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Research Article

Using GIS and outranking multicriteria analysis for land-use suitability assessment

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Abstract. Land-use planners often make complex decisions within a short period of time when they must take into account sustainable development and economic competitiveness. A set of land-use suitability maps would be very useful in this respect. Ideally, these maps should incorporate complex criteria integrating several stakeholders' points of view. To illustrate the feasibility of this approach, a land suitability map for housing was realised for a small region of Switzerland. Geographical Information System technology was used to assess the criteria requested to define the suitability of land for housing. An example dealing with the evaluation of noise levels illustrates the initial steps of this procedure. Because the required criteria are heterogeneous and measured on various scales, an outranking multicriteria analysis method called ELECTRE-TRI was used. However, using it to assess the suitability of any point in a territory was impractical due to computational limitations. Therefore, a mathematical function to evaluate closeness relationships and classify the study area into homogeneous zones was used. This function is compatible with the outranking function of ELECTRE-TRI used to assess the suitability index. The resulting maps lend efficient support to negotiation and are very useful in dealing with inherent conflicts in land-use planning.

1. Introduction

During the last few decades, governments in many countries have spent a considerable amount of money to develop large geographical databases describing their territories. Planners already commonly use and access land management documents in electronic format (e.g. plans, laws, regulations, cadastral and topographical data). These data sets have reduced delays in decision-making. Furthermore, they have improved coordination between ongoing projects in the same territory. The availability of readily accessible land information data was anticipated by several authors (Dueker and Barton 1990, Scholten and Stillwell 1990).

At the same time, land planning has become increasingly complex. The principles of sustainable development confront land planners with a paradox of two apparently contradictory objectives: nature conservation and economic development (vanLier 1998). Furthermore, land planning, which previously involved only planners and developers, has now moved into the public arena where different lobby groups also promote their points of view. NIMBY (Not In My BackYard) and LULU (Locally Unwanted Land-Use) controversies illustrate the difficulties that often arise when a development project significantly modifies its surrounding environment (Couclelis and Monmonnier 1995, Wexler 1996, Jankowski and Stasik 1997). In this new situation, planners face a double challenge. First, they must design projects and plans that maintain an ecological equilibrium but nevertheless contribute to economic growth. Second, they must be mediators trying to avoid opposition and reduce objections. These are mandatory prerequisites for the social acceptance of land planning procedures (vanLier 1998).

Progress in computing sciences, including Geographical Information Systems (GIS) and Multi Criteria Decision Analysis (MCDA) can help planners handle this complexity. The recent literature is replete with proposals combining GIS and MCDA which meet the above mentioned objectives either partially or entirely. An extensive literary review of this area of research is beyond the scope of this paper. Instead, a set of contributions concerning three areas of application of land planning has been reviewed: location choice, land suitability assessment, and collaborative decision support systems.

Choosing an appropriate location for an activity or a facility is obviously related to decision support and MCDA. The problem can be generalized as a question of what must be done and where it should be realized. The purpose of planning (what) can involve a hospital (Malczewski and Ogryczak 1990, Malczewski 1991), a solid waste transfer station (Gil and Kellerman 1993), or more generally, any type of public facility (Joerin 1995, Yeh and Hong 1996). In a series of two articles, Malczewski and Ogryczak (1995, 1996) clearly define the multiple criteria location problem. They also compare the advantages and the disadvantages of different MCDA methods. Localization problems have also been treated with a more intensive use of GIS. Carver (1991) uses GIS to evaluate various alternatives for nuclear waste sites. Then, he evaluates the effectiveness of three MCDA techniques used to compare scenarios in order to select the best one.

Land suitability assessment is similar to choosing an appropriate location, except that the goal is not to isolate the best alternatives, but to map a suitability index for the entire study area. Senes and Toccolini (1998) combine UET (Ultimate Environmental Threshold) method with map overlays to evaluate land suitability for development. Hall *et al.* (1992) and Wang (1994) also use map overlays to define homogeneous zones, but then they apply classification techniques to assess the agricultural land suitability level of each zone. These classification techniques can be based on Boolean and fuzzy theory (Hall *et al.* 1992) or artificial neural networks (Wang 1994). Combining GIS and MCDA is also a powerful approach to land suitability assessments. GIS enable computation of the criteria while a MCDA can be used to group them into a suitability index. Following a similar approach, Eastman *et al.* (1993) produced a land suitability map for an industry near Kathmandu using IDRISI® (a raster GIS) and AHP (Analytical Hierarchy Process) (Saaty 1990). Pereira and Dückstein (1993) have used MCDA and raster GIS to evaluate a habitat for endangered species. Finally, some other papers have focused on the technical aspects of combining GIS and MCDA (Jankowski 1995, Laaribi *et al.* 1996).

The request for tools supporting collaborative decisions has increased over the last few years. For example, the NCGIA (National Centre for Geographical Information and Analysis) led an initiative in this respect in 1995 (Densham *et al.* 1995, Carver *et al.* 1996). If collaborative (or negotiated) decisions are needed, computer-based Spatial Decision Support Systems (SDSS) are obviously appropriate. Discussions are easier because negotiations are not slowed down by technical difficulties and several alternatives can be quickly analysed and compared (Densham 1991). Collaborative decision problems can be analysed and supported efficiently with user-friendly computer systems combining GIS, multicriteria analysis techniques, and environmental modelling (Geertman and Toppen 1990, Fedra and Jamieson 1996, Fedra *et al.* 1996). Jankowski *et al.* (1997) have developed a Decision Support System (DSS) called Spatial Group Choice. This tool has three parts: spatial visualization, multicriteria decision making, and voting. The last module can be used, for example, for the selection of criteria and weighting methods as well as to choose between alternative ranking methods.

The research described in this paper focuses more on a decision support method than a decision support system. It aims at land suitability assessment. The project has been closely monitored and evaluated by a group of planners employed by the canton of Vaud (Switzerland). Discussions with them revealed that they need a very high level of software integration and a user-friendly interface to directly interact with a computer-based DSS. This option would have required a major investment in software development, which was neither the goal nor one of the research priorities. Furthermore, from the theoretical point of view, the risk of misuse and oversimplification seems quite high when DSS is used for land-use planning purposes.

For these reasons, a conceptual approach of decision support for land planning (MAGISTER) was developed. It provides a general framework for specialised SDSS (§ 2). Furthermore, the link between GIS and MCDA was investigated, focussing in particular on outranking methods. This type of methods has seldom been combined with GIS, despite its suitable properties for spatial decision support (§ 5). The findings have been applied to the development of a land suitability map for housing. As explained in § 5.1, the originality of this method is the use of homogeneous zones to describe the study area. This avoids a threshold effect on land description and also keeps the final results independent of this spatial districting.

