Prioritization of Municipal Water Mains Leakages for the Selection of R&R Maintenance Strategies Using Risk Based Multi-Criteria FAHP Model

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Abstract-**Municipal water network systems are composed of a wide range of complex buried infrastructure. Many of these essential infrastructures have reached or exceeded their design life cycle and need a sound rehabilitation and replacement (R&R) Maintenance Strategies. However, maintaining and repairing such an aging and complex water pipeline network systems in big urban cities presents a unique decision and management challenges for water utility companies with respect to how to carry out the ranking and evaluation process and decide which of these complex wide ranges of buried infrastructure from the networks required replacement or rehabilitation in a cost-effective manner. These decision and management challenges of maintaining water distribution pipeline network infrastructures at nearly the intended design condition by investing the minimum amount of money, and allocating limited resources utility companies have among different projects kept the water utility companies actively searching for innovative approaches for decision support methodologies based on analysis of options, that involves evaluation of many criteria and parameters in order to determine the optimal maintenance strategies.**

This paper presents how risk based Fuzzy Analytic Hierarchy Process (FAHP) decision approach can be used to rank existing or recently detected multiple leakages form WD pipeline networks. It also demonstrate how this method can benefit the decision making process for the selection of which pipeline required urgent action, and prioritize the optimal alternative rehabilitation and replacement (R&R) Maintenance Strategies by integrating value professional judgments and stakeholder preferences with limited annual budget the water utility companies may have. In conclusion, this FAHP approach would benefit the decision-makers of water utility companies where there are currently no structured approach or methods for making a responsible and defendable decision with clearly demonstrated trade-offs between stakeholder investment and water utility agencies service levels standards and objectives.

Keywords- Multi-Criteria Decision support (MCDS); FAHP Model; Urban Infrastructure; Rehabilitation and Replacement (R&R); Leakage; Asset Management

I. INTRODUCTION

Each water distribution pipeline networks has its own distinct characteristics such as different operating pressure, service location, pipe sizes, material, and deterioration factors. Today, one of the broader challenges water utility companies are facing associated with their infrastructure includes lack of when and how to evaluate, rank, plan and execute maintenance projects that restore or replace to originally designed capacity or condition in a cost-effective manner [1, 6, 7, 18]. Some of the decision challenges water utility companies are facing involve selecting the optimum possible solution among a number of competing alternatives. However, to select the best solution available in a systematic and innovative way, decision support methodologies with the desired objective in mind that facilitates comparative professional judgments and eventual optimized alternative decision options are needed. Therefore to demonstrate how risk based Fuzzy Analytic Hierarchy Process (FAHP) decision support approach can be used to rank existing or recently detected municipal water mainline leakages to select which water main pipeline require urgent action, and to prioritize the optimal alternative rehabilitation and replacement (R&R) Maintenance Strategies, with value professional judgments and stakeholder preferences a case study at Lille University has been carried out. The rest of this paper consists of a brief summary of FAHP and detail formulation of the FAHP model as well as a sample calculation to demonstrate model application using the case study of Lille University "Zone- six" water supply pipeline networks.

II. OVERVIEW OF RISK BASED MULTI-CRITERIA FAHP DECISION MAKING MODEL

Analytical hierarchy process is one of the most widely practiced decision support techniques by research scientists [2, 14]. Risk based multi-criteria decision support (MCDS) methodologies furnish a means of assessing the outcomes of each possible combination of quantifiable and qualitative attributes under the optimization constraints in a decision problem. The most powerful flair that FAHP possesses is its ability to elicit both true values of tangible elements and preference scores derived from subjective professional judgments for intangible elements in the form of ratios between absolute levels of performance of attribute pairs. AHP decomposes decision problem and filters out unimportant information. It also allows preference scores to be assigned by decision makers or stakeholders to attributes according to their perceived relative importance weights in a pairwise comparison process [12, 13, 15, 20].

III. FAHP MODEL FORMULATIONS AND APPLICATION

The Extent FAHP which is originally introduced by Chang, D.Y. (1996)[4,5,9,10], since then several research papers have been published using the FAHP procedure based on extent analysis methods and AHP decision support system in multi-criteria approaches, and demonstrated how it can be applied to different cases.

A. General AHP Approach

Let n be the number of criterion and $z_1,\ z_2,\ \ldots,\ z_n$ be their corresponding relative priority given by the water utility company decision maker. Then the judgment matrix A which contains pair wise comparison value a_{ij} for all i , j $\in \{1,2,\ldots,n\}$ is given by: Saaty L. T. (1990).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} 1 & \frac{z_1}{z_2} & \cdots & \frac{z_1}{z_n} \\ \frac{z_2}{z_1} & 1 & \cdots & \frac{z_2}{z_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{z_n}{z_1} & \frac{z_n}{z_2} & \cdots & 1 \end{bmatrix} \cdots \tag{1}$$

For multiple decision makers, let h be the number of decision maker and ${a_{ij}}^k$ be the pair wise comparison value of criteria i and j given by decision maker k, Where: - k=1, 2,…, h Then by using geometric mean of the ${a_{ij}}^k$ conducted by each decision maker, we have a new judgment matrix with element given by:

$$a_{ij} = \left[a^1{}_{ij} \times a^2{}_{ij} \times \cdots \times a^k{}_{ij} \times \cdots \times a^h{}_{ij} \right]^{\frac{1}{h}} = \left[\prod_{k=1}^{h} a^k{}_{ij} \right]^{\frac{1}{h}} \tag{2}$$

Now, normalize each column to get a new judgment matrix A'

$$A' = \begin{bmatrix} a'_{11} & a'_{12} & \cdots & a'_{1n} \\ a'_{21} & a'_{22} & \cdots & a'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a'_{n1} & a'_{n2} & \cdots & a'_{nn} \end{bmatrix} = \begin{bmatrix} \frac{a_{11}}{\sum_{i=1}^{n} a_{i1}} & \frac{a_{12}}{\sum_{i=1}^{n} a_{i2}} & \cdots & \frac{a_{1n}}{\sum_{i=1}^{n} a_{in}} \\ \frac{a_{21}}{\sum_{i=1}^{n} a_{i1}} & \frac{a_{22}}{\sum_{i=1}^{n} a_{i2}} & \cdots & \frac{a_{2n}}{\sum_{i=1}^{n} a_{in}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{a_{n1}}{\sum_{i=1}^{n} a_{i1}} & \frac{a_{n2}}{\sum_{i=1}^{n} a_{i2}} & \cdots & \frac{a_{nn}}{\sum_{i=1}^{n} a_{in}} \end{bmatrix} \tag{3}$$

Where: - $\sum_{i=1}^{n} a_{ij}$ is the sum of column j of judgment matrix A.

