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Land management with GIS and multicriteria analysis

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Abstract

In land management, conflicts are more frequent and stronger. Any important project on land becomes difficult to implement. MAGISTER (Multicriteria Analysis with GIS for TERritory) model proposes a decision support method to integrate multiple actors of land management. It is based on geographical information systems and multicriteria analysis. In land use problems, the study area is described by a set of homogeneous zones to reduce the numbers of alternatives. The homogeneity quality is assessed by use of a valued closeness relation developed in the domain of rough set theory. This function is based on the same principle as the valued outranking relation used in ELECTRE, which is then used to select the best zones, or classify them in predefined category. One application of the MAGISTER model concerns the realisation of a land suitability map for housing. Through eight criteria, this map integrates simultaneously the particularity of each place and the general principles of land management, which should be determined by decision-makers.

Keywords: Land management; GIS; Outranking methods; Homogeneity index; Suitability index

1. Introduction

In recent years, a systematic opposition has been observed to any land management project that affects local communities. This phenomenon has been illustrated by the acronyms NIMBY (Not In My Backyard) and CAVE (Citizens Against Virtually Everything) (Moor, 1994; Couclelis and Monmonnier, 1995; Dente, 1995).

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To face this phenomenon, European governments propose a new approach to land management: laws should set the general framework while at the same time allowing for specific adaptations depending on the situation (Ruegg, 1994). From a technical point of view, this approach needs efficient information processing tools and decision support methods. These methods have to meet the following objectives.

- Yield a precise description of the environmental project and identify its most notable aspects.
- Evaluate and compare various alternatives to determine the best solutions and facilitate negotiations.
- Allow the participation of different parties with conflicting and often opposing viewpoints. Opening the decision process to all interested parties is the best, and sometimes the only way to avoid legal or administrative oppositions.

2. MAGISTER model

A decision support model called MAGISTER (Multicriteria Analysis with GIS for TERritory) has been designed to meet these goals (Joerin, 1997). It is based on the use of Geographical Information System (GIS) and multicriteria analysis methods (Fig. 1). GIS manages information describing the territory and offers spatial analysis operators. These tools allow taking into account the project's environment, and also identifying and describing the various alternatives. Multicriteria analysis methods are then used to aggregate this information and choose the most adequate solution, considering the preferences of decision-makers.

Among the set of multicriteria analysis methods, we choose the family of ELECTRE methods (Roy, 1981a, 1981b, 1996). These methods do not perform a complete but a partial aggregation of the considered criteria. They are well suited to land management, because criteria are often extremely diverse (for instance of economic, ecological, or sociologic nature) and of qualitative and quantitative types. Furthermore, in this domain alternatives are sometimes incomparable, because they are fundamentally too different. This kind of method (outranking methods) is the only one that takes into account this phenomenon.

MAGISTER integrates the players in the decision making process in two different ways. First, the different parties have the possibility of negotiating the subjective parameters. They can, for example, argue about the weight to be associated with each criterion before adopting a common set of values. The second form of integration consists of repeating the multicriteria analysis to select, for each different party, a solution that is adapted to its needs. With MAGISTER the result of the multicriteria analysis can be visualised on a map describing, for instance, the best area or an index of land suitability. Parties can then discuss and negotiate by overlaying and comparing these maps, which are spatial representations of their own preferences.

MAGISTER is used in a dynamic way. Before using information processing tools, a great deal of effort is spent to define the problem clearly and to establish the decision model. In particular, decision-makers have to answer the following questions : What is the real problem?

Who are the influential players? What are the alternatives? What are the limits in precision, spatial area, systemic description, etc.? (Pictet, 1997).

3. Alternatives definition

In land use planning, for example, when searching the best area for an infrastructure (like a plant, a commerce, a housing district, etc.), each place with a sufficiently large surface could be considered as an alternative. So, one may be tempted to consider a very large number of alternatives.

The drawbacks are significant because outranking methods (like ELECTRE methods) have difficulties in handling large numbers of alternatives. This may lead us to the conclusion that these methods are impractical for land management (Pereira and Dückstein, 1993; Eastman et al., 1993; Jankowski, 1995). For this reason, even if properties of outranking methods are very interesting in this domain, the powerful combination of GIS and multicriteria analysis could be limited to methods using a complete aggregation like MAUT (Keeney and Raiffa, 1976), UTA (Jacquet-Lagrèze and Siskos, 1982), AHP (Saaty, 1990).

