Journal of International Scientific Publications:
Materials, Methods & Technologies, Volume 7, Part 1
ISSN 1313-2539, Published at: http://www.scientific-publications.net

APPLICATION OF THE ANALYTIC HIERARCHY PROCESS (AHP) TO EVALUATION OF VARIANTS OF A PLANNED ROAD INVESTMENT PROJECT

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Abstract

For successful development, economic exchange and broadly understood international cooperation, it is essential to possess a coherent transportation network. There are many regions endowed with outstanding, legally protected wildlife areas, but the economy, which grows continuously, requires construction of new roads and upgrading of the existing routes. One of the priorities is therefore to maintain the intact condition of natural environments over large areas covered by protection schemes. This paper discusses problems arising when making decisions about new investments and the barriers encountered while performing road investment projects. It has been suggested to support the decision-making process with the AHP method. This is a method which enables the user to consider various, frequently immeasurable and hardly comparable criteria in order to determine their importance. The method can be helpful when selecting a variant that will best satisfy the investor's expectations.

Key words: *road investment projects, selection criteria, selection of an investment project variant, the AHP method*

1. INTRODUCTION

When planning and designing a transportation network, we come across many problems typical of such investments. They can occur while preparing a given project or making decisions about the plan, but also when performing the construction works. Constructing a road is a large investment project and as such requires careful preparation, very good management and high financial outlays. Good preparation and planning are particularly important. At these early stages, one must foresee all possible difficulties and inconveniences associated with the project. (Šelih et al. 2008)

Most road construction projects involve elaboration and analysis of several variants. (Zavadskas et al. 2007) Most often, such variants comprise different routes of future roads as well as different design and technological solutions. Although the economic aspect is certainly an important component of the above analysis, the regulations governing the natural environment conservation and protection can significantly affect the final shape of a road construction project as well as the costs of its execution. What needs to be done is to prepare several variants of a planned road which will take into account conservation of valuable natural habitats, required protection of the acoustic climate, construction of passages for animals, protection of birds, protection of surface and groundwater, protection and management of roadside plant assemblages, landscape management, fulfilment of the required environmental compensations, environmental risks and monitoring of the wildlife status. Possible social conflicts are also identified and consultations with local communities are arranged in order to avoid the former. Besides, it is necessary to analyse whether a planned road construction project complies with the local spatial management plans.(Al-Harbi 2001) Costs of road construction are reviewed, including costs of natural environment protection (constructing safe passages for animals, protecting water bodies, protecting from noise), restrictions on the timing of actual construction works, location of road user service areas and other road maintenance facilities.

Making decisions while pursuing a road investment project, in a situation as complicated as shown above, requires application of an efficient decision-support method, a method that will enable the decision makers to consider all significant aspects (criteria) and, on the other hand, will help to best satisfy all the criteria. The Analytic Hierarchy Process (AHP) method seems to be suitable. This paper present the AHP method and shows its applicability, by taking a section of a road planned to be built in an area characterised by high natural quality as a case for analysis. (Abu Dabous, Alkass 2008)

2. DESCRIPTION OF THE AHP METHOD

The Analytic Hierarchy Process (AHP) is one of the multi-criteria analytic methods, with which it is possible to evaluate all available variants of an investment project. (Saaty 1990, 1994) The AHP approach enables the user to take into consideration various criteria which condition the attainability of the project's goal. By being a universal method, the AHP has proven practically useful in solving a broad scope of problems, from military through social and economic to technical ones. (Abu Dabous, Alkass 2008) The underlying provision of the method is that an overall goal is attainable by reaching subordinate goals, which lead to obtaining the main goal. Alternative solutions are considered, which – to a different extent- satisfy the expectations. How a given decision option fulfils the overall goal depends on the degree to which it satisfies the main criteria and, appropriately ranked, sub-criteria. Decomposition of a problem facilitates our evaluation and is the essence of the AHP method.

