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A Fuzzy Compromise Programming Environment for the ecological evaluation of land use options

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Abstract

In this paper we describe an extension of the Compromise Programming (CP a multiple criteria optimization method) into Fuzzy Compromise Programming (FCP). By linking of Fuzzy modelling, CP and multiple criteria evaluation (MCE) into a Geographical Information System (GIS), we created a Fuzzy Compromise Programming Environment for the ecological evaluation of land use options as an AML-program (Arc Macro Language). After an introduction, a short description of a framework for GIS-based multiple criteria decision analysis is given in section 2. The section 3 describes the methodology of Hierarchical Fuzzy Evaluation. The section 4 deals with the extension of the CP into FCP. Finally, the section 5 reports about application results of the AML-program for the ecological evaluation of land use options in a suburbanisation area.

1. Introduction

Multiple criteria evaluation, a process for combining data according to their importance in decision analysis, has recently received strengthened attention in the context of GIS-based decision making. In the ecological and regional development, numerous multiple criteria land-related problems require decision making. These problems do not tend to be solved by conventional mathematics; rather they require logical search procedures, leading to feasible solutions of acceptable compromise. Linking of MCE, mathematics such as multiple criteria optimization, and GIS can provide facilities for merging of knowledge of different disciplines. In this field some works were done by a team from the German IOER-Institute and the Hungarian VATI-Institute (Ferencsik 2000; Schanze et al. 2004; Thinh et al. 2004). In the ongoing work, we compared the results generated by the classical Compromise Programming and the Hierarchical Fuzzy Evaluation and merged the classical Compromise Programming and Fuzzy-Modelling in order to create a Fuzzy Compromise Programming Environment for the ecological evaluation of land use options.

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This work has been conducted as a contribution (GIS & MCE Modul) to the work package WP 4 “Land Use Information Management” of the project INTELCITIES which addresses the EU policy objective of the “Knowledge Society” by 2010 in the context of cities by developing an integrated citywide information system continuously accessible to all (planners, developers, politicians, designers, engineers, transport and utility service providers and individual citizens) that will enable more inclusive decision-making and support more sustainable life-styles.

2. Framework for GIS-based multiple criteria decision analysis (MCDA)

GIS-based MCDA can be conceived of a process that combines and transforms geographical data (input maps) into a resultant decision (output map) (see Figure 1). The MCDM procedures define a relationship between the input maps and output map.

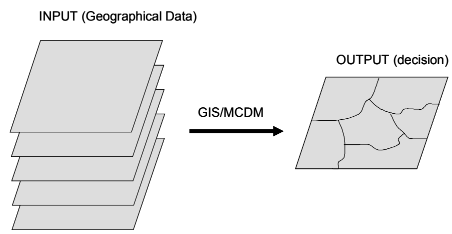


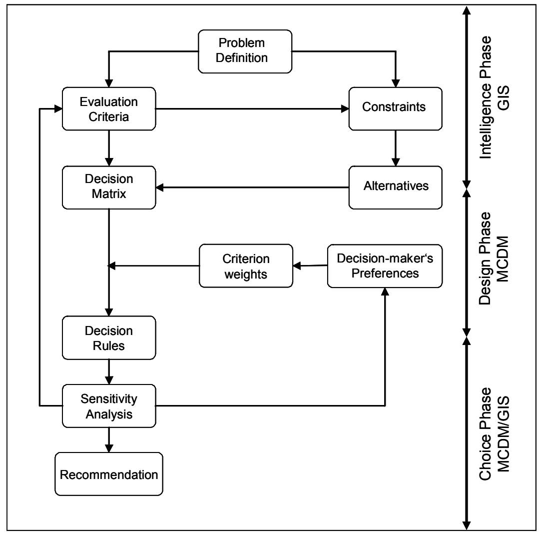
Figure 1
Spatial multiple criteria decision analysis: input-output perspective
(based on Malczewski 1999)

Figure 2 presents a three-stage hierarchy of intelligence, design, and choice to represent the decision making process. In the intelligence phase, data are acquired, processed, and exploratory data analysis is performed. The design phase usually involves formal modelling/GIS interaction in order to develop a solution set of spatial decision alternatives. The integration of decision analytical techniques and GIS functions is important for supporting the design phase. The choice phase involves selecting a particular alternative from those available. In this phase, decision rules are used to evaluate and rank alternatives. The three stages of decision making do not necessarily follow a linear path from intelligence, to design, and to choice.