2. MAGISTER model

MAGISTER (**M**ulticriteria **A**nalysis and **GIS** for **Ter**ritory) is a decision support model suited for land planning (Joerin 1998). Its main objective is to help land planners to 'translate general policy statements into concrete localisation decisions' (Geertman and Toppen 1990). MAGISTER's framework is similar to DSS and SDSS (ten Velden and Kreuwel 1990, Densham 1991). It includes three main components: a database management system, a set of models, and a module for the evaluation and selection of the alternative solutions (figure 1). The database management system is a GIS, which manages the geographical database (GDB) describing the study area. Simulations may be done with hydrologic models, air quality models or demographic models depending on the decision-making domain. Spatial analysis is the main technique used to evaluate the quality of the alternatives, which are selected or sorted using MCDA.

MAGISTER is not a software package but a conceptual combination of tools to assist land-planners. This open framework should facilitate the social acceptance of the decision support process (Wexler 1996, Jankowski *et al.* 1997, Dente *et al.* 1998). In this way, the involved actors are not faced with a predefined system, but can control choices related to the models, the software, etc. Thus, the decision support procedure is specifically adapted to the context (geographical region and scale) and to the given problem (e.g. water management and highway planning).

MAGISTER enables and promotes the participation of all actors (e.g. decision-makers, neighbours, and lobby-groups) and experts (scientists using GIS, models, and MCDA) in the decision process. The experts can be considered as a link (a translator) between the land and the stakeholders who are managing and/or using a given territory. They should ensure an efficient use of all the available data, models, software and theoretical knowledge in order to help the Decision-Makers (DMs) to consider and compare available solutions or alternatives. Ideally, experts should be neutral relative to the decision-making procedure, in order to avoid a technocratic decision that would be very difficult to defend socially (Dente *et al.* 1998).

Decision-makers and other actors should be allowed to validate each important step in the decision support process. They should spend the necessary time and effort

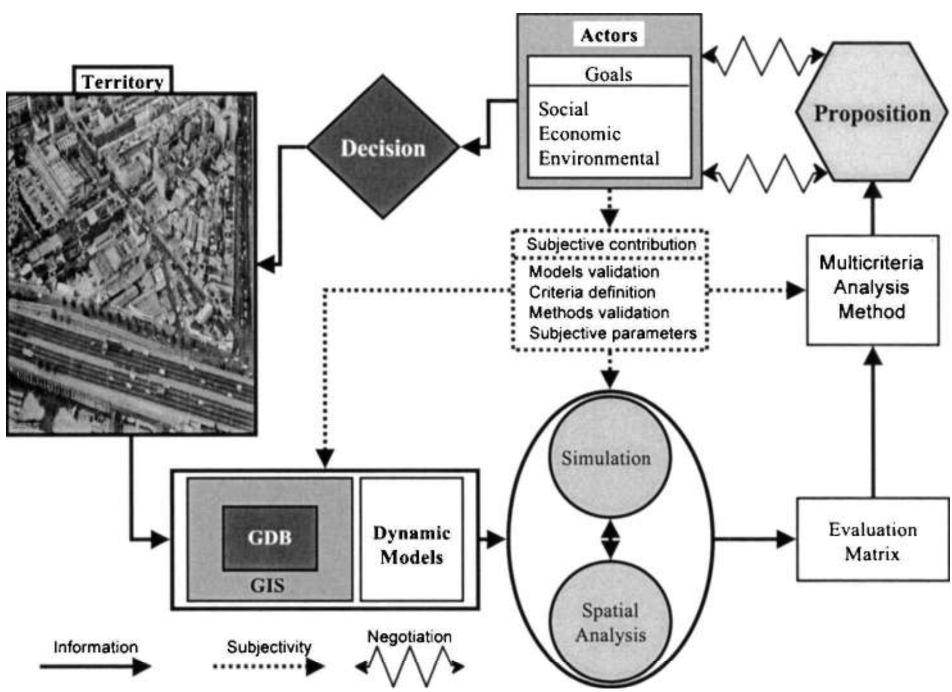

Figure 1. MAGISTER model. The 'subjective dashed arrows' illustrate the actor's roles in the decision process.

to clearly define the problem. For example, they should answer questions about: the real issues, the influential actors, the alternatives and the criteria. They also have to agree to the precision level, the geographical area, etc. (Pictet 1996). It is clearly very difficult, and sometimes impossible, to answer all these questions in the preliminary phases of the decision process. Thus, these questions and answers should be reconsidered in an iterative manner during the entire procedure.

This problem-structuring phase is also used to design the model needed to support decision-making. The different actors should then validate the model with respect to their particular points of view and objectives. This validation can also be applied to the geographical database. For example, if a stakeholder wishes to protect a specific flower variety, he should verify that the spatial distribution of this species is correctly handled in the database. In the same manner, the stakeholders could also be consulted about the simulation models and the spatial analysis procedures (Carver *et al.* 1996).

The choice of the MCDA method is very important since it has a significant effect on the final outcome. It is therefore necessary to discuss this point with all the actors. MCDA's characteristics and properties should be compatible with the specific nature of the decision problem (Laaribi *et al.* 1993, Vincke 1995, Laaribi *et al.* 1996, Salminen *et al.* 1998). For example, some MCDA techniques efficiently handle a continuous set of alternatives and criteria belonging to the same domain (e.g. economic). Other MCDA methods can only consider a small set of discrete alternatives but are more efficient to handle heterogeneous criteria (Schärlig 1985, Belton 1990). Section 5 discusses this specific aspect of the decision procedure in more detail.

If there is a conflict between the various actors, they can negotiate the subjective parameters, like the weights associated with each criterion before adopting a common set of values. It is also possible to repeat the MCDA process and thus select, for each different group of stakeholders, a solution that is adapted to its specific needs. MCDA's results can be mapped in order to display the spatial extent of the best areas or index of land suitability (see § 5.2). The negotiating parties can then discuss and compare the results by overlaying these maps, which are in fact geographical representations of their own set of preferences.

3. Land suitability

Combining GIS and MCDA for land planning involves many tasks including data gathering and structuring, and computation of criteria using spatial analysis and simulation. Due to temporal and financial constraints, such a procedure can only be done for major projects of regional importance and/or for long term planning purposes (Malczewski and Ogryczak 1990, Carver 1991, Massam 1991). It is also necessary to maintain an acceptable ratio between cost of planning and analysing a project and its overall cost or importance.

Generally, land planning departments are quite open to the idea of using GIS and MCDA. However, in most cases, they are not able to do it due to time constraints. Even when there is a high risk of significant impacts, a small set of scenarios are compared and they are not analysed in detail.

In such a situation, land suitability maps could help planners (Dueker and Barton 1990, Geertman and Toppen 1990, Wang 1994). These maps should integrate all the relevant data for the analysis of the given territory. While a significant amount of work would be necessary to develop these types of maps, they would be useful for several years and many decisions. Updating the maps would surely require much less work than was initially required to produce them.

A procedure that uses MAGISTER in land suitability assessment (figure 2) has been developed. This procedure could be applied by a land planning department to produce land suitability maps for the most important land-uses (e.g. housing, manufacturing, agriculture). Obviously, the initial developmental phase should be undertaken without a tight deadline linked to a particular project. Once the maps are available, land planners could analyse any new project by using simple operations such as map overlay or statistical analysis on a given area.

