Decision-making for increased sustainability in underground construction works using Analytical Hierarchy Process

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ABSTRACT
Decision-making in infrastructural projects involves technical, economic and environmental aspects in a modern society. The time horizons are long in infrastructural projects and it is difficult to oversee all the costs and effects of each decision. To reach sustainable solutions, decision-making that is both objective and transparent is needed. There can be economical obstacles in form of budget limitations in each phase of the project (design, construction, operation and maintenance) that discourage a long-term and sustainable view of the project solution. Generally, low investment costs are important for the choice of technical solutions to keep the costs within budget limitations. Economically, a life cycle cost perspective is needed since the costs for maintenance can be significant and it is therefore clear that the economical perspective needs to be over a life time perspective.
The aim of this paper is to present how sustainability can be included in decision-making between different technical solutions in tunnelling projects. In the study we refer to, the Analytical Hierarchy Process (AHP) was used as a decision-support tool in the design phase of an infrastructure tunnel. In the tunnel project, there are five potential systems for reinforcement and drainage and these systems were evaluated against three criteria; (I) economy based on life cycle cost, (II) environmental impact and (III) robustness & uncertainty.
The findings indicate that multi-criteria decision methods, such as AHP, are useful for incorporating other criteria than economy into decisions regarding technical solutions in tunnelling projects. The AHP supports the decision-maker as such but also simplify documenting the process and in communication of the final decision.

Keywords: Decision making, LCC, Sustainable solutions, Analytical Hierarchy Process, AHP

1 INTRODUCTION

There are increased demands in society to act in a sustainable way, and most corporations have policies for their sustainability work. However, in daily decision-making, economy tends to be the governing criteria for decisions. To get sustainability more tangible and incorporated into decisions in daily work, the concept needs a clear definition to set the frames for the aim of sustainable development.
The World Commission on Environment and Development (Brundtland Commission) defined sustainable development as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" (Bruntland report, 1987).
Following the commission, sustainable development has three dimensions:

- Ecologic sustainability
- Sociocultural sustainability
- Economic sustainability

To further define sustainability, Holmberg and Robèrt have developed four non-overlapping principles for a sustainable society (Holmberg et al., 1996; Holmberg, 1998), where they state that "for a society to be sustainable, nature's functions and diversity must not be systematically:

1. Subject to increasing concentrations of substances extracted from the earth's crust.
2. Subject to increasing concentrations of substances produced by society
3. Impoverished by over-harvesting or other forms of ecosystem manipulation.

And

4. Resources must be used fairly and efficiently in order to meet basic human needs worldwide."

The principles give guidance on how to work towards a sustainable society, but in practice there are many decisions where the impact in terms of sustainability between alternatives is not clear. Moreover, it is hard to weigh the three different dimensions on sustainability in relation to each other.

In the tunnelling industry, the concept of sustainability is generally discussed in the top of organisations, but when following the strategy to its end in decisions about technical solutions, there can be conflicts between the traditionally governing economical decision criterion and the other two dimensions. Neither is the evaluation of each dimension straightforward.

In this paper, we present a study where decision theory has been applied to a tunnel project. The aim of the study was to test if we could incorporate other criteria than economy into decisions about technical solutions. The technical solutions concerned what system to choose for drainage and reinforcement of the tunnel. The decision method we applied follows the steps of an Analytical Hierarchy Process (AHP).

The tunnel is a railroad tunnel constructed in crystalline igneous rock. Five different technical systems on drainage and reinforcement were evaluated in an AHP process against the criteria life cycle cost (LCC), environmental impact and robustness & uncertainty.

The decision alternatives, that is, the five different technical systems for drainage and reinforcement are only described as numbers, for technical specifications and differences between the alternatives see Eriksson and Edelman (2014).

2 BACKGROUND ON ANALYTICAL HIERARCHY PROCESS

During decision-making in complex projects decision theory can be used to bring structure and clarity to the process. The purpose of a decision model is to give the decision-maker support to formulate and structure thoughts and opinions. The decisions are often choices between different alternatives where different criteria are considered to be of unequal importance for the decision.

The Analytical Hierarchy Process (AHP) is a method where different alternatives are evaluated against different decision criteria. Thereafter, all different combinations are compared to decide which alternative that best fulfils the stated criteria.

Individual experts representing different expert fields compare each alternative solution par wise to each other in relation to identified criteria. The alternatives can be evaluated equal or one alternative can be evaluated as preferential using a certain scale. Additionally, the different criteria are individually evaluated based on how important they are for the decision-making. Mathematically, the statistically most preferred alternative is calculated using eigenvectors. For more details about calculations, see e.g Saaty (2008, 1980).

