# Suitability analyis

**Responsible persons: Helmut Flitter, Patrick Laube, Patrick Lüscher, Stephanie Rogers, Suzette Hägi**

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# 1. Suitability analyis

"*The wolf has struck again, this time in Ticino. On January 10, he mangled three goats at a pasture above Bellinzona. Thus, the predator was modest: the infamous wolf of Hérens valley in the Valais allegedly had 300 sheep to answer for and was therefore shot last summer. [...]*
*Any further incident fires up the debate about the wolf anew: Is there room for the voracious predator in densely populated Switzerland? While polls show that about half of the Swiss welcome the return of the wolf, shepherds want none of it. For them, the predators are pests, which descend on their sheep grazing unattended on the alps. [...]*" (Kittl 2001)

The upcoming return of the wolf in the Alps is an excellent case study for introducing the topic "Decision support with GIS. The native inhabitants of the Alps, the people, need to decide how to deal with the newcomer. Policy makers need to consider various questions:

- Where are possible habitats for the wolf?
- Which areas are particularly well suited?
- In which areas might conflicts occur between the wolf and shepherds, or mountain railway operators?

To answer these and similar other questions, the combination of decision support techniques with GIS offers a wide range of interesting approaches. To sum up, it is the following question that needs to be answered: how can the suitability of areas for a particular use be determined with GIS? The technical term for this field is called *suitability analysis* [1]. This lesson illustrates its methods using a vivid case study: the hypothetical mountain community of St. Gittal wants to clarify where the wolf could find a suitable habitat. Further, it should be clarified whether and where there are conflicts between different interest groups such as environmentalists, shepherds, and mountain railway operators. This example will be considered throughout the lesson using various perspectives.

Background information about the recapture of the Alps by the wolf can be found at the following Internet addresses:

- **KORA**: coordinated research projects for the conservation and management of carnivores in Switzerland
- **BAFU**: The Federal Office for the Environment is responsible for many issues concerning the handling of large wild animals

## Learning Objectives

- You recognize that GIS can play an important role in spatial decision making (suitability maps, hazard maps, location search)
- You can apply boolean and weighted intersection approaches to the problem of spatial decision making and discuss the pros and cons of both approaches

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[1] Suitability analysis is an evaluation of the suitability of a location or area for a certain use. Suitability analysis is usually done through an intersection of social, ecological, economic, physical, biological or other criteria. Suitability maps are usually the result of a suitability analysis. They display the spatial distribution of the determined values in a graphical form.

# 1.1. Decision support with GIS

Geographical information systems can help to aid in decision making in a variety of ways. A first approach is the creation of suitability or hazard maps. They show which locations or areas are particularly well suited for a specific purpose, or those which are specifically threatened by a hazard. Most decision support situations consider multiple decision criteria. For creation of a wolf protection zone, criteria such as vegetation form or density of prey could be considered. However, often the claims of various stakeholders should be taken into consideration before a decision is made. This may lead to conflicting objectives. For example, a mountain valley cannot be both a protected area and a ski resort.

Many aspects of *decision support with GIS* [2] appear for the first time in this unit and are revisited and deepened in the following units.

## Learning Objectives

- You can explain the difference between decision support with multiple criteria and with multiple objectives in your own words.
- You know the concept of suitability maps and you are able to interpret suitability maps in terms of decision support.
- You are able to derive and to operationalize criteria from a text for a simple GIS based decision support model.
- With the help of an example you can identify the limitations of the multi-criteria evaluation (MCE) and the decision support with multi-objective evaluation (MOE)

## 1.1.1. Suitability analysis with the help of suitability maps

The question of the suitability of an area for a particular use was one of the main motivations for the development of GIS. "What parts of St. Gittal are suitable for the resettlement of a large carnivore?" Such queries require spatial search techniques based on search criteria. A simple search with a single criterion is rarely enough ("Which areas of St. Gittal are covered with forest?"). Usually, only the combination of multiple search criteria leads to a solution. A GIS allows such combinations through the intersection of multiple levels of information. Only the superposition of information, e.g. soil type, vegetation, and topography, allows the designated query. The concept of *Suitability analysis* describes the search for locations or areas that are characterized by a combination of certain properties. Often, the result of a suitability analysis is a suitability map. It shows which locations or areas are suitable for a specific use in form of a thematic map (e.g. agricultural suitability map). The negative variation of the suitability map is the hazard or risk map. It segregates areas that are exposed to a specific hazard based on the criteria given (e.g. avalanche hazard maps).

**Two typical examples of suitability maps:**

- **Agricultural suitability map, community of Pratteln (BL)**: the agricultural suitability maps provide information on which crops are grown in a specific location with good success without compromising the fertility of the soil

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[2] Decision support in GIS is a system based on the suitability analysis to support decision-makers on issues of spatial and environmental planning. Spatial models and scenarios are used to assess different land use types. For multiple selection criteria and only one objective, a multi-criteria evaluation (MCE) is used. In the more complex case of multiple, possibly even exclusionary objectives, the different land uses need to be weighed (multiple-objective evaluation, MOE).

- [**FAO: Land Suitability Maps for Rainfed Cropping**](#) - The Food and Agriculture Organization (FAO) provides suitability maps of the world for various crops.

## 1.1.2. Spatial Decision Support Systems (SDSS)

Suitability analysis is often used to support decision making in planning processes, such as environmental planning. Frequently, the goal is to find the most suitable spot for a certain object (e.g. a powerplant, a cable car, a nature reserve). For example, for the policy-makers of the community St. Gittal, it might be useful to coordinate the location of a new cable car with possible retreating areas of the wolf. That way, confrontations between tourists and the wolves can be avoided.

A series of mathematical calculations makes it possible to weigh various alternatives of a decision based on certain criteria and valuations. Often, a wide range of methods are used. Complex Decision Support Systems, DSS, help the decision-makers compare the different options.

If it is a spatial decision problem, the combination of DSS and GIS is suitable. A GIS takes over data management, expands the DSS with spatial analysis functions, and facilitates access to the input data and the results by using cartographic representations. The combination of DSS and GIS makes it easier for the decision-makers to weigh options, and therefore leads to more impartial and open-minded decisions. Spatial Decision Support Systems (SDSS) allow different options of land use to be traded off against each other.

**Example: Hazard maps as a planning measure:**

- [**Hazard maps of the ARE**](#) Hazard maps of the ARE (Federal Office for Spatial Development): The establishment of hazard zones is an important application of spatial decision support. In Switzerland, hazard maps help decide where construction is allowed in mountainous areas and where it is forbidden.