The development of land suitability maps also presents an opportunity for all governmental departments involved in land management to compare their points of view and coordinate their policies. Furthermore, subject to the agreement of the DMs, all the interested stakeholders (e.g. the public, construction enterprises, environmental NGOs) could also be involved in the procedure. In such a case, the land suitability maps could be widely accepted and the population at large would more easily endorse decisions based on these maps.

A land suitability map for housing was built for a rural area in the canton of Vaud (Switzerland). Its total area is approximately 50 km^2. The most important town is Cossonay (about 2000 inhabitants). The database was developed in two GIS; one using vector format (MapInfo®) and the other one using raster format (IDRISI®). The vector format was mainly used for data management and querying whereas the raster format was used for most spatial analysis. In the raster GIS, the study area was represented by 80 000 elementary land units. These units are represented by pixels, each covering 625 m^2 (i.e. 25 m × 25 m).

The structuring phase includes the identification of all the actors, criteria and alternatives (figure 3). Because criteria identification is often a difficult task for DMs, a systematic analysis of all factors potentially influencing suitability for housing was undertaken (Joerin 1998). DMs can examine the resulting list of thirty factors and select those that seem relevant and important. The factors are then checked against

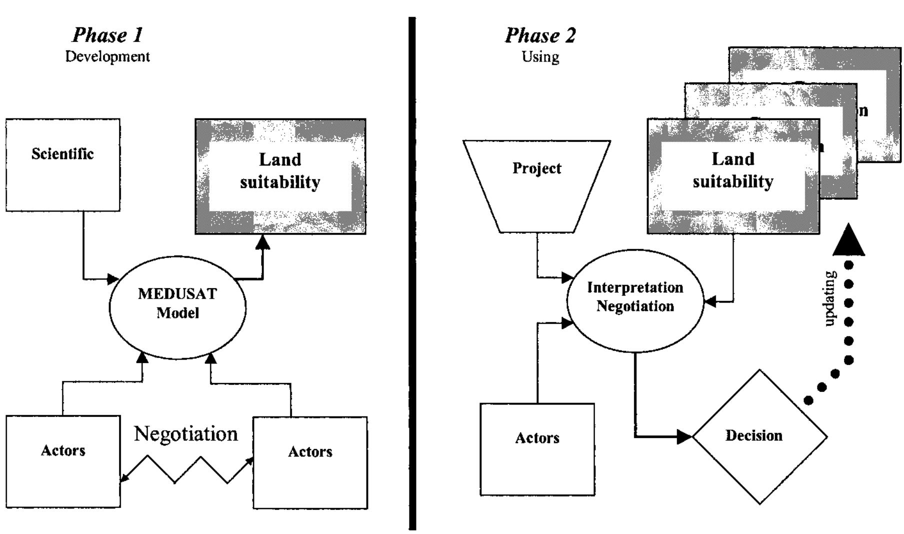

Figure 2. Land planning and management by using land suitability maps (MAGISTER is MEDUSAT in French).

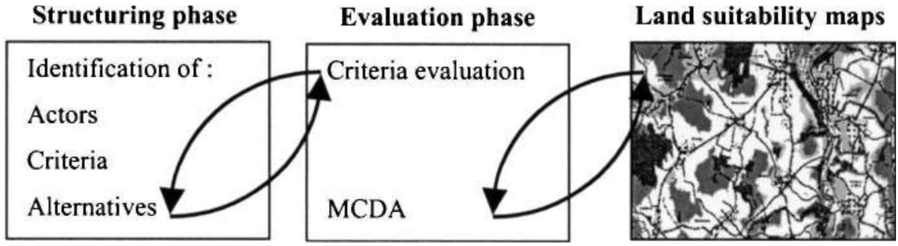

Figure 3. Main steps used to build a land suitability map.

the available data and the spatial resolution. With the agreement of DMs, some factors may be ignored because they are irrelevant in the region (e.g. there is no serious flood risk in the test area), whereas others may be merged because they basically deal with the same aspect. For example, distance to specific services (e.g. schools, recreational areas, and shopping centres) can be replaced by a surrogate criterion such as 'distance to the nearest town', when the specific locations are unavailable. For the application in the canton of Vaud, eight criteria were retained:

- *impacts* on a nature reserve, landscape, and water table
- *air pollution coming* from a waste water treatment plant, dumps, and a highway
- *noise* due to traffic
- *accessibility* measured by the estimated time needed to reach a workplace in the morning
- local *climate*: sunshine, temperature, and fog
- risk of *landslide*
- *distance* to localities and public facilities such as water supply, electricity, etc.
- *viewpoint* quality estimated from the view shed.

Selecting criteria from a list of factors should be an important step for the negotiation between actors. Some criterion will be retained by all of them, but others are only significant for certain actors. In this case, the DMs have to continue the discussion until they obtain a list of criteria that satisfies everybody. Economical aspects also have to be considered in this step. Each criterion evaluation needs data collection and analysis, leading to a substantial cost.

It is also important to remember that the purpose is to assist DMs by providing them several suitability maps, one for each main land-use. Each of these suitability maps would be based on its own list of criteria. So, these criteria lists have to be coordinated. For example, soil fertility should not be included in the suitability criteria for housing. Instead, this factor should be put aside and used only for agriculture. This avoids imbalance problems related to the overestimation of a factor's effect, when suitability maps are overlaid.

4. Generating criteria maps

Each criterion was evaluated using a different set of data, at an appropriate scale, and with a specific model. For most of the criteria, spatial analysis procedures using a raster GIS were an important part of the evaluation process. Evaluation of the noise criterion gives a good example of the processing complexity needed to obtain representative values over the studied area. The aim is not to improve noise assessment or modelling but to integrate it in a GIS for impact evaluation purposes.

Although its evaluation can not be compared to a specialised acoustic study (Stratec 1992, ECOTOX 1998, Weixiong *et al.* 1998), it does emphasise the compromise that must be accepted when the study is carried out at the regional scale. In Switzerland, the relationship between noise and housing is governed by laws (OPB 1986). Briefly, restrictions apply simultaneously to the source (e.g. the road) and to the receiver. The law defines four noise levels, and land-use must comply with the prescribed levels. A new hospital can only be planned in the quietest category. Conversely, if a new highway is to be built next to a hospital, it must provide noise mitigation infrastructure.

Many countries have developed their own methods for traffic noise simulation (OECD 1995). The Swiss Federal Environmental Protection Office uses a model coupled with software to 'standardise' the assessment of noise levels (OFEFP 1987). Its general structure is similar to most other noise simulation models (OECD 1995). Noise immissions are computed from noise emission levels using specific corrective functions (see §4.1 and §4.2).

An accurate evaluation of noise levels must take into account many parameters and a precise description of the receiving environment. Furthermore, traffic noise also depends on non-predictable parameters such as meteorological conditions and the type of vehicles. Thus, accurate noise simulation models need a very large data set and a lot of computing power. For land-use planning purposes, where the surface area of the studied zone is often very large, an accurate evaluation is not possible. So, in spite of their importance, noise impacts are generally left out during land-use planning, except when simulation or measurements are already available.