To get weight vector V by summing up each row of normalized judgment matrix A' we have

$$V = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{n} a'_{i1} \\ \sum_{j=1}^{n} a'_{21} \\ \vdots \\ \sum_{j=1}^{n} a'_{n1} \end{bmatrix} \tag{4}$$

By defining the final normalization weight vector W , we have

$$W=\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}=\begin{bmatrix} \frac{v_1}{\sum_{i=1}^{n} v_i} \\ \frac{v_2}{\sum_{i=1}^{n} v_i} \\ \vdots \\ \frac{v_n}{\sum_{i=1}^{n} v_i} \end{bmatrix} \tag{5}$$

B. The Chang's Extent Fuzzy AHP (FAHP) Approach

Let $\tilde{A}$ represent the $[n \times n]$ judgment matrix containing triangle fuzzy number (TFN) $\tilde{a}_{ij}$ for all $i, j \in \{1,2,\ldots,n\}$ as shown

$$\tilde{A}=\begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & (1,1,1) \end{bmatrix} \tag{6}$$

Where: - $\tilde{a}_{ij}=(l_{ij}, m_{ij}, u_{ij})$ with l_{ij} is the lower and u_{ij} is the upper limit and m_{ij} is the most likely value, where a fuzzy number, which is said to be a triangular of its membership function, is given as

$$\tilde{m}(x)=\begin{cases} \dfrac{x-l}{m-l} & l \le x \le m \\ \dfrac{u-x}{u-m} & m \le x \le u \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

Consider two triangle fuzzy numbers $\tilde{m}_1$ and $\tilde{m}_2$, $\tilde{m}_1=(l_1, m_1, u_1)$ and $\tilde{m}_2=(l_2, m_2, u_2)$.

The arithmetic operations between the two triangular fuzzy numbers are defined as: -

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2)=\tilde{m}_1 \oplus \tilde{m}_2=(l_1+l_2, m_1+m_2, u_1+u_2) \tag{8}$$

$$(l_1, m_1, u_1) \otimes (l_2, m_2, u_2)=\tilde{m}_1 \otimes \tilde{m}_2=(l_1 l_2, m_1 m_2, u_1 u_2) \tag{9}$$

$$(l_1, m_1, \mu_1)^{-1}=\tilde{m}_1^{-1}=\left[\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right] \tag{10}$$

The basic procedure of Chang's extent fuzzy AHP approach is given as following steps [3].

Step-1- Sum up each row of fuzzy judgment matrix $\tilde{A}$ to get the fuzzy number vector R_s.

$$R_s=\begin{bmatrix} rs_1 \\ rs_2 \\ \vdots \\ rs_n \end{bmatrix}=\begin{bmatrix} \sum_{j=1}^{n} \tilde{a}_{1j} \\ \sum_{j=1}^{n} \tilde{a}_{2j} \\ \vdots \\ \sum_{j=1}^{n} \tilde{a}_{nj} \end{bmatrix}=\begin{bmatrix} (\sum_{j=1}^{n} l_{1j}, & \sum_{j=1}^{n} m_{1j}, & \sum_{j=1}^{n} m_{1j}) \\ (\sum_{j=1}^{n} l_{2j}, & \sum_{j=1}^{n} m_{2j}, & \sum_{j=1}^{n} m_{2j}) \\ \vdots & \vdots & \vdots \\ (\sum_{j=1}^{n} l_{nj}, & \sum_{j=1}^{n} m_{nj}, & \sum_{j=1}^{n} m_{nj}) \end{bmatrix} \tag{11}$$

Step-2- Normalize the row fuzzy number vector R_s to get the fuzzy synthetic extent value vector S.

$$\tilde{S}=\begin{bmatrix}\tilde{S}_1\\ \tilde{S}_2\\ \vdots\\ \tilde{S}_n\end{bmatrix}=\begin{bmatrix} rs_1\otimes\left(\sum_{j=1}^{n} rs_j\right)^{-1}\\ rs_2\otimes\left(\sum_{j=1}^{n} rs_j\right)^{-1}\\ \vdots\\ rs_n\otimes\left(\sum_{j=1}^{n} rs_j\right)^{-1}\end{bmatrix} \tag{12}$$

Where: - $\left(\sum_{j=1}^{n} rs_j\right)^{-1}$ is the derivative of the sum fuzzy number vector R_s and it is calculated by

$$\left(\sum_{j=1}^{n} rs_j\right)^{-1}=\left(\frac{1}{\sum_{k=1}^{n}\sum_{j=1}^{n} u_{kj}},\frac{1}{\sum_{k=1}^{n}\sum_{j=1}^{n} m_{kj}},\frac{1}{\sum_{k=1}^{n}\sum_{j=1}^{n} l_{kj}}\right) \tag{13}$$

Step-3- Compute the degree of possibility to get the non-fuzzy weight vector V.

$$V=\begin{bmatrix}V_1\\ V_2\\ \vdots\\ V_n\end{bmatrix}=\begin{bmatrix}\min V(\tilde{S}_1\geq\tilde{S}_k)\\ \min V(\tilde{S}_2\geq\tilde{S}_k)\\ \vdots\\ \min V(\tilde{S}_n\geq\tilde{S}_k)\end{bmatrix} \tag{14}$$

Where for element i the subscript $k\in\{1,2,\ldots,n\}$ and $k\neq i$

The degree of possibility of $\tilde{S}_2=(l_2,\ m_2,\ u_2)\geq\tilde{S}_1=(l_1,m_1,\ u_1)$ is obtained by

$$V(\tilde{S}_2\geq\tilde{S}_1)=\begin{cases}1 & \text{of } m_2\geq m_1\\ 0 & \text{of } l_1\geq l_2\\ \dfrac{l_1-u_2}{(m_2-u_2)-(m_1-l_1)} & \text{otherwise}\end{cases} \tag{15}$$

Step-4- Define the final non-fuzzy normalization weight vector W.

$$W=\begin{bmatrix}W_1\\ W_2\\ \vdots\\ W_n\end{bmatrix}=\begin{bmatrix}\dfrac{V_1}{\sum_{i=1}^{n}V_i}\\ \dfrac{V_2}{\sum_{i=1}^{n}V_i}\\ \vdots\\ \dfrac{V_n}{\sum_{i=1}^{n}V_i}\end{bmatrix} \tag{16}$$

Where: - W is a non-fuzzy number.

