Geographic Information Technology Training Alliance (GITTA) presents:

Intermediate Suitability Analysis

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1. Intermediate Suitability Analysis

This lesson revisits two basic issues in spatial analysis – overlaying different thematic layers and allocating space to different land use classes. At the intermediate level, these problems are treated in more depth.

First, the lesson addresses the fact that our way of modeling spatial entities such as a forest using a crisp, i.e. sharp bounded, polygon very often does not fit with reality. In the real physical environment, it is often very hard to say where exactly the line limiting a forest is. To capture such uncertainties, the concept of fuzzy boundaries is used in GIS.

Identifying land that meets a set of criteria for a certain land use is already quite tricky. In some cases a GIS analyst may even face the problem of two conflicting demands for the same area. It is quite clear that the same alpine meadow can hardly be a sheep-run and a wolf habitat at the same time...or can it? The multi-objective land use allocation technique introduced in the second unit proposed a solution to problems like this.

Learning Objectives

- You learn how to adapt the fuzzy set approach for spatial analysis.
- You deepen your knowledge about land use allocation by moving from multi criteria evaluation (MCE) to multi objective evaluation (MOE).

1.1. Fuzzy overlay

Fuzzy modelling of the world

Suitability analysis aims to find sites or regions that satisfy particular geographic criteria, such as vegetation types, land use or terrain characteristics. We consider a use case to illustrate the idea. The hypothetical alpine village of St. Gittal seeks to identify potential habitats for the reintroduction of wild living wolves. Let us assume that wild wolves prefer rocky and densely forested sites far away from human settlements. Overlaying the wolves needs and the properties of the available land, environmental scientists and decision makers can identify the most suitable sites for the predator.

Panoramic view of the alp Stabelchod in the Swiss National Park. Photo Ronald Schmidt

As a first straightforward GIS operation, one could use Boolean overlay of binary data layers. Sites suited for the wolf could be selected by intersecting the features "forest" AND "rocky" AND "unsettled". In the resulting view of the world, sites could only be suited or not suited, a further subdivision like "fairly suited" or "not very suited" would be impossible. Refining the overlay operation by assigning different weights to the single data layers increases the sensitivity of the query. Performing such a weighted overlay allows, for example, the land use "unsettled" to be 2.5 times as important as the vegetation type "forest".
A major problem with Boolean as well as weighted overlay is that both assume that the input data layers correctly represent reality. Due to sparse sample points and error-prone measurements, this condition is rarely met with natural geographical phenomena. Nature may not fit into crisp point, lines and polygons or smooth and continuous fields. For instance, how could the patchy mosaic of an alpine meadow ever fit precisely into ten vegetation classes, for example? This unit introduces the concept of fuzzy overlay to handle such uncertainty and vagueness. *Fuzzy membership functions* [1] permit entities to be partial members of different, overlapping attribute classes. The unit allows you to explore different aspects of fuzzy overlay working on various interactive animations illustrating the wolf habitat use case.

[1] A function describing the degree of membership (d.o.m.) of an entity to a class with inexactly defined boundaries (fuzzy set).

Learning Objectives

- You know the difference between Boolean and fuzzy logic
- You know when to use the fuzzy set approach
- You can construct examples of fuzzy suitability analysis
- You can sketch different fuzzy membership functions on a sheet of paper to classify sample points
- You know how to carry out fuzzy overlay in the raster model

