GIS Data Sources

(4) GIS & Spatial Decision Support Systems

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Spatial decision support is why we are using GIS. Although much of what you have learned or will learn in this Summer School is process-oriented and about the things you can do with data rather than data itself – this unit is all about process. You will see how all the aspects of spatial analysis that you have learned or will learn are connected in a workflow with ultimately one goal: to make a decision about some spatial phenomenon.

In order to use a big (and often clunky) tool like GIS, the problem that we try to solve is usually a big one as well. We will therefore discuss the various categories of spatial decision problems and how we have to adapt the tools to solve them. Alternatively, the problem may be rather trivial (like where is the next cinema) – in which case the GIS component would have to be simplified in such a way that it becomes transparent to the end user. In other words, the middle part of this unit is about customization of GIS.

Finally, large problems require a structured approach, and the last third of the material will be devoted to the discussion of the Analytical Hierarchy Process.

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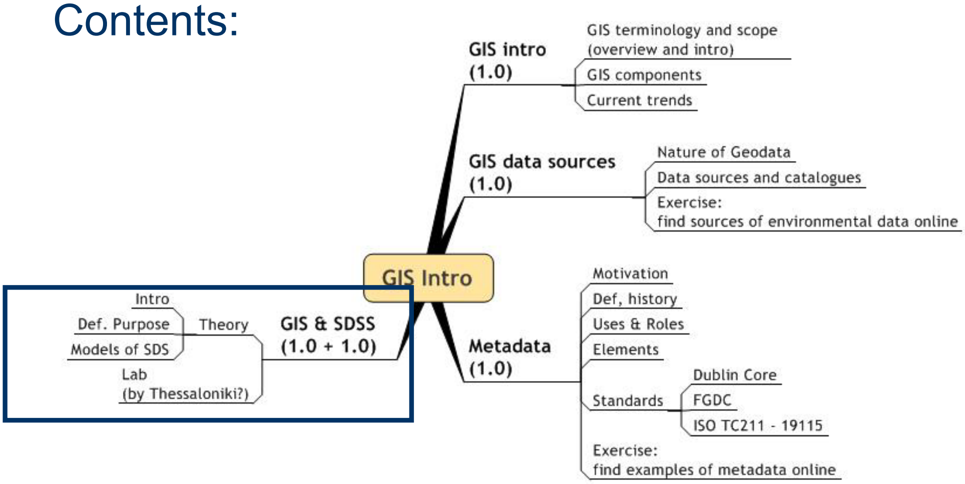
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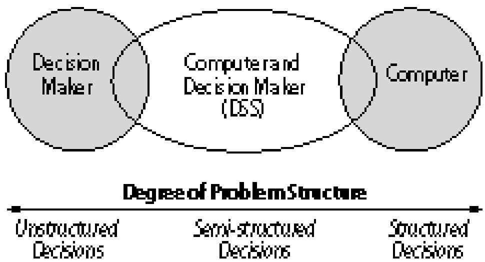
Spatial Decision Support Systems (SDSS)

- It is an interactive and computer-based system.
- Aim: higher effectiveness of decision making and minimizing uncertainties related to decisions.



Source:
MALCZEWSKI, Jack (1997)

Spatial Decision Support Systems (SDSS) is an approach where decision theory and mathematical planning are crossing with GIS. SDSS are computer-based systems that help users to explore the decision problem in an interactive and recursive fashion in all phases of the decision-making process. Its aim is to support users in achieving a higher effectiveness of decision making while solving complex spatial decision problem.

The main characteristics of spatial decision problems include the large number of decision alternatives, the spatial variability of consequences, the different preferences among decision makers, and so forth. Therefore, uncertainties to decisions arise easily.

Policy development and planning are the areas where the SDSS concept has major applications. Some problems which can be structured / modelled are solved in an rule-based *automated* manner, while non-programmable aspects are tackled by decision makers. The SDSS concept is based on the DDM (dialog, data, model) paradigm. Hence, the components of SDSS are a DBMS containing the functions to manage the geographic data base, a *Model Base Management System* (MBMS) including the functions to manage the model base, and a *Dialog Generation and Management System* (DGMS) managing the interface between the user and the rest of the system. A well-designed SDSS should have balance among the three capabilities.

