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Optimization of Pipe Materials for Water Distribution in Sumbermanjing District, Malang, Using the AHP Method

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ABSTRACT: Clean water is essential for human life, yet not all residents have access to this basic necessity. In Sumbermanjing District, many residents still lack proper access to clean water, even though many water sources are available in this district, one of which is Kali Jaruman. To distribute water from Kali Jaruman to Sumbermanjing District, a pipe network is essential. This research proposes seven pipe materials available in factory. Pipe materials proposed are HDPE PN 16, HDPE PN 12.5, HDPE PN 10, PVC PN 12.5, PVC PN 10, Black pipe SCH 40, Galvanized SCH 40. To determine the ranking of pipe material alternatives, the Analytic Hierarchy Process (AHP) method was used, using three criteria: pressure, lifespan, and construction cost. Based on the AHP analysis, Black Pipe SCH 40 ranks highest, while PVC PN 12.5 ranks lowest.

KEYWORDS: AHP, cost, lifespan, optimization, pipe material, pressure

I. INTRODUCTION

Water is an essential source, not only for humans but also for other organisms, as it supports food supply and a productive environment (Kılıç, 2020). Population growth has led to increase demand for clean water such as for domestic use, irrigation, and industrial activities (van Vliet et al., 2021). However, in recent decades, poor water management has occurred on a massive scale (Salehi, 2022). In addition, climate change, loss of biodiversity, and pollution have exacerbated water shortages (Ab Rashid et al., 2021).

The Indonesian government has set a target that a minimum percentage of 30.66% of households must have access to clean water. In 2019, this target was not achieved in 14 provinces, predominantly in Sumatra Province, including Bangka Belitung Islands, Aceh, and Riau. Even in provinces with a relatively higher percentage of water access, another problem persists: high levels of non-revenue water, which indicates inefficiencies in water distribution. In 2019, the average national non-revenue water rate was 43.69%, with a government target to reduce it to 32.67% (Kementerian Keuangan, 2023). The high rates of non-revenue water were dominated in Sumatra, Kalimantan, and Sulawesi Provinces. Overall, 17 out of 34 provinces had non-revenue water rates exceeding the national average. In addition, inequality in water access exists between urban and rural areas, with urban population generally get better access to clean water than rural communities (Daniel et al., 2021).

Governments often pay less attention to service quality and existing infrastructure in rural areas including water access (Herrera, 2019). Although many rural areas have potential water sources, such as springs or rivers, residents frequently lack the government support needed to build necessary water infrastructure. This phenomenon is evident in Sumbermanjing District, a rural area in Malang.

Based on previous research, this area has many water sources, originating from underground rivers, surface rivers, lakes, and springs. For current domestic utilization, most communities rely on springs. However, water discharge in springs decreases because of karst landscape changing (Sahrina et al., 2020). To minimize the impact of this spring decline, alternative water sources must be planned to supply the water to residents. One of the surface rivers near Sumbermanjing District is Kali Jaruman, which is 17.60 km in length (Ummah, 2019). The distance between this river and Sumbermanjing is around 30 km; therefore, a long pipe network is needed to distribute the water to residents. As a consequence, a high cost must be anticipated for constructing this network. Careful selection of pipes can help minimize construction costs, as various types of pipes are available in factories with different materials, dimensions, pressure levels, and prices.

There are several commonly used mathematical programming methods to design optimal decisions, namely linear, non-linear, and dynamic programming (Hapsari et al., 2022) (Tan et al., 2020). In addition, a method that has received significant attention in construction management in recent years is the Analytical Hierarchy Process (AHP) (Darko et al., 2019). This method helps to analyse complex problems with the aim of making the best decisions based on a pair comparison in each element (Khan et al., 2020).

In previous research on water distribution networks, AHP has been used in various aspects, including optimizing priority risks related to existing pipe damage and failures (Hassoun Nedjar et al., 2023), pump model selection (Briceño-León et al., 2021), and water meter damage analysis (Widarman et al., 2022). In this research, seven types of pipes will be analysed using AHP to create a ranking for pipe selection. The parameters used in this analysis are pressure, lifetime, and cost.

