Fuzzy AHP for selecting suppliers of construction materials

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Abstract. The selection of suppliers is one of the key issues of supply logistics of any business entity. Due to the globalization of the economy and the rapid technological progress, the choice of products and the number of vendors is growing, which makes the selection process difficult. The specific character of the construction projects (one-off contracts with no incentives of the steady orders from one client, the need to adjust the batch size to the pace of the construction works whereas this pace is affected by risks and uncertainties, short time for planning, etc.) poses extra challenges to the suppliers’ production and transportation capacities and defines what “capable suppliers” mean for the project success. Therefore, the criteria of a construction project supplier selection go far beyond the obvious “price”. They need to refer to the supplier’s bid as well as the supplier’s own qualities (financial standing, reputation, flexibility). Though the selection process is expected to be based on unequivocal and objective input, in practice, it rests upon opinions and artificial measures used in lieu of the complete information. This input is, thus, fuzzy by nature and ignoring this fact may lead to wrong decisions. Therefore, the authors analyze the ways of quantifying supplier selection criteria and the methods of using them in the decision-making process presented in the literature. Then, they present a numerical example of supplier selection based on AHP with the fuzzy input, juxtaposing it with the results of the “classical” AHP with a crisp input. The results are different. Though this difference cannot be generalized, it indicates that the method of analysis may strongly affect the decision-makers choices.

1. Introduction

Over the last decade, the scale and the number of road and rail infrastructure projects in Poland have been growing [1] resulting in high demand for bulk materials such as natural aggregates or cement; the supply was reported to not always keep pace with this raised demand posing extra risks to the projects [1, 2]. The final product of a project is the outcome of combined efforts of all project participants: the design team, the contractors and the suppliers of materials. A reliable supplier to provide timely deliveries of quality materials is expected to significantly reduce the risks of rejection of works, cost of remedial work, and project delay. The construction project participants are particularly exposed to the risk of “wrong choice” of partners: they are typically being selected per project and expected to operate as a well-oiled machine despite the fact that they may work together for the first and last time [3]. Moreover, the cost of materials with their transport and handling has a considerable share of the total cost of the works. Thus, the contractor’s ability to find even small economies in the material management process (selection of right suppliers being its key part) is likely to positively impact the outcome of a project.

The literature presents a wide choice of criteria adopted in supplier selection decisions. For instance, a broad review by Thiruchelvam and Tookey [3] listed 36 types of criteria most frequently quoted in the literature on the subject between 1966 and 2010; the criteria were related to both the qualities of the suppliers and their bids. In most cases, these criteria were neither directly measurable nor explicit. However, for practical reasons (accountability, transparency, fairness), the criteria are expected to be as clear as possible. The criteria may be country-specific, reflecting a local business culture and economic circumstances, or specific for the client organization [4, 5]. As came from the
Report [6], in the German market, delivery times and customer service played a key role in the selection of suppliers, whereas reliability and flexibility of the supplier were less important; attention was also paid to environmental aspects. In Sweden, availability was reported to be more important than price, as delays in construction can lead to huge delay damages payable to the client, and thus local suppliers were favored. Ukrainian buyers put the priority on price, choosing cheaper domestic materials, whereas the Russians leaned towards recognized brands [6]. For these reasons, the methods of multicriteria assessment of suppliers and their bids are the focus of both practitioners and researchers [7-11].

The simplest approach used in solving multicriteria ranking is the Simple Additive Weighting (SAW). After developing a list of criteria $u=(1, 2, \ldots, l)$, a weight $w_u$ is assigned to each criterion to define its relative importance. Then, using a uniform rating scale, the user provides a rating $v_{tu}$ for each decision alternative $t$, $(t=1, 2, \ldots, k)$. Typically, the higher the rating, the better a particular option satisfies the criterion. The final score of an option, $Q_t$, is calculated as a weighted sum of ratings:

$$Q_t = \sum_{u=1}^{l} w_u \cdot v_{tu} \quad (t=1, 2, \ldots, k),$$

(1)

The weights are typically subjectively defined. Similarly, the way of assigning scores is subjective: even if the criteria are precisely measurable (like price or delivery time), turning them into ratings of a uniform scale (normalization) distorts information. There are many ways of normalizing to select from, and they strongly affect final results [12]. Once the weights and normalization approach are decided, the assessment based on SAW “has a straightforward intuitive appeal and transparency” [13, 14] and involves minimal computational effort. The literature provides methods of “tuning” the weights to avoid subjectivity, e.g. Ng [15] proposed a linear programming model to refine weights and to calculate the final scores assuming that the user is able only to rank the weights without providing precise values.