The most important parameter in computing noise propagation in rural regions, like the considered study area, is topography. The use of GIS and spatial analysis has opened new prospects in this field. In particular, raster-based GIS may be readily applied to analyse natural topography using digital elevation models. In this manner, all elementary surfaces or receivers are described and treated simultaneously. Thus, using a GIS-based approach, the general methodology proposed in the official Swiss documents (OFEFP 1987) can be applied without a detailed description of all the receivers. It also does not require time-consuming computations (Joerin 1998).

Obviously, this method makes quite important simplifications. The resulting noise maps do not have the same quality as specific noise studies, which use specialized tools (models combined with measurements). However, these maps are still adequate for land-use planning, where the goal is not to obtain a precise assessment of noise levels, but rather to compare relative levels of noise pollution within a given area.

4.1. *Assessment of emission levels*

The most important noise sources in the study area are linked to road and railway traffic. Noise emission levels due to road traffic depend on traffic density (number of vehicles/hour) and road slopes (OFEFP 1987) (see appendix 1). Traffic density comes from the *Service des Nuisances de l'Etat de Vaud* which regularly monitors noise emissions. This data set includes data subsets for trucks, cars, and motorcycles.

Noise from railway traffic is a function of the type and frequency of trains. Normally, assessment of emission levels is quite difficult. However, for the purposes of this study, the Swiss Railway Company has provided noise emission values in decibels for the most important railway lines.

4.2. *Assessment of immission levels*

Noise immission levels are computed from noise emission, making adjustments for absorption by physical obstacles, air or ground, and by reflection (equation (1) and appendix 2). These corrections generally reduce the noise level. However, they may, in some circumstances, increase them to take into account sound reflection on obstacles (OFEFP 1987). Detailed information about these corrections and the general procedure for noise assessment can be found in OFEFP (1987), Joerin (1998) and Azouzi (1998).

$$I = E + \Delta L + \Delta A + \Delta R + \Delta\phi + \Delta B + \Delta H \quad (1)$$

where I: Immission (dB); E: Emission (dB); ΔL: Correction for distance (dB); ΔA: Correction for air absorption (dB); ΔR: Correction for reflection (dB); $\Delta\phi$: Correction for opening angle (neglected) (dB); ΔB: Correction for soil effect (dB); ΔH: Correction for obstacles (dB).

Corrections are computed by analysing the sound wave path between the noise source (i.e. roads or railways) and the receivers (here the pixels). Noise immission at one point generally results from multiple sources (e.g. several roads and a railway line). A precise computation should compute the specific contribution of each source (equation (1)) before aggregating them using a logarithmic addition (appendix 3).

To simplify the evaluation, the sum of all the sources of noise for each receiver (each pixel) was not computed, but only the immission due to the nearest source. With such a simplification, the propagation of noise emission can be computed using Voronoï polygons (Voronoï 1908, George and Bourouchaki 1997). The network of roads is described with a set of 100-metre-long linear segments. Each segment is associated with two Voronoï polygons, one on each side of the road (see figure 4).

This simplification could produce significant errors if, for instance, a location close to a road with low traffic noise is also not far from a road with much higher

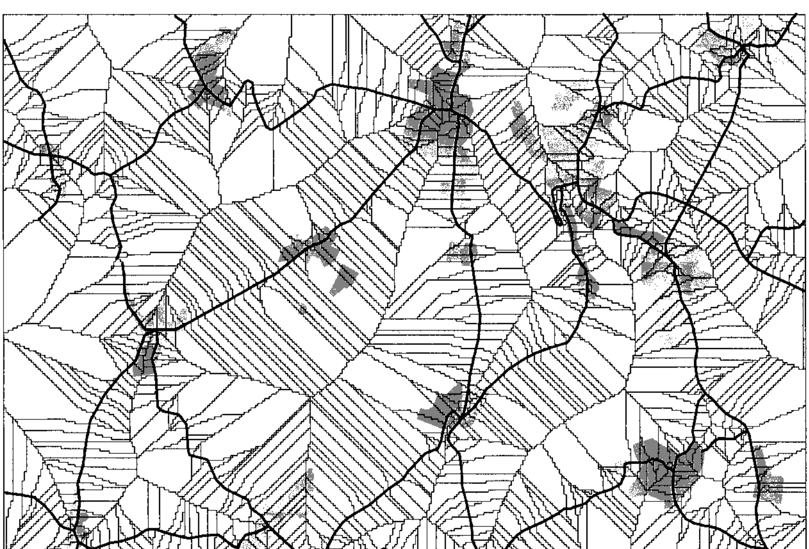

Figure 4. Noise propagation using Voronoi polygons. The road network is described by 100-m long segments. Each of them is associated with two polygons, one on either side of the segment.

traffic noise. To avoid these possible errors, the noise assessment was repeated with four different categories of noise sources: roads with high traffic, roads with low traffic, highways and railways. Noise levels were computed separately for each category and the results cumulated using a logarithmic addition. This computation yields fairly good results, when the line segments and the Voronoï polygons are small.

4.3. *Mapping the noise levels and the noise criterion*

The mathematical operations required to evaluate the emission and the immission levels have been realised with IDRISI® 4.0. This raster-based GIS is organised as a set of partially independent modules. A macro language allows successive calls to these modules in order to realise procedures. Several procedures of this type are used to compute the noise map. Once the necessary database is developed and organised, computations can be carried out in a few hours. Figure 5 shows the final computed immission levels using the road network (with highways) and the railway lines as the only sources of emission.

It is important to point out that these values must be interpreted at the regional scale. It would be inappropriate to use this map to assess the noise level at a very specific location, such as a given house in a village. Even a small wall in front of the house could completely modify noise propagation and change the immission levels.

In a study of error propagation, Azouzi (1998) has shown that this method of evaluating noise levels is reliable for land-use planning purposes. The standard deviation of the computed noise level is lower than 3 dB (A), for 95% of the study area (see figure 6).

Noise immission levels do not evaluate the noise criterion directly. In fact, land

