles from hospitals” to 0.20. The map immediately changes as is shown in Figure 7. The definition of the classes (i.e. the class boundaries) has not changed, but some options have moved from one class to another.

2.6. Dynamic table view and classification broadcasting

Perhaps, it is even more convenient than with the map to observe changes of ranks using the dynamic table view. The table view (Figure 8) is dynamic in the sense that it can show dynamic attributes and update itself when the values of these attributes change. The user may choose an attribute to be used for ordering rows in the table view. If this is a dynamic attribute, the order of the rows will change each time when the values of the attribute change. Hence, if the user selects the dynamic attribute “Ranking” resulting from a MCDM support tool to be used for ordering, the best options will always appear at the top of the table.

Ranking	N of estimated unmet visits	Burden on on-call providers	Avail of obstetrical care	Avail of emergency med services	% of population on medicare	Low-weight birth rate	Poverty rate
1	890	2.8	0.0004	0.0009	13.74	6.21	16.25
2	996	7.00	0.0000	0.0007	25.01	7.95	20.25
3	2561	7.68	0.0000	0.0003	15.89	6.43	19.83
4	8607	7.60	0.0000	0.0005	12.29	6.46	19.83
5	14733	2.99	0.0009	0.0001	17.80	6.63	19.83
6	14168	2.55	0.0011	0.0002	20.72	7.38	19.75
7	653	5.00	0.0002	0.0019	17.45	2.99	14.84
8	18078	4.03	0.0004	0.0002	10.23	4.71	26.50
9	-8282	1.29	0.0008	0.0001	21.15	4.85	16.46
10	2614	7.00	0.0000	0.0003	20.44	4.94	16.54
11	2548	2.89	0.0007	0.0008	24.28	7.15	18.40
12	-3256	1.85	0.0009	0.0007	25.61	7.85	20.25
13	4614	3.10	0.0004	0.0002	24.32	5.29	16.99
14	-11709	1.91	0.0005	0.0002	16.00	6.35	16.62
15	-25754	2.38	0.0005	0.0002	14.20	5.86	10.35
16	30283	2.47	0.0010	0.0002	16.85	5.51	13.77
17	-23994	7.00	0.0000	0.0010	13.96	6.77	13.16
18	-2481	3.07	0.0006	0.0007	28.75	6.23	16.23
19	-4127	2.90	0.0023	0.0009	22.36	4.67	13.76
20	-3967	2.40	0.0000	0.0004	12.67	5.35	12.74
21	-4677	1.87	0.0016	0.0002	23.42	5.43	17.83
22	2002	2.28	0.0000	0.0005	19.58	5.04	13.96
23	-12231	3.63	0.0011	0.0003	20.42	4.94	16.63
24	-3834	1.27	0.0022	0.0006	32.13	5.47	19.56
25	-8229	1.84	0.0007	0.0002	14.40	6.43	8.13
26	-40620	5.28	0.0000	0.0000	15.16	9.81	12.78
27	833	3.88	0.0013	0.0008	23.17	4.98	12.96
28	-5039	5.60	0.0021	0.0006	15.15	3.33	18.09
29	-7137	2.53	0.0007	0.0007	15.05	5.26	14.18
30	-2359	7.00	0.0000	0.0017	15.91	3.39	13.56
31	-18929	1.81	0.0006	0.0003	13.78	4.25	18.29
32	-6190	3.61	0.0012	0.0003	19.93	5.49	12.06
33	-29570	1.81	0.0018	0.0004	20.22	5.81	16.14
34	-6268	0.00	0.0014	0.0009	20.89	5.07	18.09
35	-2127	1.37	0.0012	0.0007	21.52	4.53	12.21
36	1927	2.46	0.0010	0.0011	16.50	4.12	13.97
37	-1019	2.15	0.0013	0.0013	16.00	5.44	7.09
38	-73023	2.20	0.0005	0.0003	22.41	3.88	12.03
39	-4533	0.52	0.0044	0.0007	24.94	5.32	16.29
40	1622	1.82	0.0007	0.0012	17.87	3.88	13.60
41	-13819	2.25	0.0017	0.0012	26.36	4.02	14.46
42	-32640	2.33	0.0025	0.0005	8.80	5.21	7.68
43	-17605	1.42	0.0031	0.0009	20.56	4.68	12.73
44	-6058	3.00	0.0061	0.0009	20.56	4.68	12.73

Figure 8. The table view dynamically updates when the current option ranks (shown in the second column) change. Since the user has specified that the rows must be ordered according to the ranks, the best options always move to the top of the table.

The user can not only see which options are the best for the current set of weights, but also view their

characteristics and compare them with those for the other options. Especially convenient for this purpose is the “Table Lens” technique [23], which draws a bar in each cell with the length proportional to the value of the attribute in this cell.

