A Fuzzy analytical hierarchy process approach in irrigation networks maintenance

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Abstract. Ponorogo Regency has 440 Irrigation Area with a total area of 17,950 Ha. Due to the limited budget and lack of maintenance cause decreased function on the irrigation. The aim of this study is to make an appropriate system to determine the indices weighted of the rank prioritization criteria for irrigation network maintenance using a fuzzy-based methodology. The criteria that are used such as the physical condition of irrigation networks, area of service, estimated maintenance cost, and efficiency of irrigation water distribution. 26 experts in the field of water resources in the Dinas Pekerjaan Umum were asked to fill out the questionnaire, and the result will be used as a benchmark to determine the rank of irrigation network maintenance priority. The results demonstrate that the physical condition of irrigation networks criterion (W1) = 0.279 has the greatest impact on the assessment process. The area of service (W2) = 0.270, efficiency of irrigation water distribution (W4) = 0.249, and estimated maintenance cost (W3) = 0.202 criteria rank next in effectiveness, respectively. The proposed methodology deals with uncertainty and vague data using triangular fuzzy numbers, and, moreover, it provides a comprehensive decision-making technique to assess maintenance priority on irrigation network.

1. Introduction

Agriculture is an important sector in the development of an country because it plays a role in the provision of basic needs and is also the livelihood of the population in rural areas. In order to support the development of agriculture, the development of irrigation infrastructure and facilities is needed so that the availability of water is sufficient. The number of problems such as breakage to irrigation-networks in the area of Ponorogo regency cause that the performance of irrigation is not optimal.

Ponorogo Regency has 440 Irrigation Areas with a total area of 17,950 Ha and based on Irrigation Infrastructure Baseline Data of 2017 showing 55.32% in good condition, 0.72% in passable condition, 14.42% in mild condition and 29.55% in severe damage. The problems that occur in addition to limiteds of the budget, years factor and lack of maintenance cause the irrigation-network has decreased function. So far to decide network maintenance of irrigation In Ponorogo District is still using a random choice system. Based on these descriptions, the right system is needed so that the maintenance activities in Ponorogo Regency can run well.
In this study criteria that are used such as physical condition of irrigation network, service area, estimated maintenance cost, and efficiency of irrigation water distribution using fuzzy AHP with reference from previous research [9] which is used criteria, physical condition of irrigation network, service area and estimation Maintenance costs and of [2] that are used criteria of the physical condition of irrigation networks, crop indexes, supporting facilities, personnel organization, documentation and P3A. Both authors use the AHP method as priority maintenance/rehabilitation of irrigation networks.

Fuzzy Logic and Fuzzy AHP methods have been widely used to define infrastructure maintenance priorities such as road maintenance [3,4,12,13], building maintenance [1] and assessment of irrigation network performance [7,13].

Montazar et al. (2012) in his research explains that this combination of fuzzy and AHP methods can improve assessment of the accuracy of procedural assessments and may be a powerful technique for assessing irrigation projects. The purpose of the research is to develop a new methodology (FAHM) and apply techniques to assess the performance of four irrigation projects. According to Jasril et al. (2011) AHP fuzzy covers the weaknesses of AHP, in the fuzzy AHP decision-making system are considered better in describing a vague decision than AHP.

The aim of this study is to make the appropriate system to determine the indices weighted of the rank prioritization criteria for irrigation network maintenance using a fuzzy - based methodology. In the previous research, a method of prioritizing the maintenance of irrigation-networks has been developed using AHP (Analytical Hierarchy Process) methods, such as [2,9] and sequence priority for cost allocation budgeting [8]. It is expected that the system developed by fuzzy AHP method will provide a solution for the maintenance activities of irrigation networks in Ponorogo Regency.

