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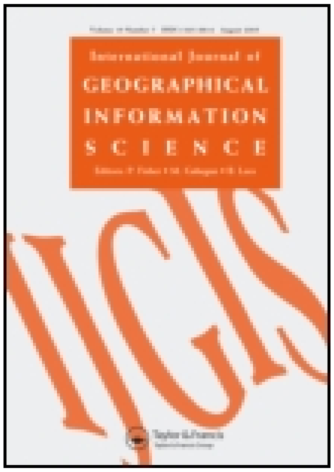

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Integrating multi-criteria evaluation with geographical information systems

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Integrating multi-criteria evaluation with geographical information systems

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Abstract. Geographical information systems (GIS) provide the decision-maker with a powerful set of tools for the manipulation and analysis of spatial information. The functionality of GIS is, however, limited to certain deterministic analyses in key application areas such as spatial search. The integration of multi-criteria evaluation (MCE) techniques with GIS is forwarded as providing the user with the means to evaluate various alternatives on the basis of multiple and conflicting criteria and objectives. An example application based on the search for suitable sites for the disposal of radioactive waste in the UK using the Arc/Info GIS is included. The potential use of a combined GIS–MCE approach in the development of spatial decision support systems is considered.

1. Introduction

Geographical information systems (GIS) provide the decision-maker with a powerful set of tools for the manipulation and analysis of spatial information. The idea of GIS as a box of tools for handling geographical data is useful. Items from the tool-box of GIS can, in various combinations, be used to solve a multitude of problems involving spatial data. Like most tool-boxes, however, the list of tools provided by GIS, although impressive, is not complete. For example, in most GIS packages spatial analytical functionality lies mainly in the ability to perform deterministic overlay and buffer operations. Such abilities, whilst ideal for performing spatial searches based on nominally mapped criteria, are of limited use when multiple and conflicting criteria and objectives are concerned. The integration of analytical techniques designed to cope with multi-criteria problems in GIS can provide the user with a valuable addition to the functionality of the GIS tool-box.

1.1. *Site-search procedures using standard geographical information system map overlays*

The application of digital map overlays for the purpose of area screening is a classic example of the applied use of one subset of tools from the GIS tool-box. One such example given by Openshaw *et al.* (1989) is the use of Arc/Info overlay routines to search a specified region of interest for areas suitable for the disposal of radioactive waste. Four siting factors are considered: geology, population distribution, accessibility and conservation. Numerical and qualitative criteria are applied to these siting factors in an exploratory investigation of the search area. However, such overlay procedures can do little more than identify areas which simultaneously satisfy all the specified criteria. There is nothing in an analysis of this kind that informs the user which individual site(s) offer the most promising characteristics for development. Additional procedures, based here on multi-criteria evaluation (MCE) techniques, are required to evaluate the suitability of sites falling within the feasible areas identified using standard GIS overlay procedures.

This paper describes one way in which MCE techniques may be integrated within a GIS framework, with special reference to their joint use as a largely self-contained methodology for site selection and decision support. An introduction to the basic principles of MCE is followed by a discussion on how the two techniques may be combined. A worked example employing an integrated GIS–MCE approach to locating sites for the disposal of radioactive waste in the UK is described. This follows the standard GIS map overlay procedures before applying MCE analyses to identify individual sites. In addition, some thoughts are offered on how GIS–MCE systems may be used in the development of effective spatial decision support systems.

2. An introduction to multi-criteria evaluation

2.1. *Origins of multi-criteria evaluation*

MCE techniques (often referred to as multi-criteria analysis or MCA) began to emerge during the early 1970s from a critique of traditional neoclassical environmental economics. A number of workers, particularly in the regional economic planning and decision-making research fields (see Voogd 1983, Nijkamp 1980, Cochrane and Zeleny 1973, Keeney and Raiffa 1976), have identified certain weaknesses in the neoclassical view of decision-making and site location. A number of amendments and alternatives to the neoclassical approach have been suggested in response to a realization that these conventional methods cannot cope adequately with external negative spillover effects from environmental and economic developments (e.g. pollution, health risks, planning blight) and neeed to include more rigorous procedural elements in the planning process. A significant proportion of these focuses on the paradigm of multi-dimensionality.

Multi-dimensional decision and evaluation models (of which MCE is a part) provide tools for analysing the complex trade-offs between choice alternatives (e.g. sites, plans) with different environmental and socio-economic impacts. The formal mathematical framework used to describe multi-dimensional decision-making is based on multi-objective optimization theory in which both conflicting and complementary objectives are described as a decision problem with multiple objectives. In multi-dimensional models appropriate units of measurement are applied to each factor in the problem rather than trying to impose artificial 'shadow' prices, as in many neoclassicial models (e.g. cost–benefit analysis).

2.2. *Basic principles of multi-criteria evaluation*

The basic aim of MCE analysis techniques is 'to investigate a number of choice possibilities in the light of multiple criteria and conflicting objectives' (Voogd 1983, p. 21). In doing so it is possible to generate compromise alternatives and rankings of alternatives according to their attractiveness (Janssen and Rietveld 1990). Given the current emphasis on site location via a process of map overlay, the problem facing decision-makers concerns the identification of best compromise sites on the basis of an evaluation of a finite number of choice alternatives by a finite number of attributes, while taking into account conflicting views and objectives. The term 'choice alternative' refers to any available option in the choice set, here defined as an individual site.

The basic starting point of any MCE analysis is the construction of an evaluation matrix, the elements of which reflect the characteristics of the given set of choice alternatives on the basis of a specific set of criteria. Assuming a matrix S consisting of $1, \ldots I$ alternatives and $1, \ldots J$ criteria, then element Sij describes the score of alternative i according to criterion j. Using this notation the evaluation matrix S can be summarized as follows:

$$S = \begin{matrix} S11 \ldots SI1 \\ \vdots \quad\quad \vdots \\ S1J \ldots SIJ \end{matrix}$$

In many analyses, especially those utilizing quantitative and mixed sources of data, some form of standardization or criterion scores is necessary to enable meaningful comparisons to be made on the basis of criteria measured on different scales. A number of common standardization techniques can be used to effect a normalization of criterion scores. These are discussed in more detail later. To evaluate a matrix purely on the basis of standardized criterion scores would not be very realistic as different criteria usually have different levels of importance. A further requirement of most MCE techniques, therefore, is the inclusion of criterion weights, $W1, \ldots WJ$. Understandably, in many real-world applications of MCE methods, there is often uncertainty surrounding the validity of the chosen weighting schemes (and indeed, of other aspects of the MCE problem). This will be made clear later in the paper, but it is sufficient to say here that some form of sensitivity analysis is required to account for uncertainties in the definition of criterion weights.