IV. DECISION MAKING UNCERTAINTY

The process of decision making is encountered with uncertainties that can be generated from lack of professional judgments and incomplete knowledge of the consequences of actions that leads to imprecision and inherent randomness. Therefore, the credibility of the decision outcomes determined by MCD methods can be affected by the embedded uncertainty if not stated explicitly or dealt with in the model [3]. Judgment uncertainties are type of internal uncertainty that deals with imprecision in the assessment of criteria scores for different alternatives and criteria weights [8, 11, 16, 17]. Therefore, to avoid such uncertainty that could arise because of the external environment which provides insufficient information and forces the DMs to make imprecise judgments during pair wise criteria scoring for different alternatives and parameter weighing process, interviews of different professional on the field of water supply operations maintenances department of NYC have been conducted to get different ranking number outcomes for this case study explained in the rest of the paper.

V. LILLE UNIVERSITY ZONE-SIX RESEARCH CASE STUDY

A. *Introduction*

The Lille University was established 1854 Lille, although its academic roots extend back to 1562. It later moved to Villeneuve d'Ascq in 1967, with 25,000 full-time students plus 15,000 students in continuing education (2011). 1,310 permanent faculty members plus 1,200 staff and around 140 CNRS researchers work there in the different institutes and 43 research labs. Lille University is a member of the European Doctoral College Lille-Nord-Pas de Calais, which produces 400 doctorate dissertations every year. The university is ranked in the world top 200 universities in mathematics by the Shanghai ranking [19, 21]. Fig. 1 below is the map of general location of the campus and "Zone-6" of the research area.

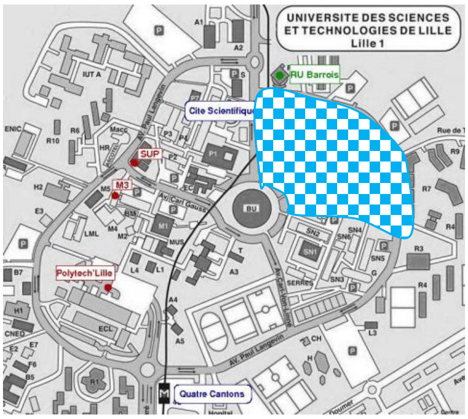


Fig. 1 general location of the campus and "Zone-6" of the research area

B. *Lille University's Water Pipeline Networks*

Lille University water pipeline network systems are divided into different supply zones Z1, Z2… etc. This case study has been carried out for the so-called "Zone-6" project area. Currently, there are approximately 3.8 km of water pipelines within the zone-six (Z6) with diameter of 150mm to 300mm. The aged of the pipe lines ranges from 10-50 years with different materials such as cast iron, ductile iron, and PVC. This network has operating pressure of approximately 4- 5 bars or 58-72 Psi. [12].The breakdown of the type of pipe, length in Km and percentage of pipeline material in service is shown in Table 1 below. Fig. 1 also shows a general map of the Zone-6 location. Fig. 2 and Table 2 below explain the overall Pipeline and existing condition.

The Pipelines data from the university database and from technical personnel feedback are used for parameters and criteria formulation required to develop FAHP approach. This includes structural data for the pipes (e.g. diameter, length of pipe, material, laying year, and soil conditions, co-ordinates, joint type...etc.).

TABLE 1 BREAKDOWN OF THE TYPE OF PIPE

Table -1 -				
Pipeline Code	**Length in km**	**Type of material**	**Diameter**	**% of pipe in service**
P-1	0.622	CI	150	22.76
P-2	0.517	CI	150	18.92
P-3	0.494	PVC	150	18.08
P-4	0.635	DC	300	23.24
P-5	0.465	DC	300	17.00