In this method, a problem is solved by going through three stages (steps), arranged in an integrated and logical sequence:

1. presenting the problem's structure and constructing a hierarchy model (determination of criteria),
2. evaluating the criteria on a nine-point scale by pairwise comparison and construction of an assessment matrix ***A*** (analysis of the matrix, determination of vectors of priorities),
3. evaluating and arranging the variants by setting the priorities (main weights), including the analysis of sub-priority vectors.

In order to analyse the variants, a 4-level hierarchy structure model is usually constructed (fig. 1).

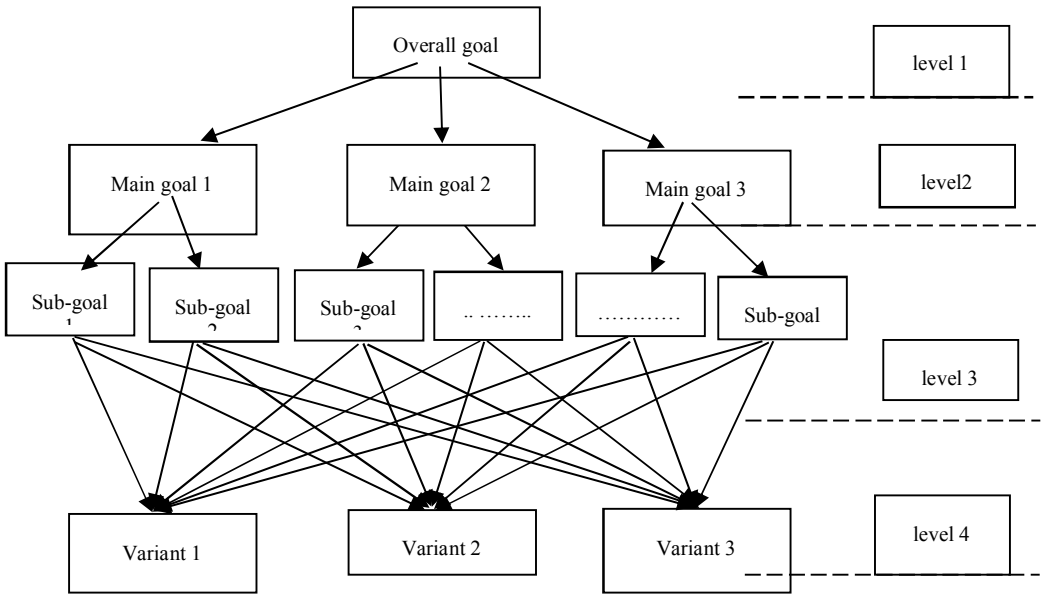


fig.1. The structure of 4-level hierarchy model (the author's own elaboration)

In the above hierarchical structure, we can distinguish:

- the overall goal (level 1), which means execution of a planned project (in this case, construction of a section of a road connecting two points in a transportation network),
- main goals – describe the main criteria related to the execution of the planned investment project (e.g. economic criteria, environmental criteria, etc.),
- sub-goals are defined in a narrower range, under each of the main goals, and they enable the user to formulate more precise requirements and to understand better the main goal (e.g. within the economic criterion, such questions as the cost of executing the project, costs of purchasing the land under construction, etc.),
- variants – alternative options of how the goal can be reached, which – to a different degree - satisfy the goals defined previously.

When applying the method, the number of criteria compared on the same level should be limited to just a few comparable ones so that it is possible to construct a cohesive matrix of comparisons. It is also necessary to assume some degree of simplification in modelling the analysed problem, to collaborate with experts and to review references as well as opinion surveys.

During the evaluation, all the criteria on a given level are compared in pairs and their mutual relations are established; thus, a decision must be made which of these criteria and to what extent will be more important for the execution of the planned project. The evaluation is achieved using an evaluation scale elaborated by Professor Thomas Saaty, which is presented below in a tab. 1.

Tab. 1. AHP fundamental scale (Saaty 1990, 1994)

Score	Specification
9	Predominance of one criterion over the other is absolute and proven to the highest degree
7	One criterion is very strongly preferred to the other and the preference is proven in practice
5	One criterion is preferred to the other
3	One criterion is slightly more preferred to the other
1	Both criteria contribute to the same degree to attaining the goal
2,4,6,8	Intermediate values, used only when necessary

The number of pairs creating the matrix and submitted to analysis depends on the number of defined criteria (tab. 2).