From Map Algebra to SDSS

Tomlin distinguishes between
- Descriptive modelling
- Prescriptive modelling

The latter is what we deal with here; it includes
- Siting of proposed land use
- Routing of freight
- Finding a restaurant in a foreign place
- etc.

•Descriptive model describes a geographic quality as a function of existing conditions.

•Prescriptive model inverts this idea by expressing the modifications necessary to satisfy the geographic qualities sought, e.g.,

of potential erosion, versus

prescribing land uses for zones of this map to avoid erosion

SDSS Process

In Tomlin's terms, SDSS is not the exclusive realm of prescriptive modelling. Some of the descriptive techniques are mandatory as well.

A typical sequence will consist of:

- initial problem statement (descriptive)
- generation of solutions to this problem (prescriptive), and
- evaluation of the results (descriptive)

Descriptive functions describe a particular situation. They are either simple queries or simple analyses to describe a particular pattern or situation.

Prescriptive functions invoke a change in a spatial situation. That change brings us closer to or even is the desired result.

We then check with the use of descriptive functions whether we accomplished what we set out to do.

Problem Typology

- Single objective
- Semi- or ill-structured problems
- Comparing the result with the objectives
- Sometimes multiple objectives
  - Heuristic vs. algorithm

•The generation of a solution is straight-forward if we have a single well-defined objective.

•The process becomes more complicated, if the described conditions are such that the problem proves to be over- or under-constrained resulting in *semi-* or *ill-structured* problems.

•The evaluation of the solution requires to describe the effects of the allocation and to compare the result with the objectives.

•Sometimes, multiple objectives have interdependencies that do not allow for a final description of the initial problem statement.

•The solution then requires a *heuristic* rather than an *algorithm.*

Heuristic vs. Algorithm

Algorithm

Specific responses to conditions that are presumed to be known with certainty

Heuristics

Responses may or may not be specific and are not necessarily certain

- Explorative process

Heuristic:

•Explorative process where we have to play with one possible solution, evaluating its result before turning to the next solution.

•We then have to compare all the evaluations in a final step of our prescriptive modelling process.

Characteristics of a DSS

- For ill-structured problems
- Powerful yet easy to use GUI
- Combining analytical models + data
- Helping to interactively explore solution space

Decision support systems are a specialized software products. Among their requirements are:

•Designed to solve ill-structured problems (there is no need for simple tasks).

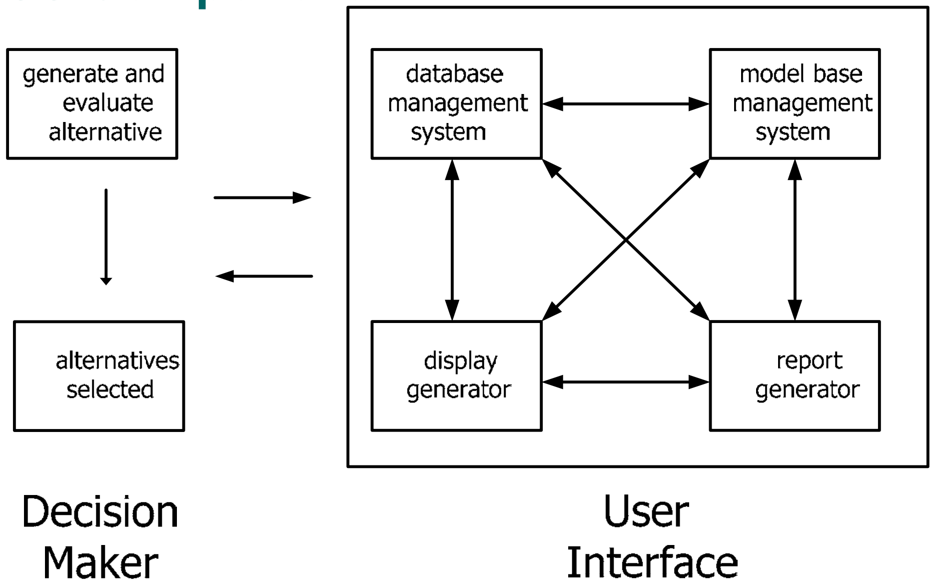
•Powerful and easy to use user interface – you be the judge whether GIS fulfil this requirement.

