كلية الهندسة بشبرا
FACULTY OF ENGINEERING AT SHOUBRA
ERJ
PRINT ISSN 3009-6049
ONLINE ISSN 3009-6022

ENGINEERING RESEARCH JOURNAL (ERJ)
Volume (52) , Issue (3)
July 2023, pp:1-12
https://erjsh.journals.ekb.eg

Assessment Factors Influencing Selection of Excavation Supporting Systems in Tunneling Projects

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Abstract: In metro-rail projects, excavation depths may reach more than 30 meters in the construction of underground stations. In such cases, the dominant proposed excavation support system is the diaphragm wall system. Secant piles, contiguous piles, berlin walls, and other systems may be proposed for use in substructures as external accesses with depths up to 15 meters. Selecting the appropriate excavation support system is a crucial challenge for builders and designers. Complex factors which are considered in the selection process and dependent on the subjective judgments of the construction practitioners based on their past expertise, create uncertainty and imprecision. Analytical Hierarchy Process (AHP), despite its popularity and wide use in the field of decision-making, is incapable of dealing with uncertainty in complex multi-criteria decision-making processes. To evaluate such complex decision-making problems, fuzzy set theory is combined with AHP in this study to use the fuzzy AHP (FAHP) technique in dealing with ambiguity and impression. To illustrate the applicability of the developed model, Heliopolis, and Kit Kat metro stations are presented, as case studies, in the greater Cairo Metro. It was concluded that the diaphragm wall system, although it is still more costly but preferable.

Keywords: Tunneling projects, Excavation support systems, Alternatives evaluation, Fuzzy set theory, Fuzzy analytical hierarchy process.

1. INTRODUCTION

Tunneling projects are more complex and highly specialized than traditional construction projects. This complexity is due to their urban constraints, underground uncertainty conditions, and a high level of interference among their components. In such a competitive field, meeting the project target requires a high level of expertise during the planning, design, and construction stages [1,2].

Furthermore, excavation in restricted and limited areas necessitates deep excavation that is vertical or near-vertical to minimize its area. An appropriate earth-retaining structure should be used to keep neighboring properties safe and excavate a hole into which a permanent structure is built safely [3–7].

In metro-rail underground stations and annexes, where required excavation depths may reach more than 30 meters, a diaphragm wall system is always the dominant proposal. In the case of stations' external accesses and underground fire tanks with lower depths, different alternatives may be strongly proposed as a competitor to the diaphragm wall system. Secant piles, contiguous piles, soldier piles with lagging or (berlin walls), and sheet piling are common systems to be used as supporting systems[3,5,6].

In the selection process, significant factors relevant to the site and construction conditions, such as safety, adjacent properties and facilities, environmental conditions, traffic density, water table level, soil conditions and excavation depth, are considered [8–13]. Additionally, relevant management factors, such as cost, time of construction and design requirements are influential [14-18].

Assessment factors in making the right decisions and selecting the appropriate supporting system are the key to a successful project's completion with good and safe performance. Budget, period, and safety are the pillars of the project's success.

On the other side, improper design and selection causes serious problems that affects the project's success and all the surrounding properties [11,12], [18–21]. Decision-makers face numerous challenges in fixing a set of rules that enable them to precisely select the appropriate system for every site or job due to the complex trade-off process between the feasible alternatives. Complex multi-criteria, subjective judgments, and imprecise information are often associated with ambiguity and vagueness [11,12,18].

To manage uncertainty and minimize its effect on making rational decisions with uncertainty, artificial intelligence (AI) methods have been employed. In recent years, (AI) techniques have been successfully used in evaluating

foundation constructions and relevant alternatives [11,12,22].
They are used to assist decision-makers in making the best choice of the supporting system for deep excavation in this project as well as similar projects. This study applied the application of (AI) techniques in multi-criteria decision-making, the fuzzy analytic hierarchy process; discussing an actual case study to illustrate the process. In this study, a model was developed considering four main criteria and 13 factors as sub-criteria influencing the selection between four common feasible alternatives.

2. LITERATURE REVIEW

Terzaghi et al. [23] classified excavation as deep excavation when its depth exceeds 6.0 meters. Chini and Genauer [21], defined excavation supporting systems as temporary structures that are the fundamental pillars of deep excavation construction projects to achieve profitability with safety, speed, and quality.

In metro projects, depths may reach 30 meters or more. They are often required in populous urban areas, which are constantly surrounded by adjacent buildings and public utilities in limited construction areas. These conditions require paying much attention to the design and planning stages to keep the surrounding utilities and adjacent structures safe by using the appropriate supporting systems. In this context, OSHA[1] recommends that any excavation or trenching work that reaches 3.5 meters or more from ground level using a suitable excavation support technique under the supervision of a competent engineer [21].

These systems can be classified as unrestrained support systems (cantilevered systems) or cast-in-place systems. The other systems are restrained systems (braced systems), such as Waller-Struts systems. The last type is tied back as nailing support systems. Another classification is as external and internal supporting systems acting according to the system of the earth pressure loading transfer [3,12,14,17,21,24].

In greater Cairo-Metro, bracing systems are commonly used in the supporting process. Diaphragm wall systems, secant bored piles, contiguous piles, berlin walls (soldier piles with lagging), and sheet piling are common retaining systems utilized in deep excavation projects. From the literature, there are lots of multi-criteria decision-making applications in excavation project selection techniques.

Pan [10] applied the fuzzy analytic hierarchy process (FAHP) technique in selecting the earth-retaining methods for deep excavation. Pan [11] and Wefki et al.[12] applied the same decision-making (FAHP) technique in selecting the appropriate excavation supporting method for deep excavation.

Cao et al.[15] and Qi et al. [20] applied the integrated Analytic Hierarchy Process (AHP) with the Delphi technique in selecting a protection method for underground excavation and applied the same technique in selecting the deep excavation construction methods in building construction. Issa et al. [18] applied the Hybrid AHP-Fuzzy TOPSIS approach for selecting a deep excavation support system. Noktehdan et al. [25]applied (FAHP) technique in ranking and selecting the innovation in infrastructure project management.

Meethom and Triwong [26] applied (FAHP) technique in evaluating urban metro construction excavated soil disposal Sites. Elashram and Ibrahim [27] used fuzzy AHP application to determine the main dewatering criteria weights in Egypt. Shaffiee et al.[28,29] applied Fuzzy Delphi Analytical Hierarchy Process (FDAHP) technique in selecting the suitable tunnel supporting system using an integrated decision support system, taking the Dolaei tunnel in Touyserkan, Iran, as a case study.

Kim et al.[29,30] used the FAHP decision-making technique to quantify the risk of excavation work failure. Zayed[30] applied the fuzzy approach in selecting the pile construction method. Masouleh[31] applied the AHP, ANP, and TOPSIS approaches in selecting excavation methods in tunneling construction.

