A Discussion on “Pythagorean fuzzy AHP based risk assessment methodology for hazardous material transportation: an application in Istanbul”

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A Discussion on “Pythagorean fuzzy AHP based risk assessment methodology for hazardous material transportation: an application in Istanbul”

Shahid Ahmad Bhat^{1*}, Akanksha Singh²

Abstract Ayyildiz et al. (Environmental Science and Pollution Research (2021), 1-13) pointed out that it is important to identify and minimize the critical risks in the transportation of hazardous material. For the same, Ayyildiz et al. proposed an effective integrated decision-making methodology by combining the Modified Delphi Method (MDM) and Pythagorean fuzzy analytic hierarchy process (PF-AHP). In this integrated methodology, PF-AHP method is utilized to obtain weights of main and sub-risk factors in order to rank these factors. In Step 5 of PF-AHP method an interval valued Pythagorean fuzzy pairwise comparison matrix is transformed into a crisp matrix and then crisp AHP is applied to obtain the normalized weights from the transformed crisp matrix. It is quite evident that the crisp AHP is used only for crisp pairwise comparison matrix. However, after a deep study, it is observed that the transformed crisp matrix, obtained on applying the steps of Ayyildiz et al. methodology, violates the reciprocal propriety of pairwise comparison matrix. Therefore, to apply crisp AHP on the transformed crisp matrix is mathematically incorrect and will lead to problematic decision-making approach. Hence, may result in a heavy loss in any value-added model such as hazardous material transportation problems. Therefore, the Ayyildiz et al. methodology is not valid in its present form and cannot be used to find the solution of such type of real-life problem. Keeping the same in mind, the focus of this discussion is to make the researchers aware about these mathematical incorrect assumptions and the necessary modification is suggested.

Keywords: Crisp pairwise comparison matrix. Crisp AHP. Pythagorean fuzzy pairwise comparison matrix. PFAHP.

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1. Introduction

Ayyildiz et al. (2021) pointed out that the most important component of hazardous material logistics is the transportation of hazardous materials. During the transportation of hazardous materials, a number of safety measures should be undertaken. Therefore, to identify and minimize the risk factors in the transportation of hazardous material is more important. Motivated by the same, different from the existing studies, Ayyildiz et al. (2021) proposed an effective integrated decision-making methodology by combining the Modified Delphi Method (MDM) and Pythagorean fuzzy analytic hierarchy process (PF-AHP) to make the risk assessment process more coherent. Also solved a real case study of Istanbul petroleum transportation.

Furthermore, a general, six step based PF-AHP method (Ayyildiz et al., 2021) is utilized to obtain weights of main and sub-risk factors in order to rank these factors. Step 1 of PF-AHP method are used to collect the information from decision maker in terms of linguistic variables and the linguistic pairwise comparison matrices are constructed and using Table 2 (Ayyildiz et al., 2021, pp. 35805)), to transform the linguistic pairwise comparison matrices into interval valued Pythagorean fuzzy pairwise comparison matrices. After the construction interval valued Pythagorean fuzzy pairwise comparison matrices Step 2 to Step 4 are used to transform the interval valued Pythagorean fuzzy pairwise comparison matrices into the interval pairwise comparison matrices. Then, the Step 5 is used to transform the interval pairwise comparison matrices into the crisp matrices and Step 6 is used to obtain weights of main and sub-risk factors.

However, after a deep study, it is observed that on applying the step 5 of the PF-AHP to transform the interval valued Pythagorean fuzzy pairwise comparison matrices into crisp pairwise comparison matrices violate the reciprocal propriety of the pairwise comparison matrices i.e., the obtained crisp pairwise comparison matrices are not crisp pairwise comparison matrices. Therefore, it is a well-known fact the crisp AHP method (Saaty, 2008)

can be applied only to obtain the normalized priority weights. If the transformed crisp matrices are crisp pairwise comparison matrices (Saaty, 2008). Recently some authors (Bhat and Kumar, 2018a, 2018b, Krejčí, 2018, 2017a) also, pointed out that to applying the crisp AHP (Saaty, 2008) on crisp non-pairwise comparison matrix, to obtain the normalized priority weights is a meaningless task and it will mislead to the decision maker.