Tab. 2. Number of nodes a_{ij} (Saaty 1990, 1994)

Number of criteria	1	2	3	4	5	6	7	n
Number of nodes	0	1	3	6	10	15	21	$\frac{n(n-1)}{2}$

The next step involves construction of a comparison matrix $\boldsymbol{A}$, in which we place the scores determined while evaluating the criteria. (Saaty 1990, 1994) The matrix has certain specific features:

the diagonal consists of values equal one because it contains a comparison of each criterion to itself, $a_{ij} = 1$ for i=j; the elements a_{ij} are a reciprocal of the elements a_{ji}. Logically, all $a_{ij} > 0$. When the preferences (a_{ij}) are established, we can calculate elements a_{ji} $a_{ji} = \frac{1}{a_{ij}}$. The pairwise assessment and establishment of other elements enables the user to construct a preferences matrix. Below, a matrix constructed for 4 criteria is shown.

$$A = \begin{vmatrix} a_{11}=1 & a_{12} & a_{13} & a_{14} \\ a_{21}=\frac{1}{a_{12}} & a_{22}=1 & a_{23} & a_{24} \\ a_{31}=\frac{1}{a_{13}} & a_{32}=\frac{1}{a_{23}} & a_{33}=1 & a_{34} \\ a_{41}=\frac{1}{a_{14}} & a_{42}=\frac{1}{a_{24}} & a_{43}=\frac{1}{a_{34}} & a_{44}=1 \end{vmatrix} \quad [1]$$

In this case, for the number of criteria = 4, the number of nodes = 6.

The literature contains calculations formulas for the subsequent steps leading to the calculation of the value of a priority criterion.

These are:

Calculations of the value of a normalised matrix:

$$\overline{w_{ij}} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad [2]$$

Determination of the value of the vector of sub-priorities:

$$\overline{w_j} = \sum_{j=1}^{n} w_j a_{ij} \quad [3]$$

where:

$$w_j = \frac{\sum_{i=1}^{n} w_{ij}}{n} \qquad i,j = 1\ldots n \quad [4]$$

To verify whether the above procedure has been correct, we determine:

- the matrix's own maximum value:

$$\lambda_{max} = \frac{1}{w_i} \sum_{i=1}^{n} a_{ij} w_j \quad [5]$$

- value of the consistency index:

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \quad [6]$$

- consistency ratio:

$C.R. = \frac{C.I.}{R.I.}$, where the CR should reach a value <10%

R.I. - random index whose value depends on the 'n' number of compared components (tab. 3).

Tab. 3. Value of the random index (RI). (Saaty 1990, 1994)

n	1	2	3	4	5	6	7	8	9	10
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3. IDENTIFICATION OF A DECISION-MAKING PROBLEM

Investment projects such as construction of sections of roads are particularly difficult. In most cases, especially when planned roads will run across areas characterised by different quality of the natural environment, it is necessary to design several alternative routes and propose different technical or transportation solutions. Having prepared several alternatives, it is now possible to find the solution which will most closely respond to the project's underlying assumptions. By taking into considerations analyses of investment projects carried out in a region endowed with high quality natural values and based on expert opinions, it has been found out that four groups are criteria are most often considered while working on road construction plans. Each group comprises most frequently cited sub-criteria. Three alternatives of the discussed project were analysed. (Šelih et al. 2008)

In the project discussed in this paper, the following criteria and sub-criteria were applied:

A. <u>transportation and communication sub-criteria:</u>

A1 - transport performance (number of vehicles x kilometres per hour)

A2 – costs due to the time it takes to transport loads, including the time wasted due to traffic jams or extension of the route,

A3 – length of the road in km,

A4 – costs due to maintenance of vehicles (repairs, fuel).