Naghadehi et al. [32] also used the FAHP technique in selecting the optimal underground mining method in Iran. However, there are many more applications of Fuzzy AHP in the selection problems in all fields.

This research used the FAHP technique with the method of extent analysis[33] and the modified method of the extent analysis[34,35] to help practitioners and designers in metro projects and similar deep excavation projects in selecting the appropriate retaining system from feasible alternatives concerning the criteria considered in their project.

Regarding factors affecting the selection of the supporting system**,** Ou [3]
categorized the factors as a) geological conditions (soil type and underground water condition), b) adjacent properties condition (their foundation and structure type), construction materials, and age. Pan [11] categorized the factors as a) management elements, including cost, safety, and time; b) site characteristics, such as the depth of excavation, the soil conditions, and the state of underground water; and c) characteristics of nearby facilities. Farzi et al.[14] categorized them as a) technical characteristics of the system, b) execution availability, c) economic conditions, and d) environmental conditions. Cao et al. [15] categorized them as a) environmental impact, b) safety criteria, c) time, and d) cost, while Qi et al.[20] added quality to the four criteria.

El-Kelesh and Hassan [16,17] considered ground conditions, excavation depth, and water table level the most significant factors in the selection process.

Issa et al. [18] categorized the factors affecting site characteristics, safety, cost, and environmental conditions. Other authors add the system's water tightness and construction availability as essential criteria.

3. RESEARCH METHODOLOGY

The framework to prioritize the most appropriate deep excavation supporting system is developed with the AHP decision-making framework. Figure 1 illustrates the schematic diagram for the proposed model's

[1] The Occupational Safety and Health Administration

implementation, and the subsections below describe each component of the proposed model in detail.

3.1 Developing the Hierarchy Breakdown Structure of the Model

As a basis for the AHP method, breakdown the problem into a structured hierarchy frame to decompose the complex problem into components. Its construction contains the main target to be achieved, the most influential criteria for selection, and sub-criteria (if any) to determine its interdependencies. Finally, at the last level, the proposed alternatives will be prioritized [40,43].

3.2 Constructing the Pairwise Comparison Matrices

The results from pairwise comparisons are then fuzzified using the 5-level fuzzy scale in table 1 and Fig. 2 using a triangular fuzzy membership function (TFNs) [36]. (TFN) is a convex normalized fuzzy set representing each linguistic variable's membership function represented by three vertices.

Suppose Ã is a triangular fuzzy number, Ã = (l, m, u), where l and u represent the smallest and largest value with the smallest membership values, respectively. m is the modal with the largest membership value μ(x), and x *is* any generic value belonging to the universe of discourse. It can be represented in Fig.3.

The inverse of Ã = (l, m, u) is $[\tilde{A}]^{-1}$ = [1/u, 1/m, 1/ l];[37,38].

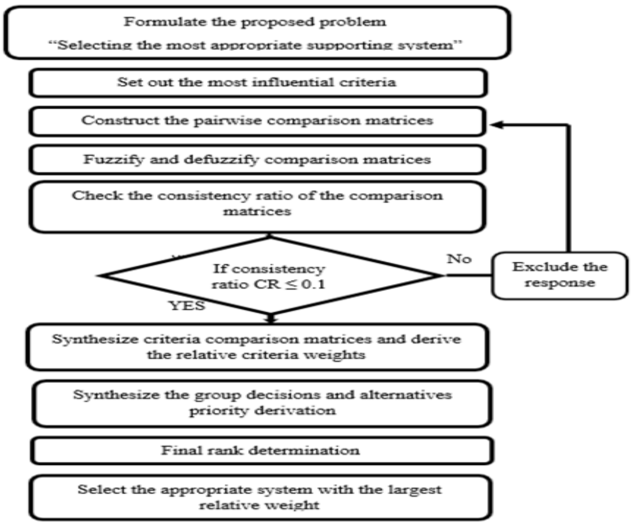

Fig 1. Proposed model implementation diagram

TABLE 1. Fuzzy scale importance rates

Importance Weight scale (linguistic variable)	**Numerical rate value**	**Fuzzy number**
Equally important (EI)	(1)	(1,1,2)
Moderately important (MI)	(2)	(1,2,3)
Strongly important (SI)	(3)	(2,3,4)
Very strongly important (VSI)	(4)	(3,4,5)
Extremely strong important (ESI)	(5)	(4,5,5)

Figure 2 illustrates the geometric and mathematical representations of the (TFN), respectively. Figure 3 shows the graphical representation of the five-level fuzzy scale for the triangular fuzzy membership function, indicating linguistic variables expressing the degree of importance between each criterion and the corresponding numerical value [36].

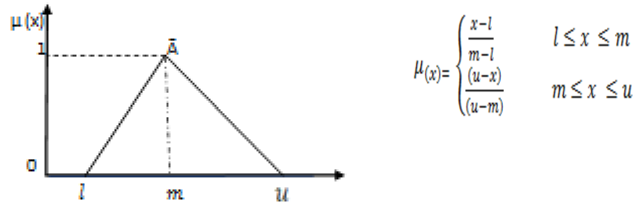

Fig 2. Triangular membership function and geometric and mathematical representation

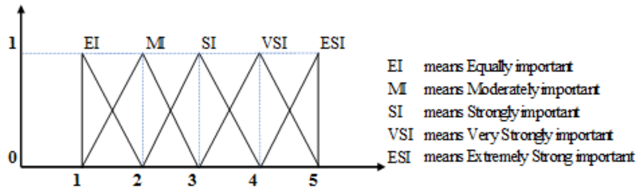

Fig 3. Five–level fuzzy scale for triangular membership function

3.3 Check Consistency

The fuzzy pairwise comparison matrices are de-fuzzified to check the consistency of the experts' judgments by one of the methods as the "center of gravity" into crisp matrices, described by Awasthi et al.[39].

$$D = (l + 4m + u)/6 \quad (1)$$

Where; D denotes the de-fuzzified value of the triangular fuzzy number. After de-fuzzifying the pairwise comparisons for each expert, it is vital to check the consistency of each expert judgment to measure its contradiction limit. The high consistency ratio indicates a high probability of a lack of problem understanding and less confidence in the final weight's reliability. The consistency index is first calculated as Saaty [40,43].

$$CI = \frac{\lambda max - n}{n-1} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

Where; CI denotes the consistency index, λ-max refers to the largest eigenvalue of the comparison matrix, and n is the matrix size.