## 1.1.3. Decision Support with multiple criteria

In the simplest case of decision support with GIS, locations or areas can be found that meet or optimize multiple criteria for one objective. In the case study of St. Gittal, the objective in a first approach is to identify the best habitat for the wolf in the municipality. Let's assume the wolf prefers areas far away from residential areas and areas covered with forest. From that, two search criteria can be formulated. If there are more than one criterion but only one objective, as in this case, it is called a multi-criteria evaluation (MCE).

**Standard procedure for MCE:**

1. Define the problem: the first step of an MCE is the definition of the problem. In the case study of St. Gittal, the problem definition could be as follows: "Which parts of the municipality is suitable wolf habitat?"
2. Select the criteria: the next step is to select the criteria. The chosen criteria should reflect the characteristics of the desired location or area as closely as possible. Criteria can be both spatial (geometry, topology) as well as factual (attributes). For example, a spatial criterion could be the distance between a potential habitat of the wolf to the nearest settlement. The restriction of the land use category "forest" on the other hand is a factual criterion. Furthermore, there are hard, "must-have" criteria and soft, "nice-to-have" criteria.
3. Operationalization of the criteria: when the criteria are determined, they must be translated to precise, measurable indicators. This process is called operationalization. The criterion "not too close to the settlement" could be translated to the specification of a minimum distance in meters of the residential

area. It is said that the criteria are to be operationalized to computable indicators. In most cases, the individual criteria correspond to one data layer in a GIS (forest layer; layer with the distance to the residential area).

4. Creation of a common reference – data integration: Data integration creates comparability through a common measurement scale, the same data type (raster / vector), and the same resolution and reference system.

5. Intersection: identification of the most suitable areas. Now the different criteria are allocated to find the desired location. There are several possible approaches:

   • Logical (Boolean) overlay: in each layer there is only binary true/false information (forest / non forest). By logically intersecting this information, the desired locations and areas wanted are determined. This topic is explained in the unit "Boolean overlay".

   • Weighted overlay: rarely is the simple distinction between true and false possible in the complexity of reality. A significant improvement of the results can be achieved by providing the individual data layers with weights. For example, in the case study, the distance to the settlement could be much less important than the forest as a sanctuary. A weighting factor of five could be assigned to the layer with the distance to the village. These topics are discussed separately (units "Weighted overlay" and "Determining the weights").

   • Fuzzy overlay: erroneous input data and the wrong choice of criteria can lead to evaluation errors. In a multi-criteria evaluation, appropriate areas could be ignored and unsuitable areas could be falsely classified as suitable. A solution to this problem is the cancelation of sharp boundaries. For the spatial data, this means that boundaries are not represented as sharp lines but as transition zones. With attributes, fuzzy ranges of values replace sharp class limits. This concept is based on the idea of the fuzzy set theory (fuzzy in the sense of blurred). These approaches are discussed further only in the intermediate level.

6. Verification / evaluation: the final step involves comparing the results with a reference. This is possible if reference data, collected in the field, are available ("ground truth"). This last step is often neglected. But be aware: a suitability map without an assessment of its quality and reliability is often not worth the paper on which it was printed!

**MCE Example:**

• **The "TWW" (TWW = Trockenwiesen- und weiden) – Assessment procedure – or finding the most valuable semi-arid grasslands and pastures in Switzerland.** How can the most valuable semi-arid grasslands and pastures in Switzerland be identified considering all the regional differences, ecological aspects and the varying approaches of the different branches of science. In the Project TWW (of the Federal Office for Environment) an assessment system was developed which allowed the combination of all these aspects.

**Determine the evaluation criteria for the multi criteria evaluation for the TWW Project.**

> Aggregatmass, measure of diversity, floristic potential, measure of structure, measure of vegetation

## 1.1.4. Decision support for multiple objectives

If the community of St. Gittal wants to preserve peace in the village, the needs and requests of environmentalists, shepherds, and hotel directors must be taken into account. However, it is easy to see that the objectives of the various interest groups are very different.

- There are cases in which various land uses exist on the same parcel of land. By following certain rules, a hiking trail could well lead through a wolf habitat.
- However, land use demands can also exclude all other claims. A lot cannot be a wolf habitat, a pasture for sheep, and a golf course at the same time. In cases like this, different planning options need to be weighed against each other and the land has to be divided according to its suitability for different uses.

When there is more than one goal, MCE is no longer sufficient for use, instead a decision support with multiple objectives (Multi Objective Evaluation, MOE) should be implemented.
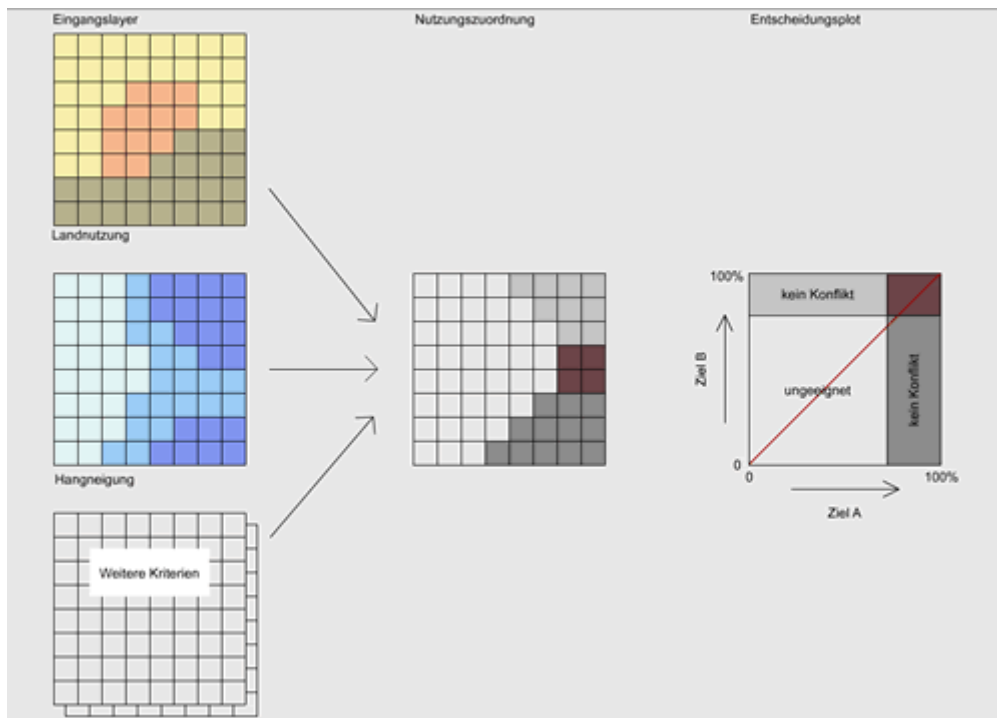


