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APPLICATION OF FAHP AND SHANNON ENTROPY IN EVALUATING CRITERIA SIGNIFICANCE IN PIPELINE DETERIORATION

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Abstract: Water Distribution Networks (WDNs) are the most important element in water supply systems. According to the Canadian Water and Wastewater Association (CWWA), there are more than 112,000 kilometers of water mains in Canada and their replacement cost is estimated to be $34 billion. Another $12 billion is required to service the projected growth. It is important to assess the long-term condition of WDNs to find their respective rate of deterioration in order to prevent disastrous failures and/or sudden shutdowns. Due to the limited data about water mains, condition of pipeline should be estimated based on available data. Therefore, to predict the pipeline condition, importance of each factor should be known. This study aims to calculate the weight of importance of factors that affect deterioration of pipelines. For this purpose, Fuzzy Analytical Hierarchy Process (FAHP) and Entropy Shannon are employed to prioritize the selected factors and calculate their relative weights based on their individual importance. Results show that pipe installation, age and material are the most effective parameters in modeling deterioration. These weights will be used in condition rating models to find the condition of pipelines based on their pipe characteristics, soil and water properties in order to estimate deterioration rate and expected remaining useful life.

1 INTRODUCTION

As Water Distribution Networks age, they experience the problem of deterioration and leakage. The frequency of leaks and breaks increase which result in loss of healthy drinking water. In Qatar, 35% of the drinking water is wasting through leaking only in Doha and 30% is wasting through other area (GWI 2010). Therefore, identifying the deterioration rates and the remaining useful life will help in performing more economical and efficient replacement and maintenance measures. Since in a number of cases, data needed for generating deterioration curves and estimating remaining useful life may be insufficient, prediction models should be employed to forecast the condition of the pipelines based on the available data such as pipe design. This paper utilizes different methods to calculate weight of importance for the most important factors affecting the condition of pipelines in condition rating models. It uses the integration of two methods to take into account the uncertainty and fuzziness of human judgements and decision making. The main objective of this research is to calculate criteria significance in pipeline deterioration in order to be used for future deterioration and remaining useful life models that will be utilized in developing a value-driven optimized intervention plans.

2 BACKGROUND

2.1 Shannon Entropy

In 1984, Claude Shannon proposed a mathematical theory to measure amount of information content of an information source. In this theory, the term of Entropy, refers to the portion of information content. This portion indicates the uncertainty of both the information source and the random variable and defines how much information is earned when result i is observed. When the raw data of the decision making matrix are identified completely, Entropy method could be used to evaluate the weights. There is more chance of occurrence for each value of i when entropy is higher. Considering P as a random variable and P_i as the probability, the theory identifies the relationship between Entropy (E) and random variable as for all the m criteria (Shannon 2001):

[1] $E_i = S(P_1, P_2, \dots, P_n) = -E_0 \sum_{i=1}^{n} P_i \ln(P_i)$

Where n is the total number of possible outcomes. Measuring uncertainty of a random variable i means that when $E_i = 0$, i would be a certain variable not a random one. Also in case of maximum quantity of E_i, i is a random variable with uniform distribution. In this formula, entropy and uncertainty are used for the same concept. In other words, average quantity of information which is collected after the observation of result xi in the random variable of X, is entropy. The concept of Shannon Entropy refers to an accepted measure of uncertainty and fuzziness. This is the main reason for choosing this method for calculating the weights. Entropy recently has been used in reliability assessment studies in WDN (Prasad and Tanyimboh 2008, Tanyimboh et al. 2011, Shibu and Reddy 2012) and was used along with AHP in weight determining in Zheng and Tian (2009).

