MULTIPLE CRITERIA SELECTION OF PILE-COLUMN CONSTRUCTION TECHNOLOGY

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Abstract. Numerous alternatives exist for foundation systems and construction technologies. The systems can be described by different criteria values which are incorporated in the conventional design process. Decision on the most suitable construction technology is vital for success and depends on many effectiveness criteria. The business success depends on the right choice. The mandate of a construction management researcher is to use rational, systematic, science-based techniques to inform and improve various decisions. The paper presents multiple criteria decision making model for selection of a pile-column technology. The technological criteria are determined by an experimental study. Based on in-situ investigation of natural soil conditions, criteria values are determined. The decision making model incorporates five different methods and techniques. To solve a problem, it uses three multiple criteria decision making methods. Integrated criteria weights are determined by using the analytic hierarchy process and the expert judgement method. This model could be used to solve complicated problems pertaining to the selection of a construction technology.

Keywords: pile-columns, technology, multiple criteria, construction site, MCDM, TOPSIS, ARAS, COPRAS, AHP, the expert judgement method, integrated weights.

1. Introduction

In construction, piles can be used in various ways. In urban areas, many high-rise buildings and viaducts are founded on a pile foundation. Construction technologies are highly dependent on in-situ conditions, e.g. soil conditions are particularly important for a foundation. The way the designed and actual founding depths of foundations correspond to variability of geological conditions has long been a concern (Zhang et al. 2011b). Tomlinson and Woodward (2008) presented a lot of pile design examples. Sivilevičius et al. (2012) presented results of an experimental study on technological indicators of pile-columns at a construction site. Based on in-situ investigation of natural soil conditions, regression equations have been determined, which can be very useful when planning similar works at a construction site. Besides, they allow determining duration and energy consumption of construction works. Zhang and Dasaka (2010) evaluated the spatial variability characteristics at a weathered soil site. Sušinskas et al. (2011) presented the process for selection of the most fitting and effective pile-column instalment alternative. The model is based on ARAS method and AHP technique. Zhang et al. (2011a) proposed a two-stage analysis method to study the behaviour of pile groups with rigid elevated caps. A single pile foundation utilizes a single, generally a large-diameter structural element to support all of the loads (weight, wind, etc.) of a large above-surface structure. Yoon et al. (2011) presented the evaluation results of the load test on columns and the rationale used for the selection of the resistance factor. Zhao et al. (2009) presented the model for stability analysis of high pile-column bridge pier. Zhang et al. (2011b) analysed excavation-induced responses of loaded pile foundations considering the unloading effect. Zhao et al. (2007) revisited the stability analysis regarding the pile-columns of a bridge pier.

Sustainable development aims to reconcile economic growth, social progress and frugal use of natural resources, to maintain ecological balance and to ensure favourable living conditions for current and future generations (Raslanas et al. 2011). Selection of an investment strategy and related decision making relies heavily on personal experience and behaviour (Wu et al. 2012; Šaparauskas et al. 2011; Banaitiënė et al. 2011). Multiple criteria decision making is an important part of modern decision science (Zavadskas, Turskis 2011; Zavadskas et al. 2008). How to select an effective algorithm for a multiclassification task is an important yet difficult issue (Peng et al. 2011). Most of the real-world multiple criteria decision-making problems contain a mixture of quantitative and qualitative criteria (Nieto-Morote, Ruz-Vila 2011; Kaklauskas et al. 2011; Merigo, Gil-Laufenste 2011). The typical MCDM problem is concerned with the task of ranking. In order to evaluate the overall efficiency of technological alternatives, typically it is necessary: a) to identify
the system for evaluation of criteria that relates the system capabilities to goals; b) to develop alternative systems for attaining the goals (generating alternatives); c) to assess a finite number of decision alternatives, each of which is described in terms of different decision criteria which are taken into account simultaneously; d) to apply a normative multiple criteria analysis method; e) to accept one alternative as the most preferable; f) to gather new information and go into the next iteration of multiple criteria optimization if the final solution is not accepted.