TABLE 2 EXISTING CONDITION OF "ZONE-SIX" PIPE LINE NETWORK

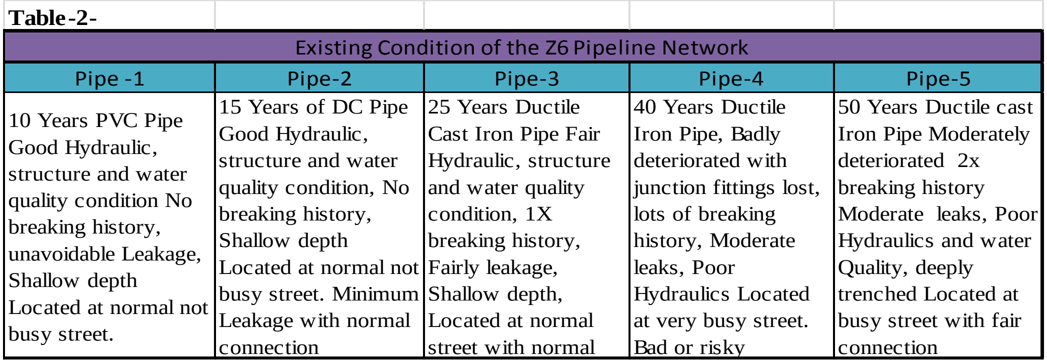
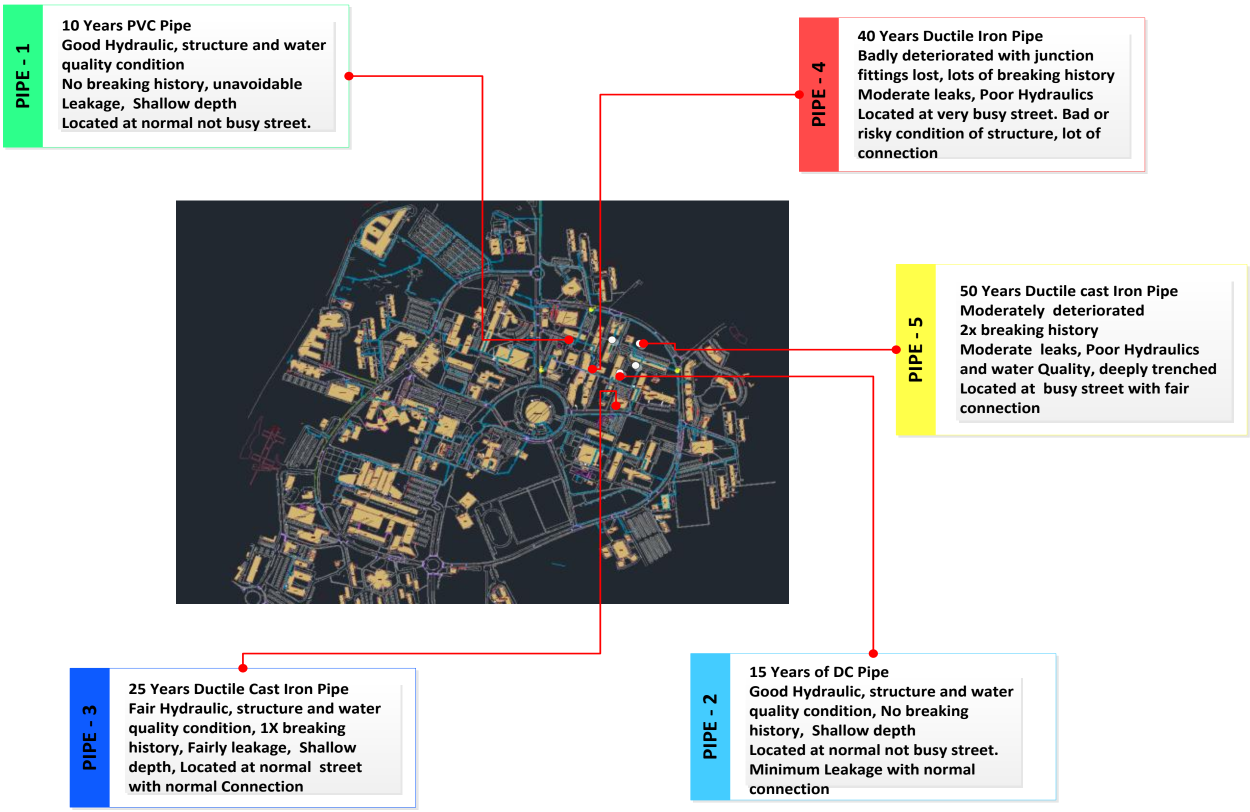


Table-2-				
Existing Condition of the Z6 Pipeline Network				
Pipe -1	Pipe-2	Pipe-3	Pipe-4	Pipe-5
10 Years PVC Pipe Good Hydraulic, structure and water quality condition No breaking history, unavoidable Leakage, Shallow depth Located at normal not busy street.	15 Years of DC Pipe Good Hydraulic, structure and water quality condition, No breaking history, Shallow depth Located at normal not busy street. Minimum Leakage with normal connection	25 Years Ductile Cast Iron Pipe Fair Hydraulic, structure and water quality condition, 1X breaking history, Fairly leakage, Shallow depth, Located at normal street with normal	40 Years Ductile Iron Pipe, Badly deteriorated with junction fittings lost, lots of breaking history, Moderate leaks, Poor Hydraulics Located at very busy street. Bad or risky	50 Years Ductile cast Iron Pipe Moderately deteriorated 2x breaking history Moderate leaks, Poor Hydraulics and water Quality, deeply trenched Located at busy street with fair connection



10 Years PVC Pipe
Good Hydraulic, structure and water quality condition
No breaking history, unavoidable Leakage, Shallow depth
Located at normal not busy street.

40 Years Ductile Iron Pipe
Badly deteriorated with junction fittings lost, lots of breaking history
Moderate leaks, Poor Hydraulics
Located at very busy street. Bad or risky condition of structure, lot of connection

50 Years Ductile cast Iron Pipe
Moderately deteriorated
2x breaking history
Moderate leaks, Poor Hydraulics and water Quality, deeply trenched
Located at busy street with fair connection

25 Years Ductile Cast Iron Pipe
Fair Hydraulic, structure and water quality condition, 1X breaking history, Fairly leakage, Shallow depth, Located at normal street with normal Connection

15 Years of DC Pipe
Good Hydraulic, structure and water quality condition, No breaking history, Shallow depth
Located at normal not busy street.
Minimum Leakage with normal connection

Fig. 2 location of all Pipeline mains and existing condition Zone-6

VI. MODEL FORMULATION APPROACH FOR MAINTENANCE STRATEGIES

The model formulation approach to rank multiple pipeline leakages to determine the optimal Maintenance Strategies for Prioritization of rehabilitation or replacement is based on the severity of the identified leakage and the potential damage that can cause the overall reliability of the system, the utility company's goals, performance objectives and target service levels standards. For the purpose of developing FAHP, and to establish risk based pair-wise comparison, the "Zone-6" water pipelines networks system was broken down into five main groups namely Physical, Environmental, Operational, Post leakage and Economic effect. Each characteristic has sub attributes listed below.

1. Physical characteristics i.e., pipe size, pipe age, material type, depth of cover, and status of appurtenances.
2. Environmental characteristics i.e., soil type location information such as proximity to highways and railroads, daily traffic.
3. Operational characteristics i.e., pipe break and leak history, repair records, leak detection reports, and water quality complaint records
4. Post leakage detection characteristics i.e., safety implications, damage to property, number / type of premises without water, volume of water leaking, traffic implications.
5. Economic assessment i.e., in cases where more than one alternative is feasible, an economic evaluation is applied to

select the best course of action from an economic standpoint.