2.2 Fuzzy Analytic Hierarchy Process (FAHP)

AHP gives weights to set of variables by organizing experiences and judgments of individuals into hierarchical structure. This structure illustrates relationships between goal, parameters and sub-parameters. Fuzzy analytical hierarchy process (FAHP) is the fuzzy format of AHP and is a well-known multi criteria decision making technique introduced by Saaty in 1988. It could be said that the ultimate goal of the AHP is collecting the expert's judgment; however it could not reflect the uncertainty in the judgments and knowledge of humans in decision making process precisely. The uncertainty could be modeled using fuzzy logic. Keliner et al. (2005) proposed a fuzzy Markov deterioration process to model failure risk of PCCP, cast and ductile iron water mains. Triangular memberships and fuzzy rules of "if-then" were employed to solve the problem. Condition of the asset was calculated from the present condition and deterioration rate, which had been identified from Markov deterioration process. Makropoulos and Butler (2005) developed a neuro-fuzzy spatial decision support system for pipe replacement prioritization. The model includes fuzzy logic and neural network back propagation algorithm which relates certain characteristics to pipe replacement. Najjaran et al. (2006) presented a fuzzy expert system to assess corrosion of cast/ductile iron pipes from backfill properties. The model comprises subjective and objective parts and two systems were suggested for fusion of the subjective and objective models. This methodology was also used in two other articles of "A Fuzzy Expert System for Deterioration Modeling of Buried Metallic Pipes" (Najjaran et al. 2004) and '"Fuzzy-Based method to evaluate soil corrosivity for prediction of water main deterioration" (Sadiq et al. 2004).

Al-Barqawi and Zayed (2006) presented a model using analytic hierarchy process (AHP) for water main conditions assessment. In this model, the effective factors were first recognized; then pair-wise comparisons were performed between each two of the factors, priorities were assigned and condition assessment records were calculated form priority matrices. Rajani and Tesfamariam (2007) proposed an approach for estimating time to failure of cast-iron water mains. The fuzzy membership function employed in this model is triangular fuzzy numbers. This model is identical to one presented in "Estimating Time to Failure of Ageing Cast Iron Water Mains under Uncertainties" (Rajani and Tesfamariam 2005) and "Possibilistic Approach for Consideration of Uncertainties to Estimate Structural Capacity of Aging Cast Iron Water Mains" (Tesfamariam et al. 2006). Al-Barqawi and Zayed (2008) also did another research about an integrated AHP/ANN model to evaluate municipal water mains' performance. They utilized AHP to calculate the weights and assign a value between 0 (critical) to 10 (excellent) to the condition of pipeline. Zhou et al. (2009) developed a Fuzzy based pipe condition assessment model which generates pipe condition rating using AHP from fuzzy first-level and second-level condition indicators. Fares and Zayed (2010) presented a hierarchical fuzzy expert system for risk of failure in water mains. The risk of failure varies between 0 (least risk) and 10 (highest risk). The impact factors of the parameters of four categories were evaluated utilizing the Mamadani rule system at first step. Then, they were used to calculate the risk of failure. FAHP is used to solve the hierarchical and multi criteria decision making problems by using trapezoidal and triangular fuzzy numbers. These two mentioned fuzzy numbers are mostly used to reduce the complexity of the problem due to the large number of criteria and decision makers. AHP has some limitations such as subjectivity and it doesn't consider uncertainty in inputs. FAHP has solved this problem. In FAHP, the experts are asked to enter all possible outcomes of modal, lowest and highest possible values in the pairwise comparison matrix. It means that they are entering the values three times more than they enter in regular AHP which is difficult and time consuming (Fares, 2008).

3 RESEARCH METHODOLOGY

The overall flow of the research process is depicted in Figure 1 and consisted of the following steps: 1) Data collection including questionnaire design, distribution and collection, 2) Data analysis and building the matrix of pairwise comparison, 3) Calculating the weights of importance of factors affecting pipeline deterioration through FAHP and Entropy individually, 4) Integration of weights calculated in previous step to find final weight of importance.

