Comparison and Analysis of Multiple Scenarios for Network Infrastructure Planning

Christoph ERLACHER, Gernot PAULUS and Peter BACHHIESL

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Abstract

This paper focuses on analysis and evaluation of cost-optimized cable laying construction scenarios for telecommunication network infrastructures. A framework for bridging the gap between cost-optimized simulation results and GIS-based spatial decision support is presented. “Simu2GIS” represents an ArcGIS prototype implementation in order to compare and evaluate different user-defined planning scenarios based on selected criteria. “Simu2GIS” is developed using C#.NET programming language and the ArcObjects Library from ESRI. Different methods for multi-criteria spatial decision analysis and definition of decision rules are implemented. This new approach facilitates the integration of expert knowledge in the decision making process in order to find the most suitable construction scenario for a cable laying in terms of expected investment costs.

1 Introduction

Scenario management for network infrastructure planning deals with the visualization, interpretation and comparison of cost-optimized cable laying scenarios in order to provide better support for decision makers. The FHplus project “NETQUEST” focuses in cooperation with the Austrian Regulatory Authority for Broadcasting and Telecommunications (RTR) on the development of decision supporting tools for network carriers which allow the simulation and optimization of cable laying routes for new networks or network augmentation projects within urban areas (PAULUS et al., 2006). The area wide expansion of fibre optic access networks (”*Last Mile*”) requires significant financial investments. The respective costs are determined on the one hand by underground construction work (cable laying) and on the other by the technical equipment to set up the network. Based on this fact, information about the relation between expected investment volume and corresponding return on investment represents a crucial competitive factor for new network- or network augmentation projects.

“NETQUEST” represents an ongoing research project funded by Austrian Research Promotion Agency (FFG) within the FHplus program. The current project is structured in 4 interrelated workflows: (1) Geospatial Data preparation, (2) Weighted graph generation, (3) mathematical optimization and (4) visualisation, comparison and evaluation of optimized results. The results of the optimization process represent different cable laying construction scenarios. In this study, these scenarios are the input data for the interpretation and analysis by applying different Multicriteria Decision Making (MCDM) methods. For users and decision makers it is a challenging task to extract relevant information, especially geospatial information, from a large set of different scenarios. Therefore, there is a strong need for a new approach to support experts in comparing, interpreting and evaluating selected cost-optimized cable laying scenarios in order to argue for a specific investment decision.

2 MCDM Analysis for Decision Support

The scenario comparison functionality is applied to the optimized cable laying routings (scenarios) and their technical equipment components like cable distributors or line routing cables. Selected scenarios have to be compared with each other in order to identify the best alternative. This scenario comparison functionality supports the decision making process of a user or a group of users (experts). According to MALCZEWSKI (1999), alternatives respectively scenarios are compared with Multicriteria Decision Making analyses techniques (MCDM Analysis). Multicriteria Decision Analysis (MCDA) and Multicriteria Decision Making (MCDM) are discussed synonymously. MCDM considers a set of alternatives (optimized cable laying routings), which are evaluated on the basis of conflicting criteria, whereas criteria involve objectives and attributes. Elaborating on this topic, different approaches exist to structure MCDM problems (SAATY, 1980; CHANKONG et al., 1983; KLEINDORFER et al., 1993). In general, MCDM problems include the following six components (MALCZEWSKI, 1999):

1. *A goal or a set of goals the decision maker (interest group) attempts to achieve,*
2. *the decision maker or group of decision makers involved in the decision-making process along with their preferences with respect to evaluation criteria,*
3. *a set of evaluation criteria (objectives and/or attributes) on the basis of which the decision makers evaluate alternative courses of action,*
4. *the set of decision alternatives, that is, the decision or action variables,*
5. *the set of uncontrollable variables or states of nature (decision environment)*
6. *and the set of outcomes or consequences associated with each alternative attribute pair (KEENEY et al., 1976; PITZ et al., 1984).*

The central part of a MCDA framework is the decision matrix. It is displayed as a table or chart consisting of columns, representing the criteria, and rows, representing the alternatives (PITZ et al., 1984). The values of the matrix itself describe the decision outcomes for the given set of criteria and alternatives. Additionally, decision matrixes include experts preferences (weights), which assign criteria a certain importance expressed in numbers. Weights are preferences, respectively evaluation criteria of decision makers. This decision matrix is embedded within the whole framework of a MCDA (Fig. 1). As mentioned above, the framework consists of a general goal, decision makers, objectives, attributes, alternatives and outcomes (MALCZEWSKI, 1999).