MAGISTER proposes to consider that an alternative is not only an area with a sufficiently

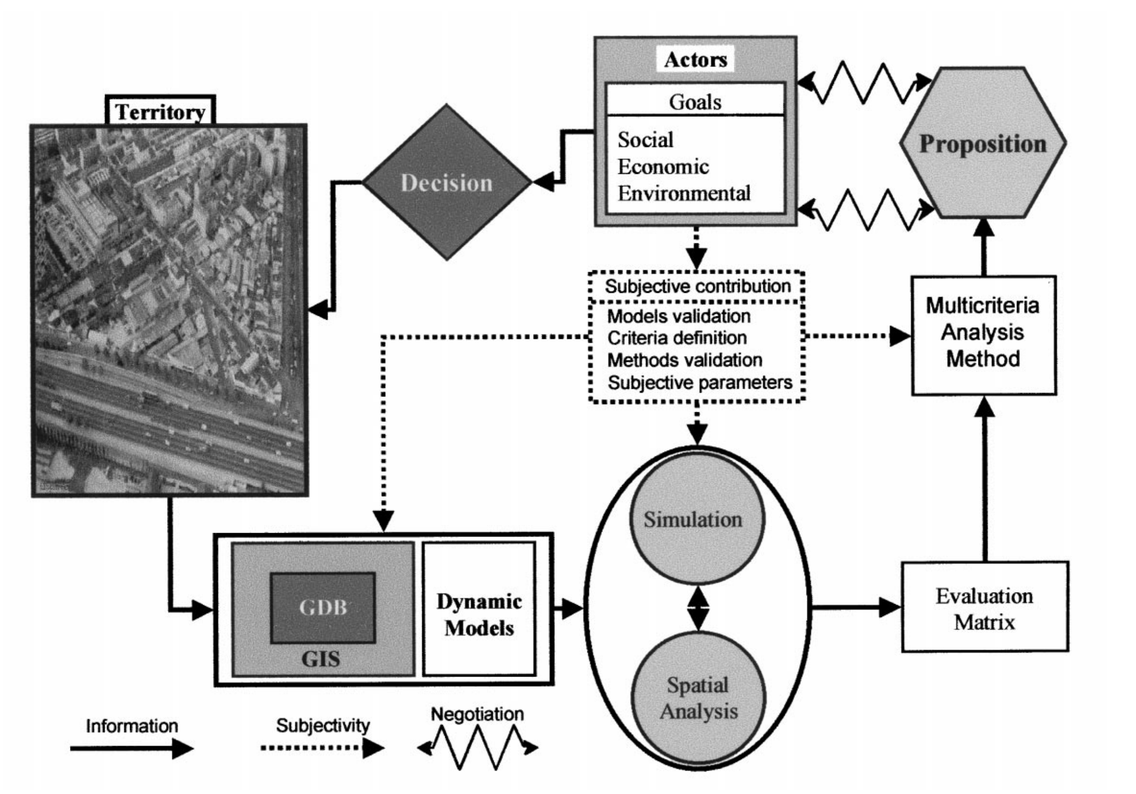

Fig. 1. MAGISTER model.

large surface, but it has to be also a particular solution. This additional condition to the alternative definition enables to group together all sub-regions sharing a similar profile with respect to the criteria considered. With this approach, alternatives are *homogeneous zones* (Joerin, 1995, 1997). These zones will bridge the gap between GIS and outranking methods for land-use planning.

3.1. Homogeneity index

The homogeneous zones are composed of a group of elementary surfaces. Their construction uses a homogeneity index, which assesses the closeness between every elementary surface and the average characteristics of the zone (Fig. 2). This closeness relation is computed with a function defined by Slowinski and Stefanowski (1994) to realise rough classification based on rough set theory (Pawlak, 1991; Slowinski, 1992). To evaluate if two elements are close, this function compares the scores difference for each criterion, with a set of indicative values chosen by the decision-makers. These indicative values are the indifference, the strict difference, and the veto defined for each criterion.

