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Using the Analytical Network Methodology, a Comparative Investigation of the Environmental Effects of Different Underground Building Methods

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a b s t r a c t

This study employs the Analytic Network Process (ANP) and the Super Decisions programme to examine numerous criteria. The assessment experiment was based on a case study of an underground building project in the city of Osnabruck, Germany. A new 700 m long sewer was being built as part of the project near the city's core. Utilizing a set of multidisciplinary criteria that take into account the project's effects on the urban environment, three potential underground construction technologies (open cut, conventional tunnelling, and microtunnelling) were assessed. The assessment experiment's findings indicate that the ANP can be used to evaluate the environmental impact of underground construction methods. Due to the following factors: (1) the similar technological and economic performance of the alternative technologies; (2) the requirement to take into account a wide range of criteria reflecting the urban environment; (3) the potential need to deal with incomplete data; and (4 the requirement for a clear presentation of the results in a numerical format, multiple criteria decision analysis, and the ANP in this particular assessment experiment, are relevant for evaluating construction technologies.

1. Introduction

Global urbanisation [1] and ever increasing aspirations for greater living conditions among the world's population are underlying drivers for the need to create urban infrastructure. Transportation, water supply, sewage, solid waste management, and telecommunications are all examples of this infrastructure. The infrastructure is installed with several subsurface parts. Due to the high demand for urban land and the accessibility of construction technologies that permit the installation of underground structures in densely populated urban settings, as demonstrated by Belanger, 2007; Pasqual and Riera, 2005 [2,3], urban underground space (UUS) has undergone intense development in recent decades.

Underground structures, and underground construction works in particular, have a substantial impact on the environment [4-7]. These environmental effects range widely and include direct effects on groundwater as well as indirect effects on the landscapes and intangible assets of cities. There is an increasing need to consider the environmental impacts of various technologies and to fully integrate environmental issues into any decision-making process relating to the choice of UCT for a specific development project given the wide range of modern underground construction technologies (UCT) and equipment available (for an overview see, for example, Maidl et al., 1996, Mathewson and Laval, 1992 [8,9]).

Many UCTs are competitive options in many projects because they offer comparable technological and economic performance. According to Thewes and Bielecki's 2007 [10] research, some projects have nearly comparable costs for various UCTs, such as Hydro shields and Earth pressure balance shields, hence the choice of UCT should be made exclusively based on how it would affect the urban environment.

Therefore, a methodology that would systematically take into account the environmental implications of various UCTs and aid in the decision-making process for a specific UUS development project is highly needed. A suitable foundation for this methodology is multiple criteria decision analysis (MCDA), which can be used to explain the environmental implications using a wide range of criteria.

The benefits and significance of using a multiple criterion decision process to solve environmental issues

linked to UUS development and UCT selection are summarised in Table 1.

Developing the U.S. is a difficult endeavour that must

be approached from a variety of angles, including economic, environmental, and security considerations. There must be tradeoffs because the criteria that relate to these areas of concern frequently conflict with one another.

nvironmental decisions entail thorough analyses of UCT's environmental effects, the relationships between these effects, an assessment of the effects, and the prioritisation of

pressing issues. The size of the project, the point in the

project's design process where a decision must be made, and the stages of the project's execution will all influence the creation of a comprehensive decision-making technique for environmental assessment of U.S. development.

Table 1
Reasons for needing a methodology to examine the environmental concerns associated with UCT choice.

Consideration	Description
Booming urban underground space development	The need for and ability to develop UUS has resulted in ever increasing underground construction in urban areas.
Variety of UCT available	Recent technological advances have resulted in a great variety of UCT, e.g. automatic tunnelling, diaphragm walls, and horizontal directional drilling.
Significant environmental concerns about using UCT in urban settings	The most significant adverse environmental impacts include disturbance in the lithosphere (uneven settlements adjacent to construction site structures) and the hydrosphere (water pollution, groundwater level and mode changing).
Variety of environmental impacts	Use of alternative UCTs may have positive (e.g. remediation) as well as negative (e.g. air pollution) environmental impacts. Comparative analysis of direct and indirect environmental benefits and costs is needed.
Uncertain relationships between UCT choice, construction costs, and the environmental impacts	Every UUS development project is unique, and its technological, economic, and environmental performance should be considered in a comprehensive and systematic way.
Improvement of the urban environment as a primary goal of UUS development	There are a growing number of urban development initiatives, including underground construction projects, that are focused on improving the environment and its sustainability. Examples: replacing open car parking in city centres with underground garages and green areas, installation of underground rainwater storage tanks for combined sewerage systems.

making methodology would address. A decision making methodology can be a component of a formal environmental assessment process, which, depending on legal requirements and the scale of the project, can take the form of Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), or Sustainability Appraisal (SA). More information on environmental assessment and the methods used can be found in Dalal-Clayton and Sadler, 2005; Fischer, 2007; Getzner et al., 2005; and Sadler and McCabe, 2002 [11-14]. Some earlier works focused primarily on technology assessment (e.g. Porter et al., 1980 [15]), however this has not been established as a distinct process within the environmental assessment family.

This study is focused on UCT assessment, and does not fall into any of the aforementioned formal environmental assessment processes. The aim of the study is to explore opportunities for MCDA use in relation to underground construction in urban areas. The study is relevant to environmental assessment in general, since it is focused on the environmental impacts. In particular it can be helpful to: (1) EIA, because alternative UCTs are considered within a specific project setting; (2) SEA, because UCT analysis is focused on the technologies' environmental performance, and it should be possible to extrapolate results to similar projects in which the assessed UCT can be used; and (3) SA, because of the inclusion of indirect impacts on the urban population and economy.

2. Osnabruck project overview

An underground construction project to replace an old conduit sewer constructed in 1897 took place in the German city of Osnabruck in 2004–2006. A new sewer with a diameter of 400 mm, 730 m long and at a depth of approximately 7 m was installed under Lotter Street. This street has a high volume of traffic, amounting to 17,000 cars per day; there are some shops in the street. The project was implemented using a trenchless underground construction method known as the gallery technique or heading (conventional tunnelling).

The Department of Tunnelling and Construction Management of Ruhr University Bochum provided technical data on the Osnabruck sewer replacement project, which was used as the basis of this assessment experiment [16]. Data on performance of the three UCTs – open cut, gallery, and microtunnelling – is available.

