

MULTI-CRITERIA METHODS IN AN ANALYSIS OF VARIANTS OF A CONSTRUCTION PROJECT

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Abstract

Execution of most building investment projects requires elaboration of several variants. This article discusses multi-criteria methods: the MCE, AHP and indicator methods. The three methods have been applied to analyze variants of a model construction investment project and used to make appropriate calculations. The results were analyzed and compared, and the calculations confirmed the purposefulness of aiding decision making processes with multi-criteria methods of analysis.

Key words: Construction projects, investment process, analysis of variants, multi-criteria methods

1. INTRODUCTION

For most construction projects, it is necessary to prepare and analyze several variants of their execution. Most often, technical and technological solutions are analyzed (Brown 2012); other fields of analysis are economic aspects and conditions related to the environment protection. The regulations which govern the natural environment preservation have a substantial impact on the shape and costs of various kinds of building projects. They are particularly important when planning the construction of roads, where alternative routes are designed to protect valuable habitats. Equally important are the requirements concerning the protection of acoustic climate, construction of wildlife corridors, protection of birds, conservation of surface and ground waters, preservation and landscaping of roadside plant communities, landscape management, etc. It is essential to comply with the rule of nature compensation and to monitor threats to and the status of the natural environment. Potential social conflicts are also analyzed, and community consulting is required to avoid them. Also, the compliance with local spatial management plans is taken into consideration. Costs of a construction project are analyzed, including expenses incurred by the natural environment protection (costs of building crossing paths for wild animals, making provisions for water protection or noise elimination), restrictions imposed by the schedule of a given construction investment, localization of service areas and road maintenance facilities (Abu Dabous, Alkass 2008, Pan 2008).

Making decisions related to such complicated construction investments should be aided by an efficient decision support method, which enables one to consider all significant aspects while helping to choose the variant which will most faithfully satisfy all conditions. With the wealth of available methods and techniques used for analyzing alternative solutions, it is frequently difficult to decide which method to use so as to achieve the desired outcome (Morris 1988, Navon 2007). When selecting a method, one should consider its clarity, quality and verifiability of results as well as the applied mathematical model. Worth considering is also the subjectivity of assessment because many popular methods rely on opinions expressed by experts and persons engaged in a given project. Thus, their assessments and the final decision can be burdened with certain error, which we need to keep in mind. A certain amount of subjectivity can be encountered mainly in method based on the evaluation of qualitative, immeasurable factors. When the so-called 'measurable factors' are considered, the evaluation of a given criterion is obvious. Two approaches can be taken to achieve an objective assessment of qualitative factors. One is a descriptive method and the other necessitates using a numerical measuring scale.

Various multi-criteria methods make provisions for using one or the other approach when making decisions, e.g. MCE, AHP, indicator methods (Yoon, Hwang 1995, Al-Harbi 2001). However, it is difficult to estimate what error the final results are burdened with. Presumably, they are acceptable approximations, but further interpretation is required in order to make a rational decision. Each

method has its distinguishing features, which in a variety of ways affect the final outcome. The diagram in fig. 1 shows step by step how an investment variant is chosen.

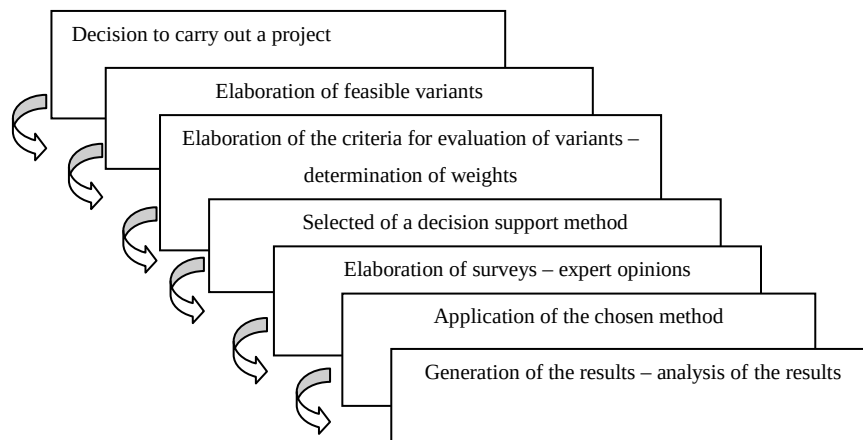


Fig. 1. Diagram illustrating the course of an analysis of alternatives of an investment project