To explain these notions, let us consider a criterion evaluating the travel time between home and workplace. If decision-makers fix the indifference at 5 min, it means that two elements (two places) with a difference in travel time smaller than or equal to 5 min are considered as identical for this criterion. The value of strict difference corresponds to the smaller significant difference on travel time. We suppose, here, that this value is fixed at 15 min. Finally, if the veto is fixed at 60 min, the hypothesis of closeness is zero for each couple of elements with a difference on this criterion equal to, or greater than this value.

The degree of credibility of the closeness relation $r(A, B)$ between two elements A and B is obtained from the global concordance index $C(A, B)$ weakened by the discordance indices $d_i(A, B)$ (Slowinski and Stefanowski, 1994):

$$r(A, B) = C(A, B) \cdot \prod_{i \in I} \frac{1 - d_i(A, B)}{1 - C(A, B)} \qquad I = \left\{ i{:}d_i(A, B) > C(A, B) \right\} \tag{1}$$

The global concordance index characterises the relative importance of the criteria considered to be in concordance with the affirmation "A and B are close". It is computed by the weighted average of partial concordance index (c_i) evaluated for each criterion (Fig. 3):

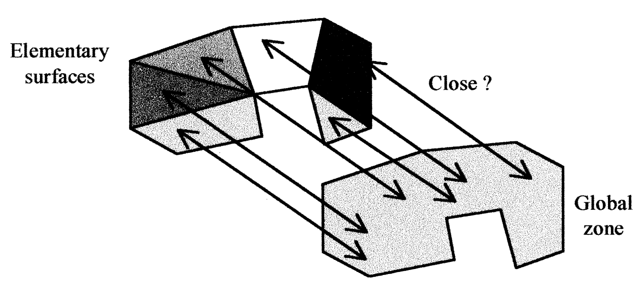

Fig. 2. Alternatives are defined as homogenous zones.

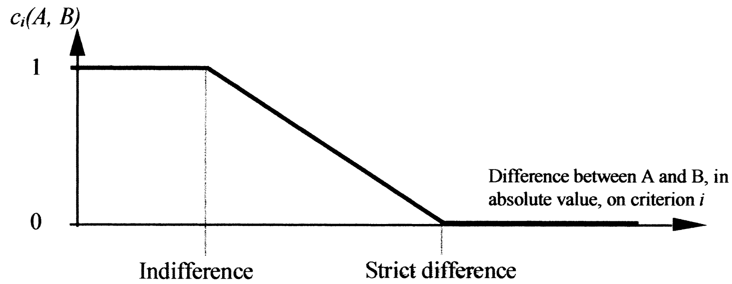

Fig. 3. Partial concordance index.

$$C(A, B) = \frac{\sum_{i=1}^{n} w_i \cdot c_i(A, B)}{\sum_{i=1}^{n} w_i} \tag{2}$$

Weights express the relative importance of criteria in the closeness relation. The partial concordance index is a function of the difference between two elements (on the considered criteria) and the thresholds defining indifference and the strict difference (Fig. 3).

Considering the example of travel times, $c_i(A, B)$ is equal to 1 if the difference between A and B is less than 5 min. For a difference between 5 and 15 min, $c_i(A, B)$ decreases linearly from 1 to 0. If the difference is more than 15 min $c_i(A, B)$ is null.

The discordance index, $d_i(A, B)$ allows considering the criteria, which are strongly opposed to the affirmation "A and B are close". If the discordance index is greater than the concordance index, it will reduce the credibility of the closeness relation (Slowinski and Stefanowski, 1994). The discordance index is computed, for each criterion separately, by comparing the difference between A and B with the strict difference and the veto (Fig. 4). In the considered example, $d_i(A, B)$ is zero if the difference is less than 15 min. It increases linearly between 15 and 60 min, and it is equal to one if the difference is more than 1 h. When partial discordance index is equal to 1, the degree of closeness relation is null, even if the difference between A and B is small on the other criteria.