Data on the three UCTs considered comprised a mix of quantitative and qualitative information. Since the gallery technology was the approach that was adopted, its costs and environmental impacts were

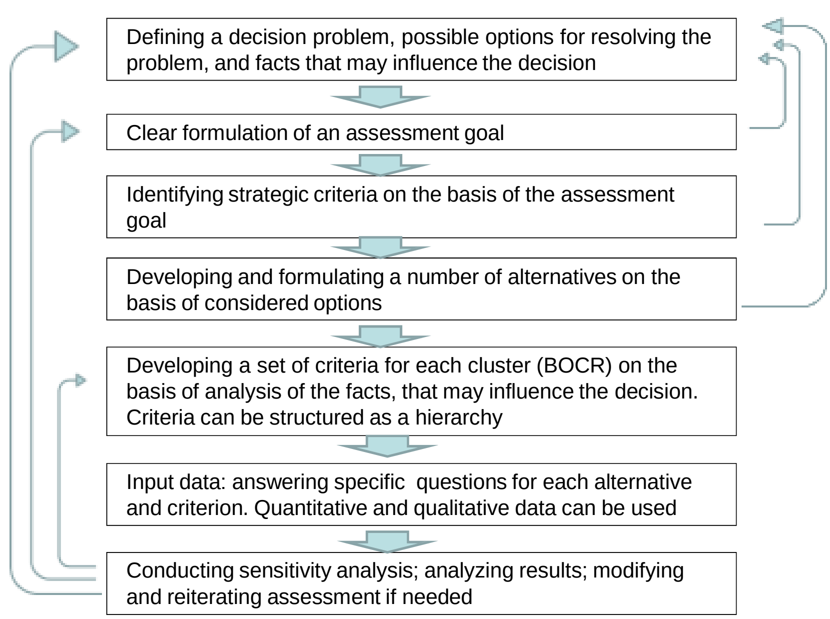


Fig. 1. Flow-chart showing how to build a model and conduct an assessment in the ANP. Broad downward arrows represent actions required to build a model and conduct the first assessment. The fine upward arrows represent further possible steps for improving the model and repeating the assessment.

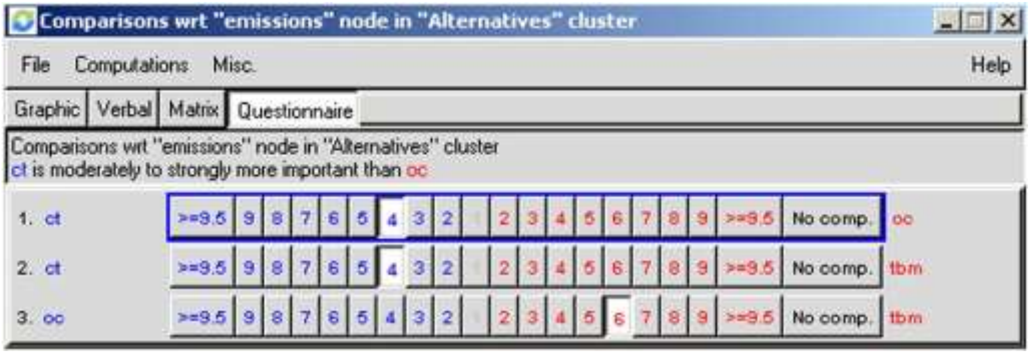


Fig. 2. The "Super Decisions" software: Pairwise comparisons, Questionnaire.

Table 2
Criteria in the "benefits" cluster.

Criterion	Description
Up-to-date infrastructure	Which UCT creates a more up-to-date infrastructure?
Low emissions	Which UCT produces less emissions?
Less consumption of resources	Which UCT consumes less resources?

available in great detail, including on site monitoring data. In addition, a feasibility study for using open cut technology was produced, with full details; it included a cost breakdown, a schedule of activities at the construction site, and modelling of city street traffic diversion due to street closure during the construction period. The feasibility study for the microtunnelling approach contained the least detail, however full costs and excavation volumes were determined.

3. Alternative technologies description

A brief description of the three alternative UCTs is presented below [8,17,18].

The *Open Cut Method* involves excavating a trench, the walls of which have to be supported by a lining. After a conduit is placed, the trench is filled with earth and the lining is removed. This method requires a large construction site, to allow transfer and temporary storage of significant volumes of excavated material.

The *Gallery Method (conventional tunnelling)* is one of the trenchless methods that involves the excavation of pits and a tunnel (gallery) supported by a permanent lining. The tunnel is accessible and conduits, cables, etc. are placed in the completed tunnel. This technology can be used when cover height is sufficient (no shallow conduits). The excavation of the soil is carried out manually with the aid of appropriate tools and/or machines e.g. excavators. Support arches made of steel rods or special steel profiles that are placed into the tunnel cross-section provide temporary support. This method requires lowering of the groundwater.

Microtunnelling is a trenchless method that is based on the use of an unmanned microtunnelling machine (shield). Usually the shield installs pipes of the required diameter and the tunnel (e.g. a sewer) is fully operational after the microtunnelling shield has traversed the length of the tunnel. It is necessary to excavate pits for placing the microtunnelling shield at the required depth. Microtunnelling technology involves excavation of the minimum volume of soil and minimal groundwater disturbance.

4. The analytic network process and data for assessment

MCDA methods can address assessment problems that require handling both qualitative and quantitative data as well as incomplete data sets. The present study uses one of these methods, namely the Analytic Network Process. More on MCDA methods in general, including an overview and comparisons of the different methods, can be found in e.g. Figueira et al., 2005; Keeney and Raiffa, 1976; Roy, 1996 [19-21]. New MCDA methods are being constantly developed; descriptions of some of the most recent ones and their application in the area of the built environment can be found in e.g. Kaklauskas et al., 2010; and Opricovic and Tzeng, 2007 [22,23].

The present study incorporates expert judgements and numerical data from feasibility studies for the three alternative UCTs. An assessment framework and criteria for assessment were developed by the author on the basis of his previous studies [24,25] and a literature review. Sets of environmental criteria (indicators) relevant to the urban environment have been developed by international organisations such as the World Bank, UNDP, UNEP, OECD, Eurostat, Metropolis and others (e.g. World Bank, 2005; Eurostat, 2007 [26,27]). Criteria relating to underground construction works have been developed on the basis of reviews of the environmental impacts of different UCTs and their performance in various urban projects [28,29].