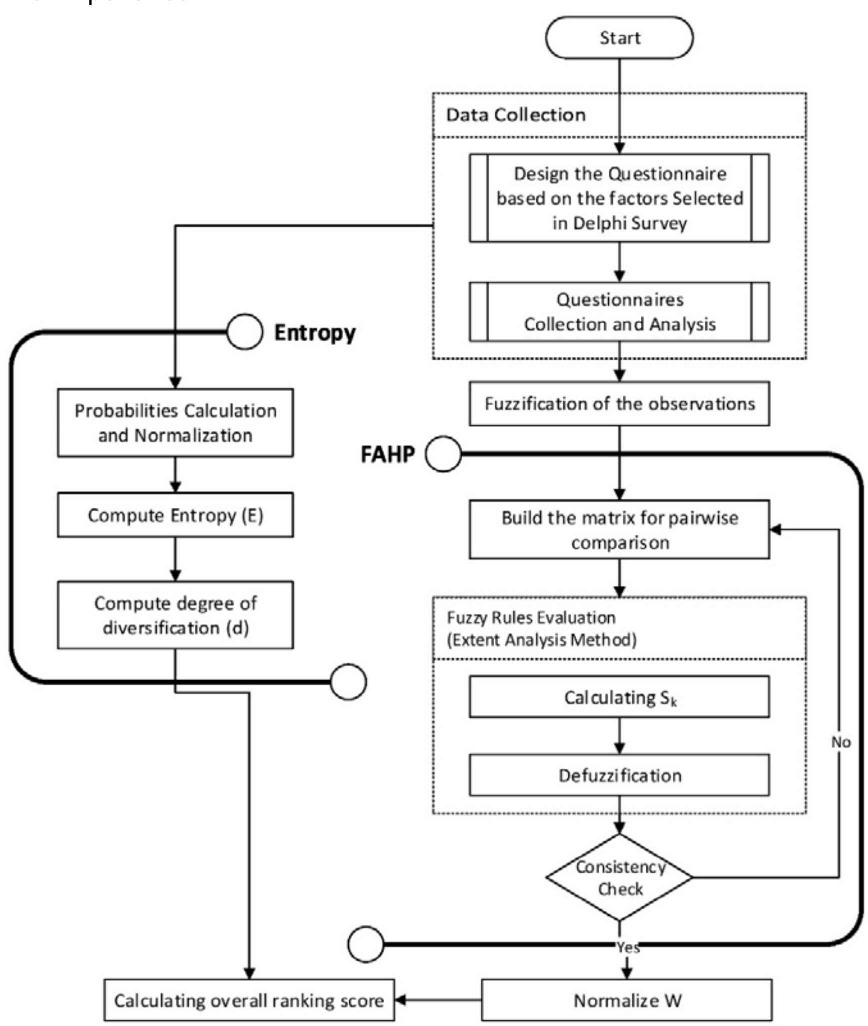

Figure 1: Overall flowchart of the research

3.1 Data Collection

The survey was performed in Fall 2014.the questionnaire was designed in an online format on Qualtrics website which is a data collection platform. 38 questionnaires were collected from experts around the world to find the weight of importance of each factor in water pipeline deterioration. The years of experience and demographic distribution of these experts is summarized in Figure 2 and 3. In the five-question questionnaire, the experts are asked to identify the relative importance of each criterion in pipeline deterioration both separately and respect to others by using linguistic variables of Table 1.