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [16] also requires that scores are normalized. It also provides no guidelines for objective assessment of criteria weights. The global assessment is based on the measurement of similarity to an “ideal” solution, combining best of the ratings observed in the options under assessment. Its merits in the selection of the most advantageous bid were presented, among others, in [17, 18].

ELECTRE I (Elimination et Choice Translating Reality) method for selecting suppliers was discussed in detail by de Almeida [19] and de Boer [20]. This method, together with PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations), PAMSSEM (Procédure d’Agrégation Multicritère de type Surclassement de Synthèse pour Évaluations Mixtes) or ORESTE (Organization, Rangement Et Synthèse de Donnés Relationnelles), belongs to the so-called European (French) school of decision making. These methods are based on pairwise comparisons and outranking relationship that, resting upon the available information (preferences, values of the criteria), enable the user to conclude that one option is at least as good as another one. The outranking relationship assumes one of the following states: strict preference, incomparability, and indistinguishability. The PROMETHEE method introduces six preference functions, providing flexibility in modeling the preferences of the decision-maker and easy interpretation of veto thresholds for each criterion [21].

The AHP (Analytic Hierarchy Process) by Saaty [22], is one of the most frequently used methods described in the literature on the supplier selection problem [14, 23, 24, 25]; the complex problem of multi-criteria evaluation has been replaced with a set of simple problems, defined at the same level of generalization (setting weights of criteria and then preferences of options/bids evaluated separately for
each criterion). On each level of the target hierarchy, calculations are repeated according to the same principle of pairwise comparisons of first the criteria and then the options, using the same verbal scale transformed to real positive numbers to capture the relative dominance [26]. The verbal scale facilitates expressing preferences on objects that are either difficult to measure or that are incompletely described. The aim of the calculations is to determine the contribution (or weight) of an individual criterion to the assessment objective and then to determine to what extent an individual option meets the requirements defined by the criteria. The decomposition of the problem results in a relatively small number of comparisons at each stage of the calculations, taking into account only one factor at a time. This makes it much easier for the decision-maker to determine the impact of this factor on the main objective. Using relative dominance makes it unnecessary to precisely quantify the values of the criteria. Liu and Hai [27] put forward a simplified procedure for determining the criteria weights in AHP applied to select suppliers [27]. However, it requires that a large number of experts are involved in the selection process.

Supplier selection criteria are either quantitative or qualitative. Small differences in the values of measurable criteria may be insignificant, but they unequivocally determine the outranking relationship. However, if the criteria values are naturally imprecise, the decision-making process becomes difficult. Quantification of qualitative criteria is subjective due to the intuitive nature of the assessment. In many cases, it is easier for the decision-maker to determine relative preferences by indicating a range of values or define them in a descriptive way rather than give a specific value from a scale. If the input is imprecise, the assessment method should retain this character [28]. Applying the fuzzy set theory to multi-criteria evaluation facilitated mapping the decision-making process (e.g. fuzzy TOPSIS [29] and fuzzy AHP [30, 31]). The first fuzzy extensions of AHP were attributed to Van Laarhoven and Pedrycz [32], Buckley [33], and Chang [34], who expressed relative preferences by triangular fuzzy numbers. In the process of defining the vector of weights on the basis of a matrix of pairwise comparisons, a variety of procedures are in use, including the geometric mean method [33], the fuzzy least squares method [32], the lambda-max method [35] and fuzzy preference programming [36].