Hence, Step 5 of the PF-AHP (Ayyildiz et al., 2021) cannot be used. Therefore, the Ayyildiz et al. (2021) proposed integrated decision-making methodology (Ayyildiz et al., 2021) is not valid in its present form and cannot be used to find the solution of any real life problem. In future, the other researchers/stakeholders may use the same method (Ayyildiz et al., 2021) in numerous real life problems which lead to problematic decision making approach and hence may result in a heavy loss in any value-added model.

Focus of the present paper is to make the researchers aware about the mathematical incorrect assumptions of Ayyildiz et al. proposed integrated decision-making methodology (Ayyildiz et al., 2021) and the necessary modifications are suggested in the Ayyildiz et al.'s proposed integrated decision-making methodology (Ayyildiz et al., 2021), for its validity to obtain more valuable outcomes.

2. Preliminaries

In this section, some basic concepts and definitions are discussed for the readers to understand the concept of the reciprocal property of pairwise comparison matrix.

2.1 Pairwise comparison matrix

The concept of pairwise comparison matrix is a key in the utilization of the crisp AHP (Saaty, 2008) method. Pairwise comparison is simply, comparing two objects at a time e.g., if a decision maker D_1 likes an Apple (A) more than a Banana (B) this judgment can be represented by using Saaty's $\left[\frac{1}{9}, 9\right]$ ratio scale (Saaty, 2008) as $\frac{A}{B} = 3$ and obviously the relation between B and A can be represented by the ratio $\frac{B}{A} = \frac{1}{3}$. Therefore, the whole judgment of decision maker D_1 regarding the alternatives A and B can be represented

mathematically in the form of a pairwise comparison matrix $T = \begin{matrix} A & \begin{pmatrix} 1 & 3 \\ \frac{1}{3} & 1 \end{pmatrix} \\ B & \end{matrix}$. Hence, the propriety $t_{ij} = \frac{1}{t_{ji}}$ of matrix $T = (t_{ij})_{m \times m}$ is known as reciprocal property of the pairwise comparison matrix. Usually, two types of the pairwise comparison matrices are used in the literature (Krejčí, 2018, Saaty, 2008, 1990) one is multiplicative pairwise comparison matrix and another is additive pairwise comparison matrix. The following definitions express the situation below.

Definition 1. A square matrix $T = (t_{ij})_{m \times m}$ of m objects $(o_1, o_2, \dots, o_m)$ is said to be a multiplicative pairwise comparison matrix if it satisfies the conditions $t_{ij} = 1 ; i = j$ and $t_{ij} = \frac{1}{t_{ji}} ; i \neq j \forall i, j = 1, 2, \dots, n$ (reciprocal propriety) where, the elements t_{ij} represents preference intensity of object o_i over the object o_j i.e., o_i is t_{ij} -times as good as o_j (Saaty, 2008).

Definition 2. A square matrix $T = (t_{ij})_{m \times m}$ of m objects $(o_1, o_2, \dots, o_m)$ is said to be a additive pairwise comparison matrix if it satisfies the conditions $t_{ij} = 0.5 ; i = j$ and $t_{ij} + t_{ji} = 1 ; i \neq j \forall t_{ij} \in [0, 1], i, j = 1, 2, \dots, n$ (Tanino, 1984).

2.2. Likelihood of intervals

In order to transform the interval valued Pythagorean fuzzy pairwise comparison matrix into the crisp pairwise comparison matrix to preserve the reciprocal property of transformed crisp matrix, in this paper, the likelihood-based comparison relations are used. The inclusion comparison probability of alternatives or criteria $C_i \geq C_j ; i, j = 1, 2, \dots, n$ is denoted by $p(C_i \geq C_j)$ and the likelihood is defined as (Shi et al. , 2020):