2. Material and methods

2.1. Analytical hierarchy process

The AHP method introduced by Thomas L. Saaty in 1980 was a functional hierarchy with the main input of human perception. This model can process data that are both qualitative and quantitative in the decision-making process. Also, AHP can solve multi-objective and multicriteria problems based on the preference comparison of each element in the hierarchy, making it a comprehensive decision-making model. Linguistic variables are useful for collecting opinions in many cases. Linguistic variables can accept the words from natural language as their values. A linguistic variable differs from a numerical variable in that its value is shown as phrases and expressions rather than numbers [4]. The setting of the quantitative scale of 1 (one) to 9 (nine) is to assess the importance comparison of an element to the others as it is shown in Table 1.

| Interest’s Intensity | Description | Explanation |
|----------------------|-------------|-------------|
| 1                    | Both elements are equally important | Two elements have the equally influence on the goal |
| 3                    | One element is slightly important than the other elements | Experience and judgment support one element more than the other |
| 5                    | One element is more important than the other elements | Experience and judgment are very in favor of one element over the other |
| 7                    | One element is clearly more important than the other elements | One strong element is sustained and dominant in practice |
| 9                    | One absolute element is more important than any other elements | The evidence that supports one element against another has the highest degree of affirmation that might be reinforcing |
| Interest’s Intensity | Description | Explanation |
|----------------------|-------------|-------------|
| 2,4,6,8              | Values between two adjacent considerations | This value is given when there are two compromises between two options |
| Contrary             | If i activity gets one score compared to j activity, then j has the opposite value compared to i |

The calculation process with the AHP method is as follows:

a. Creates a hierarchical structure of the problem to be solved and determines the matrix comparison in pairs between the criteria. The geometric mean is calculated in each value as the following equation:

\[
GM = \sqrt[n]{X_1 \times X_2 \times \ldots \times X_n}
\]  

(1)

b. Performs multiplication of elements in a row and is powered and as shown in the following equation:

\[
W_i = \sqrt[n]{a_{11} \times a_{12} \times \ldots \times a_{1n}}
\]  

(2)

c. Calculating the priority vector or eigen vector by the weight of each element can be obtained by the following equation:

\[
X_i = \frac{w_i}{\sum w_i}
\]  

(3)

The result obtained is an eigen vector (X1) as the element weight.

d. Calculating the maximum eigen value (\(\lambda_{\text{maks}}\)), by multiplying the reciprocal matrix by the weight obtained, the result of the sum of matrix operations is the maximum eigen value (\(\lambda_{\text{maks}}\)) with the following equation:

\[
\lambda_{\text{maks}} = \sum a_{ij} x X_i
\]  

(4)

e. Consistency index

This calculation is intended to determine the consistency of answers that will affect the results of the truth. The consistency index calculation can be done using the following equation:

\[
CI = \frac{\lambda_{\text{maks}} - n}{n-1}
\]  

(4.1)

To find out CI is good enough or not, please note Consistency Ratio (CR). The Consistency Ratio is a parameter to check whether pairwise comparisons have been made consequently or not using the equation below:

\[
CR = \frac{CI}{RI}
\]  

(4.2)

The Random Index (RI) value depends on the amount of the matrix as shown in the following table 2. The compilation matrix comparison is acceptable if CR value < 0.1. If CR > 0.1 then the comparison assessment should be repeated.

| Table 2. Correlation between matrix size and RI value |
|------------------------------------------------------|
| **Random Index Value (RI)** |
| The amount of the matrix | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|--------------------------|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| RI                       | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.48 | 1.56 | 1.57 | 1.59 |

2.2. Fuzzy analytical hierarchy process

In Multi Criteria Decision Making (MCDM) AHP is developed with a fuzzy approach. This method is known as fuzzy AHP. Fuzzy AHP combines the fuzzy concept with the AHP method. This method is introduced by Chang (1996) using triangular membership (Triangular Fuzzy Number / TFN). Triangle
A membership function is a combination of two lines. Graphs of triangular membership functions are depicted in figure 1. below:

![Figure 1. Triangular Fuzzy Number (Chang, 1996)](image)

The intensity value of AHP is defined into the fuzzy triangle scale that is to divide each fuzzy set by two, except for the intensity of the interest of one. The Fuzzy Triangle Scale in [10] can be seen in the table 2. below:

| Intensity of Interest AHP | The Set of Linguistics | TFN | Reciprocity |
|--------------------------|------------------------|-----|-------------|
| 1                        | Comparison of the same element (equal) | (1,1,1) | (1,1,1) |
| 3                        | One element is more important than the other (weak) | \( \left(1, \frac{3}{2}, 2\right) \) | \( \left(\frac{1}{2}, \frac{2}{3}, 1\right) \) |
| 5                        | One element is more important than that other (fairly strong) | \( \left(2, \frac{5}{2}, 3\right) \) | \( \left(\frac{1}{3}, \frac{2}{5}, \frac{1}{2}\right) \) |
| 7                        | One element is much more important than the others (very strong) | \( \left(3, \frac{7}{2}, 4\right) \) | \( \left(\frac{1}{4}, \frac{2}{7}, \frac{1}{3}\right) \) |
| 9                        | One absolute element is more important than the other (absolute) | \( \left(4, \frac{9}{2}, \frac{9}{2}\right) \) | \( \left(\frac{2}{9}, \frac{2}{9}, \frac{1}{4}\right) \) |

Fuzzy Logic completion steps according to [6] are as follows:

a. Creates a hierarchical structure of the problem to be solved and determines the matrix comparison in pairs between the criteria and TFN scale. The geometric mean is calculated in each value.

b. Defines the value of fuzzy synthetic extent (Si) with number i criteria as the following equation:

\[
S_i = \sum_{j=1}^{m} M_{ij} \otimes \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} \right]^{-1} \tag{5}
\]

To obtain the equation \( \sum_{j=1}^{m} M_{ij} \), a fuzzy sum operation is performed from the m value of the matrix in the equation below. In the final calculation phase, values (1, m, u) are obtained and used for the next phase.

\[
\sum_{j=1}^{m} M_{ij} = \left( \sum_{i=1}^{m} l_j, \sum_{i=1}^{m} m_i, \sum_{i=1}^{m} u_j \right) \tag{6}
\]
1 is the lower limit value, \( m \) is the expected value and \( u \) is the limiting upper value. To obtain the equation \( \sum_{i=1}^{n} \sum_{j=1}^{m} M_{gl} \) a fuzzy sum operation is performed from the value \( M_{gl} \) (\( J = 1, 2, \ldots, m \)) to obtain the following equation:

\[
\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gl} = \left( \sum_{i=1}^{n} l_{1j}, \sum_{i=1}^{n} m_{1j}, \sum_{i=1}^{n} u_{1j} \right)
\]

Then, calculate the inverse of the vector in the above equation to get the equation below:

\[
\left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{gl} \right]^{-1} = \frac{1}{\sum_{i=1}^{n} u_{1j}}, \frac{1}{\sum_{i=1}^{n} m_{1j}}, \frac{1}{\sum_{i=1}^{n} l_{1j}}
\]

c. Calculates the degree of possibility
To obtain the degree of possibility, \( M_{i} = (l_{i}, m_{i}, u_{i}) \geq M_{1} = (l_{1}, m_{1}, u_{1}) \) is expressed in the equation below:

\[
V(M_{2} > M_{1}) = \sup \{\min(\mu_{M_{1}}(x), \mu_{M_{2}}(y))\}
\]

And \( x \) and \( y \) are values on the axis of the membership function of each criteria. This equation can be defined as follows:

\[
V(M_{2} \geq M_{1}) = \begin{cases} 
1, & \text{if } m_{2} \geq m_{1} \\
0, & \text{if } l_{2} \geq u_{2} \\
\frac{1}{l_{2}-u_{2}}, & \text{Otherwise (9.1)} \\
\end{cases}
\]