The consistency index is then divided by the random inconsistency index RI to obtain the consistency ratio, Saaty [40]. According to Franek and Kresta [41] and Che et al.[42], the random inconsistency index depends on the matrix size (table 2). Saaty [43] has shown that if the consistency ratio is less than or equal to 0.1, it is satisfactory and acceptable to continue the analysis; otherwise, the expert judgments must be revised.

TABLE 2. Random index versus different matrices sizes

N	2	3	4	5	6	7	8	9	10	11	12
RI	0	0.53	0.88	1.11	1.25	1.34	1.40	1.45	1.49	1.51	1.54

Where; N represents the matrix size, and RI is the corresponding random index used in equation 3.

3.4 Fuzzy Analytic Hierarchy Process (FAHP)

AHP, proposed by Saaty[40,43], is a popular, extensively used multi-criteria decision-making technique to determine the relative weights of criteria and alternative priorities. It is based on pairwise comparisons and is used in several fields[38]. Due to the ambiguity and vagueness of the decision-maker's subjective judgments, (AHP) is incapable of dealing with complex decisions due to imprecision and vagueness. To deal with the uncertainty and impression, Fuzzy sets proposed by Zadeh [44] are integrated with AHP, namely the fuzzy AHP or (FAHP) method for decision-making. Van Laarhoven and Pedrycz [45] proposed a method using fuzzy triangular numbers for representing the fuzzy comparing judgment. It keeps the concepts of AHP and its advantages in essence, which makes the FAHP method a widely applied method [46]. Nowadays, FAHP has become the most popular fuzzy multi-criteria decision-making method [47] and is applied in many fields, such as machine selection, technique selection, and many other applications [36]. Chang[33]proposed the extent analysis method as one of the FAHP algorithms used to evaluate the relative criteria weights and alternatives' priority weights

If A = $(a_{ij})_{n*m}$is a fuzzy pairwise comparison matrix, where; a_{ij}= (l_{ij}, m_{ij}, u_{ij}) satisfies the condition of {$l_{ij} * l_{ji} = 1$ &$m_{ij} * m_{ji} = 1$ &$u_{ij} * u_{ji}= 1$}, the value of the fuzzy synthetic extent ($\boldsymbol{S_i}$) for (m) extent analysis values of $\boldsymbol{i^{th}}$object is defined according to Chang [33]as Eq. 4.

$$\boldsymbol{S_i} = \left(\frac{\sum_{j=1}^{m} l_{ij}}{\sum_{i=1}^{n}\sum_{j}^{m} u_{ij}} , \frac{\sum_{j=1}^{m} m_{ij}}{\sum_{i=1}^{n}\sum_{j}^{m} m_{ij}} , \frac{\sum_{j=1}^{m} u_{ij}}{\sum_{i=1}^{n}\sum_{j}^{m} l_{ij}}\right) \quad (4)$$

Where; i = 1, 2… n, and j = 1, 2… m.

Wang et al.[34,37]updated the normalization process and proposed the modified extent analysis method as per Eq. (5); if S_i is the synthetic analysis value, then,

$$\boldsymbol{S_i} = \left(\frac{\sum_{j=1}^{m} l_{ij}}{\sum_{j=1}^{m} l_{ij} + \sum_{k=1,k\neq i}^{n}\sum_{j=1}^{m} u_{kj}} , \frac{\sum_{j=1}^{m} m_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{m} m_{kj}} , \frac{\sum_{j=1}^{m} u_{ij}}{\sum_{j=1}^{m} u_{ij} + \sum_{k=1,k\neq i}^{n}\sum_{j}^{m} l_{kj}}\right) \quad (5)$$

In obtaining the estimates of weight vectors under each criterion, the principle of comparison for fuzzy numbers is applied [47].

The possibility degree (V) that a fuzzy triangular number is the greatest among several fuzzy numbers **V** ($\boldsymbol{M_i} \geq \boldsymbol{M_j}$) can be obtained using equation 6[33].

$$V(M_i \geq M_j) = \begin{cases} 1 & if \quad m_i \geq m_j \\ 0 & if \quad l_j \geq u_i \\ \dfrac{(l_j - u_i)}{(m_i - u_i) - (m_j - l_j)}, & otherwise \end{cases} \quad (6)$$

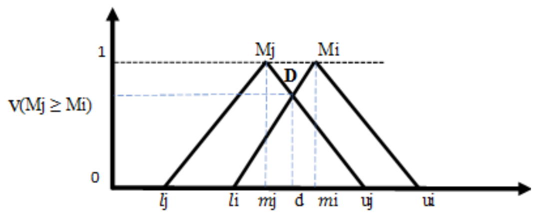

Fig 4. Fuzzy triangular number M_i and M_j

As in Fig. 4, d is the ordinate of the highest intersection point D between $\mu_{Mi}$and μ_{Mj}.The degree of possibility for a convex fuzzy number to be greater than (k) convex fuzzy numbers M_i(i= 1, 2… k) and $k \neq i$ can be calculated as per Eq.7

V (M ≥ M1, M2… Mk) = V [(M ≥ M1) and (M ≥ M2) and … and (M ≥ M_k)]

= min V (M ≥$M_{i,}$), i = 1, 2, …, $k$and $k \neq i$ (7)

The minimum of these degrees of possibilities is used as the overall score of each criterion as per equation 8.

$d'(M_{i,})$ = min $V(s_i \geq s_j)$, k =1, 2, 3, …...$n$and $k \neq i$ (8)

Finally, these scores are normalized to obtain the non-fuzzy weights of the criteria as per equations (9-10).

$$d\,(M_i) = \frac{d'(M_{i,})}{\sum_{1}^{n} d'(M_{i,})} \quad (9)$$

$$w = (d\,(M_1), d\,(M_2), d\,(M_3), \ldots\ldots\ldots\, d\,(M_n))^{T} \quad (10)$$

4.CASE STUDIES AND MODEL IMPLEMENTATION

4.1Method Verification

Figure 5 illustrates the hierarchy adapted in this study for selecting the most appropriate excavation supporting system. It indicates, in a family tree, the main criteria and sub-criteria that were most influential in the selection process

These criteria were collected and classified from the literature and structured interviews with a group of professionals working on the Greater Cairo Metro project. They were in different stages with different levels of experts ranging from a minimum of 5 years in the field to 25 years and reached 60 engineers. The questionnaire asked about the relative importance of the main criteria versus the main target of “selecting the appropriate deep excavation supporting system” as a parent criterion. The next step is to ask about the relative importance of the sub-criteria versus its parent one using the scale according to table 1. Numbers from 1 to 5 correspond to the linguistic variable from equally important (EI) to extremely high important (EHI).

The philosophy of the question is “What is the degree of importance of criterion A if compared with criterion B to select the appropriate supporting system?”. If A is strongly important than B, then the answer is equal to 3 towards A, but if B is weighted, then it will be 3 towards B, as 1/3 in the matrix, and so on. Comparison matrices are created from the results as crisp values using one matrix for the main criteria and three for the sub-criteria.