The model formulation also consists of different stages, starting with full literature review of the risk of water distribution main failure and maintenance strategies followed by data collection to build the model and apply the model to Zone-six (Z6) case study. Each of these pipeline was represented by multi-criteria parameter profile mentioned above and coded as Pipe-1, 2, 3, 4, and 5 respectively, see Fig. 2 above. For each of pipelines the important parameters according to different attributes were evaluated by professional expertise and the relative weights were given. These weights are characterized by fuzzy number using Table 2. Due to lack of pipe inventory and failure data availability, the following assumptions were made: the pipe age is ranging from 10-50 years, and leakage/ breakage is assumed once in 10-15 years, some of the pipelines are deteriorated because of their exceeding their design life cycle.

These Fuzzy Pair-wise comparisons matrixes and decision making hierarchical structures are shown in Fig. 3 and Table 4 to 8. After the formation of fuzzy pair-wise comparisons matrix, criteria and alternatives weight are determined by fuzzy AHP. According to fuzzy AHP method, combined weights must be calculated first. Refer to Table 4 to 8, and by using the related equations, combined values are calculated and the related calculation for each matrix is given below.

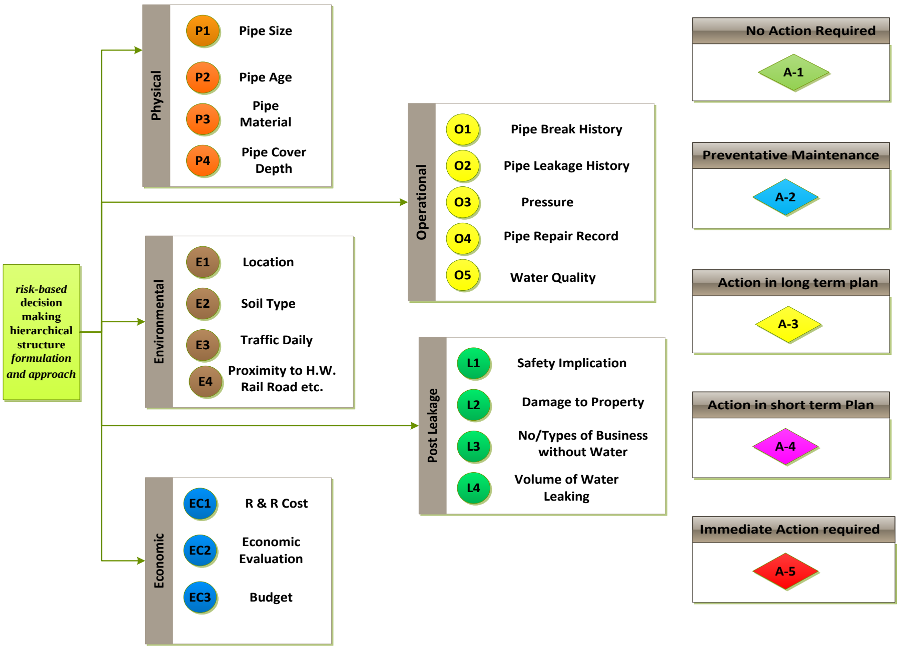


Fig. 3 risk-based decision making hierarchical structure formulation & approach

TABLE 4 SHOWS FUZZY PAIRED WISED COMPARISON MATRIX TOTAL CRITERIA

Table -4-

Criteria	Physical	Operational	Environmt.	Post Leakage	Economic	Priority Vector
Physical	(1,1,1)	(5,7,9)	(1/5,1/3,1/2)	(3,5,7)	(5,7,9)	0.154
Operational	(1/9,1/7,1/5)	(1,1,1)	(1/9,1/9,1/7)	(5,7,9)	(1/9,1/9,1/7)	0.202
Environment	(1,3,5)	(7,9,9)	(1,1,1)	(5,7,9)	(5,7,9)	0.01
Post Leakage	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1,1,1)	(7,9,9)	0.26
Economic	(1/9,1/7,1/5)	(7,9,9)	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1,1,1)	0.231

TABLE 5 SHOWS PHYSICAL CHARACTERISTICS I.E., PIPE SIZE, PIPE AGE, MATERIAL TYPE, DEPTH OF COVER

Table -5-

Pipe Network	Pipe -1	Pipe-2	Pipe-3	Pipe-4	Pipe-5
Pipe-1	(1,1,1)	(1,2,3)	(3,5,7)	(5,7,9)	(7,9,9)
Pipe-2	(1/3,1/2,1)	(1,1,1)	(1,3,5)	(5,7,9)	(1,3,5)
Pipe-3	(1/7,1/5,1/2)	(1/5,1/3,1)	(1,1,1)	(7,9,9)	(5,7,9)
Pipe-4	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1/9/1/9,1/7)	(1,1,1)	(5,7,9)
Pipe-5	(1/9,1/9,1/7)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1,1,1)

TABLE 6 SHOWS FUZZY PAIRED WISED COMPARISON MATRIX ACCORDING TO OPERATIONAL CHARACTERISTICS I.E., PIPE BREAK AND LEAK HISTORY, REPAIR RECORDS, LEAK DETECTION REPORTS

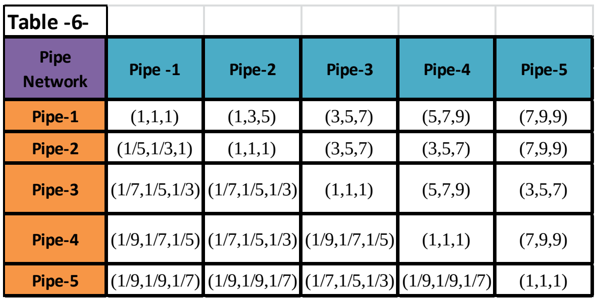


Table -6-					
Pipe Network	**Pipe -1**	**Pipe-2**	**Pipe-3**	**Pipe-4**	**Pipe-5**
Pipe-1	(1,1,1)	(1,3,5)	(3,5,7)	(5,7,9)	(7,9,9)
Pipe-2	(1/5,1/3,1)	(1,1,1)	(3,5,7)	(3,5,7)	(7,9,9)
Pipe-3	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1,1,1)	(5,7,9)	(3,5,7)
Pipe-4	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1,1,1)	(7,9,9)
Pipe-5	(1/9,1/9,1/7)	(1/9,1/9,1/7)	(1/7,1/5,1/3)	(1/9,1/9,1/7)	(1,1,1)