II. METHODOLOGY

A. Study Area

This research took place in Sumbermanjing District, Malang, located between coordinates 112.4031° to 112.4634° E and 8.2411° to 8.1443° S. The district consists of 15 villages, 11 of which do not yet receive clean water from the Regional Water Company (PDAM). These 11 villages are Sitiarjo, Kedungbanteng, Tambakasri, Tegalrejo, Ringinkembar, Sumberagung, Argotirto, Ringinsari, Klepu, Sekarbanyu, and Sidoasri. The residents in these villages depend entirely on spring water as their main water source. Figure 1 shows the location of Sumbermanjing District.

Figure 1. Map of Sumbermanjing District

B. Pipe Design

To distribute water from Kali Jaruman to Sumbermanjing District, a 62.88 km long pipe is needed. Careful pipe selection can help reduce construction costs. There are various types of pipes that are available from factories, namely High-Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), and steel (Diera et al., 2023) (Papciak et al., 2020) (Gaber et al., 2023). HDPE is a plastic pipe which is characterized by high density, chemical and corrosion resistance, and a longevity of up to 50 years. The diameter of HDPE pipes varies from 0.5 inch to 6 inches, with a nominal pressure of up to 160 meters. Similar to HDPE, PVC is a plastic pipe made from thermoplastic polymer which is chemical resistant and lightweight, and has longevity of up to 25 years. The diameter of PVC varies more widely than that of HDPE, which reaches up to 24 inches, but the maximum nominal pressure is 125 meters.

In steel materials, there are several types of pipes that are commonly used for water distribution, two of which are black and galvanized pipes. The main difference between them is in their coating where black pipes are not coated with anything, whereas galvanized pipes are coated with zinc. Regarding corrosion levels, black pipes corrode more easily than galvanized pipes. Although both have similar pressure and diameter variations, galvanized pipes have longer lifespan than black pipes. In rural areas, galvanized pipes typically last up to 50 years, while black pipes can last up to 20 years. Therefore, black pipes are cheaper than galvanized pipes. Table 1 provides a summary of HDPE, PVC, black pipes, and galvanized pipes.

Table 1. Summary of pipe type

Parameter	HDPE	PVC	Black Pipe	Galvanized Pipe
Maximum Pressure (m)	100, 125, 160	125, 100	400	400
Longevity (years)	50	25	20	50
Diameter availability (inch)	½ to 16	2 to 24	½ to 20	½ to 20
Price per meter* (Rp)	5,680 to 973,160	35,955 to 4,832,873	12,539 to 1,914,905	18,779 to 2,725,621

C. Analytic Hierarchy Process (AHP)

AHP is a popular method developed by Thomas L. Saaty that is used to solve complex problem based on mathematical principles. This method produces priorities to obtain a final objective (Awad & Jung, 2022). The objective is placed at the top of the hierarchy, with criteria derived to achieve the partial objectives at the second level. These are followed by sub-criteria at the third level and alternatives at the fourth level. The alternatives are listed and compared pairwise based on their contribution to achieving each a criterion. In brief, the steps of AHP are (Chen, 2021):

1. Setting the problem, proposing the solution, and then arranging the hierarchy of the problems.
2. Comparing each criterion in pairs by setting the criteria weight. A fundamental scale from 1 to 9 can be used, as shown in Table 2 (Leal, 2020).

Table 2. Fundamental scale

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance

3. Conducting normalization on a pairwise comparison by summing the values in each column of the comparison matrix. Then, each value in the column is divided by the total of the corresponding columns to obtain the normalization of the matrix. The formula is shown below.

$$\overline{a_{jk}} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \qquad (1)$$

4. Calculating the synthesis weight by summing the values in each row of the normalized comparison matrix.
   $\Sigma column = k_1 + k_2 + \ldots + k_n$ (2)
5. Calculating the eigenvalue by multiplying the elements in each row of the comparison matrix, then raising the result to the power of one divided by the number of criteria.
   $\lambda = (k_1 \times k_2 \times \ldots \times k_n)^{1/n}$ (3)
6. Calculating the priority weight of each criterion by dividing its eigenvalue by the sum of all eigenvalues.
7. Calculating the importance of each criterion by dividing the synthesis weight by the priority weight.
8. Calculating the maximum eigenvalue by dividing the sum of the importance values by the number of criteria.
9. Evaluating the consistency of use to ensure the judgment in the decision-making process is highly consistent.
   $$CI = \frac{\lambda_{max} - n}{n-1} \quad (4)$$
   CI : consistency index
   λ_{max} : maximum eigenvalue
   n : number of elements
10. Checking the hierarchy for consistency. If the consistency ratio (CR) is less than 0.1, the result of the calculation is considered accurate.
   $$CR = \frac{CI}{IR} \quad (5)$$
   CR : consistency ratio
   CI : consistency index
   IR : index random consistency, as shown in Table 3

