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Project management using the developed AHP–VIKOR method with the fuzzy approach

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ABSTRACT

There are many factors to consider when designing a sewerage pumping station (SPS), such as sizing the system, pump type, cooperation between pumps, SPS elevation, wastewater discharge location, system venting, correct number of inflows into the pumping station (PS) reservoir, and chemical resistance of the installations. In this study, we developed a multi-criteria-decision-making (MCDM) fuzzy AHP–VIKOR method with the aim to contribute to the improvement and development of MCDM methods. By combining and improving the existing AHP and VIKOR methods with the application of fuzzy logic theory, a novel fuzzy AHP–VIKOR method is for easier and clearer obtaining of optimal solutions. The new method was applied to obtain the findings in the analysis of four complex design solutions for canalisation, treatment, and pumping of atmospheric wastewater in the SPS in Makiš, an urban neighbourhood of Belgrade in Serbia. The analysis was carried out in relation to the stability of the solution by way of considering the use of different methods of MCDM optimisation, while taking into account ways of channelling, treatment, and evacuation of wastewater.

Key words: AHP, atmospheric wastewater, FUZZY, optimisation, VIKOR

HIGHLIGHTS

- AHP method
- VIKOR method
- Fuzzy approach
- From the previously mentioned methods and approaches, a new method was developed for multi-criteria optimisation and the selection of a design solution for the construction of the building by mathematically connecting and defining a new procedure.
- The new method is shown in the example of the designed sewage pumping station Makiš.

INTRODUCTION

In this study, the multi-criteria-decision-making (MCDM) AHP–VIKOR (analytical hierarchy process – multi-criteria optimisation and compromise solution; translated from Serbian) method with the fuzzy approach (hereinafter, fuzzy AHP–VIKOR) was developed for the purpose of solving complex project management problems. The method was developed based on the example of the ideal design and construction of the Makiš complex storm water pumping station (PS), which served as the objective function and was compared with AHP and VIKOR methods.

In the observed example, we have a complex problem; in that, it is necessary to obtain the optimal construction method, hydrotechnical solution, and project documentation for the construction of the Makiš PS.

The pipelines and manholes around the treatment and PS, which are required for the proper functioning of the system, as well as the pipeline from the PS to the recipient, were considered. The project outline is described as (translated from the Serbian version): DEVELOPMENT OF A PROJECT FOR THE CONSTRUCTION AND CONSTRUCTION OF A PUMPING STATION AND FACILITIES FOR THE TREATMENT AND DRAINAGE OF ATMOSPHERIC WATERS – Makiš (2020), Conceptual design, Institute for Water Management Jaroslav Černi, Belgrade. The storm water from the PS, Building 1, and from the separator is to be drained by gravity, through a pipeline, into the Strugara canal.

The analytical hierarchy process (AHP) method, like other MCDM methods (Alessio & Ashraf 2009; Athawale & Chakraborty 2010; Jaskowski *et al.* 2010; Kessili & Benmamar 2016), is used to prioritise risk factors in construction projects. The models (Pan 2008; Prascevic & Prascevic 2016, 2017) are used for the selection of the appropriate method of designing and constructing objects based on the fuzzy AHP, using triangular and trapezoidal fuzzy numbers (i.e., elements of fuzzy sets) employing the concept of an α cut. Prascevic & Prascevic (2016) considered the problem of choosing a structural system for the construction of an industrial hall, in accordance with the prescribed criteria.

The VIKOR method was developed to determine the MCDM optimal solution. The final decision is made by the decision-maker, who has a complex structure and an insufficiently expressed preference in the optimisation procedure (Opricović 2009; Milojkovic 2019; Abbas *et al.* 2023; Anđić & Đurović 2023; Çaloğlu Büyükselçuk & Sarı 2023; Erdebilli *et al.* 2023; Lei *et al.* 2023; Mohamad Sharaf 2023; Pramanik & Dalapati 2023; Tuskan & Basari 2023; Yang & Chen 2023; Zhang *et al.* 2023; Zhao *et al.* 2023). The capabilities of the AHP–VIKOR method have been used in various studies (Akmaludin Suriyanto *et al.* 2023; Meni̇z & Özkan 2023; Özekencia 2023). Meni̇z & Özkan (2023) used this method for vaccine selection in the COVID-19 pandemic, plus the AHP method, and a novel VIKOR hybrid approach. Özekencia (2023) used the AHP–VIKOR integrated methodology for identifying the key success factors of e-logistics in Türkiye. Akmaludin Suriyanto *et al.* (2023) present the decision support system for smart phone selection with AHP–VIKOR method recommendations.

In brief, the AHP method gives the possibility of explaining the importance of some criteria in relation to others, while the VIKOR method allows for wide possibilities of using weighting coefficients for criteria and compromise solutions. Further, fuzzy logic theory gives the possibility of a better description of the input data. To the best of our knowledge, the newly presented relations and connections of all previously mentioned methods and approaches in this work make a great contribution to a finer and clearer determination of the optimal solution.

METHODS

The goal of fuzzy logic theory is to give mathematicians a way in which to deal with the uncertainty and imprecision that are inherent in human cognitive processes, such as thinking and reasoning (Bennajeh & Ben Said 2022). Humans typically use words (i.e., qualitative method) rather than numbers (i.e., quantitative approach) to solve problems in daily life. The desire to establish a foundation for word counting with the goal of using a qualitative approach to solve problems, such as decision-making under uncertainty, handwriting and shape recognition, scene analysis, modelling of complex systems, management systems, etc. led to the development of fuzzy sets theory and fuzzy logic theory. Two-valued logic theory and traditional set theory cannot be applied, simply or even generally, because of the inherent inaccuracies of language.

As words mostly represent granular data (i.e., a kind of summarisation – compression of quantitative data), there are immanent inaccuracies in the sense of overlapping parts of the different meanings of different words. Therefore, classical set theory, which implies that an element belongs or does not belong to the observed set without any finer gradation, as well as two-valued logic theory, where a logical statement is either true or false, represents an inadequate basis for formalising approximate reasoning, and treating relations based on linguistic variables, in the general case. Fuzzy logic provides a morphology of inference, which allows it to be applied in knowledge-based systems, thus emulating the ability of approximate human reasoning. Technologies in fuzzy information processing tend to connect human experience and knowledge, expressed linguistically, with the treatment of numerical data based on mathematics.

A generalisation and a form of relaxation of classical set theory and classical logic theory can be seen in the fuzzy method. In the fuzzy approach, which was first published in 1965 in the brilliant work of Lotfi Zadeh from Berkeley, CA, USA, the fundamental innovation, and at the same time, the difference from classical set theory lies in the fact that in fuzzy sets, the elements belong to a set with different degrees of belonging (from 0 to 1), and fuzzy logic rests on higher value judgments. Because of the fact that the definition of judgments depends on a clear 'yes'/ 'no' judgment, which signifies belonging or not belonging, ordinary sets do not deal with ambiguity.

The efficiency of the fuzzy approach, from the point of view of application, rests on the relaxation of the level of aspiration regarding the quality of the solution. Namely, with the fuzzy approach, a satisfactory solution to the analysed problem is sought first and foremost, instead of the correct or the best solution. The fuzzy approach, with its tolerant attitude towards inaccuracies, indeterminacy, and partial truths, enables the expansion of the application domain in relation to classical approaches. Thus, by relaxing the accuracy requirements, then simplicity, economy, and robustness of the solution are achieved. Further, artificial neural networks (ANNs), and other models, also govern the learning of the connection between the input and output variables (Erzin & Tuskan 2017; Yildizel *et al.* 2017; Erzin & Tuskan 2019; Tuskan & Erzin 2024).

