



MULTIPLE CRITERIA ASSESSMENT OF PILE-COLUMNS ALTERNATIVES

Saulius Sušinskas¹, Edmundas Kazimieras Zavadskas², Zenonas Turskis³ ✉

¹Faculty of Technologies, Kaunas University of Technology Panevėžys Institute,
S. Daukanto g. 12–138, 37164 Panevėžys, Lithuania

^{2, 3}Dept of Construction Technology and Management, Vilnius Gediminas Technical University,
Saulėtekio al. 11, 10223 Vilnius, Lithuania

E-mails: ¹saulius.susinskas@ktu.lt; ²edmundas.zavadskas@vgtu.lt; ³zenonas.turskis@vgtu.lt

Abstract. The paper presents the process of selection the pile-columns instalment alternative, which have to be the most appropriate and effective. The selection is based on a set of criteria: Mass, Cost of instalment, Labour expenditures, Machinery expenditures, Earthwork amount and Instalment tolerance. The criteria for evaluation are selected by taking into consideration the interests and goals of the client as well as factors that influence the efficiency of construction process. Their weights were determined by applying entropy method. The entropy is described as the casual value of the uncertainty which makes it more valuable in comparison with other factors. The solution of problem was made by applying *Additive Ratio ASsessment* (ARAS) method. The proposed technique could further be applied to substantiate the selection of effective alternative of structures, technologies, investments, etc.

Keywords: pile-columns, foundation, alternative, decision making, multiple criteria, MCDM, entropy, weights, operation research, *Additive Ratio ASsessment*, ARAS.

1. Introduction

Technological progress and innovation in civil engineering, management, and conditions of life level yields an enormous influence over economic activity, employment and growth rates. There is an increasing complexity and interplay between all issues associated with property management decisions (Langston *et al.* 2008). In urban areas, many high-rise buildings and viaducts are supported by pile foundations (Zhang *et al.* 2011).

There are many reasons a geotechnical engineer would recommend a deep foundation over a shallow foundation, but some of the common reasons are very large design loads, a poor soil at shallow depth, or site. A single pile foundation utilizes a single, generally large-diameter, foundation structural element to support all the loads (weight, wind, etc.) of a large above-surface structure.

Bridges are the crucial components of highway networks. A pile bridge is a structure that uses foundations consisting of long poles (referred to as piles), which are made of wood, concrete or steel and which are hammered into the soft soils beneath the bridge until the end of the pile reaches a hard layer of compacted soil or rock. Piles in such cases are hammered to a depth where the grip or friction of the pile and the soil surrounding it will support the load of the bridge deck. Bhattacharya *et al.* (2005) cri-

tically reviewed the current understanding of pile design under earthquake loading. Tomlinson and Woodward (2008), Tonia and Zhao (2007) provided a series of simple examples of the design of piles. Zhao *et al.* (2007) presented catastrophic model for stability analysis of high pile-column bridge pier and described a pile-column calculation model (Zhao *et al.* 2009).

A good example of such structure is the pile-column (also known in the American practice as extended pile-shaft), where the column is continued below the ground level as a pile of the same or somewhat larger diameter (Fig. 1). Obviously, the design of such foundation requires careful consideration of the flexural strength and ductility capacity of the pile. An advantage of supporting a column bent on drilled pile is the cost savings associated with the construction of large cast-in-drilled-hole piles instead of multiple piles of smaller diameter. Another advantage of such a design is that localized damage that could otherwise develop at the column-pile cap joint is avoided by the pile-column combination, since there is no structural distinction between the pile and the column other than the presence of a construction joint at the pile-column interface.

