

# Chosen aspects of multi-criteria analysis applied to support the choice of materials for building structures

**E. Szafranko**<sup>1</sup>

University of Warmia and Mazury in Olsztyn, Faculty of Geodesy Geospatial and Civil Engineering, Institute of Building Engineering,  
ul. Heweliusza 4, 10-724 Olsztyn, Poland

E-mail: [elasz@uwm.edu.pl](mailto:elasz@uwm.edu.pl)

**Abstract.** When planning a building structure, dilemmas arise as to what construction and material solutions are feasible. The decisions are not always obvious. A procedure for selecting the variant that will best satisfy the expectations of the investor and future users of a structure must be founded on mathematical methods. The following deserve special attention: the MCE methods, Hierarchical Analysis Methods and Weighting Methods. Another interesting solution, particularly useful when dealing with evaluations which take into account negative values, is the Indicator Method. MCE methods are relatively popular owing to the simplicity of the calculations and ease of the interpretation of the results. Having prepared the input data properly, they enable the user to compare them on the same level. In a situation where an analysis involves a large number of data, it is more convenient to divide them into groups according to main criteria and subcriteria. This option is provided by hierarchical analysis methods. They are based on ordered sets of criteria, which are evaluated in groups. In some cases, this approach yields the results that are superior and easier to read. If an analysis encompasses direct and indirect effects, an Indicator Method seems to be a justified choice for selecting the right solution. The Indicator Method is different in character and relies on weights and assessments of effects. It allows the user to evaluate effectively the analyzed variants. This article explains the methodology of conducting a multi-criteria analysis, showing its advantages and disadvantages. An example of calculations contained in the article shows what problems can be encountered when making an assessment of various solutions regarding building materials and structures. For comparison, an analysis based on graphical methods developed by the author was presented.

## 1. Introduction

A distinguishing feature of an investment project in the construction business is that the shape of a future building depends on the decisions made at the stage of its planning. These decisions can involve various problems, depending on the type of a building. When planning to raise a building, first of all we need to choose from a variety of technologies and building materials. Comprehensive analyses are performed in order to arrive at a variant solution which will be economically viable while satisfying all other requirements which building structures are obliged to meet. Above all, the construction of a building must be reliable and durable, so that during its life as little maintenance is needed as possible.



The construction process should not generate excessive labor inputs and other costs. Moreover, the investor and future users are interested in a relatively short building time. When analyzing a planned construction project, it is necessary to identify the assessment criteria, and afterwards to optimize them [1]. Among the basic requirements, which are most often taken into consideration, the following can be listed:

- criteria of reliability, regarding the durability of a building and its functional life,
- technological criteria, dependent in the applied materials and machines, production processes, availability of materials, and possibilities of the delivery of materials to a construction site,
- criteria of functionality, depending on the type of a building, its dimensions and specificity,
- economic criteria, which define the costs, especially the costs of building and using the structure, duration of the building process, consumption of materials, total mass of the used materials, degree to which the building process is industrialized, durability of materials and the value of the recycled materials after the building has come to the end of its useful life,
- legal criteria, arising from the law governing in the given territory when the building is planned and then erected, the restrictions dictated by such law and the requirements to obtain administrative decisions,
- ergonomic and aesthetic criteria, which the investors and users of buildings pay attention to,
- ecological criteria, concerning the impact of a new building on the natural environment in its surroundings.