3 METHODS AND PROCEDURE

The process of the AHP in this study followed the order shown in Figure 1. Much of the work was done in a project group with experts from the Swedish Transport Administration and the Swedish Geotechnical Institute (SGI). The competences in the project group were rock mechanics, hydrogeology, geotechnics and maintenance.

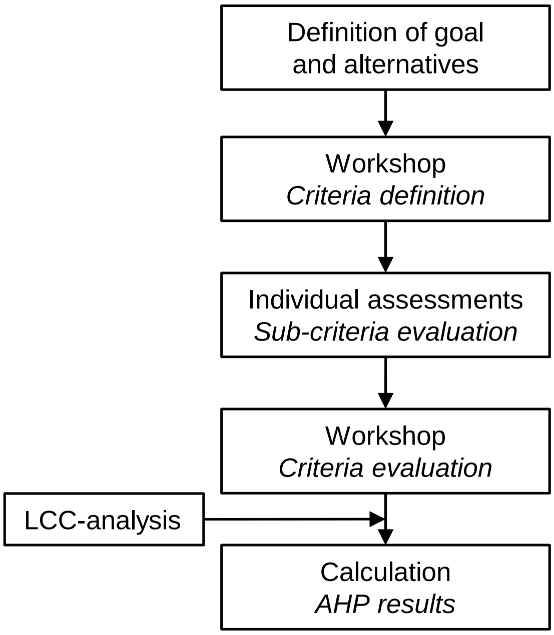

Figure 1. Flowchart of AHP procedure.

3.1 Definition of goal and alternatives

The overall goal of the tunnel project is to build a tunnel that is secure in terms water and rock mechanics. To reach this goal, different systems for drainage and reinforcement are available. The goal of the AHP process was to decide which system to use.

Five systems, based on different technical solutions on drainage and reinforcement were outlined. The systems differ also from an economical point of view, because they have different investment costs and maintenance requirements during the technical life span. The systems are described in detail in Eriksson & Edelman (2014).

3.2 Criteria definition

Important criteria for the choice of system for drainage and reinforcement were discussed in the project group.

Traditionally, an apparent criterion to consider is the investment cost. However, the investment cost does not give the full picture in this study, because the costs for maintenance differ significantly between the systems. Therefore, the life cycle cost (LCC) has been calculated for each system.

The LCC analysis also included the so called "societal costs" which are the indirect costs of disrupting the traffic system during maintenance. Hence, the LCC includes the investment cost and the sum of maintenance and societal costs in net present value.

The different technical systems are also related to different levels of environmental impact, and the Swedish Transport Administration is obliged to reduce the environmental impact of their projects. Another aspect of the decision is whether the systems are reliable or if there are known risks related to any of the systems.

The discussion resulted in three formulated decision criteria:

1. Life Cycle Cost (LCC)
2. Environmental Impact
3. Robustness & Uncertainty

The hierarchy of the decision is illustrated in Figure 2.

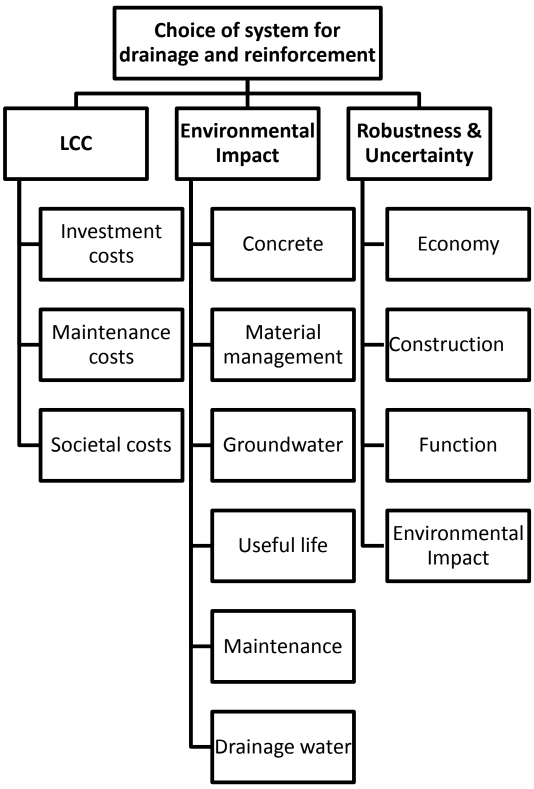

Figure 2. Hierarchy of decision problem. The decision alternatives are excluded from the diagram.

3.3 Criteria LCC– Definition and Input data

LCC is the total cost of investment and future operation and maintenance costs in net present value. A LCC analysis was performed for each technical system separately and the results correspond to the LCC criterion. The results are shown in Table 1.

Table 1. LCC of the five different technical systems.

System	LCC [SEK/m]
1	475 000
2	463 000
3	409 000
4	454 000
5	566 000

3.4 Criterion environmental impact

Environmental impact is a broad criterion that in this limited study only describes the environmental impact of the systems in qualitative terms.