The zones formation begins with a classification of the elementary surfaces (Fig. 5). This operation can be realised by an ordinary algorithm (unsupervised classification). Then, the

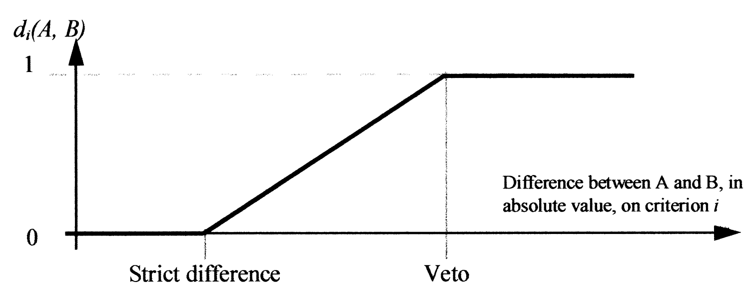

Fig. 4. Partial discordance index.

different classes are separated into zones in order to respect the discontinuous spatial limits, like administrative limits, landslide perimeters, etc. To evaluate if a zone is homogeneous, the formula (1) will be used to compute the degree of closeness between each elementary surface and the global zone (Fig. 2). The characteristics of the global zone are, for each criterion, the average scores of the elementary surfaces composing it. Homogeneity index is the smallest degree of credibility of closeness relation between the elementary surfaces and the global zone.

This definition of homogeneous zones uses the same mathematical principles as the ELECTRE methods. In particular, Eqs. (1) and (2) are very similar to the equations used in ELECTRE to compute the credibility degree of the outranking relationship. The indifference, the strict difference and the veto used in the homogeneity definition are also analogous to the indifference, preference and veto applied in ELECTRE to modelise the decision-makers' preferences. Consequently, MAGISTER proposes a complete coherent decision support system, starting from the alternatives identification, all the way to the selection of the best one.

4. Application

Land management services in public administration have frequently to take quick decisions without being able to analyse the consequences. To avoid this situation, we propose to use MAGISTER to establish land suitability maps, as a decision tool for public administrations (Fig. 6). These maps should integrate all the relevant data and some precise analysis. Their

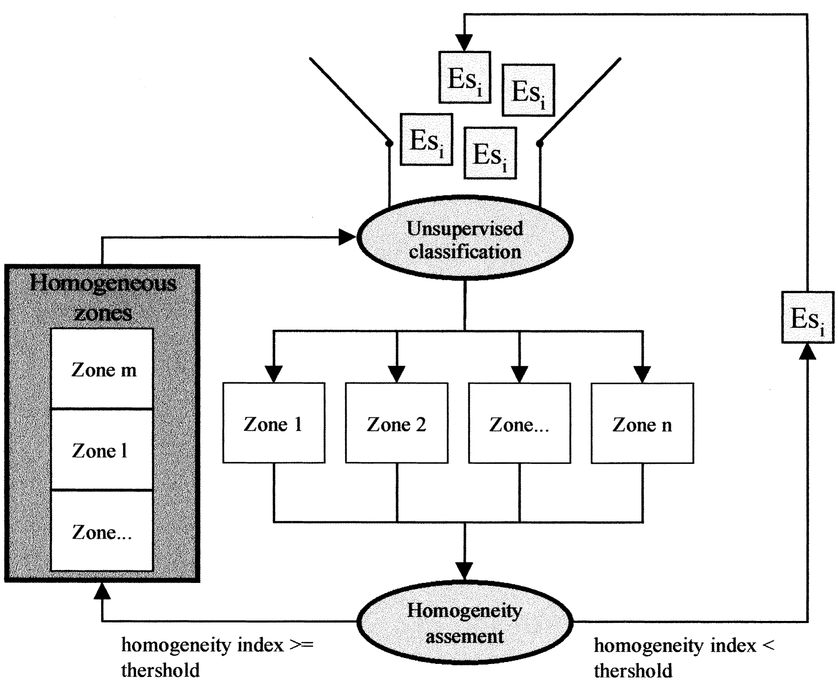

Fig. 5. Applied process to construct the homogeneous zones. Es$_i$ means elementary surface.

realisation would obviously require a significant amount of work. Therefore, the focus should be on the most important types of land use.

Assuming such maps are available, land management services just need to consult them for decision-making. If decision-makers agree, the realisation of land suitability map can integrate delegates of multiple parties (population, construction companies, organisations for the protection of the environment, etc.). In this case, the land suitability map could become a base for negotiation and the resulting decisions should not meet strong opposition.

A land suitability map for housing has been established for an area in the canton of Vaud (Switzerland). Its surface is approximately 50 km^2. The most important locality is Cossonay (about 2000 inhabitants). This study has also provided the occasion to demonstrate the importance of GIS and of spatial analysis in the criteria evaluation.