The author of fuzzy sets theory and fuzzy logic theory does not miss the opportunity to point out the basic results, upon which the success of applying the fuzzy approach is based: linguistic variable, if – then rules, fuzzy graph – functional dependence of linguistic variables.

The fuzzy approach is not a competition, but rather it is a complement to the stochastic approach to treating uncertainty and, therefore, to treating uncertain demand. Fuzzy representation of demand can be realised in two ways: firstly, based on the subjective assessment of experts, and secondly, by mapping the distribution of probability into the distribution of possibilities.

AHP method with the fuzzy approach

In the present study, the method of AHP and fuzzy logic theory was used in MCDM optimisation in the selection of the construction method.

Jaskowski *et al.* (2010) proposed an extended fuzzy AHP method for evaluating the weight of contractor selection criteria, in accordance with the Polish Public Procurement Act, which is harmonised with the European Union (EU) guidelines on the subject. Taylan *et al.* (2014) used the fuzzy AHP and fuzzy TOPSIS (Technique for Order Preference by Similarities to Ideal Solution) methods for construction project selection and risk assessment. Prascevic & Prascevic (2016) discussed the problem of choosing a constructive system for the construction of an industrial hall, in accordance with the prescribed criteria. Polat (2016) proposed an integrated decision-making approach, which uses AHP and PROMETEE (Preference Ranking Organization Method for Enrichment Evaluation; a decision-making tool) together for the subcontractor selection problem. Del Cano *et al.* (2016) presented a method for uncertainty analysis in the sustainable design of concrete structures. This method is based on requirement trees, value analysis, and AHP.

The approximate approach of the AHP method with fuzzy approach is used in finding the optimal solution for the application of the method and technology of construction works. Using the method of AHP, a model can be formed in four stages (Misita 2022):

- Structuring the problem
- Data collection
- Evaluation of relative weights
- Determining the solution to the problem.

The first stage consists of decomposing any complex decision-making problem into a series of hierarchies – alternatives, where each level represents a smaller number of manageable attributes – criteria. These are then decomposed into another set of elements, corresponding to the next level, etc. Such hierarchical structuring is an effective way of dealing with the complexity of real problems and identifying significant attributes, in order to reach the overall goal of the problem.

VIKOR method with the fuzzy approach

The considered system was processed using the VIKOR (MCDM Compromise Solution or MCDM Compromise Ranking) method – it was developed to determine the MCDM optimal solution. There is a possibility of applying the VIKOR method with the fuzzy approach, compared to the combined AHP method with the fuzzy approach. For the purposes of applying the VIKOR method, a different evaluation of alternatives is necessary, in relation to the criteria using the fuzzy approach.

The VIKOR method was developed on such methodological grounds that the decision-maker is offered an alternative (or solution) that:

(a) offers a compromise between wishes and possibilities,
(b) exemplifies a compromise between the various interests of the participants in the decision-making process.

In MCDM optimisation, desires are represented by criteria, and possibilities are represented by constraints. In the task of MCDM decision-making, the criteria are explicitly given, while the constraints are implicitly contained in the admissibility of alternatives because all alternatives from set A must satisfy all constraints ($g(x) \leq 0$ in classical optimisation). The admissibility of alternatives is tested during the generation of those alternatives. At present, when planning large systems, a compromise solution in the form of a permanent solution is sought.

A permanent (sustainable) solution to the development of the economic system, for example, is based on the consideration of the interaction of the planned system with nature, and the social environment under current and future long-term conditions. The basis for decision-making consists of scenarios of possible future changes, and not only of parameters that are directly related to the system's resources, but also of environmental conditions, and socio-economic conditions, as well as the social evaluation system. When determining a permanent solution, conditions, and effects with 'medium and low possibilities of occurrence' should be considered. A sustainable solution represents a compromise between using and degrading resource sources, as well as between using resources 'for now' and 'conserving resources for the future'. The basic feature of a permanent solution is that it should also be flexible to meet future requirements. The previous principle of optimality is expanded to include the principle of flexibility, but the problem remains within the framework of MCDM optimisation.

The proposed solution (i.e., alternative) has a high probability of being accepted as a good compromise between the different conflicting interests of decision-making participants if it:

- is supported by the majority of those parties involved in the decision-making process,
- it does not have sufficiently poor criterion indicators to provide opponents; thus, compelling any justifications for rejecting the solution.

Formulas for determining measures *S*, *R*, and *Q*

The above two conditions are covered by measures S and R in the compromise ranking, because according to measure S, the best alternative that most (sum) satisfies the criteria is determined, while according to measure R, the alternative that is not significantly bad, according to some criterion, is determined (i.e., maximum dissatisfaction of criteria is minimised). When determining a compromise, the ideal point can be used as a reference point in the space of criteria functions, if the decision-maker does not have a pessimistic attitude in relation to reaching ideal values. In most cases, the decision-maker can accept a compromise in relation to the ideal point, and this also indicates the justification for developing the VIKOR method, based on the ideology of compromise programming.

Expression of preference by certain criteria was effected by assigning weights to criterion functions. The weights of the criteria do not have a clear economic meaning, but rather they represent measures for the introduction of the relative importance of the criteria. Normalised weight values are used where $\Sigma\omega_i = 1$, $\omega_i \geq 0$. However, non-normalised values in the form of whole numbers, or amounts in percentages (of the whole sum) are used to view the relative weights. The percentage value of the weight of one criterion indicates the part of the total preference that is associated with that criterion.

Compromise: The VIKOR method proposes a multi-criterion best alternative (for the given weights ω_i), with the weight that is in the first position on the compromise ranking list for $v = 0.5$, being there only if it has i:

- a sufficient advantage over the alternative from the next position (condition U1),
- a sufficiently firm first position with weight change v (condition U2).

Solving the task of MCDM optimisation is a complex process of reaching the final solution and includes the following activities:

1. Studying and formulating the problem
2. Studying the system and generating alternatives
3. Defining the criteria
4. Evaluating alternatives
5. Applying the VIKOR method (or other methods)
6. Analysing preferential stability
7. Proposing the final solution and final project
8. Implementing the optimisation

At the decision-making level, the actor is the decision-maker, and at the technical level, the actor is the technical expert or problem solver, and the actor is usually an engineer, whose role is specifically discussed in the collection of works; hence, the role of the engineer will be more clear.

AHP–VIKOR method with the fuzzy approach

The AHP–VIKOR method with the fuzzy approach (fuzzy AHP–VIKOR) is used to determine the MCDM optimal solution. The final decision is made by the decision-maker, who has a complex structure and an insufficiently expressed preference in the optimisation procedure.

The fuzzy AHP–VIKOR method (Opricović 2009; Milojkovic 2019; Abbas *et al.* 2023; Anđić & Đurović 2023; Çaloğlu Büyükselçuk & Sarı 2023; Erdebilli *et al.* 2023; Lei *et al.* 2023; Mohamad Sharaf 2023; Pramanik & Dalapati 2023; Tuskan & Basari 2023; Yang & Chen 2023; Zhang *et al.* 2023; Zhao *et al.* 2023) requires that the values of the criterion functions are known, and that a matrix is formed for all alternatives:

$$|f_{ij}|_{nxJ} \tag{1}$$

where i is the ordinal number of criteria $i = 1, \ldots, n$, and j is the serial number of the variant $j = 1, \ldots, J$.

The method was developed based on elements from compromise programming, starting from boundary forms L_p-metrics.