2. METHODS FOR ANALYSIS OF VARIANTS

Three methods will be discussed in order to see how the most popular decision support methods are used. Multi-criteria analytical methods share one property. They are based on the determination of weights and assessment of the importance of criteria as well as the extent to which they are fulfilled by subsequent variants of an investment project. These assessments are made through questionnaires completed by experts and by persons engaged in the planning of a project. Surveys must be designed in such a way as to enable one to order the data and to decide about a scale for estimated criteria.

The MCE (multi-criteria evaluation) analysis is applied to support a decision-making process when there are quite numerous criteria. It often helps to choose a location. Its aim is to arrive at a single, mutually accepted solution. The first step in an MCE analysis is the determination of criteria leading to the attainment of the set goal (Marques, Gourc, Lauras 2011). The criteria which appear in the MCE method can be divided into two groups:

- hard ones, i.e. constraints: barriers, limitations,
- soft ones, known as factors: parameters, measures.

When applying analytical constraints, results are achieved in the form of a map, which presents areas that fulfill the set conditions and areas which fail to do so. In other cases, having applied the constraints, some of the variants are discarded. In turn, the application of soft criteria enables one to evaluate the suitability of variants for the aim defined during the analysis (Zavadskas, Turskis, Vilutiene 2010)(Marques, Gourc, Lauras 2011). The result obtained through the application of soft factors is not as unambiguous as the one achieved through the implementation of hard criteria.

The suitability is calculated from the formula:

$$S = \sum_{i=1}^n w_i \cdot x_i \quad i \in \langle 1, n \rangle \quad (1)$$

where: S – suitability, w – weight of a criterion,
x – value of a parameter, i – criterion,
n – number of criteria.

In an analysis which also comprises barrier-like criteria, the formula looks as below:

$$S = \sum_{i=1}^n w_i \cdot x_i \prod c_j \quad (2)$$

where an additional symbol appears: c_j – j^{th} barrier.

Criteria included in an analysis pertain to the fact that a given localization of an investment must meet certain conditions (Šelih, Kne, Srđić, Žura 2008). Using the hard method, criteria are defined as barriers (e.g. less than 200 m away from water; an area where the slope angle is no more than 3°). Then the suitability map is a zero-one map (1 – suitable area, 0 – unsuitable area). The final suitability map is a simple product of individual suitability maps (with the exception of the conjunction in formula 2). In some cases, criteria can be defined as soft ones (the further from the road, the better; the flatter the area, the better, etc.). Then, it will be impossible to make direct comparisons in terms of the distance from water or the incline angle at a given point). This is the reason why certain standardization of the criteria defined as above is carried out. It is accomplished with the formula:

$$x_i = \frac{R_i - R_{\min}}{R_{\max} - R_{\min}} \cdot d \quad (3)$$

where: x_i – parameter corresponding to a given condition after standardization,

R_i – value of the parameter before standardization,

$R_{\min}, R_{\max}$ – minimum and maximum value of the parameter of the criterion,

d – range of standardization (Eastman 2001).

Standardization is conducted within a defined range, e.g. 0-255. Then, the maximum suitability is 255 and the minimum one is 0. Three standardization methods are distinguished in the multi-criteria MCE analysis:

- 1) Boolean method – hard method,
- 2) Weight Linear Combination – soft method,
- 3) Ordered Weighted Average method – soft method.

The Analytical Hierarchy Process (AHP) analysis allows one to consider diverse criteria which condition the attainment of a set goal. The fundamental principle is that an overall goal is attainable through the achievement of intermediate targets leading to the attainment of the main goal. The analyzed alternative solutions satisfy the expectations to a higher or lower degree. The degree of the fulfillment of the main goal by a decision variant is determined by the degree of satisfying the main criteria and the sub-criteria arranged in appropriate groups. The decomposition of a problem facilitates our assessment and this is the core of the AHP method (Saaty 1980, 1990, 1994). Three stages (steps), aggregated in an integrated and logical series, lead to the solution:

1. Building a hierarchical model (determination of criteria),
2. Evaluating the criteria on a 9-point scale,
3. Evaluating and arranging variants by setting priorities (main weights) which take into account priority vectors of sub-criteria.

