

Article

# Selection of the Best Method for Underpinning Foundations Using the PROMETHEE II Method

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**Abstract:** This article proposes applying the preference-ranking organization method for enrichment of evaluations (PROMETHEE) II in the selection of the optimal solution and ranking of selected methods for underpinning foundations. Analysis of the selected foundation-underpinning methods was based on a complex decision-making problem that included aspects of the three pillars of sustainable development, and it was extended to include technological and constructional criteria. The study used the following criteria for assessing proposed variants: price, bearing capacity, noise and vibrations, necessary equipment, necessary excavations under final structure, failure rates, and necessary foundation shoring. Analysis using the PROMETHEE II method allowed for identifying strengths and weaknesses of selected methods for underpinning foundations. The PROMETHEE II method enabled to create a ranking of foundation-underpinning methods. Jet-grouting and root-pile methods were the highest scorers in this ranking and those that fulfilled the identified criteria to the greatest extent. Moreover, analysis showed that the PROMETHEE II method was useful in solving problems of choice in the construction industry.

**Keywords:** sustainable development; multicriteria decision-making process; jet-grouting; root pile

## 1. Introduction

The construction industry represents an economic sector that significantly affects the natural environment. The production of building materials, their use during the construction of new buildings, and their removal following demolition consume vast amounts of energy and generate vast amounts of waste, which greatly affects the natural environment [1]. More than 40% of globally generated energy is used by the construction industry. Minimizing the amount of energy and materials used for the development of the construction industry is therefore essential to economic, social, and environmental development. Sustainable development in the construction industry includes organizational sustainability, the rational use of materials, incorporating existing materials and structures whenever possible, and minimizing the environmental impact of the processing, production, use, and reproduction of building materials [2]. Materials used for construction should be selected according to considerations of their efficiency, durability, lifespan, and the amount of energy needed for their production. Future maintenance, repair, and modernization should also be considered. Sustainable-development policy gives preference to renovating existing structures instead of demolishing them and constructing new ones [3]. The renovation of existing buildings can be accomplished without further loss of land to construction [4,5]. Renovating an existing structure also helps minimize the consumption of building materials and energy used for their production. The renovation or upward growth of a building should consider how to incorporate sustainable building materials and recycled materials for their recovery and reuse [6]. The use of materials that

require low levels of energy to incorporate is recommended [7–10]. The upward growth of an existing building usually requires foundations to be deepened and strengthened through underpinning.

Foundation underpinning is an extremely difficult and dangerous procedure that requires special design, professional execution, and supervision. An appropriately underpinned foundation can extend a building's operational lifetime and improve its safety. Underpinning existing foundations is necessary for the upward growth of a building via the addition of another floor, deepening of basements, or planned construction of an adjacent building, but it may also be carried out in the case of underwashing foundations, damage related to the appearance of fractures, or ceiling and wall failures. Underpinning is also necessary if foundations are placed above the frost line. Underpinning the foundations of an existing building greatly reduces the costs involved and materials used compared to the construction of a new building. Demolishing an existing building and constructing a new one in its place require vast amounts of labor, energy, and money. Therefore, it is worthwhile to consider renovating or expanding an existing building [11,12]. Foundation underpinning can be carried out by using the following methods.

Damaged existing foundations can be strengthened through methods such as applying reinforced-concrete coats or shotcrete to fractured continuous footings. This strengthens foundations without expanding their base area. The use of shotcrete eliminates any damage or fractures. Reinforced-concrete aprons hold the foundation structure together by creating a rigid strengthening structure. Such strengthening does not require any excavation under the footing, and is not dependent on soil type [13].

Deepening foundations to underpin them may be necessary because of an increase in load transferred to the soil. This method is based on increasing the depth of the existing foundation down to a stable soil stratum. An excavated section is then filled with a concrete mix. Deepening foundation to underpin is feasible in waterfree soils [13].

Widening may be performed if the subsoil can withstand increased loads transferred from the building. Work is performed at the level of the existing foundation or slightly deeper. Widening increases the stiffness of foundations through the construction of aprons on one or two sides. New elements are made of reinforced concrete, and are permanently connected to the foundation [14].