The Analytic Network Process (ANP) was developed by an American mathematician Thomas Saaty. The ANP is a multicriteria theory of measurement used to derive relative priority scales of absolute numbers from individual judgements, or from actual measurements normalised to a relative form [30]. These judgements represent the relative influence of one of two elements over the other in a pairwise comparison process in relation to their impact on a third element in the system, with respect to an underlying control criterion. Through a supermatrix, whose entries are themselves matrices of

Table 3
Pairwise comparison sets with respect to "benefits".

Name of criteria group	With respect to	List of criteria compared	Number of pairwise comparison sets	Sample pairwise comparison question
Control criteria (3)	The goal (benefits for the environment)	Up-to-date infrastructure Low emissions Less consumption of resources	1	Which is a more important benefit for the project: "Low emissions" or "Less consumption of resources"?
Alternatives (3)	Each control criterion (3)	Open cut Galleries Microtunnelling	3	Which UCT creates more up-to-date infrastructure?

Table 4
Priorities for alternatives with respect to criteria at the lowest hierarchical level in the cluster "benefits" (normalised to a range from 0 to 100, shown to two significant figures).

Criterion	Units of measurement	Alternative technologies		
		Open cut	Galleries	Microtunnelling
Up-to-date infrastructure	Expert judgement	Equal	Equal	Equal
Low emissions	Expert judgement	08	62	28
Less consumption of resources	Expert judgement	16	29	53
Sub-net benefits	Software AHP calculation	35	29	34

column priorities, the ANP synthesises the outcome of dependence and feedback within and between clusters of elements [30].

Dominance or the relative importance of influence is a central concept of the ANP. In the ANP, a judgement at the fundamental scale is reached by answering two kinds of question with regard to the strength of dominance: 1) Given a specific criterion, which of two elements is more dominant with respect to that criterion? 2) Which of two elements influences a third element more with respect to a specific criterion? [30].

Dominance or the relative importance of elements is determined by pairwise comparisons of the elements. Since many decision-making problems are complex and involve many criteria, it is beneficial to break down a multi-element comparison into several simple ones. A detailed description of the pairwise comparisons concept can be found in the earlier works of T. Saaty [31].

ANP has a predecessor, namely the Analytic Hierarchy Process (AHP) [31]. The AHP has been used extensively: Vaidya and Kumar (2006) [32] found 150 articles investigating the AHP and its applications. However, published AHP environmental applications represent only a limited number of studies in comparison to other sectors. Ho, 2008, [33] reviewed 66 AHP applications in different sectors, of which just three were related to environmental science. The ANP is a relatively new method, and there are few published applications so far (although some of them do deal with environmental applications: Nekhay et al., 2009; Gómez-Navarro et al., 2009; Whitaker. R., 2007 [34–36]).

The ANP involves several concepts that were used in AHP (pairwise comparison, and hierarchical structures), and a few new ones (dependence, feedback, control and strategic criteria, benefits, opportunities, costs and risks). All these concepts were used to create an ANP model for assessment of the three UCTs. This model was created using the ANP software "Super Decisions", details of which are given in subsequent sections. Fig. 1 is a flow-chart representing the actions required for building the ANP model and conducting an assessment.

5. Building an assessment model in the ANP

Building an ANP model starts with defining the assessment goal. Clear formulation of the assessment goal is very important, since any judgements made should be related to it.

Table 5
Priorities for criteria at the lowest hierarchical level in the cluster "benefits" (normalised to a range from 0 to 100, shown to two significant figures).

	Units of measurement	Criteria		
		Up-to-date infrastructure	Low emissions	Less consumption of resources
Sub-net benefits	Expert judgement	81	09	09

The assessment goal can be formulated in the form of a question: which of the three alternative technologies will bring more benefits for the project? The notion of "benefits" constitutes an array of issues including construction cost, reliable performance of the sewer, rational use of underground space, and impact on the city environment during construction. All these issues and concerns are presented in the ANP in the form of assessment criteria, which have to be formulated and amalgamated into groups (nodes) during the assessment process.

In the ANP the final decision is based on four components: benefits, opportunities, costs, and risks (BOCR). Each of the four components has a specific model for its assessment, and this is called a cluster. While modelling "Benefits, Opportunities, Costs, and Risks" one should consider:

- An assessment model (ANP or AHP)
- Criteria set (the number and formulation of criteria)
- Criteria interdependence
- Criteria dependence on alternatives (feedback)
- Criteria composition into nodes

Criteria that are located at the highest hierarchical level and have sub criteria are called control criteria.

Data input at the lowest hierarchical levels can be quantitative, qualitative, or both.

Quantitative data input is known as direct data entry. The software normalises the data, thus calculating alternative priorities with respect to the criteria. The term "priority" refers to the comparative importance or impact of alternatives with respect to a particular assessment goal or criterion.

Qualitative data input requires judgements to be made and is always achieved by means of simple pairwise comparisons. The software

Table 6
Criteria associated with the "Opportunities" cluster.

Criterion	Description
Functionality	The functionality criterion is important for understanding whether an element of the infrastructure can be multifunctional, and adjust to new functions that could be required in the future. For example, service tunnels should be able to accommodate new and increased numbers of cables, underground parking should be adjustable to accommodate different types of vehicle.
Land use	The land use criterion should be considered in order to assess whether an element of the infrastructure is likely to require more or less space in the future, and to examine how a shortage of land can be tackled and an excess can be utilised.
Integration	The integration criterion is used to judge how cohesive the infrastructure is both internally and externally and how well it is integrated with other city structures. Separate underground and aboveground pedestrian crossings are an example of disintegrated structures. They pose maintenance problems, including public security issues, and are inconvenient for pedestrians. On the other hand, above- or underground road passages connected to adjacent buildings take less time to traverse and create multifunctional environments that are enjoyable for pedestrians.
Flexibility	The flexibility criterion reflects the potential for upgrading and renewing elements of the infrastructure. Installation of new equipment into structures and changing their inner spatial design are examples of flexibility.
Rationality	The rationality criterion is important with respect to the use of natural resources, including urban space. It also reflects pressures imposed by an element of the infrastructure on other natural and artificial components of the urban environment. Example: expansion of transport infrastructure may dramatically increase tourism and put unwanted pressure on the urban historic and cultural environment, thus endangering intangible city assets.
Vulnerability	The vulnerability criterion is related to a holistic view of the urban environment and provision of environmental security. Vital vulnerable infrastructure significantly increases overall city vulnerability. Example: UUI is vulnerable to flooding, so if vital urban services such as transport and emergency response services are situated underground, there may be a significant increase in an urban area's vulnerability if it is in a region that is prone to flooding.

