

Scenario-based Spatial Decision Support for Network Infrastructure Design

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Abstract

This paper describes an extended framework for scenario based spatial decision support for constructing new network infrastructure and its application in the domains of telecommunication, forestry and energy. There is an increasing need to provide new planning paradigms to support very expensive strategic investment decisions in new network infrastructure in these domains. The planning processes there are still dominated by an expert approach based on empirical knowledge and manual implementation. With this conventional approach it is impossible to consider different planning scenarios within a reasonable cost und time frame and no cost-based optimization is possible. We combined the powerful analytical and visualization capabilities of a Geographic Information System (GIS) with mathematical methods of graph theory and combinatorial optimization. This approach extends the basic spatial decision support model with a knowledge based module for scenario parameterization and graph generation, a module for geodata integration and processing, an operations research optimization module and a multi-level visualization module supporting the need of different communication channels within the decision making process.

Keywords: GIS & Operations Research; Network Infrastructure; Scenario-based planning, Investment simulation;

1 Introduction

Various media recently announced massive strategic investment of different industries in the development of new network infrastructure. German Telekom reported a planned investment volume of 3 billion Euro (Reuters, 2005) for new fiber optic infrastructure. The Österreichische Bundesforste AG rent 176.000 ha of forested area in Russia to facilitate sustainable forestry. Therefore investments on forest accessibility of several million Euros are scheduled (ÖBf, 2004). Despite the significant investment volumes, intelligent computer based decision support in network design and cost simulation is lacking. The planning process is still dominated by a manual expert approach based on empirical knowledge. With this approach it is impossible to consider, evaluate and visualize all potential route alternatives within a reasonable cost und time frame. Furthermore, no simulations of scenarios for different route alternatives are possible in order to support strategic investment decisions. We combined the powerful analytical and visualization capabilities of a Geographic Information System (GIS) with mathematical methods of graph theory and combinatorial optimization to offer a new approach for strategic planning and simulation of investment costs for constructing new network infrastructure. The following paper describes a framework for scenario based

spatial decision support and its application in the domains of telecommunication, forestry and energy transmission grids.

2 Scenario-based Spatial Decision Support (SDSS)

This chapter focuses on the generation of a scenario based spatial decision support structure based on the classical framework for multicriteria decision analysis proposed by Malczewski (1999). From this starting point we elaborate on the combination of Geographic Information Science and Technology (GI S&T), Operations Research (OR) and Graph Theory (GT) to facilitate scenario based spatial decision support.

Malczewski’s (1999) multicriteria decision framework represents the process of decision making that starts with the problem recognition and definition. Once a problem is clearly identified sets of criteria are selected that support the design of alternatives to be generated in a following stage. These criteria are divided into two groups: evaluation criteria and constraints. Evaluation criteria and their combinations measure the performance of an alternative, whereas constraints limit the possible set of alternatives. According to Malczewski alternatives can be created using standard GI S&T methods. For evaluation purposes a decision variable or a set of decision variables is defined for each alternative, and calculated from evaluation criteria. With the help of decision rules, alternatives are ranked according to decision variables. The result of this process is a recommendation that can be altered by the user’s preferences.

In the problem domain of network design, Paulus et al. (2003) state, that it is impossible to consider all possible alternatives with a manual “expert” design approach. In order to overcome the shortcomings of the manual planning approach a Geographical Information System (GIS) is coupled with methods of GT and OR to calculate the optimal solution based on given constraints out of a huge number of possible choices.

The proposed scenario based approach is divided into four different phases: scenario design phase, optimization phase, decision and feedback phase (Fig. 1). Scenario based spatial decision support starts with