The criterion comprises following parameters that also forms sub-criteria:

- Use of concrete
- Material management
- Groundwater impact
- Useful life
- Maintenance
- Drainage water

3.5 Criterion robustness & uncertainty

The technical systems can be linked to uncertainties and risks not included in the LCC analysis. These are included in the criterion of Robustness & Uncertainty.

One part of this criterion is project risk, which is a possible, but unexpected additional cost that is outside the uncertainty in the budgeted costs (Brinkhoff et al, 2015).

Parameters included in the criterion robustness & uncertainty, that also forms sub-criteria, are:

- Economy
- Construction
- Function
- Environmental and hydrogeological impact
- The system's effect on other technical systems, such as electricity, rails, etc.

A system that is valued high regarding robustness & uncertainty is assumed to result in less unexpected negative events (surprises) during construction and operation. In the early assessments they are considered to suffer from less uncertainty.

3.6 Sub-criteria evaluation

In the first part of the assessment, three experts in hydrogeology, rock mechanics and rock engineering assessed the performance of the five different systems for drainage and reinforcement against the criteria and sub-criteria. The experts made their assessments individually by placing the systems in order of precedence regarding their indirect impact and thereafter order the systems according to a scale between 1 and 5.

The first part of the assessment was formulated as following regarding environmental impact:

1. Place the systems in order of precedence regarding their indirect environmental impact due to use of concrete:
2. Place the systems in order of precedence regarding their indirect environmental impact due to excavation and transport of rock material:
3. Place the systems in order of precedence regarding their indirect environmental and hydrogeological impact during the construction phase:
4. Place the systems in order of precedence regarding their indirect environmental and hydrogeological impact during the operation phase:
5. Place the systems in order of precedence regarding their indirect environmental impact due to handling of drainage water:
6. Place the systems in order of precedence regarding their expected useful life and the environmental impact due to the length of useful life:

7. Place the systems in order of precedence regarding their indirect environmental impact due to maintenance (including transports needed for maintenance):

The scale was from 1 to 5, where 5 means largest environmental impact and 1 means smallest environmental impact.

Regarding robustness & uncertainty, the first part of the assessment was formulated as following:

1. Place the systems in order of precedence regarding their robustness about economy (cost estimations, etc.):
2. Place the systems in order of precedence regarding their robustness about the construction phase:
3. Place the systems in order of precedence regarding their robustness about their function:
4. Place the systems in order of precedence regarding their robustness about environmental and hydrogeological impact:
5. Place the systems in order of precedence regarding their robustness about their impact on other technical systems:

The scale was from 1 to 5, where 5 means high robustness (low uncertainty) and 1 means low robustness (larger uncertainty).

3.7 *Criteria evaluation*

The second part of the assessment, a mutual assessment of the criteria, took place at a workshop with seven invited experts from the Swedish Transport Administration. Following fields of expertise were represented at the workshop; hydrogeology, rock mechanics, rock engineering, technical maintenance, finance and project management.

Each person was to individually assess the three criteria pairwise against each other by answering a set of questions. A scale was presented as a guide for the evaluation, see Table 2. The questions were:

- 1a. What is most important - LCC or Environmental impact?
- 1b. How much more important based on the scale in Table 2?
- 2a. What is most important - LCC or Robustness & Uncertainty?
- 2b. How much more important based on the scale below in Table 2?
- 3a. What is most important - environmental impact or robustness & uncertainty?
- 3b. How much more important based on the scale in Table 2?

Table 2. Scale for rating of criteria (after Saaty, 1980)

Intensity of importance	**Definition**	**Comment**
1	Equal importance	Two factors contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one over the other
5	Strong importance	Experience and judgement strongly favour one over the other.
7	Very strong importance	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Extreme importance	The evidence favouring one over the other is of the highest possible validity.

3.8 Calculation – AHP Results

The points of each system and criterion were summarised and translated into a Saaty scale for comparison, see Table 3.

Table 3. Conversion between points, costs and Saaty scale. The scales of the three criteria were decided within the project group.

Saaty scale	LCC [1000 SEK/ m]	Environmental Impact [points]	Robustness & Uncertainty [points]
1	<40	<30	<21
3	80-120	39-48	29-34
5	160-200	58-66	42-47
7	240-280	77-85	55-60
9	>320	>95	>68

The calculations were made in a spreadsheet template from BPMSG-Business Performance Management (Goepel, 2013).