The MCE techniques used for evaluating choice alternatives are many and varied. A whole suite of methods has been developed for solving a range of separate multi-criteria problems. A number of these methods, especially those taken from the regional economic planning field, exhibit characteristics that are particularly relevant to the solution of complex spatial problems. However, as a general rule, most MCE techniques have been developed for evaluating small numbers of choice alternatives on the basis of only a limited number of criteria, ideally in the order of eight alternatives and eight criteria (Voogd 1983). Many problems of spatial search will inevitably involve a much larger range of alternatives and criteria, necessitating the modification and automation of MCE methods. Three MCE methods [ideal point analysis (IPA), hierarchical optimization (HO) and concordance–discordance analysis (CDA)] are modified here to evaluate the thousands of potential sites for the disposal of radioactive waste. These methods are described in the following sections.

2.3. *Multi-criteria evaluation techniques*

Some consideration of the MCE techniques adapted here for use in a GIS framework is required to explain how they work. The information in this section is derived from published sources and so represents nothing new, but it is thought desirable to provide an outline of MCE techniques before describing how they can be implemented within a GIS framework.

Both IPA and CDA models are based on the direct comparison of alternatives by those factors included in the evaluation. Since the various factors taken into account in describing each of the choice alternatives are likely to be measured in different units, the evaluation matrix S needs to be transformed onto a normalized scale (i.e. $1 = \max$, $0 = \min$). As indicated above, several common standardization techniques are available. These are described by Voogd (1983) and include methods with an additivity constraint (i.e. the standardized scores are based on raw scores divided by the sum of the raw scores), ratio scale properties and interval scale properties. The last method is used here since this is thought to be the most appropriate for use with MCE techniques involving pair-wise comparisons of criterion scores (e.g. CDA) and may also be used with techniques which utilize the magnitude of individual scores (e.g. IPA). This kind of standardization can be expressed as follows:

$$\text{Standardized score} = \frac{\text{raw score} - \text{minimum raw score}}{\text{maximum raw score} - \text{minimum raw score}}$$

$$e_{ij} = \frac{S_{ij} - \min_i S_{ij}}{\max_i S_{ij} - \min_i S_{ij}}$$

Using this method of standardization means that the worst criterion score will always have a standardized score of 0, and the best a score of 1. This equation is applicable only to 'benefit' criteria (i.e. those where a higher score implies a better score). When the jth factor is a 'cost' criterion (i.e. when a higher score implies a worse score), then the standardization procedure becomes:

$$e_{ij} = \frac{\max_i S_{ij} - S_{ij}}{\max_i S_{ij} - \min_i S_{ij}}$$

Weights or criterion priorities allow the decision-maker to specify the perceived importance of individual factors relative to the others included in the evaluation. A number of weighting methodologies have been described (e.g. complete ranking, partial ranking, paired comparison matrices). These are reviewed by Voogd (1983). A seven-point scale, first advocated by Osgood *et al.* (1957), is used in the example presented here because this is thought to be sufficient to allow the user to express adequately a level of preference. To make the scale more meaningful a semantic differential is added with the inclusion of descriptive labels, from very important (7) to unimportant (1).

Ideal point models are based on the deviation between a set of ideal solutions and a set of efficient solutions (Zeleny 1976). Although the ideal solution will almost certainly not exist, it does serve as an important frame of reference. The best compromise solution is defined as that which is the minimum distance from the theoretical ideal. Distances from the ideal with respect to individual factors are weighted by the decision-maker. Thus increasing distance from the ideal for factors placed higher on the scale of importance incurs a greater penalty than increasing distance from the ideal for those placed lower. The IPA model may be written as follows:

$$\min d = \sum_{j=1}^{I} W_j(1 - e_{ij})$$

where: $\min d$ = minimum distance from ideal solution; W_j = jth criterion weight; and e_{ij} = standardized score.

Concordance–discordance analysis is a widely used method of MCE based on the pair-wise comparison of choice alternatives. The degree to which choice alternatives and factor weightings confirm or contradict the 'outranking' relationship between alternatives is measured. Both the differences in factor weights and criterion scores are analysed separately via concordance and discordance procedures.

Aubert (1986) defines the outranking relationship for two alternatives a and a' as: (1) a scores equal or better than a' on a sufficient number of criteria (concordance index); and (2) the differences in the factor scores where a' is better than a is not too high (discordance index).

The concordance index of alternative a with respect to a' for all decision factors (i.e. where a scores equal to, or better than, a') is defined as:

$$C_{aa'} = \frac{\text{sum of weights of the criterion for which } a \geqslant a'}{\text{sum of weights for all criteria}}$$

$$C_{aa'} = \frac{\sum_{a \geqslant a'} W_j}{\sum W_j}$$

where: $C_{aa'}$ = concordance index for a compared with a'

The discordance index of alternative a with respect to a' for all decision factors is defined as:

$$D_{aa'} = \frac{\text{maximum difference between weighted scores when } a < a'}{\begin{array}{c}\text{maximum difference between weighted scores for the criterion yielding}\\ \text{the maximum difference between the weighted scores when } a < a' \text{ for}\\ \text{all alternatives}\end{array}}$$

$$D_{aa'} = \frac{\max_{aa'} W_{aa'}}{\max_I (W_{\theta a'}) - \min_I (W_{\theta a'})}$$

where: $D_{aa'}$ = discordance index for a compared with a'; $\theta = \text{argmax}(W_{aa'})$; and I = all alternatives.

Using a user-defined minimum concordance index and maximum discordance index, a dominance matrix can be calculated from the standardized evaluation matrix showing the outranking relationship of each alternative over all others. A score of 1 is accumulated each time an alternative outranks one of the others. By direct summation of each alternative's dominance score a total dominance index can be derived and the alternatives ranked accordingly. The best compromise solutions are characterized by increasingly higher total dominance indices.