Table 3. Index random consistency

Matrix	IR	Matrix	IR
1	0	7	1.32
2	0	8	1.41
3	0.58	9	1.45
4	0.90	10	1.49
5	1.12	11	1.51
6	1.24	12	1.48

III. RESULT

A. *Piping System*

To select the best pipe materials for distributing water from Kali Jaruman to Sumbermanjing District, this study recommends seven types of pipes. These pipes, which are available in factories, include: HDPE PN 16, HDPE PN 12.5, HDPE PN 10, PVC PN 12.5, PVC PN 10, black pipe SCH 40, and galvanized SCH 40. The HDPE, PVC, and steel pipes come in different available diameters. The diameters and lengths of the pipes used in this study for each pipe group are shown in Table 4.

Table 4. Pipe lengths based on types and diameter

Diameter (inches)	Long of pipe (m)		
	HDPE	PVC	Steel pipe
20			8,335.35
16	18,654.29	18,654.29	10,318.94
14	2,340.51		
12	16,717.15	19,057.66	2,340.51
10			16,717.15
8	17,063.35	17,063.35	11,936.00
6	6,510.53	8,100.50	11,637.87
5	1,589.98		
4			1,589.98
Total	62,875.80	62,875.80	62,875.80

Based on the pipe length data above, each type of pipes results in a different cost. The maximum pressure, maximum lifespan, and price for each type are shown in Table 5 below.

Table 5. Technical and Economic Characteristics of Pipe Types

Type of Pipe	Maximum Pressure (bar)	Maximum Lifespan (year)	Price (Rp)
HDPE PN 16	16	50	112,454,282,981.76
HDPE PN 12.5	12.5	50	88,250,573,345.19
HDPE PN 10	10	50	72,745,198,491.89
PVC PN 12.5	12.5	25	79,820,727,904.55
PVC PN 10	10	25	66,086,102,925.23
Black pipe SCH 40	40	20	60,258,808,407.61
Galvanized SCH 40	40	50	84,953,697,826.32

B. *Analytic Hierarchy Process (AHP) Analysis*

In this study, AHP analysis was used to determine the rankings of pipe types based on three criteria: pressure, longevity, and pipe cost.

a. Pressure Analysis
   - Based on Table 1, the maximum pressures of pipes are range from 100 meters to 400 meters. To set the criteria for this analysis, the pressure values are divided into five groups, which are less than 100 meters (C1), 100 to 150 meters (C2), 150.01 to 200 meters (C3), 200.01 to 250 meters (C4), and more than 250 meters (C5). The following sections are the results of matched comparison matrix, normalization matrix pairs, synthesis weight, eigenvalue, priority weight, value of interest, consistency index, and consistency ratio.
   - Matched comparison matrices

The values in Table 6 represent the relative importance of each pressure group (C1 to C5), following the fundamental scale shown in Table 2.

Table 6. Matched comparison matrix

Criteria	Matched comparison matrix				
	C1	**C2**	**C3**	**C4**	**C5**
C1	1	1/2	1/3	1/4	1/5
C2	2	1	1/2	1/3	1/4
C3	3	2	1	1/2	1/3
C4	4	3	2	1	1/2
C5	5	4	3	2	1
Total	15	10.5	6.83	4.08	2.28

- Normalization matrix pairs

From the Table 6, values of normalization are calculated by using equation 1. As the examples of calculation process for column 1 in line 1 and 2 are given below.

$$X_{1,1} = \frac{1}{15} = 0.067$$
$$X_{1,2} = \frac{2}{15} = 0.133$$

Table 7 shows the normalization matrix pairs for the pressure criteria. Each value is obtained by dividing an element in table 6 by the total of its corresponding column. For example, the normalization values for column C1, rows C1 and C2, are calculated as follows:

C1 (C1 column): 1/15 = 0.067

C2 (C1 column): 2/15 = 0.133.