The second questionnaire was for comparison between the alternatives to estimate the weight of each alternative under each criterion. The philosophy of the question was “To what degree do you prefer to use alternative (A) or (B) regarding criteria (X) with the same concept for creating the comparison matrices?”. The number of matrices for that was 13 pieces.

All matrices were fuzzified according to table 1 by representing each linguistic variable as a fuzzy number with a triangular membership function.

As in Fig. 2, l, m, and u, lower, modal, and upper values of the triangular membership function, respectively, are de-fuzzified by the equation of the centroid according to equation 1. Additionally, each matrix was checked for consistency according to equations 2 and 3.

Table 3 shows sample results of one matrix for the main criteria that have been de-fuzzified for one of the expert’s responses in our sample. Each cell in the table represents the relative importance of each main criterion versus the others regarding the primary goal. For example, in cell a_{14}, C1/C4 = 0.5 means that C4 is moderately important than C1, but cell a_{12} means that C1 is moderately important than C2; where; $a_{14} = 1/a_{41}$ and $a_{12} = 1/a_{21}$.

Table 4 shows the main criteria consistency results of the same expert based on table 3, where C1 represents “site and construction conditions,” C2 represents “cost,” C3 represents “design requirements,” and C4 represents “time of construction."

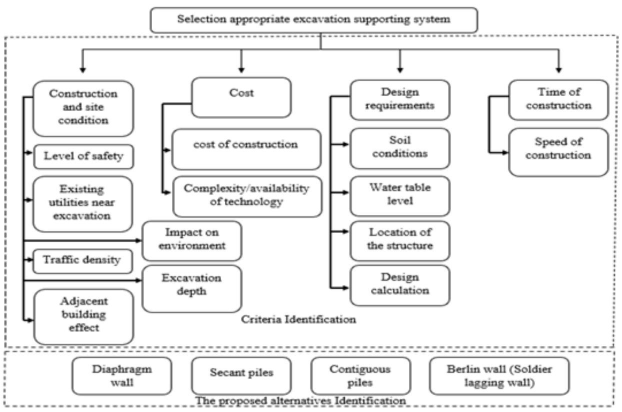

Fig 5. Hierarchy diagram for selecting the most appropriate excavation supporting system

TABLE 3. Main criteria de-fuzzified matrix

Main Criteria comparison matrix				
Criteria	***C1***	***C2***	***C3***	***C4***
C1	*1*	*2*	*1*	*0.5*
C2	*0.5*	*1*	*2*	*0.5*
C3	*1*	*0.5*	*1*	*1/3*
C4	*2*	*2*	*3*	*1*

TABLE 4. Main criteria consistency results

N = 4				*RI = 0.9*
Geometric mean	***Weight vector***	***W'***	***W''***	***CI***
1.0000 *0.8409* *0.6389* *1.8612*	*0.2304* *0.1937* *0.1472* *0.4287*	*0.9793* *0.8176* *0.6173* *1.7184*	*4.2513* *4.2210* *4.1941* *4.0081*	*0.0562*
4.3410	*1.0000*	*4.1327*	*4.1686*	
CR	*0.0624*	*< 0.1*	*Consistent*	*Ok*

Each pairwise comparison matrix had its consistency checked for each expert response. There were four matrices for the main criteria and sub-criteria and 15 for alternatives. The same sequence was applied for all matrices for each expert of the 60 experts, where there were 3 of them inconsistent. Each group of matrices was aggregated into a group comparison matrix by using the max-min method with an arithmetic mean as per equations from 11 to 13 [38], [41], [43], [48,49].

$$Where;\ l_{ij}{}^{group} = min.\{lij^k\} \quad , \quad k = 1,2 \dots m \tag{11}$$

$$Also,\ m_{ij}{}^{group} = \frac{1}{k} * \sum_{k=1}^{n} m_{ij}{}^k \quad , \quad k = 1,2 \dots m \tag{12}$$

$$And, u_{ij}{}^{group} = max.\{\ uij^k\} \quad , \quad k = 1,2 \dots m \tag{13}$$

Where; $l_{ij}{}^{group}$, $m_{ij}{}^{group}$, and $u_{ij}{}^{group}$ represent the minimum of the smallest value, the arithmetic mean of the group modal value, and the maximum value of the highest value of the comparison matrix group.

Where; $l_{ij}{}^k$, $m_{ij}{}^k$, and $u_{ij}{}^k$ represent the smallest, most likely, and largest possible values for the kth decision-maker, respectively. An example was taken to show the application of the main criteria matrix (C1, C2, C3, and C4) for the 57 experts’ results. The matrices were aggregated using the arithmetic mean as Awasth i et al.[41], and the results are indicated in table 5.

TABLE 5. Aggregated Matrix by Arithmetic Mean

(1,1,1)	(0.20,1.892,5)	(0.250,1.546,4)	(0.2,1.01,5)
(0.2,.802,5)	(1,1,1)	(0.3,0.802,5)	(0.2,0.824,4)
(0.25,1.965,3)	(0.2,1.247,4)	(1,1,1)	(0.25,1.98,4)
(0.25,0.990,4)	(0.2,1.214,4)	(0.4,1.021,5)	(1,1,1)

In estimating the relative weights of the criteria, two different methods are used: the extent analysis method by Chang [33] and the modified extent analysis method by

Wang et al.[34,35] with the arithmetic mean as per Equations 4 -10. The results are as follows:

Calculating synthetic extent value, S1, S2, S3, and S4 for the four criteria:

S1= (0.029, 0.282, 2.174) &S2= (0.30, 0.178, 2.174) &S3= (0.3,0.321,1.739)

S4= (0.33,0.219,2.029)

Calculating the degree of possibility to determine the greatest and the least among the fuzzy numbers:

V1-2 = 1 & V1-3 = 0.982 & V1- 4 = 1 leads to V- min. = 0.982

V2-1= 0.953 & V2-3 = 0.937 & V2- 4 = 0.981 V – min. = 0.937

V3-1= 1 & V3-2 = 1 & V3- 4 = 1 V- min. = 1

V4-1= 0.969 & V4-2 = 1 & V4-3 = 0.951 V- min. = 0.951

$d'(M_i\ )$ = (0.982,0.937,1.0,0.951)

w = (0.982/3.87, 0.937/3.87,1/3.87,0.951/3.87)^T

w_{C1} = 0.254 w_{C2} = 0.242 w_{C3} = 0.258 w_{C4} = 0.246

In the application of the modified extent analysis method (Wang,2006),

S1 = (0.039,0.282,0.741) & S2 = (0.040,0.178,0.743) & S3= (0.037,0.321,0.698)