<u>B – economic sub-criteria</u>

B1 – costs of constructing the road

B2 – costs of purchasing the land

B3 – costs of compensation paid

<u>C – environmental sub-criteria</u>

C1 – incursion on protected areas

C2 – length of routes running through forested areas

C3 – number of trees to be felled

C4 – cutting across routes travelled by wild animals

C5 - cutting across watercourses

D – social and planning sub-criteria

D1 – number of buildings to be demolished

D2 – number of buildings 0-50 m away from the planned road

D3 – number of buildings 50-100 m from the planned road

D4 – acreage of the land to be repossessed

D5 – collisions with the planned spatial management

According to the guidelines for using the AHP method, as described above, a hierarchy of the problem was determined (fig. 2) and the following were defined:

- the decision goal – execution of the investment project,
- main goals, referred to as the main criteria (in this case, these are transportation-communication, economic, environmental and social and planning criteria)
- intermediate goals (sub-goals or else sub-criteria) written out for every main criterion.

The analysed alternative solutions are different in the actual course of a planned route and therefore they can satisfy the previously set decision goal and sub-goals to a different extent. Below, a brief description of each variant is presented. An evaluation spreadsheet has been prepared for their evaluation (tab. 4).

Variant 1 – it most closely responds to the environmental and spatial criteria, less so to the transportation criteria and is the least profitable economically. This is the longest route but bypasses several environmental collisions.

Variant 2 – is the least expensive one, considering both the costs of construction works and the purchase of land or compensation due; it responds to the transportation criteria and – partly – the environmental ones. This is the shortest route but does not fulfil completely the transportation or environmental expectations.

Variant 3 – it most completely satisfies the transportation criteria and design-related requirements, in terms of both setting the routes and other demands; economically, it is superior to variant 1 but inferior to variant 2; it will partly satisfy the environmental requirements.