1.1.1. Fuzzy terms in everyday speech

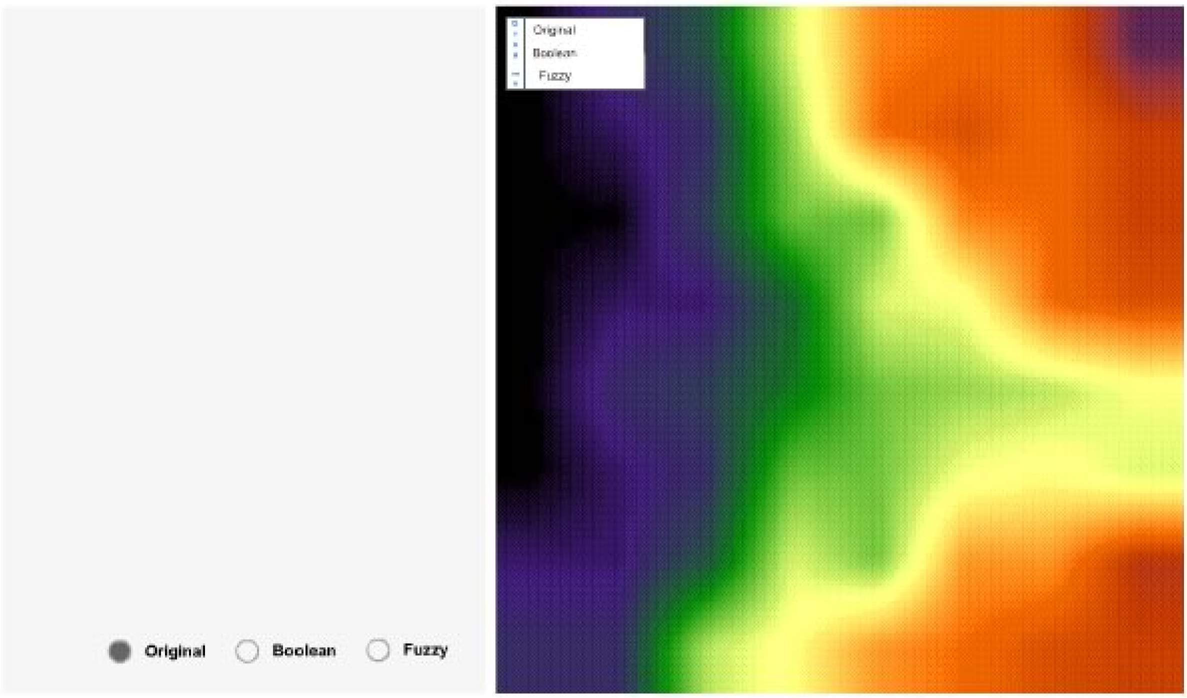
In most basic GIS courses we learn to divide the world into either crisp entities or continuous fields. Queries on the basic spatial entities normally base on the traditional binary logic of "true" or "false", "yes" or "no", 1 or 0, respectively. Let's look at the terrain characteristic "slope" as one suitability criterion in the wolf habitat analysis. Dividing "slope" into two classes "flat" (s<25°) and "steep" (s>=25°), every single site in space could only be "flat" or "steep". But what about a site ‚A' with a slope of 25.1°? Is it really appropriate to assigning that site to "steep", knowing that the slope measurement had only a limited accuracy?
Many geographic categorizations apply in such cases modifiers often used in everyday speech. Though, one could introduce an intermediate category such as "moderately" steep (20°<s<=30°). This would solve the problem for clearly intermediate sites but introduce a new problem cases at the borders of this new interval, e.g. having another site B with 29.2°.
Using Boolean or weighted overlay a location can only fulfil either a query or not fulfil a query. There is no in between, that is a location cannot be both part of the subset "steep" and not part of the subset "steep". A new concept is needed to represent our uncertainty in modelling the environment. Such a new logic should extend our limited binary logic of only "true" and "false" allowing vagueness and uncertainty. This is where the idea of fuzziness enters the overlay story.

Only pictures can be viewed in the PDF version! For Flash etc. see online version. Only screenshots of animations will be displayed. [link]

1.1.2. Idea of Fuzzyness

Fuzzy logic is based on the concept of partial truth. Whereas, classical logic holds that everything can be expressed in binary terms, fuzzy logic replaces Boolean truth values with degrees of truth, very similar in nature to probabilities (except that they need not sum to one). "*Fuzziness is a type of imprecision characterising classes that for various reasons cannot have or do not have sharply defined boundaries. These inexactly defined classes are called fuzzy sets* [2] " (Burrough et al. 1998) . Thus, handling "slope" in our use case would require discriminating three fuzzy sets: "easy-angled, "medium" and "steep". For every site in space we could then calculate a certainty of a location being a member of "easy-angled, "medium" and "steep". The certainty of an entity belonging to a fuzzy set is derived from a *fuzzy membership function (FMF)*. The degree of membership (d.o.m.) takes values from 1 to 0, with 1 representing complete certainty of membership and 0 representing non-membership. Let us use the fuzzy set "medium" to illustrate the idea of MF.

[2] *Inexactly defined classes, i.e. classes that cannot or do not have sharply defined boundaries.*



Fuzzy Membership Function

The map panel (right) shows first the digital elevation model (DEM) of the use case space in a raster format. Clicking on the button "Boolean" in the control panel (bottom left) you can visualize first the Boolean set for medium slope. The map panel now shows a map with a clear-cut black region containing the sites (pixels) belonging to the set "medium slope". In this Boolean case, the boundaries of the classes are sharp, so called crisp, allowing no doubt about the membership of an entity. The d.o.m. of a site may only be 1 for belonging to "medium slope" or 0 for not belonging to "medium slope". This is represented in the MF panel (top left).

- Sites with an elevation between 20° and 30° take a d.o.m. of 1, thus are with complete certainty members of the class "medium slope".
- Sites with an elevation below 20° and above 30° take a d.o.m. of 0, thus are not members of the class "medium slope".

All possible d.o.m. plotted against all elevation values build the membership function. In the Boolean case, the MF has a rectangular shape with vertical transitions from 0 to 1. Clicking around in the map panel highlights the elevation values and their associated d.o.m.
The most obvious change using the fuzzy set (click "Fuzzy" button) is the dissolving of the crisp region in the map panel. This fuzzification is best plotted in the transition of the rectangular MF into a trapezoidal shaped function in the MF panel. Read the FMF as follows:

- Only sites with an elevation between 24° and 26° are assigned to medium slope with a d.o.m. of 1.
- The d.o.m. increases linearly from 0 to 1 between 16° and 24°, and decreases linearly from 1 to 0 between 26° and 34° respectively.
- Sites with elevation values below 16° and above 34° get a d.o.m. of 0.