Table 7
Pairwise comparison sets for the “Opportunities” cluster.

Name of criteria group	With respect to	List of criteria compared	Number of pairwise comparison sets	Sample pairwise comparison question
Alternatives (3)	Each control criteria (6)	Functionality Land use Integration Flexibility Rationality Vulnerability	6	Which UCT would provide more opportunities for integration of the underground structure with existing structures?
Control criterion (6)	Alternatives (3)	Open cut Galleries Microtunnelling	3 feedback	What would be the main benefit of UCT TM? flexibility, rationality, etc.?
All but one of the control criteria in the cluster (6 − 1=5)	This control criterion (1 Rationality) (the maximum possible number is 6)	Functionality Land use Integration Flexibility Vulnerability	1 Interdependent (the maximum possible number is 6)	What is more important to ensure rationality: flexibility, integration, etc.?

“Super Decisions” [37] allows expert judgements to be examined in graphic, matrix, verbal, and questionnaire forms. An example of pairwise comparisons using the questionnaire form is presented in Fig. 2. After pairwise comparisons have been conducted, the software calculates priorities and displays an inconsistency index, which reflects how consistent a decision-maker was while making judgements.

Mixed qualitative-quantitative data input is necessary when some numerical data is missing. The most convenient way to integrate qualitative and quantitative data is to use the matrix form in pairwise comparisons.

Developing a set of criteria for “Benefits”

Under the category “Benefits” relating to the decision to use a particular UCT we assess the direct benefits of the project to the city's environment. The three assessment criteria here (Table 2) represent a simple single level hierarchy. The number and descriptions of pairwise comparison sets for the benefits are shown in Table 3. Tables 4 and 5 present priorities calculated by the software after expert judgements have been made. Results of the assessment with respect to the “Benefits” cluster are shown in Table 4.

Table 8
Priorities for alternatives with respect to criteria associated with the “Opportunities” cluster (normalised to a range from 0 to 100, shown to two significant figures).

Criterion	Brief rationale for the judgement	Alternative technologies		
		Open cut	Galleries	Microtunnelling
Functionality	Galleries can create multifunctional infrastructure, allowing additional installations if necessary.	16	66	16
Land use	If the sewer requires more space in the future, galleries would be the easiest way to facilitate expansion.	10	80	10
Integration	Galleries have the potential to be connected to other structures.	12	75	12
Flexibility	Galleries provide the most flexible infrastructure, sewers can be replaced within a gallery.	25	50	25
Rationality	Microtunnelling uses the UUS resource in a frugal manner. Open cuts create high levels of disturbance.	4	16	78
Vulnerability	The sewer is going to be completely covered by soil and isolated irrespective of the specific UCT selected.	Equal	Equal	Equal
Sub-net opportunities	Software ANP calculation	19	55	25

Discussion of the intermediate results for the cluster “Benefits”

Creation of an up-to-date infrastructure is the main goal of UUS development projects, thus it is considered to be the main benefit of UCT use. However in the Osnabruck project all three UCTs can create an equally up-to-date infrastructure. The other two criteria (low emissions and resource consumption) made a modest contribution to the benefits of the UCT use, and overall assessment results for the three UCTs do not differ much.

Developing a Set of criteria for “Opportunities”

“Opportunities” are potential benefits of a project. For UUS development “Opportunities” are very important because they reflect long-term planning needs and urban sustainability. A set of criteria associated with “Opportunities” has been developed during previous studies by the author [24,25] and is the result of continuous observations and analysis of urban underground infrastructure performance in different cities. The criteria associated with “Opportunities” are presented in Table 6.

These criteria have the following features, they:

- represent complex concepts,
- are difficult to measure,
- are subjective,
- are difficult to prioritise with respect to an assessment goal.

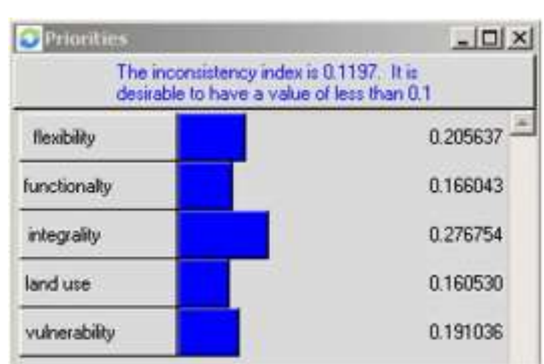


Fig. 3. Inner dependent comparisons for Rationality in the cluster criteria.

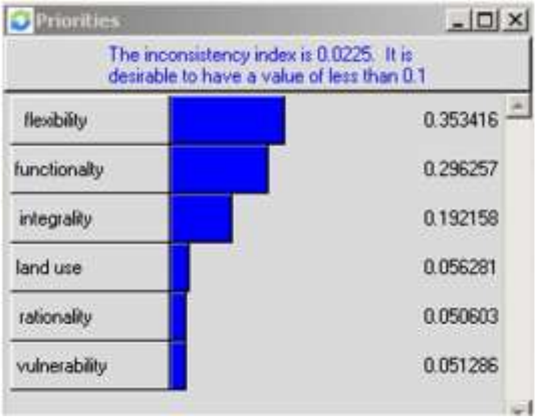


Fig. 4. Feedback comparisons for the Galleries UCT. Galleries can create underground infrastructure, rather than simply a stand-alone sewer. In a gallery it is possible to install additional conduits, to renovate and to connect the gallery with other structures.

The criteria associated with “Opportunities” are best evaluated by measuring them in the context of the alternatives. This assessment type is known in the ANP as “feedback”. These criteria may also be interdependent, and this is measured using inner dependent comparisons in the ANP. Inner dependent comparison is a comparison of a cluster against another cluster with respect to itself as the parent cluster, i.e. taking into account the influence of criteria in the same cluster on each other. A detailed description of the comparisons associated with “Opportunities” is presented in Table 6, all the comparisons in the cluster “Opportunities” were based on expert judgements. The number and description of the pairwise comparison sets for the “Opportunities” cluster are shown in Table 7. Table 8 presents priorities calculated by the software after the judgements were made.