Typically, a hierarchical model of the structure, composed of 4 levels, is built for the evaluation of variants. During the analysis, all criteria on a given level are compared pairwise, thus establishing their mutual relations and deciding which ones and to what extent are important for the performance of a given project. The analysis employs a scale with values from 1 to 9, proposed by Professor Thomas Saaty and shown as a table (Saaty, 1990, 1994).

The evaluation of criteria through pairwise comparisons and determination of the remaining components enables an analyst to build a matrix of preferences. An example is shown in the figure below:

$$A = \begin{vmatrix} a_{11}=1 & a_{12} & a_{13} & a_{14} \\ a_{21}=\frac{1}{a_{12}} & a_{22}=1 & a_{23} & a_{24} \\ a_{31}=\frac{1}{a_{13}} & a_{32}=\frac{1}{a_{23}} & a_{33}=1 & a_{34} \\ a_{41}=\frac{1}{a_{14}} & a_{42}=\frac{1}{a_{24}} & a_{43}=\frac{1}{a_{34}} & a_{44}=1 \end{vmatrix} \quad (4)$$

The references (Saaty1980,1990, 1994). provide formulas for calculations performed in the subsequent stages in order to compute the value of the priority index. These are:

Calculation of the eigenvalue of a normalized matrix:

$$\overline{w}_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad (5)$$

Determination of the value of the priority vector of sub-criteria:

$$\overline{w}_j = \sum_{j=1}^n w_j a_{ij} \quad (6)$$

where:

$$w_j = \frac{\sum_{i=1}^n w_{ij}}{n} \quad i,j = 1 \dots n \quad (7)$$

In order to check whether the suggested procedure is proper:

- we set the matrix's maximum eigenvalue:

$$\lambda_{\max} = \frac{1}{w_i} \sum_{i=1}^n a_{ij} w_j \quad (8)$$

- the Consistency Index:

$$C.I. = \frac{\lambda_{\max} - n}{n - 1} \quad (9)$$

- the Consistency Ratio:

$$C.R. = \frac{C.I.}{R.I.} \quad (10)$$

where C.R. should be < 10% for sufficient consistency

R.I. – the Random Index, whose value depends on the n number of compared elements.

Tab. 1. An example of the arrangement of analyzed factors according to pairwise evaluation

Main criteria	A	B	C	D
A	1	0,50	0,14	0,50
B	2	1	0,33	3
C	7	3	1	5
D	2	0,33	0,20	1
aij sum	12,00	4,83	1,67	9,50

The final step in the AHP analysis is to decide which of the considered variants fulfills the set criteria to the highest degree. For this aim, calculations are run to find out to what extent individual criteria are satisfied by the subsequent variants. Values of priority vectors for each of the main criteria and individual variants in the context of the analyzed criteria are examined as sums of their products (Navon 2007) (Yoon., Hwang 1995). The example of the calculation are shown on table 1.

$$w_i^A = \sum \overline{w_i^K} w_i^w \quad (11)$$

where: w_j^k - the priority vector for main criteria

w_i^w - the priority vector for variants

Indicator methods rely on matrices in which individual effects on the environment are described with the help of weights that define the importance of the effect on the environment (Szafranko 2014). Table2- 2 shows a model matrix (Naveh, Marcus 2005) (Negahban, Baecher, Skibniewski(2012).