For standardising point deviation $F(x)$ from the ideal point, the F^* L_p metric is used, defined by the relation:

$$L_p(F^*, F) = \left[\sum_{i=1}^{n} (f_i^* - f_i(x))^p\right]^{1/p}, \quad 1 \leq p \leq \infty \tag{2}$$

where parameter p plays the role of a balancing factor between the total benefit and the maximum individual deviation. As the parameter p increases, the total benefit decreases, but the maximum individual deviation from the ideal point also decreases. Measures of deviation from the ideal point, depending on parameter p, for the j-th variant look like this:

- Measure of satisfaction of most criteria

$$S_j = \sum_{i=1}^{n} \omega_i \frac{f_i^* - f_{ij}}{f_i^* - f_i^-} \quad (p = 1) \tag{3}$$

$$f_i^* = \max_j f_{ij} \quad f_i^- = \min_j f_{ij} \tag{4}$$

(if its f_i criterion function is maximised)
where f_{ij} is the value of the i-th criterion functions for the j-th variant, ωi is the weight i-th on the criterion functions, i is the ordinal number of criteria $i = 1, ..., n$, and j is the serial number of the variant $j = 1, ..., J$.

- Minimum individual deviation

$$R_j = \max_i \omega_i \frac{f_i^* - f_{ij}}{f_i^* - f_i^-} \quad (p = \infty) \tag{5}$$

Measures S_j and R_j are a ranking list for variants as determined by a_j.

The ranking lists obtained in this way differ; hence, a procedure for evaluating the variants according to a unique criterion is required. The task is reduced to two criteria, with criteria S_j and R_j, where size is adopted as the ranking measure Q_j:

$$Q_j = v\frac{S_j - S_j^*}{S^- - S^*} + (1 - v)\frac{R_j - R_j^*}{R^- - R^*} \quad ; \quad j = 1, \ \ldots, \ J \tag{6}$$

$$R^- = \max_j R_j \qquad S^- = \max_j S_j \tag{7}$$

$$R^* = \min_j R_j \qquad S^* = \min_j S_j \tag{8}$$

where v is the weight of the strategy to satisfy most of the criteria.

$$QR_j = \frac{R_j - R_j^*}{R^- - R^*} \qquad \mathrm{QS}_j = \frac{S_j - S_j^*}{S^- - S^*} \tag{9}$$

$$Q_j = v\mathrm{QS}_j + (1 - v)QR_j \tag{10}$$

$$Q_j = v(QS_j - QR_j) + QR_j \quad \Rightarrow \quad Q_j \text{ is a linear function of weight } v \tag{11}$$

with coefficient v, it is possible to influence the choice of the strategy of satisfying most of the criteria:

$v > 0.5$ – when one wishes to give preference to the satisfaction of many criteria,
$v < 0{,}5$ – if no great dissatisfaction of any criterion is allowed.

The VIKOR method introduces a modified measure R_j, so that on value R_j a size value r_j is added, which is determined based on the relationship:

$$r_j = \frac{(\mathrm{S}_j - R^-)}{100} \;\; ; \;\; j = 1, \; \ldots, \; J \tag{12}$$

This modified value is only used for cases where $R_j = R^-$ for multiple indexes j (variants), to enable ranking by R_j for cases when $R_j = 1$ for every j (which can occur when the values are equal to and $n < J$).

In cases where values R_j are mutually different, the specified modification is not used. R^* is the unmodified value.

Basic algorithmic steps of the method:

1. Determination of the ideal point based on the value of the criterion function.

$$f_i^* = ext_j f_{ij} \; ; \; i = 1, \; \ldots, \; n \tag{13}$$

where *ext* denotes the maximum if the i-th criterion function represents the benefit or profit, or the minimum for damages or costs. The ideal point can be specified by the decision-maker by specifying the ideal values of the criterion functions as satisfaction levels. If the decision-maker sets the ideal point without first determining the allowable value intervals of the criterion functions, one of the following two unfavourable situations may occur:

- The ideal point is far above the admissible set, or there is no connection between the ideal point and the admissible set, thus introducing a subjective influence on the compromise solution,
- The given ideal point can be in the admissible space of criterion functions, so that the obtained compromise solution can be inferior.

2. Transformation of heterogeneous criterion functions into dimensionless functions with a range in the interval [0,1]. In many cases, the values of criterion functions are not expressed in the same units of measure; that is, there are diverse criterion functions (heterogeneous criterion space). In order to use the compromise ranking metric in those cases, a certain transformation is introduced, which is achieved by dividing by the length of the range (the length of the value interval) of the criterion function:

$$d_{ij} = \frac{f_j^* - f_{ij}}{f_i^* - f_i^-} \; ; \; i = 1, \; \ldots, \; n \; ; \; j = 1, \; \ldots, \; J \tag{14}$$

The introduction of this transformation involves the assumption of linear dependence between the criterion function f_i and the general benefit achieved by satisfying the corresponding criterion, as well as the assumption that the ranges of the criterion functions are comparable from the point of view of the benefit achieved.

3. Calculation of the criteria weight vector ω_{i} – they represent the preferences of the decision-maker. Determination of weights was made using AHP algorithms for determining weights. The method uses normalised weight values:

$$\sum \omega_i = 1, \quad \omega_i \geq 0 \tag{15}$$

In order to determine the weights for the various criteria, one starts by creating a matrix comparing criteria $\boldsymbol{A}$. Matrix $\boldsymbol{A}$ is a matrix $m \times m$, where m is the number of considered criteria. Every entry a_{jk} in matrices $\boldsymbol{A}$ represents the importance of the j-th criterion in relation to the k-th criterion and is termed the intensity of importance (significance) of the criterion. If it is

$a_{jk} > 1$, then it is the j-th criterion that is more important than the k-th criteria, and if it is $a_{jk} < 1$, then it is the j-th criterion that is less important than the k-th criteria. If two criteria have the same importance, then it is $a_{jk} = 1$. Criteria significance intensities a_{jk} and a_{kj} meet the following constraint:

$$a_{jk} \cdot a_{kj} = 1 \quad (16)$$

It is obvious that $a_{jj} = 1$ for every j. The relative importance between the two criteria is measured according to a numerical scale from 1 to 9, where it is assumed that the j-th criterion is equal to or more important than the k-th criterion. The explanations in the interpretation are only suggestive and can be used to translate the qualitative ratings of the relative importance between the two criteria, which is made by the decision-maker, and represented by numbers. It is also possible to assign mean values that do not correspond to a precise interpretation. On the other hand, ratings can generally show slight inconsistencies. However, they do not create serious difficulties for the applied method.

4. Assigning weight v – this depends on the procedure for making the final decision. If it is decided by a majority of votes that $v = 0.9$ or $v = 1.0$ if certain DMs (decision-makers) represent certain criteria, and if there is a veto right. In the VIKOR method, $v = 0.5$ is often used.
5. Determining S_j, R_j, Q_j, $j = 1, \ldots, J$ is pursued in accordance with the following relations:

$$S_j = \sum_{i=1}^{n} \omega_i \frac{f_i^* - f_{ij}}{f_i^* - f_i^-} \quad (p = 1) \quad (17)$$

$$R_j = \max_i \omega_i \frac{f_i^* - f_{ij}}{f_i^* - f_i^-} \quad (p = \infty) \quad (18)$$

$$f_i^* = \max_j f_{ij} \qquad f_i^- = \min_j f_{ij} \quad (19)$$

$$Q_j = v \frac{S_j - S_j^*}{S^- - S^*} + (1 - v) \frac{R_j - R_j^*}{R^- - R^*} \quad ; \quad j = 1, \ldots, J \quad (20)$$

$$R^- = \max_j R_j \qquad S^- = \max_j S_j \quad (21)$$

$$R^* = \min_j R_j \qquad S^* = \min_j S_j \quad (22)$$

6. Ranking – this is achieved by sorting the alternatives according to the values of the measures QS, QR, or Q.

$$QR_j = \frac{R_j - R_j^*}{R^- - R^*} \qquad QS_j = \frac{S_j - S_j^*}{S^- - S^*} \quad (23)$$

$$Q_j = vQS_j + (1 - v)QR_j \quad (24)$$

The best alternative is where the value of the measure is minimal, and it ranks first in the ranking list.