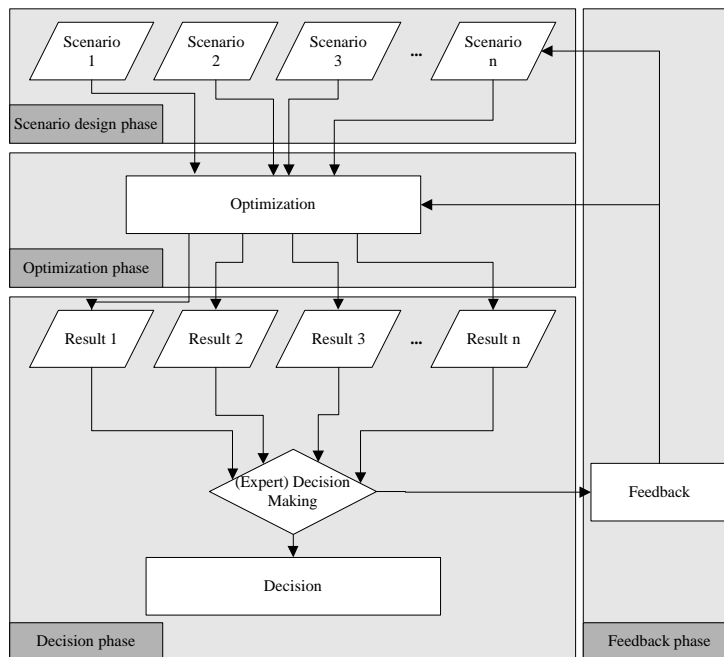


Fig. 1: Generic phases of a SSDDS for planning network infrastructure

the generation of different planning scenarios that may have conflicting objectives: e.g. ecology vs. economy.

Each scenario is developed with the use of GIS and add-on applications that support the setting of evaluation criteria and constraints. Hence, evaluation criteria values are assigned to distinct spatial feature classes (e.g. cost factor for constructing fibre cable line) and constraints (e.g. for maximum slope for constructing forest roads) for each scenario.

The optimization phase calculates the optimal or near optimal result for each scenario by methods from OR and Graph theory. These include Graph optimization techniques, dynamic programming, simulated annealing, local search, etc, which have been investigated in literature (Jungnickel 2002; Kirkpatrick et al. 1983; Papadimitriou et al. 1998). To calculate an optimal solution for the network design task the area of interest is modelled as Graph $G = (V, E, w)$, where V denotes the set of vertices, E the set of edges and $w: E \rightarrow R^+$ the weights or costs of each edge (Jungnickel 2002). This leads to Graph optimization problems that have gained a lot of interest in the field of OR.

Within the decision phase the results and their according decision variable or set of decision variables are calculated and presented in a GIS respectively. Subsequently the expert chooses the scenario that solves the problem best. The planning expert accomplishes that decision process with quantitative analysis of the decision variables and/or with a visual analysis of the generated maps, which serve as guidance in the decision process.

A feedback control system is included in the feedback phase that enhances the decision making process by altering the input parameters in the scenario design phase (evaluation criteria and constraints) and in the optimization phase (Vacik and Lexer 1999). The novel approach in the scenario based spatial decision support is the fact that scenarios and their results may be directly reused for the generation of new scenarios by changing the parameters. In addition, the system can calibrate itself by analyzing the results and decisions made, and adjust the parameters accordingly.

3 Extended SDSS Framework for Network Infrastructure Design

We propose an extended SDSS framework for network infrastructure design. Four complimentary extensions are added to the basic SDSS framework. We extend the model with a knowledge based approach for parameter definition and graph generation, a part for geodata integration and processing and a visualization part for result representation and parameter manipulation. The OR part is the kernel of the system where mathematical scenario optimization and result derivation takes place.

3.1. Knowledge

Expert domain knowledge is fundamental to acquire proper decision knowledge. This knowledge is acquired through various knowledge acquisition techniques like interviews, text analysis and technical domain report review. The knowledge gathered is still in a rather unstructured form like plain text. To organize it and for communication purposes the gained domain expertise is structured in a diagram based system which we call an informal ontology (Guarino and Giarretta 1995). This implies that the structure is a weak ontology similar to conceptual model (Obrst 2006) with focus on human and not machine interpretability.

In the next step, the informal ontology will be rewritten in a formal language like the Ontology Web Language (OWL) (W3C 2006) to suit as knowledge base (Gómez-Perez et al. 2004). This knowledge base, includes all relevant network design parameters as rules for the graph generation algorithms. Beside that the ontology is the basis for geodata modelling and the framework for the evaluation criteria like the cost factors for cable laying.

3.2. *Geo data*

The geodata model is derived from the informal ontology and has to satisfy the requirements of the network planning domain. During the process of geodata integration different data formats are integrated into one database format, while during data pre-processing semantic issues from the different data models are consolidated. The geodata processing delivers well structured data sets of planning relevant land cover and land use classes which are used as input for graph generation.

3.3. *Operations Research (OR)*

OR Methods and their combination are able to calculate the optimal solutions for a given problem due to a problem definition and a set of criteria and constraints. Possible strategies include: simulated annealing or dynamic programming. Kirkpatrick et al. (1983) proposed simulated annealing as a technique for optimizing combinatorial problems, without becoming trapped in local minima. Dynamic programming is a useful technique for optimization problems, where decisions are dependent on previous decisions. With graph theory it is possible to solve a number of relevant spatial problems like routing problems (Jungnickel 2002) (shortest path, travelling salesman problem, etc.) or Network flows (Ahuja et al. 1993).