The figure shows the result of a suitability analysis for two mutually exclusive usage rights for the municipality of St. Gittal: the two goals are called "suitable wolf habitat" (Objective A) and "suitable for sheep grazing" (Objective B). On the far left you will see a number of input layers for suitability analysis. Amongst others, there are the layers for both "Land Use" (above) and "slope" (middle). The map on the right shows the spatial allocation of the municipal area on the two uses. White is suitable for neither (A) nor (B). Dark gray was assigned to (A) and light gray to (B). Where light gray and dark gray overlay, there is a land use conflict (red). In the diagram on the far right, any point in the area can be entered according to its suitability for (A) and (B). The more a point corresponds to one criterion, the higher is its corresponding percentage. For both (A) and for (B) a limit can be set beyond which a point of such property is assigned to the congruent land use. All points lying in the red rectangle in the upper right represent a usage conflict. For each one of these points it has to be individually decided as to which land use they are assigned. In the simplest case, a point in dispute is assigned to the land use it is better suited: if the point lies above the red line in the diagram, it will be land use (B), otherwise land use (A).

## 1.1.5. Derivation of the criteria for suitability analysis

For this job, put yourself in the role of a scientist with the task of carrying out a multi-criteria analysis to determine potential habitats of the wolf in the municipality of St. Gittal. Your task is to determine the criteria for the desired areas using different sources. Study the two texts below:

1.  KORA: **Dokumentation Wolf** (KORA 2005)
2.  Facts: "**Die Räuber kommen wieder**" (Baumgartner 1995)

**Task:**

Write up at least three criteria for the characterization of potential wolf habitats in the community of St. Gittal. Each criterion should be represented in a spatial data layer. From all layers, the overall suitability should be calculated. From where you will obtain the data is currently not a concern.

- Topography: steep and rocky areas
- Vegetation: wooded areas
- Prey: high density of wildlife (Chamois, roe deer, ibex)

# 1.2. Boolean Overlay

In simple suitability analysis, the logical combination of true/false information often leads to a more or less straightforward solution. Let's suppose the wolf visiting St. Gittal only settles inside the forest and only in steep areas. In this case, a few logical considerations are enough to determine the suitable habitat. Each of these two criteria can be modeled using a binary information layer (forest / non-forest and steep / not steep). The areas which satisfy both criteria constitute the potential habitat, that is, areas that are forested AND steep. This method of spatial query is called *Boolean Overlay* [3] and is a commonly used analysis function in GIS.

In addition to the intersection with "AND" there are other logical combinations. This unit deals with the basic idea of Boolean overlay and shows its application in suitability analysis with GIS.

## Learning Objectives

- You can explain the principle of Boolean overlay in a few sentences
- You can sketch examples for Boolean operators with Venn diagrams
- You know the limitations of Boolean overlay and can judge whether this method is suitable for different types of suitability analysis or not

## 1.2.1. Overlay

The principle of the overlay of spatial data can be illustrated through the example of producing maps. When printing a map, different layers of spatial information are printed one after the other onto white paper. Each color represents new information on the paper: green represents vegetation, blue for hydrography, and red for the signatures representing residential areas. All the colors together give a very detailed model of reality: the map. This is the main basis of overlays in GIS. First, two or more layers of information from the same area are overlaid onto each other. Then, the topology of the new layer is updated: if a point now lies within a polygon, it gets assigned this information as a new attribute. If two lines intersect ("arcs") a new node will be added at their intersection. If two polygons intersect, a unique identification number is given to the intersecting set and so forth. Ultimately, the overlay results in an information gain. In order for this integration to make sense, all input layers must have the same reference system and scale. The map will only be legible if all the layers fit together exactly in regards to position and scale. The process itself is independent of whether a raster or a vector model is used. With a raster model, the overlay operation is rather an overlay than an intersection. The integration of information from various sources through overlay is one of the most important functions of a GIS.

The following three types of overlay are independent of whether a vector or a raster model is used.

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[3] The Boolean Overlay is an intersection of binary coded data layer using the Boolean operators AND, OR, XOR, and NOT. The result of a Boolean Overlay is again a data layer with areas that are true and areas that are false.
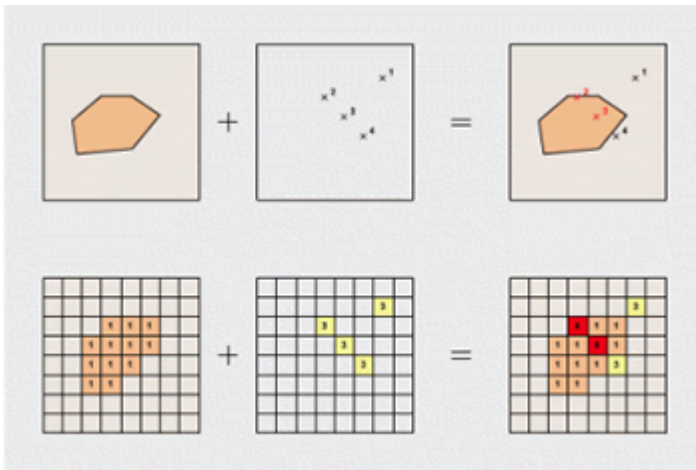
Point-in-polygon: in the vector model, this overlay determines the points lying inside a specific polygon. In the example, we are looking for all hotels that are located in the settlement areas. In the resulting layer, the points have the additional information whether or not they are in the settlement area. In the raster model, the points in question are visible through the addition of the two input layers.
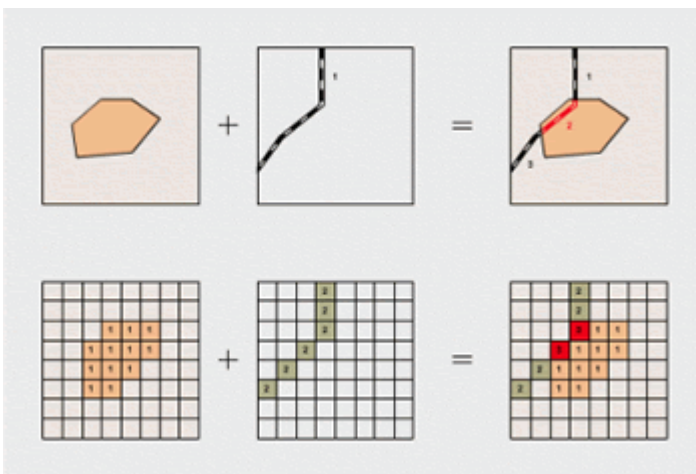