7. Compromise solution – the fuzzy AHP–VIKOR method is proposed as the best MCDM variant (for given weights ω_I), regarding the variant that is in the first position on the compromise ranking list for $v = 0.5$, but only if it has the following characteristics:

- Sufficient advantage over the alternative from the next position (condition U1)
- Sufficiently stable first position with weight change v (condition U2)

Condition U1

The difference between the measures is used to evaluate the advantage Q_i for $v = 0.5$. Alternative *a'* has sufficient advantage over the next a'' from the ranking list if it is:

$$Q(a') - Q(a'') \geq DQ \tag{25}$$

$$DQ = \min\left(0.25; \frac{1}{J - 1}\right) \tag{26}$$

where DQ is the advantage threshold, which is determined based on the theoretical value Q.

With 0.25, the threshold is limited for cases with a small number of variants. If the first variant from the compromise ranking list does not meet the priority condition, it is considered that it is not sufficiently better than the variant in the next position.

Condition U2

The first alternative in the compromise ranking has a sufficiently stable first position if one of the following conditions is met:

- it has the first position in the Q ranking for $v = 0.25$ and $v = 0.75$.
- it has the first position in the ranking according to QS.
- it has the first position in the ranking according to QR.

If the first-position alternative from the Q list does not meet conditions U1 and U2, then it does not have sufficient advantage over the second-position alternative; hence, a set of compromise solutions is formed, in which the first-position alternative and the alternative behind it enter into that set.

If the first alternative from the Q list does not meet the condition U2, only the next alternative from the Q list enters the set of compromise solutions.

If the first alternative from the Q list does not meet the condition U1, the set of compromise solutions contains alternatives from the Q list $a^{'}_{,}\ a^{''}_{,...,}\ a^{(k)}$, for which it is:

$$Q(a^{(k)}) - Q(a') < DQ \tag{27}$$

8. Determining the stability interval – by analysing the weights and preferential stability of the compromise solution, MCDM decision-making is facilitated, because the decision-maker avoids the requirement to precisely set the weights of the criteria.

The weight with the i-th criterion function changes in relation to the given initial value, and the weight ratio of the other criterion functions remains unchanged.

The interval in which the weight of the criteria can be changed, so as not to change the compromise solution, is considered. That interval is the stability interval for most of the i-th criterion.

The same process can be undertaken for a subset of criteria.

The fuzzy approach refers to the application of triangular fuzzy numbers, described below, and shown in Figure 1, that were used to define the criteria values for certain alternatives.

Parametric presentation of the triangular fuzzy number (hereinafter, fuzzy number) $A(\alpha)$ with level α:

$$A(\alpha) = [A_l(\alpha), A_u(\alpha)], \tag{28}$$

$$A_l(\alpha) = a_l + (a_m - a_l)\alpha,$$

$$A_u(\alpha) = a_u - (a_u - a_m)\alpha, \tag{29}$$

$$0 < \alpha \leq 1 \qquad a_l \leq a_m \leq a_u.$$

Since the alternatives and criteria were evaluated using fuzzy numbers shown in Figure 2, Table 1 shows the ratio of the rating according to the Saaty scale and the value of the fuzzy number of the evaluation of criteria and alternatives.

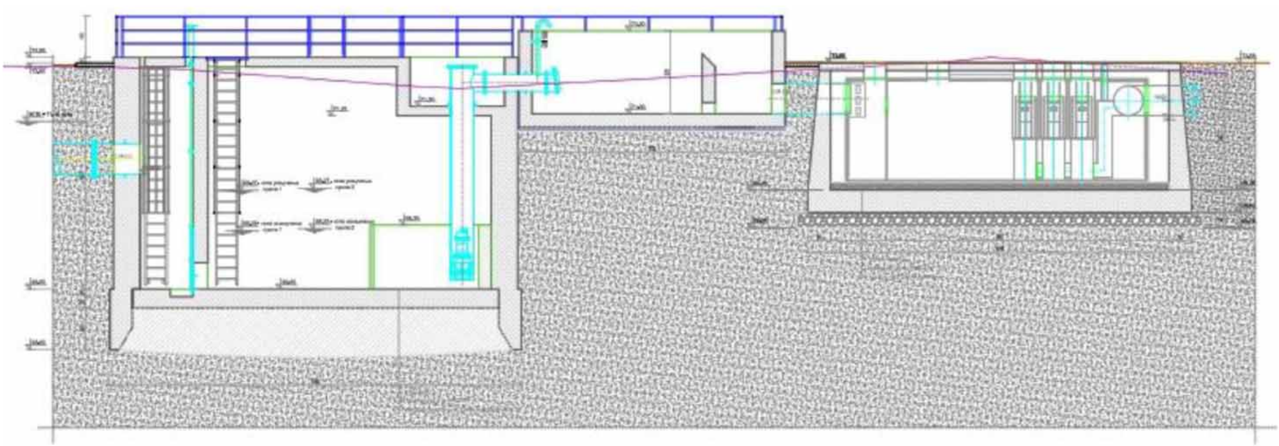

Figure 1 | The Makiš complex – Makiš sewerage pumping station (SPS) – longitudinal section.

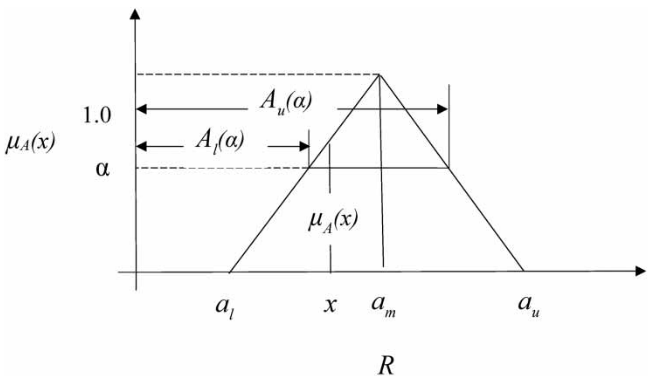

Figure 2 | Triangular fuzzy number (elements of fuzzy sets – fuzzy number) with the concept of an α cut $A(\alpha)$.

Table 1 | Rating scale for measuring the mutual importance of criteria or alternatives

Rating	Fuzzy number	Rating	Reciprocal fuzzy number	Linguistic value
1	(0.5, 1, 1.5)	1^1	(1/1.5,1/1,1/0.5)	Equally significant
3	(2.5, 3, 3.5)	3^1	(1/3.5,1/3,1/2.5)	Slightly significant
5	(4.5,5, 5.5)	5^1	(1/5.5,1/5,1/4.5)	Very significant
7	(6.5,7, 7.5)	7^1	(1/7.5,1/7,1/6.5)	Very significant
9	(8.5, 9, 9.5)	9^1	(1/9.5,1/9,1/8.5)	Absolutely significant
2, 4, 6, 8 mean values				

RESULTS AND DISCUSSION

System description

In the analysis, alternative solutions for the treatment of storm water for the Makiš complex, the pipelines and the shafts around the treatment and PS were considered, shown in Figures 3 and 4. Specifically, this paper analyses the design and execution of the Makiš PS facility, and the pipeline from the PS to the recipient location – the Strugara canal. The PS building has a rectangular base, with dimensions 5.4 × 10.9 m and a total height of 7.75 m. It was dug up to an elevation of 65.05 m above sea level (ASL) and was found in a layer of sand and gravel. There are two variants for the designing and building of a PS:

Figure 3 | Research methodology showing the circle flow chart for the fuzzy AHP–VIKOR method.