Obviously, it is not always necessary to review all possible criteria [2]. Depending on the goal to be achieved, several criteria must be defined, which will be specific for a given building construction. However, even when the number of criteria is limited, we may have difficulty making the right decision in a direct way. When many requirements have to be satisfied, we are facing the problem of a multicriteria analysis, which entails making a choice out of a set of solutions so as to satisfy the defined criteria to the highest degree. The conditions that are most often taken into account by investors, planners or developers are to minimize the costs, which in recent years have been the most common consideration, and to reduce the weight and volume of the construction in respect of the proportions of materials, labour and machines. An optimal construction solution is also the one which respects the question of potential, strain and elastic strain energy, striving to minimize these types of energy and to achieve the lowest possible proper vibration [3]. Adding to the above criteria, it is worth remembering about another essential aspect, such as ensuring the reliability and safety of a building. A construction which is neither reliable nor safe does not fulfill the functions it is assigned to perform and it is therefore automatically disqualified from any analysis [4]. All the above assumptions mean that architects and engineers face a considerable challenge when planning a new building. Apart from knowing the principles and rules of planning a building structure, they should also have sound knowledge of the current construction industry market, the latest technical solutions and directions in which this market is likely to develop in the future, as this will help them justify the choice they make. This article shows methods for comparative analysis of the building materials chosen for erecting a single-aisle framework construction. It also suggests a scheme of a approach including an additional technique, such as the graphical analysis method developed by the author of the paper.

## **2. Preparation of the study, the scheme of the proceeding**

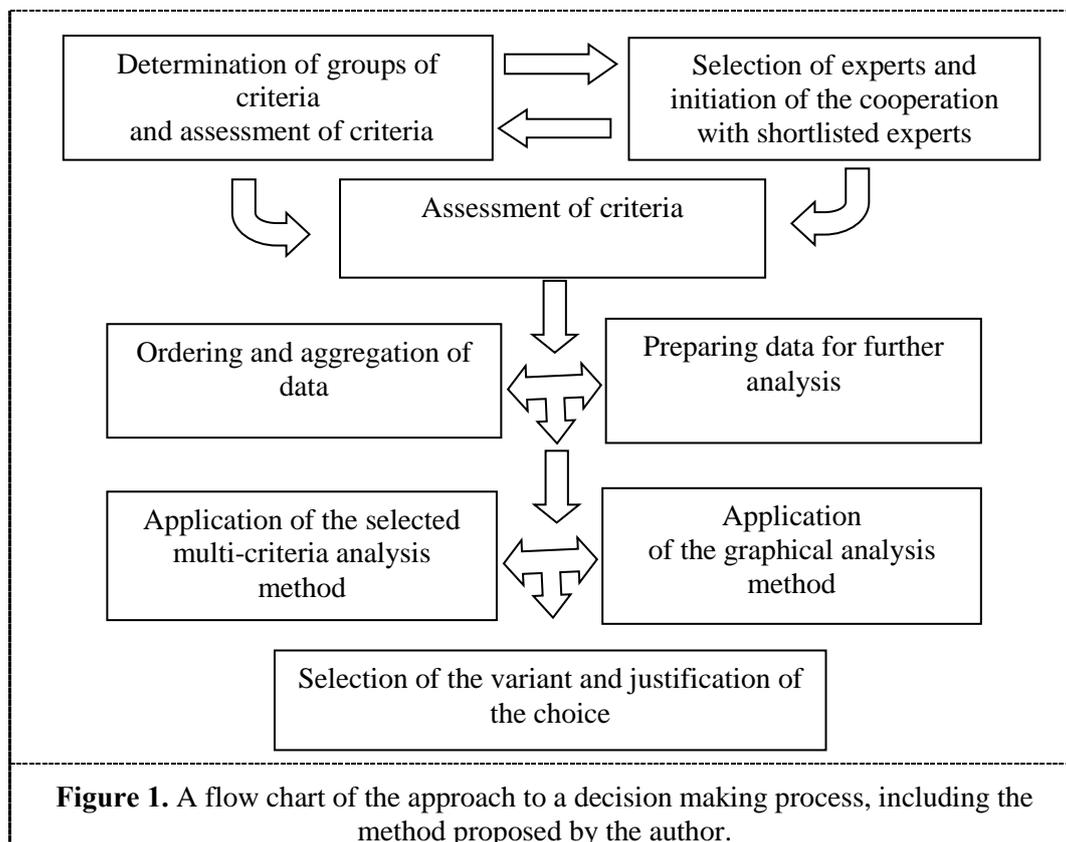
The procedure begins by working out a list of expectations which the planned structure is to fulfill. This is an essential step because it will enable us to develop variants of the plan that will comply with the defined requirements and, on the other hand, will allow us to identify criteria for an assessment of the prepared variants [5]. It is necessary to obtain expert opinions in order to determine the validity of the proposed criteria. This stage is extremely difficult and the acquisition of such data should be carried out in such a way as to facilitate the application of the chosen multi-criteria analysis method.

