PARTICIPATORY MULTI-OBJECTIVE DECISION-MAKING IN GIS

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ABSTRACT

To be effective in a broad range of decision making contexts, GIS procedures for multiobjective decision making need to be *participatory* in nature -- where participatory implies that the decision maker plays an active role in the decision process and finds the procedures used to have a simple intuitive understanding. In this paper we concentrate on the development of such a procedure for multi-objective decision making in cases with conflicting objectives. The procedure is based on a choice heuristic that is simple to understand and is capable of rapidly processing the massive data sets of raster GIS. Details of the algorithm are presented along with an experimental assessment of alternative procedures for the resolution of conflict cases.

INTRODUCTION

As an analytical technology, GIS offers to environmental management the opportunity for a more explicitly reasoned decision making process, particularly in cases where multiple objectives and criteria are involved. However, the field has been slow to adopt explicit decision support procedures, most commonly relying upon Mathematical Programming solutions external to the GIS (e.g., Diamond and Wright, 1988; Janssen and Rietveld, 1990; Carver, 1991; Campbell et al, 1992). While such procedures may be effective in certain contexts, they are unworkable in the context of raster GIS (because of data volume), require software often unavailable to most GIS users, and are intimidating to the majority of decision makers. As a result, the Clark Labs have been involved, over the past year and a half, in the development of *participatory* GIS decision making procedures.

PARTICIPATORY TECHNIQUES

The need for participatory techniques arises most particularly from the recognition that decisions happen over a broad spectrum of management levels, often requiring the input from groups of affected persons. For example, a government organization might enact a directive that will allow small land owners the opportunity to plant certain cash crops once only permitted to large estate holders. This is a *policy decision*, made by individuals who perhaps quite nicely fit our traditional concept of decision makers. However, the decision of whether to actually plant a particular crop on a given piece of land (a process

^{*} The Clark Labs for Cartographic Technology and Geographic Analysis comprise one of four Centers within the George Perkins Marsh Institute of the Graduate School of Geography at Clark University. The Clark Labs produce and distribute on a nonprofit basis the IDRISI Geographic Information System software package.

be called a *resource allocation decision*) is left to the community members. Thus decisions that affect the environment can take place at a variety of levels, from national to regional, to district and community levels -- even to that of individual farms!

In this example, both groups of decision makers could benefit from GIS. At the policy level, the system would typically be used to provide contextual information. Very rarely, it might be used to predictively simulate the decision behavior of relevant stakeholders so that the potential impacts of policy decisions can be evaluated. At the resource allocation level, individual communities could benefit from an examination of the many criteria that affect the suitability of land for a particular use. Ideally, the GIS would also be used to weight the differing criteria associated with any particular objective and to allow comparative evaluation of differing objectives that compete for access to the land.

All of these scenarios, however, are unlikely in the current climate of GIS. The technology requires a broad background in areas as diverse as statistics, geographic modelling, geodesy, cartography, remote sensing, photogrammetry and the like, and requires demonstrated skills in computer use and the extensive suite of software tools involved in the typical GIS. In addition, being new and very dramatic in its presentational quality, it is commonly wrapped in a mystique of high science and overstated expectations. To add to this the highly mathematical nature of techniques such as linear programming only compounds the problem. As a result, these are hardly the circumstances suitable for involving the majority of national and regional level decision makers, let alone individual farmers!

From this we have concluded the need for *participatory* techniques that can involve the broad spectrum of potential stakeholders in the decision making process. At the outset we see a different role for the GIS analyst -- not as an expert possessor of the new science, but as a facilitator, much like a focus group leader, that can work with groups and individuals to make the system work for them. However, this role is unlikely to succeed without the development of new analytical procedures that are :

- suitable for use with groups of stakeholders as well as individuals. To do so, they must explicitly incorporate procedures for the development of consensus and the active participation of all. In addition, they must have;
- an immediate intuitive appeal. The need for a rigorous mathematical basis is important. However, without a strongly intuitive character they are unlikely to gain the confidence and support of the decision makers involved.