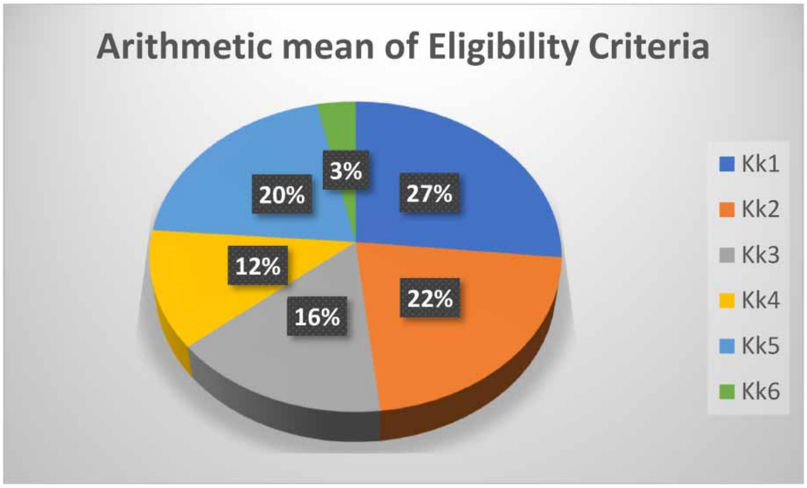

Figure 4 | Evaluations of the arithmetic mean of eligibility criteria.

A1 – Variant 1 – in this alternative solution, the alternative implies the execution of the PS in an open excavation with a spout at a right angle to the axis of the channel.

A2 – Variant 2 – in this alternative solution, the alternative implies the execution of the PS in an open excavation with a spout at an angle in relation to the axis of the channel.

A3 – Variant 3 – this alternative envisages that the PS is constructed as an open caisson – a well with a spout at a right angle to the axis of the channel.

A4 – Variant 4 – this alternative envisages that the PS is designed as an open caisson – a well with a spout at an angle in relation to the axis of the channel.

The well is lowered by undermining without pumping water when lowering to the designed elevation. To lower the well, it is necessary to form a working plateau.

After the completion of lowering the well, it is necessary to concretise the pillow (plug), which is made of non-reinforced waterproof concrete, with compressive strength class C25/30. The next stage is the execution of the foundation of the reinforced concrete slab, with constant pumping of water from the well. After that, all the other parts of the structure (foundation slab, secondary concrete, walls, and top slab, made of non-reinforced secondary concrete) are constructed.

The maximum designed flow of SPS Makiš is approximately 800 L/s.

Alternatives are evaluated based on the following criteria:

- K1 Impact of excavation on existing buildings.
- K2 Impact on existing infrastructure lines.
- K3 Impact on the occupancy of the building plot by excavation.
- K4 Impact of construction works on the work of the Makiš Drinking Water Treatment Plant.
- K5 Influence of underground water on execution.
- K6 Influence on the weight of the object.

K1 – The impact of excavation on existing buildings includes the size of the excavation, and the type of excavation – whether it is an open excavation, an excavation with a substructure, or an excavation below the groundwater level, depending on the chosen design solution. The aim is to undertake as little excavation as possible above the groundwater level or to use techniques such as well construction where the use of subgrades is not required. The type and method of excavation greatly influence the way buildings are constructed, and this criterion has a great influence on the preparation of project documentation, and the future construction of buildings.

K2 – The impact on existing infrastructure lines implies problems with crossing and displacement of existing lines, which in the observed system of buildings and equipment represents an exceptional problem. In addition to the crossing with the main water pipeline Ø1500, whose purpose is to supply the City of Belgrade with drinking water, there is also the external service ring of the Makiš Drinking Water Treatment Plant Ø500, the damage and interruption of which would cause the interruption of the entire Makiš Drinking Water Treatment Plant and the interruption of the water supply to consumers in an area of the City of Belgrade, with approximately 2,000,000 inhabitants. This criterion is of critical importance for the functioning of the entire water supply system, and it has a decisive influence on the preparation of project documentation, and the future construction of facilities. If the aforementioned infrastructure is damaged, the water supply system will be interrupted, which must not be allowed under any circumstances.

K3 – The impact on the occupation of the building plot by the excavation is important. The work is carried out in the vicinity of the water supply facilities of national importance; hence, it is desirable to disturb the contents as little as possible in the observed primary zone of sanitary protection. Excessive occupation of the plot on which buildings are being constructed is also not allowed. The functioning of the existing facilities must be enabled. This is a very important criterion.

K4 – The impact of construction work on the work of the Makiš Drinking Water Treatment Plant implies the aspiration to minimise the disturbance of the subject plant during the delivery of construction materials and equipment, as well as during the operation of construction machines for the construction of the target sewage pipelines and sewage pumping station (SPS). The supply of drinking water must not be disturbed in any way by construction works. This criterion is very important for all activities from research works and design documentation to the completion of construction of future facilities.

K5 – The impact of underground water on the performance can be significant due to the proximity of the Sava River and the level of underground water at the location is directly dependent on the level of the Sava River. For a more complete overview of the hydrogeological characteristics of the wider area of the investigated terrain, a series of piezometers were installed at different distances, which have the task of registering the free levels of underground water, and their uninterrupted monitoring over a longer period of time. From the data taken from piezometer measurements for the period of 2000–2019, the maximum level of underground water was recorded, which is higher than the elevation of the terrain and is 75.65 MASL. For flotation control, the safety coefficient would be greater than 1.0, which means that floatation safety can be considered to be satisfactory. The adopted working level is the average value of the 20-year water, which is 71.1 MASL. During the geotechnical investigations, the underground water level was determined to be at a depth between 6 and 7 m, or approximately at an altitude of 65.0 MASL. The work is designed in the drinking water source zone where underground water is used. Absolutely no negative impact on groundwater is allowed.

K6 – The impact on the weight of the object can be significant because the well construction requires a greater weight of the structure, so that it can go to the designed depth during successive excavation. This implies a larger amount of embedded concrete and reinforcement, which increases the cost of execution, and makes it more difficult to deliver building materials. This criterion has a very significant impact on the operation of the construction of buildings.

AHP method with fuzzy approach

Alternatives are evaluated based on criteria that are often used in such analyses (Jevtic *et al.* 2011; Milojkovic *et al.* 2016a, 2016b; Milojkovic & Romanović 2018; Milojkovic 2019). There are six criteria in total. The criteria and the alternatives are described in the previous section, and these were chosen. If sewerage facilities are well designed and constructed, virtually the only maintenance required is the occasional cleaning of conduits (Jevtic *et al.* 2011). Evaluation of alternatives is carried out according to the above criteria functions, which can be expressed in the form of quantitative economic indicators, technical indicators, or quantitative and qualitative indicators (Milojkovic *et al.* 2016a). A good choice of alternatives and criteria greatly affects the optimisation result. It is crucial for the owner (Zhu *et al.* 2020) of a construction project to select an appropriate project delivery system (PDS), during the early decision-making stages of the project. Due to project uncertainty or a lack of project information, the parameters of a PDS are difficult to measure and quantify (Zhu *et al.* 2020); hence, a systematic decision-making model is used to select the appropriate PDS by using the combination of case-based reasoning (CBR) and a robust nonparametric production frontier method. In this research, in accordance with previous research, alternatives and criteria were carefully chosen, and the novel fuzzy AHP–VIKOR method that was developed in the present study was used to describe and explain the alternatives in relation to the criteria, in order to choose the optimal solution.