Again, you may click any pixel in the map panel to derive its d.o.m. to "medium slope" from the position of the vertical bar in the MF panel. The FMF can have different shapes. Triangular, trapezoidal and bell-shaped functions are often seen. In this unit, we will not discuss when to choose which shape. You can find a discussion on this in Burrough et al. (1998).

The d.o.m. is often classified in discrete intervals called alpha-cuts. An alpha-cut is the subset of all entities whose d.o.m. is greater than some threshold alpha, whereas 0<alpha<1. For example the 0.8 alpha-cut denotes all entities whose d.o.m. lies above 0.8. From the table you can see that all these entities lie in the interval between 22.4 and 27.6. If you click on a raster cell in the map panel, the corresponding alpha-cut is highlighted in the table.

Can you define the slope values of cells with d.o.m. greater than 0.6 for the Boolean and the fuzzy MF given in the animation above?

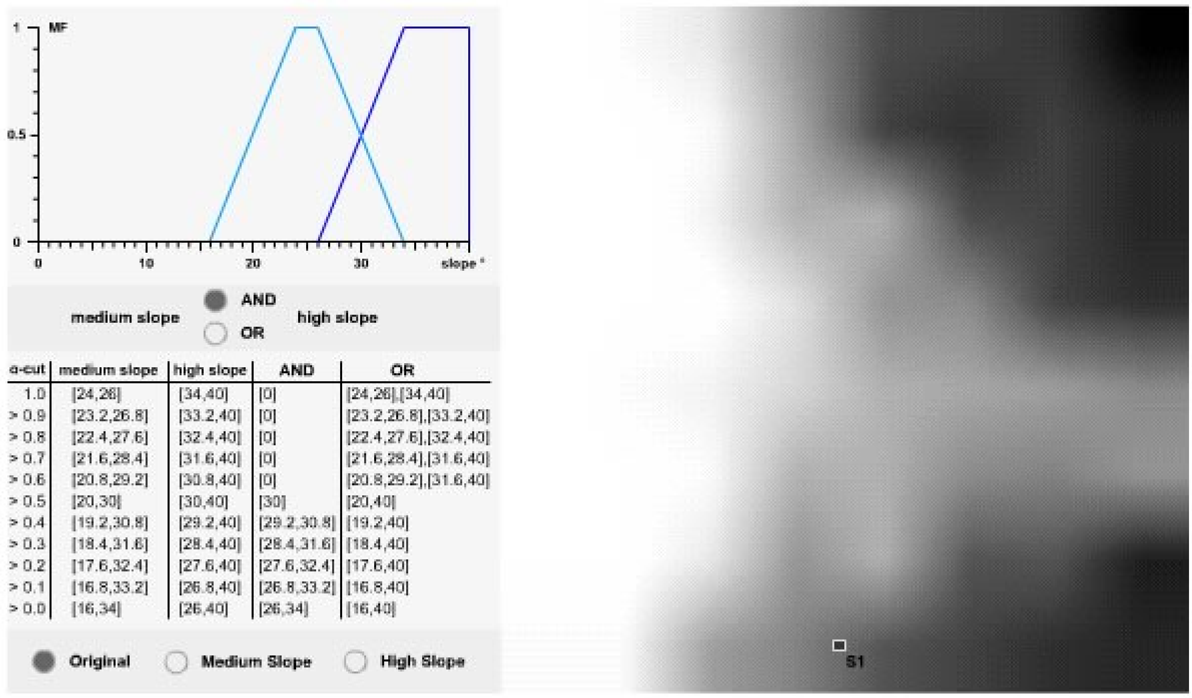
- Boolean MF: slope between 20° and 30°.
- Fuzzy MF: slope between 20.8° and 29.2°.

1.1.3. When use fuzzy ideas?

Every GIS-based suitability analysis uses a conceptual data model, a human conceptualization of reality. This abstraction of the real world incorporates only those properties thought to be relevant to the analysis. Whenever this conceptual data model features ambiguity, vagueness and uncertainty, you may want to use fuzzy concepts. There are several ambiguous and uncertain aspects when modelling the wolf habitat. For example, the crisp sketching of a tree line somewhere in the gradual transition from meadow to forest is highly uncertain. Or the regular and apparently smooth DEM surface is probably interpolated from relatively sparse sample points. Thus, modelling slope with three crisp sets hardly represents reality. For this reason we use fuzzy concepts of the different slope classes.

Attribute fuzzification vs. space fuzzification

The above use of FMF performs a fuzzification of the attributes of uncertain geographic information. The fuzziness reflects the uncertainty of an entity belonging or not belonging to an attribute class (here called set). In contrast, one could also fuzzify the spatial aspect of geographic information by dissolving e.g. the crisp boundaries of a map of categorical data. In this case, the fuzziness reflects the uncertainty of the exact location of, the borderline of a polygon, assigning central sites in the polygon a high d.o.m. and marginal sites a low d.o.m. Here the fuzzified polygon boundary gets the character of a transition zone from 0 (not member) to 1 (member).