The first of these issues has been addressed in previous papers (e.g., Eastman et al., 1992; Eastman et al., 1993a; Eastman et al., 1993b), particularly the use of group interactive techniques for the development of weights in Multi-Criteria Evaluation. In this paper, however, we address the issue of decision procedures with strong intuitive appeal, with particular reference to the problem of multi-objective decision making under conditions of conflicting objectives.

MULTI-OBJECTIVE DECISION MAKING

In the context used here, an *objective* is understood to be a perspective or philosophy that guides the structuring of a decision rule (see Eastman et al., 1993a and Eastman et al., 1993b for a more extensive treatment of terms and definitions). Thus a multi-objective

problem is one in which several different perspectives are drawn upon to determine the allocation of a particular resource. In some cases multiple objectives are complementary, as in multiple-use land allocations. However, very frequently, objectives are in conflict and must be resolved either by means of prioritization or by conflict resolution. Our concern here is with the latter.

In the procedure developed here, each of the objectives is first dealt with as an independent multi-criteria evaluation problem. The results of these single objective solutions are then used to determine areas of conflicting claims in need of a compromise solution.

SINGLE OBJECTIVE MULTI-CRITERIA EVALUATION'

The first step in the single objective evaluations is to identify the relevant criteria that will allow, for each piece of land, a determination of suitability for that objective. These criteria may be either in the form of continuous factors (such as slope gradients) or boolean constraints (such as protective buffers). Continuous factors are then scaled to a standardized range and a set of weights are developed to express their relative importance to the objective under consideration. Here a group participation technique is used whereby each pairwise combination of factors is rated for relative importance using a simple 9-point relative rating scale (see Eastman et al., 1993b). The principal eigenvector of this pairwise comparison matrix is then calculated (using the WEIGHT module in IDRISI) to develop a set of best-fit weights that sum to 1.0 (Saaty, 1977). The criteria are then combined by means of a weighted linear combination and subsequently masked by each of the boolean constraints in turn (using the MCE module in IDRISI). The result is a continuous suitability map with the same numeric range as the standardized factor maps.

Once the suitability map has been produced, the final issue concerns which cells to choose in order to meet a specific areal goal (e.g., the best 1500 hectares of land for that objective). In the context of traditional approaches to land allocation, this problem would typically be expressed as the need to determine that set of cells in which the sum of suitabilities is maximized, subject to the constraint that the total area of the included cells match a specific goal. This is known variously as an *objective function* or *performance index* (see Diamond and Wright, 1989). In this discussion it will be called a *choice function*, to distinguish it from its counterpart, a *choice heuristic*. With a choice heuristic, rather than define a mathematical basis for selecting the optimum set, a procedure is set out that accomplishes the same result, or is its close approximation. From a participatory perspective, choice heuristics are desirable because of their simplicity of understanding and ease of application.

In the case being considered here, selecting the best x hectares of land for a particular objective, using a choice function, is extremely tedious. In theory, every possible combination of cells would need to be tested to evaluate which would maximize the sum of suitabilities. Most procedures that use choice functions use techniques to reduce the number of examined cases to only those that are likely candidates (such as the Simplex Method in Linear Programming). Regardless, the procedure is calculation intensive and essentially impossible with the large data volumes of raster GIS. However, a simple choice heuristic can accomplish the same result with a minimum of work. By simply rank ordering the cells in the suitability map and taking the best ranked cells to meet the area target, the same result is achieved -- the sum of the suitabilities will be the maximum possible.

* See Eastman et al., 1993a and 1993b for more detailed discussions of this process.