Problem definition

The decision problem is a perceived difference between the desired and existing states of a system. It is a gap between the desired and existing states as viewed by a decision maker. The GIS capabilities for data storage, management, manipulation, and analysis offer major support in this stage.

Figure 2
Framework for spatial multiple criteria decision analysis



(based on Malczewski 1999, modified)

Evaluation criteria

This step involves specifying (1) a comprehensive set of objectives that reflects all concerns relevant to the decision problem, and (2) measures for achieving those objectives. The evaluation criteria are associated with geographical entities and relationships between entities and therefore can be represented in the form of maps (thematic map or data layer in GIS terminology). The GIS is used to generate inputs to SMCDA.

Criterion weights

The preferences of decision makers are typically expressed in terms of the weights of relative importance assigned to the evaluation criteria under consideration. The derivation of weights is a central step of the evaluation and decision process. A number of criterion weighting procedures have been proposed in the multiple criteria decision literature. A collection of the most popular procedures can be found in Thinh et al. (2004).

Recommendation

This step should be based on the ranking of alternatives and sensitivity analysis. It may involve the description of the best alternative or group of alternatives considered candidates for implementation. Visualization techniques (e. g. Hasse-Diagram technique, see Brüggemann et al. 2001) are of major importance in presenting and communicating the results to decision makers.

3. Hierarchical Fuzzy Evaluation of land suitability

In the context of decision analysis, the attributes can be thought of as indicators of future outcomes rather than past achievements. For any given objective, several different attributes might be necessary to provide a complete assessment of the degree to which the objective might be achieved. The relationship between objectives and attributes has a hierarchical structure. At the highest level are the most general objectives. At the lowest level of the hierarchy are attributes, which are quantifiable indicators of the extent to which associated objectives are realized. To demonstrate the hierarchical fuzzy evaluation, we consider an example of evaluating the suitability of land parcel for residential settlement in a south eastern suburban area of Dresden. Figure 3 displays a hierarchical structure of the objectives and associated attributes (indicators). The overall objective is to select the suitable site for residential settlement. Toward fulfilling this objective, the following more specific objectives are chosen: (1) optimize the location, (2) maximize the nature protection, and (3) maximize the soil conservation. To realize these objective 11 attributes (indicators) are considered (see the lowest level of the hierarchy in Fig. 3).

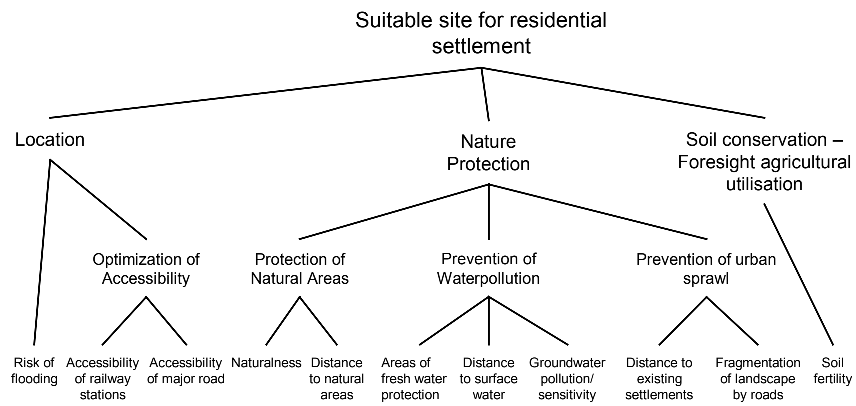


Figure 3
A hierarchical structure of the objectives and associated indicators for fuzzy evaluation