The authors analyze the ways of quantifying supplier selection criteria and the methods of using them in the decision-making process presented in the literature. Then they present a numerical example of supplier selection based on AHP with fuzzy input (a simple approach with triangular fuzzy assessments and defuzzification of the vector of weights and vectors of local preferences of options before calculating the final scores. The results were compared with the results of the “classical” AHP with crisp input. The results are different in terms of final crisp measures representing aggregated scores of options. Though this difference cannot be generalized, it indicates that the method of analysis may strongly affect the decision-makers choices.

2. Fuzzy AHP
The supplier selection algorithm starts with defining a finite set of supplier bids to be assessed according to a consistent set of criteria. Like the “classical” AHP, it comprises a number of steps [37, 38]:

1) Constructing a hierarchical model of the problem;
2) Deriving criteria weights: constructing a matrix of pairwise comparisons of the criteria, checking its consistency, and calculating the generalized weights;
3) Deriving preferences on bids, separately for each criterion: constructing matrices of pairwise comparisons, checking their consistency, and calculating generalized preferences.
4) Deriving overall priorities by synthesis of the results: final scores expressed by numbers are the basis of selecting the winning bid; the score is a linear additive utility function as in Eq. (1).

The decision maker is expected to determine the relative dominance of a criterion (or a bid assessed according to a criterion) over each of the remaining criteria (or bids). To do so, the decision maker needs a preference scale. A linguistic description of dominance is expressed by a fuzzy number \( \tilde{a} = (l, m, u) \) of a triangular membership function defined on the range \([l, u]\) and assuming a value of 1 in point \( m \). The values of \( l, m, \) and \( u \) are odd values from the range of \([1, 9]\), as in the classic AHP. An example of a preference scale is presented in Table 1. However, if a five-level scale is not precise enough, it can be expanded by analogy to introducing intermediate levels expressed as even numbers in the classical AHP.

| Verbal scale of dominance judgment | Fuzzy number \((l, m, u)\) | Classical scale |
|------------------------------------|-----------------------------|-----------------|
| Equally important                  | \((1, 1, 3)\)               | 1               |
| Moderately more important          | \((1, 3, 5)\)               | 3               |
| Strongly more important            | \((3, 5, 7)\)               | 5               |
| Very strongly more important       | \((5, 7, 9)\)               | 7               |
| Extremely more important           | \((7, 9, 9)\)               | 9               |

The results of pairwise comparisons are collected in the matrix \( \tilde{A} \):

\[
\tilde{A} = \begin{bmatrix}
\tilde{a}_{11} & \tilde{a}_{12} & \ldots & \tilde{a}_{1n} \\
\tilde{a}_{21} & \tilde{a}_{22} & \ldots & \tilde{a}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{a}_{n1} & \tilde{a}_{n2} & \ldots & \tilde{a}_{nn}
\end{bmatrix}
\]

Its elements are triangular fuzzy numbers \( \tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}) \), where \( i, j = 1, 2, \ldots, n \) are the numbers of criteria (step 2 of the analysis), or the numbers of compared bids (step 3 of the analysis). The comparison matrix is symmetrical: \( \tilde{a}_{ij} = (1, 1, 1) \forall i = j \) and \( \tilde{a}_{ij} = \frac{1}{\tilde{a}_{ji}} \forall i \neq j \). The literature puts forward a number of prioritization methods. Let us select the geometric mean approach for calculating the vector of weights on the basis of the matrix of pairwise comparisons [33, 39]. The geometric mean is:

\[
\tilde{r}_i = \left( \prod_{j=1}^{n} \tilde{a}_{ij} \right)^{1/n}; \quad i = 1, 2, \ldots, n,
\]

and the weight is:

\[
\tilde{w}_i = \tilde{r}_i \odot \left( \tilde{r}_1 \odot \tilde{r}_2 \odot \ldots \odot \tilde{r}_n \right)^{-1}; \quad i = 1, 2, \ldots, n.
\]

Operations on fuzzy numbers are defined as follows:

\[
\tilde{a}_1 \oplus \tilde{a}_2 \cong (l_1 + l_2, m_1 + m_2, u_1 + u_2),
\]

\[
\tilde{a}_1 \odot \tilde{a}_2 \cong (l_1 \cdot l_2, m_1 \cdot m_2, u_1 \cdot u_2),
\]

\[
\tilde{a}_1^{-1} \cong \left( \frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1} \right).
\]
1\ 1 \ 11 
\[ \left[ \begin{array}{c}
1 \\
\frac{1}{3} \\
\frac{1}{5} \\
\frac{1}{7}
\end{array} \right] \] (7)