S4= (0.042,0.219,735)

V1-2 = 1& V1-3 = 0.95 & V1- 4 = 1 leads to V- min. = 0.95

V2-1= 0.87 & V2-3 = 0.83 & V2- 4 = 0.94 V - min. = 0.83

V3-1= 1 & V3-2 = 1 & V3- 4 = 1 V- min. = 1

V4-1= 0.92 & V4-2 = 1 & V4-3 = 0.87 V- min. = 0.87

$d'(M_i\ )$ = (0.95,0.83,1.0.0,0.87)

w = (0.95/3.65, 0.83/3.65,1/3.65,0.87/3.65)^T

w_{C1} = 0.260 w_{C2} = 0.227 w_{C3} = 0.274 w_{C4} = 0.238

Table 6 illustrates the ranking of the main criteria, which indicates that the design requirements, including soil conditions, water table level, expected stresses, and location of the structure, have the highest importance, while site and construction conditions come in second, and cost comes in last in the ranking of the criteria.

TABLE 6. Main criteria ranking by Extend and Modified Extent with arithmetic mean

	Rank	Description
MAIN CRITERIA	1	Design Requirements
	2	Construction and site condition
	3	Time of construction
	4	Cost

The weight of the sub-criterion is calculated relative to each other and then multiplied by the weight of its parent. For example, if the relative weight of sub-criterion C_{ij} is w_j relative to J^s sub-criterion and w_i is the weight of parent criterion i; consequently, the global sub-criteria weight of C_{ij} relative to all other criteria will be:

$$w_{ij} = w_j * w_i; \text{ such that } \sum_{j=1}^{n} w_{ij} = w_i; \ n = 1, 2, \ldots, j \quad (14)$$

Where; n is the number of sub-criteria. Using the Visual Basic application to analyze all the matrices, calculate the ranking of the main criteria and sub-criteria as shown in table 10.

TABLE 7. Construction and site conditions sub-criteria ranking by extend and modified extent with arithmetic mean (relative to each other)

	Rank	Description
Construction and site conditions	1	Level of safety
	2	Adjacent building effect
	3	Existing utilities near the excavation
	4	Excavation depth
	5	Traffic density
	6	Impact on environment

TABLE 8. Cost sub-criteria ranking by extend and modified extent with arithmetic mean (relative to each other)

	Rank	Description
Cost	1	Cost of construction
	2	The complexity and availability of the used technology

TABLE 9. Design requirements sub-criteria ranking by extend and modified extent with arithmetic mean (relative to each other)

	Rank	Description
Design requirements	1	Water table level
	2	Expected stresses
	3	Soil condition
	4	Location of structure

Table 7 illustrates the ranking of the construction and site conditions sub-criteria relative to each other, while table 8 shows the cost sub-criteria ranking relative to each other. Finally, table 9 illustrates the ranking of design sub-criteria.

Table 10 illustrates the results of calculations for the relative weights of different criteria as global weights; each weight belonged to its parent criterion. It is shown from the table that safety requirements for the system, in construction and site condition main criterion, occupy the highest importance.

On the other hand, the impact of the system on the environment occupies the last place in importance. Regarding the construction cost, it occupies the first place in importance compared to equipment and system technology. Water table level and expected stresses occupy the first and second degrees of importance in the design requirements, while the location of the structure comes last. Table 8 lists the ranking of the site and construction conditions sub-criteria, while tables 9 and 10 list the ranking of the cost and design sub-criteria, respectively.

The identical sequences are followed to estimate the priorities of the alternatives after calculating the overall priority by Equation 15. The sum of the priorities for alternative A_i across all criteria and sub-criteria determines its overall priority [36].

$$\sum_{j=1}^{n} wj \text{ X } Pj^{Ai} \qquad (15)$$

Where; wj represents the weight of criterion or sub-criterion j; Pj^{Ai} represents the priority of A_i under criterion j, and n represents the number of criteria or sub-criteria. The final results are shown in table 11.

TABLE 10. Main criteria and sub-criteria relative weights results

Name of Criterion	Extent with Arith. Mean	Rank	Modified Extent Arith. Mean	Rank
1.Construction and site condition	0.254	2	0.262	2
2. Cost	0.242	4	0.227	4
3. Design requirements	0.258	1	0.274	1
4. Time of construction	0.246	3	0.237	3
1.1 Level of safety in each method	0.0498	1	0.0524	1
1.2 Existing utilities near the excavation	0.0447	3	0.0477	3
1.3 Traffic density	0.0373	5	0.0393	5
1.4 Adjacent building effect	0.0475	2	0.0498	2
1.5 Impact on environment	0.0318	6	0.0293	6
1.6 Excavation Depth	0.0429	4	0.0435	4
2.1 cost of construction	0.1271	1	0.1165	1
2.2 Complexity/availability of Technology used	0.1149	2	0.1105	2
3.1 Soil conditions	0.0637	3	0.06713	3
3.2 Water table level	0.0857	1	0.08494	1
3.3 Location of structure	0.0421	4	0.05343	4
3.4 Expected stresses	0.0665	2	0.06850	2

TABLE 11. Alternatives weights as EAM and MEAM with Arithmetic mean

Alternative	Weight by Extend with Arith. method	Rank	Weight by Modified Extend with Arith. method	Rank
Diaphragm wall	0.284	1	0.262	1
Secant piles with a strut beam system	0.253	2	0.231	2
Contiguous piles	0.201	3	0.192	3
Berlin wall (Soldier lagging wall)	0.165	4	0.124	4

According to table 11, the diaphragm wall system has the highest priority, while the secant pile system ranks second. Later comes contiguous piling walls and berlin walls

4.2 Actual Case Studies and Model Validation

Figures 6, 7, and 8 illustrate screenshots of a software application that was published in this paper to rank any criteria that can be suggested by the user. The software was based on the methodology discussed in subsection 3.4 and was applied in studying the selected case studies (KitKat and Heliopolis metro stations)

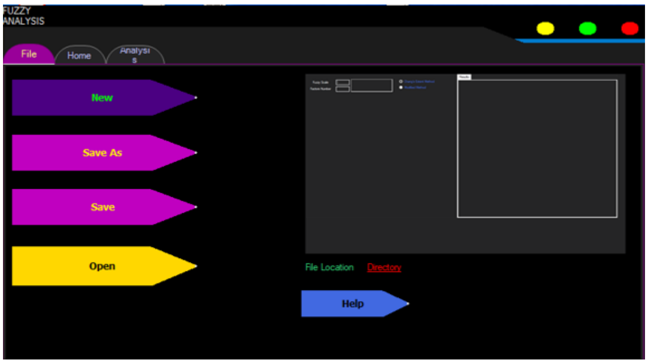

Fig 6. Homepage (File Tab)

Figure 6 illustrates the model homepage, showing the File, Home, and Analysis Tabs. There are file tabs for New File, Open Existing File, Save, Save as File, and Help. In addition to minimizing, maximizing, and closing tabs on the left side of the screen.