Hierarchical optimization models attempt to rank all factors according to their relative priorities. Optimization is carried out in a step-wise fashion so that higher ranking factors are maximized before the lower ranking factors. After the relative order of priority assigned to individual factors has been established by complete ranking methods, then the evaluation matrix can itself be ranked, first by the factor with the highest priority, then the second, and so on. After each ranking, the evaluation matrix is truncated according to goals or achievement levels specified by the decision-maker for the factor in question. In this way choice alternatives not meeting attainment levels are removed from consideration. No standarization of criterion scores is required since there is no direct comparison of disparate criteria. This technique is inherently interactive, requiring that the user goes through a learning process of multiple model runs before a satisfactory solution is found. A hierarchical model can be formalized as follows:

$$\text{Step 1}\ldots \quad \max_{i\in S} S_1(i)$$

$$\text{Step 2}\ldots \quad \max_{i\in S} S_2(i)$$
$$S_1(i) \geqslant \beta S_1(i_1^0)$$

$$\text{Step 3}\ldots \quad \max_{i\in S} S_3(i)$$
$$S_1(i) \geqslant \beta_1 S_1(i^0)$$
$$S_2(i) \geqslant \beta_2 S_2(i_2^0)$$

etc...

where β_1 = tolerance parameter indicating the maximum deviation from the optimum $S_j(i_j^0)$ allowable by the decision-maker.

Voogd (1983) summarizes some of the advantages and disadvantages of MCE methods. Among the advantages cited are that they provide a more surveyable classification of the problem and a better insight into the various objectives, and increase the accountability, structure, control and considered nature of the decision-making process. Among the disadvantages associated with the MCE methods are their complex nature and the risk of their being used as a 'scientific sauce' over decisions already made. Although it is generally accepted that the advantages gained outweigh the disadvantages, the complexity of use and the lack of a suitable framework of application represent significant barriers to the successful and widespread implementation of MCE methods in spatial search and general evaluation tasks. It is this problem that this paper addresses.

3. Limitations of overlay analyses

GIS are often used to identify suitable areas for land development, be it for afforestation, a new hospital or, as in the example given here, a radioactive waste disposal facility. As was suggested earlier, however, the functionality of GIS in this context is essentially limited to overlaying deterministic digital map information to define areas simultaneously satisfying two or more siting criteria. Few, if any, GIS provide the user with a comprehensive set of tools for the evaluation of problems involving multiple criteria and conflicting policy objectives. Overlays are ideal for area screening using deterministically defined siting criteria but have certain limitations when dealing with information of a non-deterministic nature. These are summarized by Janssen and Rietveld (1990) as follows:

(1) Digital map overlays are difficult to comprehend when more than four or five factors are involved.
(2) Most overlay procedures in GIS do not allow for the fact that variables may not be equally important.
(3) When mapping variables for overlay analyses the problem arises of how the threshold values used therein are defined (the outcome of area screening depends strongly on the choice of threshold values).
(4) The use of threshold values to map continuous variables, such as population density, on a nominal basis will inevitably lead to substantial losses of information.

Ways of further reducing the number of choice alternatives from a series of feasible areas to a restricted short-list of potentially suitable sites and, finally, the site chosen are therefore limited. It is not thought here to be practicable to proceed past the area screening stage with overlay routines or other standard GIS tools. Add-on procedures are required if site-specific evaluation analyses are to be undertaken successfully within a GIS framework. The following description of a methodology for site-search and evaluation is based on the combination of both GIS and MCE techniques.

4. Adding multi-criteria evaluation to the geographical information systems tool-box

4.1. *A combined GIS–MCE approach to facility location*

The combined GIS–MCE approach to facility location described here can be divided into two stages: (1) survey and (2) preliminary site identification. In the survey stage standard GIS facilities are used to input, transform, store and manipulate digital map data relevant to the problem. Area screening techniques are used to identify all the potentially feasible areas in which to look for sites suitable for development. This is achieved by overlaying relevant siting factors (e.g. population distribution) to identify all the areas which simultaneously satisfy the specified numerical and qualitative criteria (e.g. population density less than 500 persons per km^2). The siting criteria used in this stage of the analysis are often very deterministic in nature. For example, the site is required to be within 3 km of a motorway junction (i.e. an inclusion criterion) and must be outside any conservation areas (i.e. an exclusion criterion). This allows the decision-maker to progress from a very large number of alternatives to a smaller and more manageable short-list in a single, well defined set of operations. GIS based overlay routines are well suited to this kind of analysis and also allow for quick comparative re-evaluation ('What if?' modelling) to be carried out on selected factors. Thus, despite the deterministic nature of their application, GIS allow a degree of flexibility to be maintained, thereby allowing survey stage siting criteria to be changed as desired to meet particular requirements.

The survey stage can, however, only point to those areas in which all the specified criteria are met. There is nothing in an analysis of this kind that informs the decision-maker which sites within the defined feasible areas offer the best combination of site-specific characteristics. It may be possible to combine all conceivably relevant siting factors in a massive polygon overlay exercise and so identify which areas satisfy all the specified criteria. It stands to reason, however, that these areas (if indeed any were to remain!) would be very limited in extent and so would contain an unnecessarily restrictive set of choice alternatives. One possible exception to this general rule is the use of weighted overlay functions provided by some GIS systems (e.g. Tydac Technologies' Spans). Such hybrid overlay techniques allow map layers and the categories they contain to be weighted and overlayed to identify degrees of desirability in the composite map, using (in the case of Spans) an average ranking technique. This is similar to weighted summation, one of the most basic MCE techniques.

The second stage of the proposed methodology, that of preliminary site identification, is aimed at identifying compromise solutions from the whole range of alternatives taken from the feasible areas identified by GIS based area screening. This stage is operationalized using MCE techniques embedded in the GIS framework and additional site-specific information relevant to secondary siting factors. These factors are, unlike those used in the overlays of the survey stage, of a non-deterministic nature and are weighted according to their perceived level of importance. The evaluation matrix containing site information is built using the data-handling facilities provided by GIS. MCE techniques are used to identify 'best' compromise solutions on the basis of this site-specific information and associated weights. Once a satisfactory result has been obtained, short-listed sites can be displayed using the graphical capabilities of the GIS.

4.2. *Practical problems*

From this desciption it might seem that the proposed GIS–MCE approach to site location is simple. However, there are several points which need elaboration: how are evaluation matrices produced from the feasible areas identified in the overlay based survey stage; how are MCE techniques embedded in the overall GIS framework; and how are differences in the results from applying different MCE techniques and weighting schemes accounted for? These questions are answered in the following section.