Definition 3. Likelihood of interval $C_1 = [c_1^L, c_1^U]$ and $C_2 = [c_2^L, c_2^U]$ are defined as

$$p(C_1 \geq C_2) = \max \left\{ 1 - \max \left\{ \frac{c_2^U - c_1^L}{(c_1^U - c_1^L) + (c_2^U - c_2^L)}, 0 \right\}, 0 \right\} \text{ and satisfies the following}$$

properties (Shui and Li, 2003):

$$(i) \ 0 \leq p(C_1 \geq C_2) \leq 1$$

$$(ii) \ p(C_1 \geq C_2) = p(C_2 \geq C_1) = 0.5, \text{ if } p(C_1 \geq C_2) = p(C_2 \geq C_1)$$

$$(iii) \ p(C_1 \geq C_2) + p(C_2 \geq C_1) = 1$$

$$(iv) \ p(C_1 \geq C_2) = 0 \text{ if } c_1^U \leq c_2^L, p(C_1 \geq C_2) = 1, \text{ if } c_1^L \geq c_2^U$$

$$(v) \text{ For any interval numbers } C_1, C_2 \text{ and } C_3, p(C_1 \geq C_3) \geq 0.5, \text{ if } p(C_1 \geq C_2) \geq 0.5 \text{ and}$$

$$p(C_2 \geq C_3) \geq 0.5; p(C_1 \geq C_3) = 0.5 \text{ if and only if } p(C_1 \geq C_2) = p(C_2 \geq C_3) =$$

$$0.5$$

3. Mathematical incorrect assumptions of Ayyildiz et al.'s proposed integrated decision-making methodology

To point out the mathematical incorrect assumptions considered in the PFAHP proposed by (Ayyildiz et al., 2021), there is a need to discuss the steps of PF-AHP proposed by (Ayyildiz et al., 2021). For the convenience of the readers, instead of explaining the general steps of the PFAHP proposed by (Ayyildiz et al., 2021) the steps of a numerical example are discussed.

The following steps of the PFAHP proposed by (Ayyildiz et al., 2021), are used to obtain the weights of the criteria/alternatives of the decision matrix are as:

Step 1: Construct the interval valued Pythagorean fuzzy pairwise comparison matrix $A = (a_{ij})_{m \times m}$ based on the linguistic scale (Ayyildiz et al., 2021), where, $a_{ij} = \langle \mu_{ijL}, \mu_{ijU}, \nu_{ijL}, \nu_{ijU} \rangle$ is a Pythagorean fuzzy number (Yager, 2016). Also μ_{ijL} , μ_{ijU} and ν_{ijL} , ν_{ijU} are lower, upper membership and non-membership functions respectively. For example, consider the interval valued Pythagorean fuzzy pairwise comparison matrix of criteria C_1 and C_2 are shown in table 1.

Table 1 Interval valued Pythagorean fuzzy pairwise comparison matrix A of criteria C_1 and C_2

Criteria	C_1	C_2
C_1	$\langle [0.1965, 0.1965], [0.1965, 0.1965] \rangle$	$\langle [0.65, 0.80], [0.20, 0.35] \rangle$
C_2	$\langle [0.20, 0.35], [0.65, 0.80] \rangle$	$\langle [0.1965, 0.1965], [0.1965, 0.1965] \rangle$

124 **Step 2:** Transform the interval valued Pythagorean fuzzy pairwise comparison matrix A into
125 difference matrix $= (\langle d_{ijL}, d_{ijU} \rangle)_{m \times m}$, where, $d_{ijL} = \mu_{ijL}^2 - v_{ijU}^2$ and $d_{ijU} = \mu_{ijU}^2 - v_{ijL}^2$.
126 Therefore, the interval valued Pythagorean fuzzy pairwise comparison matrix (shown by
127 Table 1) will be transformed into difference matrix D (shown by Table 2).

128 **Table 2** Difference matrix D of criteria C_1 and C_2

Criteria	C_1	C_2
C_1	$\langle 0, 0 \rangle$	$\langle 0.3000, 0.6000 \rangle$
C_2	$\langle -0.6000, -0.3000 \rangle$	$\langle 0, 0 \rangle$

129
130 **Step 3:** Transform the difference matrix $D = (\langle d_{ijL}, d_{ijU} \rangle)_{m \times m}$ into the interval
131 multiplicative matrix $S = ([s_{ijL}, s_{ijU}])_{m \times m}$, where $s_{ijL} = \sqrt{1000^{d_{ijL}}}$ and $s_{ijU} = \sqrt{1000^{d_{ijU}}}$.
132 Therefore, the difference matrix D (shown by Table 2) will be transformed into the interval
133 multiplicative matrix S (shown by Table 3).