In the case of infrastructure network design the input for optimization is a weighted Graph that results from the transformation of the geodata basis, which is expert knowledge driven. The optimization process itself relies on standard OR methods that are extended and adapted to solve complex problems related to network infrastructure design. Bachhiesl et al. (2003) demonstrated a successful approach of combining OR-methods with GIS for calculation of optimized fibre optic access networks.

3.4. *Visualization*

Visualization is important during the complete process of decision support, but there are some important process stages to emphasize.

Visualization is not limited to present simulation results but is also an integral part of the system development and system interaction process. As an example, the informal diagram oriented ontology is used for interdisciplinary communication not only between domain experts but between novice and expert users or technicians and managers (Mizoguchi et al., 1995). Effective workflow diagrams will result in an easy to handle user interface that supports the complexity of the model as efficient as the simplicity of user navigation (Alexander and Maden, 2004).

For the validation of input data and simulation results by the domain expert the integration of visualization of intermediate and final optimization results in conjunction with adequate reference data is indispensable. Such high quality and comprehensively visualized scenario results can provide different communication channels like a.) from system to expert; b.) from expert to expert; or c.) from expert to laymen, which is increasingly important in public participation processes.

3.5. Extended SDSS process model

The above defined four additions extend the phase model as follows (Fig. 2):

Geodata are the initial input and serve as the basis of the decision support system. Visualization is applied in several phases of the process and guides the user through the decision making. All parameters are based on expert knowledge, which is also used during graph generation from planning-relevant land use classes.