Tab. 2. Fragment of a matrix for two alternative variants of a new road

No	Criterion	variant 1 of the investment			variant 2 of the investment			variant 3 of the investment			Weight of the criterion
1	A1	P ₁₁	Q ₁₁	R ₁₁	P ₁₂	Q ₁₂	R ₁₂	P ₁₃	Q ₁₃	R ₁₃	W ₁
2	A2	P ₂₁	Q ₂₁	R ₂₁	P ₂₂	Q ₂₂	R ₂₂	P ₂₃	Q ₂₃	R ₂₃	W ₂

The partial assessment on the effect of the j^{th} variant on the i^{th} criterion:

$$Q_{ij} = (P_{ij} + R_{ij}) * W_i \quad (11)$$

where:

P_{ij} – direct effect of a subsequent variant in the context of criterion A;

R_{ij} - indirect effect of a subsequent variant in the context of criterion A;

W_i – weight of criterion A

The number in the top left-hand corner of each cell describes a direct effect, while the number in the bottom right-hand corner shows an indirect effect on the environment. The number in the middle is the sum of effects multiplied by the weight. The sum of particular effects is an intermediate evaluation of the impact of a given variant on the environment. Expert opinions are necessary to assign weights (Yang, Chen, Wang 2012). Surveys should also enable respondents to express negative opinions on effects of a planned investment project.

3. IDENTIFICATION OF A DECISION PROBLEM

Let us consider an investment project such as constructing a section of a road, for which 3 variants have been prepared. Based on analyses of other road construction investments executed in the same region (Szafranko 2013), endowed with high qualities of the natural environment, and following expert opinions, it has been concluded that four groups of criteria are most often taken into consideration. In each group, most frequently repeated sub-criteria have been identified:

A - Transport:

A1 – transport load (number of vehicles x kilometers per diem)

A2 – costs due to time of transport including costs of the time wasted in traffic jams or due to longer route

A3 – length of road in km

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

B - Economic:

B1 – cost of building the road

B2 – cost of land acquisition

B3 – compensation costs

C – Environmental:

C1 – interference with areas of protected nature

C2 – length of the road running through woodlands

C3 – number of trees to be felled

C4 – crossing with routes taken by wild animals

C5 – crossing with watercourses

D- Social and spatial:

D1 – number of buildings to be demolished

D2 – number of buildings located at 0-50 m

D3 – number of buildings located at 50-100 m

D4 – area of land to be repossessed

D5 – collisions with the planned spatial management

The following were determined:

- the overall goal – to perform the investment project,
- main goals determined in the project as main criteria (in this case, these are: Transport & Communication, Economic, Environment, and Social & Planning criteria).
- intermediate goals (sub-criteria) written in detail for every main criterion.

The following alternatives of the investment have been included:

Variant 1 – It meets the environmental and spatial criteria to the highest degree, less so with respect to transport and is the least satisfying economically. It is a longer road but circumvents several environmental collisions.

Variant 2 – It is the cheapest variant in terms of both the cost of construction and the cost of purchasing land and paying compensation; it fulfills the transport criteria and partly the environmental criteria. This is the shortest road, but it does not satisfy completely the communication and environmental goals.

Variant 3 – This alternative fits the best the transport criteria and the design requirements regarding the delineation of roads and others; economically it is better than Variant 1 but worse than Variant 2; it fulfills the environmental criteria only partly.

4. SOLUTION OF THE PROBLEM

The problem presented above has been analyzed using the three methods discussed at the beginning of the article. The analysis covered only two groups of criteria. It was decided that group A (Transport) and group C (Environment) encompassed most important criteria for the given investment.

The Multi-Criteria Evaluation Analysis. As described before, the first step in the MCE procedure is to establish the criteria leading to the set goal. Criteria which appear in an MCE analysis can be divided into hard (barriers) and soft ones (parameters, factors). In the analyzed case, all the criteria are parameters. This method does not limit the number of simultaneously compared factors. Therefore, it is possible to prepare juxtaposition of all factors.

Using the formula given earlier, we can calculate the suitability of each variant:

$$S = \sum_{i=1}^n w_i \cdot x_i \quad i \in \langle 1, n \rangle \quad (12)$$

where: S – suitability,
w – weight of a criterion,
x – value of a parameter,
i – criterion,
n – number of criteria.

The weights were assigned based on a SWOT analysis performed on the basis of opinions collected among users of the planned investment and experts.

The value of each weight ranges from 0 to 1. Values of parameters for each variant were determined according to opinions expressed by experts, designers and the investor. A 0-6 scale was adopted, where 0 means an assessed criterion is not fulfilled, and 6 stands for the highest degree of its fulfillment. Our calculations are presented in table 3.