In case of a single pile-column, formation of a plastic hinge in the pile shaft is the only mechanism by which

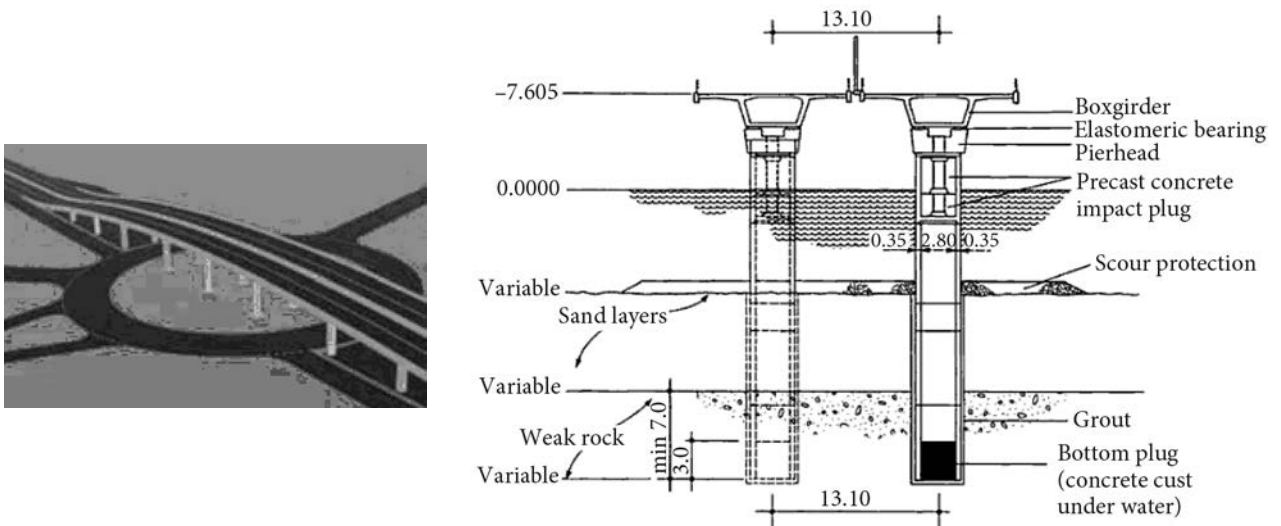


Fig. 1. Stand alone foundation piles-columns for buildings and bridges, dimensions in meters

ductile performance can be attained. A pile-column bent may first tend to plastify at the column-beam joint, but the full flexural capacity of the system can only be obtained through the formation of a secondary plastic hinge, belowground surface (at least slightly below). Bending moment distribution varies with height, but diminishes after attaining a max bending moment below the ground level. A typical depth for max bending moment, and possibly the location of the plastic hinge, ranges from one to three or four pile diameters below ground surface, depending on the above-ground height and soil stiffness.

Deep mixing/mass stabilization techniques are essentially variations of in situ reinforcements in the form of piles, blocks or larger volumes. Cement, lime/quick lime, fly ash, sludge and/or other binders are mixed into the soil to increase bearing capacity. The result is not solid as concrete, but should be seen as an improvement of the bearing capacity of the original soil.

It is difficult to apply probability-based approaches in structural safety predictions (Kudzys, Kliukas 2010). There is an urgent need for a systematic methodology for condition assessment of the bridges structures. It is necessary to learn about criteria determining both development and downfall of feasible alternatives (Kapliński 2008). In a mono-criterion approach, the analyst builds a unique criterion capturing all the relevant aspects of the problem. Such a one-dimensional approach is an oversimplification of the actual nature of the problem. All new ideas and possible variants of decisions in real world must be compared according to a set of multiple conflicting criteria (Turskis et al. 2009). Sasmal and Ramanjaneyulu (2008) made attempt to develop a systematic procedure and formulations for condition evaluation of existing bridges using Analytic Hierarchy Process in a fuzzy environment. Computer programs have been developed based on the formulations

presented in this paper for evaluating condition of existing bridges and the details are presented in the investigation.

Classical methods of multiple criteria optimization and determination of priority and utility function were first applied by Pareto in 1896 (Pareto 1971). Methods of multiple criteria analysis were developed to meet the increasing requirements of human society and the environment.

