GIS and Multicriteria Decision Analysis

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Multicriteria – what does it mean?

GIS – what does it mean?

Definition of MCDM

"Multi-Criteria Decision Making (MCDM) is the study of methods and procedures by which concerns about multiple conflicting criteria can be formally incorporated into the management planning process", as defined by the International Society on Multiple Criteria Decision Making

Could it be…..?
Measuring and Integrating a multitude of attributes together to answer a common…. Social Factors Biodiversity Engineering Land Use Environmental Considerations

To Help See the Whole Picture

What helps you in seeing the whole picture?

- What do you need to make a choice? Data? Question?
- Problem?
- How do you end up with choices that are worthwhile to choose from?
- Is there some higher logic that should be taken into account?
- Why is deciding so hard?
- Could someone or perhaps a group of people do the decision ... or decision process instead of me 😊?
- ...  ...

The Decision Theory

- Decision analysis looks at the paradigm in which an individual decision maker (or decision group) contemplates a choice of action in an uncertain environment.
- The decision theory helps identify the alternative with the highest expected value (probability of obtaining a possible value).
- The theory of decision analysis is designed to help the individual make a choice among a set of pre-specified alternatives.
- The decision making process relies on information about the alternatives.
- The quality of information in any decision situation can run the whole gamut from scientifically-derived hard data to subjective interpretations, from certainty about decision outcomes (deterministic information) to uncertain outcomes represented by probabilities and fuzzy numbers.
- This diversity in type and quality of information about a decision problem calls for methods and techniques that can assist in information processing.
- Ultimately, these methods and techniques (MCDA, MCDM) may lead to better decisions
So much depends on data & their scales

Four Types of Data

GIS
Nominal
Discrete
Ordinal
Interval
Continuous
Ratio


A typical Multi-criteria Evaluation Problem

Indicators
Composite Index

The Decision Paradigm

- Our values, beliefs and perceptions are the force behind almost any decision-making activity.
- They are responsible for the perceived discrepancy between the present and a desirable state. Values are articulated in a goal, which is often the first step in a formal (supported by decision-making techniques) decision process. This goal may be put forth by an individual (decision-maker) or by a group of people (for example, a family).
- The actual decision boils down to selecting "a good choice" from a number of available choices.
- Each choice represents a decision alternative.
- In the multi-criteria decision-making (MCDM) context, the selection is facilitated by evaluating each choice on the set of criteria.
- The criteria must be measurable — even if the measurement is performed only at the nominal scale (yes/no; present/absent) and their outcomes must be measured for every decision alternative.
- Criterion outcomes provide the basis for comparison of choices and consequently facilitate the selection of one, satisfactory choice.

Classification of Multi-criteria Decision Problems

Multi-Criteria Decision Making (MCDM)

Multi-attribute Decision Making (MADM)

Individual Group

Individual Group

Certainty Uncertainty

Certainty Uncertainty

Bayesian

Evidence Theory

Zadeh

Fuzzy Set

Evidence Theory

Zadeh

Fuzzy Set

Different Decision Methods

- At a practical level, mathematical programming under multiple objectives has emerged as a powerful tool to assist in the process of searching for decisions which best satisfy a multitude of conflicting objectives, and there are a number of distinct methodologies for multi-criteria decision-making problems that exist.
- The decision theory is descriptive when it shows how people take decisions, and prescriptive when it tells people how they should take decisions.
- These methodologies can be categorized in a variety of ways, such as form of model (e.g. linear, non-linear, stochastic), characteristics of the decision space (e.g. finite or infinite), or solution process (e.g. prior specification of preferences or interactive).
- For an example of a multi-objective methodology for the management of water resources integrating climate change and climate variability data, look at the article on Climate and Water in the West: Science, Information, and Decision-Making.

Decision Support Systems

- Decision support systems (DSS) are computerized information systems that support decision making activities.