Data input to the MCE techniques is performed using the advanced data-handling facilities of the GIS. In more traditional site-search procedures, preliminary site identification is, owing to restrictions on time and resources (including information), based on a sample of sites taken from the feasible areas defined in the survey stage (e.g. UK Nirex Ltd 1989). With a GIS based approach it is possible to include all the sites contained within the feasible areas in the preliminary stage of site identification. This is achieved here by dividing the output of feasible areas from the survey stage into site-sized land parcels on a grid basis. The GIS are then used to compile a database of site-specific information using new and existing data sources (i.e. those used in the survey stage). It is noted that the division of the feasible areas into sites on a grid basis is not essential and other areal units may be used if available. Under most circumstances, however, it is unlikely that appropriate parcels of data (with units of near uniform size approximating the amount of land required for development) would be available. The division of feasible areas on a grid basis is therefore deemed to be the most convenient and acceptable solution.

Site-specific information is attached to individual grid cells using point, line and area overlays. For example, point-in-polygon routines are used to determine the attributes of grid cells by overlaying their centroids on the relevant digital maps (e.g. land use, soil type, relief, conservation status, or administrative boundaries). In addition, nearest neighbour routines are used to find the distances of grid cells from point, line and area features (e.g. distance of grid cell centroids from the nearest rail head may be used as a proxy for accessibility). The site-specific database compiled in this manner forms the basis of the evaluation matrix used by the add-on MCE routines.

The focus here is on using GIS as a framework for the application of MCE techniques. The MCE techniques are in themselves only mathematical formulae with no in-built means of data handling (i.e. input, output, display, analysis, reporting). Used on their own, the successful application of MCE techniques, relies heavily upon the skill and experience of the user in supplying the appropriate data, using appropriate models and interpreting the results correctly. This fact alone remains one of the main barriers to their widespread use. The MCE algorithms used here are programmed externally to the GIS in FORTRAN 77. They are run from within the GIS via system or macro commands to analyse the contents of the site evaluation matrix held in the GIS database. The three MCE techniques described earlier have been programmed and implemented within the Arc/Info GIS in this way and are outlined in the next section.

Different MCE techniques, together with different weighting schemes, will inevitably produce different results when applied to the same evaluation matrix. These sources of variation may be referred to as technique and priority bias, respectively. Technique bias results from the different ways in which MCE techniques rank alternatives and calculate trade-offs between conflicting characteristics and objectives. Priority bias refers simply to how different weighting schemes specified by various parties (possibly reflecting divergent views) affect where and how trade-offs are made between choice alternatives. Assuming three MCE techniques and three weighting schemes are used in conjunction with a single evaluation matrix, then nine separate short-lists of sites will be produced. Some form of sensitivity analysis is therefore required to account for the variation introduced by technique and priority bias and so to provide a single short-list of sites.

One solution is simply to identify those sites which are common to all (or most) of the original nine short-lists. A distance factor is also included which allows the number of adjacent sites to be counted within a specified radius. This attempts to take the effects of spatial autocorrelation, data uncertainty and methodological differences between MCE techniques into account. In this way it is possible to count the number of times that a particular site and also its close neighbours appear in any of the nine short-lists. This simple tally is used as the basis for a crude indicator of 'robustness' for each site. This sensitivity analysis is again carried out in a FORTRAN 77 program run from within the GIS, the final list of compromise sites being displayed using its graphical output capabilities.

This method assumes that the definition of short-lists is an objective process. As with most analyses, however, there are several subjective inputs, e.g. choice of MCE model and definition of weighting schemes. The reliability of these depends very much on the knowledge and expertise of the decision-maker. This is especially true in the case of the HO model, which is inherently interactive (as opposed to the 'grey' box approach of the IPA and CDA models) and requires the decision-maker to go through a step-wise procedure specifying the desired achievement levels (goals) at each stage of the optimization process. A second approach towards sensitivity analysis, therefore, is to allow for a more subjective role for the decision-maker by finding and agreeing on a final compromise solution through incremental changes to weighting schemes and multiple model runs.

4.3. *User interface*

Most GIS allows the user to write macro programs to link together existing GIS functions and run external routines (e.g. the Arc Macro Language (AML) in ESRI's Arc/Info GIS package). The following example of searching for nuclear waste disposal sites using Arc/Info makes use of AML to link external MCE routines into the GIS framework. Using AML programs, the user interface of GIS–MCE tools can be designed around a format similar to existing Arc/Info commands. Alternatively, AML programs may be used to create menu-driven interfaces between the user, the GIS and the MCE routines. Whether the standard Arc/Info command format or menu interface is used, by embedding the MCE routines in AML programs an apparently seamless join between GIS and MCE can be created.

Most of the AML programs developed in this work are specific to the nuclear waste example and its associated databases, but it is envisaged that more general tools could evolve from these and across a range of other GIS packages. These may, in the case of Arc/Info, appear similar to existing add-on packages which surround the core Arc package (e.g. Arcplot, Arcedit, Tin). Creating an evaluation matrix for input and evaluation using MCE tools is very problem-specific. The contents of the matrix depend on how the problem is regarded and what criteria are considered relevant. However, the evaluation matrix itself is stored as an Arc/Info point coverage with the characteristics of each point or site stored as attributes in the point attribute table (PAT). Compiling point coverages and adding attribute information from other coverages and databases to the coverage PAT is common practice in Arc/Info using standard tools which should be familiar to all users. No new add-on tools are therefore considered necessary for the construction of evaluation matrices. Once such an evaluation matrix has been created, then the MCE tools used can be entirely generic with inputs from the user stating which matrix is to be evaluated and by which method, and the criterion priorities to be used.

The times taken for some of the more complex MCE models (e.g. concordance–discordance analysis) to run are fairly long (depending on the size of the evaluation matrix), and as such are perhaps more suited to batch rather than interactive processing at a terminal or work station. Simpler models, such as ideal point analysis, can easily be run with fairly large evaluation matrices (e.g. 5878 by 16 as used in the following example) over just a few minutes, depending on the hardware configuration. This is, of course, an important consideration to be taken into account when designing any GIS–MCE interface, but as GIS work stations become ever faster and more powerful, this may cease to be a significant problem.

5. Searching for nuclear waste sites: an example application

Openshaw *et al.* (1989) discuss the use of the Arc/Info GIS to identify feasible sites for the disposal of radioactive waste in the U.K. The GIS operations therein constitute little more than a sequence of map overlays in the form of a Boolean search. This process is re-examined here with the addition of MCE techniques to the overall GIS based analysis.

The object of the overlay analysis is to determine which areas of the U.K. are potentially suitable for the deep geological disposal of low and intermediate level radioactive wastes using the four siting factors given in the Introduction (geology, population distribution, accessibility and conservation).