The weights calculated this way are triangular fuzzy numbers \((l_{wi}, m_{wi}, u_{wi})\). To convert them into crisp values, the center of gravity method was applied:

\[ w_i = \frac{l_{wi} + m_{wi} + u_{wi}}{3}; \quad i = 1, 2, \ldots, n. \] (8)

Then, to normalize the weights so that their sum equals 1, the following operation is to be conducted:

\[ w_{ni} = \frac{w_i}{\sum_{i=1}^{n} w_i}; \quad i = 1, 2, \ldots, n. \] (9)

This concludes calculations in Step 2. Step 3 (pairwise comparisons of bid assessments and converting them to normalized crisp values) is to be conducted accordingly.

3. Numerical example

3.1. Fuzzy calculations

Let us consider the following problem: a project manager is to select a supplier of ready-mixed concrete for a project located in the middle of a large city. Delivery of the mix in the city center is difficult due to traffic conditions, so not only the distance matters. Due to the constraints on delivery time (concrete setting), the number of suppliers is limited, and the batching plant location becomes the most important criterion. All suppliers are able to produce the mix according to a precise specification, so the quality criterion is not considered. Apart from the price, an important criterion is the capacity of the batching plant, understood as the ability to adjust production level and assure delivery of the mix to the building site. From the contractor’s point of view, the payment conditions are important: the longer the trade credit offered by the supplier, the better. It is relatively easy to change the supplier of ready-mixed concrete without a negative impact on the course of works on the construction site. Thus, in the problem of selecting the best supplier out of three potential ones, four following criteria are considered sufficient: the price of the mix (1), the location of the batching plant (2), terms of payment (3) and the batching plant’s capacity (4).

In the course of pairwise comparisons of the criteria in terms of their relative importance, it was assumed that the location is essentially more important than both the price and the terms of payment, and that it is of equal importance with the plant capacity. The capacity is considered weakly more important than the terms of payment and the price. The price was found weakly more important than the terms of payment. On the basis of the scale of relative dominance (Table 1), the following values of elements of the matrix of comparisons were assumed:

\[ \tilde{A} = \begin{bmatrix}
(1, 1, 1) & \left( \frac{1}{7}, \frac{1}{5}, \frac{1}{3} \right) & (1, 3, 5) & \left( \frac{1}{5}, \frac{1}{5}, 1 \right) \\
(3, 5, 7) & (1, 1, 1) & (3, 5, 7) & (1, 1, 3) \\
\left( \frac{1}{5}, \frac{1}{5}, 1 \right) & \left( \frac{1}{5}, \frac{1}{5}, \frac{1}{3} \right) & (1, 1, 1) & \left( \frac{1}{5}, \frac{1}{5}, 1 \right) \\
(1, 3, 5) & \left( \frac{1}{5}, 1, 1 \right) & (1, 3, 5) & (1, 1, 1)
\end{bmatrix} \]

The geometric mean of the scores for the price criterion, according to Equations 2, 5 and 7, was:
\[ \tilde{r}_i = \left( \tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \tilde{a}_{i3} \otimes \tilde{a}_{i4} \right)^\frac{1}{2} = \left( \left[ \frac{1}{7}, 1, \frac{1}{5} \right], \left[ \frac{1}{5}, 1, \frac{1}{3} \right], \left[ \frac{1}{3}, 1, \frac{1}{7} \right] \right)^\frac{1}{2} = (0.411, 0.669, 1.136) \]

and for the remaining criteria: \( \tilde{r}_2 = (1.732, 2.236, 3.482), \) \( \tilde{r}_3 = (0.275, 0.386, 0.760), \) \( \tilde{r}_4 = (0.760, 1.732, 2.236). \) Therefore, \( \tilde{r}_1 \otimes \tilde{r}_2 \otimes \tilde{r}_3 \otimes \tilde{r}_4 = (3.178, 5.023, 7.614). \)