The Computer-Aided Decision

- A decision involves making a selection from a set of alternative choices. Broadly speaking, a decision-support systems (DSS) is simply a computer system that helps you make a decision by leveraging the multi-criteria decision-making model. DSS provide a means for decision-makers to make decisions on the basis of more complete information and analysis. Among the main advantages of the use of DSS are the following:
- Increased number of alternatives examined
  - Better understanding of the business / problem
  - Faster response to unexpected situations
  - Improved communication
  - Cost savings
  - Better decisions
  - More effective teamwork
  - Time savings
  - Better use of data resources
When Theory Meets Practice

- There is a need for approaches that combine available quantitative data with the more subjective knowledge of experts.
- Decision-theory techniques applied by high-end knowledge professionals have been successfully used for contrasting expert judgments and making educated choices.
- The multi-criteria decision-making model, by coupling theory and knowledge, provides an analytical approach to expert consultation and is adapted for a variety of technology and business fields aiming at suitability assessments.

Spatial Multicriteria Analysis

- Decision making with GIS
- Ranking definable units
- Weighting evaluation criteria
- Suitability modeling for areas not defined by some geographic unit
- Fuzzy logic modeling

Decision making with GIS

- Making decisions is part of everyday life
- Often we learn from what has worked or not worked in the past and use the experience to help us make future decisions.
- If we don’t have prior experience, we often can benefit from a systematic and comprehensive approach to decision making.
- The multi-criteria methodology is such an approach

Decision making

- Define the desired goals, objectives, or purpose of the project
- Select evaluation criteria that can relate technology capabilities for achieving the desired project goals or objectives
- Once the criteria are selected they are traditionally rated among each other using weights which reflect the decision makers preference structure
- Identifying the alternatives that are candidates for ranking
- Perform the selection process using an MCDM model
- Perform sensitivity analysis

MCDM (just to remind you)

- Multiple criteria decision making
- Helps decision makers choose among alternatives by showing the tradeoffs between the criteria
- Helps decision makers voice their preferences and make choices in a rational, consistent, and a documentable manner
- Decision makers usually strive to find an optimal compromise among several objectives
- In a multiple criterion problem human value judgments, tradeoff evaluations, and assessments of the importance of criteria are an integral part of the problem
- Powerful tool when combined with GIS data for decision making

MCDM framework
For example if…

The overall goal is to rank watersheds based on landscape factors that are conducive to pollution runoff

Steps

1. Define the objective or goal in the ranking/prioritization of the features
2. Select appropriate evaluation criteria, these will be attributes to build data for in the GIS layer
3. Evaluate if the criteria is a positive (+) or negative (-) factor in the ranking
4. Normalize the data to comparable units
5. Calculate a score for each feature and display results

Example: Step 1

Define the objective or goal in the ranking/prioritization of the features
The overall goal is to rank watersheds based on landscape factors that are conducive to pollution runoff

Example: Step 2

Select appropriate evaluation criteria, these will be attributes to build data for in the GIS layer
The criteria we will include are:
- road length
- elevation change
- row crop %
- area that is surface mines
- area that is wetlands

Example: Step 3

Evaluate if the criteria is a positive (+) or negative (-) factor in the ranking
- road length -> More roads will increase runoff
- elevation change, -> More elevation change will increase runoff
- row crop %, -> More row crops will increase pollution
- area that is surface mines, -> More surface mines will increase pollution
- area that is wetlands -> More wetlands will decrease pollution

“The overall goal is to rank watersheds based on landscape factors that are conducive to pollution runoff”
Example: Step 4

1. Find maximum value for each criteria
2. Create a new field
3. Calculate values = (value/max value for the field) * 100

Example: Step 4 continued

1167 was the largest value for elevation, it is now normalized to a 0 to 100 range, repeat for all other fields using max value

Example: Step 5

- Add a field “results” and calculate a score for each feature and display results
  - Use the table calculator to add a new field and add criteria that will increase pollution and subtract the criterion which will decrease pollution using the normalized values

NOTE:

Weighting evaluation criteria

Result

- Use legend to classify and display results
Methods to create weights for criteria

- Point allocation
- Rank sum
- Rank reciprocal
- Rank exponent
- Pairwise comparison

Point allocation

- Weights are estimated by the decision maker on a predetermined scale, for example 0 to 100.
- In this approach, the more points a criterion receives, the greater its relative importance.
- The total of all criterion weights must sum to 100. This method is easy to normalize.