At the beginning of his book, Zeleny (1982) stated that “It has become more and more difficult to see the world around us in a unidimensional way and to use only a single criterion when judging what we see”. In reality, the modelling of engineering problems is based on a different kind of logic taking into consideration the existence of multiple criteria, the conflicting aims of decision maker, the complex, subjective and different nature of the evaluation process, and the participation of several decision makers. The use of the new and modernisation of the existing technologies as well as the selection of the most suitable alternative among those feasible with the help of different models are challenging tasks for the modern civil engineering (Prentkovskis et al. 2012; Krayushkina et al. 2012). Estimation and modelling of problems depends the recent advances achieved in different fields (Dzemyda, Sakalauskas 2011). Selection of the right construction technology plays a vital role in the overall performance of a project, thus posing the most crucial challenge for any contractor. Numerous and often conflicting objectives and alternatives, such as tender price, completion date, and experience, need to be considered. Recently, to assist contractors and stakeholders in decision-making, there has been a trend to move away from the “lowest-price wins” principle and subjective judgement to the multiple criteria selection approach in the selection of alternatives (San Cristóbal 2012).

2. Case study

Projects with pile-columns are complex systems that are rather difficult to select in practice. For this reason, a decision-maker should possess a large amount of multidisciplinary knowledge and be familiar with multidisciplinary techniques of operations research. The case study presents the process of selecting the pile-column alternative for a building that stands on the aquiferous soil. The aim of the study is to design and install the most effective pile-columns. The study shows how a decision-maker can find the most reasonable alternative with the help of a certain dataset. Taking into account the aforementioned suggestions and references of experts as well as the aim to install the most effective pile-columns, the five following alternatives were considered (Table 1).

| Table 1. Considered technological alternatives for installing pile-columns (driving the rings) |
|---|---|
| Alternative | Short description of the alternative |
| $a_1$ | Driving the reinforced concrete ring using a punch, driving the pole, construction, positioning and adjustment of the mounting jig for the column, placing in situ concrete, and column mounting. |
| $a_2$ | Driving the reinforced concrete ring by applying a punch, driving the pile, placing in situ concrete mixture basement with a nest for the column mounting, and column mounting. |

Driving the reinforced concrete ring | Driving the pole | Positioning and adjusting the mounting jig | Column mounting
Driving the reinforced concrete ring | Driving the pole | Positioning and adjusting the mounting jig | Column mounting
The construction technology of alternatives is described by six criteria. The set of criteria was determined by qualified civil engineers and shown in Table 2. The selection is based on a set of criteria: labour expenditures ($x_1$, hours), cost of instalment ($x_2$, €), consumption of concrete ($x_3$, m$^3$), consumption of steel ($x_4$, kg), machinery expenditures ($x_5$, hours), and consumption of energy ($x_6$, GJ). The criteria set for evaluation is selected considering the factors that influence the efficiency of the construction process. Significance of criteria significances (weights) was determined with the help of the expert judgement method and the analytic hierarchy process (AHP) method. Integrated criteria weights were applied in the solution process.
The expert judgement method was implemented at the follow-

ing the hypothesis about the agreement of independent expert
calculation of values

 Experts, then

E1 E2 E3 E4 E5 E6 E7 E8 E9 E10 E11 E12 E13 E14 E15 E16 E17 E18 E19 E20 E21 E22 E23 E24 E25 E26
5 1 3 4 6 3 5 4 6 3 5 4 6 3 5 4 6 3 5 4 6 3 5 4 6 3 5 4 6
6 5 3 4 2 1 6 5 3 4 2 1 6 5 3 4 2 1 6 5 3 4 2 1 6 5 3 4 2 1 6 5 3 4 2 1 6 5 3 4 2 1 6 5 3 4 2 1
4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2
3 5 4 2 6 3 5 4 2 6 3 5 4 2 6 3 5 4 2 6 3 5 4 2 6 3 5 4 2 6 3 5 4 2 6 3 5 4 2 6 3 5 4 2 6
4 5 6 3 1 2 5 6 3 4 2 1 5 6 3 4 2 1 5 6 3 4 2 1 5 6 3 4 2 1 5 6 3 4 2 1 5 6 3 4 2 1 5 6 3 4 2 1
2 4 6 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2
1 2 4 6 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2 4 6 5 3 1 2