It was investigated, applied and developed a wide range of multiple criteria decision-making methods (MCDM): COPRAS – *Complex Proportional Assessment* (Zavadskas et al. 2009b), its modification COPRAS-G (*Complex Proportional Assessment Method with Grey Interval Numbers*) (Zavadskas et al. 2009a), ARAS (*Additive Ratio Assessment*) method (Zavadskas, Turskis 2010), ARAS-G, ARAS-F (Turskis, Zavadskas 2010a, 2010b) and other methods.

An alternative in multiple criteria evaluation is usually described by quantitative and qualitative criteria (Zavadskas et al. 2009b). The criteria have different units of measurement. Normalization aims at obtaining comparable scales of the criteria values. Different techniques of criteria value normalization are used. The impact of the decision-matrix normalization methods on the decision results has been investigated by many authors (Peldschus 2009; Zavadskas 1987).

Techniques and planning methods and decision making methods develop dynamically (Kalibatras, Turskis 2008; Peldschus 2008; Peldschus et al. 2010; Turskis 2008). MCDM researches in civil engineering and management is dominated in the Lithuanian-German-Polish triangle (Vilnius Gediminas Technical University, Poznan University of Technology, and Leipzig University of Applied Science) (Brauers et al. 2010; Brauers, Ginevičius 2009; Maskeliūnaitė et al. 2009; Podvezko et al. 2010; Radziszewska-Zielina 2010; Sivilevičius 2011).

2. Case study

Case study presents the process of selection the column-piles alternative for building which stands on the aquiferous soil (Fig. 2). The aim of problem is to design and install the piles-columns. The aim of this study is to show how a decision-maker can find the most reasonable alternative having the set of certain data.

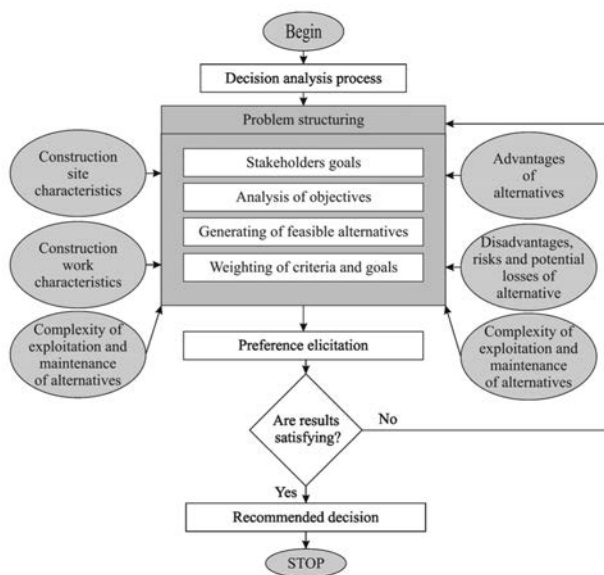


Fig. 2. Structure of the decision support system based on the ARAS method and SWOT analysis

Projects of pile-columns are complex systems, and they are quite difficult to select in practice. For this reason, a decision-maker should possess a large amount of multidisciplinary knowledge and should be familiar with multidisciplinary techniques of operations research. Ope-

rations research is based on four main assumptions (Turskis, Zavadskas 2010a):

- the problem situations exist as realities and do not depend on a decision-maker and aims of problem solution;
- the analysis of problem is objective (not related to different viewpoints of stakeholders, contractors, final user and impact on the environment) and described only by quantitative data;
- all participants of decision-making seeks optimal solution;
- the solutions are clearly optimal and can be implemented without complications.

The problem of a decision-maker consists of evaluating a finite set of alternatives in order to find the best one, to rank them from the best to the worst, to group them into predefined homogeneous classes, or to describe how well each alternative meets all the criteria simultaneously.

A decision-maker first of all must understand and describe the situation. This stage includes determination and assessment of the stakeholders, the different alternatives of feasible actions, the large number of different and important decision criteria, the type and the quality of the information, etc. It appears to be the key point defining MCDM as a formal approach (Fig. 2).