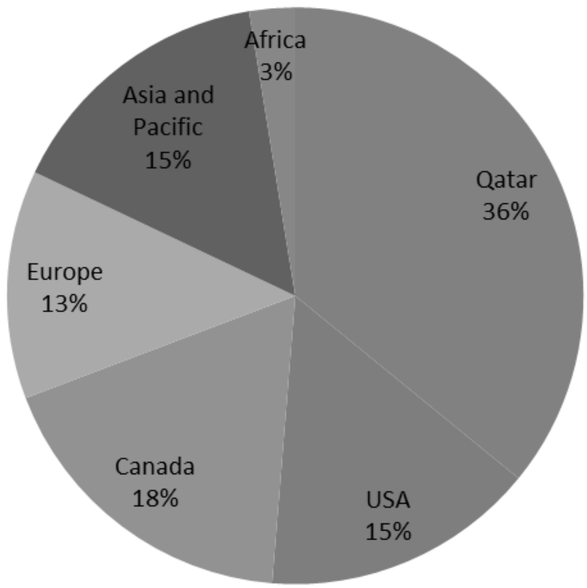

Figure 2: Demographic distribution of the experts

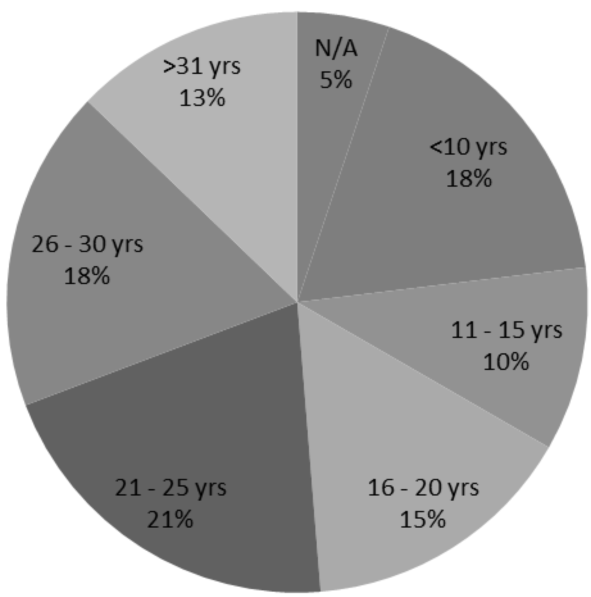

Figure 3: Years of experience of participants

Table 1: Linguistic variables for the importance weight of each criterion (Chen, 2000)

Linguistic Term	Fuzzy triangular Number
Extremely Low (EL)	(0.0, 0.0, 0.1)
Very Low (VL)	(0.0, 0.1, 0.3)
Medium Low (ML)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Medium High (MH)	(0.5, 0.7, 0.9)
Very High (VH)	(0.7, 0.9, 1.0)
Extremely High (EH)	(0.9, 1.0, 1.0)

3.2 Fuzzy Analytic Hierarchical Process (FAHP)

3.2.1 Pairwise comparison matrix

The very early step for analysis is building the matrix for pairwise comparison and checking its consistency. After that, the relative weights of parameters and sub-parameters were determined (Vahidnia, Alesheikh, Alimohammadi, & Bassiri, 2008).

$$A = \begin{vmatrix} 1 & W_{12} & \cdots & W_{1n} \\ W_{21} & 1 & \cdots & W_{2n} \\ \vdots & \vdots & 1 & \vdots \\ W_{n1} & W_{n2} & \cdots & 1 \end{vmatrix}$$

In this matrix, W_{12} is the weight of parameter 1 respect to parameter 2. All the arrays in matrix A are fuzzy triangular numbers of (l_{ij}, m_{ij}, u_{ij}).

3.2.2 Extent Analysis Method

To analyze FAHP, Larhorn and Pedric (1983) suggested a method which was based on minimum logarithmic squares. This method did not become popular due to its complexity and ambiguity (Nepal, Yadav, & Murat, 2010). After that, Chang (1996) proposed 'Extent Analysis Method (EA)' that used fuzzy triangular numbers which becomes more common in FAHP calculations (Nepal et al., 2010) and is used in this study. Considering $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the arithmetic functions are (Chang 1996):

[2] $M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$

[3] $M_1 \times M_2 = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2)$

[4] $M_1^{-1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right)$, $M_2^{-1} = \left(\frac{1}{u_2}, \frac{1}{m_2}, \frac{1}{l_2}\right)$

In this method, the triangular number of S_k is calculated for each row of the pairwise comparison matrix from below in which k is row number, i is alternative and j is criterion.