Line-in-polygon: the overlay of lines and polygons is more complex. The example shows the calculation of road sections located in the settlement area. In the vector model, the topology changes: the original line is cut into shorter segments by the intersection points. It has to be specified for each segment whether it is inside or outside the settlement polygon. In the raster model, a simple addition identifies the interest areas.
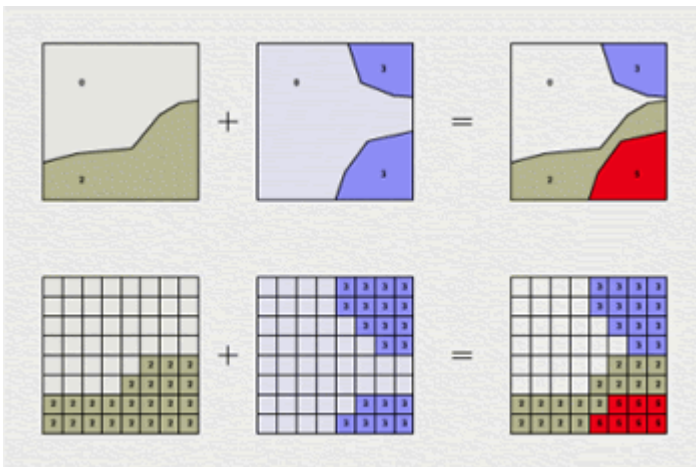


Polygon-on-polygon: in the vector model, the most complex case is the intersection of polygons. The result is a data layer with a whole new topology. The overlay of contour lines results in a variety of new intersections and polygons for which the attributes have to be reassigned. In addition, for non-cut areas it has to be checked whether they contain areas of another information layer i.e. whether island polygons were created. Raster overlay is very simple, however. Again, the cell values of the input layers are calculated.

## 1.2.2. Overlay with Boolean Operators

Spatial intersection produces a new information layer with a variety of new spatial units. It is important to decide which newly created spatial units should be summarized and which must be recorded separately when applying this information to suitability analysis. For this task, Boolean algebra is used. It was established by the English mathematician and logician George Boole (1815 – 1864).

*Boolean algebra* [4] is based on the basics of binary logical operations. It forms a mathematical structure that is based only upon the values 1 (true) and 0 (false). In addition, Boolean algebra provides different links that can be "true" or "false" but never both. The Boolean operators that are used in GIS for linking two spatial selection criteria are AND, OR, XOR, and NOT.

| AND | Conjunction | Results in "true" for all areas that meet both the first and the second criterion | "Which areas are forested and steep?" |
| OR | Disjunction | Results in "true" for all areas that meet either the first or the second criterion, independent on the areas overlapping or not. In other words, at least one criterion has to be "true" | "Which areas are forested or steep?" |
| XOR | Exclusive disjunction | Results in "true" for all areas that meet either the first or the second criterion but not both | "Which areas are either forested or steep but not both at the same time?" |
| NOT | Negation | Results in "true" for all areas that meet the first criterion but not the second. | "Which areas are forested but not steep?" |

*The four Boolean operators*

In many GIS programs Boolean operators directly correspond to available functions and often carry a similar name. Functions like INTERSECT (AND), UNION (OR), and ERASE (NOT) are common functions in many GIS software. The last function is often called "cookie cutting" because the shape of the second criterion is "cut out" of the shape of the first – just like a cookie is cut from the dough. For suitability analysis, the actual Boolean overlay is usually preceded by a selection operation. In the case study, first the polygons with the attribute "forest" will be selected and translated to their own data layer with true / false information: "true" for "forest", and "false" for "no forest". The selection operation can also be carried out based on spatial operators. If a distance criterion is set (such as "at least 100 meters distance to the street"), a buffer function is applied before the overlay. The resulting binary information layers can then be combined with Boolean overlay.

The easiest way to explain Boolean operators is with the help of Venn diagrams. Each circle in the diagram stands for one criterion (criteria A and B). The sets are highlighted in blue if their corresponding Boolean expression results in "true". Choose a set in the Venn diagram and compare it with the corresponding Boolean expression. You can also proceed from the reverse: choose a Boolean expression and compare it with the selected set in the Venn diagram.

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[4] Boolean algebra is a type of mathematics that does not deal with numbers but with truth conditions ("true" / "false"). Instead of the basic arithmetic operations, Boolean algebra handles operations that link two truth conditions as input values together and result in another condition of truth. The most important operators are AND (intersection), OR (union), XOR (exclusive union), and NOT (negation).

The following animation illustrates the Boolean overlay in the case study "Suitability analysis for a wolf habitat" in St. Gittal. Input data are slope and land use. Again, the vector and raster model are compared. First, choose the land use and slope categories you want to overlay (checkboxes in legend window). Second, choose the Boolean operator. The icon "Calculate" shows the result. An example: the operationalization of the criteria for potential habitats resulted in the land use "forest" and slope ">30%". Both are hard criteria and must be met (conjunction or intersection, AND). Select the appropriate checkboxes and the function AND. Calculate the Boolean overlay or the sought habitat respectively. Use the two animations to deepen your understanding of the Boolean overlay. Also, compare the vector and the raster solution.
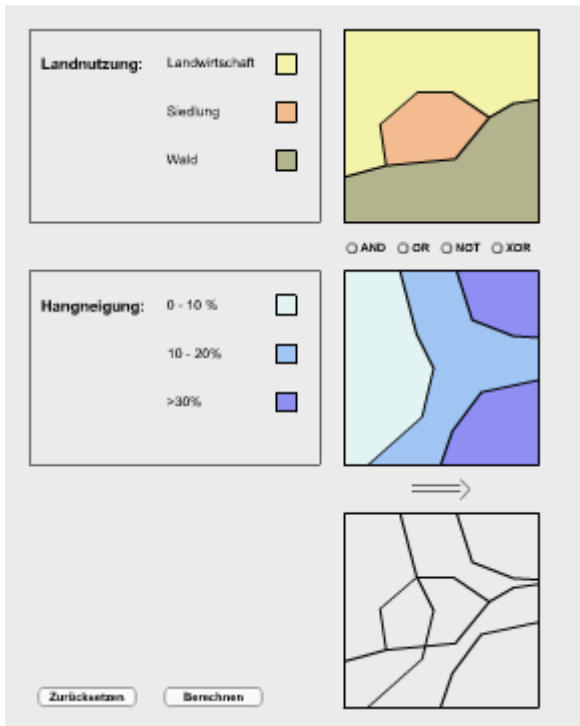