The numerical and qualitative criteria applied to these four siting factors are:

(1) The site must be within an area characterized by a suitable deep hydrogeological environment.
(2) The site must be located in an area with a population density less than 490 persons per km^2.
(3) The site must be within 3 km of the rail network.
(4) The site must not be within a designated conservation area.

Using these factors, mapped according to the four criteria, it is possible to define all the potentially feasible areas using the basic overlay and buffer, functions in Arc/Info. These are, however, only feasible areas, and actual sites need to be identified before development can take place. Here, feasible areas resulting from the overlay analyses are rasterized into 2×2 km grid cells. This is the approximate size of site (i.e., 400 ha) considered by the U.K. nuclear industry to be necessary for development to take place (UK Nirex Ltd. 1989). Each of these grid cells represents a single site-sized land parcel for the purposes of further analysis. There are in total 5878 such sites in this example. The data handling capabilities of Arc/Info are then used to create an evaluation matrix in the Info database using new and existing data sources on non-deterministic secondary siting factors. Sixteen separate factors are considered (table 1). The evaluation matrix is output from the Info database as an ASCII file and normalized for use with the IPA and CDA models. Three different hypothetical weighting schemes are defined and assumed for the purposes of this work to be representative of the views of the three major interest groups. These emphasize site remoteness, accessibility and ecological suitability, respectively (table 2). The three MCE techniques are run interactively to identify the 25 best compromise sites for each of the three weighting schemes. These are analysed for coincidence and adjacency to identify 'robust' sites. Site data are then displayed using the map-drawing facilities of Arc/Info.

Figure 1 shows the feasible areas identified using overlay analyses in the survey stage. From these areas 5878 sites are derived. Figure 2 shows the distribution of all nine sets of the top 25 compromise sites identified in the application of three MCE routines with three different criterion weighting schemes. The rather confusing scatter of potential sites in this map demonstrates the combined effect of technique and data uncertainty on the results from the nine MCE model runs and exemplifies the need for sensitivity analyses to filter out truly robust locations. Attention is drawn to the apparent clustering of 'best' sites which indicates some degree of homogeneity in the results. Technique and priority bias are investigated here by keeping one source of bias constant and altering the other.

Table 1. Evaluation criteria for sites for the disposal of radioactive waste.

Site No.	Description
j1	Host rock type
j2	Hydrogeological environment
j3	Coastal environment
j4	Population density
j5	Population potential/accessibility
j6	Proximity to built-up area boundary
j7	Strategic accessibility
j8	Proximity to existing nuclear installation
j9	Proximity to railway line
j10	Proximity to motorway
j11	Availability of on-site rail access
j12	Quality of on-site road access
j13	Proximity to conservation area
j14	Proximity to conservation site
j15	Land-use type
j16	Political marginality

Table 2. Hypothetical criterion weights for the nuclear industry, the general public and environmental groups.

	Criteria															
Views	j1	j2	j3	j4	j5	j6	j7	j8	j9	j10	j11	j12	j13	j14	j15	j16
Nuclear industry	7	6	5	0	0	0	7	5	5	5	3	3	0	0	0	1
General public	0	0	2	5	7	3	0	0	0	0	0	0	0	0	0	0
Environmentalists	0	0	0	4	5	3	0	6	0	0	0	0	7	6	3	0

Weights specified on seven-point scale with key to criteria in Table 1.

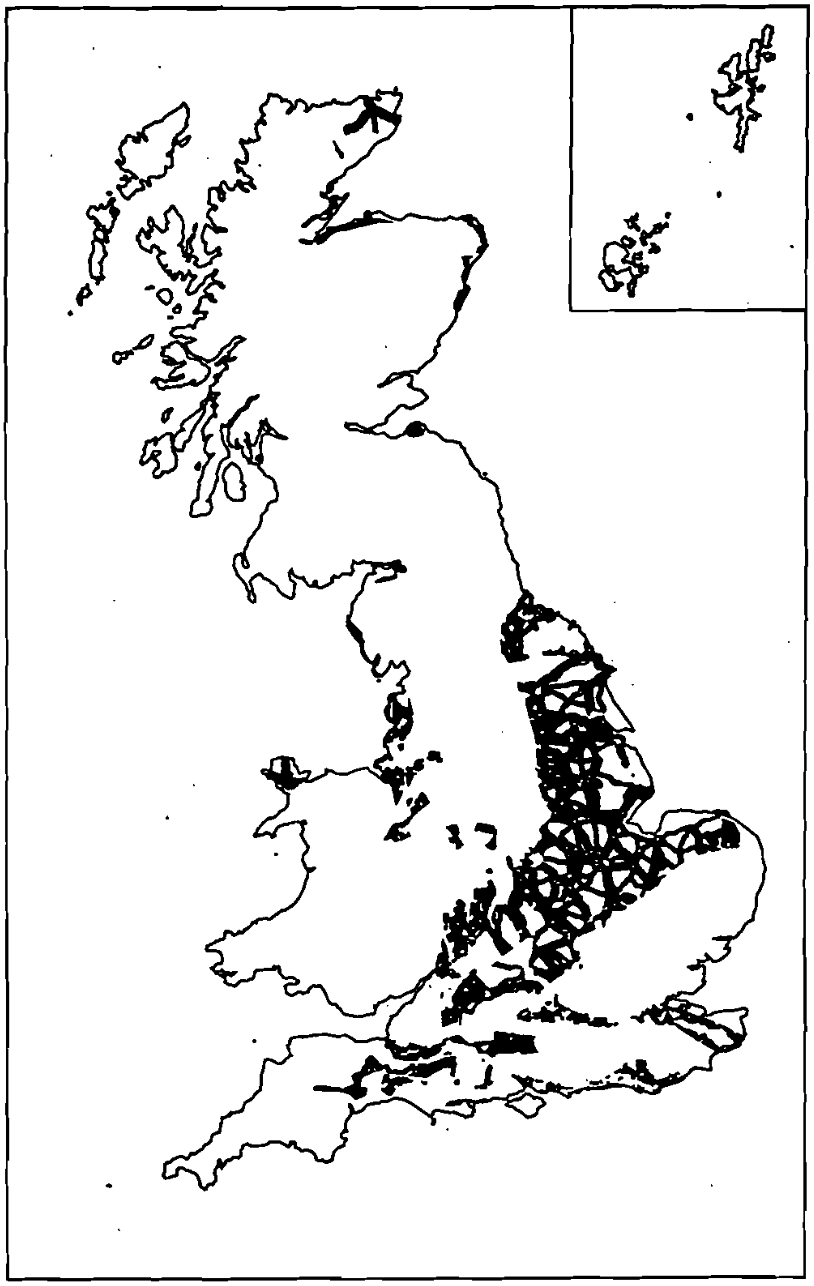

Figure 1. Feasible areas for the disposal of radioactive waste using GIS overlay analyses.