Literature [6, 7] describes how to prepare appropriate surveys and [8] how to process the acquired data.

This step is characteristic for all methods based on the evaluation of many criteria, and tends to be labor consuming. It can create many problems; both in terms of identifying the right set of experts and while processing the acquired information. In many cases, the data obtained from surveys turn out to be inconsistent and therefore require certain pre-processing.

The collated information is a starting point for further calculations. Because of the high number of criteria, it is recommended to apply decision-making support methods [9, 10]. In cases when variant solutions are analyzed by examining numerous criteria, multi-criteria analytical methods prove to be helpful. The following can be mentioned: Multi Criteria Evaluation, Scoring Method, Weighting Method, and Hierarchical Analysis Method [11, 12].

By using a selected method, it is possible to analyze the available solutions, but - has been demonstrated through research - parallel application of several methods does not always produce satisfying results of the analysis. Moreover, the solution indicated by a given method may not be the optimal one [13, 14] Thus, after many years of analyses, the author has elaborated a method consisting of a comparative analysis of graphic profiles of variants compared and contrasted with a reference template of criteria. This method can be used parallel to mathematical methods in order to suggest an alternative solution. The approach is shown schematically in flow chart in figure 1.



### 3. Research methodology

As mentioned before, analyses of variant solutions of materials for building constructions can be supported by various methods. Some are more popular than others. Some are recommended for a higher number of criteria, others when fewer criteria are dealt with. While selecting a method, some thought should be given to the process of data preparation and the complexity of the mathematical apparatus. To illustrate the procedure followed when calculation methods support the decision-making process, an example of calculations will be given as well as an alternative approach with the graphical method.

### 3.1. Analysis of variant solutions for materials used in a building structure

A one-story, single-aisle framework structure with solid columns and spandrel beams supporting a lean-to roof and with external forces applied to the roof and walls were submitted to our analysis. It was assumed that the construction could be built from reinforced concrete (variant 1) or, alternatively, from steel (variant 2). For both steel and reinforced concrete constructions described above, it was necessary to assume that the joints should be stiff because this type of a joint is made in a monolithic construction. The aisle span (i.e. the transverse span of the columns) was varied, while the longitudinal span of the frames as well as the angle of the spandrel beams were constant, as a result of which the heights of the columns were different, corresponding to the varied span of the aisle and the assumed constant height of the whole structure.

The structure describe above is composed of columns and a spandrel beam. The vertical elements, at the assumed work of the construction, are subject to bending and shearing. For the reinforced concrete construction, a rectangular cross-section was assumed depending on the presumed conditions, with the adequate dimensions typically 25% less than the span of symmetrically reinforced beams.

With respect to the steel spandrel beam, HEB double-T beams were used. The roof construction is supported by columns anchored in the foundation bases of various heights, deepening on the slope of the roof. They are the main elements which are submitted to compression and which transfer all forces to the elements of the foundation. Same as for the horizontal element, the dimensions of the full reinforced cross-section oscillate within  $\frac{1}{4}$  of the span and their reinforcement is symmetrical, whereas in the steel construction it is made from double-T beams.