Table 7. Normalization matrix pairs

Criteria	Normalization of pairwise				
	C1	**C2**	**C3**	**C4**	**C5**
C1	0.067	0.048	0.049	0.061	0.088
C2	0.133	0.095	0.073	0.082	0.109
C3	0.200	0.190	0.146	0.122	0.146
C4	0.267	0.286	0.293	0.245	0.219
C5	0.333	0.381	0.439	0.490	0.438

- Synthetic weight

The next step is to calculate the synthetic weight using Equation 2, by summing the values in each row of the normalization matrix pairs in Table 7. An example to calculate the synthetic weight for the first row (C1) is shown below.

C1 = 0.067 + 0.048 + 0.049 + 0.061 + 0.088
= 0.312

The complete results of the synthetic weight calculation are presented in Table 8.

Table 8. Synthetic weight

Criteria	Weight Synthetis
C1	0.312
C2	0.493
C3	0.805
C4	1.309
C5	2.081

- Eigenvalue

To obtain the eigenvalue, each row of the paired comparison matrix (Table 6) is multiplied element-wise, and then the nth root of the product is taken where n is the number of criteria (in this case, 5). This process is defined in Equation 3. For example, the eigenvalue for C1 is calculated as follows:

$C1= (1\times0.5\times0.33\times0.25\times0.2)^{1/5} = 0.384$

The same method is applied to calculate the eigenvalues for the remaining criteria. The results are summarised in Table 9 below.

Table 9. Eigenvalue

Criteria	Eigenvalue
C1	0.384
C2	0.608
C3	1.000
C4	1.644
C5	2.605
Total	6.241

- Priority weight

The priority weight is obtained by dividing the eigenvalue of each criterion by the total eigenvalue. For example, the priority weight for C1 is:

$$C1 = \frac{0.384}{6.241}$$
$$= 0.062$$

The summary of priority weight is shown in Table 10 below.

Table 10. Priority weight

Criteria	Priority Weight
C1	0.062
C2	0.097
C3	0.160
C4	0.263
C5	0.417

- Value of interest

The value of interest is calculated to be used in determining the consistency index in the next step. This value is obtained by multiplying the priority weight of each criterion by the total from the corresponding column in the comparison matrix. For example, the value of interest for C1 is calculated as follows:

C1 = 0.062 × 15
= 0.923

Table 11. Value of interest

Criteria	Value of interest
C1	0.923
C2	1.024
C3	1.095
C4	1.075
C5	0.953
Total	5.069

- Consistency index

  Based on Equation 4, the consistency index for the pressure criterion is calculated as follows:

  $$CI = \frac{(5.069-5)}{4}$$
  $$= 0.017$$

- Index Random Consistency

  Based on Table 3, for 5 matrices, the Index of Random Consistency (IR) is 1.12.

- Consistency Ratio

  Based on Equation 5, the consistency ratio for the pressure criterion is:

  $$CR = \frac{0.017}{1.12}$$
  $$= 0.016$$

  Because the value of CR is less than 0.1, the calculation is considered accurate.

b. Longevity and Cost Analysis

Similar AHP steps are applied to the longevity and cost aspects. For longevity, the criteria are divided into three groups: less than 20 years (C1), 20 to 40 years (C2), and more than 40 years (C3). The comparison matrices for longevity are shown in Table 12 below.

Table 12. Comparison matrices for longevity

Criteria	Matched comparison matrix		
	C1	C2	C3
C1	1	1/3	1/5
C2	3	1	1/3
C3	5	3	1
Total	9	4.33	1.53

The number of criteria in the cost matrix is greater than that in the pressure and longevity matrices, which uses 8 groups to allow for a more detailed analysis. This is because cost is the most important factor in choosing a pipe alternative. Pipes with construction costs of less than 65 million are categorized as C1, and every addition 5 million in cost corresponds to C2 through C6. C7 includes pipes which cost from 90 to 100 million, while C8 represents pipes which cost more than 100 million. The matched comparison matrices for the cost criteria are presented in Table 13.