The table shows whether the sub-criteria are satisfied and the sums show which variant fulfills the analyzed criteria to the highest degree. The analysis shows that Variant 1 is the best.

Tab. 3. Multi-criteria evaluation for three variants of the investment

No	Analyzed criteria	Weight of a criterion (w)	Value of parameter (x) for variant 1	Fulfillment of criterion by variant 1	Value of parameter (x) for variant 2	Fulfillment of criterion by variant 2	Value of parameter (x) for variant 3	Fulfillment of criterion by variant 3
1	A1	0,05	4	0,2	3	0,15	5	0,25
2	A2	0,02	5	0,1	4	0,08	3	0,06
3	A3	0,1	3	0,3	4	0,4	6	0,6
4	A4	0,03	4	0,12	3	0,09	2	0,06
5	C1	0,4	6	2,4	3	1,2	2	0,8
6	C2	0,1	3	0,3	3	0,3	3	0,3
7	C3	0,05	2	0,1	3	0,15	5	0,25
8	C4	0,2	3	0,6	4	0,8	5	1
9	C5	0,05	4	0,2	4	0,2	5	0,25
	sum	1		4,32		3,37		3,57

The AHP method. Calculations were completed according to the procedure presented previously. The evaluation of pairwise compared criteria was conducted for main criteria in the context of the transport, economic, environmental and spatial conditions presented above.

Tab. 4. Matrix of comparisons for main criteria

Main 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. Values of the normalized matrix and priority vector for main criteria

Main criteria	A	B	C	D	sum wij	Priority vector W_i
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

- we determine the matrix's maximum eigenvalue:

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

-value of the consistency index:

$$C.I. = \frac{\lambda_{\max} - n}{n - 1} = \frac{4.11528 - 4}{4 - 1} = 0.0384$$

- consistency ratio:

$$C.R. = \frac{C.I.}{R.I.} \quad - \quad \text{where C.R. should reach a value} < 10\%; \quad R.I. = 0.9 \quad (\text{Saaty 1994})$$

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

In many cases, it is necessary to analyze sub-criteria described in sub-groups subordinated to main criteria. On the one hand, analyzing sub-criteria is necessitated by the limited number of criteria compared directly. On the other hand, direct comparison of some of these criteria would be difficult.

In the analyzed case, there were 3 variants of the investment project. Each variant, to a different degree, fulfills the distinguished criteria. Because our main interest is in the improvement of the transportation grid while respecting the requirements concerning the environment protection, pairwise comparisons are run in the context of the sub-criteria identified in groups A and C.

Tab. 6. Matrix of comparisons of the variants in the context of 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. 7. Values of the normalized matrix and priority vector in the context of criterion A

wij	w1	w2	w3	sum 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

$$\lambda_{\max} = 3.01118 ; C.I. = 0.00559 ;$$

$$C.R. = 0.00964 \times 100\% = 0.96\% < 10\% ; R.I. = 0.58 \text{ (Saaty 1994)}$$

The values of the priority vector for the analyzed variants show that Variant 3 fulfills the best the expectations regarding an improved flow of traffic.

Tab. 8. Matrix of comparisons of the variants in the context of 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. 9. Values of the normalized matrix and priority vector in the context of criterion C

wij	w1	w2	w3	sum 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

$$\lambda_{\max} = 3,005395 ; C.I. = 0,0027 ;$$

$$C.R. = 0,00465 \times 100\% = 0.465\% < 10\% ; R.I. = 0,58 \text{ (Saaty 1994)}$$

The analysis of the variants in the context of environmental criteria proves that Variant 1 meets these criteria most faithfully.