We need the values of \( V(M_{2} \geq M_{1}) \) dan \( V(M_{i} \geq M_{2}) \) to compare \( M_{1} \) and \( M_{2} \).

d. Compares the degree of possibility among the criteria
The comparison between degrees of possibility between \( M_{i} \) (\( i = 1, 2, 3, 4, 5, \ldots, k \)) can be defined by: \( V(M_{i} \geq M_{j}, M_{j} \geq M_{k}) = V([M_{i} \geq M_{j}], [M_{j} \geq M_{k}]) \) and \( min \) \( V(M_{i} > M_{j}) \) (\( i=1,2,3,\ldots,k \)).

Assume that the equation (10) is:

\[
d'(A_{i}) = \min V(S_{i} \geq S_{k})
\]

for \( k = 1, 2, 3, 4, 5, \ldots, n \); \( k \neq i \). Then the weight vector is given by (11) as follows:

\[
W' = (d'(A_{1}), d'(A_{2}), \ldots, d'(A_{n}))^{T}
\]

Where \( A_{i} \) (\( i=1,2,3,4,5,\ldots,n \)) is \( n \) element.

e. Normalization
Normalization of vector weight is given by the following equation:

\[
W = (d(A_{1}), d(A_{2}), \ldots, d(A_{n}))^{T}
\]

Where \( W \) is a non-fuzzy number of the weight vector.

3. Research Method
The method applied in this study is quantitative descriptive, i.e. research using data from the variables studied. Data for weights between criteria for prioritizing maintenance are obtained by assessing interest in the AHP scale. According to [6] in [1] on the application of AHP method, the primary is the data quality of the respondents and does not depend on the quantity. Therefore, the AHP assessment requires experts as respondents in decision making in alternative selection. The experts here are competent people who have mastered, influence the decision-making or know the information needed.

Data retrieval using a purposive sampling method that is sampled determination technique with a certain consideration. In this study, the data source is the decision makers proposed irrigation network maintenance plan and staff of the Water Resources Sector on Dinas PUPR Ponorogo Regency.
4. Result and Discussion

The problem faced in determining the priority of maintaining irrigation-networks is how to identify the section which should take precedence. Determining the priority of irrigation network element maintenance is effective because of the limited maintenance fund. In this research, priority maintenance system for irrigation-network is designed to determine the rating on the irrigation-network section that have been ravaged so will generate the priority order of the parts in the irrigation-network is prioritized for maintenance. The phases in preparing this system are as follows:

4.1. Converted comparison between criteria into TFN scale

The first task of the fuzzy AHP method is to decide on the relative importance of each pair of factors in the same hierarchy by using formula (1 - 4.2). The goal is to know the consistency of scores between criteria. After going through the consistency test and stated the importance of interest between the criteria is consistent, then by using triangular fuzzy numbers on table 3., the scale of interest assessment with AHP converted into TFN / FAHP scale and then calculated in each value the (geometric mean) by applying formula (1). At this stage, the task undertaken is to recapitulate the questionnaire results that have been dispersed to the competent experts in the irrigation-network maintenance field to determine the criteria weight. Total respondents of 26 (twenty-six) persons, the result of the comparison between criteria on TFN / FAHP scale shown in Figure 2.

![Figure 2. Comparison between criteria on TFN/ FAHP scale](image)

4.2. Compiling pairwise comparison

Pairwise comparison of the fuzzy evaluation matrix shown in Table 4. below:

| Physical condition of irrigation networks | Area of service | Estimated maintenance cost | Efficiency of irrigation water distribution |
|------------------------------------------|----------------|---------------------------|---------------------------------------------|
| Area of service                          |                |                           |                                             |
| Estimated maintenance cost               |                |                           |                                             |
| Physical condition of irrigation networks|                |                           |                                             |
| Efficiency of irrigation water distribution|                |                           |                                             |
| Estimated maintenance cost               |                |                           |                                             |