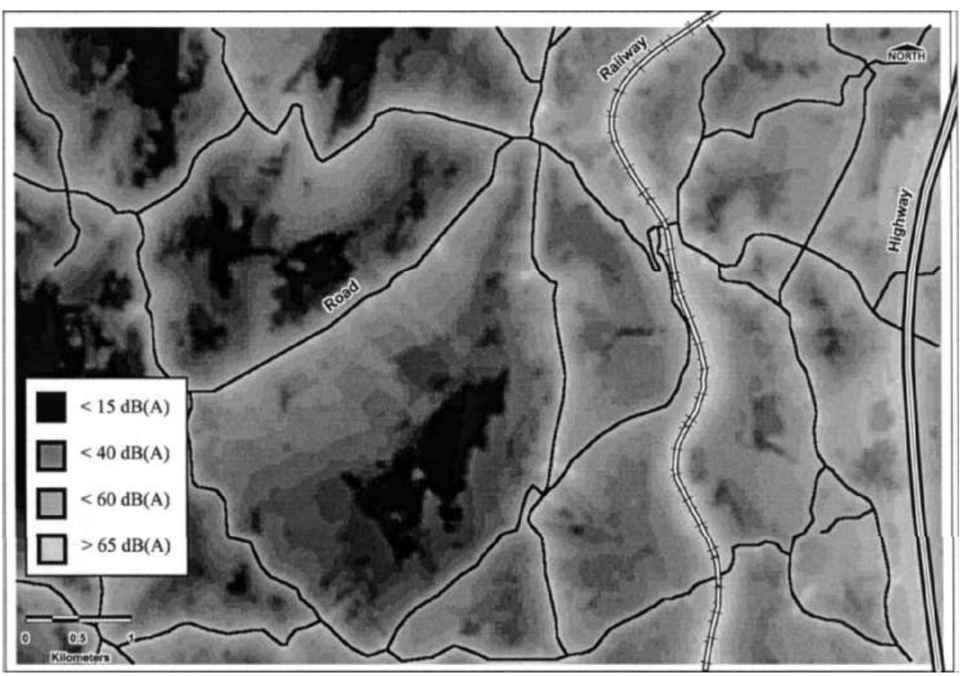

Figure 5. Final map of immission due to transport activities. Grey scale shows different levels of noise.

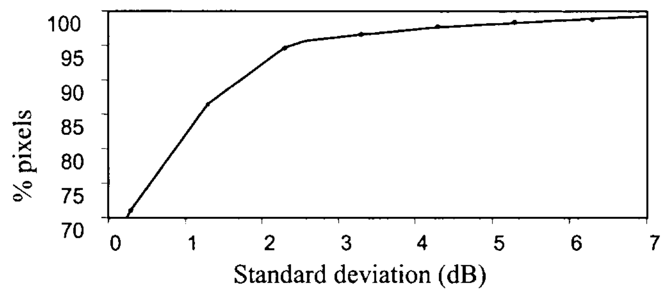

Figure 6. Cumulative frequency of pixels and standard deviation for immission (produced with data from Azouzi (1998).

suitability for housing is not a linear function of noise. An area with an immission level of 10 dB (A) is not really quieter, and thus more suitable than an area with a level of 30 dB (A). This difference between the noise criterion and the computed immission value corresponds to the distinction that should be made between an observed phenomenon and its perception in a specific decision-making process (in this case land suitability for housing). Similar differences have been noticed for almost all criteria used in this study. Fuzzy set theory is an adequate way to integrate a subjective perception within the definition of a criterion. It enables the definition of criteria using a membership function linked to favourable conditions for housing (e.g. absence of nuisances, and good climate). The membership function that identifies quiet areas was defined using threshold values fixed by federal legislation (in Switzerland) related to noise impact (figure 7) (OPB 1986). Application of this function to the immission values (figure 5) produces an index between 0 and 1. It evaluates land suitability for housing with respect to noise impact (figure 8).

Obviously, these analytical procedures assessing noise immission levels due to transportation activities could be improved to yield a better level of precision and higher reliability. However, it should be remembered that land planners do not need a very precise computation, but rather a good evaluation that is cost effective. For this reason, detailed error propagation studies would be very helpful. This sensitivity analysis would probably highlight procedural steps to improve and others to simplify.

5. Suitability index

Criteria modelling produces a set of maps, one for each criterion, on which the score for each elementary surface is indicated. The next step is to aggregate the partial suitability indexes into a holistic suitability index. This aggregation can be realized with a multicriteria decision analysis method. There are many MCDA methods, but two main categories can be considered: methods using a complete

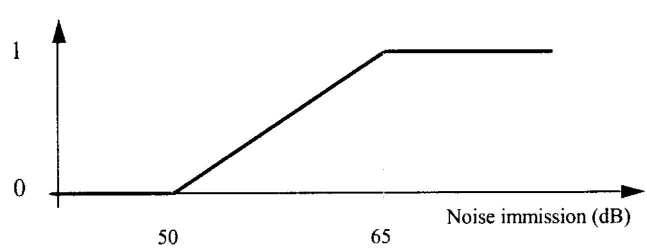

Figure 7. Membership function for a quiet area.

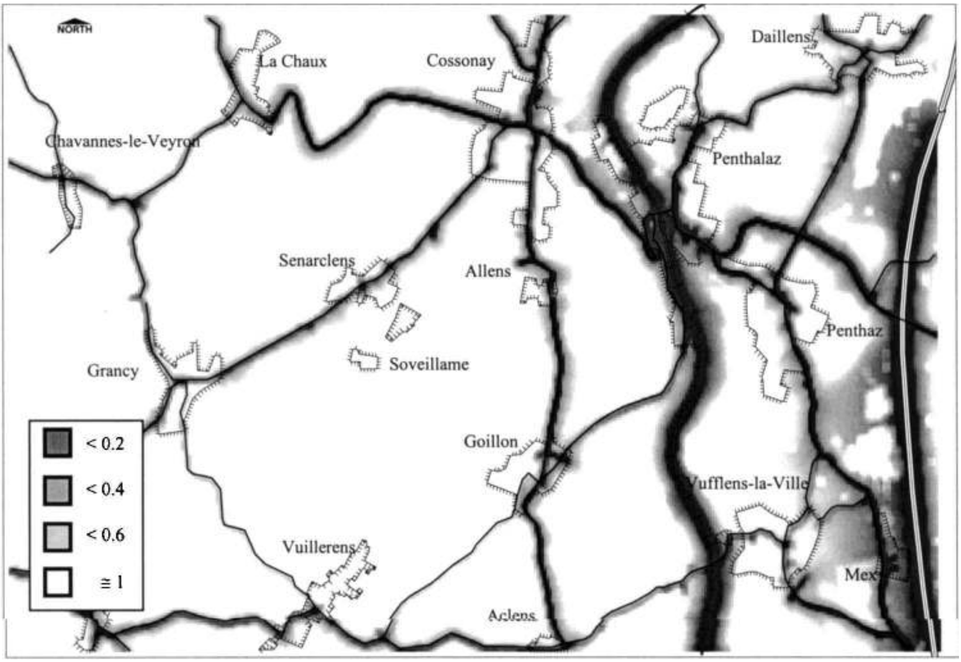

Figure 8. Map of noise criteria. Grey scale represents the suitability index considering noise immission. Clearer areas are more favourable to housing.

aggregation, such as MAUT (Keeney and Raiffa 1976), UTA (Jacquet-Lagrèze and Siskos 1982) and AHP (Saaty 1990), and methods using a partial aggregation, like ELECTRE (Roy 1985) or PROMETHEE (Brans *et al.* 1984). The latter are called outranking methods.

Outranking methods are well suited for land planning purposes. They can handle simultaneously qualitative and quantitative criteria. Criteria scores can be left in their own units, which is important when they are related to diverse domains (e.g. economics, ecology and sociology). This avoids questions like 'What is the price of loosing this plant species?' Furthermore, in land planning, alternatives can be very different. For example, it happens frequently that an alternative has a lot of economic advantages and serious environmental impacts, while another presents the opposite characteristics. In such a case, DMs may be unable to rank them. These alternatives are thus considered as incomparable, and outranking methods are the only methods that can take into account this situation (Belton 1990).