The weight of price criterion was calculated according to Equations 3, 4, 5 and 6 as follows:

\[ w_r = (0.411, 0.669, 1.136), \]

and similarly, the weights of the remaining criteria were, correspondingly,

\[ w_2 = (0.054, 0.133, 0.358), \]

\[ w_3 = (0.036, 0.077, 0.239), \]

\[ w_4 = (0.100, 0.345, 0.704). \]

Defuzzified values of the weights were calculated according to Equation 8: \( w_1 = \frac{1}{3} (0.054 + 0.133 + 0.358) = 0.182, w_2 = 0.589, w_3 = 0.117 \) and \( w_4 = 0.383. \)

Normalization according to Equation 9 produced the following results:

\[ w_{n1} = 0.182 / (0.182 + 0.589 + 0.117 + 0.383) = 0.143, w_{n2} = 0.464, w_{n3} = 0.092, w_{n4} = 0.301. \]

The assessment of preferences on the options (suppliers) according to the particular criteria followed the same pattern. The second supplier offered a price significantly lower than the others, so this supplier was very strongly preferred over the remaining ones. The price offered by the third supplier was slightly lower than that offered by the first supplier, hence the assumption of a weak dominance. The relative dominance of the bids considered in the light of the price criterion is represented by the matrix \( \tilde{A}_1. \) The comparisons against the criteria of location, terms of payment and capacity are presented, correspondingly, in the matrices \( \tilde{A}_2, \tilde{A}_3, \) and \( \tilde{A}_4. \)

\[
\tilde{A}_1 = \begin{bmatrix}
(1, 1, 1) & \left( \frac{1}{9}, \frac{1}{7}, \frac{1}{5} \right) & \left( \frac{1}{5}, \frac{1}{3}, 1 \right) \\
(5, 7, 9) & (1, 1, 1) & (5, 7, 9) \\
(1, 3, 5) & \left( \frac{1}{9}, \frac{1}{7}, \frac{1}{5} \right) & (1, 1, 1)
\end{bmatrix},
\tilde{A}_2 = \begin{bmatrix}
(1, 1, 1) & \left( \frac{1}{7}, \frac{1}{5}, \frac{1}{3} \right) & \left( \frac{1}{5}, \frac{1}{3}, 1 \right) \\
(1, 3, 5) & (1, 1, 1) & \left( \frac{1}{7}, \frac{1}{5}, \frac{1}{3} \right) \\
(7, 9, 9) & (3, 5, 7) & (1, 1, 1)
\end{bmatrix},
\tilde{A}_3 = \begin{bmatrix}
(1, 1, 1) & \left( \frac{1}{9}, \frac{1}{7}, \frac{1}{5} \right) & (5, 7, 9) \\
(5, 7, 9) & (1, 1, 1) & (7, 9, 9) \\
\left( \frac{1}{9}, \frac{1}{7}, \frac{1}{5} \right) & \left( \frac{1}{9}, \frac{1}{7}, \frac{1}{5} \right) & (1, 1, 1)
\end{bmatrix},
\tilde{A}_4 = \begin{bmatrix}
(1, 1, 1) & \left( \frac{1}{7}, \frac{1}{5}, \frac{1}{3} \right) & \left( \frac{1}{7}, \frac{1}{5}, \frac{1}{3} \right) \\
(3, 5, 7) & (1, 1, 1) & (1, 1, 1) \\
(3, 5, 7) & \left( \frac{1}{3}, 1, 1 \right) & (1, 1, 1)
\end{bmatrix}.
\]

Crisp preferences on the supplier’s bids according to particular criteria were calculated according to the same pattern as in the case of weights. The results are summarized in Table 2.