Furthermore, the table view may show not only option ranking (along with the other characteristics), but also the classification of the options according to the ranking. In general, any object classification can be propagated from the map display in which the classes are defined to all displays currently present on the screen. In a table view, this results in colouring the table rows according to the classes the corresponding objects fit in and in grouping the rows by the classes. Any changes of the classes are immediately reflected in the table view. The classes may change as a result of changing the values of the dynamic attribute(s) used for the classification, but the user can also interactively redefine them, for example, by moving the class boundaries.

2.7. Automatic sensitivity analysis

The capability of the MCDM support tools to immediately react to changes of the input parameters by re-computing the results, and the capability of the displays representing the results to immediately update when the results change, can be used for testing the robustness of the solutions provided by the MCDM methods. However, with a large number of decision criteria, the process of the interactive alteration of the input parameters (in particular, criteria weights) may become time-consuming. Therefore we have implemented in CommonGIS a procedure of automatic variation of the weights, which is called “sensitivity analysis”. For each criterion, the user may specify the variation range and the number of intermediate steps between the minimum and the maximum. In response, the system will assign different weights from the specified interval to the criterion, proportionally adjust the weights of the other criteria, and compute the aggregated scores and the ranks for the resulting set of weights. The same procedure is repeated for each criterion. The computation results are summarised into four new attributes specifying for each option the minimum rank received in the course of weight variation, the maximum rank, the mean rank, and the variance. These attributes can be visualised, for example, as is shown in Figure 9. Certainly, a decision-maker is interested most of all in the options with the smallest values of all the attributes.

On the map in Figure 9, one of the counties (marked by the thick border) has all bars of zero length. This means that it is extremely robust with respect to the weight variation and, hence, this is the most appropriate candidate for receiving funding. If the funding were to be distributed among several counties, the second candidate

would be the southern neighbour of the top candidate: it has the heights of all the bars close to zero. The exact values of the minimum, mean, and maximum ranks and the variance can be accessed by pointing on the counties on the map with the mouse, as is shown in Figure 9.

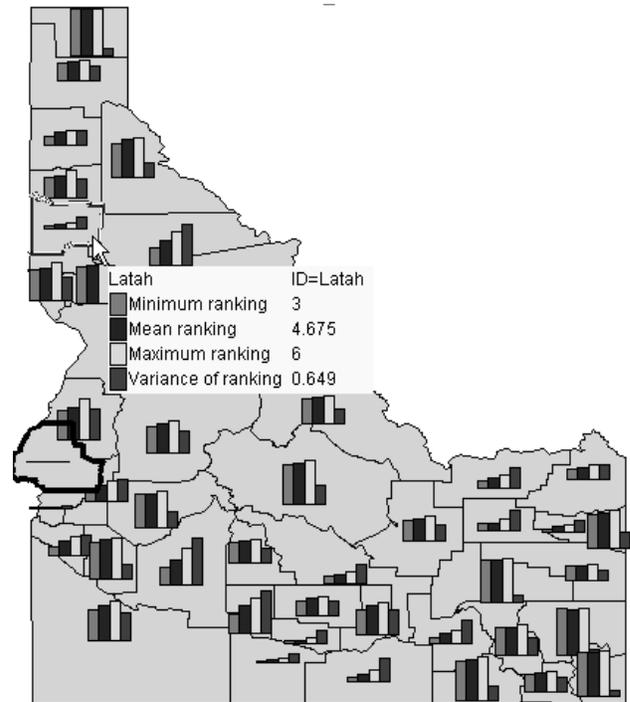


Figure 9. Results of the sensitivity analysis (minimum, mean, maximum ranking, and variance of ranking) are represented by bar charts.

3. Coordination mechanisms

CommonGIS has a configurable, extensible component-based architecture. It contains a large number of components realising various methods of data visualisation or computational procedures. The components are independent of each other: adding or removing any component does not affect the other components.

The components are coordinated through various types of events. In the examples considered above, the following types of events were used:

- object selection;
- attribute change;
- object classification.

Selection and classification events are managed by an internal component called system’s core. The core registers receivers of these types of events, i.e. all components that can react to the events. When, working with some system component, the user performs an operation that can be treated as object selection or

indirectly results in object selection, this component sends an event to the core, and the core propagates it to all registered event receivers. For example, an object selection event is generated when the user clicks on an object in a map display (direct selection) or when the Feasible Goal method finds options approximating the user-specified goal (indirect selection). Object classification events may originate from a map with any type of object classification. The user interface for classification includes a checkbox “Broadcast classification”. Classification events are generated when the user selects or deselects this checkbox and when she/he interactively changes the classes while the checkbox is in the “selected” state. Like selection events, classification events are sent to the core and then propagated to all receivers.

Irrespective of the source of an event, all components that receive it react to it in their specific ways. Selection events usually result in object highlighting, which occurs in multiple displays in parallel. However, other results of selection are also possible, for example, appearance of a list of object characteristics in a special subwindow called “Object view”. The barchart map display shown in Figures 2 and 3 is set to the mode of drawing the charts only for the currently selected objects. Upon receiving an object selection event, it removes the charts of the objects that are no more selected and draws the charts for the selected ones. Hence, there is no need to directly link the barchart map to the decision map display: cartographic representation of the options approximating the user’s goal is achieved through the general event mechanism of CommonGIS.