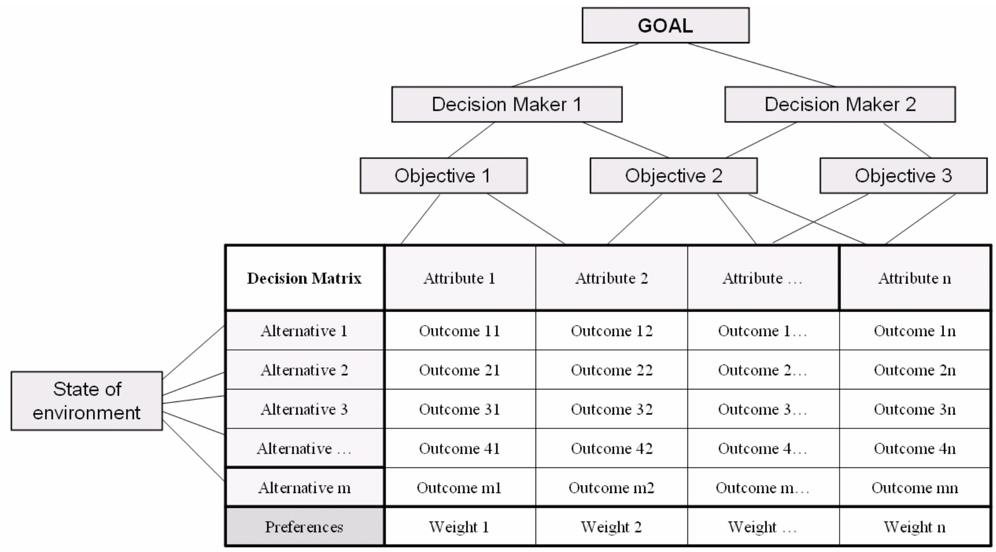

Fig. 1: The components of a MCDA include the embedded decision matrix (Source: MALCZEWSKI 1999, Figure 3.1, p. 82)

The determination of the necessary information elements for a spatial decision is an important issue in order to set up a decision matrix. ACHATSCHITZ (2005) proposed the implementation of a spatial allocation process in order to respond to user needs to answer a specific spatial question.

The goal of the decision making process is the top level element of the framework for multicriteria decision analysis. Such a goal in the context of this study is the minimization of investment costs for a utility company or internet- or telecommunication providers for setting up a new fibre-optic communication network within a city or specific area. Decision makers and expert analysts are the persons who are typically involved in such complex decision problems. These interest groups are identified by unique preferences reflected by the weights of the criteria that represent the importance of each criterion (objective and attribute).

MALCZEWSKI (1999) states that decision making is a process, which incorporates activities that start with the recognition of the problem and end with its recommendations. The quality of a decision lies in the sequence in which the activities are undertaken. As defined by KEENEY (1992) two major approaches exist: (1) the alternative-focus approach and (2) the value-focused approach. The alternative-focus approach supports the generation of decision alternatives, whether the value-focused approach uses evaluation criteria in form of values as the basis of decision analysis. The difference of these approaches is that the value-focused approach specifies the values before generating the alternatives and that the alternative-focused approach identifies the alternatives at first, followed by the specification of the values. Both approaches of the spatial multicriteria decision analysis framework incorporate the following steps of the decision making process:

2.1 Problem Definition and Evaluation Criteria

The problem definition deals with the desired and existing states from the point of view of decision makers. It involves searching the decision environment for conditions calling for decisions. In the next step data is obtained, processed and examined to identify problems. After defining the problem the focus is centred on the evaluation criteria.

2.2 Decision Alternatives and Constraints

The decision maker has to choose alternative courses of action, called decision options. Each decision alternative consists of two elements: action and location. The action gives information on what has to be done and the location where it has to be done. The alternative is specified completely by defining the values of the decision variables, which owns a definite value at every instant. The variables that are controlled by the decision maker are then called decision variables (MALCZEWSKI, 1999). As stated by KEENEY (1980) constraints are limitations imposed by the nature or by human beings that do not permit certain actions to be taken. To specify constraints, value or professional judgments are needed. Furthermore, the specification is based on available resources and regulations. Furthermore, constraints limit various sets of decision alternatives.

2.3 Criterion Weighting

Criterion weighting includes the preferences of the decision maker with respect to the evaluation criteria in the decision model. They are expressed in weights in order to describe the importance of each criterion relative to others. The higher the value of a weight the, the more significant the criterion is. In general, weights are normalized where the sum of all weights is equal to one. MALCZEWSKI (1999) described the criterion weighting methods like Ranking-, Rating, Pairwise Comparison- and Trade-off Analysis Method to estimate the set of weights.