**Table 2.** Defuzzified local preferences on bids, defuzzied criteria weights and final scores

| Supplier no. | price | location | t. of payment | capacity | Final score Q |
|-------------|-------|----------|---------------|----------|--------------|
| Supplier1   | 0.087 | 0.083    | 0.198         | 0.12     | 0.105        |
| Supplier2   | 0.755 | 0.187    | 0.751         | 0.496    | 0.413        |
| Supplier3   | 0.158 | 0.73     | 0.051         | 0.384    | 0.481        |
| defuzzified norm. weights | 0.143 | 0.464    | 0.092         | 0.301    | -            |
The final synthetic score, a weighted total of preferences, calculated according to Equation 1, was: 

\[ Q_1 = 0.143 \cdot 0.087 + 0.464 \cdot 0.083 + 0.092 \cdot 0.198 + 0.301 \cdot 0.120 = 0.105, \]

\[ Q_2 = 0.413, \]

\[ Q_3 = 0.481. \]

This indicated that the preference relation between the suppliers was: Supplier 3 \( \succ \) Supplier 2 \( \succ \) Supplier 1.

3.2. Classical approach

The same problem was described by “crisp” values of a classical AHP scale. In this case (later referred to as the base scenario), the judgments corresponded to the middle values of the triangular fuzzy numbers used in calculations presented in Section 3.1. The matrix \( A \) of pairwise comparisons of criteria according to perceived importance was:

\[
A = \begin{bmatrix}
1 & 1/5 & 3 & 1/3 \\
5 & 1 & 5 & 5 \\
1/3 & 1/5 & 1 & 1/3 \\
3 & 1 & 3 & 1
\end{bmatrix}
\]

The geometric means of scores for consecutive criteria were:

\[ r_1 = \left( \frac{1}{5} \cdot \frac{1}{3} \cdot \frac{1}{3} \right)^{1/3} = 0.669, \]

\[ r_2 = 2.236, \]

\[ r_3 = 0.077, \]

and the sum of geometric means was:

\[ r_1 + r_2 + r_3 + r_4 = 5.023. \]

The normalized weights:

\[ w_{s1} = r_1 \left( r_1 + r_2 + r_3 + r_4 \right)^{-1} = 0.133, \]

\[ w_{s2} = 0.445, \]

\[ w_{s3} = 0.077, \]

\[ w_{s4} = 0.345. \]

The consistency of the vector of weights was checked by means of the formulas proposed in the case of geometric means-based calculations in [39, 40] by comparing the calculated Geometric Inconsistency Index (GCI, Equation 10) with threshold values proposed by Aguarón and Moreno-Jiménez [40]; if GCI is not greater than the threshold, the matrix of comparisons can be considered consistent.

\[
GCI = \frac{2}{(n-1)(n-2)} \sum_{i<j} \log^2 \left( \frac{a_{ij}w_{ij}}{w_{ij}} \right).
\]

In this case, \( GCI = 0.046 \). The threshold value corresponding to Saaty’s Consistency Ratio CR of 0.1 and the order of the matrix \( n = 4 \) is 0.353 [40]. Therefore, the matrix was deemed consistent.

In the next steps, preferences on bids were derived according to one criterion at a time according to the above pattern. Then, using the values of weights, final scores of options were calculated according to Equation 1. The results are summarized in Table 3. The preference order corresponded to the one obtained in the fuzzy analysis in Section 3.1.

Table 3. Results of classical AHP (; pairwise assessments corresponding to middle values of fuzzy triangular numbers): local preferences, GCI, criteria weights and final scores

| Supplier no. | Criteria | Final score Q | price | location | t. of payment | capacity |
|--------------|----------|---------------|-------|----------|---------------|---------|
| Supplier1    | 0.076    | 0.070         | 0.243 | 0.091    |               |         |
| Supplier2    | 0.766    | 0.178         | 0.669 | 0.455    | 0.390         |         |
| Supplier3    | 0.158    | 0.751         | 0.088 | 0.455    | 0.519         |         |
| GCI (threshold [40] 0.315) | 0.076 | 0.016 | 0.181 | 0.000 | -             |         |
| weight       | 0.133    | 0.445         | 0.077 | 0.345    | -             |         |