It will be interesting to find which aspect will be a decisive one. For this purpose, calculations are run demonstrating to what degree individual criteria are satisfied by each variant. Values of the priority vector for each of the main criteria and individual variants in the context of the analyzed criteria will be analyzed as sums of their products. Let us limit our analysis to selected criteria.

$$w_i^A = \sum \overline{w_i^K} w_i^w \quad (13)$$

where: w_j - priority vector for main criteria

w_i^w - priority vector for variants

For the first variant:

$$W_i = 0,5817 \times 0.6479 + 0.0812 \times 0.1638 = 0.3769 + 0.0133 = 0.3902$$

For the second variant:

$$W_i = 0,5817 \times 0.2299 + 0.0812 \times 0.02973 = 0.1337 + 0.0241 = 0.1578$$

For the third variant:

$$W_i = 0,5817 \times 0.1222 + 0.0812 \times 0.5390 = 0.0711 + 0.0438 = 0.1149$$

The above results show that Variant 1 fulfills the selected criteria the best.

Solution with the indicator method relies on a matrix in which individual effects on the environment are described with the aid of weights which define the importance of a given effect on the environment. The number in the upper left-hand corner of each cell describes the direct effect, whereas the number in the lower right-hand corner describes indirect effects of the analyzed factor. The sum of effects multiplied by weights is written in the middle. The sum of particular effects is a partial evaluation of the effect on the environment generated by a given variant. Expert opinions are necessary to assign weights. Analyses of the designs are needed to determine effects of a given investment project.

Tab. 10. Matrix for calculations according to the indicator method

No	Analyzed criterion	Variant 1 of the investment			Variant 2 of the investment			Variant 3 of the investment			Weight of the criterion
1	A1	2	5	3	2	4	2	3	5	2	1
2	A2	-3	-2	2	1	6	2	1	8	3	2
3	A3	3	2	-2	-1	0	1	2	8	2	2
4	A4	2	6	4	2	4	2	4	7	3	1
5	C1	-1	0	1	-1	-12	-1	-1	-12	-1	6
6	C2	-2	6	4	-1	3	2	-2	-9	-1	3
7	C3	-2	-5	1	-2	-15	-1	2	0	-2	5
8	C4	-1	3	2	-1	-6	-1	-1	3	2	3
9	C5	2	6	1	1	4	1	-1	0	1	2
	sum	21			-12			10			

The highest value in the summation of the calculations implies the best solution. In our case, this is Variant 1 prepared for the planned investment.

5. COMPARISON AND ANALYSIS OF THE RESULTS

The results of our analyses performed according to the three methods are congruent in part. The MCE and AHP methods yield comparable results and put Variant 1 on the first position. The diagrams in fig. 3 show that in both cases Variant 1 is superior owing to its eco-friendly character. The difference between the assessments of Variants 2 and 3 is small and the fact that Variant 3 comes in the second place according to the MCE analysis and the third when analyzed with the AHP method does not matter. The scores are illustrated by the diagrams in fig. 2.

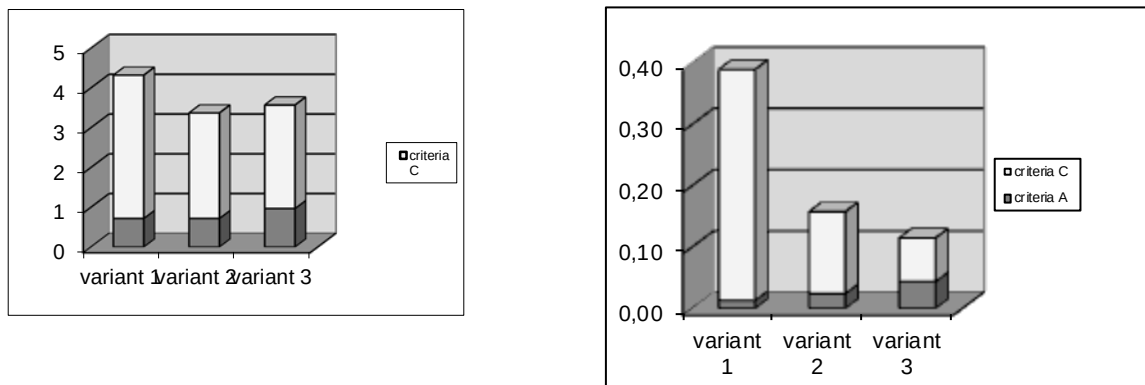


Fig. 2. Diagram illustrating scores assigned to the analyzed criteria of the three variants by the MCE and AHP method.