To represent geographic information in a fuzzy scheme, a raster data layer (grid) in a GIS can be defined as a fuzzy set because most geographic features do not have sharp boundaries, and each grid cell as the set element. Each grid cell can be assigned to a group of membership grades to indicate the extent to which the cell belongs to certain attributes (linguistic scales or terms), e. g. {very good, good, moderate, bad, very bad}. In this way, we generated for each of 11 indicators 5 grids according to 5 linguistic terms. Fig. 4 presents 3 grids {very long, moderate, very short} for the indicator "Distance to natural areas". Using the software SAMT (Wieland et al. 2004) and the hierarchy (Fig. 3) we conducted a fuzzy rule-based evaluation of the suitability of each cell for residential settlement. The work with SAMT consists of developing of IF-AND-THEN-rules such as

IF indicator A is very good AND indicator B is long THEN result is suitable (for aggregation of two inputs) or IF attribute C is high AND attribute D is good AND attribute E is less valuable THAN result is suitable (for aggregation of three inputs).

This relationship (expert knowledge) can also be represented in a table or matrix form. Rules are much easier to develop, and simpler to debug and tune.

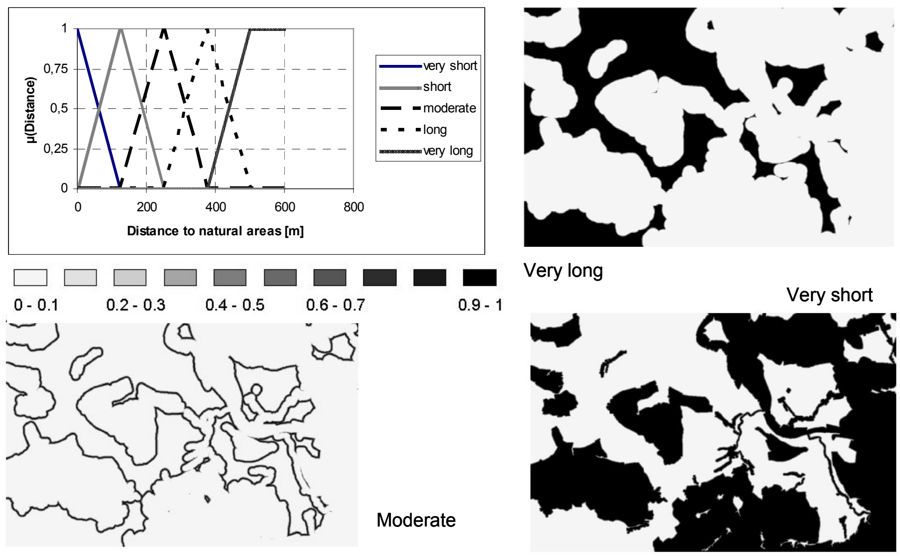


Figure 4
Fuzzy modelling and generation of grids to linguistic terms of an indicator

4. Extension of the classical CP into Fuzzy Compromise Programming

The basic idea of CP is to identify solutions which are closest to the ideal point as determined by some measure of distance. The CP uses the family of L_p metrics and attempts to minimize the distance from the ideal solution (e. g. see Zeleny 1982, 322; Romero & Rehman 1989, 90; Ehrgott 2000, 90).

$$L_p(w) = \left[\sum_{j=1}^{n} w_j^p \left| \frac{z_j^* - z_j}{z_j^* - z_{*j}} \right|^p \right]^{1/p} \rightarrow \min! \quad (1)$$

Thereby z^*_j is the ideal value for the j-th objective, and z_{*j} is the anti-ideal or nadir point for this objective. Any point $z = (z_1, z_2, ..., z_n)$ is a compromise solution if it minimizes $L_p(w)$ for some choice of weights $w_i > 0$, $w_1 + w_2 + ... + w_n = 1$, and $p \geq 1$ (p is a natural number). $L_p(w) \rightarrow$ min has been denoted by Ehrgott (2000, 92) the weighted compromise programming problems. It is general practice to calculate $L_p(w)$ for $p = 1$, $p = 2$, and $p = \infty$.

After successful application of the CP for ecological evaluation of land use options (see Thinh et al. 2004), our main objective was to create another extension of CP into FCP compared to the extension concept by Bender & Simonovic (2000). The authors proposed an approach by transforming distance metric L_p into a fuzzy set by changing all inputs from crisp to fuzzy and applying the fuzzy extension principle.