Rank ordering the enormous volume of data in a raster image is not trivial! Standard automated procedures such as a Bubble, Shell or Quick Sort simply cannot handle the problem in sufficient time. Accordingly, a simpler procedure was used in the development of the RANK module for the IDRISI system. By specifying that the suitability map must be in the form of an 8-bit integer (i.e., byte) image, only values from 0-255 can occur. This was felt to give adequate precision to the suitability map and allowed a rapid procedure for sorting based on the allocation of image cells to a 256-bin counting array. RANK also allows the sorting of ties by reference to a second image. Thus the counting array consists of a 256 x 256 bin structure. Sorting in this fashion is extremely rapid, with the rank image being output as a real number floating point image to accommodate the large numbers that can result.

Once the suitabilities have been ranked, it is a simple matter to select a set consisting of the best cells for a particular area goal. If, for example, the best 5000 cells were required, the rank map would be reclassified into a Boolean map of the result, by assigning a 1 to the ranks from 1 to 5000 (assuming descending ranks) and a 0 to all that are higher.

THE MULTI-OBJECTIVE PROCEDURE

Given the basic logic of the RANK/RECLASS procedure for allocating land based on a single objective, we developed a multi-dimensional extension named MOLA (for *Multi-Objective Land Allocation*) for extending a similar logic to cases with conflicting objectives.

The Basic Allocation Procedure

In teaching the MOLA procedure, we have commonly started by producing singleobjective allocation maps for a two-objective problem and then overlaying the results to see how they conflict. Doing so (using the CROSSTAB procedure in IDRISI) yields four classes:

- 1. areas selected by Objective 1 and not by Objective 2
- 2. areas selected by Objective 2 and not by Objective 1
- 3. areas not selected by either objective, and
- 4. areas selected by both objectives (and thus in conflict).

Clearly it is the conflict areas that need to be resolved. This can also be understood by means of a decision space established by using the suitability scale for each objective as a separate axis in a multi-dimension space (Figure 1). Each cell in the region can be located in this space based upon its suitability on each objective. The RANK/RECLASS procedure discussed earlier is thus equivalent to moving a perpendicular decision line down from the position of maximum suitability until enough cells are captured to make up the areal goal. In the case of two objectives, the two decision lines clearly delineate the four regions just discussed (Figure 1). The basic underlying procedure of MOLA is thus a reclassification of ranked suitability maps with a subsequent resolution of conflicting cells.

Resolution of Conflicts

Clearly the simplest procedure for the resolution of conflicts would be to split the conflicting cells evenly between the objectives. A simple heuristic for doing this would be to



draw a diagonal across the conflict zone and thereby allocate cells to that objective for which it is marginally best suited (Figure 2). However, we have found that a better procedure is to allocate conflicting cells based on a single decision line that bisects the entire decision space (Figure 3). To the extent that this line divides the conflict zone, the proportional division of cells will be determined (Figure 4).



The logic of using a single decision line comes from a simple consideration of the problem at hand. With a conflict cell, a decision needs to be made about which of the objectives it should be allocated to. Logically, it would seem that this should be that objective for which the cell is most inherently suited. With conflicting objectives, each can be considered to have an *ideal point* defining the case of a cell that is maximally suited for that objective and minimally suited for all others (Figure 3). This single line (actually a hyperplane in multidimensional space) thus defines the best allocation for each cell based on a *minimum-distance-to-ideal-point* logic.

If one now considers how this single decision line differs in its resolution of conflicts from the conflict zone diagonal approach (Figure 5), it is clear that in the latter case, suboptimal allocations might be made. Whenever the areas to be allocated to each objective differ considerably, the conflict zone will form an elongated rectangle that is displaced from the *minimum-distance-to-ideal-point* line. As a result, some cells that are better suited for one objective will be allocated to the other (the shaded zone in Figure 5).

This effect is quite dramatic and can lead to substantially counterintuitive allocations. As a consequence we have adopted the use of the single *minimum-distance-to-ideal-point* decision line in the MOLA procedure. However, there are four further reasons for adopting this approach. First, this single *minimum-distance-to-ideal-point* decision line provides a simple logic for the weighting of objectives. Using the case of two objectives for illustration, a 45 degree line implies equal weight being assigned to the two objectives in the allocation of conflict cases. Changing this relative weight requires no more than simply



changing the angle of the line. In fact, the ratio of the relative weights assigned to those objectives defines the tangent of that angle. In practice, however, assignments are made by the equivalent process of comparing the magnitudes of the weighted suitabilities. Second, a 45 degree line will maintain weighting consistency during the iteration process (with the simple diagonal, the weight will vary as the rectangle changes in form).