134 **Table 3** Interval multiplicative matrix S of criteria C_1 and C_2

Criteria	C_1	C_2
C_1	$\langle 1, 1 \rangle$	$\langle 2.8184, 7.9433 \rangle$
C_2	$\langle 0.1259, 0.3548 \rangle$	$\langle 1, 1 \rangle$

135
136 **Step 4:** Calculate the determinacy value $\tau = (\tau_{ij})_{m \times m}$ where, $\tau_{ij} = 1 - (\mu_{ijU}^2 - \mu_{ijL}^2) -$
137 $(v_{ijU}^2 - v_{ijL}^2)$. Therefore, from Table 1, the determinacy matrix $T = \begin{bmatrix} 1.00 & 0.700 \\ 0.700 & 1.00 \end{bmatrix}$.
138 **Step 5:** To transform the interval multiplicative matrix $S = ([s_{ijL}, s_{ijU}])_{m \times m}$ into crisp
139 matrix $= (t_{ij})_{m \times m}$, where, $t_{ij} = \left(\frac{s_{ijL} + s_{ijU}}{2} \right) \tau_{ij}$. Therefore, the interval multiplicative
140 matrix S (shown by Table 3) will be transformed into the crisp matrix T (shown by Table 4).

141 **Table 4** Crisp comparison matrix T of criteria C_1 and C_2

Criteria	C_1	C_2
C_1	1	3.7666
C_2	0.1682	1

142

143 **Step 6:** Finally using the crisp AHP to calculate the normalized priority weights of
 144 transformed crisp matrix T , using the relation $W_i = \frac{\sum_{j=1}^n t_{ij}}{\sum_{i=1}^n \sum_{j=1}^n t_{ij}}$. For example, on applying the
 145 crisp AHP on the crisp matrix (shown by Table 4), the normalized priority weights of
 146 criteria $C_1 = 0.8032$ and $C_2 = 0.1968$.

147 However, in order to calculate the priority weights of alternatives/criteria with the help of
 148 crisp AHP method (Saaty, 2008) the following condition is necessary for its implementation:

149 (I) Every criteria/alternative matrix should satisfy the reciprocal propriety of pairwise
 150 comparison matrix i.e., $a_{ij} = 1, i = j$ and $a_{ij} = \frac{1}{a_{ji}}, i \neq j, \forall i, j = 1, 2, \dots, n$
 151 (Krejčí, 2018; Saaty, 2008).

152 If the above condition will be satisfied for the transformed crisp matrix, then we will apply
 153 the crisp AHP method (Saaty, 2008) to determine the normalized priority weights of
 154 criteria/alternative of the crisp pairwise comparison matrix.

155 However, on applying the steps of Ayyildiz et al.'s PF-AHP (Ayyildiz et al., 2021),
 156 discussed above, in Step 5, it can be easily verified that for the elements of the transformed
 157 crisp matrix (shown by Table 4) the reciprocal property $a_{ij} = \frac{1}{a_{ji}}, i \neq j, \forall i, j = 1, 2, \dots, n$ is
 158 not is not satisfying i.e., $a_{12} = 3.7666 \neq \frac{1}{a_{21}} = 0.1682$. Therefore, the transformed crisp
 159 matrix, on applying Step 5, of Ayyildiz et al.'s proposed PF-AHP (Ayyildiz et al., 2021),
 160 discussed above, violates the reciprocal propriety of pairwise comparison matrix i.e., $a_{ij} \neq$
 161 $\frac{1}{a_{ji}}, i \neq j, \forall i, j = 1, 2, \dots, n$.

Moreover, the transformed crisp matrix, on applying the steps of Ayyildiz et al.'s proposed PF-AHP (Ayyildiz et al., 2021), neither satisfying the conditions (I) nor the Definition 1, Definition 2, so applying the crisp AHP on crisp non-pairwise comparison matrices, to calculate the normalized priority weights is a meaningless task and will mislead to the decision maker, that can result in a heavy loss in any value-added model. Therefore, Step 2 to Step 5 of the framework proposed by (Ayyildiz et al., 2021) cannot be used. Hence, the Ayyildiz et al. integrated method (Ayyildiz et al., 2021) is not valid in its present form. Keeping the same in mind, in the next section, the necessary modifications are suggested for it is validity.