α-cut	medium slope	high slope	AND	OR
1.0	[24,26]	[34,40]	[0]	[24,26],[34,40]
> 0.9	[23.2,26.8]	[33.2,40]	[0]	[23.2,26.8],[33.2,40]
> 0.8	[22.4,27.6]	[32.4,40]	[0]	[22.4,27.6],[32.4,40]
> 0.7	[21.6,28.4]	[31.6,40]	[0]	[21.6,28.4],[31.6,40]
> 0.6	[20.8,29.2]	[30.8,40]	[0]	[20.8,29.2],[31.6,40]
> 0.5	[20,30]	[30,40]	[30]	[20,40]
> 0.4	[19.2,30.8]	[29.2,40]	[29.2,30.8]	[19.2,40]
> 0.3	[18.4,31.6]	[28.4,40]	[28.4,31.6]	[18.4,40]
> 0.2	[17.6,32.4]	[27.6,40]	[27.6,32.4]	[17.6,40]
> 0.1	[16.8,33.2]	[26.8,40]	[26.8,33.2]	[16.8,40]
> 0.0	[16,34]	[26,40]	[26,34]	[16,40]

Fuzzification in the attribute space

Just as with Boolean sets, fuzzy sets can be combined using logical operators. In this unit we focus on fuzzy union and intersect, corresponding to Boolean OR and AND. In contrast to Boolean logic, the fuzzy membership functions permit entities to be partial members of different, overlapping sets. Thus, for site S1 with a measured slope of 26.84° we could at the same time indicate two different d.o.m. to the set "medium slope" (d.o.m. = 0.895) and "high slope" (d.o.m. = 0.105). This seems to be rather strange at first glance, so let’s take a closer look at that with the above animation!

The MF panel shows the FMF of the two adjacent classes "medium slope" and "high slope". Switching in the control panel (bottom left) from the "Original" to "medium slope" or "high slope" respectively, you may visualize the two fuzzy subsets of the variable "slope" in the map panel. Selecting any site by clicking in the map panel highlights its position in the FMF with a vertical bar and plots its attributes (slope, d.o.m. medium slope, d.o.m. high slope). But what happens if you select a site in the transition zone between medium and high slope, where the FMF overlaps?

Let’s look again at site S1 with a slope of 26.84°. Click it in the animation! From the FMF we get 0.895 for medium slope and 0.105 for high slope. The combinations of union and intersect use a rather intuitive approach.

Union: maximise

> If we want to know to which possibility a site is a member of either medium or high slope, we take the maximum of the two values:
>
> `d.o.m (A OR B) = max {d.o.m. A, d.o.m. B} (1)`

With A representing the fuzzy set "medium slope" and B representing the fuzzy set "high slope". The use of maximise for union becomes obvious looking at the vertical bar. At position 26.84 the two single FMF overlap. If site S1 must only be a member of one of the two sets to fulfil the logical query, it is best represented choosing the higher possibility of membership. Which is in this case the 0.895 of medium slope. Note that the corresponding a-cut is selected in table panel.

Intersect: minimise

In contrast, if we are interested in the possibility site S1 is a member of medium and high slope, we take the minimum of the two values:

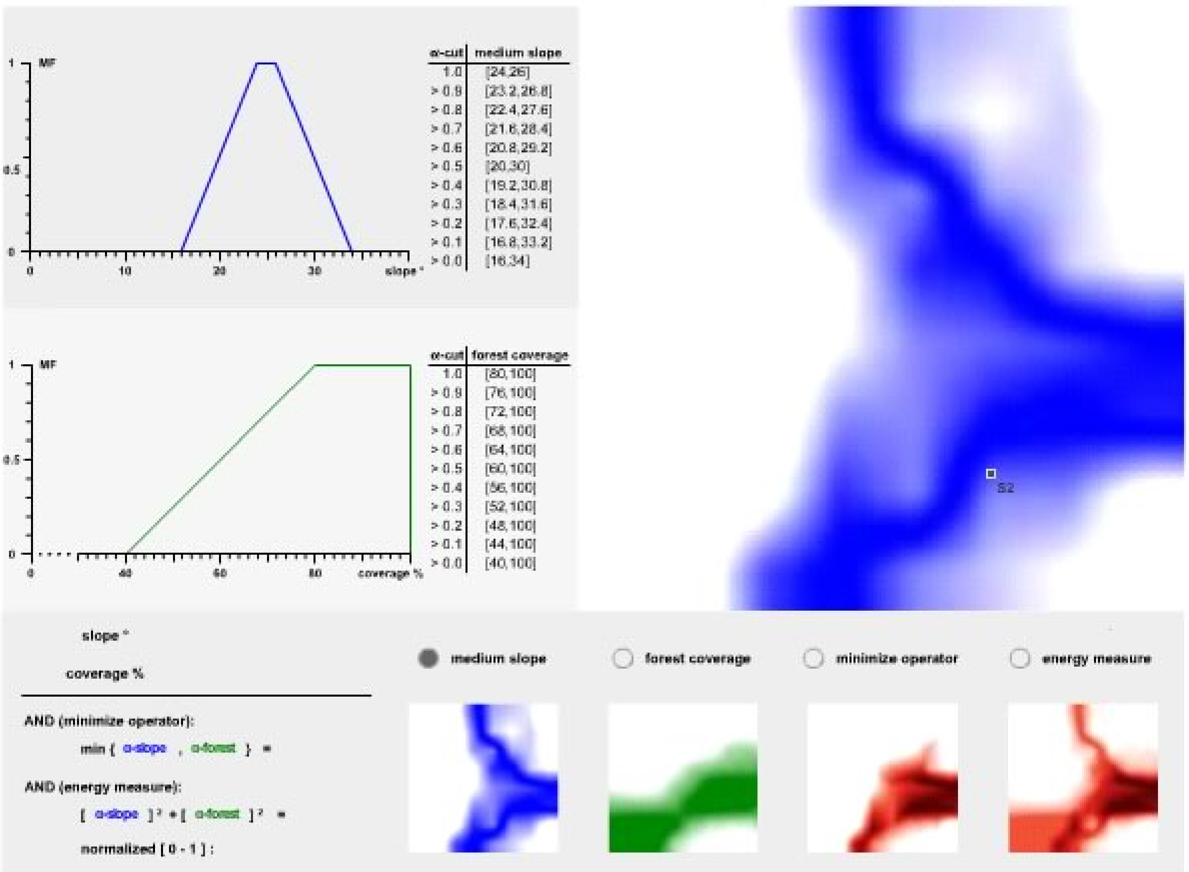
```
d.o.m (A AND B) = min {d.o.m. A, d.o.m. B} (2)
```