Jet grouting does not require any excavation below the base of the foundation. This method also does not require the division of underpinned foundations into working sections, greatly reducing working time. The jet-grouting method entails drilling boreholes through existing foundations to the intended depth, and forming a column by injecting cement grout. A column created through this technique consists of soil and grout. Higher bearing capacity is achieved by transferring loads to lower soil strata [14–16].

Piling is used in weak soils, in unfavorable soil–water conditions, or wherever it is impossible to excavate underneath or beside the foundation. Installing piles changes the foundation type from shallow to deep [11,17–20].

Megapiles are commonly used to strengthen foundations of protected buildings. Piles of this type are precast and pressed into the ground. They consist of 100, 80, or 60 cm sections. This method requires excavation approximately 2 to 2.5 m below the level of existing foundations.

Root piles, despite their small diameter (80–250 mm), are capable of withstanding large loads and transferring them deep into the ground. The root piles are installed by rotary drilling and jetting. These piles do not require any excavation or additional shoring. They do not generate any vibrations or noise. Unfortunately, they have higher costs than those of other piling methods [11,13,21,22].

During installation of a jacked-down Franki Miga system, existing foundation is used as a thrust block. In order to underpin a foundation using jacked-down piles, it is necessary to excavate a narrow pit approximately 0.8 m under the foundation, install the initial section of the pile in the pit, and press it into the ground with a hydraulic actuator, using existing foundation for support. Other sections are then successively constructed and connected to the previous ones until the target-bearing capacity of the piles is achieved; lastly, the remaining void is filled with concrete [13,23].

## 2. Methods

Decision-making methods are increasingly implemented because of ongoing economic development that generates ever more complex decision-making problems. Decision-making processes include multidimensional comparative analysis (MCA) or multicriteria decision-support (MCDS) methods. Implementing decision-making methods significantly facilitates the selection of the best option (through MCDS) or the performance of comparative analysis (through MCA). MCDS methods are commonly used to make decisions and solve sustainability problems [24–28]. The multicriteria decision-making method is based on analysis of many different decision options and assessments [29–31], and it supports the resolution of complex decision-making problems, including their environmental, economic, ecological, social, constructional, and technological aspects [32]. Analysis carried out in this article was based on the three pillars of sustainable development, and was further extended to include technological and constructional criteria. It began with the formulation of a decision-making problem, and the selection of decision options and uniform criteria for evaluating the analyzed options. Typically, implementation of the obtained results concludes analysis. Multicriteria decision-making covers a number of methods that are mainly classified into the following groups: methods based on the rate of exceedance, methods based on the function of usability, and methods integrating reference points [33–38].

The preference-ranking organization method for enrichment of evaluations (PROMETHEE) II belongs to the PROMETHEE family of methods, which are based on the rate of exceedance and used on a finite set of evaluated options. The aim of the PROMETHEE II method is to create a ranking of options that classifies the evaluated options in order from most to least preferred. The first phase of PROMETHEE methods is the formulation of the decision-making problem. Decision options and uniform assessment criteria are defined during this phase. Scores are attributed on the basis of the differences between decision–option pairs in the context of individual criteria. Higher difference demonstrates the high significance of a decision option with respect to a given criterion. Criteria are defined by a preference function that can assume values of 0 to 1 [35,39–42]. The transformed preference-function values form aggregated preference indices that serve as the basis for the definition of exceedance flows that are necessary for ranking decision options. The PROMETHEE II method enables the creation of a ranking based on positive and negative exceedance-flow values.

The PROMETHEE and PROMETHEE II methods found applications in disciplines such as urban planning and architecture, land management, logistics, healthcare, banking, and quality analysis in general [33,43–45]. Their area of application also includes sustainable development [46,47]. In her paper, Ogrodnik [48] applied the PROMETHEE method to evaluating sustainable-development indices of specific cities in Poland. Sustainable-development indices were also analyzed using the PROMETHEE method by Vivas et al. [49], who compared reports on sustainable development. Using the PROMETHEE method, Tsolaki-Fiaka et al. [32] explored scenarios to restore abandoned quarries, while Cerreta et al. [50] presented an adaptive decision-making process for creating a development strategy for the commercial port of Naples. These publications presented the applications of the PROMETHEE method in the context of sustainable development. Hermoso-Orzáez et al. [51] used the PROMETHEE method for assessing the competitiveness of public tenders.