Land suitability maps are based on eight criteria: impacts, air quality, noise, accessibility, climate, landslide, technical networks (water, electricity, etc.) and view. These criteria have been evaluated by use of simulation models (solar radiation, noise propagation) and spatial analysis (Fig. 7). The study area contains more than 80,000 land units (pixels) with a surface of 625 m^2. By use of a homogeneity index a total of 650 zones composing the set of alternatives were formed (Fig. 8). Each zone is described by nine fields. These fields store the scores for the eight criteria and the value of the homogeneity index. To be considered as homogeneous, a zone must have an index greater than a chosen threshold (0.8 for this map). Increasing this threshold will increase the numbers of homogeneous zones. Obviously, their surface will also become smaller. Decision-makers should give their point of view about the value of indifference, strict difference and veto. Then, the threshold has to be fixed in order to obtain a reasonable number of alternatives. However, it should not be smaller than 0.6 neither bigger than 0.9. A value smaller than 0.6 would mean that the homogeneity conditions could be quite easily transgressed, while a value bigger than 0.9 would impose very strongly these conditions.

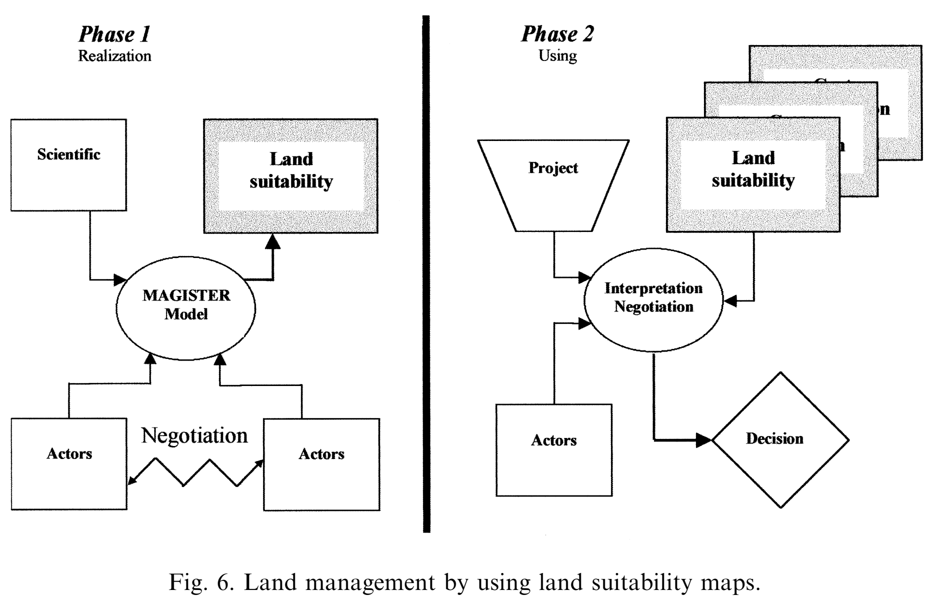

Fig. 6. Land management by using land suitability maps.