Table 4. Pairwise matrix comparison

| Area of service | Estimated maintenance cost | Efficiency of irrigation water distribution |
|-----------------|---------------------------|---------------------------------------------|
| Physical condition of irrigation networks|                |                                             |

| Physical condition of irrigation networks | Area of service | Estimated maintenance cost | Efficiency of irrigation water distribution |
|------------------------------------------|----------------|---------------------------|---------------------------------------------|
| 1.000                                    | 1.000          | 1.000                     | 0.879                                       |
| 0.879                                    | 1.088          | 1.320                     | 1.020                                       |
| 1.020                                    | 1.272          | 1.581                     | 0.742                                       |
| 0.742                                    | 0.931          | 1.148                     |                                             |

| Area of service | Estimated maintenance cost | Efficiency of irrigation water distribution |
|-----------------|---------------------------|---------------------------------------------|
| 0.758           | 0.919                      | 1.137                                       |
| 1.000           | 1.000                      | 1.000                                       |
| 0.974           | 1.200                      | 1.466                                       |
| 0.919           | 1.083                      | 1.263                                       |

| Efficiency of irrigation water distribution | Estimated maintenance cost | Area of service | Physical condition of irrigation networks |
|---------------------------------------------|---------------------------|----------------|------------------------------------------|
| 0.795                                       | 0.987                      | 1.211          |                                           |
| 0.870                                       | 1.098                      | 1.320          |                                           |
| 0.802                                       | 1.272                      | 1.581          |                                           |
| 0.742                                       | 0.931                      | 1.148          |                                           |
maintenance cost
Efficiency of irrigation water distribution

|                | L    | M    | U    |
|----------------|------|------|------|
| Physical condition of irrigation networks | 0.871 | 1.074 | 1.347 |
| Area of service | 0.792 | 0.924 | 1.088 |
| Estimated maintenance cost | 0.792 | 0.924 | 1.088 |
| Efficiency of irrigation water distribution | 0.826 | 1.013 | 1.257 |

4.3. Determination of fuzzy synthetic extent value (Si)

In defining the value of fuzzy synthetic extent (Si) then used equation 5. The value of \( \sum_{i=1}^{n} M_{gi} \) is the sum of the fuzzy numbers in each matrix. An example addition of fuzzy value for the physical condition of irrigation networks criterion irrigation can be explained as follows:

\[
\sum_{i=1}^{n} M_{gi} = (\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i)
\]

= \(\{1 + 0.879 + 1.020 + 0.742, (1 + 1.088 + 1.272 + 0.931), (1 + 1.320 + 1.581 + 1.148)\}\)

= \(\{3,642; 4,292; 5,048\}\)

The value for all matrix-criteria is shown in Table 5.

| Table 5. Addition of Fuzzy Value |
|----------------------------------|
| \(\sum\) L | \(\sum\) M | \(\sum\) U |
|------------------|-----------|-----------|
| Physical condition of irrigation networks | 3.642 | 4.292 | 5.048 |
| Area of service | 3.650 | 4.202 | 4.866 |
| Estimated maintenance cost | 3.110 | 3.606 | 4.218 |
| Efficiency of irrigation water distribution | 3.489 | 4.011 | 4.692 |
| \(\sum M\) | 13.892 | 16.110 | 18.824 |

Next inverse vectors for all matrix-criteria are performed:

\[
\left[\sum_{i=1}^{n} M_{gi}\right]^{-1} = \frac{1}{\sum_{i=1}^{n} u_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} l_i}
\]

= \(0.0531; 0.0621; 0.0720)\)

Then the value of fuzzy synthetic extent (Si) for the physical condition of irrigation networks criteria can be calculated

\[
Si = \sum_{i=1}^{n} M_{gi} \otimes \left[\sum_{i=1}^{n} M_{gi}\right]^{-1}
\]