Fig. 3 shows an example of inner dependent comparisons of cluster criteria. Not all of the six criteria (Functionality, Land use, Integration, Flexibility, Rationality, and Vulnerability) depend on each other. But rational use of UUS probably depends on the other five criteria. Results of the pairwise comparisons show that Integration is the most important criteria to enhance Rationality of UUS use. It shows that these two criteria are synergistic.

Figs. 4, 5 and 6 and Table 8 demonstrate the feedback feature of the ANP model. Criteria are evaluated with respect to alternatives in order to identify the main features (strengthens/weaknesses) of a particular UCT.

Fig. 5. Feedback comparisons for the Open cut UCT. Open cuts do not perform well under any of the opportunities criteria. Vulnerability is apparently the criterion for which this technology performs most strongly, perhaps because it results in complete sewer isolation.

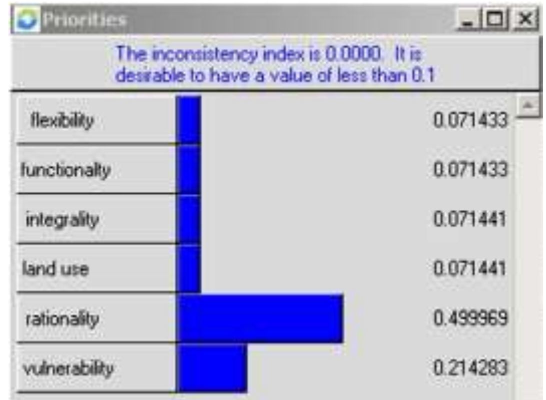


Fig. 6. Feedback comparisons for the Microtunnelling UCT. The main strength of the Microtunnelling UCT is its rational use of UUS, causing minimum disruption and minimising use of the UUS resource.

Results of assessments relating to the cluster “Opportunities” are shown in Table 7.

Discussion of the intermediate results for the cluster “*Opportunities*”The Galleries UCT appears to be the best option in the “Opportunities” cluster because of its potential to create not onlythe sewer, but a structure that has the potential to deliver other functions, and create a flexible infrastructure element (Table 9).

Developing a Set of criteria for “*Costs*”

Criteria associated with the “costs” cluster were modelled as an AHP. The assessment goal was to determine the costs (negative impacts) of a particular UCT. The criteria associated with costs can be separated into four main groups:

- Direct cost of construction
- Indirect costs due to inconvenience to the city
- Environmental costs
- Costs of intangible assets

Thus, the hierarchical structure can have several levels: control criteria, criteria, and subcriteria. However the assessment model for the “costs” cluster was simplified by avoiding giving priorities to criteria (i.e. criteria were not compared with respect to their importance to overall costs of the decision). This also allowed the exclusion of hierarchies with several levels by having just one level but with many criteria. One reason for this decision was the difficulty in prioritising the control criteria due to lack of data. For example, pairwise comparison of the importance of the “environment” versus “indirect costs due to inconvenience to the city” should have been made on the basis of knowledge of the local situation and the priorities of the city authorities.

Table 10 presents data on the criteria. These data include priorities calculated by the software after judgements had been made and

Table 9
Main results of the ANP feedback comparisons in the “Opportunities” cluster.

Summary	Alternative technologies		
	Open cut	Galleries	Microtunnelling
The main strength of the UCT	Vulnerability	Flexibility Functionality Integration	Rationality
Weaknesses of the UCT	Rationality Integration	Rationality Vulnerability	Flexibility Functionality Integration

Table 10
Input data and priorities for alternatives with respect to criteria at the lowest hierarchical level in the "costs" cluster (when there was expert judgement, this was normalised to a range from 0 to 100 and is shown to two significant figures).

Criterion	Units of measurement	Alternative technologies		
		Open cut	Galleries	Microtunnelling
Direct cost of construction	Euro	4,003,000	3,568,000	4,150,000
Rerouting public buses	Euro	960,000	0	0
Rerouting street traffic	km	1200	0	0
Revenue retail loss	Euro	664,000	19,000	19,000
Real estate value loss	Expert judgement	77	11	11
Soil stability	Expert judgement	61	26	11
Soil contamination	Expert judgement	72	17	10
Ground vibrations	Expert judgement	73	18	08
Air pollution from city traffic	Expert judgement	66	16	16
Air pollution from construction site	Expert judgement	72	17	10
Noise	Expert judgement	80	10	10
Groundwater level alteration	Expert judgement	45	45	09
Waste water from UCT equipment	Expert judgement	16	16	66
Rainwater/groundwater removal from construction site as waste water	Expert judgement	66	20	13
Excavated material removal	m^3	15,940	6381	1150
Road cover removal	Expert judgement	72	18	09
Water consumption for construction operations	Expert judgement	12	12	75
Building material consumption	Expert judgement	58	34	06
Sand for refilling excavations	Euro	215,000	145,000	42,000
Road and pavement renovation	Euro	116,000	27,000	55,000
Energy consumption by machinery and supporting equipment on the construction site	Expert judgement	17	11	70
Landscape aesthetic value	Expert judgement	81	09	09
Sub-net costs	Software AHP calculation	60	19	20

quantitative project data. Table 10 presents the number and descriptions of the pairwise comparison sets. Results of the assessment relating to the "costs" cluster are also shown in the last row of Table 11.

5.3.1. Discussion of the intermediate results for the cluster "Costs"

The Open cut UCT was found to be the most costly approach; this means that it has the highest value of adverse impacts on the city's environment. The Galleries and Microtunnelling UCTs produced very similar results in this assessment; this means that the choice between these two UCTs cannot be taken on the basis of the costs analysis alone.

Developing a Set of criteria for "Risks"

Risks are potential costs of the project in case of accidents, unknown geological conditions, poor performance of equipment and similar failures. Careful consideration of risks is quite important for the UCT assessment. All the assessments associated with the "Risks" cluster relied on expert judgements.