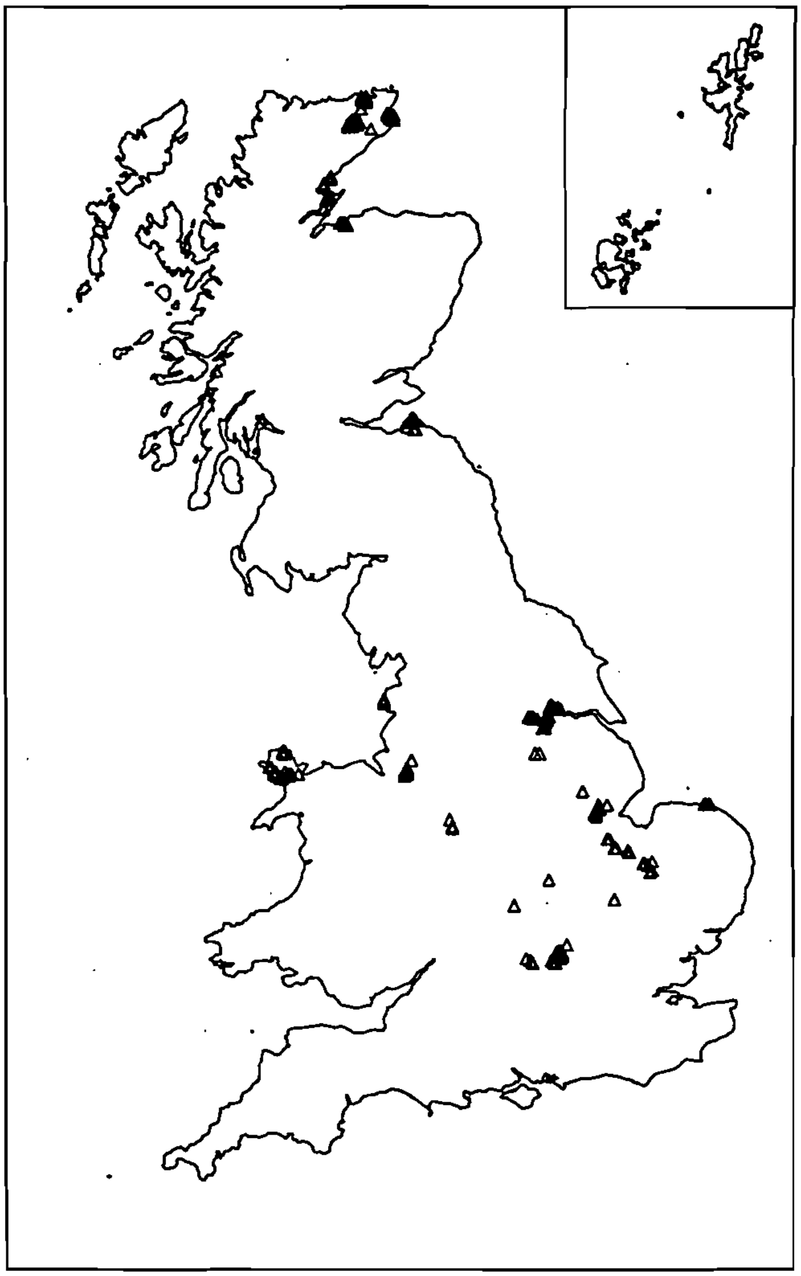

Figure 2. Distribution of all compromise sites. (△) Compromise site.

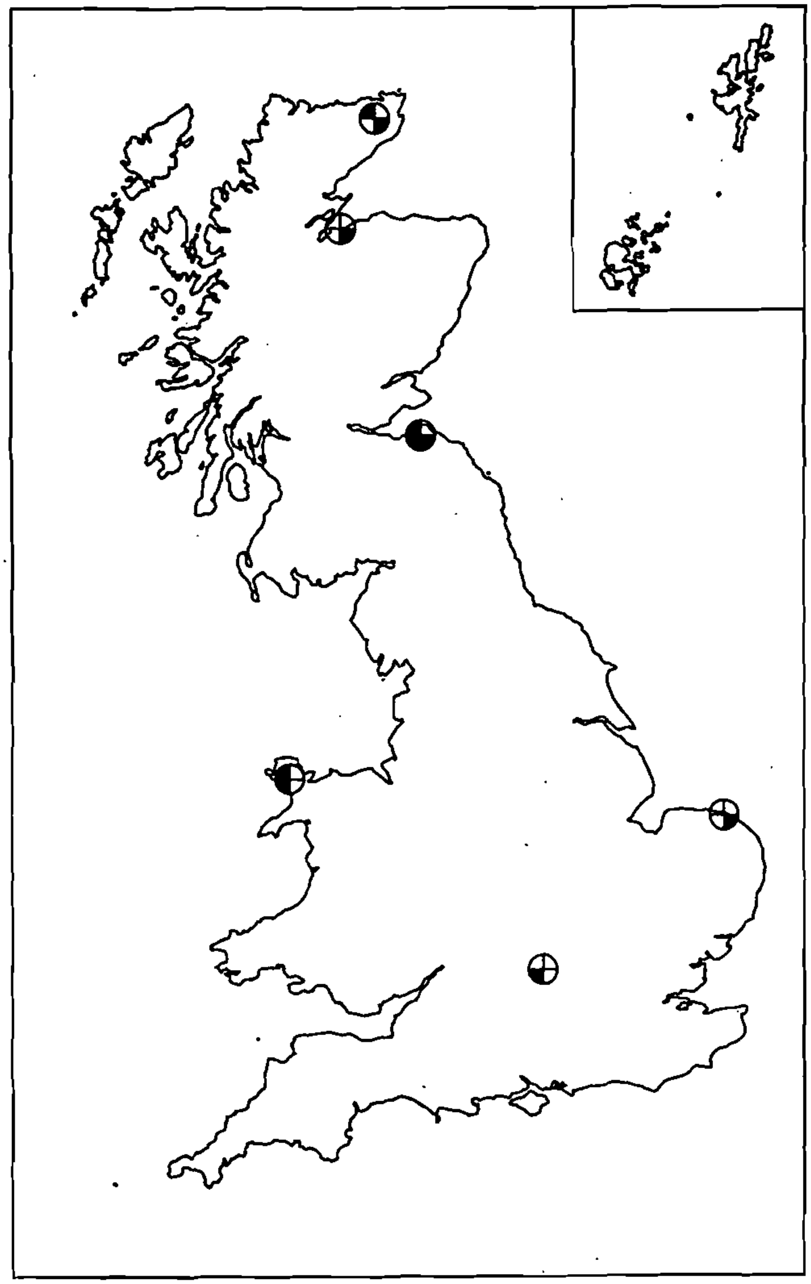

Figure 3. Technique bias: nuclear industry preferred site. MCE technique. ⊕ IPA; ⊕ HO; and ⊕ CDA.