The results of the site investigation are presented in a detailed report, which provides a step-by-step account of the processes undertaken.

Taking into account the aforementioned suggestions and references of experts and the aim to install the most effective of pile-columns, the seven following alternatives were considered (Figs 3, 4).

Criteria, their optimality direction (the max or min value is preferable), criteria measuring units and their weights w_j are presented in Tables 1 and 2.

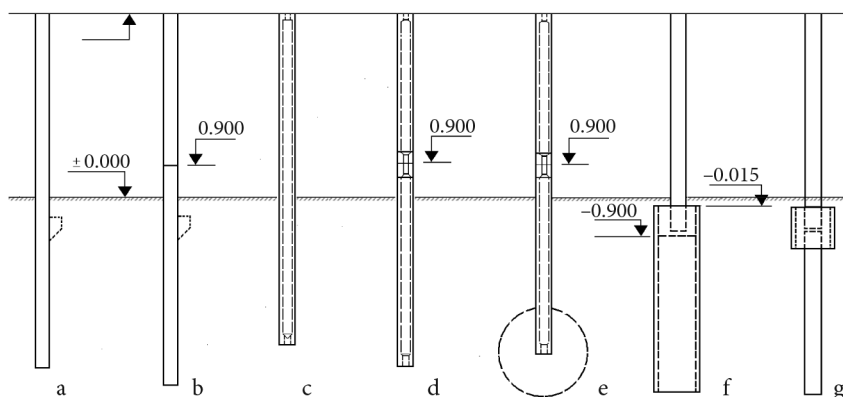


Fig. 3. Column-piles with increased bearing capacity: a – square cross-section solid column-piles (A_1); b – Integrated column-piles (A_2); c – centrifugal solid square cross-section column-piles (A_3); d – centrifugal square cross-section integrated column-piles (A_4); e – centrifugal column-piles (deep mixing/mass stabilization techniques are applied) (A_5); f – shell centrifugal pile with build in column (A_6); g – column-piles with non welding joint (concrete is Cast-in-Situ on the deeply driven short cylindrical pile) (A_7); dimensions in meters



Fig. 4. Inserting circular steel casing into ground by hydraulic hammer mounted on crawler crane

2.1. Entropy-based criteria weights determination

To achieve the goal, first of all criteria weights were determined by applying Entropy method. The initiator of the method (Shannon 1948) gave the following equation of Entropy method (1) (quantity of information in a dataset):

$$S = \frac{1}{N} \sum_j x_j \ln(x_j), \quad (1)$$

where S – entropy matrix; N – number of criteria; x_j – criteria value; j – criteria index ($j = 1 \dots n$).

This method was applied to solve multiple criteria problems in construction (Zavadskas 1987). Mamtani *et al.* (2006), You and Zi (2007), Li (2009), Ye (2010), Taheriyoun *et al.* (2010), Hsieh *et al.* (2010), Liu and Zhang (2011) applied this method to solve different problems. The block diagram of Entropy method is presented in Fig. 5.

The weights demonstrate which criterion is the most important in comprising the other criteria. For determining criteria weights, the criteria are transformed in such a manner that max value of each criterion would be the best. While preparing initial data for multi-criteria assessment of feasible alternatives, first of all the criteria set is deter-

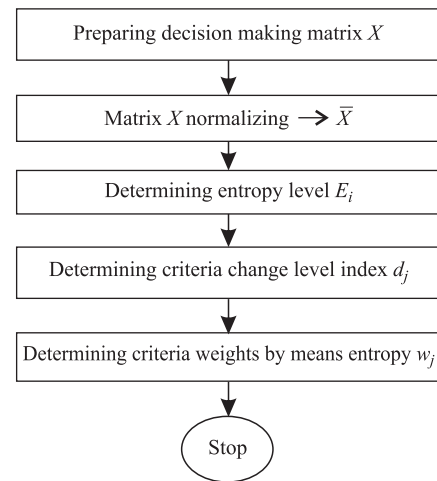


Fig. 5. The block diagram of Entropy method (Zavadskas 1987)

mined. These criteria have an impact on the problems solution results. Further in the article the following criteria will be analyzed: mass, cost of instalment, labour expenditures, machinery expenditures, earthwork, instalment tolerance.