Criteria in the cluster Risks were modelled as an AHP. The assessment goal can be formulated as "possible negative impacts on the environment of a particular UCT". The hierarchical structure had two levels: control criteria and subcriteria. Table 12 gives assessed priorities of the control criteria and their performance based on sub-criteria. Table 13 shows assessment under the subnet "Geo" and Table 14 under "Minor incidents". The "Quality of the constructed sewer" criterion does not have a subnet and its assessment is given in Table 12.

Table 11
Pairwise comparison sets associated with the "costs" cluster.

Name of criteria group	With respect to	List of criteria compared	Number of pairwise comparison sets	Sample pairwise comparison question
Alternatives (3)	Each control criterion (22)	Open cut Galleries Microtunnelling	22	Which UCT is more costly due to groundwater level alteration? (environmental costs)

The number and descriptions of the pairwise comparison sets for benefits are shown in Table 15. Results of the assessment for the "Risks" cluster are shown in the last row of Table 12.

Discussion of the intermediate results for the "Risks" cluster

The Galleries UCT exhibited the best performance under all the control criteria. Assessments using the AHP model for the "Risks" cluster were quite stable, all three UCTs were prioritised in the same order for all major (highly prioritised) criteria.

Table 12
Priorities for alternatives with respect to control criteria and the assessment goal associated with the "Risks" cluster (normalised to a range from 0 to 100, shown to two significant figures).

Control criterion	Priorities of the control criteria	Alternative technologies		
		Open cut	Galleries	Microtunnelling
Geo	47	18	13	68
Minor incidents	05	39	20	39
Quality of the constructed sewer	47	23	13	62
Sub-net risks	Software AHP calculation	21	14	62

Table 13
Priorities for alternatives with respect to the "Geo" control criterion associated with the "Risks" cluster (normalised to a range from 0 to 100, shown to two significant figures).

Criterion	Priorities of the control criteria	Alternative technologies		
		Open cut	Galleries	Microtunnelling
Major ground collapses	72	18	12	68
Minor ground settlements	10	13	23	62
Accidental discovery and collision with objects in the underground space	16	19	10	70
Sub-net Geo	Software AHP calculation	18	13	68

5.5. Rating BOCR and strategic criteria

Strategic criteria are required in the ANP to rate alternatives under the benefits, opportunities, costs, and risks categories. Such rating is required when using "Additive-Negative" assessment formulae. Strategic criteria reflect overall strategic goals of a particular project and give a perspective on or a vision of the performance of alternative UCTs from different points of view. Descriptions of the strategic criteria and their weights, obtained via pairwise comparisons by experts, are presented in Table 16.

Rating of each UCT with respect to the strategic criteria was conducted using three grades (high, medium, and low) (Fig. 7). Rating was conducted keeping in mind the best UCT with respect to the benefits, opportunities, costs, and risks. These data were derived from the previous assessment stages and is presented in Table 17.

Table 18 describes the judgements needed to be made at this assessment stage and Fig. 7 outlines these judgements.

6. Formulae for calculating the final assessment rating

The final ANP assessment step is to synthesise the whole model and combine the benefits, opportunities, costs, and risks. This can be done using two alternative formulae: "Additive-Negative" and "Multiplicative". The formulae, their features and the assessment results for the entire assessment experiment are presented in Table 19.

7. Sensitivity analysis and the assessment results

The results show quite robust performance of the Galleries alternative when priorities (BOCR coefficients) are set to be almost equal. Allowing moderate differences between the BOCR weights

Table 16
Strategic criteria.

Criterion	Priority	Description
Reliable performance of new infrastructure	53	Major goal for a project undertaking. A certain service, which the city needs (e.g. sewerage)
Minimum disruption of the city environment during construction	29	A safeguard and indispensable condition for project implementation
Extended renovation of the urban area (opportunities for subsidiary projects)	16	An additional goal, service, or benefit that the city can get as a result of the project. Carefully selected subsidiary goals can sometimes provide good synergy with the main project goal.

represents a fairly pragmatic approach to the decision problem, since criteria under all four BOCR clusters are important. Figs. 8-11 show the performance of BOCR when the weights (BOCR coefficients) vary.

The Additive-Negative formula was used for the sensitivity analysis.

When the benefits coefficient (b) varied, the sensitivity analysis exhibited a peak with respect to the "Galleries" option at about 20% of the potential coefficient value.

The three alternatives converged at a high b coefficient value, indicating that no decision could be made if only the benefits of the project were taken into account.

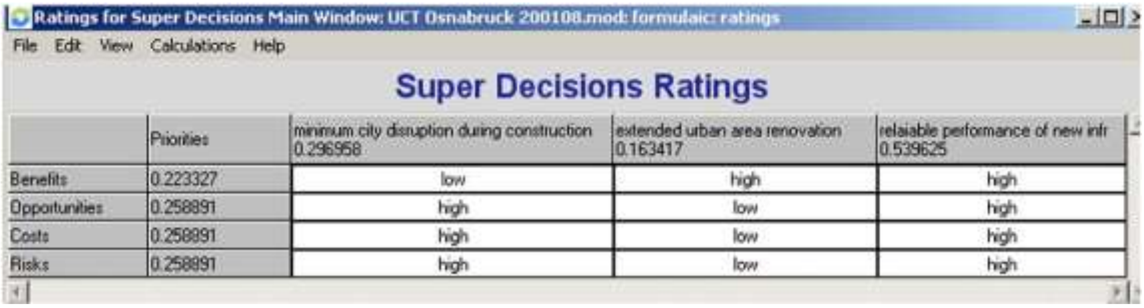
The sensitivity analysis for "Opportunities" exhibited a similar trend to that for the "Benefits". However, when the "o" coefficient was allocated a high value, the "Galleries" technology still performed significantly better than the two alternatives. This indicates that the performance of the "Galleries" technology under the "Opportunities" criteria is very robust, and "Galleries" is obviously the best technology

Table 14
Priorities for alternatives with respect to the "Minor incidents" control criterion associated with the "Risks" cluster (normalised to a range from 0 to 100, shown to two significant figures).

Criterion	Priorities of the control criteria	Alternative technologies		
		Open cut	Galleries	Microtunnelling
Soil and groundwater contamination	69	25	25	50
Flooding of construction pits	23	75	09	15
Smell (various underground features can produce smells)	06	60	20	20
Sub-net Minor incidents	Software AHP calculation	39	20	39

Table 15
Pairwise comparison sets associated with the "Risks" cluster.