•Combining analytical models and data.

•Helping the user to explore the solution space by using the models to generate a series of feasible alternatives.

•Interactive and recursive solution seeking strategies offering multiple paths rather than a single sequence.

DSS Components



The user interface is the 5th necessary component of a DSS. It combines the other components, hiding the boundaries between the individual components and providing a common look and feel as well as a coherent workflow.

Spatial Additions

- Ability to process spatial data
- Representation of complex spatial relations
- Spatial *analytical* techniques
- Map output

Everything on the previous slides cannot be done without a GIS.

GIS is good for handling, managing, indexing, archiving, and accessing spatial data.

GIS is essential for representing or querying about spatial relations.

GIS is ok for basic spatial analysis, although a number of statistics packages (especially 'R') are doing a better job.

GIS is finally pretty good at creating acceptable cartographic output. The proverbial picture saying more than a thousand words (or spreadsheet columns).

GIS is NOT good at doing any of the tasks described on the previous slides.

We therefore have to marry different systems or to develop systems from scratch to have a true SDSS.

Use of Conceptual Models

Locational models as basis for planning support
- Economics
- Ecology
- Transportation

Importance of having a well-grounded theoretical foundation

Locational Models as a Basis for Planning Support

•Have a well-developed system structure

•Are organized in terms of hierarchies and networks of sub-systems

•With system behaviour that strikes a balance between various forces:

economics: demand and supply

ecology: predator and prey, etc.

Balances of Power

•Cities as a system of markets with land as commodity and rent being the balancing item between demand and supply

•Other examples for equilibrating forces:

congestion in transport systems

wages on the labour market

•Planning is supposed to resolve failures of this type of market situation

Well-developed Theories

• Human geography

housing markets

travel demand

retail location

• Physical geography

User Interfaces for SDSS

- Interactively changing model parameters
- Customization of/with/by GIS

•Exploring the nature of *semi-structured*, *locational* problems by enabling them to *iteratively* change model parameters and to examine the effects of these changes.

•This is where your GIS customization comes into play.

Decision Support Terminology

- Decision
- Criterion
  - Factors and constraints
- Objective
- Decision rule
- Choice function and heuristic

Decision
A choice between alternatives. These alternatives may represent:

different courses of action,

different hypotheses about the character of a feature, or

different sets of features

Criterion
A criterion is some basis for a decision that can be measured and evaluated. It is the evidence upon which a decision is based.

There are two types of criteria:

A factor enhances, or detracts from, the suitability of a specific alternative under consideration. It is measured on a continuous scale. Factors are also known as *decision variables* or *structural variables*.

A constraint serves to limit the alternatives under consideration.

Objective
Perspective that guides the structuring of decision rules.

Example:

If you were to allocate forest land for timber harvesting, an objective may be to do so with the least impact on recreational uses or the ecological integrity of the forest ecosystem.

The objective then guides the choice of criteria and weights to be assigned to these criteria.

Decision Rule

The procedure by which criteria are combined to arrive at a particular evaluation, and by which evaluations are compared and acted upon.

Decision rules may be simple thresholds applied to a single criterion, or complex combinations, or comparisons, of multi-criteria evaluations.

Decision rules typically contain procedures for combining criteria into a single composite index and a statement of how alternatives are to be compared using this index.

Choice Function

Choice functions provide the mathematical means to compare alternatives.

They involve some form of optimization (such as maximizing or minimizing some measurable characteristic).

Evaluation

The process of applying a decision rule to a set of alternatives

- Multi-criteria
- Multi-objective
  - Complementary
  - Conflicting
- Forest use example

Multi-Criteria Evaluation

The process in which several criteria are evaluated in order to meet a specific objective.