Initial criteria values for evaluation of 7 feasible alternatives are presented in Table 1.

Further the normalization of the initial matrix (Table 1) was performed as follows:

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \quad (2)$$

$$\bar{x}_{ij} = \frac{\min_i x_{ij}}{x_{ij}}, \quad (3)$$

where \bar{x}_{ij} – criteria normalized values, x_{ij} – criteria initial values.

Table 1. Criteria values for evaluation – initial decision-making matrix X^*

Alternative	Criteria					
	Mass, kg/m ³	Cost of instalment, €	Labour expenditures, man-hours	Machinery expenditures, machine-hours	Amount of earthworks, m ³	Instalment tolerance, points
	x_1^*	x_2^*	x_3^*	x_4^*	x_5^*	x_6^*
Optim. direction	min	min	min	min	min	min
A_0 (optimal values)	180	23.2	4.06	15.1	0.2	1
A_1	260	23.2	4.15	15.5	0.6	1
A_2	260	25.8	4.8	16.1	0.6	2
A_3	180	24.0	4.2	15.7	0.2	1
A_4	180	24.8	4.06	15.95	0.2	2
A_5	185	26.2	4.46	16.2	0.4	3
A_6	190	27.0	5.3	15.2	0.2	2
A_7	265	25.3	4.85	15.1	0.2	2

Table 2. Entropy level, j index change level and criteria weights

Criteria	Mass	Cost of instalment	Labour expenditures	Machinery expenditures	Earthwork	Instalment tolerance
E_j	0.4367	0.2611	0.3260	0.1270	0.5545	0.9006
d_j	0.5633	0.7389	0.6740	0.8730	0.4455	0.0994
w_j	0.1660	0.2177	0.1986	0.2572	0.1313	0.0293
Priority order	4	2	3	1	5	6

Thus, the normalised decision-making matrix \bar{X} is obtained.

Entropy level for each criterion E_j is determined as follows:

$$E_j = -k \sum_{i=1}^m \bar{x}_{ij} \ln \bar{x}_{ij}; \quad (i = \overline{1, m}; j = \overline{1, n}), \quad (4)$$

where $k = \frac{1}{\ln m}$ is known as entropy index, which varies by interval $[1, 0]$, so

$$0 \leq E_j \leq 1; \quad (j = \overline{1, n}), \quad (5)$$

j – index change level in current problem is determined:

$$d_j = 1 - E_j; \quad (j = \overline{1, n}). \quad (6)$$

If all criteria are equally important i.e. there are no subjective or expert evaluations of their values, weight of j criterion (Table 2) is determined as follows:

$$w_j = \frac{d_j}{\sum_{j=1}^n d_j}; \quad (j = \overline{1, n}). \quad (7)$$

After determination of criteria weights, the priority order for considered criteria can be specified (Table 2): machinery expenditures \succ cost of instalment \succ labour expenditures \succ mass \succ earthwork \succ instalment tolerance.

Further ARAS method (Zavadskas, Turskis 2010; Zavadskas *et al.* 2010; Tupėnaitė *et al.* 2010) is applied to evaluate the priority of each alternative under investigation.

2.2. The determination of priority and importance of considered alternatives by ARAS method

According to the ARAS method, a utility function value determining the complex relative efficiency of a feasible alternative is directly proportional to the relative effect of values and weights of the main criteria considered in a project.