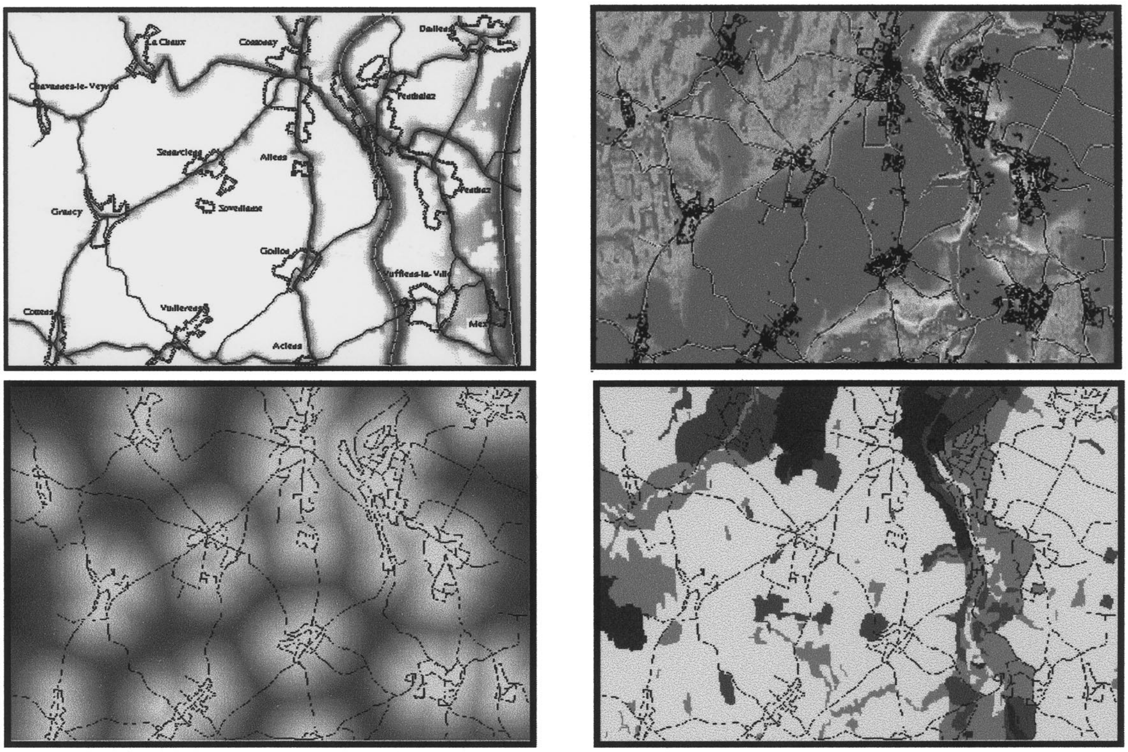

Fig. 7. Examples of maps resulting from the criteria evaluations. From left to right and top to bottom: noise, climate, distance to technical networks and impacts. Clearer areas are better suited for housing.

The possibility to consult at any time the homogeneity index of any zone constitutes a security in the decision process. If multicriteria analysis focuses on an area with a weak homogeneity index, it could be better to get more information on this region to improve its description.

As explained before, the homogeneous zones construction follows several iterations. Table 1 presents the intermediate results for each iteration step in the process. The number of

Table 1
Intermediate results during the homogeneous construction process

Iteration step	Number of homogeneous zones built	Number of pixel belonging to any zones
0	0	73,549
1	250	28,000
2	79	13,400
3	117	6700
4	71	3350
5	36	1500
6	38	630
7	114	120

homogeneous zones build at each step is irregular (between 36 and 250), but the number of pixels belong to any homogeneous zone decreases systematically from 50%. The entire process, which is realised in seven iterations, formed 705 zones. Using the valued closeness relation, 55 very small zones have been merged with the biggest zones. The hundred pixels still not classified at the last step belong to a few zones with a homogeneity index smaller than the chosen threshold (0.8).

Finally, these zones were classified in three categories of land suitability: favourable, uncertain, and unfavourable. This classification has been realised with ELECTRE TRI (Roy, 1981b) in collaboration with an administrative land manager. The maps obtained meet all expectations (Fig. 9). This application indicates that even if some changes might be necessary, a similar (larger scale) approach could efficiently support the tasks of a land management service.