TABLE 7 SHOWS FUZZY PAIRED WISED WATER QUALITY COMPLAINT RECORDS AND ENVIRONMENTAL CHARACTERISTICS I.E., SOIL TYPE LOCATION INFORMATION SUCH AS PROXIMITY TO HIGHWAYS AND RAILROADS, DAILY TRAFFIC

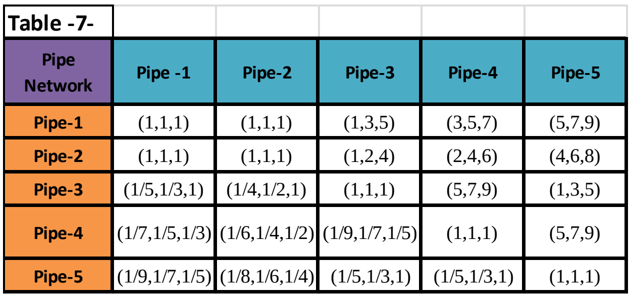


Table -7-					
Pipe Network	**Pipe -1**	**Pipe-2**	**Pipe-3**	**Pipe-4**	**Pipe-5**
Pipe-1	(1,1,1)	(1,1,1)	(1,3,5)	(3,5,7)	(5,7,9)
Pipe-2	(1,1,1)	(1,1,1)	(1,2,4)	(2,4,6)	(4,6,8)
Pipe-3	(1/5,1/3,1)	(1/4,1/2,1)	(1,1,1)	(5,7,9)	(1,3,5)
Pipe-4	(1/7,1/5,1/3)	(1/6,1/4,1/2)	(1/9,1/7,1/5)	(1,1,1)	(5,7,9)
Pipe-5	(1/9,1/7,1/5)	(1/8,1/6,1/4)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)

TABLE 8 SHOWS FUZZY PAIRED WISED COMPARISON MATRIXES ACCORDING TO POST LEAKAGE DETECTION CHARACTERISTICS I.E., SAFETY IMPLICATIONS, DAMAGE TO PROPERTY, NUMBER / TYPE OF PREMISES WITHOUT WATER, VOLUME OF WATER LEAKING, TRAFFIC IMPLICATIONS

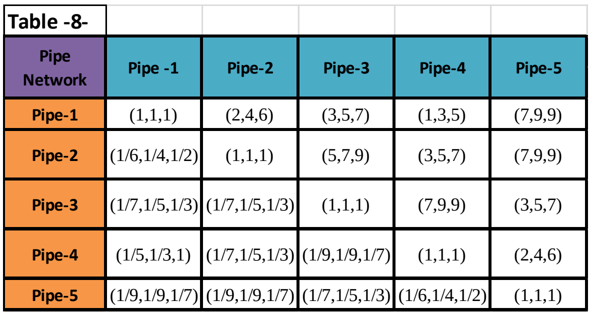


Table -8-					
Pipe Network	**Pipe -1**	**Pipe-2**	**Pipe-3**	**Pipe-4**	**Pipe-5**
Pipe-1	(1,1,1)	(2,4,6)	(3,5,7)	(1,3,5)	(7,9,9)
Pipe-2	(1/6,1/4,1/2)	(1,1,1)	(5,7,9)	(3,5,7)	(7,9,9)
Pipe-3	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1,1,1)	(7,9,9)	(3,5,7)
Pipe-4	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/9,1/9,1/7)	(1,1,1)	(2,4,6)
Pipe-5	(1/9,1/9,1/7)	(1/9,1/9,1/7)	(1/7,1/5,1/3)	(1/6,1/4,1/2)	(1,1,1)

TABLE 9 SHOWS ECONOMIC ASSESSMENT I.E., IN CASES WHERE MORE THAN ONE ALTERNATIVE IS FEASIBLE, AN ECONOMIC EVALUATION IS APPLIED TO SELECT THE BEST COURSE OF ACTION FROM AN ECONOMIC STANDPOINT

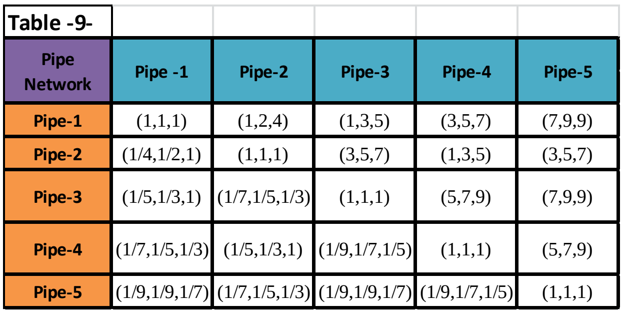


Table -9-					
Pipe Network	**Pipe -1**	**Pipe-2**	**Pipe-3**	**Pipe-4**	**Pipe-5**
Pipe-1	(1,1,1)	(1,2,4)	(1,3,5)	(3,5,7)	(7,9,9)
Pipe-2	(1/4,1/2,1)	(1,1,1)	(3,5,7)	(1,3,5)	(3,5,7)
Pipe-3	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(5,7,9)	(7,9,9)
Pipe-4	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1,1,1)	(5,7,9)
Pipe-5	(1/9,1/9,1/7)	(1/7,1/5,1/3)	(1/9,1/9,1/7)	(1/9,1/7,1/5)	(1,1,1)

VII. DEMONSTRATED SAMPLE CALCULATIONS AND PROCEDURE

Sample of mathematical calculation of FAHP and pairwise comparisons are demonstrated below Table 3 The fundamental scale of Fuzzy AHP from [10, 13]. The pair-wise comparison matrix for the main attributes is built and illustrated in the following table and other matrices are constructed in the same manner.