## 3. Results

Analysis based on the PROMETHEE II method began with the selection of decision options. The following decision options were considered: jet grouting, jacked-down Franki Miga piles, root piles, and megapiles. During the initial classification phase, we eliminated all traditional methods (i.e., strengthening using coats, deepening and widening of foundations) because these methods were more likely to cause structural failure due to the need to perform an excavation; therefore, they were replaced by newer ones. The methods of foundation underpinning selected for analysis were compared on the basis of criteria that considered environmental, social, economic, construction, and technological conditions, that is, price, bearing capacity, noise and vibrations, necessary equipment, necessary

excavations under the final structure, failure rates, and necessary foundation shoring. Chosen criteria were related to sustainable development, minimizing potentially significant adverse effects on the environment and society in the future [50]. The authors extended sustainability criteria to include additional technological and constructional aspects [24].

Subsequently, a matrix was created to present the scores achieved by various decision options with respect to each criterion, with the appropriate weight attributed to these criteria (see Table 1). This served as a basis for calculating the value of differences between option pairs for each criterion. Ratings for options were allocated on the basis of a scoring scale (where the highest rating, five, meant a strong preference for one option over the other), while the bearing capacity of each option was measured in kN. Differences between option pairs were calculated using the following equation:

$$d_k(a^i, a^j) = f_k(a^i) - f_k(a^j) \tag{1}$$

**Table 1.** Scores for decision options.

| Decision Options (ai, j)                    | Jet Grouting | Franki Miga System | Root Piles | Megapiles | Weight |
|---|--------------|--------------------|------------|-----------|--------|
| Price                                       | 3            | 5                  | 3          | 5         | 0.05   |
| Bearing capacity                            | 1000         | 700                | 800        | 400       | 0.25   |
| Noise and vibrations                        | 5            | 5                  | 5          | 5         | 0.05   |
| Necessary equipment                         | 4            | 4                  | 5          | 3         | 0.15   |
| Necessary excavations under final structure | 5            | 3                  | 5          | 2         | 0.30   |
| Failure rate                                | 4            | 3                  | 4          | 4         | 0.10   |
| Necessary foundation shoring                | 5            | 3                  | 5          | 2         | 0.10   |
| Total                                       |              |                    |            |           | 1.00   |

The value of difference between scores demonstrated strength of preference for decision option with respect to a given criterion. Large difference demonstrated strong as not concluded by implementing our findings in real conditions, unlike that of Vuj preference for a given option, whereas small difference was a sign of weak preference or equivalence of decision options. The values of the preference function were then successively calculated in accordance with Equation (2).

$$G_k(d_k) = \begin{cases} 0, & \text{if } d_k \leq 0 \\ 1, & \text{if } d_k > 0 \end{cases} \tag{2}$$

The final phase of the PROMETHEE II method comprised the calculation of aggregated-preference indices in accordance with the following equation:

$$\pi(a^i, a^j) = \sum_{k=1}^n w_k G_k(a^i, a^j) \tag{3}$$

The following aggregated-preference indices (see Table 2) were calculated and used to calculate exceedance flows (see Table 3) using the following equations:

$$\varphi^+(a^i) = \frac{1}{m-1} \sum_{j=1}^m \pi(a^i, a^j) \tag{4}$$

$$\varphi^-(a^i) = \frac{1}{m-1} \sum_{j=1}^m \pi(a^j, a^i) \tag{5}$$

$$\varphi(a^i) = \varphi^+(a^i) \tag{6}$$

Table 2. Aggregated-preference indices.

| $\pi(a^i, a^j)$    | Jet-Grouting | Franki Miga System | Root Piles | Megapiles |
|--------------------|--------------|--------------------|------------|-----------|
| Jet grouting       | 0            | 0.750              | 0.250      | 0.8       |
| Franki Miga system | 0.05         | 0                  | 0.05       | 0.85      |
| Root piles         | 0.15         | 0.900              | 0          | 0.8       |
| Megapiles          | 0.050        | 0.100              | 0.000      | 0         |

Table 3. Exceedance flows.

| $\pi(a^i, a^j)$    | $\phi+$ | $\phi-$ | $\phi$ | Ranking Position |
|--------------------|---------|---------|--------|------------------|
| Jet grouting       | 0.450   | 0.063   | 0.388  | I                |
| Franki Miga system | 0.238   | 0.438   | -0.200 | II               |
| Root piles         | 0.463   | 0.075   | 0.388  | I                |
| Megapiles          | 0.038   | 0.613   | -0.575 | III              |

Graphical representation of exceedance flows is shown in Figure 1.