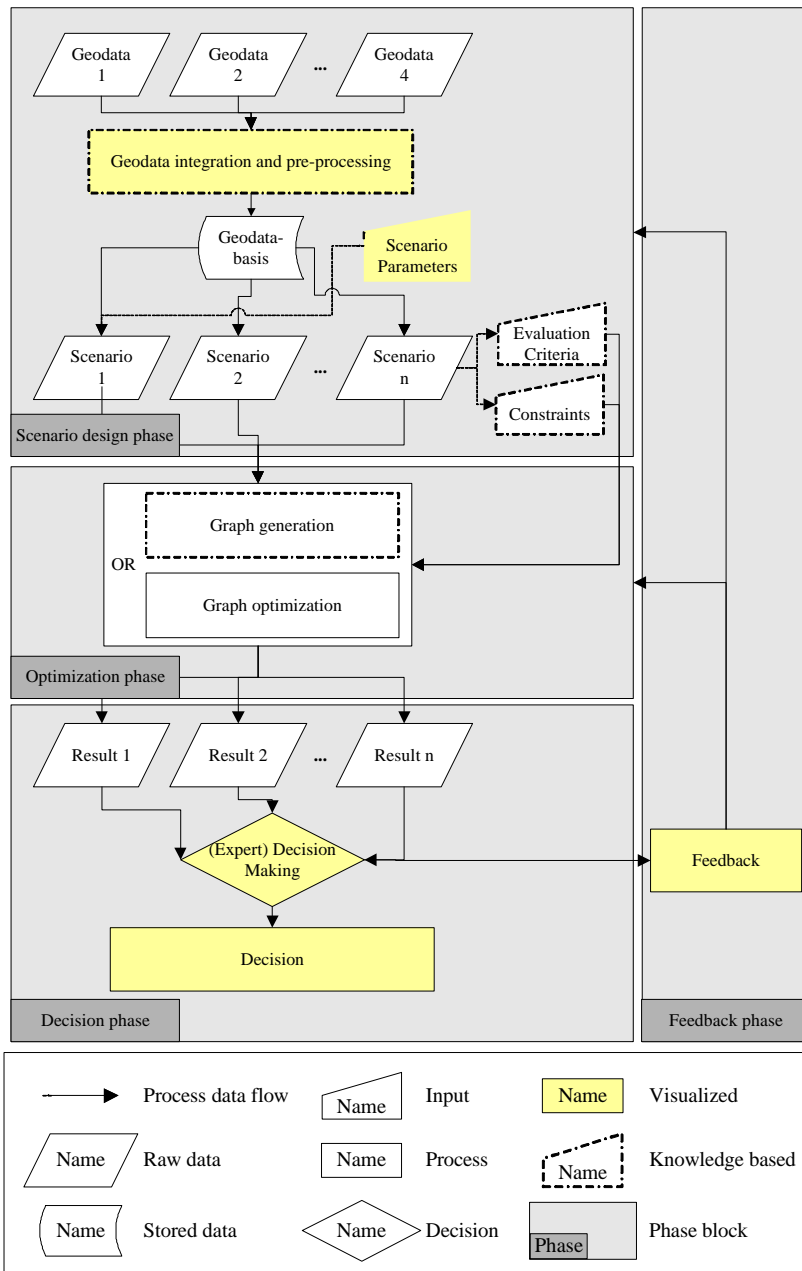


Fig. 2: Extended SSDS process model

5 Applications and visualization

Scenario based spatial decision support can be used in forest road planning, which serves as basis for sustainable forestry. Together with the Österreichische Bundesforste AG (ÖBf) a pilot study has been conducted to evaluate the benefit of a GIS and spatial decision support in forest road planning (Gruber and Scholz 2005). This work shows the potential of sustainable forest road planning with methods of GIS&T and OR which build up scenario based decision support. Furthermore it is mentioned, that the developed project allows the forest engineer to create alternative forest road networks and evaluate them directly, which supports an interactive decision making process.

Currently the extended SDSS process model is applied in the FHplus project NETQUEST focusing on the planning of urban telecommunication networks with a special emphasis on fiber optic network infrastructure. Especially the facilitation of expert knowledge through ontologies and the voluminous data in urban planning scenarios are subject of ongoing research. First benchmark projects with industry partners have shown the relevance of the approach. Fig. 3 shows the results of a benchmark project for designing a network infrastructure for a given set of 37 customers based on planning relevant land use classes. The land use classes for this particular benchmark project are street, sidewalk, street crossing and private property, each of them specific construction costs (e.g. street: 300 €/m; side walk: 150 €/m) are assigned. The customer locations to be connected, the geometry of the land use classes and the specific construction costs represent the input data for the weighted graph generation. The cost optimized network and the expected investment costs for this particular scenario are visualized using high resolution aerial views as reference data set.

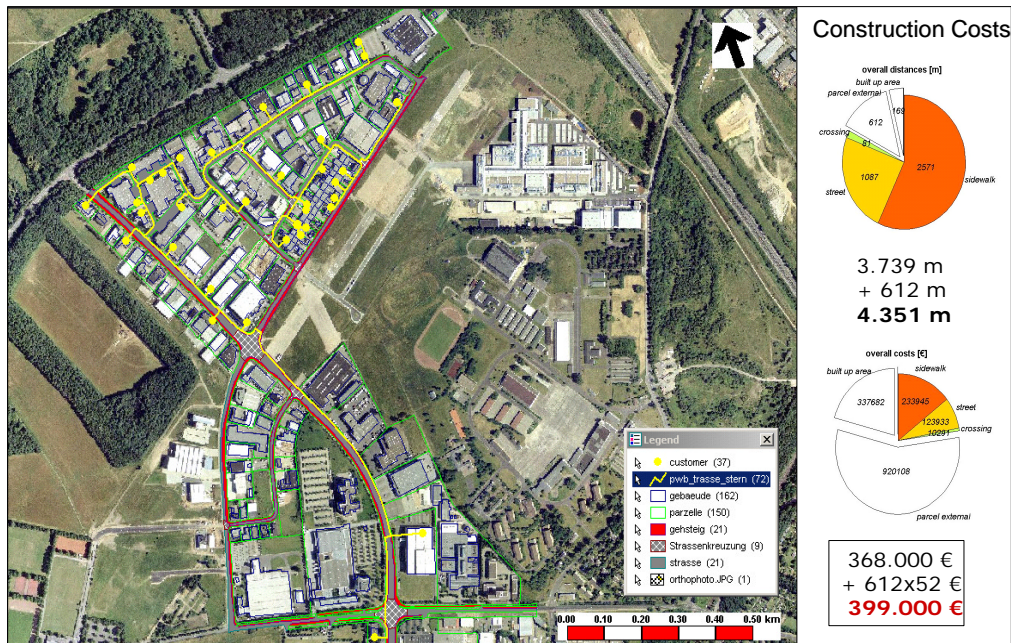


Fig. 3: Visualization of a cost optimized fiber optic network design together with expected construction costs for one specific scenario. (Benchmark project implemented for industry partner NetCologne in Köln-Ossendorf, Germany).

We applied this framework successfully as an innovative transparent planning approach in a major 380 kV high voltage ring closure project in Austria. In this project it is impossible for a network planner to consider and evaluate all potential route alternatives with a manual approach based on empirical knowledge. The more customer nodes exist, and the larger the spatial extent of the project area is, the more alternatives for laying a transmission line can theoretically exist depending on the combination and consideration of individual factors and constraints like economic, ecologic or social issues in the planning process. The planner has to simplify his task to a feasible problem dimension, which results in most cases in non- optimized and non-transparent decisions. Furthermore, with this manual approach, no cost- and time effective simulations of investment and laying scenarios for different route alternatives are possible.