TABLE 3 CHARACTERISTICS OF THE TRIANGULAR FUZZY NUMBER

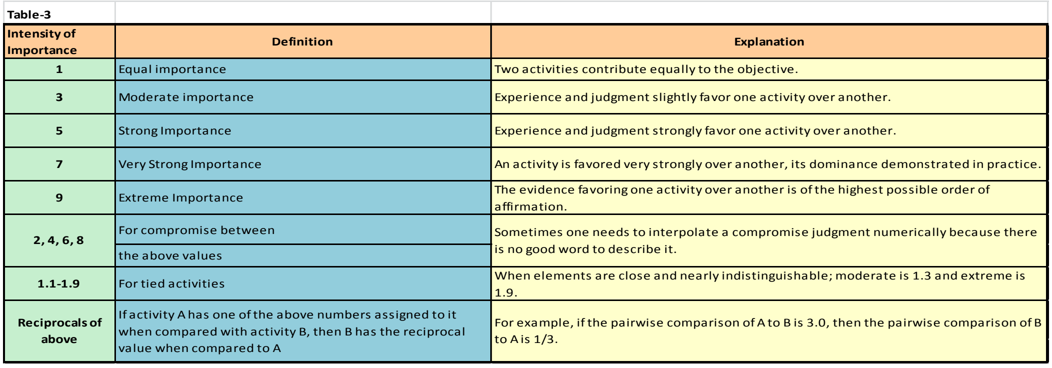


Table-3

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one activity over another.
5	Strong Importance	Experience and judgment strongly favor one activity over another.
7	Very Strong Importance	An activity is favored very strongly over another, its dominance demonstrated in practice.
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it.
1.1-1.9	For tied activities	When elements are close and nearly indistinguishable; moderate is 1.3 and extreme is 1.9.
Reciprocals of above	If activity A has one of the above numbers assigned to it when compared with activity B, then B has the reciprocal value when compared to A	For example, if the pairwise comparison of A to B is 3.0, then the pairwise comparison of B to A is 1/3.

Sample calculation for Post leakage characteristics matrix

$$R_s = \begin{bmatrix} rs_1 \\ rs_2 \\ \vdots \\ rs_n \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{n} \tilde{a}_{1j} \\ \sum_{j=1}^{n} \tilde{a}_{2j} \\ \vdots \\ \sum_{j=1}^{n} \tilde{a}_{nj} \end{bmatrix} = \begin{bmatrix} (\sum_{j=1}^{n} l_{1j}, & \sum_{j=1}^{n} m_{1j}, & \sum_{j=1}^{n} m_{1j}) \\ (\sum_{j=1}^{n} l_{2j}, & \sum_{j=1}^{n} m_{2j}, & \sum_{j=1}^{n} m_{2j}) \\ \vdots & \vdots & \vdots \\ (\sum_{j=1}^{n} l_{nj}, & \sum_{j=1}^{n} m_{nj}, & \sum_{j=1}^{n} m_{nj}) \end{bmatrix}$$

$$\begin{bmatrix} (1,1,1) & (1,2,4) & (3,5,7) & (5,7,9) & (7,9,9) \\ (1/3,1/2,1) & (1,1,1) & (1,3,5) & (5,7,9) & (1,3,5) \\ (1/7,1/5,1/2) & (1/5,1/3,1) & (1,1,1) & (7,9,9) & (5,7,9) \\ (1/9,1/7,1/5) & (1/9,1/7,1/5) & (1/9,1/9,1/7) & (1,1,1) & (5,7,9) \\ (1/9,1/9,1/7) & (1/5,1/3,1) & (1/9,1/7,1/5) & (1/9,1/7,1/5) & (1,1,1) \end{bmatrix} = \begin{bmatrix} 17.00 & 24.00 & 38.00 \\ 8.33 & 14.50 & 21.00 \\ 13.34 & 17.53 & 20.50 \\ 7.33 & 9.40 & 10.54 \\ 1.53 & 1.72 & 2.54 \end{bmatrix}$$

$$\left(\sum_{j=1}^{n} rs_j \right)^{-1} = \left(\frac{1}{\sum_{k=1}^{n} \sum_{j=1}^{n} u_{kj}}, \frac{1}{\sum_{k=1}^{n} \sum_{j=1}^{n} m_{kj}}, \frac{1}{\sum_{k=1}^{n} \sum_{j=1}^{n} l_{kj}} \right) = \left(\frac{1}{82.76}, \frac{1}{66..96}, \frac{1}{46.44} \right) = [0.012, 0.015, 0.022]$$

$$\tilde{S} = \begin{bmatrix} \tilde{S}_1 \\ \tilde{S}_2 \\ \vdots \\ \tilde{S}_n \end{bmatrix} = \begin{bmatrix} rs_1 \otimes \left(\sum_{j=1}^{n} rs_j \right)^{-1} \\ rs_2 \otimes \left(\sum_{j=1}^{n} rs_j \right)^{-1} \\ \vdots \\ rs_n \otimes \left(\sum_{j=1}^{n} rs_j \right)^{-1} \end{bmatrix} = \begin{bmatrix} 0.168 & 0.330 & 0.616 \\ 0.194 & 0.334 & 0.583 \\ 0.135 & 0.231 & 0.389 \\ 0.041 & 0.085 & 0.186 \\ 0.018 & 0.025 & 0.467 \end{bmatrix}$$

$$V(\tilde{S}_2 \ge \tilde{S}_1) = \begin{cases} 1 & \text{of } m_2 \ge m_1 \\ 0 & \text{of } l_1 \ge l_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases}$$

$$\begin{bmatrix} S_1 \ge S_2 = 1 & S_2 \ge S_1 = 1 & S_3 \ge S_1 = 0.05 & S_4 \ge S_1 = 0.00 & S_5 \ge S_1 = 0.41 \\ S_1 \ge S_3 = 1 & S_2 \ge S_3 = 0.65 & S_3 \ge S_1 = 0.65 & S_4 \ge S_2 = 0.00 & S_5 \ge S_2 = 0.47 \\ S_1 \ge S_4 = 1 & S_2 \ge S_4 = 0.03 & S_3 \ge S_1 = 1 & S_4 \ge S_3 = 0.00 & S_5 \ge S_3 = 0.62 \\ S_1 \ge S_5 = 1 & S_2 \ge S_5 = 0.47 & S_3 \ge S_1 = 1 & S_4 \ge S_4 = 0.00 & S_5 \ge S_4 = 0.88 \end{bmatrix}$$

$$V=\begin{bmatrix}V_1\\V_2\\\vdots\\V_n\end{bmatrix}=\begin{bmatrix}\min V(\tilde{S}_1\geq\tilde{S}_k)\\\min V(\tilde{S}_2\geq\tilde{S}_k)\\\vdots\\\min V(\tilde{S}_n\geq\tilde{S}_k)\end{bmatrix}=V_{\min}\begin{pmatrix}1, & 0.03 & 0.05 & 0.00 & 0.41\end{pmatrix}$$

$$W=\begin{bmatrix}W_1\\W_2\\\vdots\\W_n\end{bmatrix}=\begin{bmatrix}\dfrac{V_1}{\sum_{i=1}^{n}V_i}\\\dfrac{V_2}{\sum_{i=1}^{n}V_i}\\\vdots\\\dfrac{V_n}{\sum_{i=1}^{n}V_i}\end{bmatrix}=\begin{bmatrix}0.68\\0.02\\0.04\\0.00\\0.28\end{bmatrix}$$

Similar Calculation has been performed for the rest of the matrix and summarized and the result is recorded on see Table 10 below, and the final ranking is calculated as shown below.