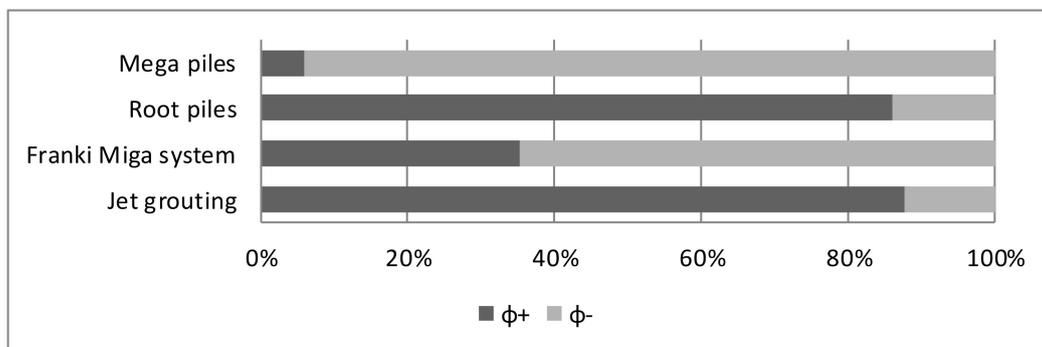


Figure 1. Graphical representation of exceedance flows (%).

After graphing results of the exceedance flow for each decision option, options with higher positive flows and smaller negative flows are represented in the upper-left corner of Figure 2. These methods of foundation underpinning were those that would obtain the best results according to applied criteria. In particular, the best options were jet grouting and root piles. Figure 3 graphically represents the best decision options for each criterion.

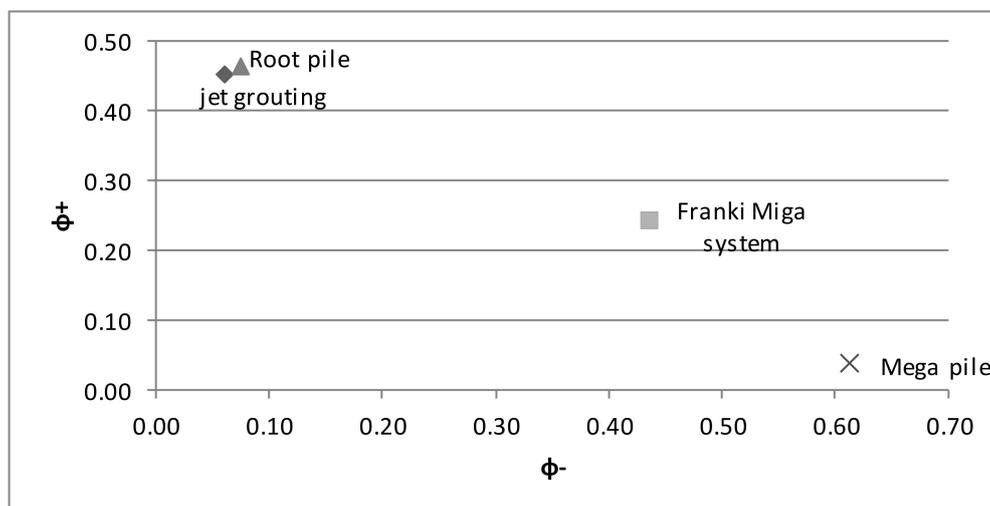


Figure 2. Analysis results.