[5] $S_k = \sum_{j=1}^{n} M_{kj} \times \left[\sum_{i=1}^{m} \sum_{j=1}^{n} M_{ij}\right]^{-1}$

Computing S_k, their magnitude should be determined respect to others and the result should be normalized from equation 9.

[9] $W_i = \frac{w_i'}{\sum w_i'}$

After finding acceptable results, the priority matrices are combined together by multiplying the weight of factors (W_i) and weight of sub-factors (Y_i), to calculate the overall scores (Saaty, 1988). Subsequently, Consistency index (CI) which is a degree of deviation from consistency is checked. Afterward, consistency ratio (CR) defined as the ratio of the consistency index (CI) divided by the random inconsistency index (RI) for random comparisons is calculated (Saaty, 1988).

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

Table 2 : Random inconsistency indices (Saaty, 1988)

Number of Criteria	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.3 Shannon Entropy

The built pairwise comparison matrix for FAHP was used again to perform Shannon Entropy method. Normalizations were performed in Step 1 and entropy was calculated from Step 2. In Step 3, the degree of diversification and weight of importance were computed from calculated entropy.

[11] $\overline{W_{ji}} = \frac{W_{ji}}{\sum_{j=1}^{n} W_{ji}}\ j = 1, \ldots, n; i = 1, \ldots, n$

Compute entropy E_i as

$E_i = -E_0 \sum_{j=1}^{n} \overline{W_{ji}}\, ln\ \overline{W_{ji}}\ \ i = 1, \ldots, n$ Where E_0 is the entropy constant and is $\frac{1}{\ln(n)}$.

[12] $d_i = 1 - E_i$.

[13] $w_i = \frac{d_i}{\sum_{i=1}^{n} d_i},\ i = 1, \ldots, n.$

3.4 Integration of FAHP and Shannon Entropy

After finding the weights of importance from FAHP (w_j), they can be combined with computed degree of importance from Entropy (y_j) using equation below.

[14] $W_j = \frac{y_j w_j}{\sum_{j=1}^{n} y_j w_j} \qquad \forall j$

4 RESULTS AND DISCUSSION

The collected responses were analysed and total weight of importance for parameters identified through FAHP are summarized in Table 3. As can be seen, physical factors has the highest effect in deterioration of the water pipelines. Operational and Environmental factors are ranked as second and third important categories in pipeline deterioration. In physical factors, pipe material, pipe installation and pipe age are the first three significant factors. In category of Environmental factors, bedding soil type, seismic activity and backfill material are the most important factors in deterioration of water pipelines respectively. Furthermore, water pressure and O&M practices are the operational parameters that affect the deterioration of water pipelines at most. Computed global weight of importance for each category is multiplied by the local weight of importance of each sub-category to find the total weights of importance for each factor. It can be seen that criteria of pipe material, water pressure, pipe installation, pipe age and bedding soil type are the most important factors in pipeline deterioration in water infrastructure which has been determined by FAHP method. Consistency was checked for the pairwise comparison matrices and results are summarized in Table 3. The pairwise comparison matrix for identifying the global weights is also presented in Table 4.

Table 3: Total weights of importance for all parameters in FAHP

	Global weights	Factors	Local weights	Weights of importance
Physical	0.369129	Pipe material	0.178801	0.085314
		Pipe installation	0.149646	0.071402
		Pipe age	0.146582	0.069940
		Pipe lining and coating	0.135983	0.064883
		Pipe wall thickness	0.130229	0.062138

		Dissimilar metals	0.132782	0.063356
		Type of joints	0.125644	0.059950
Environmental	0.309955	Bedding soil type	0.233744	0.066893
		Backfill material	0.198028	0.056672
		Soil pH	0.164687	0.047130
		Seismic activity	0.220882	0.063212
		Disturbance	0.182371	0.052191
Operational	0.320865	Water pressure	0.313768	0.074364
		O&M practices	0.246516	0.058425
		Leakage	0.201185	0.047681
		Water pH	0.238179	0.056449