The other two reasons supporting the use of a single *minimum-distance-to-ideal-point* decision line relate to the ability of the procedure to achieve an exact solution and the speed with which it is able to converge. These will be dealt with in the following two sections.

Iteration

Having divided the conflict cells between the objectives, it is clear that both will be short on meeting their area targets. As a result, the MOLA procedure then calculates the deficit for each objective and moves the decision lines further down into the zone of poorer choices. This procedure continues until either an exact solution is achieved or it is clear that the procedure cannot converge on a solution. From experience with the two procedures for resolving conflicts discussed above, it has been noticed that the simple conflict zone diagonal approach quite commonly has difficulty in reaching an exact solution, while the single *minimum-distance-to-ideal-point* decision line rarely does. It would appear that this results from the allocation of sub-optimal cells. In fact, the simple diagonal bisection approach gives weight in the resolution of conflicts that is directly proportional to the size of areal targets. Thus an objective with only modest areal goals will have difficulty in competing for conflict cells with another that is destined for a much larger allocation.

To illustrate this problem, consider the case of a multi-objective decision looking to allocate 1500 hectares to be zoned for industrial uses and 6000 hectares for agriculture^{*}. Figure 6a illustrates the suitability map for industry developed from a multi-criteria evaluation using factors of proximity to water, proximity to roads, proximity to power lines, slope gradient and proximity to market. Figure 6b shows the suitability map for agriculture based on soil capability, proximity to water, proximity to roads, proximity to market, and slope gradient. Figure 6c shows the result of applying the MOLA procedure in IDRISI

This case study was conducted for the Kathmandu Valley area of Nepal. The industry under consideration was the production of hand-woven carpets. More details about this study can be found in Eastman et al., 1993a and 1993b.



Figure 6 : The results of a Multi-Objective allocation using the two procedures discussed for conflict resolution. Figure 6a (top left) shows the suitability map for industry developed using the MCE module, while Figure 6b (top right) shows the suitability map for agriculture. Figure 6c (bottom left) shows the result from the MOLA module using the single minimum-distance-to-ideal-point decision line. Figure 6d (bottom right) shows the result using multiple decision lines that bisect the conflict zone.

using its single *minimum-distance-to-ideal-point* decision line and equal weight between the objectives. Figure 6d shows the result using a modified version of this procedure that uses a bisection of the conflict zone, leading to multiple decision lines, again with equal weight assigned to the objectives. Table 1 provides additional summary data about these results.

	Rank Goal	Maximum Rank Achieved		
		Single Decision Line	Multiple Decision Lines	% Difference
Industry	16,666	22,818	35,265	55
Agriculture	66,666	80,638	76,960	-5
Iterations		11	19	73

Table 1: Comparison of Multi-Objective Allocations using the Single and Multiple Line Conflict Resolution Techniques. In Table 1 the *Rank Goal* specifies the lowest (i.e. maximum) rank that would exist among the cells assigned to that objective if it were successful in winning all cases of conflict resolution. The *Maximum Rank Achieved* indicates the worst rank that does occur after the multi-objective procedure. In essence, this indicate how far the horizontal and vertical decision lines in Figures 2 and 5 had to be moved to capture the required number of cells after iterative solution to conflict resolution. As can be seen in Table 1, the use of the multiple decision line procedure had little effect on agriculture (in fact its worst rank improved by 5%) but had a major effect on industry (where the maximum rank got worse by 55%). As can clearly be seen, the larger land claim by agriculture (a four-fold difference) gave it a disproportionate weight in the conflict resolution procedure using the multiple line procedure. Clearly, the single decision line procedure as used in the MOLA module provides a much more even division of land.