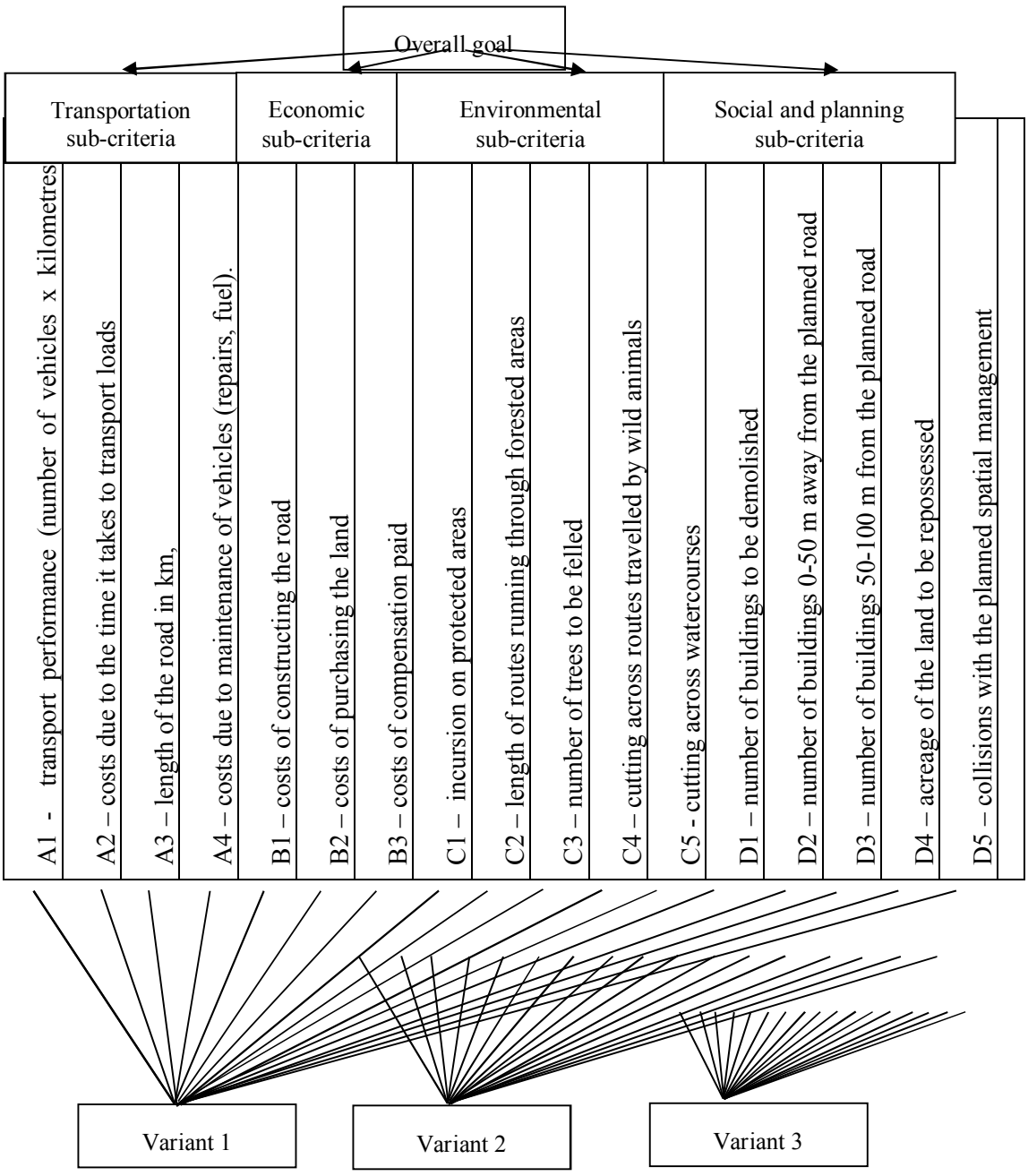


Fig. 2. Hierarchy of criteria and sub-criteria (the author's own elaboration)

4. SOLVING THE PROBLEM WITH THE AHP METHOD

The calculations were carried out according to the procedure discussed above. The evaluation of the particular criteria compared pairwise was completed including the transportation, economic, environmental and spatial considerations.

Tab. 4. The comparison matrix for the main criteria (the author's own elaboration)

Superior criteria	A	B	C	D
A	1	0.5	0.1429	0.5
B	2	1	0.3333	3
C	7	3	1	5
D	2	0.3333	0.2000	1
sum aij	12.0000	4.8333	1.6762	9.5000

Tab. 5. The value of the normalised matrix and the priority vector for the superior criteria

Superior criteria	A	B	C	D	sum wij	Vector of priorities w_j
A	0.0833	0.1034	0.0852	0.0526	0.3246	0.0812
B	0.1667	0.2069	0.1989	0.3158	0.8882	0.2221
C	0.5833	0.6207	0.5966	0.5263	2.3269	0.5817
D	0.1667	0.0690	0.1193	0.1053	0.4602	0.1151

For the main criteria:

- we set the matrix's own maximum value:

$$\lambda_{\max} = \frac{1}{w_i}\sum_{i=1}^{n} a_{ij} w_j = 12 \text{ x } 0.0812 + 4.8333 \text{ x } 0.2221 + 1.6762 \text{ x } 0.5817 + 9.5 \text{ x } 0.1150 = 4.11528$$

- the value of the consistency index:

$$C.I. = \frac{\lambda_{\max} - n}{n-1} = \frac{4{,}11528 - 4}{4-1} = 0.0384$$

- the inconsistency ratio:

- $C.R. = \frac{C.I.}{R.I.}$ where C.R. should reach a value <10% $R.I. = 0.9$ (Tab.3.)

$$C.R. = \frac{0{,}0384}{0{,}9} = 0.0427 \text{ x } 100\% = 4.27\%$$

In many cases, it is necessary to additionally analyse the sub-criteria. They are set in groups subordinated to the main goals. Analysis of groups of sub-criteria, on one hand, is necessitated by the limited number of criteria compared directly with one another and, on the other hand, by the fact that some of these criteria would be difficult to compare directly. Comparability of criteria, in turn, ensures that we can construct a coherent comparison matrix, which is an essential condition. Sometimes, matrices for selected (most important) sub-criteria are constructed. Whenever it is necessary to establish a hierarchy of all included sub-criteria, all their groups undergo analysis. In our example, we

present calculations for the sub-criteria from the group that attained the highest value of the priority vector, i.e. the environmental criterion C.