Name of criteria group	With respect to	List of criteria compared	Number of pairwise comparison sets	Sample pairwise comparison question
Control criteria (3)	The goal (risks)	Geo; Minor incidents; Quality of the constructed sewer	1	What is more important for the project: "Risks associated with the lithosphere (Geo)" or "Quality of construction"?
"Geo" criteria (3)	The goal (risks associated with lithosphere)	Major ground collapses; Minor ground settlements; Accidental discovery and collision with objects in the underground space	1	What is more important with respect to the Geo risks: "Major collapses" or "Minor settlements"?
"Minor incidents" criteria (3)	The goal (risks associated with "Minor incidents")	Soil and groundwater contamination; Flooding of construction pits; Smell	1	What is the more important risk: "Smell" or "Groundwater contamination"?
Alternatives under "Geo" (3)	Each control criterion (3)	Open cut Galleries Microtunnelling	3	Which UCT is more risky with respect to ground settlement?
Alternatives under "Minor incidents" (3)	Each control criterion (3)	Open cut Galleries Microtunnelling	3	Which UCT is more risky with respect to pit flooding?
Alternatives under "Quality of the constructed sewer" (3)	The control criterion	Open cut Galleries Microtunnelling	1	Which UCT is more likely to result in poor construction quality?



Ratings for Super Decisions Main Window: UCT Osnabruck 200108.mod: formulaic: ratings

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Super Decisions Ratings

	Priorities	minimum city disruption during construction 0.296958	extended urban area renovation 0.163417	relaiable performance of new infr 0.539625
Benefits	0.223327	low	high	high
Opportunities	0.258891	high	low	high
Costs	0.258891	high	low	high
Risks	0.258891	high	low	high

Fig. 7. The ANP assessment model for UCT ratings.

according to these criteria. Thus, the decision based on this group of criteria is an obvious one and multiple criteria analysis would not be needed if the technologies were being judged solely on the basis of the "Opportunities" group of criteria in the Osnabruck project.

The sensitivity analysis for "Costs" showed that the project was not worth undertaking if the "c" coefficient value was above about 50%, in which case all three alternatives had a negative value. The "Open cut" alternative exhibited the poorest performance with respect to costs, while the "Galleries" and "Microtunnelling" options converged at high "c" coefficient values. Thus, it would not be possible to make a decision about the preferred technology if only the costs of the project were taken into account.

If the "Risk" priority was above about 60% all three alternative technologies had negative assessment values, indicating that the project should not be undertaken; the "Microtunnelling" technology exhibited significantly poorer performance. The "Microtunnelling" curve on the graph indicates that this technology is risk-sensitive, which correlates with general knowledge about its wider implementation [38]. On the sensitivity analysis graph, the "Open cut" curve exhibits almost stable performance as the risk priority varies, which means that performance of this technology is the most predictable, and its use in a project cannot be decided on the basis of associated risks.

Table 17
Performance of the UCT with respect to benefits, opportunities, costs, and risks.

Decision components	Best UCT	Alternative technologies performance		
		Open cut	Galleries	Microtunnelling
Benefits	Open cut	35	29	34
Opportunities	Galleries	19	55	25
Costs	Galleries	60	19	20
Risks	Galleries	21	14	62

Table 18
Assessment ratings.

Name of criteria group	With respect to	Judgements	Sample judgement questions
Strategic criteria (3)	Overall assessment goal: environmental quality (best from the environmental standpoint)	1 pairwise comparison set	What is the main project goal? What is the priority of one of the project goals?
The best performing UCT	Strategic criteria	12 ratings	What is the importance (e.g. high, medium, and low) of the best alternative with respect to the benefits (Open cut) for the strategic criteria e.g. "Extended renovation of the urban area"?

Overall, the results of the sensitivity analysis show that:

- The "Galleries" technology would be associated with the strongest "Opportunities", and the best performance across all criteria;

Table 19
Final results of the assessment experiment.

Synthesis formula	The best UCT	Alternative technologies' performance		
		Open cut	Galleries	Microtunnelling
"Additive-Negative" bB+ oO-cC-rR coefficients are based on the rating using strategic criteria	Galleries	−0.026478	0.779149	0.194373
"Multiplicative" BO/CR Does not use strategic criteria	Galleries	0.053588	0.860473	0.085939

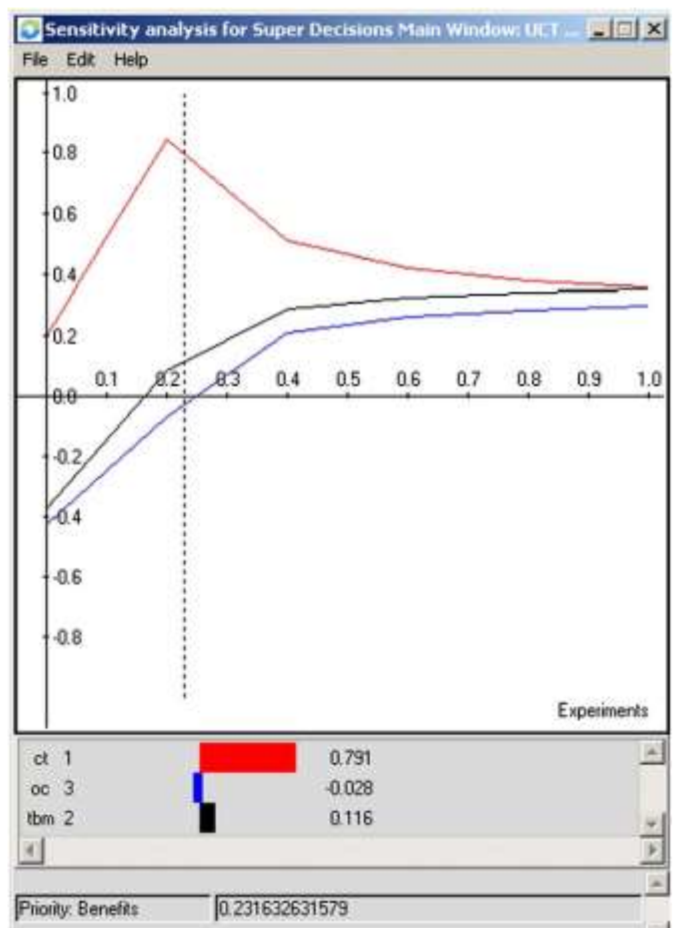

Fig. 8. Sensitivity analysis for the benefits.