*Boolesche Verschneidung im*
*Vektormodell (zum Vergrössern klicken)*
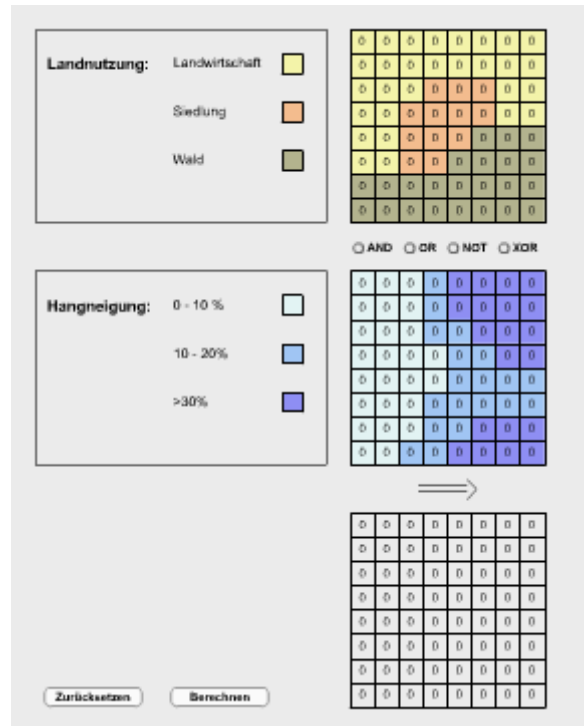
*Boolesche Verschneidung im*
*Rastermodell (zum Vergrössern klicken)*

## 1.2.3. Assessment, limitations, and problems

The Boolean overlay works best for suitability analysis with sharp-edged and clear exclusionary criteria. If settlement area and farmland can be excluded as wolf habitat from the beginning, the potentially suitable area can be narrowed down easily with a simple Boolean overlay. However, for many questions the division of the world into only two categories is unsatisfactory. Additionally, criteria for the natural environment can seldom be set selectively. In the next unit you will learn about more precise approaches to suitability analysis with GIS.

**Raster or vector overlay in suitability analysis?**
Overlays, and in particular Boolean overlays, are possible using both vector and raster models. In general, vector overlay is more complex, time-consuming, and computationally intensive than raster overlay which is easier, faster, and more efficient. Nevertheless, before a raster overlay can be performed, a set of elaborate preprocessing steps must be conducted to approximate the cost for the two methods. There are other reasons to opt for one or the other of the two data models. The following list shows when each model should be considered.

**Advantages of vector overlay:**

- Clear, sharp-edged criteria, e.g. no-building zones in a hazard map where you are not allowed to build under any circumstances;
- Clear, sharp-edged input data;
- Clear distance criteria, e.g. maintaining a minimum distance, "at least 100 meters away from the settlement area."

**Advantages of raster overlay:**

- Fluffy or fuzzy criteria, e.g. the criterion "steep" is difficult to clearly delineate;
- Continuous and arguable data;
- The creation of cost surfaces.

## 1.2.4. Self Assessment

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In these animations you have the chance to check your understanding of Boolean overlay. Proceed as follows:

1. The first step is to decide which input variables you want to use for your suitability analysis. Click the legend boxes of the corresponding attribute classes from the two thematic layers land use and slope. The selected areas are highlighted
2. Select a Boolean operator for the link
3. Click and select the sub-areas in your resulting map that correspond to your query. In the vector model click the resulting polygons; in the raster model, click the resulting pixels
4. Check if you have selected the correct areas by pressing "Check". If you have trouble, do not worry – after several failed attempts you will get help.

# 1.3. Weighted overlay

Boolean overlay of binary thematic layers offers a simple and quick approach to a suitability analysis with GIS. However, for many applications the division of reality into two categories ("true" and "false") is an inadequate representation of reality.

First, with Boolean analysis all influencing factors are of equal importance, by definition. However, most often criteria are not equally influencing the decision. When someone buys a new car, its color and brand might have a heavier weight than its fuel consumption or susceptibility to breakdowns. This principle of assigning weights to influencing factors is used for suitability analysis in GIS as well. This approach is called *weighted overlay* [5] and is discussed in this unit.

Natural phenomena are not defined by sharp boundaries and can seldom be squeezed into binary categories. To be able to create a realistic model of potential wolf habitats, the binary classification into "forest" and "not forest" is not enough. A more precise breakdown of vegetation cover needs to be considered. Binary categories are not fit to measure the influence of spatial variables such as annual precipitation or decreasing values regarding distance to the road. Interval or ratio data (percent forest cover) should be used instead of categorical data (forest / no forest).

## Learning Objectives

- You are able to describe the key advantages of weighted overlay compared to Boolean overlay;
- You know the principle of standardization and can apply it to simple examples;
- You can create your own examples of which to use weighted overlay in GIS;
- You can assess when to use weighted overlay for a suitability analysis.

## 1.3.1. What is a weighted overlay?

In many suitability analyses, some eligibility criteria are more important than others. Often, it is the expectation in a location search to be able to compare several suitable candidates whether, and how strongly, they meet a set of criteria of differing importance. By using the layer principle, one can easily extend the overlay by assigning levels of importance to each criterion.

A numerical weighting factor is assigned to each thematic layer according to its relative importance compared to all other layers. After that, the weighted layers are overlaid as before. This process is called *weighted overlay*. In principle, weighted overlay is possible with rasters and vectors just like Boolean overlay. For example, wolf experts in St. Gittal could explain that the forest, due to its protective nature, is 1.5 times more important for the wolf than steep and rocky terrain. The corresponding weights would be: weight factor 3 for the forest layer but only 2 for the terrain layer. It should be noted that value ranges of the input data layers should correspond to a range between suitable and not suitable (e.g. from 0 to 1). In the resulting suitability layer, the areas or locations with high values are the most suitable.