TABLE 10 SHOWS THE SUMMARIZED RESULTS OF FUZZY PAIRED WISED COMPARISON MATRIXES FOR FINAL RANKING CALCULATIONS

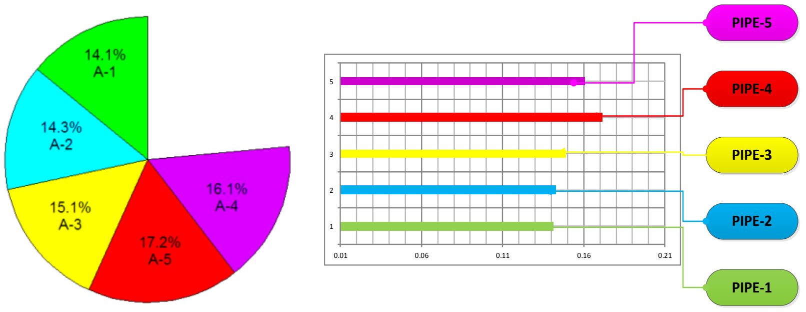
Table -10 -

	Physical	Operational	Envirt.	Post Leakage	Economic
P-1	0.38	0.43	0.32	0.68	0.19
P-2	0.22	0.35	0.28	0.02	0.41
P-3	0.27	0.2	0.24	0.04	0.22
P-4	0.07	0.02	0.16	0	0.18
P-5	0.08	0	0	0.28	0

$$\begin{bmatrix}0.38&0.22&0.27&0.07&0.08\\0.43&0.35&0.20&0.02&0.00\\0.32&0.28&0.24&0.16&0.00\\0.68&0.02&0.04&0.00&0.28\\0.19&0.41&0.22&0.18&0.00\end{bmatrix}\otimes\begin{bmatrix}0.151\\0.202\\0.01\\0.26\\0.23\end{bmatrix}=\begin{matrix}0.141=14.1\%=5th=A-1\\0.143=14.3\%=4th=A-2\\0.151=15.1\%=3rd=A-3\\0.172=17.2\%=1st=A-5\\0.161=16.1\%=2nd=A-4\end{matrix}$$

VIII. RESULT ANALYSIS, DISCUSSIONS AND CONCLUSION

The research results and analysis from the case study shows promising performance which could be used to support the water utility companies decision making process to present credible evidence and maintenance Strategies. The proposed methodology could be used for five different actions and to set priorities which pipeline require replacement or rehabilitation (R&R) actions, namely A-1. Excellent -No action required, A-2. Very Good -Preventive Maintenance action, A-3. Good -Mitigation action in long term plan, A-4. Fair-Mitigation action in short term plan, and A-5. Bad or Risky-Immediate Rehabilitation or Replacement action required as shown in Figs. 4 and 5. This allows the water utility companies to better understand the components that are economically feasible and critical to the overall reliability of the system and make a decision for the most feasible method of water main rehabilitation or maintenance strategies. In conclusion, this FAHP approach would benefit the decision-makers of water utility companies where there are currently no structured approach or methods for making responsible and defendable decision with clearly demonstrated trade-offs between stakeholder investment and water utility agencies service level standard and objectives.



Where: -
[A-1] Excellent No action required,
[A-2] Very Good Preventive maintenance
[A-3] Good Mitigation action in long term plan
[A-4] Fair Mitigation action in short term plan
[A-5] Bad or Risky Immediate Rehabilitation or Replacement action required

Fig. 4 Schematic representation of decision making & priority listing

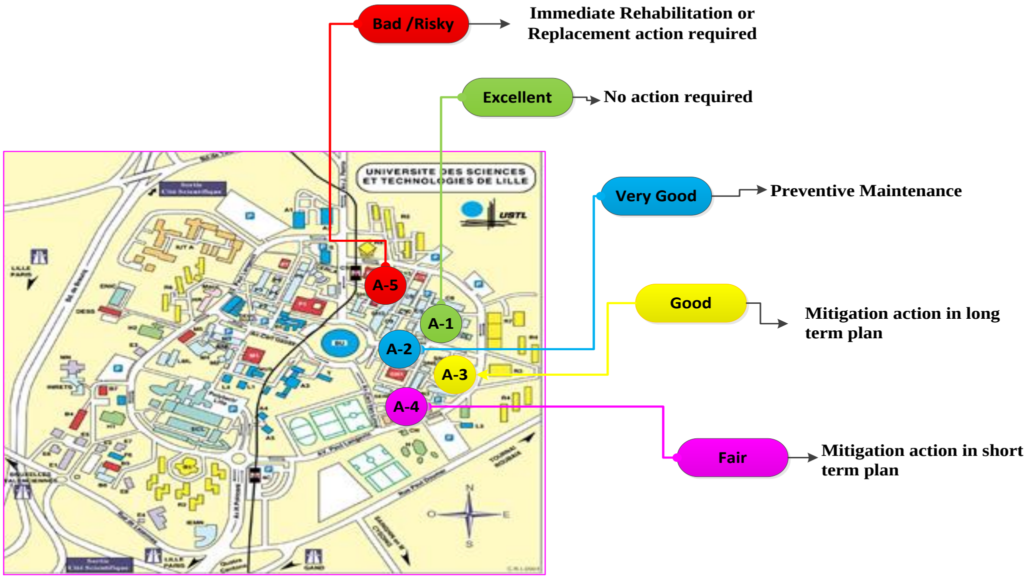


Fig. 5 Decision making & priority listing

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