Taking several criteria into account in an evaluation can be achieved through *weighted linear combination* or *concordance-discordance analysis.*

Multi-Objective Evaluation

The decision process in which several objectives must be satisfied simultaneously

These objectives may be complementary,

two or more objectives are met through this decision in some specified manner at the same time, or

the objectives may be conflicting, i.e. they cannot be met at the same time.

Example:

Land is to be allocated to various types of land uses:

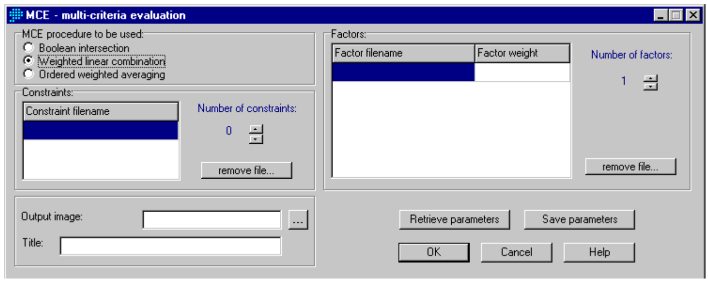
Wildlife preservation (objective 1) and recreation (objective 2) are often seen as complementary objectives.

Wildlife preservation and maximum timber harvesting (objective 3) are usually considered as conflicting objectives.

Decision rules determine how to settle conflicting (competing) objectives.

Multi-Criteria Evaluation (MCE)

- MCE ranks criteria in terms of their importance.
- Implemented MCE keeps the decision-finding process more accessible to others.



Source: IDRISI

At a conceptual level there is nothing complicated about multi-criteria evaluation (MCE). MCE methods involve either the qualitative or quantitative weighting, scoring or ranking of criteria in terms of their importance to either a single or multiple set of objectives. MCE trades off one factor against the other by comparing the pros and cons.

To help illustrate how MCE methods work it is useful to take a simple example. Someone has been given an new job and he must move to a new city. One of his first task will be to find a new residence. In order to assist him in searching for a new residence it is likely that he will put together a list (mentally or on paper) of the factors he need to consider (e.g. type of neighbourhood, cost of property, proximity to schools, nature of the environment, rural or urban). Such an informal weighting and scoring method is the most common modelling technique used by decision makers.

Implemented MCE routines in GIS software are often realized by a graphical user interfacing approach, which permits the decision maker to work with familiar concepts. This will allow exploration of the options resulting from the application of different techniques, and in particular offers the capability to explore the sensitivity of the decision rule and the effects of variations in the importance attached to criteria. MCE is e.g. implemented in IDRISI.

Weighted Linear Combination

Weighted factors are summed up to yield a suitability map S

$$S = \sum w_i x_i$$

w_i = weight of factor *i*

x_i = (standardized) criterion score of factor *i*

We rescale attributes to a common evaluation scale (0..1 or 0..100) and then average the scores.

Often we also apply an importance weight to each factor.

Ordered Weighted Average

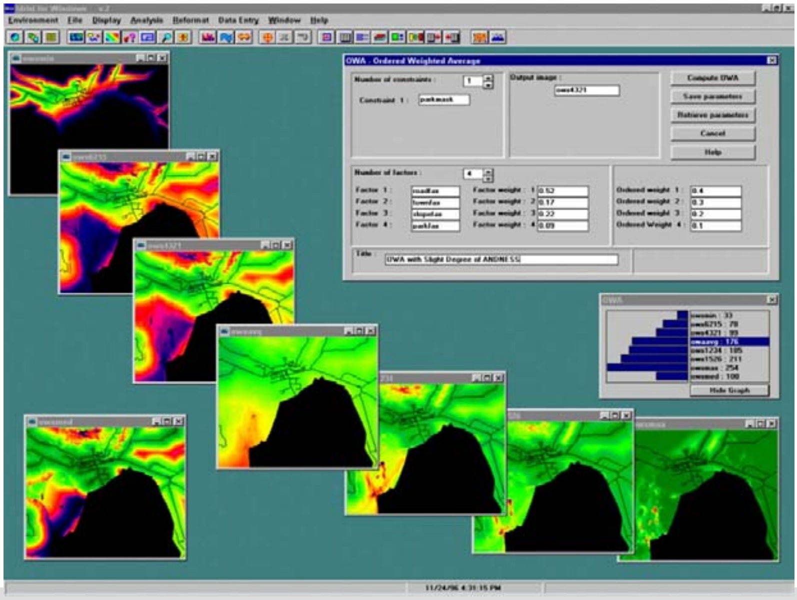
The OWA procedure results in decision strategies that vary along two dimensions: risk and tradeoff. At one extreme, we have a solution which assumes the least risk possible and consequently allows no tradeoff (the lower left corner of this triangle). This corresponds most closely with the Boolean intersection operator and is, in fact, the same as the most commonly used fuzzy set intersection operator (the minimum operator). This result is illustrated by the upper-leftmost solution in the above figure.