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[5] Weighted overlay is an intersection of standardized and differently weighted layers in a suitability analysis. The weights quantify the relative importance of the suitability criteria considered.
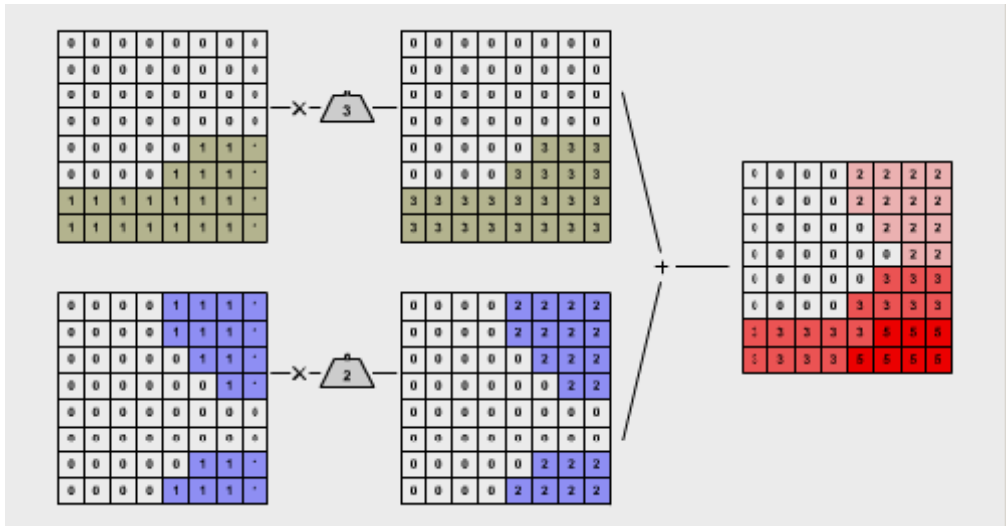
*Weighted overlay - raster model*
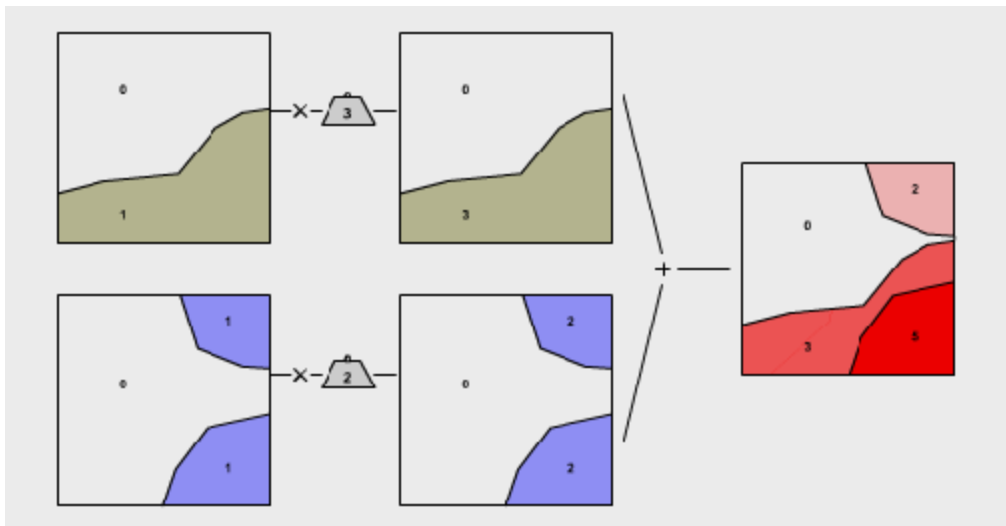


*Weighted overlay - vector model*

In this illustration, both suitability criteria for the wolf habitat in St. Gittal were given weights according to their relative importance. The information layer "forested" is weighted by a factor of 3; the layer "steep terrain" by a factor of 2. After assigning weights, the two layers are added. Suitability values for the resulting layer range from 0 (not suitable) to 5 (very suitable).

## 1.3.2. Weighted linear summation

**Case study St. Gittal**
The following paragraph examines weighted overlay using the example of the wolf habitat in St. Gittal in more depth. To gain a more realistic model of suitable habitats, the example no longer uses only binary input data as the Boolean overlay, but ratio data:

- Vegetation density rather than "forest / non forest"
- Slope rather than "steep / not steep"

- Population density rather than "settlement / no settlement"

The simplest approach to a weighted overlay is the weighted linear summation in the raster model. The following steps show the standard approach to the application of this algorithm:

1. Selecting the criteria: the first step is to choose criteria that characterize the area you are looking for;
2. Standardization: the different measurement scales of the input data need to be matched. It does not make sense to calculate the percent slope directly with population density. Therefore, different units of a standardized numerical index scale (e.g. 0-1, 0-100, 0-255) are assigned to the input data. Consequently, the values of the resulting suitability layers will no longer have units but a numerical suitability index. Assigning input values to the index scale can be accomplished in different ways. The simplest is a linear assignment. With weighted overlay, the translation of heterogeneous input data into a uniform scale for all layers is called *standardization* [6].
3. Distribution of weights: each information layer receives a weight. The weight reflects the relative importance of the each layer respective to the other. The largest weight is assigned to the most important layer. The correct choice of weights is discussed in the section "**Determining the weights**".
4. Application of the algorithm: the algorithm of the weighted linear summation multiplies all grid cells of a layer by their weight. Then, the layers are added together. In the resulting suitability layer the suitable cells have high values while the not suitable cells have low values.

This animation provides you with the possibility to conduct a suitability analysis of your own for the community of St. Gittal. The task is to find potential habitat for the wolf. Decide how the input layers are standardized and weighted.

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1. Selecting the criteria: Selecting the criteria: as you have seen earlier, the wolf prefers dense vegetation and steep, rocky terrain. Now you can also take into consideration that he is likely to avoid settlement areas. The following information layers are available:

   - Forest density (top row): 4 vegetation categories: bare (0%), little vegetation (40%), heavily vegetated (60%), and totally covered with vegetation (100%).
   - Slope (middle row): 3 slope categories: low (10), medium (20), high (30).
   - Population density (bottom row): 3 categories of population density: uninhabited (0), sparsely populated (100), and densely populated (200).

2. Standardization: all input grids should be converted to the value range from 0 to 1. Fill in the values 0 and 1 into the appropriate fields in the animation. Note that for some thematic layers you need to invert the range of values in addition to the standardization. This is the case when a high value of the input layer is unsuitable for the wolf. In that case, the value 0 needs to be assigned.

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[6] Standardization with weighted overlay is defined as the translation of the heterogeneous input data into a uniform scale for all layers (e.g. 0-1, 0-100, 0-255).

3. Distribution of weights: as an expert on wolves, you need to assign weights to each layer. Enter the weights into the fields shaped like weight-stones. The protective forest gets the greatest importance; the forest layer gets a weight of 5; the slope a weight of 3; and the uninhabited areas a weight of 2.
4. Application of the algorithmthe requested suitability layer is the result of multiplying the layers with their weights and the final summation of the layers. A click on the "calculate"-button delivers the results. The areas most suitable for the wolf (with the given assumptions) have values ranging from 7.5 to 8.5. Areas not suitable for the wolf show low values through to 0 (=totally unsuitable).

Now it is your turn to try other standardizations and weightings. Experiment with extreme weight distribution. Pay attention to the changes in the resulting suitability map and try to interpret the results.