The first stage is Decision-Making Matrix (DMM) forming. In the MCDM of the discrete optimization problem any problem to be solved is represented by the fol-

lowing DMM of preferences for m feasible alternatives (rows) rated on n signfull criteria (columns):

$$X = \begin{bmatrix} x_{01} & \cdots & x_{0j} & \cdots & x_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}; \quad i = \overline{0, m}; j = \overline{1, n}, \quad (8)$$

where m – number of alternatives; n – number of criteria describing each alternative; x_{ij} – value representing the performance value of the i alternative in terms of the j criterion; x_{0j} – optimal value of j criterion.

If optimal value of j criterion is unknown, then

$$x_{0j} = \max_i x_{ij}, \text{ if } \max_i x_{ij} \text{ is preferable, and} \\ x_{0j} = \min_i x_{ij}^*, \text{ if } \min_i x_{ij}^* \text{ is preferable.} \quad (9)$$

Usually, the performance values x_{ij} and the criteria weights w_j are viewed as the entries of a DMM. The system of criteria as well as the values and initial weights of criteria are determined by experts. Then the determination of the priorities of alternatives is carried out in several stages.

Usually, the criteria have different dimensions. In order to avoid the difficulties caused by different dimensions of the criteria, the ratio to the optimal value is used. The values are mapped either on the interval $[0; 1]$ by applying the normalization of a DMM.

In the second stage the initial values of all the criteria are normalized – defining values \bar{x}_{ij} of normalised decision-making matrix \bar{X} :

$$\bar{X} = \begin{bmatrix} \bar{x}_{01} & \cdots & \bar{x}_{0j} & \cdots & \bar{x}_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \bar{x}_{i1} & \cdots & \bar{x}_{ij} & \cdots & \bar{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \bar{x}_{m1} & \cdots & \bar{x}_{mj} & \cdots & \bar{x}_{mn} \end{bmatrix}; \quad i = \overline{0, m}; j = \overline{1, n}. \quad (10)$$

The criteria, whose preferable values are max, are normalized as follows:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_{i=0}^m x_{ij}} \tag{11}$$

The criteria, whose preferable values are min, are normalized by applying two-stage procedure:

$$x_{ij} = \frac{1}{x_{ij}^*}; \quad \bar{x}_{ij} = \frac{x_{ij}}{\sum_{i=0}^m x_{ij}} \tag{12}$$

When the dimensionless values of the criteria are known, all the criteria, originally having different dimensions, can be compared.

The third stage is defining normalized-weighted matrix – \hat{X} . It is possible to evaluate the criteria with weights w_j . The values of weight w_j are determined by the entropy method. Normalized-weighted values of all the criteria are calculated as follows:

$$\hat{x}_{ij} = \bar{x}_{ij} w_j; \quad i = \overline{0, m}, \tag{13}$$

where w_j is the weight (importance) of the j criterion and \bar{x}_{ij} is the normalized rating of the j criterion.

$$\hat{X} = \begin{bmatrix} \hat{x}_{01} & \cdots & \hat{x}_{0j} & \cdots & \hat{x}_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{x}_{i1} & \cdots & \hat{x}_{ij} & \cdots & \hat{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{x}_{m1} & \cdots & \hat{x}_{mj} & \cdots & \hat{x}_{mn} \end{bmatrix}; \quad i = \overline{0, m}; \quad j = \overline{1, n}. \tag{14}$$

The following task is to determine values of optimality function:

$$S_i = \sum_{j=1}^n \hat{x}_{ij}; \quad i = \overline{0, m}, \tag{15}$$

where S_i – the value of optimality function of i alternative.

The biggest value is the best, and the least one is the worst. Taking into account the calculation process, the optimality function S_i has a direct and proportional relationship with the values x_{ij} and weights w_j of the investigated criteria and their relative influence on the final result. Therefore, the greater the value of the optimality function S_i , the more effective the alternative. The priorities of alternatives can be determined according to the value S_i . Consequently, it is convenient to evaluate and rank decision alternatives when this method is used.