The decision about the final choice between alternative material solutions is based on the fulfillment of the following criteria:

#### A. Technological criteria:

A1 – availability of materials,

A2 – availability of machines and equipment needed for the assembly of the structure,

A3 – possibilities of the delivery of materials to the construction site,

A4 – degree of the complexity of technological processes at the construction site;

#### B. Functionality of the solution:

B1 – with respect to the type of a building,

B2 – with respect to the dimensions of the building,

B3 – with respect to the specific character of the building;

#### C. Economic criteria:

C1 – costs of the renovation after 10 years,

C2 – costs accompanying the construction works,

C3 – costs of the consumption of material per 1 m<sup>2</sup> of the wall surfaces,

C4 – costs of the consumption of material per 1 m<sup>2</sup> of the floor surface,

C5 – costs of fire protection;

#### D. Ecology, ergonomics, aesthetics:

D1 – safety and durability of the structure

D2 – recyclability,

D3 – possibility of encasing (covering) elements,

D4 – resistance to corrosion,

D5 – size of the cross-section of the construction elements;

### 3.2. The analytical method

The validity of criteria can be assessed step-wise (hierarchical analysis) or at one level (score analysis). The hierarchical analysis method proves to be more useful for a higher number of criteria. In our case, there are 17 criteria, which would make it difficult to assess them all in one group. It is much easier to analyze the main criteria and to assign to them subcriteria. As a result, we obtain a slightly different distribution of the values and their greater differentiation. This method definitely helps to

identify the criteria which are decisive for the choice of the best solution. The calculations and results are presented in tables 1 and 2.

**Table 1.** Evaluation of weights in the hierarchical method.

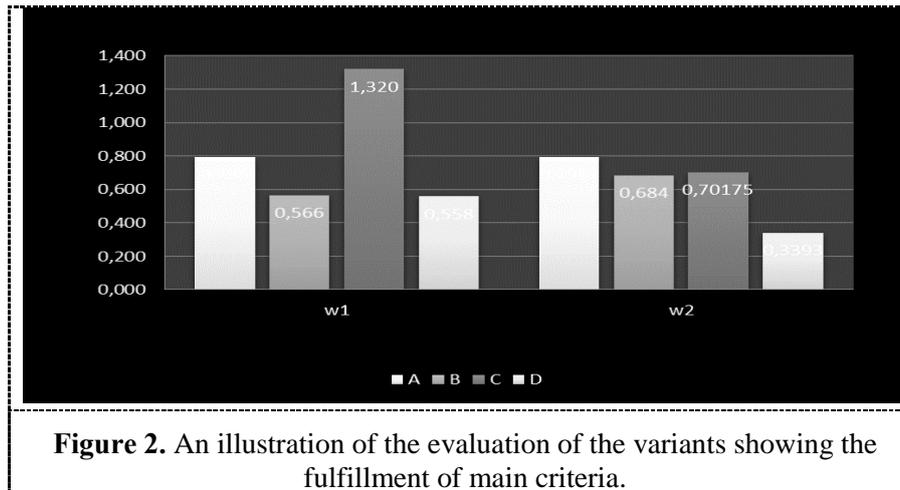
Main criteria	Subcriteria	Weights of main criteria	Weights of subcriteria	Final weights
<b>A</b>	a1	0.28	0.07	0.0196
	a2	0.28	0.18	0.0504
	a3	0.28	0.35	0.0980
	a4	0.28	0.4	0.1120
<b>B</b>	b1	0.19	0.22	0.0418
	b2	0.19	0.36	0.0684
	b3	0.19	0.42	0.0798
<b>C</b>	c1	0.35	0.3	0.1050
	c2	0.35	0.24	0.0840
	c3	0.35	0.15	0.0525
	c4	0.35	0.17	0.0595
	c5	0.35	0.14	0.0490
<b>D</b>	d1	0.18	0.16	0.0288
	d2	0.18	0.25	0.0450
	d3	0.18	0.29	0.0522
	d4	0.18	0.2	0.0360
	d5	0.18	0.1	0.0180