Table 13. Comparison matrices for pipe construction cost

Criteria	Matched comparison matrices							
	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	2	3	4	5	6	7	8
C2	1/2	1	2	3	4	5	6	7
C3	1/3	1/2	1	2	3	4	5	6
C4	1/4	1/3	1/2	1	2	3	4	5
C5	1/5	1/4	1/3	1/2	1	2	3	4
C6	1/6	1/5	1/4	1/3	1/2	1	2	3
C7	1/7	1/6	1/5	1/4	1/3	1/2	1	2
C8	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1
Total	2.72	4.59	7.45	11.28	16.08	21.83	28.5	36

The following steps, from the calculations of normalization of the pairwise comparison matrices to consistency ratio, are carried out in the same way as in the AHP process for the pressure analysis. A summary of this analysis is presented in Table 14.

Table 14. AHP resume for longevity and pipe costs

Parameter	Longevity	Pipe Cost
Synthetic weight		
C1	0.318	2.614
C2	0.781	1.819
C3	1.900	1.255
C3		0.861
C4		0.587
C5		0.398
C6		0.272
C7		0.193
C8		2.614
Eigenvalue		
C1	0.405	3.764
C2	1.000	2.662
C3	2.466	1.819
C3		1.223
C4		0.818
C5		0.550
C6		0.376
C7		0.266
C8		3.764
Priority weight		
C1	0.105	0.328
C2	0.258	0.232
C3	0.637	0.159
C3		0.107
C4		0.071
C5		0.048
C6		0.033
C7		0.023
C8		0.328

Parameter	Longevity	Pipe Cost
Value of Interest		
C1	0.943	0.891
C2	1.119	1.065
C3	0.977	1.181
C3		1.202
C4		1.146
C5		1.046
C6		0.933
C7		0.833
C8		0.891
Consistency Index (CI)	0.019	0.043
Index Random Consistency (IR)	0.580	1.410
Consistency Ratio (CR)	0.033	0.030

Based on Table 14, both longevity and cost have consistency ratios less than 0.1, which means that the calculations are accurate.

c. Alternative priority

The first step to get the alternative priority of pipe materials is calculating the priority weight of each criterion using AHP. In this analysis, 3 criteria were used, namely pressure (C1), longevity (C2), and pipe construction cost (C3). Based on the same steps used in the AHP process, the priority weight of pressure is 0.105; longevity is 0.258, and cost is 0.637. These numbers are multiplied by the priority weight of each alternative to determine the ranking of the pipe materials alternative. Table 15 shows the result of grading for each pipe type.

Table 15. Ranking of pipe alternatives

Alternative	Pressure	Longevity	Cost	Total
HDPE PN 16	0.017	0.165	0.015	0.196
HDPE PN 12.5	0.010	0.165	0.031	0.205
HDPE PN 10	0.006	0.165	0.101	0.272
PVC PN 12.5	0.010	0.067	0.068	0.145
PVC PN 10	0.006	0.067	0.148	0.221
Black pipe SCH 40	0.044	0.027	0.209	0.280
Galvanized SCH 40	0.044	0.165	0.045	0.254

Based on Table 15, the values in the Total column are used to determine the priority ranking of the pipe material alternatives. The alternative with the highest score is given the highest priority, followed by those with lower scores. It can be concluded that the ranking of pipe materials for water distribution in Sumbermanjing District is as follows: Black Pipe SCH 40, HDPE PN 10, Galvanized SCH 40, PVC PN 10, HDPE PN 12.5, HDPE PN 16, and PVC PN 12.5.

IV. CONCLUSIONS

Based on the research conducted, there are seven pipe material alternatives that can be used to distribute water from Kali Jaruman to Sumbermanjing District. To rank these seven pipe alternatives, the AHP method was used. The analysis was based on three criteria: pressure, longevity, and cost. The results show that, from the highest to the lowest priority, the recommended pipe material alternatives are Black Pipe SCH 40, HDPE PN 10, galvanized SCH 40, PVC PN 10, HDPE PN 12.5, HDPE PN 16, and PVC PN 12.5.

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