Some table content:

| Expert | \(x_1\) | \(x_2\) | \(x_3\) | \(x_4\) | \(x_5\) | \(x_6\) |
|--------|--------|--------|--------|--------|--------|--------|
| E1     | 5      | 6      | 4      | 3      | 1      | 2      |
| E2     | 1      | 5      | 6      | 3      | 2      | 4      |
| E3     | 3      | 5      | 6      | 4      | 1      | 2      |
| E4     | 5      | 4      | 6      | 3      | 1      | 2      |
| E5     | 6      | 5      | 3      | 4      | 2      | 1      |
| E6     | 3      | 4      | 6      | 5      | 2      | 1      |
| E7     | 4      | 6      | 5      | 3      | 1      | 2      |
| E8     | 1      | 3      | 5      | 4      | 2      | 6      |
| E9     | 5      | 3      | 6      | 4      | 1      | 2      |
| E10    | 6      | 5      | 3      | 4      | 1      | 2      |
| E11    | 5      | 6      | 4      | 3      | 2      | 1      |
| E12    | 5      | 6      | 3      | 2      | 4      | 1      |
| E13    | 5      | 2      | 6      | 4      | 3      | 1      |
| E14    | 4      | 3      | 6      | 5      | 1      | 2      |
| E15    | 6      | 5      | 3      | 4      | 2      | 1      |
| E16    | 3      | 4      | 6      | 5      | 1      | 2      |
| E17    | 5      | 6      | 4      | 3      | 2      | 1      |
| E18    | 5      | 6      | 3      | 4      | 2      | 1      |
| E19    | 6      | 4      | 5      | 3      | 1      | 2      |
| E20    | 5      | 6      | 4      | 3      | 1      | 2      |
| E21    | 4      | 6      | 5      | 3      | 2      | 1      |
| E22    | 4      | 6      | 3      | 5      | 1      | 2      |
| E23    | 5      | 6      | 1      | 2      | 4      | 3      |
| E24    | 5      | 6      | 3      | 4      | 1      | 2      |
| E25    | 5      | 6      | 2      | 4      | 3      | 1      |
| E26    | 5      | 6      | 4      | 3      | 1      | 2      |

Sum of rank: 116 133 109 94 45 49
Mean value: 4.462 5.115 4.192 3.615 1.731 1.885
Rank: 2 1 3 4 6 5
Weight of criterion, \(p\): 0.212 0.244 0.200 0.172 0.082 0.090

| Expert | \(x_1\) | \(x_3\) | \(x_4\) | \(x_5\) |
|--------|--------|--------|--------|--------|
| E1     | 0.249 | 0.379 | 0.102 | 0.16  |
| E2     | 0.043 | 0.249 | 0.379 | 0.16  |
| E3     | 0.16  | 0.249 | 0.379 | 0.102 |
| E4     | 0.249 | 0.102 | 0.379 | 0.16  |
| E5     | 0.379 | 0.249 | 0.16  | 0.102 |
| E6     | 0.16  | 0.102 | 0.379 | 0.249 |
| E7     | 0.102 | 0.379 | 0.249 | 0.16  |
| E8     | 0.043 | 0.102 | 0.249 | 0.16  |
| E9     | 0.249 | 0.379 | 0.16  | 0.102 |
| E10    | 0.379 | 0.249 | 0.16  | 0.102 |
| E11    | 0.249 | 0.379 | 0.102 | 0.16  |
| E12    | 0.249 | 0.379 | 0.16  | 0.102 |
| E13    | 0.249 | 0.102 | 0.379 | 0.16  |
| E14    | 0.16  | 0.102 | 0.379 | 0.249 |
| E15    | 0.102 | 0.16  | 0.379 | 0.249 |
| E16    | 0.249 | 0.379 | 0.16  | 0.102 |
| E17    | 0.249 | 0.379 | 0.16  | 0.102 |
| E18    | 0.249 | 0.102 | 0.379 | 0.16  |
| E19    | 0.379 | 0.102 | 0.249 | 0.16  |
| E20    | 0.249 | 0.379 | 0.16  | 0.102 |
| E21    | 0.102 | 0.379 | 0.249 | 0.16  |
| E22    | 0.249 | 0.379 | 0.16  | 0.102 |
| E23    | 0.379 | 0.249 | 0.16  | 0.102 |
| E24    | 0.249 | 0.379 | 0.102 | 0.16  |
| E25    | 0.249 | 0.379 | 0.16  | 0.102 |
| E26    | 0.249 | 0.379 | 0.16  | 0.102 |

\[ \chi^2 = \frac{(n-1)\alpha}{W} \]
Integrated criteria weights were calculated during the third stage of criteria weight determination (Table 4).