The third result is of a slightly different nature. Because the indicator method includes also negative scores, differences between the assessments are much bigger and in some cases partial scores are negative. The evaluation fulfills the transport criterion for W1 – (11), W2 – (14) and W3 – (28). The values assigned to the environmental criteria are W1 – (10), W2 – (-14), W3 – (-18). The diagram in fig. 5-2 and 6-1 shows how these values affect the final evaluation.

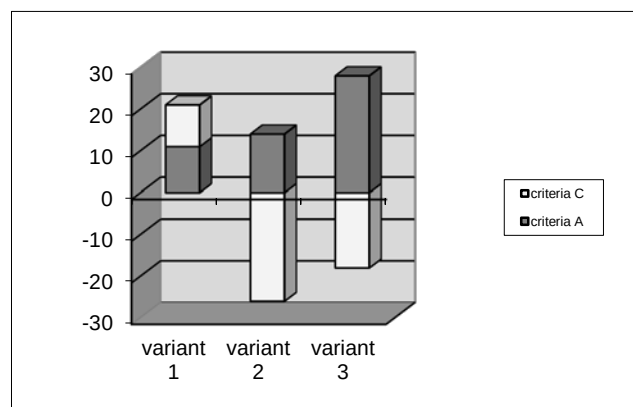


Fig. 3. Diagram illustrating values of the assessment of the analyzed criteria with the indicator method.

As demonstrated above, the three methods dealt with in the article create different analytical options, but their final outcome is congruent. With any of the methods, the variant which satisfies the best the established criteria is Variant 1 (W1), mainly because it fulfills the environmental attributes.

6. SUMMARY AND CONCLUSIONS

Preparations for the execution of a construction project are an extremely important step, which involves analyses of various alternative solutions. Variants should be analyzed using mathematical decision support methods. The three methods discussed in this paper can be successfully used for analyses of measurable and immeasurable criteria. The MCE method enables direct comparisons of all the criteria. The AHP method, through the decomposition of main criteria, helps the user to realize what actually shapes the importance of the principal criteria. Finally, the indicator method, by using negative scores as well, is better at revealing negative effects of a project than the other two methods.

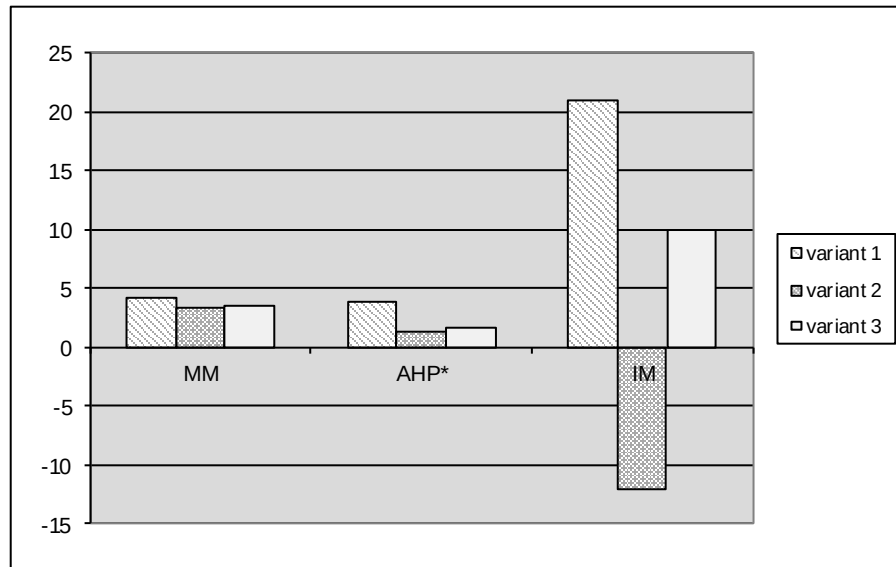


Fig. 4. Comparison of the results obtained by discussed methods (*The results are scaled for comparison) MM- Multi-criteria evaluation Method ; AHP- Analytical Hierarchy Process; IM- Indicator methods

Our comparative analysis shows the usefulness of three multi-criteria analytical methods applied to assessment of alternative construction projects and highlights the role of such analyses in the building practice.

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