2.4 Decision Rules

To perform the decision rules, the previous steps have to be brought together. The main focus of setting up decision rules is to provide the user with the ability to rank alternatives based on criteria. The ranking of the alternatives relies on different mathematical approaches like the SAW- (Simple Additive Weighting), the AHP- (Analytic Hierarchy Process) or the Concordance-method, which represent the decision rules (MALCZEWSKI, 1999).

2.5 Sensitivity Analysis and Recommendation

To determine the robustness, sensitivity analyses are performed. Sensitivity analysis records, respectively, identifies potential effects of changes in the inputs and in the decision maker's preferences. If these changes significantly affect the ranking of the alternatives, then the ranking is considered as not stable and refinement of the problem formulation is necessary (MALCZEWSKI, 1999). The final result of the decision making process is a recommendation for future action. It is based on the ranking of alternatives and sensitivity analyses and incorporates the description of the best alternative considering this scenario for implementation.

3 Project- and Data Description

The implemented overall project workflow consists of the consecutive modules geospatial data preparation, weighted network generation, mathematical optimization and visualisation, comparison and evaluation of optimized results. Primary data input for the project are landuse data provided by the Austrian Digital Cadastre and customer nodes, which have to be connected to the network. These so called connection objects represent either business- or residential end users having different connection potentials in terms of needed bandwidth. The geospatial data sets are topologically validated and construction costs for underground work are assigned per planning-relevant landuse class and providing the input data for the geometric weighted graph (Candidate Graph) generation process. The Candidate Graph forms the cable laying network that incorporates connection edges to all end users of a specific test area. Different optimized cable laying network scenarios are computed based on the candidate graph representation. These scenarios are calculated by different optimization algorithms like (Price Collecting) Steiner trees and Minimum Spanning Tree (MST) Heuristics (BACHHIESL, 2007) and selected costs for planning relevant landuse classes (e.g. main building, street; street intersection, agriculture). The optimized results include the cable laying network and their technical components (e.g. main cable range, distribution cable range, cable end, cable distributor) for setting up the network. Currently, most of the optimization results are descriptive and difficult to interpret for experts, especially when a comparison of a large number of different scenarios must be performed. The interface between the optimization process and the MCDM analysis are ASCII files. These ASCII files include all relevant results of the optimization process like spatial representation of a cable laying in terms of construction costs and technical components. The different optimized results (scenarios) and their components represent the input for the MCDM analysis.

4 Implementation and Results

The scenario comparison tool for cable laying routings is an integral part of “Simu2GIS”, an implemented ArcGIS 9.2 Toolbar that provides the functionalities for data preparation, visualisation and comparison of network infrastructure.

4.1 Development Environment

The “Simu2GIS” Toolbar is implemented in Microsoft Visual Studio and C#.NET using the ArcGIS Framework and the ArcObjects from ESRI. ArcObjects is a library of software components that make up the foundation of ArcGIS. ArcGIS Desktop, ArcGIS Engine, and ArcGIS Server are all built using the ArcObjects libraries. The “Simu2GIS” Toolbar is extensible because of the modular implementation of its functionalities.

4.2 MCDM Decision Framework

The MCDM Decision Framework incorporates specifying a set of criteria in respect to their objectives, some alternatives and mathematical operations for weighting the criteria computing the best alternative (decision rules). The overall objective of the "NETQUEST" project is the identification of the most adequate cable laying alternative in respect to the following evaluation criteria:

- Sub-Objectives: Minimization of the cable laying costs and maximization of the number of connected end users to the network.
- Attributes: Optimized constructions costs, technical component costs, number of business and residential users.

The evaluation criteria are identified by a group of experts in the field of tele-communication and network engineering. The optimized costs and the component costs are expressed in Euro and the number of integrated residential- and business users is expressed as percentage values of the total number of users available.

For this project an alternative represents one optimized cable laying result for one specific area. The optimized results are computed by the "RTR_R2007a" tool and include the optimized cable laying routings and their components (BACHHIESL, 2007).

The comparison of the cable laying routings and their components is based on the Pairwise Comparison Method developed by SAATY (1980). This method is used to retrieve values of the criterion weights for the AHP decision rule.