4 RESULTS

4.1 Criteria evaluation

Based on each workshop participant's pairwise assessment of the decision criteria LCC, environmental impact, and robustness & uncertainty, the individual weighting of the criteria was calculated, see Table 4. It was noted, that the assessments of one person resulted in inconsistent priority of the alternatives, however, the assessments were not excluded from further calculations. For the whole group, a 91% consensus is achieved amongst the individuals, and the prioritisation of criteria is:

1. LCC (48%)
2. Robustness & Uncertainty (41%)
3. Environmental Impact (11%)

Table 4. Individual weights of decision criteria based each participant's assessments.

Criteria	Participants weights (%)						
	1	2	3	4	5	6	7
LCC	33	43	68	30	46	51	62
Robustness & Uncertainty	8	14	6	9	22	10	9
Environmental Impact	59	43	26	62	32	39	30

4.2 Rank of systems according to criteria

Based on the second part of the assessment, i.e. how well the systems fulfil the criteria environmental impact and robustness & uncertainty, an order of precedence of the systems were made for each criterion, see Table 5. The order of precedence for the criterion LCC is based on the calculated costs of the LCC analysis.

Table 5. Order of precedence of the five systems for each criterion.

System	Rank		
	LCC	Environmental Impact	Robustness & Uncertainty
1	4	2	4
2	3	3	3
3	1	1	3
4	2	2	2
5	5	1	1

4.3 Total result AHP

After the final calculations, Systems 3 showed to be the preferred system according to the conditions and decision criteria stated for this study. The total prioritisation is shown in Figure 3.

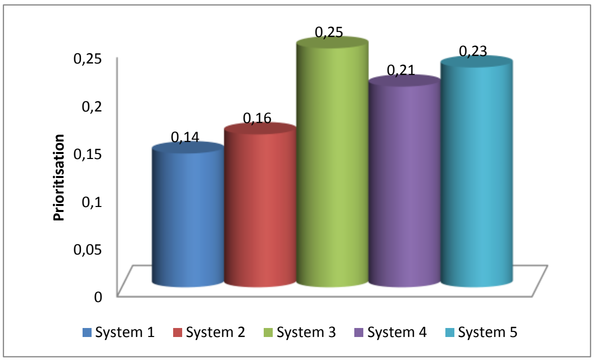

Figure 3. Total result of AHP calculations.

5 DISCUSSION

The aim of this study was test if we could incorporate other criteria than economy into decisions about technical solutions. An initial hypothesis was that the costs alone are considered as the most important aspect. Hence, it is interesting to notice that the participants in the workshop evaluated robustness nearly as high as the costs. Our interpretation is that certainty in knowing that you get what you have ordered is important.

The criterion environmental impact was not highly prioritised by the group of experts attending the workshop. One reason for this was revealed in the discussion that followed the individual, first part of the assessment. Several of the experts considered that environmental impact of the different systems had a low priority since all alternatives fulfil existing environmental legislations. It should be noted though, that expertise in sustainability or environmental issues were not represented in the group.

No members of the project group had previous experience of working with a decision analyses process, but after an introduction to the AHP method, this was accepted and understood by the project group. The discussion about the decision criteria and their definitions was a learning process itself where different views of the decision were presented by the experts

The choice of decision criteria in an AHP should reflect the decision-maker’s preferences. Nevertheless, by choosing and defining criteria it is possible to highlight aspects that easily could be foreseen otherwise. The use of LCC instead of investment costs is a step towards a more holistic view of the costs for an underground project. The criterion environmental impact could be further developed to include a Life Cycle Analysis (LCA). However, both LCC and LCA are time demanding analyses and the assumptions and limitations are often debated.

It is possible to develop the criteria of environmental issues further. It is also possible to include social aspects in the methodology presented here, in order to focus the decision towards sustainability even further.

An underlying question is how to include aspects on sustainability in underground construction works. On one hand, one could argue that the most environmentally sustainable solution should be chosen. However, the economic aspect must be included as well, since gained economic strength for the society can be used to finance other projects. For instance, a cost saving in one project can finance a more sustainable solution in another project. Therefore, decision making that includes several different aspects is necessary for targeting increased sustainability in underground construction works.

6 CONCLUSIONS

The main conclusions from this study are:

- It was possible to apply the AHP method to the decision process in a real case, and it was possible to include environmental impact as one among other aspects considered during the decision making.
- The method was easily accepted by the experts in the project group after a short introduction, indicating that the method is suitable for usage in forums where decision analysis is not commonly adopted.
- The results obtained by using the method are transparent. Moreover, sensitivity studies can easily be performed to demonstrate the robustness of the result in relation to the decision.
- Using decision analyses, in this case AHP, supports including environmental aspects and promotes more sustainable solutions. In the process of doing the decision analysis all questions that should have an impact on the decision will be revealed, hence sustainable solutions will be high lightened.
- The discussions that emerged during the assessment process were valuable, on their own, because they triggered a more creative and interdisciplinary focus in the tunnel project.

7 ACKNOWLEDGEMENTS

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