Table 4: Pairwise comparison matrix for identifying the global weights

	Physical Factors	Environmental Factors	Operational Factors
Physical Factors	(1, 1, 1)	(0.60, 0.78, 0.92)	(0.29, 0.44, 0.60)
Environmental Factors	(0.08, 0.21, 0.40)	(1, 1, 1)	(0.47, 0.64, 0.78)
Operational Factors	(0.40, 0.56, 0.71)	(0.22, 0.36, 0.53)	(1, 1, 1)

Table 5: Consistency in pairwise matrices

Pairwise comparison Matrix	CI	CR
Global weights	0.58075	1.0013
Physical factors	0.42589	0.4732
Environmental factors	0.53143	0.4026
Operational factors	0.54461	0.4863

The collected responses were also analysed for Entropy method. The entropy, degree of diversification and weight of importance of the deterioration factors were shown in the Table 6.

Table 6: Entropy, degree of diversification and weight of importance of the factors

Criteria/ Responses	e_j^*	d_j	w_j
Pipe material	0.43974	0.56026	0.066174
Pipe installation	0.53391	0.46609	0.080345
Pipe age	0.53840	0.46160	0.081019
Pipe lining and coating	0.56588	0.43412	0.085155
Pipe wall thickness	0.58516	0.41484	0.088057
Dissimilar metals	0.58820	0.41180	0.088515
Type of joints	0.59528	0.40472	0.089579

Bedding soil type	0.31559	0.68441	0.047492
Backfill material	0.36496	0.63504	0.054921
Soil pH	0.40421	0.59579	0.060827
Seismic activity	0.34103	0.65897	0.051320
Disturbance	0.38311	0.61689	0.057651
Water pressure	0.18103	0.81897	0.027242
O&M practices	0.23985	0.76015	0.036094
Leakage	0.27448	0.72552	0.041305
Water pH	0.29442	0.70558	0.044306

*e_j = entropy

d_j = degree of diversification

w_j = weight of importance

Since Outputs are not the same in both Entropy and FAHP methods, therefore the final weight will be an integration of both methods. Equation 14 is used to find the weights of importance of the parameters.

Table 7: Weights of factors from Entropy and FAHP

Criterion	Weights of importance
Pipe installation	0.09101
Pipe age	0.08989
Pipe material	0.08956
Dissimilar metals	0.08896
Pipe lining and coating	0.08765
Pipe wall thickness	0.08680
Type of joints	0.08519
Seismic activity	0.05146
Bedding soil type	0.05040
Backfill material	0.04937
Disturbance	0.04773
Soil pH	0.04548
Water pH	0.03967
O&M practices	0.03345
Water pressure	0.03214
Leakage	0.03124

The weights of importance from FAHP, Entropy method and integration of both methods are illustrated in Figure 4. The factors are organized based on the weights from the integration of both methods. It can be seen that the prediction of weight of importance for most of the criteria are approximately the same in the 3 calculations and the differences are less than 2% Greater differences are detected in water pressure, dissimilar metals, lining and coating and pipe wall thickness respectively. This confirms that the computed weight of importance for each of the criterion is calculated correctly and shows that more researches and clarifications are required to identify the effects of these criteria precisely.