Figure 7 depicts the home tab, which includes the Add, Remove, and Rename tabs. The worksheet enables the user to select the fuzzy scale (5-scale or 9-scale) and select the number of the understudy criteria. This page also contains three boxes: one for the model's name, one for consistency check monitoring, and the last one for the results. The diagram depicts a model application analysis using a pairwise comparison matrix (4x4) for four criteria and a 5-scale for importance rate.

The consistency check result and importance weights determined by the extent analysis method are monitored.

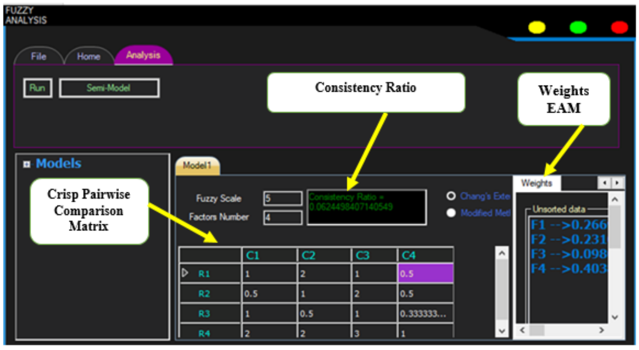

Fig 7. Consistency checks and weights by extend analysis method

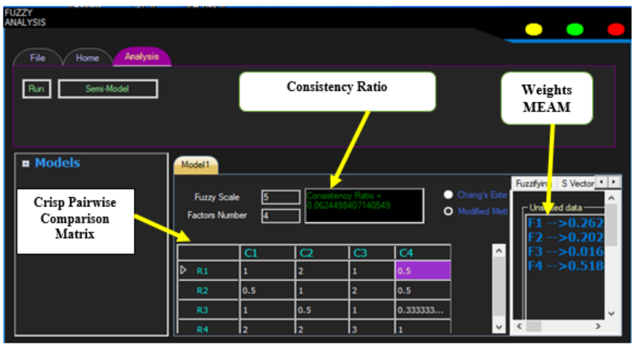

Fig 8. Consistency checks and weights by modified extend analysis method

The modified extent analysis method used to calculate the relative importance weights is depicted in Fig.8.

To validate the model, actual case studies, KitKat and Heliopolis metro stations are presented. KitKat metro station is one of the underground line - 3 stations in the greater Cairo metro. It has a length of 150 meters and 22 meters in width (divided into three boxes, 1, 2, and 3, by slurry walls). It has two external accesses, 1 and 2, and an underground water tank.

Heliopolis metro station, is also one of line -3 and phase – 4, underground stations of the greater Cairo metro, with a length of 220 meters and 22 meters' width. It has eight external accesses with three boxes.

TABLE 12. Significant aspects in the three case studies

Key aspects	KitKat access	KitKat water tank	Heliopolis access
Site conditions Level of safety	Extremely significant	Slightly significant	Moderately significant
Existing utilities	Very significant	Very significant	Very significant
Environmental impact	Slightly significant	Slightly significant	Slightly significant
Traffic density	Slightly significant	Not significant	Very significant
Excavation depth	17 to 22 m	12 m	12 m
Adjacent buildings	Extremely significant	Not significant	Slightly significant
Design requirements Soil condition	Fill, sandy silt, to sand	Fill, sandy silt, to sand	Fill, sand, to clay
Water table level	high	high	Very low
Location of structure	Very significant	Slightly significant	Slightly significant
Design calculation	significant	Slightly significant	Slightly significant
Cost Cost of construction	Very significant	Slightly significant	Moderately significant
Technology availability (Excavation machine)	Available	Not available	Not available
Time of construction Speed of construction	Extremely significant	Slightly significant	Moderately significant

Table 12 illustrates the different conditions of each case study. These data are collected from semi-structured interviews conducted with site managers represent the contractor, the consultant, and the client.

Each condition in table 12 is translated to linguistic variable and numerical rate value as in table 1 and entered to the software to create the pairwise comparison.

Input data entry for the model is the relative degree of importance between the two compared criterion or alternatives.

The output from the software for the main criteria rank is as follows:

1. **KitKat external access**

TABLE 13. Main criteria rank

	Description	Relative weight	Rank
MAIN CRITERIA	Design Requirements	0.4838	1
	Construction and site condition	0.3574	2
	Time of construction	0.0812	3
	Cost	0.0776	4

TABLE 14. Alternatives priorities

Alternative	**Relative weight**	**Rank**
Diaphragm wall	0.4065	1
Secant piles with a strut beam system	0.3089	2
Berlin wall (Soldier lagging wall)	0.2399	3
Contiguous piles	0.0447	4

2. **KitKat water tank**

TABLE 15. Main criteria rank

	Description	Relative weight	Rank
MAIN CRITERIA	Design Requirements	0.4455	1
	Cost	0.3059	2
	Construction and site condition	0.1927	3
	Time of construction	0.0559	4

TABLE 16. Alternatives priorities

Alternative	**Relative weight**	**Rank**
Berlin wall (Soldier lagging wall)	0.3896	1
Secant piles	0.2355	2
Contiguous piles	0.2047	3
Diaphragm wall	0.1701	4

2. **Heliopolis access**

TABLE 17. Main criteria rank

	Description	Relative weight	Rank
MAIN CRITERIA	Construction and site condition	0.3877	1
	Cost	0.3367	2
	Time of construction	0.2228	3
	Design Requirements	0.0528	4

TABLE 18. Main criteria rank

Alternative	**Relative weight**	**Rank**
Berlin wall (Soldier lagging wall)	0.3812	1
Contiguous piles	0.3311	2
Secant piles	0.2011	3
Diaphragm wall	0.0866	4

4.3 Results and Discussion

According to the analysis that was done based on the collected answers from the questionnaires, design requirements, including water table level, soil conditions, and location of a structure, rank first. Construction and site conditions rank second in terms of practitioner interest. This is due to the fact that their components are critical to the safety of all surrounding properties. Due to the urgency of completing this project on time and the high cost of the technology used in these types of projects, time and cost are also concerns.

Regarding the alternatives' priorities, the diaphragm wall system occupies the top rank, despite its high cost and the fact that it is suitable for most of the critical conditions in that type of construction, in addition to its advantage of being used as a permanent structure.

On the other hand, regarding the actual case studies, KitKat metro station access, according to table 13, the design requirements criterion gets the highest rank and site conditions come second.