In this case, site S1 must be at the same time a member of both fuzzy sets which is only fulfilled for the minimum value taken at the position of the vertical bar.

Clicking around in the above animation you can now see that an individual entity in the transition zone can be a partial member of two sets of the same variable (slope).

1.1.4. Fuzzy overlay

Since our initial scope in this use case was to identify potential habitat regions for the reintroduction of the wolf, we must now ask how to overlay different fuzzified variables. How can we identify suitable regions that have a "medium slope" and are "densely forested"? Now the problem gets tricky and the GIScience literature gives different approaches to this question. The subsequent work with the animation below will clarify some ideas for fuzzy overlay.



Fuzzy overlay

Please be very clear about the basic differences to the combinations described above. Whereas we compared above small apples with big apples, we now compare their size with their colour. Above we combined classes of the same variable of a site, we now have to combine different variables in order to perform our suitability analysis.

Brute force: minimise

> The simple brute force approach again uses the "minimise operator" for this intersection task (AND):
>
> `d.o.m (A AND B) = min {d.o.m. A, d.o.m. B} (3)`
>
> With A representing the fuzzy set "medium slope" and B representing the fuzzy set "densely forested". Click for instance on site S2 in the animation. The arising problem is that one of the participating d.o.m. values dominates by assigning its value to the whole decision criterion.

In the literature, there are several other approaches for the logical combination of fuzzy sets of different variables. These approaches are in most cases complex and their results are difficult to interpret. However they provide better results than brute force minimising. In this unit, we focus only on the illustration of one idea, the use of an "energy measure".

Energy measure: add the squares

This measure combines the d.o.m. for both sub-layers by adding their squares (Gupta et al. 1988).

$$\text{d.o.m (A AND B)} = [\text{d.o.m. A}]^2 + [\text{d.o.m. B}]^2 \quad (4)$$

With A representing the fuzzy set "medium slope" and B representing the fuzzy set "densely forested". Note that the energy measure should be normalized in the fuzzy domain [0,1]. This measure accounts for both variables. Using the squares favours the variable with the greater possibility of fitting the criteria posed by the decision makers. Check again S2, now using the energy measure.

1.1.5. Critical Review

The main contribution of the use of fuzzy sets in Geographic Information Science is the development of a set of ideas to deal with uncertain and vague geographic information. Environmental scientists have emphasized again and again the need for tools able to cope with the uncertain information often encountered in their field. The use of fuzzy sets improves the information content of environmental data because it provides information about (un)certainty instead of simply assuming perfect data.
Problems arise choosing the FMF. Even if sophisticated methods help the user to choose the FMF and their parameters, this choice significantly influences the results of fuzzy analyses. Different class boundaries and transition widths may produce different results. Another drawback is related to the limits of the cartographic power of GIS. Using fuzzy sets for attributes and/or spatial boundaries for several features produces a confusing variety of data layers hard to visualize in a comprehensible way and that is difficult to interpret for non-specialists.

1.1.6. Where is the tree line?

Investigate the orthophoto of the alpine meadow Stabelchod in the Swiss National Park in the Engadine. Your task is to sketch the tree line delimiting the meadow and the woods. Compare and discuss your results in the class.

Aerial photo of the alpine meadow Stabelchod in the Swiss National Park. Where is the treeline? (Swiss National Park 2000)

1.2. Multi-objective analysis

Suitability analysis of differing complexity

Geographic Information Systems (GIS) are ideal tools to monitor and manage natural resources. Thus, GIS is often used to support politicians and other decision makers in spatial planning issues. Such a spatial planning issue could be the estimation of the suitability of different sites for specific uses or the allocation of land to different uses. GIS has here the function of a decision support system (DSS), or more precisely a spatial decision support system (SDSS). This unit is built around a simple use case to illustrate the idea of suitability analysis and spatial decision support: A hypothetical alpine village, we will call it St. Gittal, seeks to identify potential habitats for the reintroduction of wild wolves.