In order to identify the best alternative in respect to the evaluation criteria and the user preferences the SAW-, the AHP- and the Concordance method are implemented, which represent the decision rules. The SAW method is the mostly used decision rule in MCDM because of its simplicity. Attribute values within the decision matrix are first standardized (values from zero to one) and weighted (multiplied with the user preference values). Afterwards the row sum for each alternative is computed in order to rank them. The Concordance method refers to a pairwise comparison of alternatives. Two alternatives are evaluated qualitatively. It can be determined that one alternative is better than the other, but this method cannot indicate how much one alternative is better than the other one. The AHP method was developed by SAATY (1980) that based on the three phases, which are called Decomposition, Comparative Judgment and Synthesis of Priorities. At the decomposition phase, the decision problem is decomposed into a hierarchy, which consist of the most important elements of the decision problem. The root of the hierarchy represents the overall goal that has to be specified into more specific elements (Goal, Objectives, Attributes and Alternatives). The second phase concentrates on comparing the decision elements on a pairwise base. Two elements of one level are considered at any given time. A comparison matrix from top to bottom is generated for each level of the hierarchy. Afterwards, the weights for each element of the hierarchy are calculated. The last phase refers to construct an overall priority rating. Hereby, a sequence of multiplications of the relative weights at each level is done.

4.3 Graphical User Interface

The first section of the Multicriteria Decision Making Analysis Window (Fig. 2) loads a set of user-defined and selected scenarios from a user-defined storage device. These scenarios provide the input data for the computation of the best alternative. Afterwards, the matrices of the Multicriteria Decision Making Analysis Window (data grid views) are filled with the loaded data. This MCDM Analysis part is responsible for calculating the best scenario according to the criteria. The Criteria Weighting part is located at bottom of the Multicriteria Decision Making Analyses Window. Here, four sliders are integrated for the criteria weighting of the SAW- and Concordance methods. The calculations of all methods are step wise integrated. Therefore, the computations are more comprehensible for the users respectively experts.

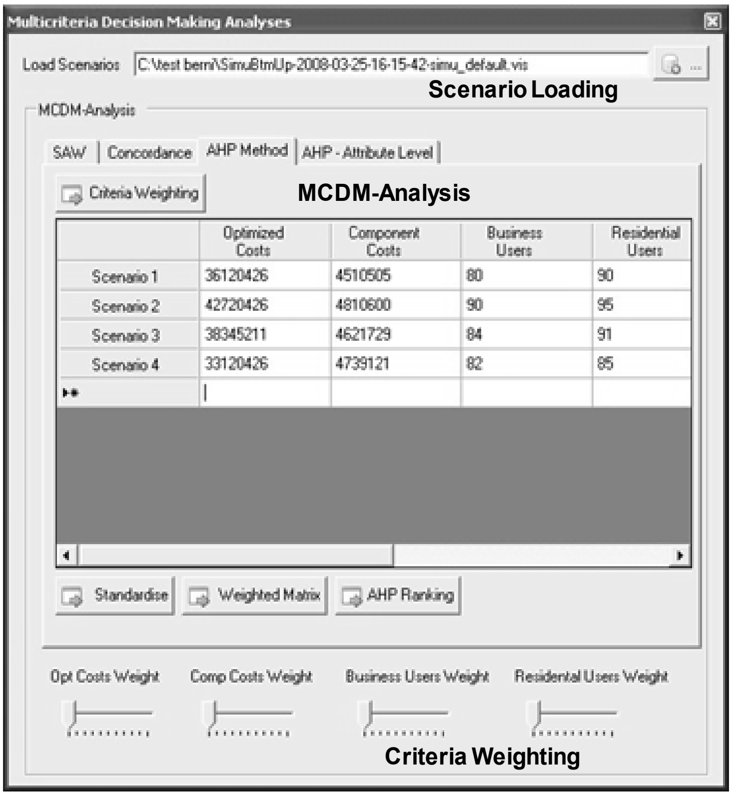

Fig. 2: The Graphical User Interface of the Multicriteria Decision Making Analyses Window for identifying the most suitable alternative in respect to the evaluation criteria