<table>
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<th>Weight</th>
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<tr>
<td>Elev change</td>
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</tr>
<tr>
<td>Wetlands</td>
<td>25</td>
</tr>
<tr>
<td>Roads</td>
<td>5</td>
</tr>
<tr>
<td>Row crops</td>
<td>40</td>
</tr>
<tr>
<td>Mining</td>
<td>20</td>
</tr>
<tr>
<td>-------------</td>
<td>--------</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

Criterion Weighting, ranking

- Rank sum, where normalised weight $w_j$ for the $j$th criteria, $n$ is number of criteria and $r_j$ is the rank position of the criterion

$$ w_j = \frac{n - r_j + 1}{\sum_k (n - r_k + 1)} $$

- Rank reciprocal

$$ w_j = \frac{1}{r_j \sum r_k} $$

- Rank exponential

$$ w_j = \frac{(n - r_j + 1)^p}{\sum_k (n - r_k + 1)^p} $$

Notes on rank sum, reciprocal, exponent

- These three ranking methods are very attractive due to their simplicity.
- They also provide a satisfactory approach to weight assessment. As a starting point in deriving weights, the three ranking methods provide a way to simplify multicriteria analysis.
- However, they are limited by the number of criteria to be ranked.
- This method is really not appropriate for a large number of criteria since it becomes very difficult to straight rank as a first step.
- Another problem is in the lack of any real theoretical foundation.

Rank sum, reciprocal, exponent

- Straight rank is first step

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rank sum</th>
<th>Rank reciprocal</th>
<th>Rank exponential</th>
</tr>
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<tr>
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<td>10</td>
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</tr>
<tr>
<td>Wetlands</td>
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<td>25</td>
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</tr>
<tr>
<td>Roads</td>
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<tr>
<td>Row crops</td>
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<td>20</td>
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<tr>
<td>-------------</td>
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<td>------</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Pairwise comparison

<table>
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<th>Rank 1</th>
<th>Rank 2</th>
<th>Rank 3</th>
<th>Rank 4</th>
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<tbody>
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<td>Elev change</td>
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<td>9</td>
<td>8</td>
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<tr>
<td>Wetlands</td>
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<td>37</td>
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<tr>
<td>Mining</td>
<td>20</td>
<td>19</td>
<td>18</td>
<td>17</td>
</tr>
</tbody>
</table>

| Weights | 1.395 | 5.280 | 10.000 |

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Rank 1</th>
<th>Rank 2</th>
<th>Rank 3</th>
<th>Rank 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elev change</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Wetlands</td>
<td>25</td>
<td>26</td>
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<td>28</td>
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<td>Roads</td>
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<td>7</td>
<td>8</td>
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<tr>
<td>Row crops</td>
<td>40</td>
<td>39</td>
<td>38</td>
<td>37</td>
</tr>
<tr>
<td>Mining</td>
<td>20</td>
<td>19</td>
<td>18</td>
<td>17</td>
</tr>
</tbody>
</table>

| Weights | 1.395 | 5.280 | 10.000 |
Example of pc sheet

Notes on pairwise comparison

Advantages of pairwise comparison include:
- The method requires only two criteria to be considered at one time,
- And the method has been tested theoretically and empirically for a variety of decision situations including spatial decision making (Malczewski, 1999)

Multiattribute Decision Rule (SAW)

- Simple Additive Weighting (SAW) method

\[ A_i = \sum_j w_j x_{ij} \]

Steps in GIS based analysis
1. Define set of evaluation criteria and set of feasible alternatives
2. Standardize each criterion map layer
3. Define the criterion weights
4. Construct the weighted standardized map layers (multiply w and x)
5. Generate the overall score for each alternative using add overlay operation on the weighted standardized layers
6. Rank alternatives according to the overall performance score

Integrating the weights into the ranking model

- Say we decided to use the weights from the rank sum method

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elev chang</td>
<td>.133</td>
</tr>
<tr>
<td>Wetlands</td>
<td>.267</td>
</tr>
<tr>
<td>Roads</td>
<td>.067</td>
</tr>
<tr>
<td>Row crops</td>
<td>.333</td>
</tr>
<tr>
<td>Mining</td>
<td>.200</td>
</tr>
</tbody>
</table>

\[ \sum_j w_j u_{ij} \]