**Table 2.** Evaluation of the analyzed variants.

Main criteria	Subcriteria	Weights	Variant 1 (w1)		Variant 2 (w2)	
			Fulfilment of criterion	Rating	Fulfilment of criterion	Rating
<b>A</b>	a1	0.0196	2	0.039	3	0.059
	a2	0.0504	2.5	0.126	3.5	0.176
	a3	0.0980	3	0.294	2.5	<b>0.392</b>
	a4	0.1120	3	<b>0.336</b>	1.5	0.168
<b>B</b>	b1	0.0418	1	0.042	3	0.125
	b2	0.0684	3	0.205	3.5	0.239
	b3	0.0798	4	0.319	4	0.319
<b>C</b>	c5	0.0490	5	0.245	3	0.147
	c3	0.0525	4	0.210	1.5	0.079
	c4	0.0595	5	0.298	2	0.119
	c2	0.0840	3	0.252	3	0.252
	c1	0.1050	3	0.315	2.5	0.105
<b>D</b>	d5	0.0054	1	<b>0.005</b>	4	0.022
	d1	0.0198	2	0.040	1.5	0.029
	d4	0.0486	4	0.194	1	0.049
	d3	0.0522	3	0.157	2	0.104
	d2	0.0540	3	0.162	2.5	0.135
<b>sum</b>		1		3.2875		2.5202

The table which summarizes the evaluation of the variants contains highly discrepant values - from 0.005 to 0.336. This is the consequence of making an assessment on two levels, i.e. main criteria and

subcriteria. After multiplication, values of the main criteria increase, whereas values of the criteria presumed to be less important decrease. Regarding the score assessment, the surveys are constructed in such a way as to enable direct evaluation of all analyzed factors. Such assessment would certainly lead to a much lower variation among the resulting values, which could make it more difficult to identify the criteria decisive for the selection of a better variant and for making the final decision. Our analysis showed that variant 1, i.e. the reinforced concrete frame, fulfils better the pre-defined expectations. The diagram in figure 2 shows that the predominance of this variant was mainly achieved by the fulfillment of group C criteria.



**Figure 2.** An illustration of the evaluation of the variants showing the fulfillment of main criteria.

The presented example of calculations gives the results in the form of tables, containing series of values, which are not easily readable and therefore unwillingly accepted in the world of engineers. The author, who has long been conducting studies on the evaluation of variants in construction projects and buildings, has developed her own graphic method, which is easier to comprehend.

### 3.3. The graphic method

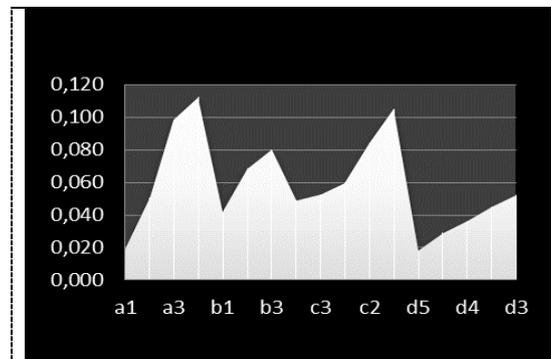
In order to perform an analysis with the method of graphic templates compared to the profile of variant solutions, we should first prepare data regarding the assessment of the variants, arranging them in the increasing order according to the main criteria and in the subgroups, according to the same scheme. Figure 3 shows a template developed based on the data generated for the case study presented herein. The template implicates that criteria comprised in group A (a3 and a4) and in group C (c2 and c1) are the most important ones for the planned structure. Criteria grouped in sets B and D are less important.

An analogous shape of the profile can be seen for variant 2. Values of the criteria a3 and c2 are very high at much lower values of the criteria from group D. The profile of variant 2 is much closer in shape to the template of criteria than the profile of variant 1. Analysis of the graphs illustrating the profiles of the discussed alternative solutions would implicate that the steel construction responded better to the conditions defined as the base of the template of criteria.