The use of GIS for suitability analysis and decision support can have different levels of complexity. For many simple questions, it might be enough to combine spatial layers using Boolean overlay functions. Regions could be considered suitable if they are "forested" AND "unsettled". If some criteria would be more important than others, more complex weighted overlay functions may be used. "Unsettled" could thus be considered twice as important than "forested" and be assigned a weight of 2 in the suitability measure. Whenever uncertainty, ambiguity, and vagueness blur the trust in the input data, one might want to further raise the level of complexity introducing fuzzy concepts. In order to model uncertainty, the crisp class "forested" could be replaced by the fuzzy set "densely forested", i.e. a class without sharp boundaries assigning all sites a degree of membership to the set "densely forested".

Some suitability analysis tasks simply require the identification of land that meets some criteria, e.g. "identify sites suited for the reintroduction of the wolf". Such processes are called single objective, *multi-criteria evaluations (MCE)* [4]. Sometimes in contrast, the problem is to divide up regions of land according to their suitability for different objectives. This would be the case, if for example, wildlife conservationists and shepherds both required some land for their obviously differing needs. In this unit we focus on this last process, termed *multi-objective evaluation (MOE)* [5]. Since MOE integrates various procedures of minor complexity, it is rather complex. To make life easier, we use an intuitive, graphical and thus comprehensible approach to illustrate the basic ideas about MOE, the so called MOLA approach (Multi-Objective Land Allocation).

Learning Objectives

- You can describe the basic concept of multi-objective evaluation (MOE)
- You can explain the difference and the links between multi-criteria evaluation (MCE) and multi-objective evaluation (MOE)
- You can sketch a MOLA decision diagram for two conflicting objectives
- You can explain how heuristics can be used in a Spatial Decision Support System

1.2.1. Conflicting and non-conflicting objectives

The objectives to be satisfied for a decision may be complementary or conflicting in nature. On the one hand we might want to allocate land for both wildlife conservation and recreation use. This is an obvious case of non-conflicting objectives, we would select areas that satisfy both objectives to the maximum degree possible. On the other hand, in some cases the land could only be assigned to one use, but not to both. In our use case,

[4] Suitability analysis that satisfies several criteria with respect to a single objective.

[5] Suitability analysis that satisfies several, possibly conflicting objectives.

such a situation would arise when conflicting objectives were introduced by a strong shepherds' lobby. Even if peaceful ways of coexistence between shepherds and wolves are possible, let us assume that we have here conflicting objectives, competing for the available land. The rest of this unit illustrates one possible approach to solving such a problem.

Other typical examples of conflicting objectives would be:

- Areas suited for industrial development vs. wildlife preservation,
- Industrial development vs. agriculture.

1.2.2. Decision heuristics

Let the available land of St. Gittal be 64 km^2, represented in a raster model with 1 km^2 resolution. The task shall now be to select 16 km^2 of sheep pasture and 20 km^2 of suitable wolf habitat. Since sheep and wolves share common needs they compete for at least some regions. Thus, it is very likely that the sets of raster cells, in which the sum of suitabilities is maximized for the single use, overlap considerably.
But how can the best of the many possible combinations of dividing up the conflicting cells be selected? There are computationally expensive, mathematical means of comparing alternatives. Such choice functions often involve some form of optimization, i.e. they require that each alternative be evaluated in turn. This is not practical for many realistic applications using large raster data sets. However, this problem can be avoided using approximation procedures called choice heuristics instead of choice functions. A *heuristic* [6] is a procedure designed to solve a problem that ignores whether the solution is theoretically correct, but which in general produces a good solution or solves a simpler problem that contains or intersects with the solution of the more complex problem. Heuristics specify a procedure to be followed rather than a function to be evaluated. A heuristic is rather a "rule of thumb", based on experience or experiments. The following animation shows such a heuristic procedure to allocate land in our use case.

1.2.3. MOLA

Only pictures can be viewed in the PDF version! For Flash etc. see online version. Only screenshots of animations will be displayed. [link]

I. Map the cells in the decision space

The Multi-Objective Land Allocation (MOLA) procedure was introduced by Eastman et al. (1993). MOLA is a hierarchical extension of the multi-criteria evaluation process: A set of suitability maps, each derived as a single objective multi-criteria evaluation, serve as factors for a new evaluation in which the objectives are

[6] Procedure designed to solve a problem that ignores whether the solution is provably correct, but which usually produces a good solution or solves a simpler problem that contains or intersects with the solution of the more complex problem. It is a "rule of thumb", based on experience or experiments rather than on a formal solution. The term comes from the same Greek root "euriskw" as "eureka" meaning "to find".

themselves weighted and combined. For reasons of simplicity we start with the normalized maps showing "suitability for sheep pasture" and "suitability for wolf habitat". Our task is now to balance the needs of the different objectives.