According to table 14, the first candidate support system to be used is the diaphragm wall system. In this case, the model results match what happened in reality as in Fig.9.

In the case of the water tank, as in table 15, design requirements also get the highest rank, and cost comes in second. According to table 16, the berlin wall system gets the highest degree of priority, and secant piles come in second, perhaps due to their higher cost and slightly greater significance as site restrictions. The model results are also consistent with what actually occurred as in Fig.10.

Finally, due to slight design constraints, Heliopolis metro station's site conditions and cost rank first and second, respectively, in table 17. According to table 18, the berlin Wall system gets the first priority, and contiguous piles come in second with very little difference in the degree of priority. In this case, the model is inconsistent with very little difference with what happened in reality as in Fig.11.

Fig 9. Diaphragm walls in KitKat metro station access

Fig 10. Berlin wall for Water tank in KitKat metro station

Access (6, 7, 8) layout

(a)

Access (7) contiguous CFA piles

(b)

Fig11. Heliopolis metro station accesses

5. CONCLUSIONS

The research aimed at developing a multi-criteria decision-making model using the FAHP technique to help designers and practitioners in the field of tunneling projects or similar projects select the most appropriate alternative.

First, the criteria that influenced the selection were classified from the literature and structured interviews. A group of professionals with different experiences in specialized companies in the same field in metro projects were utilized. Four primary criteria and thirteen sub-criteria were considered to select the most appropriate deep excavation support system between the diaphragm wall, secant pile, contiguous pile, and berlin wall systems. The model was applied on case studies of Heliopolis and KitKat metro stations in the greater Cairo Metro to demonstrate its applicability.

Based on the results of this research, specific conclusions can be summarized, as follows:

1. Design requirements, particularly water table level, soil conditions, and anticipated stresses, are highly concerned and almost always take precedence in the selection of the support system.
2. The level of safety, adjacent buildings, crossings, and nearby utilities, as well as excavation depth, are all important factors to consider when making a decision.
3. Due to the nature and volume of these projects, time and construction costs are important considerations.
4. Regarding the alternative selection, diaphragm wall systems come first and secant pile systems second due to their suitability for these construction projects in urban areas. Berlin wall system comes last, although it is used widely at sites but in depths ranging from 5.0 to 15.0 meters. The contiguous pile wall system is preferable if compared with the berlin wall system in the case of adjacent properties because it is executed before excavation to retain soil during excavation,

whereas, in the berlin system, the excavation is in progress as sheeting progresses.

5. The model presented in this study is applicable to any deep excavation project; the only difference is that the project's criteria must be identified. Determine the feasible alternatives that can be researched. The model presented in this research is applicable for any deep excavation project; the only difference is identifying the project’s criteria. Furthermore, determine the feasible alternatives that can be studied.
6. The model can be used by multiple users with multiple factors to generate pairwise comparison matrices. In addition to dealing with subjective judgements, imprecise information, and uncertainty factors, and evaluating the relative weights of criteria. It provides the user with the final priorities for the feasible alternatives.

For future research, the current method can be expanded by integrating it with other fuzzy strategies with trapezoidal membership functions. Additionally, make a model that collects the most systems and all available types to consider all factors influencing the selection.

REFERENCES

[1] M. Khosravi and K. Kähkönen, “Management and planning under complexities of metro construction,” Procedia Economics and Finance, vol. 21, pp.415–421, 2015.

[2] R. Jameson, J. Starcevich, R. Hanke, and N. Turus, “North American Trends and Developments of Complex Support of Excavation Systems,” in IFCEE 2015, 2015, pp. 1358–1369.

[3] C.-Y. Ou, Deep excavation: Theory and practice. Crc Press, 2014.

[4] S. W. Australia, “Excavation Work-Code of Practice,” New South Wales: Work Cover. Available from: http://www. safework. nsw. gov. au, 2015.

[5] K. Datta and S. Nath, “Deep Excavation: An Overview & Case Studies,” in Indian Geotechnical Conference (IGC 2016), IIT Madras, 2016.

[6] M. M. E. Zumrawi and A. El-Amin, “Importance of deep excavation support and its influence on adjacent buildings,” in 7th Annual Conference for Postgraduate Studies and Scientific Research, 2016.

[7] M. S. Hossain, J. Mydlinski, K. N. Rao, and M. A. Haque, “Temporary Excavation Support System—A Case Study in Virginia,” in Geo Congress 2006: Geotechnical Engineering in the Information Technology Age, 2006, pp. 1–5.

[8] I. E. G. Davey-Wilson, “Fuzzy set adaptation for foundation construction,” Advances in Engineering Software, vol. 32, no. 10–11, pp. 813–820, 2001.

[9] R.-J. Dzeng and N.-F. Pan, “Learning heuristics for determining slurry wall panel lengths,” Automation in Construction, vol. 15, no. 3, pp. 303–313, 2006.

[10] N. F. Pan, “Selection of Earth Retaining Methods for Deep Excavation in Kaohsiung Area Using Fuzzy AHP,” Journal of Architecture (Architectural Institute of Taiwan), vol. 58, pp. 19–40, 2006.

[11] N. F. Pan, “Selecting an appropriate excavation construction method based on qualitative assessments,” Expert System Application, vol. 36, no. 3, pp. 5481–5490, 2009.

[12] H. Wefki, E. Elbeltagi, and M. Emam, “Selecting an appropriate excavation support system in Egypt using fuzzy AHP,” Al-Azhar University Engineering Journal, JAUES, vol. 5, no. 1, pp. 510–522, Dec. 2010.

[13] H.-C. Yang and C.-C. Liu, “Selection of interruptive protection methods in rapid transit underground construction: Hsi-Chi Yang Chen-Chung Liu,” in Civil, Architecture and Environmental Engineering, CRC Press, 2017, pp. 260–265.

[14] M. Farzi, M. S. Pakbaz, and H. A. Aminpour, “Selection of support system for urban deep excavations: a case study in Ahvaz geology,” Case studies in construction materials, vol. 8, pp. 131–138, 2018.

[15] X. Cao, Z. Liu, and H.-C. Yang, “A Case Study for Selecting a Protection Method in Underground Excavation,” in 2019 IEEE International Conference on Architecture, Construction, Environment and Hydraulics (ICACEH), 2019, pp. 1-4.

[16] A. M. El-Kelesh and D. A. Hassan “Factors Affecting Selection of Excavation Support System,” Design Engineering, vol. 2021, no. 7, pp. 9711–9730, Aug. 2021, doi: 10.17762/de.vi.3550.

[17] A. M. El-Kelesh and D. A. Hassan, “Impact of ground conditions and excavation depth on selection of excavation support system,” International Journal of Construction Management, pp. 1–12, 2022.