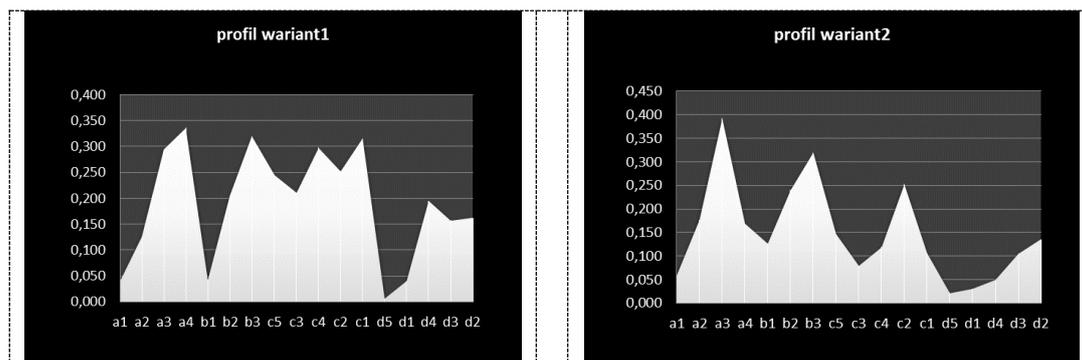
## 4. Analysis of results and discussion

In this article, an analysis of alternative solutions for selecting construction materials was performed with the analytical and graphical method. This is the last step in the scheme presented in figure 1. Comparison of the results should enable us to make a decision which of the two variants to choose. The outcome of the analysis made with the calculation method points up variant 1, while the graphical method suggests variant 2 as the one which more closely responds to the pre-defined conditions. This discrepancy is a consequence of the differences in the two approaches to the analysis. In the calculation method, the sum result of the evaluation of the variants is affected by partial assessment

results and points scored for satisfying all, even less important criteria. When these evaluation results are summed up, what we receive is the information about the fulfillment of all criteria. On the other hand, the graphical method shows which variant satisfies to a higher degree the most important conditions.



**Figure 3.** A template of criteria.



**Figure 4.** Graphic profiles of variants 1 and 2.

## 5. Summary and conclusions

The analysis described in the paper is an illustration of how to apply the methodology proposed in the introduction. It is possible to notice that the graphical illustration in the form of profiles of variants is a more user-friendly method, showing the fulfillment of specific conditions. An idea of using calculation methods and making labor-consuming analyses does not appeal to engineers, and therefore is not often done in practice. An attempt undertaken by the author to develop graphic templates for investment projects in the construction industry and to present their practical application have aroused more interest among engineers. Preliminary experiments involving this innovative approach seem to implicate that the proposed method can have broader application in the world of building engineers.

## 6. References

- [1] Black, C., Akintoye, A., Fitzgerald, E. 2000 *International Journal of Project Management*, 18(6), pp 423-434
- [2] Szafranko E. 2015 *International Scientific Publication, Materials, Methods & Technologies*, Volume 9/2015, pp 155-168
- [3] Ford, I., Torsney, B., & Wu, C. J. 1992 *Journal of the Royal Statistical Society. Series B (Methodological)*, pp 569-583
- [4] Austin, S., Baldwin, A., Li, B., & Waskett, P. 1999 *Design studies*, 20(3), pp 279-296
- [5] Eliasson, J., & Lundberg, M. 2012 *Transport reviews*, 32(1), pp 29-48

- [6] Szafranko, E. 2013 *Inżynieria Morska i Geotechnika*, 5, pp 400-404
- [7] Szafranko E. 2014 *Technical Transactions*, 2-B (6), 2014(111), pp 41-48
- [8] Szafranko E. 2016 *Archives of Civil Engineering*. Vol. 62, Issue 2, pp 205–216
- [9] Almeida, A., & Azevedo, A. 2016 *Journal of Innovation Management*, 4(2), pp 125-155
- [10] Dziadosz, A., & Kończak, A. 2016 *Archives of Civil Engineering*, 62(1), pp 111-126
- [11] Zavadskas, E. K., Antuchevičienė, J., & Kapliński, O. 2015 *Engineering Structures and Technologies*, 7(4), pp 151-167
- [12] Saaty, T. L. 2016 *Multiple Criteria Decision Analysis* (New York: Springer) p 363-419
- [13] Szafranko E. 2015 *International Journal of New Technologies in Science and Engineering*, Vol. 2, Issue. 5, pp 39-46
- [14] Komarowska, A., Ustinovichius, L., Shevchenko, G., & Nazarko, L. 2015 *International Journal of Strategic Property Management*, 19(1), pp 84-95