4.4 Results

“Simu2GIS” is an ArcGIS 9.2 toolbar that provides the opportunity to convert, to visualize and to compare different optimized cable laying routes. First, the optimized graphs are converted to a GIS based format (Geodatabase) and displayed in ArcMap 9.2. Afterwards the user has the possibility to analyze two different scenarios simultaneous in two digital maps. The third functionality of this application is the scenario evaluation in respect to MCDM techniques that is the main focus of this paper. The output of the MCDM analyses tool represents comparison results of different optimized cable laying networks that return the best alternative according to the defined decision criteria and the expert's preferences. This chapter illustrates the results of a scenario comparison that uses the Analytical Hierarchy Process including four cable laying routings for the evaluation. The input data for this example are represented in Figure 2. The evaluation criteria are formed by the optimization- and component costs in Euros and the number of integrated residential- and business users within the network in percentage values. The AHP approach refers to a pairwise comparison of the criteria elements for each hierarchical level. The hierarchy consists of the levels Overall Goal, Objectives and Attributes (Fig. 3). At first, the overall goal is divided into two objectives: "Minimization of the Cable Laying Costs" and "Maximization of the Implied End Users". The first objective consists of two attributes: "Optimization Costs" and "Component Costs". The second objective holds the two attributes: "Business End Users" and "Residential End Users". The importance of the hierarchy elements can be expressed through the sliders. The scale of the importance for the weights ranges from 1/9 to 9. If objective one is two times more relevant than objective two, the slider is dragged to the position 2/1. If objective two is three times more important than objective one, then the slider value is equal to 1/3. The same evaluation procedure is applied for the remaining levels.

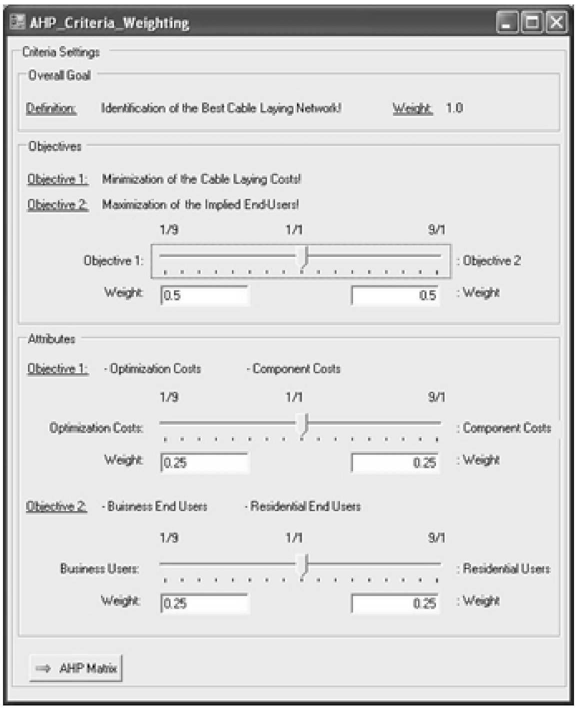

Fig. 3: AHP Criteria Weighting framework that consists of the levels Overall Goal, Objectives and Attributes

After determining the values of the weights, the GIS based rating of the alternative is processed. At the beginning of the GIS based rating of the alternatives, the criterion values have to be standardized. The next step multiplies the standardized criterion values by the computed preferences. Finally, the row sum for each alternative is calculated and standardized. At the end, the most suitable alternative can be determined by the highest standardized row sum value (Fig. 4).