The map panel (left) shows the 64 km^2 available land of St. Gittal in a raster model, each cell representing 1 km^2. Blue colour tones represent the suitability "wolf habitat", green tones indicate the suitability "sheep meadow". In the decision panel (right) the suitability for a purpose may be thought of as an axis of a two-dimensional diagram, the decision space. Every raster cell in the map panel can be located within the decision space according to its suitability level according to each of the two objectives. You can verify this by clicking on the raster cells and checking their corresponding position in the decision space, and vice versa. Note that the location of a point in the decision space is solely dependent on the two suitabilities of its correspondent raster cell.

II. First allocation

Finding the best 20 km^2 of land for "wolf habitat" you simply move a perpendicular decision line down from the position of maximum suitability until enough cells are captured to fulfil the areal goal. Use the +/- arrows until the counter shows the required number of cells. Holding the shift key, increases the step size. Finding the best 16 km^2 of land for "sheep pasture" you proceed in an equal way with a decision line perpendicular to the second axis. Doing so, you divided the decision space in four rectangular sub-areas holding pixels…

- not suitable at all,
- suitable for wolf, but not suited for sheep (blue cells, respectively blue points in decision space)
- suitable for sheep, but not suited for wolf (green cells, respectively green points in decision space), and
- suitable for wolf and suitable for sheep, i.e. conflicting cells (red cells, respectively red points in decision space).

III. Iterative resolution of conflicts

The red cells lying in the top right area are judged suitable for both purposes. To resolve these conflicts, a simple partitioning of the affected cells is used. For every cell we check for which use it is more suited, i.e. which suitability measure is higher and assign it to this land use. Click "solve conflicts" to show the red dividing line. Having divided the conflict cells between the two objectives, it is clear that both will be short on meeting their area goals, the counters decreased. As a result, the decision lines have to be lowered for both objectives to gain more territory. This process of resolving conflicts and lowering decision lines is repeated until the exact area targets are achieved.

IV. Weighting the objectives

Another useful feature of the MOLA approach is that unequal weighting of the two objectives is possible and very intuitive. If two objectives are equally weighted, the red dividing line has a gradient of 45°. For an unequal weighting we can simply change the gradient of the dividing line, such that the angle’s tangent represents the ratio of the new unequal weights. Use the blue arrow to increase the weight of the purpose "wolf habitat", use the green arrow to increase the weight of the purpose "sheep" pasture. Again the shift key lets you increase the step size. Move the dividing line and note the change of the allocation in decision and real space.

What makes this procedure a heuristic?

We did not compute all possible allocation possibilities and choose an optimal one. Instead we formulated a first guess in the decision space and experimented with the decision lines until the areal goal was met. This approach used a set of simple rules to approach a sensible solution, but is not formally repeatable.

IDRISI - MOLA implemented in a GIS

The MOLA procedure is integrated in the IDRISI System. IDRISI is a combination of raster GIS and digital image processing modules in an integrated package. IDRISI features modules for display and map composition, data base query, image analysis, time series analysis, statistics, surface modelling and geostatistics, developer tools, as well as decision support. The decision support module provides various tools for multi-criteria as well as multi-objective evaluations. Below is some publicity material for IDRISI. You can find more information on the Clarkslab Website.

1.2.4. Critical review of the MOLA approach

The MOLA procedure is easy to understand and thus very well suited for participatory decision making processes. Furthermore, it is fast and capable of processing large data sets. Although we examined only two conflicting objectives, the 2D decision space could be extended to a multi-dimensional space representing many conflicting objectives. However, with more than three objectives the approach loses its graphic simplicity and becomes harder to interpret.

The MOLA-approach is not the only way to allocate land use. Almost any optimization technique can be used. Another commonly used approach within the GIScience field is called linear programming. Linear programming is a method of finding an optimal solution to problems that require several factors to be balanced against each other. In our case these factors are conflicting land-use objectives. Thus, linear programming for land-use allocation is used to achieve optimal land-use, where defined objectives can be maximized and constraints are respected. It is called linear programming because the optimization is achieved by optimizing a set of linear functions representing the decision variables.

The further reading section of this unit gives you some starting points to explore the literature on linear programming with GIS.

1.2.5. Self Assessment

Read the paper Eastman et al. (1993) about the Kathmandu case study. First extract the objectives of the stakeholders, and then extract thereafter the criteria for the multi-criteria evaluation.

Objectives of stakeholders:

- Carpet industry: find additional land best suited for carpet industry, zone 1500 hectares of current agricultural land for industry use
- Agriculture: protect lands that are best suited for agriculture, preserve unpolluted land, prevent encroachment of agricultural land, protect 6000 hectares for agriculture

Criteria for multi-criteria evaluation:

1. siting the carpet industry:
   - proximity to water
   - proximity to roads
   - proximity to power line
   - proximity to the market
   - easy-angled terrain
2. agriculture land protection
   - proximity to water
   - proximity to market
   - slope gradient
   - easy-angled terrain

1.2.6. Self Assessment

Check the following statements:

Only pictures can be viewed in the PDF version! For Flash etc. see online version. Only screenshots of animations will be displayed. [link]

1.2.7. Recommended Reading

- **Chuvieco, E.**, 1993. Integration of linear programming and GIS for land-use modeling. *International Journal Geographical Information Systems*, Vol. 7, No. 1, p. 71-83.