Tab. 6. Comparison matrix for the sub-criteria of the environmental criterion.

Environmental sub-criteria	C1	C2	C3	C4	C5
C1	1	2	3	2	3
C2	0.5000	1	2	3	1
C3	0.3333	0.5	1	2	0.3333
C4	0.5	0.3333	0.5000	1	0.3333
C5	0.3333	1	3	3	1
sum aij	2.6667	4.8333	9.5000	11.0000	5.6667

Tab.7. Value of the normalised matrix and priority vector for the sub-criteria under the environmental criterion

Environmental sub-criteria	C1	C2	C3	C4	C5	sum wij	Vector of priorities w_j
C1	0.3750	0.4138	0.3158	0.1818	0.5294	1.8158	0.3632
C2	0.1875	0.2069	0.2105	0.2727	0.1765	1.0541	0.2108
C3	0.1250	0.1034	0.1053	0.1818	0.0588	0.5744	0.1149
C4	0.1875	0.0690	0.0526	0.0909	0.0588	0.4588	0.0918
C5	0.1250	0.2069	0.3158	0.2727	0.1765	1.0969	0.2194

$\lambda_{max} = 5{,}33125$; $C.I. = 0{,}08281$; $C.R. = 0{,}073939$ x 100% =7.39% < 10% ; $R.I.$ = 1.12 (Tab.3.)

The calculations conducted on the group of environmental sub-criteria yielded the highest value of sub-criterion C1: incursion on protected areas is $w_1 = 0.3632$, which therefore weighs most heavily on selecting the most suitable project's variant. The second most important criteria were C5 – crossing watercourses $w_5 = 0.2194$ and C2 – length of the road running through forested areas $w_2 = 0.2108$.

In the case analysed in this article, we have 3 alternative variants of the project's execution. They were briefly characterised in the third part of the article. The three variants cannot be compared directly. Each will differently fulfil the criteria distinguished previously. A simplified analysis is often performed, which takes into account satisfying one or two most important main criteria. However, since we are interested in a complex analysis of the variants, we shall compare them pairwise with respect to all the criteria listed before.

Tab. 8. Comparison matrix for variants with respect to criterion A

variant	w1	w2	w3
w1	1	0.5	0.3333
w2	2	1	0.5
w3	3	2	1
sum	6	3.5	1.8333

Tab. 9. Values in the normalised matrix and priority vector with respect to criterion A

wij	w1	w2	w3	Sum of wij	Priority vector W_i^w
w1	0.166667	0.142857	0.181818	0.491342	0.1638
w2	0.333333	0.285714	0.272727	0.891775	0.2973
w3	0.5	0.571429	0.545455	1.616883	0.5390

$\lambda_{max} = 3{,}01118$; $C.I. = 0{,}00559$; $C.R. = 0{,}00964$ x 100% =0.96% < 10% ; $R.I. = 0.58$ (Tab.3.)

Tab. 10. Comparison matrix for variants with respect to criterion B

variant	w1	w2	w3
w1	1	0.3333	0.5
w2	3	1	3
w3	2	0.3333	1
sum	6	1.6667	4.5

Tab. 11. Values in the normalised matrix and priority vector with respect to criterion B

wij	w1	w2	w3	Sum of wij	Priority vector w_i^w
w1	0.166667	0.2	0.1111	0.477778	0.1593
w2	0.5	0.6	0.666667	1.766667	0.5889
w3	0.333333	0.2	0.222222	0.755556	0.2519

$\lambda_{max} = 3{,}07037$; $C.I. = 0{,}03519$; $C.R. = 0{,}060664$ x 100% =6.066% < 10%; $R.I. = 0.58$ (Tab.3.)

Tab. 12. Comparison matrix for variants with respect to criterion C

variant	w1	w2	w3
w1	1	3	5.0000
w2	0.3333	1	2
w3	0.2	0.5	1
sum	1.5333	4.5	8

Tab. 13. Values in the normalised matrix and priority vector with respect to criterion C

wij	w1	w2	w3	Sum of wij	Priority vector w_i^w
w1	0.652174	0.666667	0.6250	1.943841	0.6479
w2	0.217391	0.222222	0.25	0.689614	0.2299
w3	0.130435	0.111111	0.125	0.366546	0.1222

$\lambda_{max} = 3{,}005395$; $C.I. = 0{,}0027$; $C.R. = 0{,}00465$ x 100% =0.465% < 10% ; $R.I. = 0.58$ (Tab.3.)