[18] U. Issa, F. Saeed, Y. Miky, M. Alqurashi, and E. Osman, “Hybrid AHP-Fuzzy TOPSIS Approach for Selecting Deep Excavation Support System,” Buildings, vol. 12, no. 3, p. 295, 2022.

[19] G. Horodecki and E. Dembicki, “Impact of deep excavation on nearby urban area,” 2007.

[20] J. Qi, X. Zhao, and H.-C. Yang, “Selection of deep excavation construction methods in building construction,” in 2020 IEEE 2nd International Conference on Architecture, Construction, Environment and Hydraulics (ICACEH), 2020, pp. 72–75.

[21] S. A. Chini and G. Genauer, “Excavation support systems for construction operations,” J. Construction. Education, vol. 2, pp. 156–170, 1997.

[22] G. Phillips-Wren and N. Ichalkaranje, Intelligent decision making: An AI-based approach, vol. 97. Springer Science & Business Media, 2008.

[23] K. Terzaghi, R. B. Peck, and G. Mesri, Soil mechanics in engineering practice. John Wiley & Sons, 1996.

[24] M. U. Ergun, “Deep excavations,” Electronic Journal of Geotechnical Engineering, Available at: www. ejge. com/Bouquet08/UfukErgun_ppr. pdf, 2008.

[25] M. Noktehdan, M. R. Zare, J. Adafin, S. Wilkinson, and M. Shahbazpour, “Application of fuzzy analytic hierarchy process (AHP) for ranking and selection of innovation in infrastructure

project management," in Smart and Sustainable Cities and Buildings, Springer, 2020, pp. 147–170.

[26] W. Meethom and T. Triwong, "Evaluating Urban Metro Construction Excavated Soil Disposal Sites based on fuzzy AHP," 2016.

[27] M. M. M. E. Elashram and A. H. Ibrahim, "Application of Fuzzy AHP on Determining the Dewatering Main Criteria Weights in Egypt," MEJ. Mansoura Engineering Journal, vol. 43, no. 3, pp. 13–20, 2020.

[28] S. Shaffiee Haghshenas, R. Mikaeil, M. Abdollahi Kamran, S. Shaffiee Haghshenas, and H. Hosseinzadeh Gharehgheshlagh, "Selecting the Suitable Tunnel Supporting System Using an Integrated Decision Support System, (Case Study: Dolaei Tunnel of Touyserkan, Iran)," Journal of Soft Computing in Civil Engineering, vol. 3, no. 4, pp. 51–66, 2019.

[29] D.-I. Kim, W. S. Yoo, H. Cho, and K.-I. Kang, "A fuzzy AHP-based decision support model for quantifying failure risk of excavation work," KSCE Journal of Civil Engineering, vol. 18, no. 7, pp. 1966–1976, 2014.

[30] T. M. Zayed, "Selecting pile construction method using fuzzy approach," in Construction Research Congress 2005: Broadening Perspectives, 2005, pp. 1–10.

[31] M. Foroughi Masouleh, "Multi-Attributed Selection of Excavation Methods in Tunneling Construction," 2015.

[32] M. Z. Naghadehi, R. Mikaeil, and M. Ataei, "The application of fuzzy analytic hierarchy process (FAHP) approach to selection of optimum underground mining method for Jajarm Bauxite Mine, Iran," Expert System Application, vol. 36, no. 4, pp. 8218–8226, 2009.

[33] D.-Y. Chang, "Applications of the extent analysis method on fuzzy AHP," Eur J Oper Res, vol. 95, no. 3, pp. 649–655, 1996.

[34] Y.-M. Wang, T. M. S. Elhag, and Z. Hua, "A modified fuzzy logarithmic least squares method for fuzzy analytic hierarchy process," Fuzzy Sets System, vol. 157, no. 23, pp. 3055–3071, 2006.

[35] Y.-M. Wang, Y. Luo, and Z. Hua, "On the extent analysis method for fuzzy AHP and its applications," Eur J Oper Res, vol. 186, no. 2, pp. 735–747, 2008.

[36] Y. Liu, C. M. Eckert, and C. Earl, "A review of fuzzy AHP methods for decision-making with subjective judgments," Expert System Application, vol. 161, p. 113738, 2020.

[37] C.-T. Yeh, "On improving trapezoidal and triangular approximations of fuzzy numbers," International Journal of Approximate Reasoning, vol. 48, no. 1, pp. 297–313, 2008.

[38] C.-T. Yeh, "Existence of interval, triangular, and trapezoidal approximations of fuzzy numbers under a general condition," Fuzzy Sets System, vol. 310, pp. 1–13, 2017.

[39] A. Awasthi, K. Govindan, and S. Gold, "Multi-tier sustainable global supplier selection using a fuzzy AHP-VIKOR based approach," Int. J Prod Econ, vol. 195, pp. 106–117, 2018.

[40] T. L. Saaty, "The analytical hierarchy process, planning, priority," Resource allocation. RWS publications, USA, 1980. [41] J. Franek and A. Kresta, "Judgment scales and consistency measure in AHP," Procedia economics and finance, vol. 12, pp. 164–173, 2014.

[42] L. Che, Y. Zhang, J. Wang, and M. Bai, "A New Method for Deriving Weights in Group Fuzzy Analytic Hierarchy Process and Evaluation Measures," IFAC-Papers Online, vol. 53, no. 2, pp. 7941–7946, 2020.

[43] T. L. Saaty, Decision making for leaders: the analytic hierarchy process for decisions in a complex world. RWS publications, 2001.

[44] L. A. Zadeh, "Fuzzy sets," Information and control, vol. 8, no. 3, pp. 338–353, 1965.

[45] P. J. M. Van and W. Pedrycz, A fuzzy extension of Saaty's priority theory. Department of Mathematics and Informatics, University of Technology, 1982.

[46] T. Demirel, N. Ç. Demirel, and C. Kahraman, "Fuzzy analytic hierarchy process and its application," in Fuzzy multi-criteria decision making, Springer, 2008, pp. 53–83.

[47] S. Kubler, J. Robert, W. Derigent, A. Voisin, and Y. le Traon, "A state-of the-art survey & testbed of fuzzy AHP (FAHP) applications," Expert Syst. Appl., vol. 65, pp. 398–422, 2016.

[48] N. Elshaboury, T. Attia, and M. Marzouk, "Comparison of several aggregation techniques for deriving analytic network process weights," Water Resources Management, vol. 34, no. 15, pp. 4901–4919, 2020.

[49] N. Elshaboury, "Prioritizing risk events of a large hydroelectric project using fuzzy analytic hierarchy process," Journal of Project Management, vol. 6, no. 3, pp. 107–120, 2021.