## 1.3.3. Weaknesses, problems, and evaluation

As with Boolean overlay, weighted overlay also has its weak points and problems. The largest problem is with the selection of weights. As you have seen for yourself, weights considerably influence the results of suitability analyses. What justification was used to give the vegetation layer the heaviest weight in the example above? Usually, experts facilitate the weighting process and thereby rely on specialist literature. However, different experts implement the weightings according to their own interests. Biologists, tourism professionals, and hunters will have different opinions about the weights used for calculation of the wolf habitat in St. Gittal. In the example above, weighting was arbitrarily conducted. The following unit shows other approaches. Further, it should be noted that experimental use of the weight distribution is applied in many SDSS-applications on purpose. In terms of "what if" scenarios, the influence of different criteria in a suitability analysis can be investigated. Another problem is the choice of the evaluation algorithm. Instead of a linear assignment of the input to an index scale, other functions could be used. For example, instead of adding the weighted input layers, they could be multiplied just the same. Suitability analysis results can vary considerably even with identical input data and identical weights due to different calculation methods. For this reason, the conditions used should be explicitly stated. Only then can the suitability maps serve as what they really are: an objective tool for decision support.

## 1.3.4. Self Assessment

**Addition vs. multiplication**
Suppose that the two layers of the figure **weighted overlay: raster / vector model** are not added but multiplied. What will happen to the resulting layer? Evaluate the following statement: "Cells with 0 in the input layer will have less impact because - opposed to addition – when using multiplication, values are transmitted to the resulting layer."

1. + because + (i.e. first part of sentence correct; second part correct; logical link correct)
2. +/+ (i.e. first part of sentence correct; second part correct; logical link wrong)
3. +/- (i.e. first part of sentence correct; second part wrong; logical link wrong)
4. -/+ (i.e. first part of sentence wrong; second part correct; logical link wrong)
5. -/- (i.e. first part of sentence wrong; second part wrong; logical link wrong)

**Solution**

4. Cells with an input value of 0 are getting a higher influence in multiplication because (b) counts.

**Weights machine**

To consolidate your knowledge about weighted overlay you can now calculate the suitability value of certain pixels in the resulting map to the right. The yellow values from the map on the far right are sought. Insert the values into the fields and click "check". If you are untrained in mental arithmetic, take a sheet of paper to jot down your notes.

**Click to enlarge**

# 1.4. Determining weights

Let's go back to the example of the decision making from the unit "Weighted overlay" about buying a new car. Perhaps the father is interested in the horsepower, the mother pays attention to the safety of the vehicle, and the kids want to decide the color of the car. Of course this example is over-simplified. Nevertheless, it shows that in the process of decision making different stakeholders (father, mother, kids) feel differently about the individual criteria. But how can we find the car that suits the family best? Do the demands of the parents have more weight than the kids'? The same question arises in the search for a new habitat for the wolf in St. Gittal. Let's assume that the experts had agreed on using a weighted overlay for their suitability analysis. How should they weigh the particular criteria or layers of information? How do they decide that the criterion "forest retreat" should be 1.5 times more important than "steep and rocky terrain"? The distribution of weights in a suitability analysis with weighted overlay is as important as it is difficult. This unit shows three approaches to weigh criteria in dialogue with experts.

## Learning Objectives

- You know three different methods to determine the weights of the criteria of an MCE
- For each method you are aware of the disadvantages and advantages and can compare them with each other
- You can perform simple methods for determining the weight in a spreadsheet
- You know how to fill in a cross matrix in Saaty's AHP for relative weighting of factors of an MCE

## 1.4.1. Weighting by ranking

The easiest way is weighting the criteria by ranks in either ascending or descending order. Ascending means that the most important criterion is given rank 1, the second criterion rank 2 etc. When ranking in descending order, rank 1 is given to the least important criterion etc. Once the ranks are assigned, the numerical weights corresponding to the ranks are derived in different ways:

- Rank sum: With n criteria, rank r receives the weight n-r+1
- Reciprocal rank: With n criteria, rank r receives the weight 1/r, its reciprocal value
- Rank exponent: With n criteria, rank r receives the weight (n-r+1)p. The exponent p is a parameter to control the distribution of the weights. If p=0 then all the criteria will receive the same weight. If p=1 then the weighting is as in "Rank sum". The higher the value of p, the steeper the weight distribution is.

Usually, individual weights are normalized for comparability's sake, By dividing the individual weights by the sum of all weights, the individual weights are converted to fractions between 0 and 1. The sum of all normalized weights is 1.

**Advantages and disadvantages**

Weighting by ranking is a popular method because it is easy. However, its explanatory power decreases quickly with an increasing number of criteria. The results of this approach should be interpreted cautiously and documented carefully. They may be used as a first approximation only.

The wolf experts need to evaluate the criteria vegetation cover, slope, population density, distance to the road, and density of prey for a weighted overlay. To do this, the criteria are ranked according to their relative importance. The table shows a possible ranking and the resulting weights. You can make your own ranking and change the exponent p (colored fields).

## 1.4.2. Weighting by rating

Another common method is rating. Here, the ranked criteria receive a score according to their relative importance.

- Point allocation: the overall score is to be distributed within the chosen criteria. For example, with a total score of 100, criteria could receive the weights 35, 30, 20, 10, and 5 points with decreasing importance.
- Ratio estimation: each criterion is provided with an arbitrary score from a defined range of values. The most important criterion receives the highest score (e.g. 100) and the insignificant criteria receive a score of 0.

**Advantages and disadvantages**

This method is easy and therefore quite popular. It is particularly suitable for problems with a few simple criteria whose relative importance can be estimated with common sense or expertise. However, the distribution of the scores is again subjective and often only poorly justified.

This time, a score should be assigned to the five known criteria according to their relative importance. Please note that the sum of the scores needs to correspond to the total score. Again, the weights are normalized for better comparability. Try your own score distributions and compare the resulting weights.

## 1.4.3. Weighting by pairwise comparison

Another method for weighting several criteria is the pairwise comparison. It stems from the Analytic Hierarchy Process (AHP), a famous decision-making framework developed by the American Professor of mathematics (1980).

The following three steps lead to the result:

- Completion of the pairwise comparison matrix: Step 1 – two criteria are evaluated at a time in terms of their relative importance. Index values from 1 to 9 are used. If criterion A is exactly as important as criterion B, this pair receives an index of 1. If A is much more important than B, the index is 9. All gradations are possible in between. For a "less important" relationship, the fractions 1/1 to 1/9 are available: if A is much less important than B, the rating is 1/9. The values are entered row by row into a cross-matrix. The diagonal of the matrix contains only values of 1. First, the right upper half of the matrix is filled until each criterion has been compared to every other one. If A to B was rated with the

relative importance of n, B to A has to be rated with 1/n. If the vegetation cover is a little more important than slope (index 3), the slope is a little less important than vegetation cover (index 1/3). For reasons of consistency, the lower left half of the matrix can thus be filled with the corresponding fractions.