Table 4. Integrated criteria weights

| Criteria | Weights |
|----------|---------|
|          |        |

Table 5. Description of TOPSIS, COPRAS and ARAS methods

| TOPSIS | COPRAS | ARAS |
|--------|--------|------|
|        |        |      |

2.2. Problem solving

Three different multiple criteria decision making methods – TOPSIS, COPRAS and ARAS – were selected to solve the investigated problem. An Additive Ratio Assessment (ARAS) method (Zavadskas, Turskis 2010; Turskis, Zavadskas 2010a) is based on the argument that complicated phenomena could be understood by using simple relative comparisons. It is argued that the ratio of the sum of normalised and weighted values of criteria, which describes an alternative under consideration, to the sum of the values of normalised and weighted criteria, which describes the optimal alternative, is the degree of optimality, which is reached by the alternative under comparison.

The recent developments of decision making models based on the ARAS method are listed below: Keršulienė and Zavadskas (2010b) performed multiple criteria analysis in order to select the location for a logistics centre; and Zavadskas et al. (2010b) analysed foundation alternatives.

The method of complex proportional assessment COPRAS (Zavadskas, Kabalkauskas 1996) assumes direct and proportional dependence of significance and utility degree of investigated alternatives on a system of criteria adequately describing the alternatives, and on values and weights of the criteria. This method was used to solve various problems in construction.

The recent developments of decision making models based on COPRAS methods (Podvezko 2011) are listed below: Datta et al. (2009) solved the problem of determining the compromise to selection of a supervisor; Bin- du Madhuri et al. (2010) presented the model for selection of alternatives based on COPRAS-G and AHP methods; Uzsilaityte and Martinaitis (2010) investigated and compared different alternatives for the renovation of buildings taking into account energy, economic and environmental criteria while evaluating impact of renovation measures during their life cycle; Chatterjee et al. (2011) presented materials selection model based on COPRAS and EVAMIX methods; Yazdani et al. (2011) applied the COPRAS method to analyse critical infrastructures.

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method determines a solution with the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution (Hwang, Yoon 1981). Kalibatas et al. (2011) used it in order to solve the problem of the assessment of dwellings, determining the ideal indoor environment. Rudziankaite-Kvaraciejiene et al. (2010) evaluated the effectiveness of road investment projects.

The description of the methods is presented in Table 5.

First of all, the initial decision making matrix was prepared. The problem was solved by applying three different multiple criteria decision making methods: TOPSIS, COPRAS and ARAS. The solution process of the problem is presented in Table 6.
The separations of each alternative from the positive ideal solution $D^+_i$ and from the negative ideal solution $D^-_i$ in Euclidean distance are given as

\[ D^+_i = \left( \sum_{j=1}^{n} (\hat{x}_{ij}^+ - \hat{x}_{ij}^P)^2 \right)^{\frac{1}{2}} \]

\[ D^-_i = \left( \sum_{j=1}^{n} (\hat{x}_{ij}^+ - \hat{x}_{ij}^P)^2 \right)^{\frac{1}{2}} \]

The utility degree $K_i$ of the alternative $a_i$ is

\[ K_i = \frac{D^+_i}{D^+_i + D^-_i} \]

The ranking of alternatives is obtained as $\max_i K_i$, which is the most preferable.
### Table 6. The problem solution process and results

| Alternatives | Attributes | \(x_1\) | \(x_2\) | \(x_3\) | \(x_4\) | \(x_5\) | \(x_6\) |
|--------------|------------|--------|--------|--------|--------|--------|--------|
|              | \(\alpha_1\) | 0.099  | 0.116  | 0.091  | 0.061  | 0.033  | 0.044  |
|              | \(\alpha_2\) | 0.104  | 0.123  | 0.091  | 0.061  | 0.042  | 0.030  |
|              | \(\alpha_3\) | 0.088  | 0.116  | 0.087  | 0.122  | 0.033  | 0.052  |
|              | \(\alpha_4\) | 0.100  | 0.092  | 0.087  | 0.061  | 0.038  | 0.025  |
|              | \(\alpha_5\) | 0.081  | 0.094  | 0.091  | 0.061  | 0.037  | 0.044  |
|              | \(\alpha^*\) | 0.081  | 0.092  | 0.087  | 0.061  | 0.033  | 0.025  |