4. Suggested modification

To overcome the flaws of Ayyildiz et al.'s proposed PF-AHP (Ayyildiz et al., 2021), in this section, the necessary modifications are suggested in the Ayyildiz et al.'s proposed PF-AHP method (Ayyildiz et al., 2021) for its validity. Using definition 3, discussed in Section 2, the likelihood-based comparison relations (Shui and Li, 2003) to preserve the reciprocal property of crisp pairwise comparison matrices. In order to construct the crisp pairwise comparison matrices the steps of the modified PF-AHP approach are as follows:

Step 1: Construct the Pythagorean fuzzy pairwise comparison matrix $A = (a_{ij})_{m \times m}$ based on the linguistic scale (Ayyildiz et al., 2021, Table 2, pp. 35805), where, $a_{ij} = \langle \mu_{ijL}, \mu_{ijU}, v_{ijL}, v_{ijU} \rangle$ is a Pythagorean fuzzy number. Also μ_{ijL}, μ_{ijU} and v_{ijL}, v_{ijU} are lower, upper membership and non-membership functions respectively

Step 2: Transform the interval valued Pythagorean fuzzy pairwise comparison matrix A into difference matrix $= (\langle d_{ijL}, d_{ijU} \rangle)_{m \times m}$, where, $d_{ijL} = \mu_{ijL}^2 - v_{ijU}^2$ and $d_{ijU} = \mu_{ijU}^2 - v_{ijL}^2$.

Step 3: Transform the difference matrix $D = (\langle d_{ijL}, d_{ijU} \rangle)_{m \times m}$ into the interval multiplicative matrix $S = ([s_{ijL}, s_{ijU}])_{m \times m}$, where $s_{ijL} = \sqrt{1000^{d_{ijL}}}$ and $s_{ijU} = \sqrt{1000^{d_{ijU}}}$.

186 **Step 4:** Transform the interval multiplicative matrix $S = ([s_{ijL}, s_{ijU}])_{m \times m}$ into a column
187 interval matrix $C_i = [C_i^L, C_i^U] = ([p_{ijL}, p_{ijU}])_{m \times 1}$ where, $p_{ijL} = \frac{\sum_{j=1}^m s_{ijL}}{m}$ and $p_{ijU} = \frac{\sum_{j=1}^m s_{ijU}}{m}$.
188 **Step 5:** Using Definition 3, discussed in Section 2 the likelihood-based comparison relations
189 $p(C_i \geq C_j) = \max \left\{ 1 - \max \left\{ \frac{C_j^U - C_i^L}{(C_i^U - C_i^L) + (C_j^U - C_j^L)}, 0 \right\}, 0 \right\}$ to obtain the likelihood matrix
190 $P = (p_{ij})_{m \times m}$ of $C_i \geq C_j ; i, j \in \{1, 2, \dots, m\}$.
191 **Step 6:** Transform the matrix $P = (p_{ij})_{m \times m}$ into the multiplicative pairwise comparison
192 matrix $M = (m_{ij})_{m \times m}$, where $m_{ij} = 9^{2 \times p_{ij} - 1}; \forall p_{ij} \in [0, 1]$. Therefore, the reciprocal
193 property $m_{ij} = 1; i = j$ and $m_{ij} = \frac{1}{m_{ji}} ; i \neq j$ will always satisfied for matrix M .
194 **Step 7:** Calculate the determinacy value $\tau = (\tau_{ij})_{m \times m}$ where, $\tau_{ij} = 1 - (\mu_{ijU}^2 - \mu_{ijL}^2) -$
195 $(v_{ijU}^2 - v_{ijL}^2)$.
196 **Step 8:** Finally using the crisp AHP to calculate the normalized priority weights of
197 transformed crisp pairwise comparison matrix T , by using the relation $W_i = \frac{\sum_{j=1}^n m_{ij} \times \tau_{ij}}{\sum_{i=1}^n \sum_{j=1}^n m_{ij} \times \tau_{ij}}$.
198 **5. Exact transformation of interval Pythagorean fuzzy pairwise comparison matrix into**
199 **the crisp pairwise comparison matrix**
200 In order to obtain the exact weights of criteria/alternatives, we need to transform the
201 interval Pythagorean fuzzy pairwise comparison matrix into the crisp pairwise comparison
202 matrix without losing any information, given by the decision maker. Therefore on applying
203 the steps of the modified PFAHP approach discussed in Section 4, for the convenience, it can
204 be easily verified with the help of the same example, discussed in Section 3, that the
205 transformed crisp matrix, on applying Steps of modified PF-AHP, always preserves the
206 reciprocal property of crisp pairwise comparison matrix i.e., $a_{ij} = 1, i = j$ and $a_{ij} = \frac{1}{a_{ji}}, i \neq$
207 $j, \forall i, j = 1, 2, \dots, n$ (Saaty, 1980).