Using the terminology of MCDA, an alternative is an object, which has to be evaluated, compared, or ranked. In a land suitability study, each location represented by an elementary surface should be associated with a suitability index. This implies that each land unit could be considered as an alternative, yielding a huge number of alternatives to compare (80 000 pixels in our study area). Unfortunately, outranking methods are not able to compare a lot of alternatives. In other words, outranking methods seem inappropriate for land suitability assessment (Pereira and Dückstein 1993, Eastman *et al.* 1993, Jankowski 1995).

This limitation in the choice of the MCDA methods has significant consequences. No existing method seems efficient for all kinds of decision-making applications

(Guitouni and Martel 1998). Furthermore, as already mentioned, the choice of a MCDA method is part of the problem structuring phase, and the DMs must fully agree with the chosen method. The decision support method is quite useless if the actors do not trust the procedure that is applied to compare the alternatives.

For these reasons, the feasibility of outranking methods for land management purposes and land suitability assessment was analysed. The chosen method is ELECTRE-TRI (Roy 1981a, b, Roy 1985).

In land suitability studies, outranking methods can be applied if the study area is divided into zones. These zones are fewer than the elementary surfaces or pixels, and they provide a manageable set of alternatives (Hall *et al.* 1992, Wang 1994). Nevertheless, this operation has important disadvantages. First, the resulting maps are very sensitive to the spatial division. Second, as the number of zones is limited, the description territory becomes quite rough, resulting in a substantial loss of information.

In order to solve this dilemma, a modified definition of what constitutes an alternative in a land suitability study is proposed. From our point of view, an alternative does not only correspond to a sufficiently large area (to build houses in our case), but it must also correspond to a particular solution. This additional condition enables the grouping of sub-regions (such as pixels) which have a similar score with respect to the criteria defined for the decision-making. Alternatives thus become zones, which are *homogeneous* with respect to the decision that has to be made. As explained in the following section, assessment of the homogeneity may be computed using similar processes as those applied in the outranking method called ELECTRE. Therefore, these homogeneous zones bridge the gap between GIS and outranking methods in land suitability assessment studies.

5.1. *Homogeneity index*

The grouping of elementary units into homogeneous zones is based on the use of a homogeneity index. A zone is declared homogeneous when every elementary area composing the zone has a score, which is close to the average characteristic score of the zone. This closeness relationship is evaluated using a function defined by Slowinski and Stefanowski (1994) to create rough classifications based on rough set theory (Pawlak 1991, Slowinski 1992) (table 1). This function uses the differences between the score of the elementary surface and the average scores for the entire zone, computed for each criterion. These values are then compared with a set of indicative values chosen by the DMs. The set of values (which correspond to subjective parameters) define: indifference (q_i), strict difference (p_i), and veto (v_i) for each criterion (table 1). A complete description of this homogeneity evaluation procedure can be found in Joerin and Musy (1998).

Zone formation (pixel clustering) begins with a classification based on the set of criteria maps (figure 9). This operation can be done by an ordinary classification algorithm (unsupervised classification) (Sneath and Sokal 1973, Everitt 1993). Then, the different classes are separated with respect to the discontinuous spatial limits, such as administrative limits or landslide perimeters. These sub-classes are called zones. The equation given by Slowinski and Stefanowski (1994) is then applied to compute the degree of credibility of the closeness relationship between each elementary surface and the entire zone. The homogeneity index is the smallest degree of credibility of the closeness relationship between the entire zone and all the elementary surfaces that make it up. To be considered homogeneous, a zone must have an index

Table 1. Formula and variables used to compute the closeness relationship between two elements A and B characterized by their scores in the set of criteria.

Formula	Variables used
$A: [N_{a,1}, N_{a,2}, \ldots, N_{a,n}]$ $B: [N_{b,1}; N_{b,2}; \ldots, N_{b.n}]$	A: element A B: element B $N_{j,i}$: score of element j for the criterion i.
$r(A,B) = C(A,B) \cdot \prod_{i \in 1} \frac{1-d_i(A,B)}{1-C(A,B)}$	$r(A,B)$: Degree of credibility of closeness relationship between A and B. $r(A,B) \in [0;1]$.
$I = \{i: d_i(A,B) > C(A,B)\}$	$C(A,B)$: Global concordance. $C(A,B) \in [0;1]$ $d(A,B)$: discordance index on criteria i. $d_i(A,B) \in [0;1]$
$C(A,B) = \frac{\sum_{i=1}^{n} w_i \cdot c_i(A,B)}{\sum_{i=1}^{n} w_i}$	w_i: weights on criteria i. $w_i \in [0;1]$ $c_i(A,B)$: concordance index on criteria i. $c_i(A,B) \in [0;1]$
$c_i(A,B) = \begin{cases} 1 & \text{if } Xi < q_i \\ \frac{p_i - X_i}{p_i - q_i} & \text{if } Xi \in [q_i; p_i] \\ 0 & \text{if } Xi > p_i \end{cases}$	$c_i(A,B)$: concordance index, $c_i(A,B) \in [0;1]$ q_i: indifference on criterion i. q_i: in criteria units p_i: strict difference on criterion i. p_i: in criteria units X_i: Absolute difference between A and B on criterion i.
$X_i = \lvert N_{A,i} - N_{B,i} \rvert$	$N_{A,i}$: score of A on criterion i. $N_{B,i}$: score of B on criterion i.
$d_i(A,B) = \begin{cases} 0 & \text{if } Xi < p_i \\ \frac{p_i - X_i}{p_i - v_i} & \text{if } Xi \in [p_i; v_i] \\ 1 & \text{if } Xi > v_i \end{cases}$	$d_i(A,B)$: discordance index on criterion i. $d_i(A,B) \in [0;1]$ p_i: strict difference on criterion i. p_i: in criteria units v_i: veto on criterion i. v_i: in criteria units.

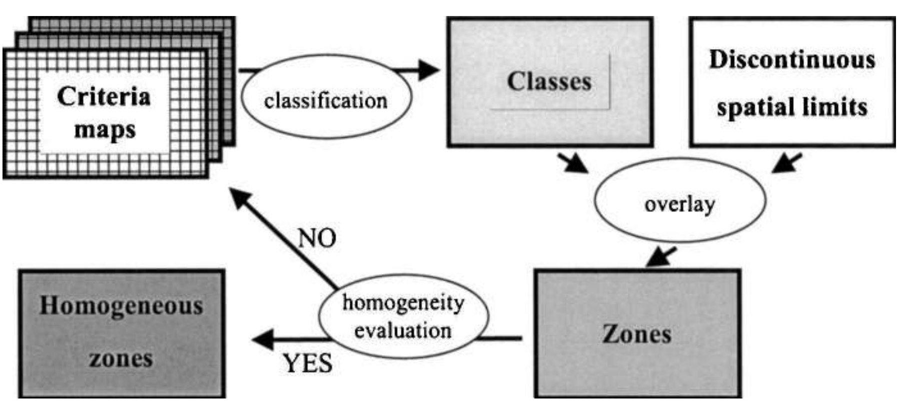

Figure 9. Procedure used to group the study area into homogeneous zones.

greater than a chosen threshold value. Increasing this threshold will increase the number of homogeneous zones. Obviously, their surface will also become smaller.