### TOPSIS method

| Optimum | \(\alpha_1\) | \(\alpha_2\) | \(\alpha_3\) | \(\alpha_4\) | \(\alpha_5\) | \(\alpha^*\) |
|---------|--------------|--------------|--------------|--------------|--------------|--------------|
| \(\alpha_1\) | 0.099  | 0.116  | 0.091  | 0.061  | 0.033  | 0.044  |
| \(\alpha_2\) | 0.104  | 0.123  | 0.091  | 0.061  | 0.042  | 0.030  |
| \(\alpha_3\) | 0.088  | 0.116  | 0.087  | 0.122  | 0.033  | 0.052  |
| \(\alpha_4\) | 0.100  | 0.092  | 0.087  | 0.061  | 0.038  | 0.025  |
| \(\alpha_5\) | 0.081  | 0.094  | 0.091  | 0.061  | 0.037  | 0.044  |
| \(\alpha^*\) | 0.081  | 0.092  | 0.087  | 0.061  | 0.033  | 0.025  |

### COPRAS method

| Optimum | \(\alpha_1\) | \(\alpha_2\) | \(\alpha_3\) | \(\alpha_4\) | \(\alpha_5\) | \(\alpha^*\) |
|---------|--------------|--------------|--------------|--------------|--------------|--------------|
| \(\alpha_1\) | 0.045  | 0.052  | 0.041  | 0.029  | 0.015  | 0.020  | 0.000  | 0.202  | 0.197  | 0.905  | 3      |
| \(\alpha_2\) | 0.047  | 0.055  | 0.041  | 0.029  | 0.019  | 0.014  | 0.000  | 0.204  | 0.195  | 0.895  |        |
| \(\alpha_3\) | 0.040  | 0.052  | 0.039  | 0.058  | 0.015  | 0.024  | 0.000  | 0.227  | 0.175  | 0.804  |        |
| \(\alpha_4\) | 0.045  | 0.041  | 0.039  | 0.029  | 0.017  | 0.011  | 0.000  | 0.183  | 0.218  | 1.000  | 1      |
| \(\alpha_5\) | 0.036  | 0.042  | 0.041  | 0.029  | 0.016  | 0.020  | 0.000  | 0.185  | 0.215  | 0.989  | 2      |

### ARAS method

| Optimum | \(\alpha_1\) | \(\alpha_2\) | \(\alpha_3\) | \(\alpha_4\) | \(\alpha_5\) | \(\alpha^*\) |
|---------|--------------|--------------|--------------|--------------|--------------|--------------|
| \(\alpha_1\) | 0.040  | 0.045  | 0.039  | 0.038  | 0.018  | 0.015  |     | 0.195  | 0.897  | 3      |
| \(\alpha_2\) | 0.038  | 0.042  | 0.039  | 0.038  | 0.014  | 0.022  |     | 0.194  | 0.893  | 4      |
| \(\alpha_3\) | 0.045  | 0.045  | 0.041  | 0.019  | 0.018  | 0.013  |     | 0.181  | 0.831  | 5      |
| \(\alpha_4\) | 0.040  | 0.057  | 0.041  | 0.038  | 0.016  | 0.026  |     | 0.217  | 1.000  | 1      |
| \(\alpha_5\) | 0.049  | 0.055  | 0.039  | 0.038  | 0.016  | 0.015  |     | 0.213  | 0.981  | 2      |
| \(\alpha^*\) | 0.049  | 0.057  | 0.041  | 0.038  | 0.018  | 0.026  |     | 0.217  | 1.000  | 1      |

### 3. Conclusions

Overall, the main advantages that the MCDM provides in decision making could be summarized in the following aspects: the possibility to analyse complex problems; the possibility to aggregate both quantitative and qualitative criteria in the evaluation process; good evidence of decisions; the option for a decision-maker to participate actively in the decision-making process; and the use of flexible scientific methods in the decision making process.

According to the newly proposed model, the priorities of alternatives can be determined according to the utility function value. Consequently, it is convenient to evaluate and rank decision alternatives when this model is used.

The degree of the alternative utility is determined by comparison of the analysed variant with ideally the best one. It can be stated that the ratio with an optimal alternative may be used in cases when it is required to rank alternatives and find ways to improve alternative projects.

Three MCDM methods were applied. Alternatives according to all methods rank in the same way: \(\alpha_4 \succ \alpha_5 \succ \alpha_1 \succ \alpha_2 \succ \alpha_3\).

This means that the most preferable alternative is \(\alpha_4\) that must be selected and implemented.

The proposed model can be modified and applied to solve different problems: to select, assess and rank constructions, technologies and other alternatives.

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