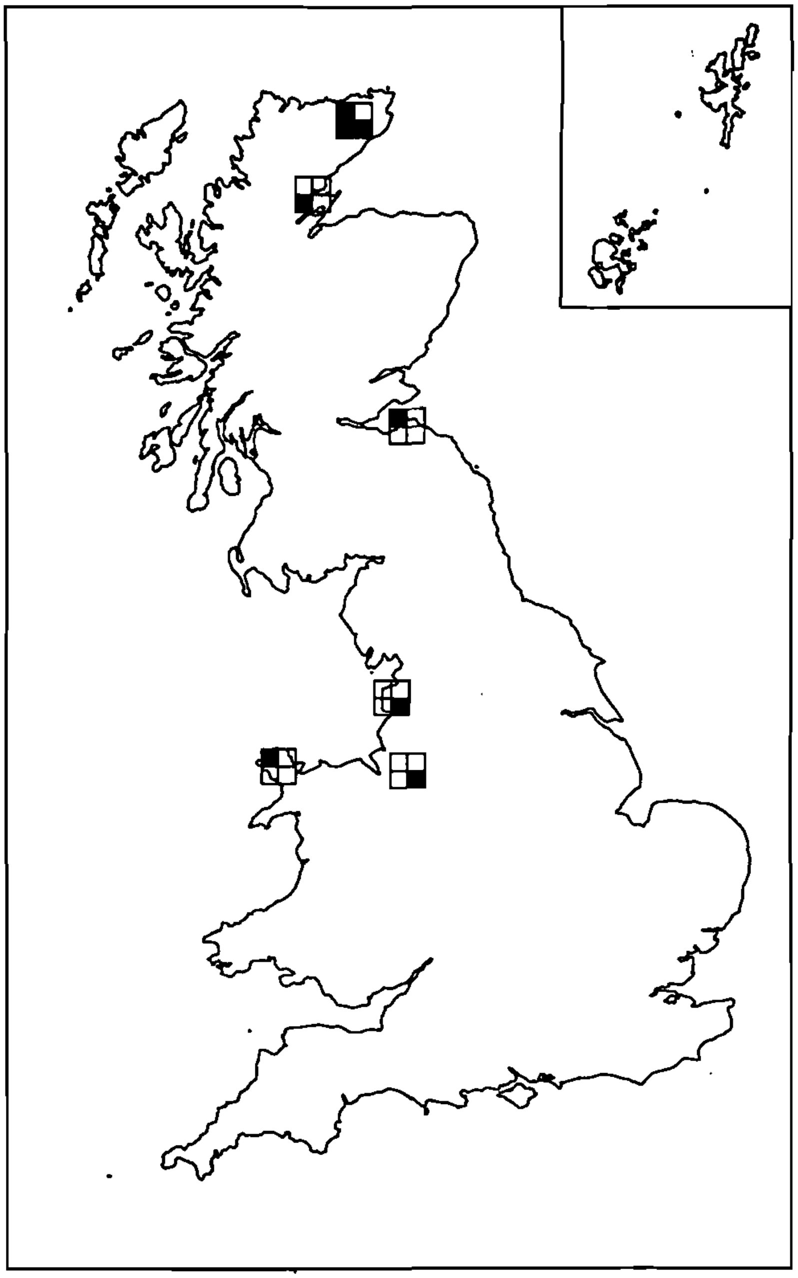

Figure 4. Priority bias: ideal point analysis model. Weighting scheme. ▣ Nuclear industry; ▣ general public; and ▣ environmental groups.