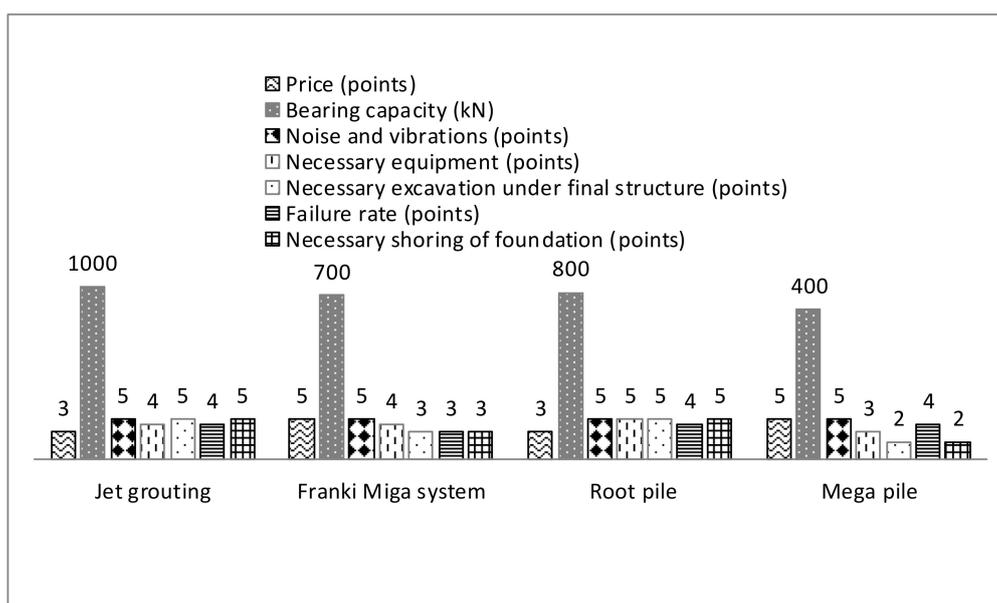


Figure 3. Case comparison.

#### 4. Discussion

Multicriteria methods are considered a powerful tool to help decision makers choose the best sustainable solution for a wide range of civil-engineering projects. Multicriteria analysis using the PROMETHEE II method was previously shown to be a solution worth implementing in the construction field [52–54]. The PROMETHEE II method provided an appropriate approach for assessing methods of foundation underpinning. Moreover, it is easy to use and commonly used to solve decision-making problems. Our analysis was not concluded by implementing our findings in real conditions, unlike that of Vujić et al. [55], who implemented their results. As in the work of Samani et al. [54], sustainability criteria, which were extended to include technological and constructional criteria, were applied. In their work, Palczewski et al. [56] also chose the PROMETHEE II method as a decision-support tool. In this example, the authors focused on examining the impact of various normalization methods on the obtained results. Results obtained using different normalization methods were disparate. In our work, we used only one normalization method. Therefore, in future studies, it would be of interest to use different normalization methods.

Jet grouting was characterized by the highest bearing capacity among the analyzed decision options (see Figure 3). Jet grouting and root piles did not require excavation and support for the foundation under the final structure. During the installation of foundation support via technologies such as jet grouting, root piles, and megapiles, emergencies rarely occurred. All assessed technologies were characterized by low vibration and noise levels. The characteristic feature of the Franki Miga system and megapiles was their relatively low price. The weak points of megapiles were their bearing capacity, the lowest among the analyzed solutions, as well as the necessity for shoring the foundation and excavating under the target structure. As a result of analysis, jet-grouting technology and root piles obtained the highest positions in the PROMETHEE-II-method ranking. The Franki Miga system and megapiles occupied the second-lowest and lowest positions, respectively.

#### 5. Conclusions

- Multicriteria decision-support methods have been applied in many fields, including sustainable development.
- Critical analysis of publications allowed us to identify various methods of foundation underpinning and uniform criteria for the assessment of decision options.

- The PROMETHEE II method enabled us to create a ranking of foundation-underpinning methods. The jet-grouting and root-pile methods were the highest scorers in this ranking, and the methods that fulfilled the identified criteria to the greatest extent. They were followed by Franki Miga piles and megapiles.
- This method is not suitable for demonstrating the relationship between a criterion and a decision option. Analysis was limited to a hierarchy of only the selected foundation-underpinning methods. In future research, it is of interest to extend this proposal to analysis of all available foundation-underpinning methods, and to apply more criteria, which could be grouped. It is also of interest to carry out analysis using other multicriteria methods, and compare the obtained results using several methods. In the second of these analyses, it is worthwhile to apply a separate criteria-weighting method because the current one is insufficient. The method could be based on expert analysis. Another aspect worth analyzing is specific objects and conditions.

However, the findings of this research could be a supporting tool for decision making, as they demonstrated the applications of the PROMETHEE II method in the construction field.

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