= \(3,642; 4,292; 5,048\) \(\otimes\) \(0.0531; 0.0621; 0.0720)\)

= \(0.193; 0.266; 0.363)\)

For the value of fuzzy synthetic extent (Si) on all criteria shown in Table 6.

| Table 6. Value of fuzzy synthetic extent (Si) |
|---------------------------------------------|
| Value of Fuzzy Synthetic Extent (Si) | L    | M    | U    |
|----------------------------------------|------|------|------|
| S1 (Physical condition of irrigation networks) | 0.193 | 0.266 | 0.363 |
| S2 (Area of service) | 0.194 | 0.261 | 0.350 |
| S3 (Estimated maintenance cost) | 0.165 | 0.224 | 0.304 |
| S4 (Efficiency of irrigation water distribution) | 0.185 | 0.249 | 0.338 |
4.4. Calculates the degree of possibility
To get the value of the degree of possibility used equation 9.1. With an explanation as follows:

\[ V(M_2 \geq M_1) = \begin{cases} 
1 & m_2 \geq m_1 \\
0 & \frac{l_1-u_2}{(m_2-u_2)-(m_1-l_1)} \\
& l_1 \geq u_2 
\end{cases} \]

From Table 6. values are obtained:

- \( V(S_1 \geq S_2) = 1 \);
- \( V(S_1 \geq S_3) = 1 \);
- \( V(S_1 \geq S_4) = 1 \);
- \( V(S_2 \geq S_3) = 1 \);
- \( V(S_2 \geq S_4) = 1 \);
- \( V(S_3 \geq S_2) = 0,825 \);
- \( V(S_3 \geq S_4) = 0,748 \);
- \( V(S_3 \geq S_1) = 0,892 \);
- \( V(S_4 \geq S_1) = 0,825 \);
- \( V(S_4 \geq S_2) = 0,924 \);
- \( V(S_4 \geq S_3) = 1 \);
- \( V(S_2 \geq S_1) = 0,965 \);
- \( V(S_2 \geq S_3) = 0,924 \);
- \( V(S_2 \geq S_4) = 1 \);
- \( V(S_3 \geq S_2) = 0,965 \);
- \( V(S_3 \geq S_4) = 0,892 \);
- \( V(S_4 \geq S_1) = 0,892 \);
- \( V(S_4 \geq S_3) = 1 \).

4.5. Compares the degree of possibility among the criteria
Accomplishment of the degree of possibility follows equation 10. with the following explanation:

\[ d'(A_i) = \min \{ V(S_i \geq S_k), k = 1, 2, 3, 4, 5, \ldots, n; k \neq i \} \]

- \( d'(1) = V(S_1 \geq S_2, S_3, S_4) \)
- \( d'(2) = V(S_2 \geq S_3, S_4, S_1) \)
- \( d'(3) = V(S_3 \geq S_4, S_1, S_2) \)
- \( d'(4) = V(S_4 \geq S_2, S_3, S_1) \)

\[ W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))' \]

\[ W = (0.279, 0.270, 0.202, 0.249) \]

The weight vector of the criteria is shown in Figure 3.

![Figure 3. The weight vector of the irrigation network maintenance criteria](image-url)
5. Conclusion
Based on the analysis using Fuzzy Logic Method, the weight for each criterion is as follows: physical condition of irrigation networks is (W1) = 0.279, the area of service is (W2) = 0.270, the estimated maintenance cost criteria is (W3) = 0.202, and the efficiency of irrigation water distribution is (W4) = 0.249.

Based on the analysis, the area of service becomes the second most important criteria after the physical condition of irrigation networks which became the first criterion to decisive. It shows that both criteria are crucial in the process of decision-making of irrigation-network maintenance.

The proposed methodology deals with uncertainty and vague data using triangular fuzzy numbers, and, moreover, it provides a comprehensive decision-making technique to assess maintenance priority on irrigation network.

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