208 Consider the interval valued Pythagorean fuzzy pairwise comparison matrix A of criteria
 209 C_1 and C_2 as shown in Table 5.

210 **Table 5** Interval valued Pythagorean fuzzy pairwise comparison matrix A of criteria C_1 and
 211 C_2

Criteria	C_1	C_2
C_1	$\langle [0.1965, 0.1965], [0.1965, 0.1965] \rangle$	$\langle [0.65, 0.80], [0.20, 0.35] \rangle$
C_2	$\langle [0.20, 0.35], [0.65, 0.80] \rangle$	$\langle [0.1965, 0.1965], [0.1965, 0.1965] \rangle$

212
 213 Using Step 2 and Step 3 of the modified PFAHP discussed in Section 5, to transform the
 214 interval valued Pythagorean fuzzy pairwise comparison matrix A of criteria C_1 and C_2 (shown
 215 by Table 5) into the interval multiplicative matrix S (shown by Table 6).

216 **Table 6** Interval multiplicative matrix S of criteria C_1 and C_2

Criteria	C_1	C_2
C_1	$\langle 1, 1 \rangle$	$\langle 2.8184, 7.9433 \rangle$
C_2	$\langle 0.1259, 0.3548 \rangle$	$\langle 1, 1 \rangle$

217
 218 Now using Step 4 of modified PFAHP discussed in Section 5, to transform the interval
 219 multiplicative matrix S (shown by Table 6) into the column vector $C_1 = [1.9092, 4.4716]$
 220 and $C_2 = [0.5629, 0.6774]$.

221 Using Step 5, of modified PFAHP discussed in Section 5, to obtain the likelihood matrix
 222 $P = \begin{pmatrix} 0.50 & 1 \\ 0 & 0.50 \end{pmatrix}$ and using Step 6 of modified PFAHP discussed in Section 5, to
 223 transform the matrix $P = (p_{ij})_{m \times m}$ into the multiplicative pairwise comparison matrix $M =$
 224 $\begin{pmatrix} 1 & 9 \\ \frac{1}{9} & 1 \end{pmatrix}$. Therefore, it can be easily verified that the matrix M is a crisp pairwise
 225 comparison matrix i.e., $a_{12} = 9$ and $a_{21} = \frac{1}{9}$ and preserves the reciprocal property $a_{ij} =$
 226 $1, i = j$ and $a_{ij} = \frac{1}{a_{ji}}, i \neq j, \forall i, j = 1, 2, \dots, n$ of crisp pairwise comparison matrix M .

Finally, using Step 7 and Step 8 of modified PFAHP discussed in Section 5 to obtain normalized priority weights of criteria C_1 and C_2 are 0.7059 and 0.2941 respectively.

6. Conclusion

On the basis of the present study, it can be easily concluded that the Ayyildiz et al.'s integrated decision-making methodology (Ayyildiz et al., 2021) is not valid in its present form. Also, the necessary modifications are suggested for its validity.

Compliance with ethical standards

Conflict of interest The author declare that there is no conflict of interests regarding this work.

Ethical Approval: Not applicable

Authors Contributions

Authors Shahid Ahmad Bhat: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing.

Akanksha Singh: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing.

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