The second phase begins with data collection and the measurement of those data. The rater or evaluator will then assign relative scores in pairs of attributes of one hierarchical level, for given attributes of the next higher hierarchical level. The same process is repeated for all levels of the entire hierarchy. The most famous scale with nine points for assigning weights – the Saaty scale is given below, and its application in solving real problems has proven to be extremely reliable (Saaty 1972; Zhu *et al.* 2020).

The Saaty nine-point scale:
9 – The absolute most significant/preferred
8 – Very strongly important to most significant
7 – Very strongly important
6 – Strongly important to very strongly important
5 – Strongly important
4 – Weakly important to strongly important (i.e., no firm decision)
3 – Weakly important
2 – Equally important to weakly important
1 – Equally important/desirable.

The fuzzy approach is used to define the criteria values for certain alternatives.

Since the alternatives and criteria in this study were evaluated using fuzzy numbers, Table 1 shows the ratio of the rating according to the Saaty scale and the value of the fuzzy number of the evaluation of criteria, and alternatives.

In the third phase, the concrete values of the criteria for different alternatives are entered, and the relative weights of both the criteria themselves and the alternatives according to individual criteria are evaluated by calculating the assessment matrices.

Evaluating the weights of the criteria that exist as $n = i$, in this case, $n = 6$ is carried out through the matrix of criteria:

$$\tilde{K} = \begin{bmatrix} K_{11} & \cdots & K_{1i} \\ \vdots & \ddots & \vdots \\ K_{i1} & \cdots & K_{ii} \end{bmatrix}, \tag{30}$$

in which the importance of the criteria is determined in a mutual comparison, and at the end, the final weight of the criteria is arrived at via the sums in the column values, and the division of individual values by the sum of the columns and their addition by rows.

Criteria evaluation fuzzy values:

$$\tilde{K} = \begin{bmatrix} (1,1,1) & (4.5,5,5.5) & (4.5,5,5.5) & (2.5,3,3.5) & \left(\frac{1}{7.5},\frac{1}{7},\frac{1}{6.5}\right) & (0.5,1,1.5) \\ \left(\frac{1}{5.5},\frac{1}{5},\frac{1}{4.5}\right) & (1,1,1) & (0.5,1,1.5) & (6.5,7,7.5) & (6.5,7,7.5) & (4.5,5,5.5) \\ \left(\frac{1}{5.5},\frac{1}{5},\frac{1}{4.5}\right) & \left(\frac{1}{1.5},\frac{1}{1},\frac{1}{0.5}\right) & (1,1,1) & (4.5,5,5.5) & (0.5,1,1.5) & (8.5,9,9.5) \\ \left(\frac{1}{3.5},\frac{1}{3},\frac{1}{2.5}\right) & \left(\frac{1}{7.5},\frac{1}{7},\frac{1}{6.5}\right) & \left(\frac{1}{5.5},\frac{1}{5},\frac{1}{4.5}\right) & (1,1,1) & (6.5,7,7.5) & (4.5,5,5.5) \\ (6.5,7,7.5) & \left(\frac{1}{7.5},\frac{1}{7},\frac{1}{6.5}\right) & \left(\frac{1}{1.5},\frac{1}{1},\frac{1}{0.5}\right) & \left(\frac{1}{7.5},\frac{1}{7},\frac{1}{6.5}\right) & (1,1,1) & (8.5,9,9.5) \\ \left(\frac{1}{1.5},\frac{1}{1},\frac{1}{0.5}\right) & \left(\frac{1}{5.5},\frac{1}{5},\frac{1}{4.5}\right) & \left(\frac{1}{9.5},\frac{1}{9},\frac{1}{8.5}\right) & \left(\frac{1}{5.5},\frac{1}{5},\frac{1}{4.5}\right) & \left(\frac{1}{9.5},\frac{1}{9},\frac{1}{8.5}\right) & (1,1,1) \end{bmatrix} \tag{31}$$

Score according to the Saaty scale based on the fuzzy values:

$$\tilde{K} = \begin{bmatrix} 1 & 5 & 5 & 3 & \frac{1}{7} & 1 \\ \frac{1}{5} & 1 & 1 & 7 & 7 & 5 \\ \frac{1}{5} & 1 & 1 & 5 & 1 & 9 \\ \frac{1}{3} & \frac{1}{7} & \frac{1}{5} & 1 & 7 & 5 \\ 7 & \frac{1}{7} & 1 & \frac{1}{7} & 1 & 9 \\ 1 & \frac{1}{5} & \frac{1}{9} & \frac{1}{5} & \frac{1}{9} & 1 \end{bmatrix} \tag{32}$$

For the different alternatives that are $m = j$, in this case $m = 4$, their evaluations are given based on individual criteria and also based on a mutual comparison of alternatives according to individual criteria. The evaluation matrices are for each alternative j according to criteria i:

$$\tilde{A} = \begin{bmatrix} A_{11} & \cdots & A_{1j} \\ \vdots & \ddots & \vdots \\ A_{j1} & \cdots & A_{jj} \end{bmatrix} \tag{33}$$

The weight of the alternatives according to the individual criteria is determined by the same procedure as when determining the mutual weights of the criteria. The results of the calculation are given in Figure 5.

In the last phase of the AHP method, the determination of the solution to the problem is carried out. After calculating the evaluations of the alternatives according to individual criteria, the total expected utility was calculated according to all criteria and their weights.

Each criterion weight is multiplied by the weight of the alternative according to the given criterion, and the sum of all the previously mentioned multiplications gives the utility of the alternative in the utility matrix:

$$\widetilde{AK} = \begin{bmatrix} A_{11} \cdot K_{k1} + & \cdots & + A_{1i} \cdot K_{ki} \\ \vdots & \vdots & \vdots \\ A_{j1} \cdot K_{k1} & \cdots & + A_{ji} \cdot K_{ki} \end{bmatrix} \tag{34}$$

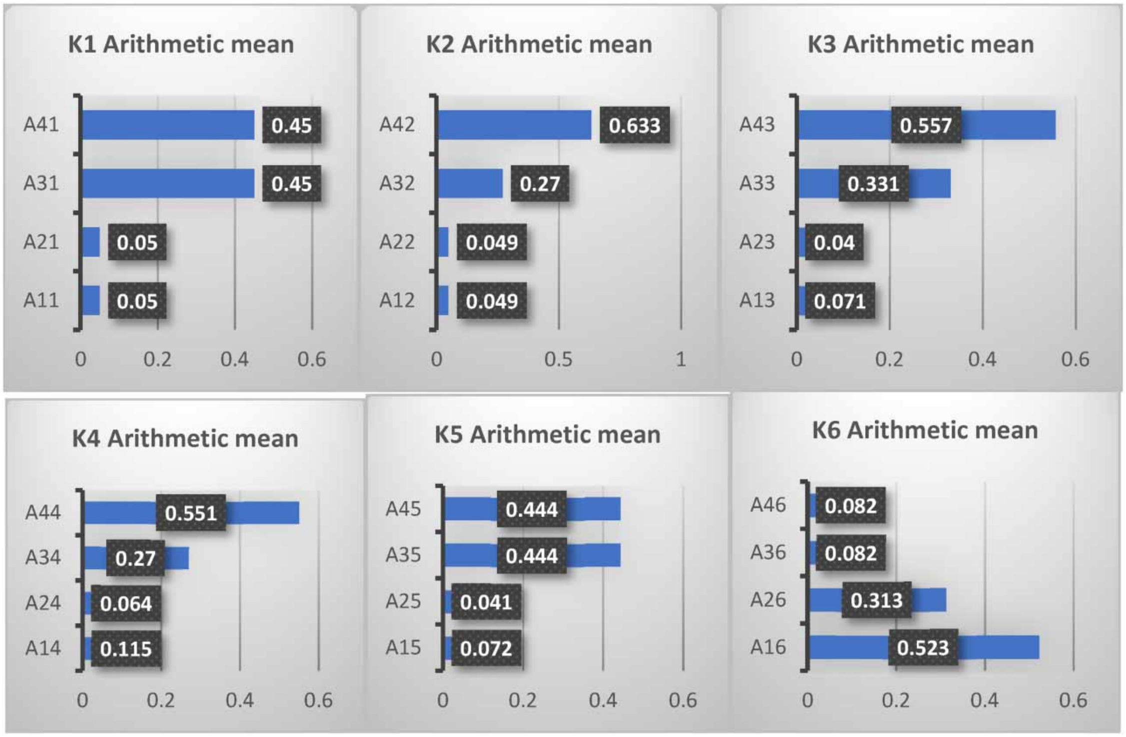

Figure 5 | Evaluations of alternatives by individual criteria.