This process is based on a homogeneity definition, which is specific to the application's context. The DMs can contribute to this definition. For example, they could be asked for the greatest acceptable difference in a homogeneous zone, for each criterion. To answer these questions, DMs can use their (professional) experience and the uncertainties assessed with the criteria evaluation. These answers allow fixing the values of indifference, strict difference, and veto. The homogeneity threshold is chosen in order to obtain an acceptable compromise between the number of alternatives and the degree of precision.

By applying a homogeneity index threshold value of 0.8, 650 zones have been formed in the study area (figure 10). These zones make up the set of alternatives. Each zone has some attributes made up of its score with respect to the different criteria and its homogeneity index. The ability to consult at any time the homogeneity index of any zone constitutes a safety feature in the decision process. If during the MCDA, an area with a relatively weak homogeneity index is selected, one could find it useful to get more information on this region to improve its description.

5.2. *Suitability index assessment*

Detailed descriptions of outranking methods can be found in the literature (Roy 1981a, Schärlig 1998). However, as these methods are still quite new, it is useful to highlight their fundamental principles.

Outranking methods compare possible alternatives on a criterion by criterion basis. They basically compute an index for each pair of alternatives that qualifies or ranks one alternative relative to another. This index is called the degree of credibility of the outranking method. If a comparison is made between alternative A and B the index is calculated twice. The outranking degree of credibility of A over B is first

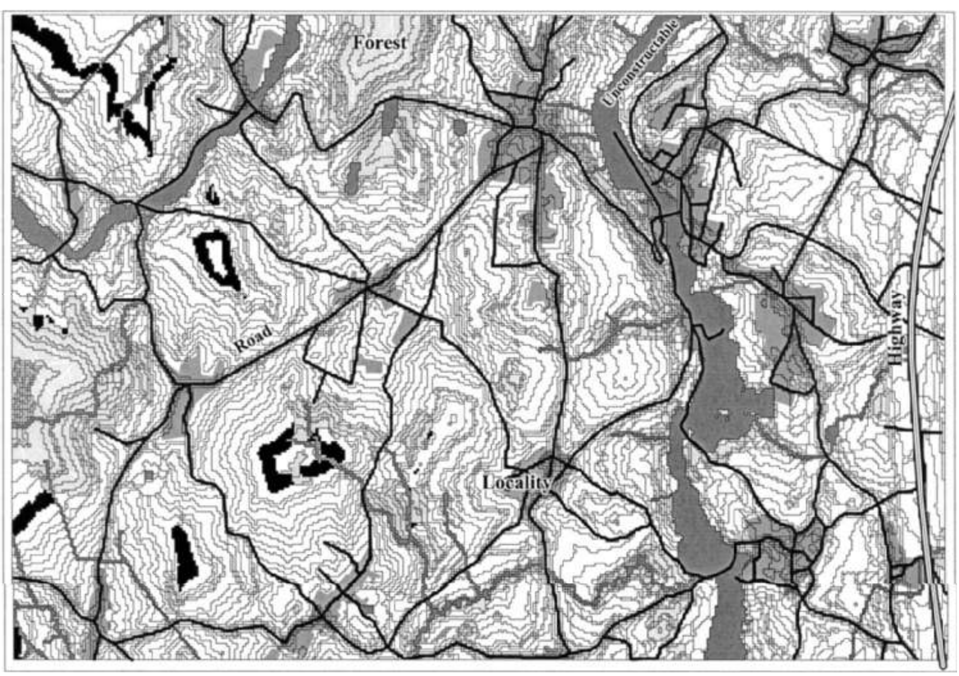

Figure 10. Map of the homogeneous zones. The area in black represents one homogeneous zone. It shows that a zone can be composed of several discontinuous polygons.

calculated, and then of B over A. If focus is on the relationship of A over B, the outranking degree of credibility (which has a value between 0 and 1) is estimated and used to assess whether the hypothesis: A is at least as good as B, is true. It is the product of two factors: the concordance and the discordance. The concordance is computed with the criteria where the score of A is at least as good as the score of B. The discordance factor is based only on the criterion with the most important difference in favour of B. If this difference is very big, there is a veto effect, and the discordance factor puts the degree of credibility at zero. Both values of the degree of credibility (A over B and B over A) define the relationship between A and B. Four relationships are possible: A is preferred to B, B is preferred to A, A and B are indifferent, or A and B are not comparable.

ELECTRE-TRI classifies the alternatives (the zones) according to predefined categories (Roy 1981a). In this study, three categories of land suitability are defined as favourable, doubtful, and unfavourable. To define this classification the DMs must assign values to a set of subjective parameters that express their preferences. The most important subjective parameters are composed of two sets of reference alternatives (zones). The good references give the limits separating favourable and doubtful suitability, whereas bad references define the limits among doubtful and unfavourable suitability. Each zone is compared with the two sets of reference zones. If a zone is clearly better than the good references, it is qualified as favourable. In an analogous way, it is unfavourable if it is clearly weaker than the bad references. A doubtful zone is not better than the good references, and not weaker than the bad ones.

Other subjective parameters are weight, indifference, preference, and veto, which are associated with each criterion. Weight expresses the relative importance of the criteria. Indifference is the largest value that may be considered insignificant. Preference is the smallest value constituting a clear advantage (Vincke 1992, Schärlig 1998). These parameters are very similar to those used in the homogeneity evaluation (see table 1). Thus, it is possible to re-use these values, even if DMs are nevertheless allowed to modify them.

The output of this MCDA is a map that can be immediately reviewed by the DMs. If they are not satisfied with the result, they can modify any of the subjective parameters to produce new maps. Priority should be given to redefining the set of reference zones, which are certainly the most sensitive parameters. If a conflict arises between the DMs, they can negotiate the set of subjective parameters. Building a consensus on subjective parameters should encourage acceptance of the final map by all stakeholders. However, DMs may sometimes prefer to develop their own version of a land suitability map, and then negotiate by overlaying their personal maps.

All data used by ELECTRE-TRI are stored in MapInfo® tables. The alternatives and reference zones are in tables linked with spatial objects. The weights and the three thresholds (indifference, preference, and veto) associated with each criterion are stored in a non-spatial table. It is quite simple to program the ELECTRE-TRI algorithm in the MapBasic® language, allowing to run the multicriteria analysis inside the GIS.