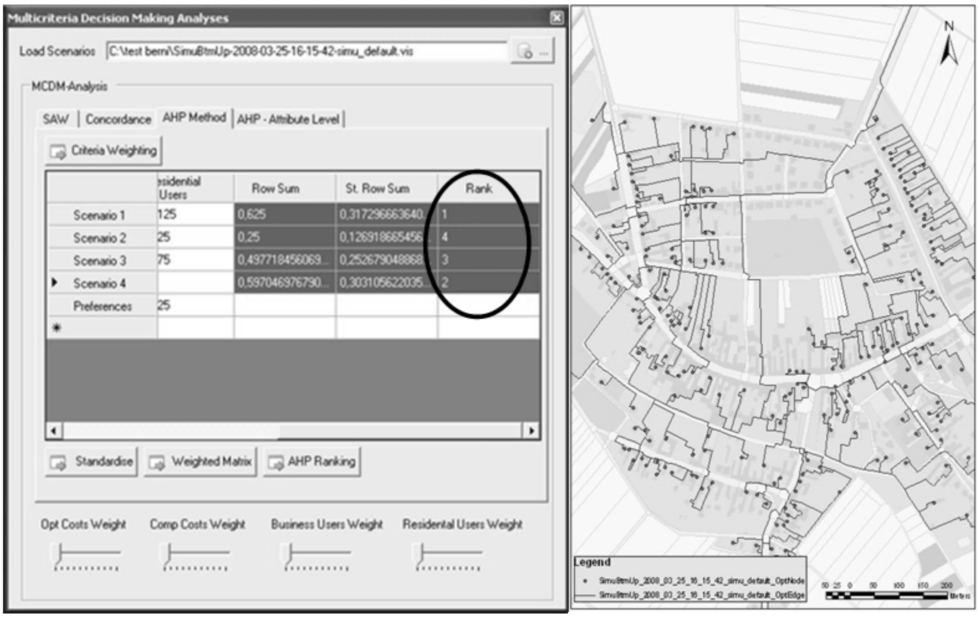

Fig. 4: Identification of the best alternative in respect to the standardized row sum value in descending order. The rank indicates the best scenario according to the evaluation criteria and weights. The left side of the figure displays the map-based graphical representation of the best alternative.

5 Summary and Future Prospects

The scenario comparison tool of the "Simu2GIS" toolbar identifies the best alternative in respect to the decision criteria and the expert's preferences. The conversion tool of "Simu2GIS" is currently tested by the project partner RTR. Major focus in the future will be the enhancement of the application that incorporates the graphical analyses of two scenarios with help of two digital maps and the MCDM analyses. For the MCDM analyses a set of different decision rules is implemented in order to support the decision makers. The evaluation criteria were identified as the crucial attributes by experts in the field of utility networks. The criterion values (weights) used in this study represent fictive numbers for demonstration purposes and may not correspond in all detail with expert knowledge in this domain. A further perspective will be the comparison of the implemented decision rules in order to obtain the most suitable decision rule for the identification of the best scenario. Another important improvement of this study and its focus on providing an intuitive user interface for scenario comparison is the idea of direct manipulation (SHNEIDERMAN 1983). Direct manipulation and information visualization promise to bring greater comprehensibility, predictability, and control to advanced interfaces. Direct manipulation in the context of this study depends on visual representation of the scenarios and actions of interest, physical actions or pointing and rapid incremental reversible operations whose effect on the scenarios of interest should be immediately visible (MAES et al. 1997).

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References

ACHATSCHITZ, C. (2005), Identifying the necessary information for a spatial decision: Camping for Beginners. Proc. of CORP 2005 & Geomultimedia05, (SCHRENK, M., Ed.), Feb. 22-25 2005, in Vienna, Austria, Published by Selbstverlag des Institutes für EDV-gestützte Methoden in Architektur und Raumplanung, pp. 325-331.

BACHHIESL, P. (2007), RTR_R2007a – Ein transferierbares System zur Simulation des Wiederbeschaffungswertes der Telekom-Infrastruktur im Wählamtsbereich. FHplus Project NETQUEST Internal Working Report, Carinthia University of Applied Sciences, Klagenfurt.

CHANKONG, V. & HAIMES, Y. Y. (1983), Multiobjective Decision Making: Theory and Methodology. North-Holland, New York.

KEENEY R. L. (1980), Siting energy facilities. CA: Academic Press, San Diego.

KEENEY R. L. (1992), Value-focused thinking: a path to creative decisionmaking. Cambridge, Harvard University Press.

KEENEY, R. L. & RAIFFA, H. (1976), Decisions with Multiple Objectives: Preferences and Value Tradeoffs. New York, Wiley.

KLEINDORFER, P. R. & KUNREUTHER, H. C. & SCHOEMAKER, P. J. H. (1993), Decision Sciences: An Integrative Perspective. Cambridge, Cambridge University Press.

MAES, P., SHNEIDERMAN, B. & MILLER, J. (1997), Intelligent Software Agents vs. User-Controlled Direct Manipulation: A Debate. Proceedings CHI 97 – Conference on Human Factors in Computing Systems (22-27. March 1997, Atlanta, Georgia, USA).

MALCZEWSKI, J. (1999), GIS and Multicriteria Decision Analysis. New York, Wiley.

PAULUS, G., KRCH, M., SCHOLZ, J., BACHHIESL, P. (2008), Scenario-based Spatial Decision Support for Network Infrastructure Design. In BERNARD et al. (Eds.), The European Information Society: Taking Geoinformation Science One Step Further. Berlin/ Heidel–berg, Springer, pp.323-337.

PITZ, G. F. & MCKILLIP, J. (1984), Decision Analysis for Program Evaluations. Thousand Oaks, CA, Sage Publications.

SAATY, T. L. (1980), The analytic hierarchy process. New York, McGraw-Hill.

SHNEIDERMAN, B. (1983), Direct manipulation: a step beyond programming languages. IEEE Computer, 16 (8), pp. 57-69.