Figure 6 shows the diagram and the relationship between the expected benefits of the alternatives, where it is obvious that the maximum benefit is expected from alternative A4. As part of the fuzzy AHP method, the alternatives previously presented were considered, where the optimal alternative, which is Variant 4, has the highest ratings.

VIKOR method with the fuzzy approach

By applying the fuzzy VIKOR method, as described in the present study, compared to the combined fuzzy AHP method, the results described below are obtained. For the purposes of applying the VIKOR method, a different evaluation of alternatives is necessary in relation to the criteria using the fuzzy approach, as shown in Table 2.

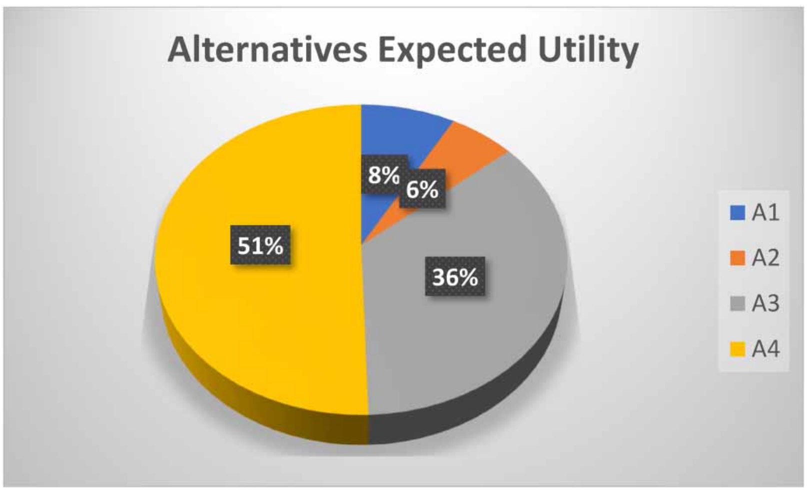

Figure 6 | Expected utility of alternatives according to the AHP method with the fuzzy approach.

Table 2 | Fuzzy values of criterion functions for alternatives and application of the fuzzy AHP method

Alternatives	Values of criterion functions – fuzzy					
	K1	K2	K3	K4	K5	K6
A1	(0.5, 1, 1.5)	(0.5, 1, 1.5)	(0.5, 1, 1.5)	(0.5, 1, 1.5)	(0.5, 1, 1.5)	6
A2	(0.5, 1, 1.5)	2	(0.5, 1, 1.5)	(0.5, 1, 1.5)	(0.5, 1, 1.5)	6
A3	(4.5,5, 5.5)	(4.5,5, 5.5)	6	6	8	2
A4	(8.5, 9, 9.5)	(8.5, 9, 9.5)	(8.5, 9, 9.5)	(8.5, 9, 9.5)	8	2
Extremisation	Max	Max	Max	Max	Max	Max

By applying the values shown in Table 3, the results of the fuzzy AHP–VIKOR method, with the adopted criteria weights and the adopted coefficient $v = 0.6$, are obtained as recommended.

– A compromise solution

A1–A2	A2–A3	A3–A4
0.017	0.680	0.303

The threshold for sufficient advantage is 0.25; thus, alternative A4 has sufficient advantage (condition U1 fulfilled).

It can be noted that slightly different solutions were obtained by applying different methods of the fuzzy AHP method, and the fuzzy VIKOR method. By ranking according to the fuzzy AHP method, the solutions A4, A3, A1, and A2 are obtained. While by ranking using the fuzzy VIKOR method, the solutions A4, A3, A2, and A1 are obtained, and the stability of the obtained optimal solution A4 is observed.

Fuzzy AHP–VIKOR method

Finally, Table 3 (together with Figures 7, 8, 9 and 10) shows solutions made using the third fuzzy AHP–VIKOR method; first, using coefficient $v = 0.5$. Determination of weights was made using AHP algorithms, in order to determine the criterion function and the weight of the criterion, shown in Figure 8.

– A compromise solution

A2–A1	A1–A3	A3–A4
0.028	0.600	0.371

The threshold for sufficient advantage is 0.25, and alternative A4 has sufficient advantage (condition U1 fulfilled).

The third and final newly proposed combined method also obtains, as an optimal solution, the alternative A4, and the solution is similar to the results of the fuzzy AHP–VIKOR method. It is noticeable that the proposed solution is significantly better explained using this final method, where a well-reasoned optimal solution was obtained while considering

Table 3 | Fuzzy AHP–VIKOR method

Alternatives	Values of criterion functions					
	K1	K2	K3	K4	K5	K6
A1	0.05	0.049	0.071	0.115	0.072	0.523
A2	0.05	0.049	0.040	0.064	0.041	0.313
A3	0.45	0.270	0.331	0.270	0.444	0.082
A4	0.45	0.633	0.557	0.551	0.444	0.082
Extremisation	Max	Max	Max	Max	Max	Max

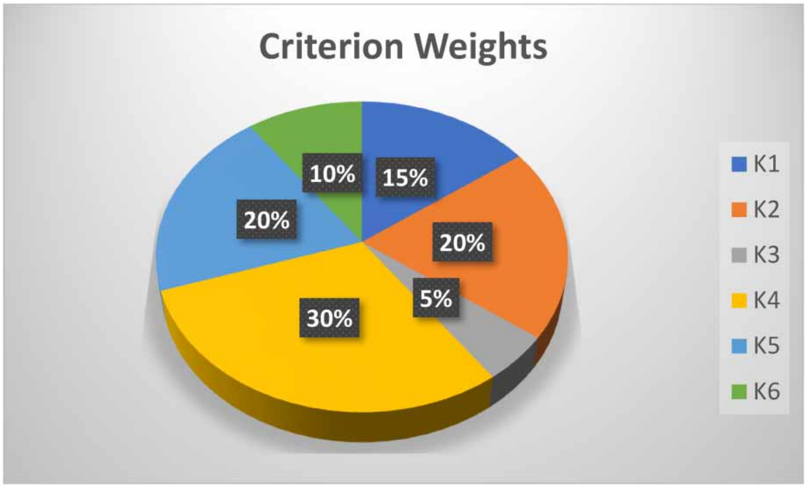

Figure 7 | Determination of weights.