A typical result of classification events is using the colours assigned to the classes for painting display elements corresponding to the objects classified. Examples of other possible results are grouping rows in a table view and (re)computing various statistics for the classes in some components.

Attribute change events are managed by “internal tables”, that is, internal components storing attribute data. Several internal tables may exist simultaneously. Every component representing data from some table or using these data for other purposes is registered as a receiver of data change events from this table. Such events may originate from components that produce new attributes or change values of the existing attributes. The table propagates the events to all registered receivers. A receiver should check whether the change affects it. For example, when a map display receives a notification about some attribute having been changed, but this attribute is not currently represented on the map, no reaction to the event is needed.

The most common reaction to attribute change events is redrawing of the displays representing the attribute(s) that have been changed. Some components may re-

compute statistics or re-order their elements, like, for example, rows in a table view.

Attribute change events allow the user, in particular, to observe on various displays how results of the computational MCDM support methods change when some of the input parameters are altered. This enables an interactive sensitivity analysis for testing the robustness of the proposed solutions.

Another important type of event that was not demonstrated in the examples is a query change event. Events of this type are generated by the dynamic query component when the user interactively changes the query conditions. Typically, all displays react by hiding the objects that do not satisfy the current conditions. In decision-making, the dynamic query can be used for removing options with inappropriate characteristics.

Besides these general event types, there may be some special events being only relevant to particular components. For example, an event of selecting particular attribute values is relevant for the barchart map shown in Figures 2 and 3. Such an event may be generated, in particular, by a decision map display, in which the user specifies her/his goal. In response to the event, the map shows by the bars the differences between the attribute values for the corresponding objects and the selected values.

4. Conclusion

Most decisions in people’s everyday life are made ad hoc, without any sophisticated analysis. However, when the cost of making a poor decision may become quite high, such an analysis becomes necessary. Therefore, organisations and companies, where the decision equity is usually high, often use software for decision support. Such software usually realises one or more computational MCDM methods [10] [27].

Malczewski [20] acknowledges that techniques of EDA, which involve various methods of data visualisation and user interaction, are useful in the initial phase of the process of decision-making, the so-called intelligence phase [25]. We believe, however, that visualisation and interaction should be also applied during the choice phase as a complement to the computational methods. Whatever mathematical model is used in a MCDM support tool, any solution of a decision problem it suggests inevitably involves trade-offs between conflicting goals, since a perfect solution never exists in real-world situation. A person who makes the decision and, hence, bears the responsibility for it must understand why the tool recommends this or that solution and what trade-offs are involved. Visualisation allows the decision-maker to see the position of the suggested solution in the attribute (as well as geographical) space with respect to other feasible alternatives. It discloses which of the

characteristics of the solution are not optimal and how this is compensated by better values of other attributes. Multiple coordinated displays allow comprehensive, multi-sided investigation of the outcomes of MCDM methods.

Another reason for using visualisation tools in combination with MCDM methods is that the latter often base their computations on subjective information such as the desired goal or the relative importance of the criteria. Such information is difficult to quantify, and the decision-maker can usually provide only approximate judgements. It is important to find a solution that is insensitive to minor fluctuations of these judgements. Hence, the decision-maker must be given the opportunity to test whether the solutions suggested by a MCDM tool are sufficiently robust. A possible way to achieve this is to allow the decision-maker to alter the input information of the MCDM tool so that the tool immediately re-computes the results and the visual displays immediately update to reflect the changes. Hence, visualisation and its dynamic integration with computational methods can greatly contribute to making informed, well-substantiated decisions.

The dynamic integration of computational and visual tools is realised in our system CommonGIS by means of a generic mechanism of event propagation. This makes the system easily extendable to new visualisation techniques and computational methods.

5. Implementation notes

CommonGIS is implemented in Java language and can run either as a local application or as an applet in the Web. The major part of the system is available for downloading at the URL <http://www.CommonGIS.de/>. However, this does not include the Feasible Goal method and the Decision Map visualisation component, according to an agreement with the copyright owners, the Department of Mathematical Methods for Economic Decision Analysis of the Computing Centre of the Russian Academy of Sciences (<http://www.ccas.ru/mmcs/mmeda/>). The downloadable package contains extensive software documentation, including a programmer's manual for those who would like to configure or extend the system, or combine it with other software.

Acknowledgements

We thank Prof. P. Jankowski (University of Idaho) and H. Voss (Fraunhofer AIS) for fruitful discussions of various issues related to multi-criteria decision support. We are grateful to Prof. A. Lotov and the staff of his Department of Mathematical Methods for Economic

Decision Analysis in the Computing Centre of the Russian Academy of Sciences for providing the Decision Map software. We thank P. Gatal'sky (Fraunhofer AIS) and A. Martynkin (Pushchino State University, Russia) for the participation in the implementation of the CommonGIS components described in the paper.

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