Standardization

The procedures above describe the complete working of the MOLA routine. However, a vitally important issue is that of standardization. The suitability maps developed through multi-criteria evaluation (such as with the MCE procedure in IDRISI) are developed in isolation without any broader concern for meaning relative to other objectives. Thus there is no inherent reason to believe that a suitability rating of 100 on one objective means the same as a rating of 100 on another.

One obvious procedure for standardization would be to transform the suitability maps to standard scores by subtracting the means and dividing by their standard deviations. A module named STANDARD was created in IDRISI to facilitate this operation. However, the results were rarely satisfactory since the underlying distributions were seldom normal. As a consequence, a non-parametric procedure of standardization was sought.

Considering the case of converting images to standard scores, the underlying logic is one of matching the two distributions to be compared. Another possibility that would meet the non-parametric criterion would be to undertake a histogram equalization of the suitability maps before comparison with MOLA. To illustrate the concept, consider Figure 7a. Here we see the income distribution of two hypothetical countries -- one in which the majority of people have low incomes and the other in which most have high incomes. Comparing two persons from these two countries with equal income it is clear that their level of affluence is unlikely to be the same. In the case of the rich country, that person is likely to be considered fairly poor and would find that their income did not buy a great deal of goods and services. However, the same income in a poorer country would probably be considered to be quite substantial with a corresponding increase in affluence.

With histogram equalization the data values are monotonically changed such that a uniform distribution is achieved. As can be seen in Figure 7b, this results in a substantial repositioning of the two individuals considered above. Now they are no longer considered as equals since the equalization of the poorer country distribution required a net movement of most values to the right while that for the richer country required a net movement to the left.

The simplest means of histogram equalization is simple rank ordering! As a consequence, the input requirement for the basic allocation stage using the RANK/RECLASS decision heuristic is also that which will lead to a non-parametric equalization of the distributions. In effect, histogram equalization gives each cell a value that is relative to the



entire group. Thus comparing a value of 100 on a ranked scale for one objective does have a similar meaning to a value of 100 on another.

One of the consequences of rank ordering suitabilities before comparison is that cells will tend to line up along the 45 degree diagonal in decision space -- objectives are commonly correlated to some degree. As a result, the single minimum-distance-to-ideal-point decision line will have a tendency to bisect the scatter of cells in decision space. Thus this single decision line will tend to more equitably divide the group in any conflict resolution. We have noticed that the single minimum-distance-to-ideal-point decision line technique for conflict resolution tends to solve substantially faster than the simple conflict region diagonal approach. For example, in Table 1 it can be seen that multiple decision line technique took almost twice as many iterations as the single minimum-distance-to-ideal-point decision line technique. We believe that to some extent this is because the minimumdistance-to-ideal-point decision line is more advantageously situated relative to the main pool of cells. However, it is also clearly related to the increasing tendency of the multipleline technique to undertake inappropriate conflict resolutions as the difference in areal claims increases. For example, with a 10-fold difference in areal claims (as opposed to the four-fold difference illustrated here), the percentage increase in iterations changes from 73% to 600%!

DISCUSSION AND CONCLUSIONS

In our work with United Nations Institute for Training and Research (UNITAR) and the United Nations Environment Programme Global Resources Information Database (UNEP/GRID) we have had the opportunity to test the MOLA procedure with decision makers in Nepal, Chile, and a variety of the Baltic nations. Participants have uniformly found the Multi-Objective MOLA procedure to be very simply understood and to be a useful complement to the other participatory techniques, such as the MCE and WEIGHT modules used for Multi-Criteria Evaluation. It is clear from these results that the single *minimum-distance-to-ideal point* conflict resolution procedure is the superior choice over the multiple line technique also discussed -- it avoids the problem of unintended differential weighting based on the relative size of areal claims. Furthermore, in addition to being simply understood, it is fast and capable of processing the large data sets associated with raster GIS -- strong requirements of a procedure that can effectively operate in the interactive context of participatory decision making.

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