Value/Utility Function Approaches (see also group utility functions)

- Simple Utility method (preferential and utility independence)

\[ U_{ij} = \sum_j w_j u_{ij} \]

Steps in GIS based analysis
1. Define set of attributes and set of feasible alternatives
2. Estimate the value (utility) function for each attribute and use the function to convert the raw data to utility map
3. Standardize each criterion map layer
4. Define the criterion weights
5. Construct the weighted standardized map layers (multiply w and x) and generate the overall score
6. Rank alternatives according to the aggregate value (utility), the alternative with highest value is the best alternative

Suitability modeling
### Suitability models

- An interpretation of data with respect to its suitability for something (e.g. activity)
- Typically used to locate something (no definable units to compare)
- Results in a numeric measure of suitability
- Used when the problem is complex or important
- Suitability scores can be subjective or quantitative
- If designed properly, the model results in potential locations being identified and assigned a relative suitability score for the activity. (the best sites have the highest suitability scores)
- Helps you systematically organize your criteria and decisions

### Building suitability models, steps

1. Define the problem or goal
2. Decide on evaluation criteria
3. Normalize and create utility scales
4. Define weights for criteria
5. Calculate a ranking model result
6. Evaluate result

### Step 1

Find suitable areas a focal inventory of a rare species

Note: this modeling approach not only finds potential areas but rates each area based on how suitable it is

### Step 2

Appropriate evaluation criteria:

1. Elevation
2. Slope percentage
3. Direction of hillsides (aspect)
4. Distance to water

### Step 3, create utility scales

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>(Elevations between 580m and 1000 are preferred)</td>
</tr>
<tr>
<td>Slopes</td>
<td>(steeper slopes over 20%)</td>
</tr>
<tr>
<td>Aspect</td>
<td>(Northern facing slopes are better)</td>
</tr>
<tr>
<td>Hydrology</td>
<td>(Distance to water sources is important for eco)</td>
</tr>
</tbody>
</table>

### Constructing utility scales

- Should be linear as opposed to logarithmic or exponential
- Typically range from 1 (worst) to 9 (best)
- You must use the same range of utility with the same order for all goals (it would not be legal to use a scale from 1 to 9 to rate soils and a scale of −1 to 1 to rate slopes)
- Define at least three points on your scale to serve as reference points. Worst = 1, Best = 9, Mid = 5
- You do not have to define every point on the scale just the end points and enough intermediate points
Utility scales

Elevation

9 – elevations over 1000m
8
7
6
5 – elevations between 700m and 1000m
4
3
2
1 – elevations up to 580m

Use the grid reclassify function

Utility scales

Slopes

9 – 20% or higher
8 – 18%
7 – 15%
6 – 13%
5 – 11%
4 – 9%
3 – 7%
2 – 5%
1 –

Utility scales

Aspect

9 – North facing slopes
8 – North west
7 – North east
6
5 – West
4
3 – South west
2 – South east
1 – South

Utility scales

Distance to water sources

9 – within 10m from potential site
8 –
7 –
6 –
5 – greater than 50m
4 –
3 –
2 – greater than 150m
1 –

Step 4, define weights for criteria

Goals

Weights to 100

Elevation

[higher elevations are preferred]

20

Slopes

[steeper are better]

35

Aspect

[Northern facing slopes are better]

35

Distance to water sources

[Closer locations to water sources are preferred]

10

100

Step 5, apply a solving equation

- There are many goal programming algorithms that could be used
- A linear weighted or multiple utility function works fine

Total Suitability = (goal1 * weight1) + (goal2 * weight2) + ...
Results in a suitability map

- Areas more suitable have a higher modeled grid value result
- Weights can easily be changed to test the spatial sensitivity of preferences

Fuzzy logic and applications in GIS

Fuzziness

- Refers to vagueness and uncertainty, in particular to the vagueness related to human language and thinking
  - “the set of tall people”
  - “all people living close to my home”
  - “all areas that are very suitable for corn”
- Provides a way to obtain conclusions from vague, ambiguous or imprecise information. It imitates the human reasoning process of working with non precise data.