Tab. 14. Comparison matrix for variants with respect to criterion D

variant	w1	w2	w3
w1	1	2	3
w2	0.5	1	2
w3	0.3333	0.5	1
sum	1.8333	3.5	6

Tab. 15. Values in the normalised matrix and priority vector with respect to criterion D

wij	w1	w2	w3	sum of wij	Priority vector w_i^w
w1	0.545455	0.571429	0.5000	1.616883	0.5390
w2	0.272727	0.285714	0.333333	0.891775	0.2973
w3	0.181818	0.142857	0.166667	0.491342	0.1638

$\lambda_{max} = 3{,}01118$; $C.I. = 0{,}00559$; $C.R. = 0{,}00964$ x 100% =0.96% < 10% ; $R.I. = 0.58$ (Tab.3.)

The values of the priority vector obtained for the analysed variants demonstrate that, depending on the analysed criterion, different variants prove to be superior. The is caused by the fact that the analysed criteria are satisfied differently by the analysed variants. A question arises which of the analysed aspects (criteria) will prevail when making the final decision.

5. CREATING A HIERARCHY OF THE VARIANTS

The final stage in the AHP analysis of the variants consists of determination which variant fulfils best the determined criteria. For this aim, computations are run in order to calculate to what extent particular criteria are satisfied by the subsequent variants. Values of the priority vectors for each of the main criteria and for particular variants in the context of the analyse criteria are studied as sums of their products:

$$w_i^A = \sum \overline{w_j} w_i^w$$

where:

w_j - vector of priorities for the main criteria

w_i^w - vector of priorities for the variants

Computations of the global priority for the analysed variants will look as follows:

For variant one:

$$W_1 = 0.5817 \times 0.6479 + 0.1151 \times 0.5390 + 0.0812 \times 0.1638 + 0.2221 \times 0.1593 = 0.3769 + 0.0620 + 0.0133 + 0.0354 = \mathbf{0.4876}$$

For variant two:

$$W_2 = 0.5817 \times 0.2299 + 0.1151 \times 0.2973 + 0.0812 \times 0.2973 + 0.2221 \times 0.5889 = 0.1337 + 0.0342 + 0.0241 + 0.1308 = \mathbf{0.3229}$$

For variant three:

$$W_3 = 0.5817 \times 0.1222 + 0.1151 \times 0.1638 + 0.0812 \times 0.5390 + 0.2221 \times 0.2519 = 0.0711 + 0.0189 + 0.0438 + 0.0559 = \mathbf{0.1897}$$

6. SUMMARY

Three variants have been suggested while planning to execute a road investment project. The analysis presented above have enabled us to distinguish four groups of criteria which play an important role in designing and executing such construction projects. The analysis carried out with the AHP method allowed us to decompose the main criteria, which helps to realise what actually matters in establishing the weight of the main criterion. The AHP analysis, which entails determination of sub-criteria, requires users to conduct surveys, analyse various solutions and consult experts. This article contains a detailed analysis of the environmental criterion, and the result of this analysis provided designers and engineers with new information to consider. The analysis has demonstrated that the final decision with respect to the environmental criteria was most strongly affected by the subcriterion which dealt with the incursion on protected areas. The analysis of the main criteria showed that the highest priority was assigned to the environmental criterion (C), with the economic one (B) in the second place. The hierarchy of the variants, constructed in the last part of the article, proved that variant 1 is best for reaching the analysed goals and this result was most significantly shaped by the high degree to which this variant fulfils the environmental criteria.

The above analysis confirms the applicability of the AHP method as a tool supporting decision making while choosing a variant project of a road construction investment. This method enables users to choose an optimum solution while simultaneously considering many factors, including the ones which are difficult to measure or compare.

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