5. Conclusions

Development of geographical databases supports efficient land management. When a

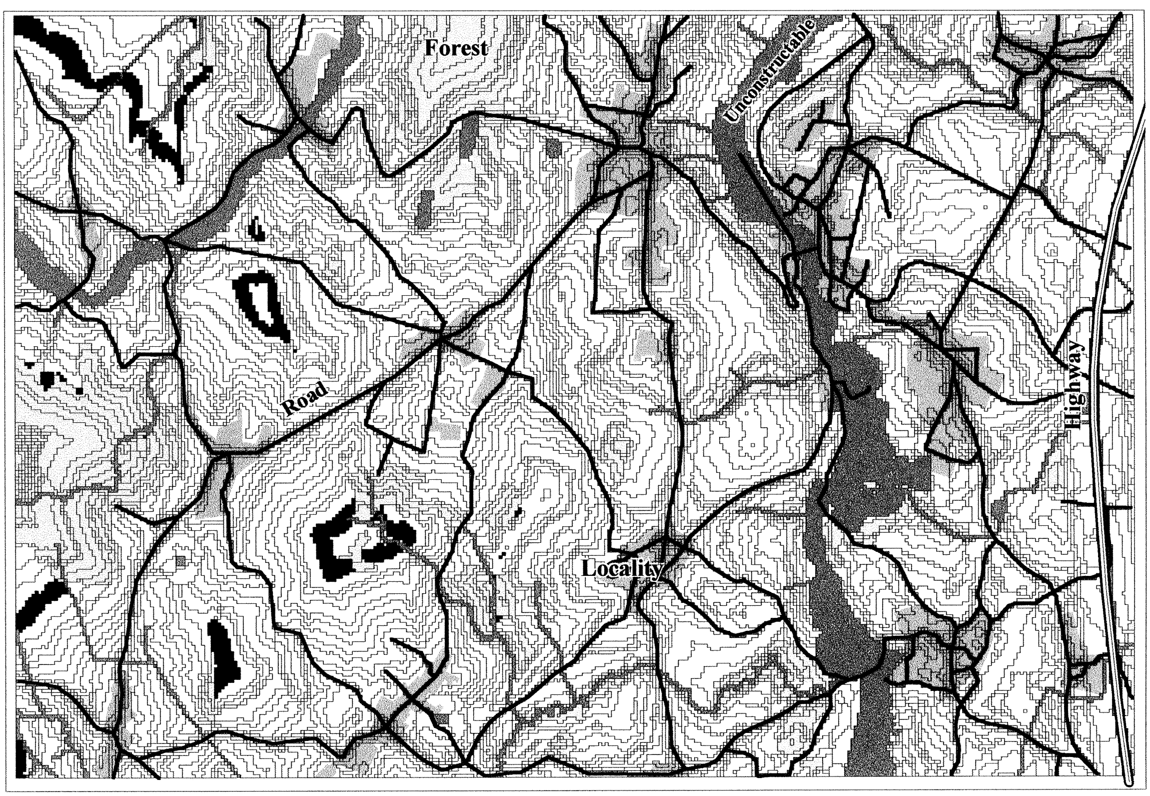

Fig. 8. Map of homogeneous zones. The thin lines delimit the 650 homogeneous zones. One of them is presented in black, in order to show that a zone can be composed of several separated areas.

decision has to be taken, these data give precious information about all the impacts and the consequences of the considered project. However, this improvement in information also produces difficulties. Decision-makers need to be well informed, but they also need synthetic information to make a choice. So, GIS have to be combined with multicriteria analysis methods, which are developed to realise this synthesis, to propose a complete decision support method in land management.

Among the set of multicriteria analysis methods, outranking methods seem particularly well adapted to this domain. Unfortunately, they are not able to manage more than hundreds of alternatives, which is very little when alternatives are defined as elementary surfaces. To avoid this important limitation in the choice of the multicriteria analysis method, we propose to define alternatives as homogeneous zones. These homogeneous zones are composed of a set of land units, which are close in respect to the criteria used for decision-making. Decision-makers give their own homogeneity definition by fixing a set of parameters. These parameters allow computing the degree of credibility of the closeness relation between the elementary surfaces and the global zone. Evaluation of this closeness relation uses similar principles to the valued outranking methods introduced by Roy (1996). If decision-makers adopt this type of multicriteria analysis method (for example, ELECTRE), the definition of alternatives as homogeneous zones offers a complete coherent process.

Homogenous zone construction introduces three new parameters in the decision support process (indifference, strict difference and veto). However, these parameters are analogous to those used in ELECTRE methods (indifference, preference, and veto). Therefore, to simplify the decision-makers involvement, the analyst can either choose the same value, or either deduce one set of parameters from the other set.

Fig. 9. Example of a land suitability map for housing.

Describing territory by a set of zones is not new in land management. Nevertheless, the approach proposed in this paper open up new areas, because the zones are not defined by census tracts or in respect to administrative limits, but as homogeneous zones based on the criteria chosen for decision-making. This way, there is no rupture between the alternatives definition and their comparison by multicriteria analysis.

In future research, it will be interesting to propose an approach that is able to solve cases where the decision-makers can not agree on a unique definition of homogeneity. This situation would impose the co-existence of multiples homogenous zones on the same surface. A similar problem could occur when land managers have to make several decisions and, for each of them, the set of criteria is different.

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