Crisp sets versus fuzzy sets

Crisp sets (~Binary)

Characteristic function

\[ X_A : X \rightarrow \{0, 1\} \]

where

\[ X_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases} \]

Fuzzy sets

Membership function

\[ U_A : X \rightarrow [0, 1] \]

where

\[ U_A(x) \] is the membership value of \( x \) in \( A \)

Example of crisp sets versus fuzzy sets

- Height of three adults: A is 178cm, B is 166cm, and C is 181cm

<table>
<thead>
<tr>
<th>Crisp set</th>
<th>under 170cm</th>
<th>170 to 180cm</th>
<th>over 180cm</th>
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<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Membership Function

\[ \begin{array}{c|c|c} \text{height} & \text{short} & \text{ave} & \text{tall} \\ \hline 170 & 0 & .4 & .6 \\ 180 & .8 & .2 & 0 \end{array} \]
The grade of membership should be 1 at the center of the set. The membership function should fall off in an appropriate way from the center through the boundary. The point with membership grade .5 (crossover point) is at the boundary of the crisp set.

The membership function depends on the application. EX: moderate elevation may be defined much differently in Finland versus moderate elevation in Norway. There are linear and sinusoidal membership functions, I will focus on linear in the example which follows.

We want to find an ideal location to perform Saintpaulia inventories based on the following criteria:
- Steeply sloped terrain
- North facing hillside
- Higher elevation
- Near water

Slope is favorable when it is above 20 percent
Aspect if favorable when the terrain is oriented toward the North
In this study area, preferred elevation is 500 to 1000 meters
It is favorable to be within 50 meters of water

```
0            20 195
Moderate slope = 0 x < 20
             (x-20) / 175 20 <= x <= 195
```

```
1 0 <= x <= 22 or 337 <= x <= 360
22 < x <= 67
292 < x <= 337
0 67 < x < 292
```

```
0   22   45  67    90     135  157   180  202   225  247   270  292   315   337  360
Favorable Aspect =
```

```
1 0 <= x <= 22 or 337 <= x <= 360
(x – 22) / 45 22 < x <= 67
(x – 292) / 45 292 < x <= 337
0 67 < x < 292
```

```
0 45 90 135 180 225 270 315 360
```

```
```

**Elevation membership function**

“preferred elevation is between 500 and 1000 meters”

- High elevation: $0 \quad 500 < x \text{ or } x > 1000$
  \[
  \frac{(x - 250)}{250}, \quad 500 \leq x \leq 750
  \]
  \[
  \frac{(1000 - x)}{250}, \quad 750 < x \leq 1000
  \]

**Water membership function**

“It is favorable to be within 150 meters of water”

- Preferred distance: $0 \quad x = 150$
  \[
   \frac{(150 - x)}{150}, \quad x \leq 150
  \]

**Calculation within ArcGis spatial analyst**

For Slope example, use the con function which is an If then else statement

- Calculation within ArcGis spatial analyst

**Calculation**

\[\text{Con}(\text{condition, true expression, false expression})\]

- Moderate slope: \(x < 20\)
  \[
  \frac{(x - 20)}{175}, \quad 20 \leq x \leq 195
  \]

**Comparison of map overlay, suit model, fuzzy logic model**

- Map overlay = method has most errors due to boolean operator
- Suitability model = most subjective due to utility scales and weight allocation method, however weights don’t have to be incorporated
- Fuzzy number method = least subjective and often the best method due to the ability to incorporate scale, accuracy errors in a “gentler” comparison method
- Overall you must determine what is most important to you in the study and choose a method that fits time, money, your expertise

**What have you learned and Where can you continue?**

- you should come on Thursday to listen to Buce who will continue with a similar topic
- Don’t miss out on some reading

by E. Triantaphyllou
Summary of GIS-based Multi-criteria Evaluation Methods for Information Synthesis and Integration

<table>
<thead>
<tr>
<th>Method</th>
<th>Aggregation Functions</th>
<th>Decision Types</th>
<th>GIS-based</th>
<th>Applications</th>
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<tbody>
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<td>Σ value/utility</td>
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References and further reading


References


Thank you for your attention

Special thanks to Prof. Timo Tokola explaining some of the harder issues related to this …& borrowing some of his material