At the other extreme is the solution at the lower-right of the triangle. This corresponds to the logical “OR” operation and is the most optimistic solution. In this case, locations are characterized by their best qualities, clearly with a necessary assumption of risk by the analyst (i.e., the risk that the poorer qualities that are ignored will adversely affect its actual performance as a solution). Note that this solution exactly corresponds with the Fuzzy Set union (maximum) operator.

The remaining corner of the triangle (the apex) represents the standard Weighted Linear Combination solution of the previous slide. Here we have a case of full tradeoff, and consequently intermediate risk. Here poorer qualities are not ignored, but they can be compensated for.

A glance at the triangle shows that many other solutions are possible. In fact, there is a cascade of solutions by systematically varying the degree of risk and tradeoff in the solution. Thus it is possible to produce solutions that are strongly conservative (risk averse) but which allow some flexibility in trading off small imperfections by strong qualities in other factors. OWA can produce any possibility within this triangle.

OWA Application



This figure is an evaluation of suitability for development based on proximity to roads and the town centre, slope and distance from a protected nature reserve - green and yellows areas are best; red and blue are worst.

In the upper-leftmost window, we have a solution which assumes the least risk possible and consequently allows no tradeoff (the lower left corner of this triangle). This corresponds most closely with the Boolean intersection operator and is, in fact, the same as the most commonly used fuzzy set intersection operator (the minimum operator).

The solution in the right-most window corresponds to the logical “OR” operation and is the most optimistic solution. In this case, locations are characterized by their best qualities.

The cascade of solutions windows shows the effects of systematically varying the degree of risk and tradeoff in the solution. The progression from the left-most to the right-most solution corresponds with a trajectory from the lower-left corner of the triangle on the previous slide, to the top of the triangle, and then back down to the lower-right.

Uncertainty and Risk

Uncertainty
- Database uncertainty
- Decision rule uncertainty

Risk
- Probabilistic likelihood of being wrong
- Resulting from uncertainty

Database uncertainty

Assessment of the criteria which are enumerated in the decision rule.

Measurement errors and conceptual errors are common sources of this type of uncertainty.

Decision rule uncertainty

Manner in which criteria are combined and evaluated to reach a decision.

Inadequate model parameterization or threshold setting and lack of theoretical understanding of a phenomenon are common sources for this type of uncertainty.

Risk

Probabilistic likelihood that a certain decision will be wrong.

Risk is a result of uncertainty.

In different fields of science, risk is more specifically defined to include a measure of cost or consequence of a wrong decision or non-desired event.

Analytical Hierarchy Process

Two-step process

- Creating hierarchy of problem features
- Pair-wise comparison between elements at each level of hierarchy

Subordinate features may be

- Objectives
- Scenarios
- Events
- Actors
- Outcomes
- Alternatives

Used to determine the weights of factors

Two steps:

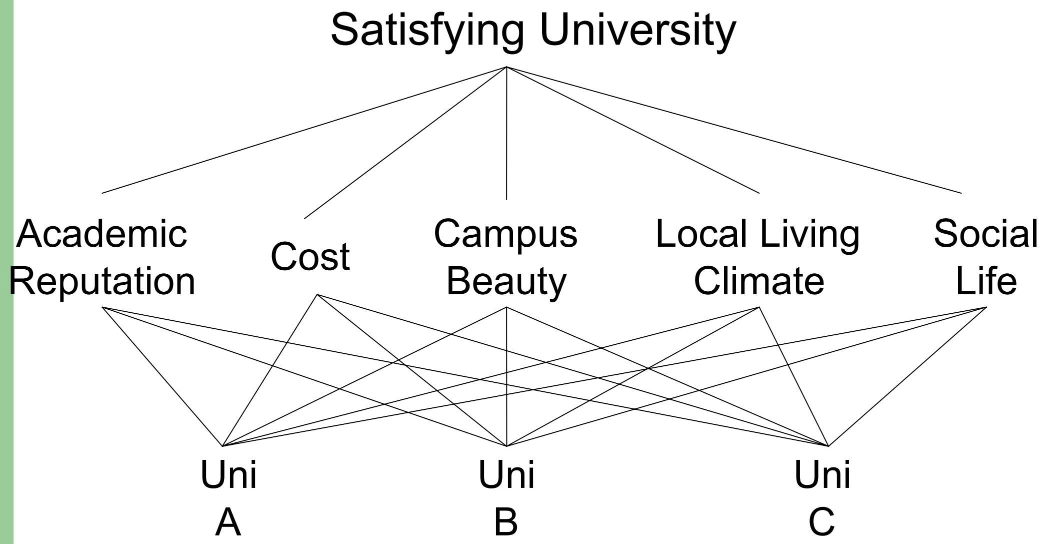
Structuring of a problem in a hierarchy consisting of goal and subordinate features of the problem.

Pair-wise comparisons between elements at each level.

Subordinate features may be objectives, scenarios, events, actors, outcomes, or alternatives.

Analytical Hierarchy process (AHP) is a quantitative method for ranking decision alternatives by developing a numerical score to rank each decision alternative based on how well each alternative meets the decision maker’s criteria.

AHP Example, part I



The AHP method is based on two principles:

•Build a hierarchy of criteria, in the form of graph where, on the top end you represent the decision to make and on the bottom end you represent the alternatives among which you have to decide the preferred one.

•At each node of the hierarchy perform a weighting, summing to 1, which gives the relative preferences of the decision maker at this level of the hierarchy for the object that are directly linked to the node. This weighting is realized through a sequence of pair-wise comparisons from which a consistent normalized set of weights is deduced.

The next slide gives an example of the actual procedure.

AHP Example, part II

	Academic Reputation	Cost	Campus Beauty	Local Living Climate	Social Life
Academic Reputation	1	3	5	3	7
Cost	1/3	1	5	5	9
Campus Beauty	1/5	1/5	1	1	3
Local Living Climate	1/3	1/5	1	1	3
Social Life	1/7	1/9	1/3	1/3	1

We can easily make pair-wise comparisons. For example we compare alternatives 1 and 2. We can take the analogy of a scale and give a ratio between 1 and 9 that will represent our level of preference for the most valuable of the two alternatives. A ratio equal to 1 means that the two alternatives are equivalent. A ratio 9 means that alternative 1 weighs 9 time more than alternative 1. Indeed if we were weighing alternative 2 in comparison with alternative 1 we should obtain a ratio 1/9, in this case.

We can repeat the pair wise comparison for another pair of alternatives

We thus obtain a matrix of ratios between each of the alternatives in a series of pair-wise comparisons. The problem now is to infer from this table the relative weights of the three alternatives. We have to normalize the columns, which then gives us the relative weight for each of the criteria – something that we would have a hard time to come up with if asked directly.

Summary

- Spatial decisions are everywhere
- Only ill-structured problems require a systematic procedure
- SDSS goes beyond traditional GIS or decision support
- Criteria and objectives
- Methodologies

Again, in this lesson, we have barely scratched the surface of this topic. There are semester-long courses just on SDSS. What you want to take from this lesson is:

1.We constantly make decisions, many of which are influenced by location and geography.

2.Many decisions are easy to make or have become routine. Decision support systems are only needed if the number of criteria are overwhelming or if the objectives are conflicting.

3.If you thought that GIS is complicated – full-blown SDSS are monsters, typically requiring a team of experts.

4.We need to understand the role of criteria and objectives.

5.They determine the rules and procedures that are applicable in a particular situation.