  This IJGIS article gives you a nice example of linear programming for a land-use planning scenario in Spain. It shows the integration of the basically aspatial method LP within a GIS.
- **Jones, C.B.**, 1997. *Geographical Information Systems and Computer Cartography*. Addison-Wesley Longman.

  Section on linear programming, p. 218-221. Rating: These few pages in Jones" basic GIS textbook give you a first overview on the topic and help you to compare LP with other decision support approaches.

1.3. Summary

This lesson revisits "spatial overlay" and "land use allocation" and discusses these two key concepts of spatial analysis in more depth. First, spatial overlay is extended by fuzzy logic, complementing Boolean overlay ("true" or "false") by concepts partial truth. Fuzzy overlay allows vagueness and uncertainty because nature often can't be modeled by crisp points, lines and polygons having crisp attribute classes. The fuzzy membership function (FMF) describes the degree of membership of an entity to a class that does not have sharply defined boundaries (fuzzy set). The degree of membership (d.o.m.) takes values from 1 to 0 with 1 representing complete certainty of membership and 0 representing non membership. For example, crisp slope classes (medium slope is between 20º and 30°) could be replaced by fuzzy slope classes, modeled by FMFs. This would allowing a site with, for example, 26.8° to have only a membership of 0.9 to the fuzzy class "medium slope", but also a small membership of 0.1 to "high slope". Fuzzy overlay then combines fuzzy spatial layers by use of logical combinations of fuzzy sets. The second unit in this lesson is about multi-objective analysis, where GIS adopts a decision support system (DSS) function. The problem at hand is to divide up land into use classes according to its suitability for different objects that may or may not be conflicting. Typical examples include areas suited for industrial development vs. wildlife preservation or industrial development vs. agriculture. Such problems require a multi-objective evaluation (MOE), most commonly performed through the Multi Objective Land Allocation (MOLA) approach. MOLA is a hierarchical extension of multi-criteria evaluation in which potentially conflicting objectives are weighted and thereafter combined: a set of suitability maps, each derived as a single objective, are themselves weighted and combined. A prominent feature of the MOLA approach is that unequal weighting of objectives is possible and very intuitive. Allocation conflicts are solved by allocating the respective cells to the classes they are most suited for (decision heuristic). MOLA is relatively easy to understand and hence well suited for a participatory decision making process.

1.4. Recommended Reading

- **Burrough, P. A., MacDonell, R. A.**, 1998. *Principles of Geographical Information Systems. Fuzzy sets and fuzzy geographical objects*. New York: Oxford University Press. [p. 265–291]
- **Eastman, J.R., Jiang, H., Toledano, J.**, 1998. Multi-criteria and mulit-objective decision making for land allocation using GIS. *In:* **Beinat, E., Nijkamp, P.**, ed. *Multicriteria Analysis for Land-Use Management*. Dordrecht: Kluwer Academic Publishers, p. 227-251.

1.5. Glossary

Fuzziness:

A type of imprecision characterising classes that for various reasons cannot have or do not have sharply defined boundaries. The term fuzzy may cause misconceptions. "Fuzzy" is said to have a negative connotation, usually suggesting something imprecise. However, fuzzy logic is not any less imprecise than other forms of logic, but rather is an organized and mathematical method of handling inherently uncertain information.

Fuzzy membership function (FMF):

A function describing the degree of membership (d.o.m.) of an entity to a class with inexactly defined boundaries (fuzzy set).

Fuzzy overlay:

Fuzzy overlay results from applying fuzzy logic to spatial overlay. Fuzzy overlay hence combines for a given location not certainty values (e.g., steep slope AND densely forested), but rather values indicating uncertain, i.e. fuzzy, memberships to slope and forestation classes (e.g., membership for steep slope is 0.8, membership for densely forested is 0.7).

Fuzzy sets:

Inexactly defined classes, i.e. classes that cannot or do not have sharply defined boundaries.

Heuristic:

Procedure designed to solve a problem that ignores whether the solution is provably correct, but which usually produces a good solution or solves a simpler problem that contains or intersects with the solution of the more complex problem. It is a "rule of thumb", based on experience or experiments rather than on a formal solution. The term comes from the same Greek root "euriskw" as "eureka" meaning "to find". (Wikipedia)

Multi-criteria evaluations (MCE):

Suitability analysis that satisfies several criteria with respect to a single objective.

Multi-objective evaluation (MOE):

Suitability analysis that satisfies several, possibly conflicting objectives.

1.6. Bibliography

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  Download: http://mapcontext.com/autocarto/proceedings/auto-carto-11/pdf/participatory-multi-objective-decision-making-in-gis.pdf
- **Gupta, M.M., Yamakawa, T.**, 1988. *Fuzzy Logic and Knowledge Based Systems, Decision and Control*. Amsterdam: Elsevier Science Publishers B.V.
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