This integration allows the realization of the entire procedure while keeping the link with the spatial dimensions of the decision. The reference zones can be directly selected from the maps describing the study area. This geographical interface has been tested with a group of public sector land-planners. The study area was presented

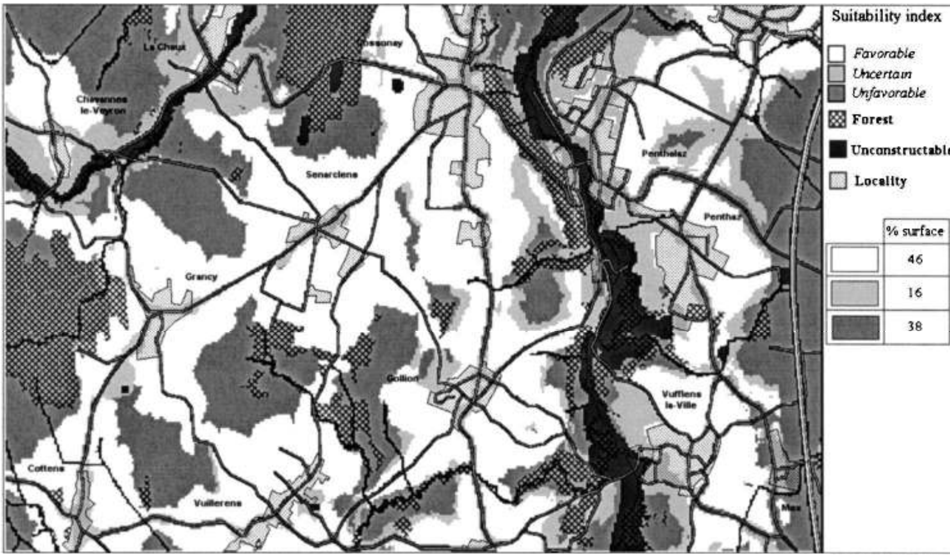

Figure 11. Example of a land suitability map for housing.

using a classical topographical scanned map (1/25 000). All data concerning the zones were displayed in the background. Planners can move around the region using their geographical knowledge to choose the references zones. When a zone is selected with the mouse, it appears along with its attributes. If the planner decides that this zone could be a reference zone, it is then simply copied into the reference zone table.

The above mentioned test and the maps obtained met nearly all the actors' expectations (figure 11). This suggests that even if some improvements might be necessary, this approach could efficiently support the current tasks of a governmental land-planning department. It is important to emphasise that this electronic land suitability map is much more useful than a paper map. All the information ranging from primary data to synthesised (integrative) indexes may be consulted at any time. If, for example, a zone has a weak suitability index, the responsible criterion may be readily identified. It is possible to investigate the underlying reasons in order to find factors that explain the low score for a given criterion. In the end, DMs get a comprehensive decision support tool and can debate the reasons behind a given decision. This is a fundamental advantage whenever a decision process requires negotiation. Finally, the suitability maps are valuable tools that may be used to analyse and understand territorial dynamics and structure.

6. Conclusion

Land-use planning can certainly benefit from new technologies such as GIS. However, improvements in data access and analysis are critical issues for land planners. Sometimes, they are overwhelmed with data analysis, making subsequent decisions difficult. Thus, DMs do not only need accurate raw data, but also holistic information.

MAGISTER is a decision support procedure using GIS and MCDA. It satisfies the descriptive and analytical needs of land planners, as well as the necessary integrative data syntheses. GIS is used for the detailed analysis of the spatial decision context whereas MCDA is applied to compare the set of identified alternatives.

An application of this decision support model has shown its usefulness for land planning purposes. Land planners must often make complex decisions within a short period of time. A comprehensive set of land-use suitability maps would be very useful in this respect. Ideally these maps should integrate heterogeneous data and, with the consent of the decision-makers, all the different stakeholders' points of view. To validate our approach, a land suitability map for housing has been developed for a small region of Switzerland. The suitability index integrates eight different criteria. Each criterion required a considerable amount of data and complex analysis procedures. An example dealing with the assessment of noise levels illustrates the use of GIS for computation of criteria. It highlights the methodological compromises that must be made when evaluations are performed at the regional scale.

To compute the suitability index based on these criteria, the ELECTRE-TRI procedure was added to a commercial GIS package (MapInfo®). ELECTRE-TRI is an outranking multicriteria method that efficiently classifies scenarios into ordered categories.

Although outranking MCDA methods have useful properties for land planning purposes, they have seldom been combined with GIS. To the best of our knowledge, they have not been used for the evaluation of land suitability. This fact can probably be explained in two points. First, as an index value has to be mapped everywhere in the study area, the number of alternatives is generally very high for land suitability assessment. Second, outranking methods have difficulties dealing with more than a hundred alternatives. To avoid this methodological limitation, a mathematical function, evaluating closeness relationships among land units, was used to divide the study area into homogeneous zones. This function mimics the outranking function used by ELECTRE-TRI to assess the suitability index for the entire region. Thus, a complete coherent decision support method, starting from the definition of the criteria and the alternatives and ending with the final suitability map, was developed.

This system provides an efficient method to produce land-use suitability maps based on complex evaluation criteria. It may greatly facilitate negotiations between land-users and other stakeholders. Using the resulting set of suitability maps, one for every possible land-use at a specific location, planners may quickly compare scenarios. Hence, they can make decisions with good knowledge of the impacts as well as the inherent constraints on future developments. Finally, the analysis procedure favours negotiation with respect to both stakeholders' objectives and constraints, which should make it an excellent tool for the promotion of democratic decision-making in the field of land planning.

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Appendix 1

Calculation of noise emission LE_i dB (A).

Cars	Trucks and motorcycles	Variables used
$E_1' = 12.8 + 19.5 \times \log(V_1)$	$E_2' = 34 + 13.3 \times \log(V_2)$	V_i: traffic speed (km/h)
$E_1'' = 45 + 0.8 \times (I - 2)$	$E_2'' = 56 + 0.6 \times (I - 1.5)$	I: slope of the route (%)
$E_1 = \max(E_1', E_1'')$	$E_2 = \max(E_2', E_2'')$	N_i: number of vehicles per hours
$LE_1 = E_1 + 10\log(N_1) + A$	$LE_2 = E_2 + 10\log(N_2) + A$	A: factor depending on road surface

Appendix 2

Corrections applied on emission value to obtain immission (OFEFP 1987).

	Correction	Formula	Variables used
ΔL	Distance	$\Delta L = 10\log(d)$	D: horizontal distance from source to receptor (m) (e.g. road—pixel)
ΔA	Air	$\Delta A = 0.005\,d$	D: horizontal distance source–receptor (m)

ΔR	Reflection	$\Delta R = B_0\,(3 + 2\,B_1)$	B_1: density of built area on the side of the receptor B_0: density of built area in front of the receptor $B_0, B_1 \in (0, 1)$
ΔB	Soil effect	$\Delta B = 20 \dfrac{\exp\left(\dfrac{-d}{300}\right)}{h+1}$	d: horizontal distance source—receptor (m) h: mean elevation of sound wave (m)
ΔH	Obstacles	$\Delta H = 10 \log(5 + 80\,w)$	w: difference between direct (without obstacle) and indirect path (m)

Appendix 3

Logarithmic addition of multiplied noise sources

$$T = A \oplus B = T = 10 \log(10^{0.1 \times A} + 10^{0.1 \times B})$$

where T: Total immission level (dB); A: Immission level from source A (dB); B: Immission level from source B (dB).