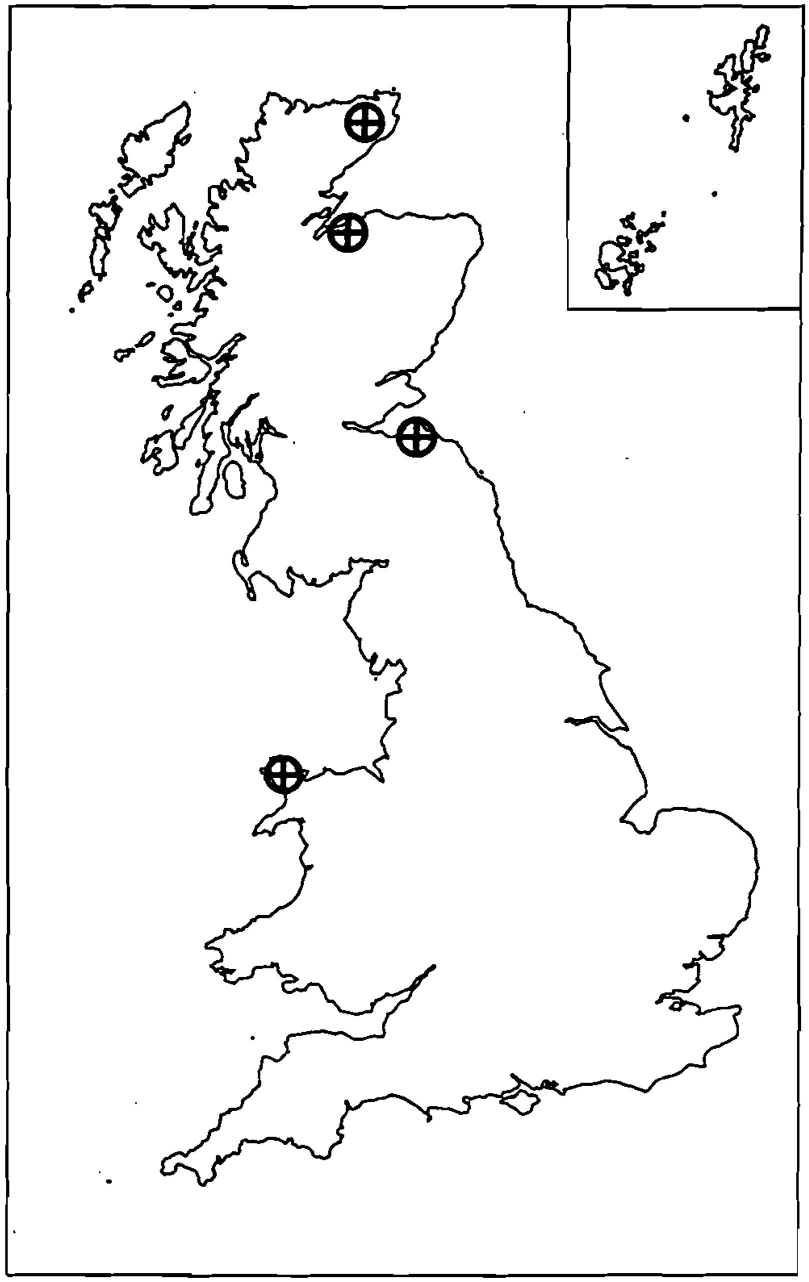

Figure 5. Robust sites: upper quartile of 'robustness' index distribution for all model runs. Symbols represent robust sites in upper quartile.

Figure 3 illustrates the effect of technique bias on the distribution of results using the 'nuclear industry' preferred weights from table 2. The symbols used represent groups or 'clusters' of short-listed sites and are split and shaded according to how each appears in the different model runs. The variation in the distribution of sites shows how different evaluation techniques can affect the outcome of the site search. Similar variations appear when testing for technique bias with the other two weighting schemes in table 2. Although any particularly robust sites should appear when using most MCE methods, it is suggested that two or more methods should be applied to dilute the effect of technique bias. Figure 4 shows the effect of priority bias on the distribution of results using, in this case, the IPA method. The variation in the distribution of sites shows how different weighting schemes can affect the outcome of the site search. Again, similar variations are evident when testing for priority bias with the other two MCE techniques described here.

Although considerable variations are evident between the results, it is also notable that groups of short-listed sites cluster with recurring regularity in certain areas of the country (e.g. Anglesey, East Lothian and Caithness). Figure 5 illustrates how this is reflected in the distribution of the most robust sites (i.e. those in the upper quartile of the 'robustness' index frequency distribution). It is noted that some of the additional 'scatter' exhibited by the results in figures 3 and 4 may be attributable to the limited number of very robust sites in the U.K. The most robust sites are picked out by all or the majority of the nine model runs and so occur in most or all of the maps. Sites of lower robustness are relatively mediocre and so suffer more from the effects of technique and priority bias. As a result, these sites show a more scattered distribution in figures 3 and 4. It should be noted that figures 3–5 have been drawn in a diagrammatic fashion to enhance their clarity. As such the location of groups or 'clusters' of short-listed sites are approximate, indicating only the general areas in which they are located.

5.1. *Spatial decision support systems for facility location*

The advantages gained from combining GIS and MCE suggest that this approach represents a major contribution towards the development of effective spatial decision support systems (SDSS). SDSS based around GIS–MCE systems may be used to assist decision-makers in site identification and plan evaluation. Ideally, SDSS provide a framework for the integration of spatial analysis, database management systems (DBMS), graphical display, tabular reporting and the expert knowledge of the decision-maker. Although it is normal to find certain spatial analysis techniques, DBMS, graphical and tabular output in GIS, only the addition of advanced spatial analysis capabilities (e.g. MCE), the expertise of the decision-maker and a suitable user interface can constitute an SDSS.

Many spatial problems, such as facility location, are complex (often involving multiple criteria and objectives) and so require the use of spatial analysis models for their solution. It is suggested here that the siting of nuclear installations, such as facilities for the disposal of radioactive waste, is a typical example of a complex spatial problem. Site-search procedures could significantly benefit from the use of SDSS, from initial surveys to the final decision and public inquiry. It is envisaged that a PC or work station based GIS–MCE system and an experienced operator in a committee room could create significant improvements in the way decisions for siting are made. In addition to these roles of decision-making and support, SDSS may also have an important role to play in providing more effective means of public participation and consultation throughout the site-search process by allowing for public input through interaction with customized GIS–MCE systems and feedback to decision-makers regarding public sentiment.

6. Conclusions

GIS overlay analyses, while ideal for performing spatial searches on nominally mapped criteria, are of limited use when multiple and conflicting criteria and objectives are concerned.

MCE techniques offer a means of making and supporting complex siting decisions, involving multiple criteria. In this context of site location, a combined GIS–MCE approach is advocated for use in the making of controversial decisions on siting. The advantages of pursuing such an approach (and in conjunction with its use as the basis for a dedicated SDSS) can be summarised as follows:

(1) GIS is an ideal means of performing deterministic analyses on all types of geographical data.
(2) GIS provides a suitable framework for the application of spatial analysis methods, such as MCE, which do not have their own data management facilities for the capture, storage, retrieval, editing, transformation and display of spatial data.
(3) MCE procedures provide the GIS with the means of performing complex trade-offs on multiple and often conflicting objectives while taking multiple criteria and the expert knowledge of the decision-maker into account.
(4) GIS and MCE based systems have the potential to provide a more rational, objective and non-biased approach to making decisions on siting than used hitherto.

Much work has been carried out on the development of both GIS and MCE techniques, but mostly in isolation. By combining the two approaches in the way described their full potential as evaluatory and decision-making tools may be realized. There now exists the opportunity to develop combined GIS–MCE methodologies further by including MCE routines as add-ons to existing GIS packages. There is currently a fundamental lack of basic spatial analysis tools in most proprietary GIS packages over and above that provided by map overlay and buffer operations. Little or no means of carrying out an evaluation of a siting problem past the area based analyses of map overlays is provided in the standard GIS tool-box. By the addition of MCE functionality as suggested here, the user is fully able to take a site-search from the basic sieve-mapping stage, through the evaluation of a large number of potential sites, to the final evaluation and choice between a limited number of alternatives on the basis of information taken from all available sources (including field surveys) using standard GIS tools.

Integrating MCE with GIS for spatial decision-making purposes is both a worthwhile aim and one which will be of widespread utility to those involved in what is (and will contine to be) a mainstay application of GIS technology. This will in turn create the opportunity for the increased use of GIS based technology as the basis of decision support systems. It is important to note, however, that GIS and MCE techniques are merely tools which provide a means to an end. Without the knowledge and expertise of the operator and decision-maker, and without appropriate data, such tools would be useless. Nevertheless, GIS–MCE applications appear to represent potentially fruitful areas for further research and development.

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