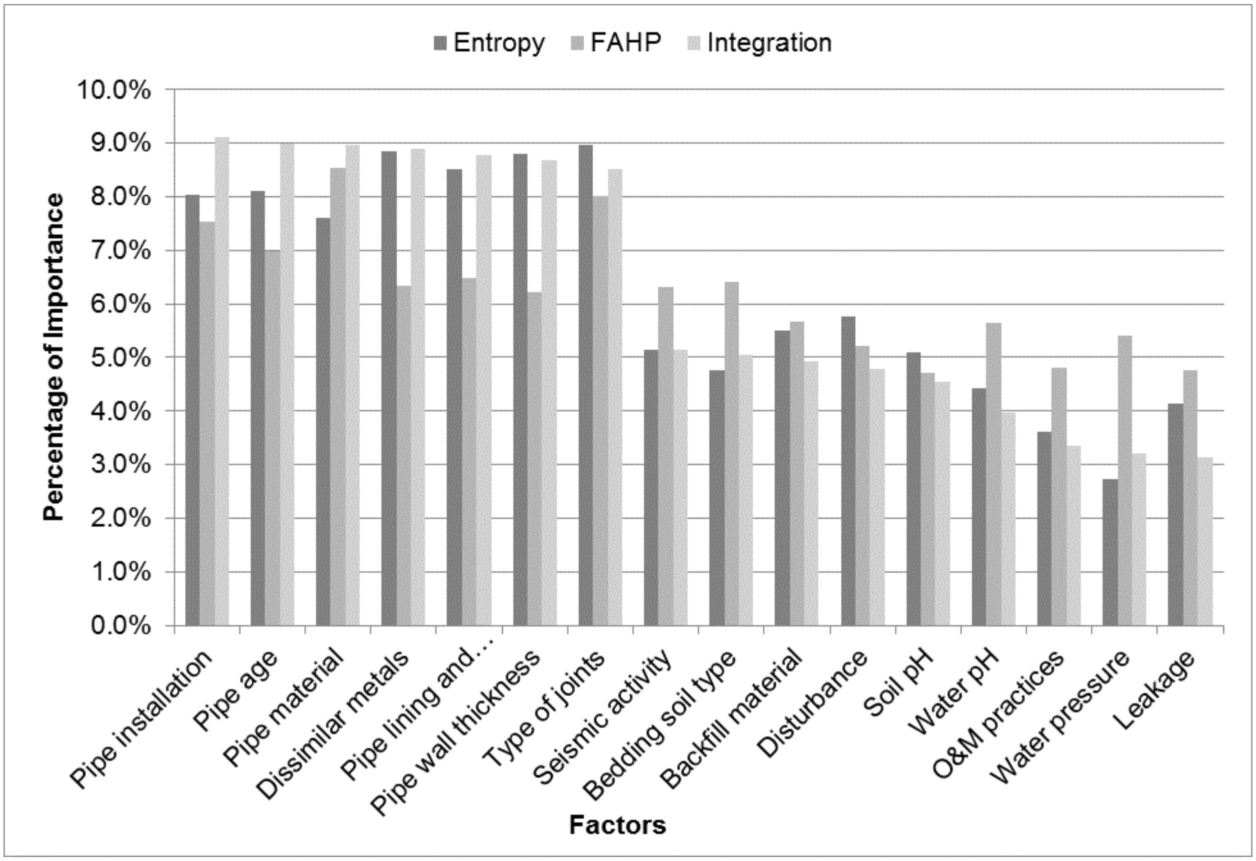

Figure 4 : Comparison of weights from different methods

5 CONCLUSIONS

As pipelines deteriorate, they are more exposed to failure from internal and/or external causes, therefore knowing the importance of effective factors in deterioration of water pipeline is essential in infrastructure management. This study applies Fuzzy Analytic Hierarchical Process (FAHP), Shannon Entropy and Integration of two methods to determine the weight of importance of the selected factors considering the deterioration process. Results show that physical factors and operational factors are the most and least important category of factors respectively. Pipe specifications such as installation, age, material, utilizing dissimilar metals and lining and coating proved to have the most influence on pipeline deterioration through analysis which should be take into account while designing durable and reliable pipelines. The outcome of this research also reveals consistency between the weights calculated in three highlighted ways except in water pressure, dissimilar metals, lining and coating and pipe wall thickness which brings the need for further investigations on the effect of these factors. The calculated weights of importance from integration of FAHP and Entropy will be used for future development of models for condition rating and deterioration.

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