We suggest another way. Our idea to extend the CP into FCP for suitability evaluation is follows: a number of linguistic terms and appropriate grids to n indicators are given; we consider any linguistic term and any cell; let z_j the membership degree of the linguistic term at the cell to the indicator j (j=1(1)n); our idea is to create a membership degree from these n z_j through a plausible way; that means we create a new membership function from n membership functions; using the CP we can accomplish this. First we compute the distance of the vector $(z_1, z_2, \ldots, z_n)^T$ to the vector of n ideal membership degree $(1, \ldots, 1)^T$ by using the L_p metric. The minimum of this distance is zero, and maximum is

$$M(w) = \sqrt[p]{\sum_{i=1}^{n} w_i^p} \quad (2)$$

Next we transform the set of all calculated distances into a membership function

$$\mu(z) = 1 - \frac{\sqrt[p]{\sum_{i=1}^{n} w_i^p (1 - z_i)^p}}{M(w)} \quad (3)$$

After the calculation of all membership functions to the linguistic terms, our FCP is completed by defuzzify in order to get an overall result grid. For the described methodology we have developed an AML-program (Arc Macro Language) as a Fuzzy Compromise Programming Environment for ecological evaluation of land use options with a number of techniques to determine the weights w_j (see Fig. 5). A discussion about the integration of mathematical methods and models in GIS by developing of AML-programs can be found in Thinh 2002.

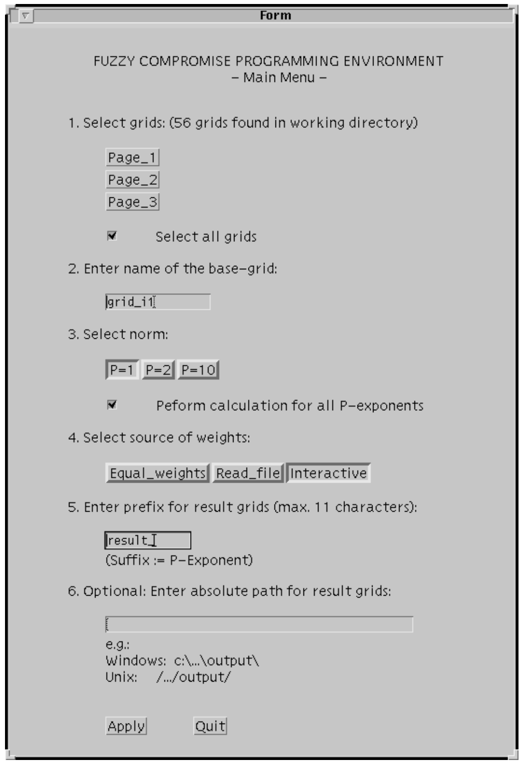


Figure 5
The main menu of our AML-program in ArcGIS

5. Application results and discussion

Using the developed AML-program we can create a set of CP-solutions as well as FCP-solutions for site selection for any given land utilisation type. Thus we can generate several alternatives for decision support. Furthermore we can also carry out Hierarchical Fuzzy Evaluations of suitability of sites for land use options by combining with the software SAMT (Wieland et al. 2004). For reasons of space the description of the AML-program should not be included in this paper.

Fig. 6 shows that the three methods (FCP, CP, and Hierarchical Fuzzy Evaluation) yield plausible results. Thereby the results of FCP and CP have been calculated with equally weighted w_j ($w_j = 1/n$, $j = 1(1)n$).