- Calculating the criteria weights: Step 2 – the weights of the individual criteria are calculated. First, a normalized comparison matrix is created: each value in the matrix is divided by the sum of its column. To get the weights of the individual criteria, the mean of each row of this second matrix is determined. These weights are already normalized; their sum is 1.

- Assessment of the consistency matrix: Step 3 – a statistically reliable estimate of the consistency of the resulting weights is made  (1999). This method however, goes beyond this course and is not discussed any further.

**Advantages and Disadvantages**

This method allows a concentration on the comparison of only two criteria at a time. Thereby, the effort required to compare each criteria with every other one is increasing rapidly when handling many classes (to be exact: with n criteria there are n(n-1)/2 comparisons). The integration of the method into a digital environment is easy and can be mastered with a spreadsheet or a GIS. A successful example of the latter is the use of this method in the environmental SDSS in "IDRISI". You can find further information about IDRISI at **Clark Labs**.

This animation allows you to try out the AHP with your own weightings for the case study of the wolf habitat. As an expert on wolves you are asked to evaluate all five criteria in their relative importance. How the standard values can be read: starting in the first row, vegetation was evaluated as "equally to slightly more important" than slope; this cell gets an index of 2. The value 0.5 in the last cell of this first line indicates that slope is "equally or slightly less important" than vegetation. The whole upper right half of the matrix is filled in this manner. The lower left half contains the corresponding fractions of the evaluations. Replace the standard values with your own weightings and study the change of weights.

> **Only pictures can be viewed in this version! For Flash, animations, movies etc. see online version. Only screenshots of animations will be displayed. [link]**

| Definition | Index | Definition | Index |
|---|---|---|---|
| Equally important | 1 | Equally important | 1/1 |
| Equally or slightly more important | 2 | Equally or slightly less important | 1/2 |
| Slightly more important | 3 | Slightly less important | 1/3 |
| Slightly to much more important | 4 | Slightly to way less important | 1/4 |
| Much more important | 5 | Way less important | 1/5 |
| Much to far more important | 6 | Way to far less important | 1/6 |
| Far more important | 7 | Far less important | 1/7 |

| Far more important to extremely more important | 8 | Far less important to extremely less important | 1/8 |
|---|---|---|---|
| Extremely more important | 9 | Extremely less important | 1/9 |

*Weights*

## 1.4.4. Closing assessment

The three methods differ in their underlying scale: they range from ordinal (weighting by ranking), to interval (weighting by rating), to ratio scale (pairwise comparison). While the first two stand without theoretical basis, the last method can be statistically secured. Which of the three approaches used depends on a number of questions: how accurate does the analysis need to be? How vast is the experts' expertise and experience with weighted overlay? How difficult is the method's integration into a GIS? The risk in using weights in a spatial MCE is the inexperienced, careless, or even erroneous determination of weights. Wrong weights lead to wrong results of suitability analysis and thus to wrong decisions. This risk exists in all three methods since ultimately, the weighting is the responsibility of experts. Therefore, each suitability map should inform in detail how it was created and what its underlying assumptions are.

## 1.4.5. Self Assessment

Create an Excel-spreadsheet that can calculate the weights for the five criteria of the case study with the three approaches discussed.

You can find the three methods as separate worksheets in this Excel file: **EXCEL-Datei Weight.xls**

# 1.5. Summary

Suitability analysis with GIS is an evaluation of a location or area for certain use. The evaluation is usually done by intersecting social, ecological, economic, physical, biological, and other criteria. The result of a suitability analysis is usually a suitability or hazard map. It must be distinguished – depending on the selection of criteria for a purpose – if several criteria apply (Multi Criteria Evaluation MCE), or if exclusionary land use claims exist that must be balanced (Multi Objective Evaluation MOE). Overlay refers to the digital integration of location and attribute information of several spatial layers. Boolean overlay is based on the assumptions that different combinations can be either "true" or "false", but never both (e.g. we are looking for areas for which the combination "forest" and "eastern slope" are "true"). Boolean overlays available in common GIS software are intersection (AND), union (OR), exclusive union (XOR), and negation (NOT). A distinction in categories of only "true" and "false" is rarely realistic. Therefore, layers based on interval and ratio scales and weighted decision criteria are introduced. The weak spot of weighted overlay is the fair allocation of weights. It can vary considerably depending on the interests of the experts who are assigning the weights. It can also noticeably influence the results. Rules for weighting are defined by different methods to avoid arbitrariness. The simplest weighting is based on ranking the criteria: the higher the rank of a layer the larger is its weight. Another method is rating: a part of the set overall score is assigned to the layers according to their importance. Furthermore, weighting can be done using pairwise comparison: the essence of this approach is that two criteria are evaluated at a time to determine their relative importance. The weight of each layer is calculated in a comparison matrix. All three methods involve the risk of producing results of limited significance by careless and untrustworthy weighting.

# 1.6. Recommended Reading

- **Heywood, I.; Cornelius, S.; Carver, S.**, 2006. *An Introduction to Geographical Information Systems.* 3rd Edition. New York: Longman.  [p. 238-243]

# 1.7. Glossary

**Boolean algebra:**

Boolean algebra is a type of mathematics that does not deal with numbers but with truth conditions ("true" / "false"). Instead of the basic arithmetic operations, Boolean algebra handles operations that link two truth conditions as input values together and result in another condition of truth. The most important operators are AND (intersection), OR (union), XOR (exclusive union), and NOT (negation).

**Boolean Overlay:**

The Boolean Overlay is an intersection of binary coded data layer using the Boolean operators AND, OR, XOR, and NOT. The result of a Boolean Overlay is again a data layer with areas that are true and areas that are false.

**Decision support with GIS:**

Decision support in GIS is a system based on the suitability analysis to support decision-makers on issues of spatial and environmental planning. Spatial models and scenarios are used to assess different land use types. For multiple selection criteria and only one objective, a multi-criteria evaluation (MCE) is used. In the more complex case of multiple, possibly even exclusionary objectives, the different land uses need to be weighed (multiple-objective evaluation, MOE).

**Standardization:**

Standardization with weighted overlay is defined as the translation of the heterogeneous input data into a uniform scale for all layers (e.g. 0-1, 0-100, 0-255).

**Suitability analysis:**

Suitability analysis is an evaluation of the suitability of a location or area for a certain use. Suitability analysis is usually done through an intersection of social, ecological, economic, physical, biological or other criteria. Suitability maps are usually the result of a suitability analysis. They display the spatial distribution of the determined values in a graphical form.

**Weighted overlay:**

Weighted overlay is an intersection of standardized and differently weighted layers in a suitability analysis. The weights quantify the relative importance of the suitability criteria considered.

# 1.8. Bibliography

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