Various planning scenarios were simulated and visualized using aerial views and 3D animation. Planning relevant land use classes in this project are residential area, agriculture, fallow land, forest and willow trees, which are weighted using factors representing different paid compensation for crossing a land use class in €/m. Another constraint was that any residential area must be passed by the high voltage transmission line at a minimum distance of 50m. High quality geo data like high resolution aerial views and digital terrain models provide additional important realistic visualisation possibilities. This offers new opportunities in communicating the results to the public. Especially for any application dealing with visualizations at a very details level (e.g. single parcel) high resolution data are necessary. Figure 4 shows three scenarios visualized using a digital terrain model.

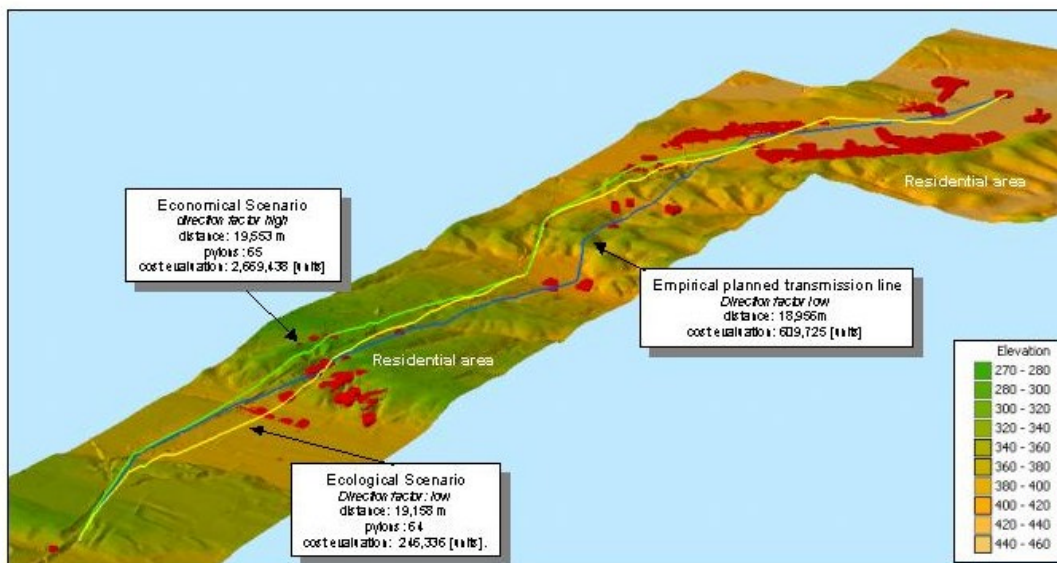


Fig. 4: Decision support by comparison of three scenarios for the laying of the 380 KV high voltage transmission line. *Green*: Economic scenario (forest = “cheap”); *Yellow*: Ecologic scenario (forest = “expensive”); *Blue*: Empirical planned transmission line. (Paulus et al. 2003)

6 Conclusions and future work

The proposed extended SDSS planning framework provide the following opportunities for designing, simulating and presenting different scenarios and results of a planning process to its relevant stakeholders:

1. Different planning scenarios can be very efficiently calculated and compared. This will result in better understanding of the complex planning process by the public. Relevant scenarios to the public can be surveyed using e-voting, open discussions or other public participation processes. Different views on the project which are the relevant land use classes and which cost factors should be assigned can easily be considered.
2. Increased principal availability of high quality geo data (e.g. cadastre data, orthophotos, high resolution digital terrain models) allows fully digital planning workflows. Limiting factor here are the still high costs for high resolution geo data, especially for DTM's or orthophotos. Furthermore, realistic visualisation of different results using 3D-animation is another important issue for public acceptance.
3. The level-of-detail of the calculated scenarios is totally flexible and can range from regional level down to a very detailed single-parcel level. Real investment costs as well fictive weighting units can be considered. Theoretically, it is possible to assign unique cost factors for every single feature in a project area under investigation. The finer the spatial planning resolution the more complex are the resulting weighted graphs.
4. Visualization interfaces at different levels of the decision making process are important in order to provide an interactive decision support process. We suggest three levels of visualization interfaces: (1) Scenario Design Phase Level, (2) at the network graph generation level and (3) at the Decision phase level, where the results of the different scenarios are compared. Future research will focus on how to visualize and analyze the characteristics of alternative planning scenarios especially when dealing with a large number of scenarios.
5. Another topic of future research is the linking of the extended SDSS framework with web mapping technology. This approach will integrate various stakeholders in the planning process providing a user-defined access to planning scenarios and personalized views on optimization results.

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