A limited sensitivity analysis was conducted by checking changes to criteria weights, assuming that local comparisons of suppliers according to each criterion provided true results. Three scenarios were
considered: a) the crisp judgments $a_{ij}$ of relative importance are “stronger” and correspond to $u_{ij}$ of the triangular numbers representing fuzzy assessments collected in the matrix of comparisons $\tilde{A}$ from Section 3.1 if criterion $i$ is deemed more important than criterion $j$, and $l_{ij}$ in the other case, b) the assessments are “weaker”, c) criteria are equally important. Corresponding matrices of pairwise comparisons, $A_a$, $A_b$, $A_c$, are presented below:

$$A_a = \begin{bmatrix} 1 & 1/7 & 5 & 1/5 \\ 7 & 1 & 7 & 3 \\ 1/5 & 1/7 & 1 & 1/5 \\ 5 & 1/3 & 5 & 1 \end{bmatrix}$$

$$A_b = \begin{bmatrix} 1 & 1/3 & 1 & 1 \\ 3 & 1 & 3 & 1 \\ 1 & 1/3 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

$$A_c = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

All pairwise comparison matrices for the above scenarios proved consistent (Equation 10, results compared with thresholds by Aguarón and Moreno-Jiménez [40]. The weights, juxtaposed with defuzzified weights obtained by means of the fuzzy AHP and in the base case of the classical AHP, are presented in Table 4. Scenarios a) and b) maintained the logic of the base assessment of the relative importance of the criteria and the logic in AHP, and the relative importance of the criteria follows the pattern location $\succ$ capacity $\succ$ price $\succ$ terms of payment, but the values are in fact different. For instance, the base scenario’s weights of the price, the location and the terms of payment were lower, and the weight of the capacity was higher compared with defuzzified weights of the fuzzy AHP.

Table 4. Weights of fuzzy AHP and all scenarios of classical AHP

| Criteria       | Fuzzy AHP (defuzzified) | Classical AHP, base scenario | Classical AHP, scenario a) | Classical AHP, scenario b) | Classical AHP, scenario c) |
|----------------|-------------------------|-------------------------------|----------------------------|----------------------------|----------------------------|
| price          | 0.143                   | 0.133                        | 0.101                      | 0.179                      | 0.250                      |
| location       | 0.464                   | 0.445                        | 0.574                      | 0.407                      | 0.250                      |
| t. of payment  | 0.092                   | 0.077                        | 0.045                      | 0.179                      | 0.250                      |
| capacity       | 0.301                   | 0.345                        | 0.280                      | 0.235                      | 0.250                      |

Table 5. Total scores – summary of scenarios

| Supplier | Fuzzy AHP | AHP | Scenario a) | Scenario b) | Scenario c) |
|----------|-----------|-----|-------------|-------------|-------------|
| Supplier1| 0.105     | 0.091| 0.084       | 0.107       | 0.120       |
| Supplier2| 0.413     | 0.390| 0.337       | 0.436       | 0.517       |
| Supplier3| **0.481** | **0.519** | **0.578** | **0.457** | 0.363       |

The final suppliers’ scores are summarized in Table 5, with the preferred supplier’s score marked bold. Scenarios: base, a) and b) followed the logic of the fuzzy AHP assessment of the relative importance of the criteria and did not change the preference order established in Section 3.1. (Though, it is not a general rule, as the values of weights differ). In Scenario c), the weights were significantly different, what (in these particular circumstances) changed the preference order.

4. Discussion and conclusions

Both the classical and the fuzzy AHP, though, created to handle the judgments impossible to express by means of direct precise measures, rest upon artificially precise numbers subject to algebraic transformations in consecutive steps of the methods. Their output – a single numerical score for each option – relies heavily on the approach to coding and handling the input. The literature on AHP and its modifications are extremely rich [41], and there is no consensus on the methods to be used in any of
its steps to assure the credibility of the analysis [42], [43], the merits of checking the consistency of pairwise comparisons [42, 44], and even the judgment scales [45].

Assessing the credibility of suppliers, their skills, experience, equipment, ability to perform, financial standing etc. is usually based on the incomplete information and assessed by means of imprecise measures. Expressing relative preferences in the form of fuzzy numbers provides a way of expressing uncertainty in the formulation of the judgements in the decision-making process. This uncertainty is characteristic of the construction project environment. The presented fuzzy AHP approach is easy to use and involves moderate computational efforts.

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