The degree of the alternative utility is determined by a comparison of the variant, which is analysed with the ideally best one S_0 . The Eq used for the calculation of the utility degree K_i of an alternative A_i is given below:

$$K_i = \frac{S_i}{S_0}; \quad i = \overline{0, m}, \tag{16}$$

where S_i and S_0 are the optimality criterion values, obtained from Eq (15).

The calculated values of K_i are in the interval [0, 1] and can be ordered in an increasing sequence, which is the wanted order of precedence. The complex relative efficiency of the feasible alternative can be determined according to the utility function values.

According to the above proposed algorithm of ARAS method the problem was solved and the results are presented in Table 3 and Fig. 6.

On the basis of results obtained in Table 3 it can be concluded that according to selected criteria, reflecting

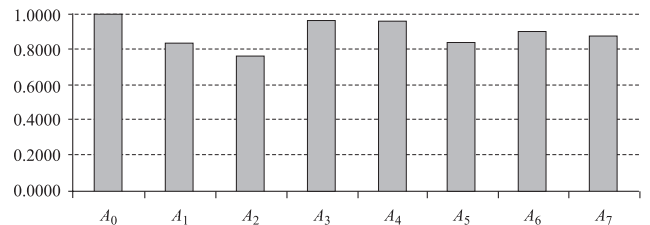


Fig. 6. Comparison of foundation instalment alternatives performance level

Table 3. Weighted-normalised criteria values of foundation instalment alternatives (weighted-normalised DMM \hat{X}) and solution results

Alternative	Criteria						Solution results		
	\hat{x}_1	\hat{x}_2	\hat{x}_3	\hat{x}_4	\hat{x}_5	\hat{x}_6	S	K	Rank
A ₀	0.0238	0.0292	0.0272	0.0332	0.0212	0.0054	0.1401	1.0000	0
A ₁	0.0165	0.0292	0.0267	0.0323	0.0071	0.0054	0.1172	0.8364	5
A ₂	0.0165	0.0263	0.0230	0.0311	0.0071	0.0027	0.1067	0.7616	7
A ₃	0.0238	0.0282	0.0263	0.0319	0.0212	0.0054	0.1369	0.9775	1
A ₄	0.0238	0.0273	0.0272	0.0314	0.0212	0.0027	0.1337	0.9545	2
A ₅	0.0231	0.0259	0.0248	0.0309	0.0106	0.0018	0.1172	0.8363	6
A ₆	0.0225	0.0251	0.0209	0.0330	0.0212	0.0027	0.1254	0.8953	3
A ₇	0.0161	0.0268	0.0228	0.0332	0.0212	0.0027	0.1229	0.8772	4

the effectiveness of pile-columns construction and their weights, the most reasonable alternative according to the calculation results is the third (A_3).

The priority order of the investigated pile-columns instalment alternatives can be represented as follows (Fig. 6):

$$A_3 \succ A_4 \succ A_6 \succ A_7 \succ A_1 \succ A_5 \succ A_2. \quad (17)$$

It means that the worst alternative is the second.

It can be stated that the alternative 3 is 97% of optimal alternative performance level, and the performance of the worst alternative 2 is only 76%.

According to the given data on the criteria describing the pile-columns instalment alternatives, rational solutions about its construction improvement and cost reduction can be made.

3. Conclusions

Traditional optimization, statistical and econometric analysis approaches used within the engineering context are often based on the assumption that the considered problem is well formulated and decision-makers usually consider the existence of a single objective, evaluation criterion or point of view that underlies the conducted analysis. In such a case the solution of engineering problems is easy to obtain.

According to the proposed ARAS method the utility function value, determining the complex efficiency of a feasible alternative, is directly proportional to the relative effect of values and weights of the main criteria considered in a project.

The degree of the alternative utility is determined by a comparison of the variant, which is analysed with the ideally best one.

It can be stated that the ratio with an optimal alternative may be used in cases when it is seeking to rank alternatives and find ways of improving alternative projects.

In conclusion, the proposed model has a promising future in the construction engineering field, because it offers a highly methodological basis for decision support.

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