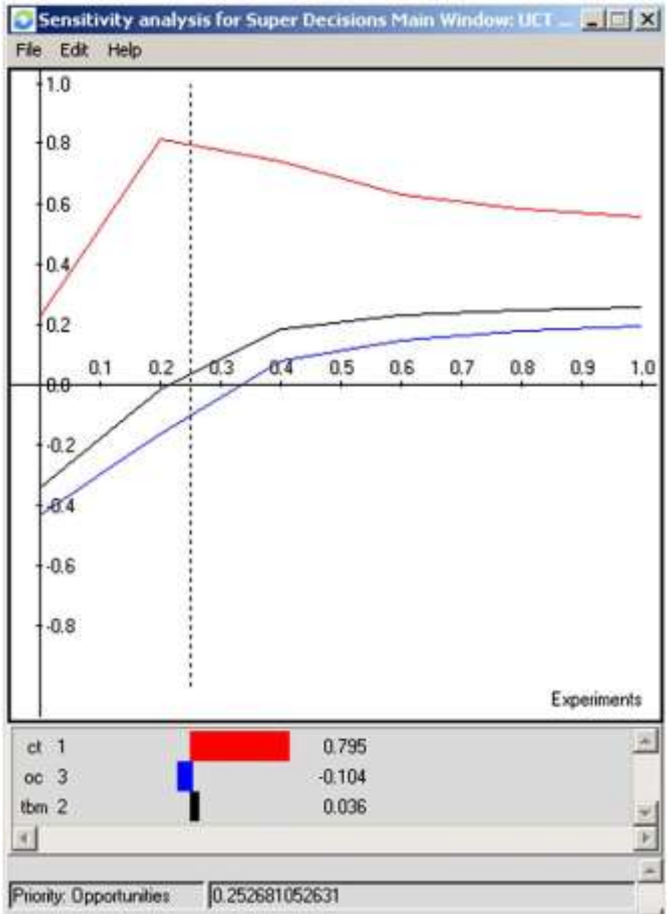

Fig. 9. Sensitivity analysis for the opportunities.

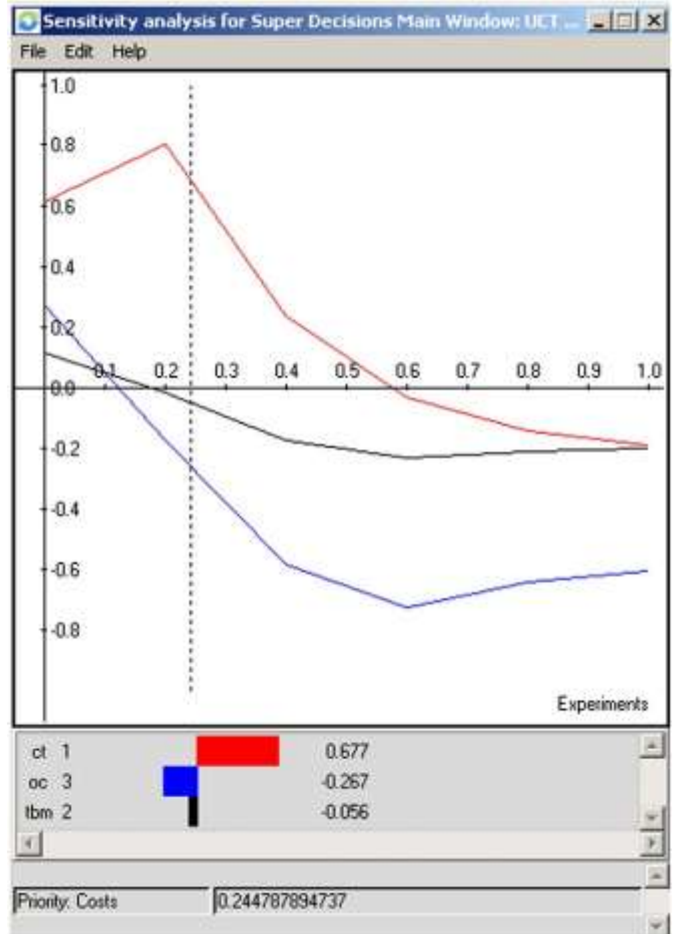

Fig. 10. Sensitivity analysis for the costs.

- The main drawback of the “Open cut” technology is “Costs”; the main drawback of “Microtunnelling” is “Risks”;
- No decision about the project could be taken solely on the basis of “Benefits”, since the alternatives exhibit similar performances;
- If costs and risks are the main concerns (high c and r coefficients) all the alternatives are negative—it is, therefore, not advisable to undertake the project.

8. Conclusion

The results of the assessment experiment suggest that the ANP can be successfully used for environmental assessment of UCTs. The ANP is particularly relevant to the evaluation of these technologies because of: (1) similar technological and economic performance of the different technologies; (2) the need to consider a large number of criteria reflecting the urban environment; (3) the facility to make use of incomplete data; and (4) clear presentation of the results in a numerical form.

The ANP helps to structure the assessment process, and integrate criteria that otherwise would not be sufficiently visible in the assessment results. In the routine practise of underground construction, environmental assessment decisions are often based on several high priority criteria (e.g. costs, risk of damaging existing structures, groundwater). Criteria of low priority (e.g. energy efficiency, water consumption, and green areas) are often considered only on the periphery of project decision-making, and are likely to be mentioned only descriptively in any environmental assessment study. The ANP helps to give fair consideration to all the relevant criteria, taking into account their relative importance.

The most important factors in a reflective ANP process are a comprehensive, properly structured set of criteria and reliable information on their performance.

The great benefit of using ANP is the opportunity to integrate complex concepts into decision making, making use of its inner dependence and feedback features. In the assessment experiment described herein, this approach was applied to the “Opportunities” cluster. Despite the fact that the “Opportunities” cluster exhibited both robust and trivial results in this assessment, the approach helped to address the complex concept of rational underground space use, which could not otherwise have been integrated into a quantitative assessment.

The author suggests that ANP is appropriate for use in complex environmental assessments.

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