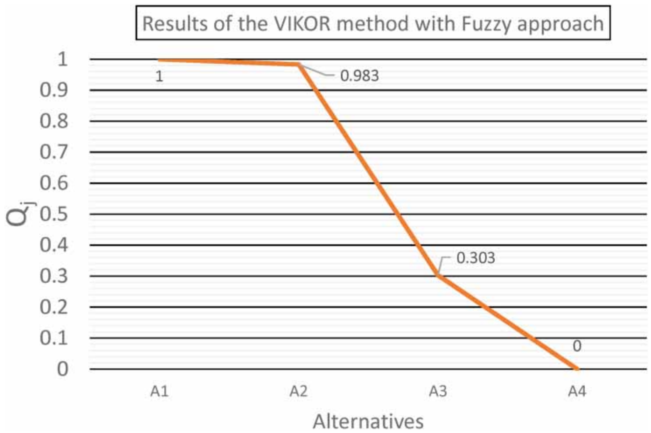

Figure 8 | Results of the fuzzy VIKOR method.

single-criteria solutions and certain criteria weights using the AHP algorithm, and further reasoning and determination of the optimal solution using the VIKOR algorithm.

In the first iteration, the condition U1 is satisfied, with the application of coefficient $v = 0.5$. To satisfy the condition of U2, it is necessary to examine the changes in the optimisation results for different values of coefficient v.

Below is an overview of the results for different values of coefficient v.

Weight v	$v = 0$	A compromise solution (i.e., the difference) A2–A1 = 0.002, A1–A3 = 0.567, A3–A4 = 0.431
Weight v	$v = 0.5$	A compromise solution (i.e., the difference) A2–A1 = 0.028, A1–A3 = 0.600, A3–A4 = 0.371
Weight v	$v = 0.6$	A compromise solution (i.e., the difference) A2–A1 = 0.034, A1–A3 = 0.607, A3–A4 = 0.359
Weight v	$v = 0.7$	A compromise solution (i.e., the difference) A2–A1 = 0.039, A1–A3 = 0.614, A3–A4 = 0.347
Weight v	$v = 0.9$	A compromise solution (i.e., the difference) A2–A1 = 0.049, A1–A3 = 0.627, A3–A4 = 0.324
Weight v	$v = 1.0$	A compromise solution (i.e., the difference) A2–A1 = 0.055, A1–A3 = 0.634, A3–A4 = 0.312

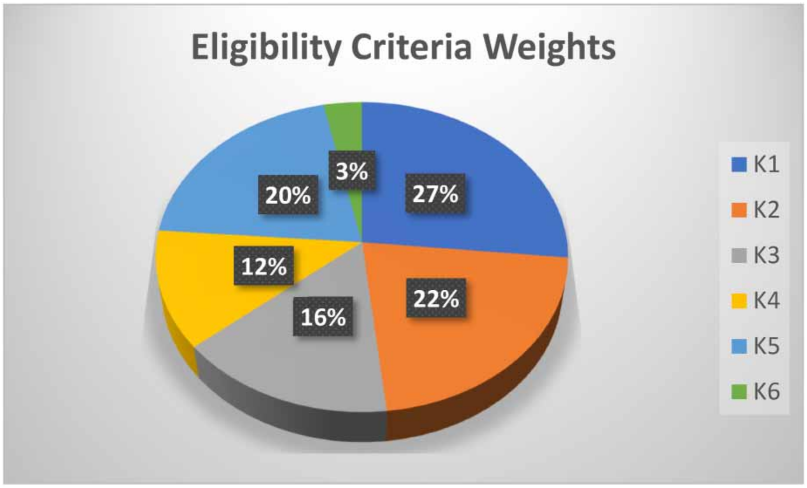

Figure 9 | Determination of eligibility criteria weights using AHP algorithms.

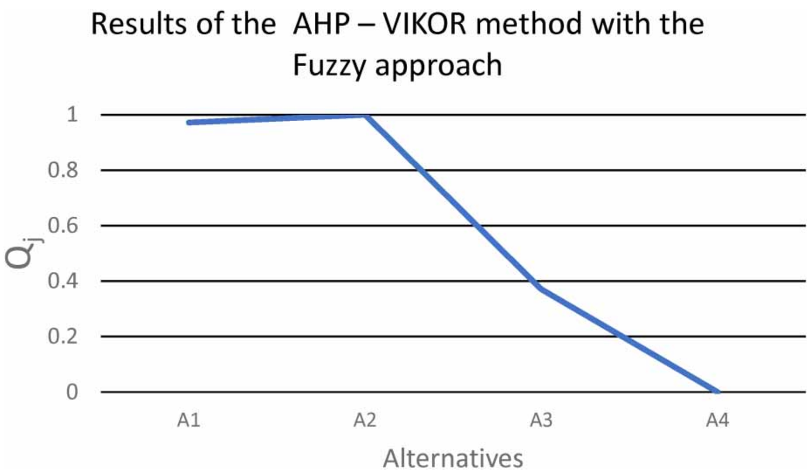

Figure 10 | Results of the fuzzy AHP–VIKOR method.

Ranking

QS:	A4. A3. A1. A2
QR:	A4. A3. A1. A2
Q:	A4. A3. A1. A2

Fulfilment of conditions U1 and U2:

The threshold for sufficient advantage is 0.25, where alternative A4 has sufficient advantage (condition U1 fulfilled).

Alternative A4 has a firm and sufficient first position with the weight change v (condition U2 fulfilled).

Based on the results shown above, it can be concluded that the solutions of the fuzzy AHP–VIKOR method are very consistent, and always give an excellent result in proposing the optimal solution. Thus, it is concluded in the observed example that condition U2 is also satisfied in the sense of satisfying the firm position of alternative A2.

The application of the method that has been developed in this study becomes somewhat more difficult with any increase in the number of alternatives and criteria. However, with the correct choice of alternatives and criteria, this problem is easily overcome.

CONCLUSION

In the presented developed MCDM optimisation procedure fuzzy AHP–VIKOR method, the following solution was obtained as optimal: Variant 4. This alternative envisages that the Makiš SPS should be constructed as an open caisson – a well with a spout at an angle in relation to the axis of the Strugara canal which, after a detailed analysis mentioned above using MCDM optimisation (MCO) methods is considered better than other variants.

The result of the optimisation agrees with the real requests, sent by interested parties and competent commissions, for the construction of the objects in question, and provides confirmation of the application of the method that has been developed in this study. The developed method gives a stable solution that does not contradict the solutions of other optimisation methods. The developed method has justified its use in solving a real problem, which gives the possibility for the future research and development of this method.

The well method in Variant 4 of the construction of the PS avoids interaction with the surrounding pipelines, as well as with the external service ring of the factory for the production of drinking water – Makiš Ø500, especially with the main water pipeline Ø1500 whose purpose is to supply the City of Belgrade (with approximately 2,000,000 inhabitants) with drinking water. The well method in Variant 4 also avoids any potential damage and interruption, which in turn would cause the interruption of the operation of the entire factory for the production of drinking water at Makiš, and the interruption of the water supply to consumers in the area of the City of Belgrade.

A good choice of alternatives and criteria is most important for the optimisation result (Milojkovic *et al.* 2016a, 2016b; Milojkovic 2019; Zhu *et al.* 2020), and our novel fuzzy AHP–VIKOR method was used to describe and explain the alternatives in relation to the criteria, in order to choose the optimal solution, in accordance with what has been demonstrated in previous research.

In future research in the application of our novel fuzzy AHP–VIKOR method, there are extremely large opportunities in finding optimal solutions in various industries, such as water management and construction. Extensive research into the stability of marginal solutions using this method, research into the stability of marginal solutions with different weights of criteria and compromise solutions, and further development and improvement are possible.

It is equally important to avoid interaction with other lines in the immediate environment, thus leaving enough space for planned execution and maintenance of pressure regulators, and other important factors. A somewhat heavier building construction is obtained, but it is significantly less harmful in relation to the overall problems that were avoided by this chosen variant.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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