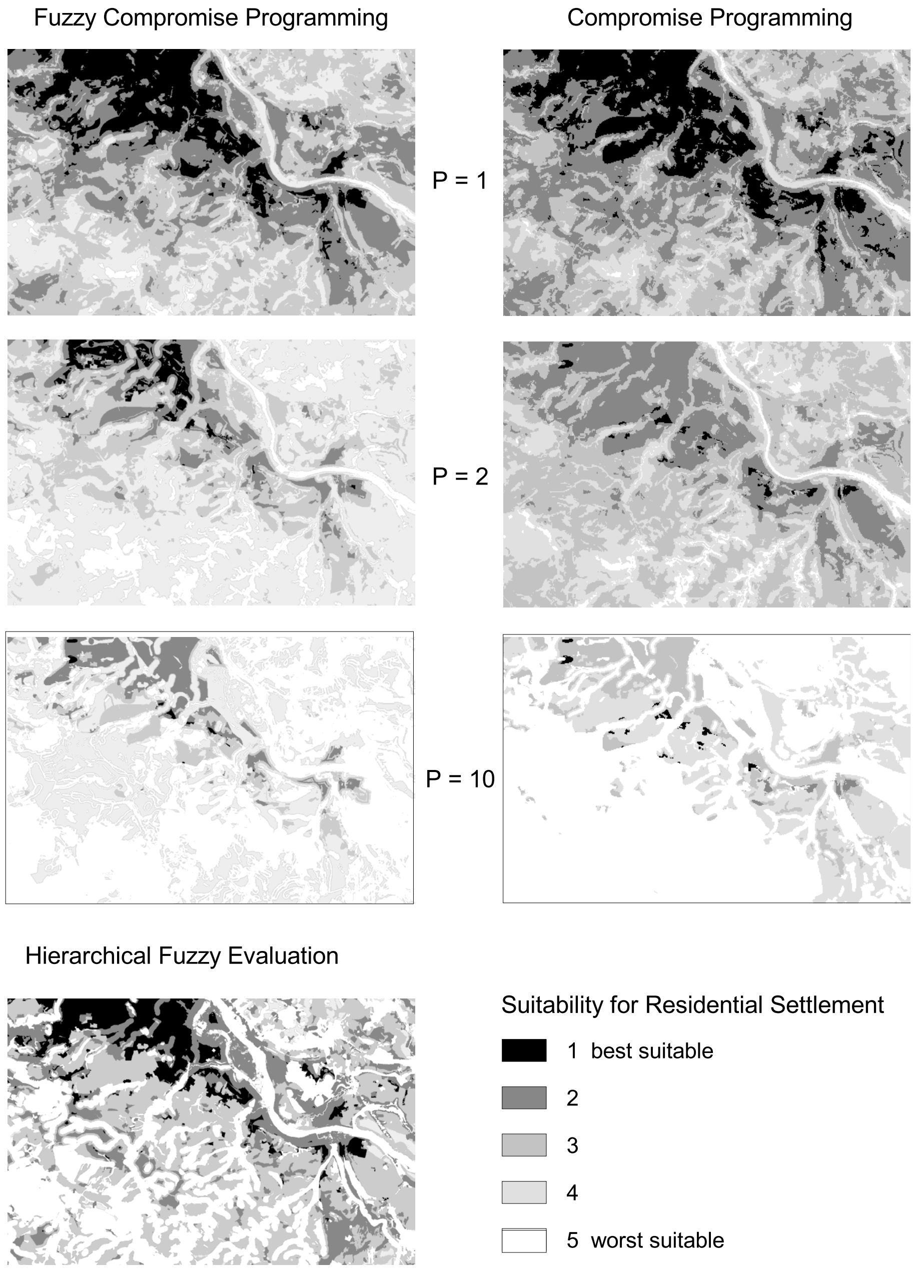


Figure 6
Results of three methods FCP, CP, and Hierarchical Fuzzy Evaluation

One can see as p becomes larger the evaluation results become more pessimistically. The reason for it lies in that as p becomes larger the distance L_p is increasingly affected by the largest deviation from the ideal solution or the ideal membership degree and the other terms become negligible. A correlation analysis confirms a significant correlation between the results of the three methods.

The results illustrate one advantage of the FCP-method, namely, that this approach provides more detail about the gradual transition of the suitability of land use options (see p = 10 in the Fig. 6). The FCP and Hierarchical Fuzzy Evaluation presented in this paper are useful in situations where only qualitative or vague knowledge exist for the evaluation of the suitability. However, the application of fuzzy set theory in the context of GIS-based decision making is not without its problems. The most pressing problem is the derivation of membership functions.

Our research reveals that the theoretical framework underlying the CP at first sight seems quite simple, but the concept of a displaced ideal is a powerful paradigm competing with the traditional concept of optimality.

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