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Multi Criteria Decision Analysis framework for risk management of oil and gas pipelines

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ABSTRACT: Oil and gas pipelines are subject to different degrees of failure and degradation during operation. Common pipeline failure mechanisms include corrosion, mechanical damage, third-party damage, and design imperfections. One or a combination of these failure mechanisms could eventually lead to rupture, carrying huge human, financial, and environmental loss. Hence, the need for reliable and cost effective risk management processes becomes more imperative. This paper proposes a decision based method for risk management of oil and gas pipelines. The method is based on a Multi Criteria Decision Analysis (MCDA) framework, utilizing an Analytic Hierarchy Process (AHP) to prioritize oil and gas pipelines for design, construction, inspection and maintenance. A case study application on pipelines in Nigeria is used to demonstrate the proposed methodology. The methodology is an improvement in the existing qualitative risk assessment of pipelines. Furthermore, with enhanced accuracy in risk assessment, considerable cost savings in the inspection and maintenance planning of the pipeline may be achieved.

1 INTRODUCTION

1.1 *Background*

Integrity maintenance of pipelines is a major challenge of service companies, especially those involved in the transmission of oil and gas. Two major factors have been the driving force behind this challenge. These are the need to minimize costs of installation, service and maintenance, and second is risk minimization. Safety analysis (or risk assessment) of pipelines entails the study of the probability of its failure and any associated consequences in terms of economic loss, human hazards, and degradation of the environment. Pipeline leakage or burst could be disastrous, having catastrophic influence on human and marine lives and huge economic loss. Pipeline disasters have been recorded in both developed and developing countries, including Venezuela, UK, Russia, Canada, Pakistan, Nigeria, and India (Dey *et al*. 2004 & Al-Khalill *et al*. 2005), necessitating the development of more effective risk management strategies.

Ideally, most pipeline operators ensure that during the design stage, safety provisions are created to provide a theoretical minimum failure rate for the life of the pipeline. While in operation, operators often used subjective estimate to carry out their routine based maintenance. However, subjective risk estimate is prone to inaccuracies with sometimes an unreliable outcome.

Transmission pipelines are complex in nature, and their risk analysis could be simplified by using an hierarchical approach, (Huipeng Li 2007). However, little has been achieved on hierarchical risk analysis of petroleum pipelines, as an aid to decision analysis, which is required in making inspection and maintenance decisions. Analytic hierarchy process is a promising method for this application. AHP, developed by Saaty fundamentally works by using opinions of experts in developing priorities for alternatives and the criteria used to judge the alternatives in a system, (Saaty 1980). The outcome is a relative scale which gives managers a rational basis for decision making. It has found applications in diverse industries, such as agriculture, (Quresh and Harrison 2003), oil and gas, (Al-Khalill *et al*. 2005 & Cagno *et al*. 2000), and the public sector, (Dey 2002).

In this paper, a systematic risk-based approach to risk management of oil and gas pipelines is presented. The method is based on a multi criteria decision analysis framework, utilizing an analytical hierarchy process to prioritize operating pipeline for design, construction, inspection and maintenance. The overall objective, sub-objectives, attributes and decision alternatives are represented in an hierarchy.

Three different oil and gas pipelines operated by the Nigerian National Petroleum Company (NNPC) have been used as a case study. Their failure factors and historical failure records were obtained from literatures and historical records from the company. The failure factors are listed as the sub-objective factors in the MCDA. They have been grouped and identified as external interference, corrosion, operational error, structural defects and other minor failures. Each sub-objective factor is further divided into attribute(s), as appropriate. For example, corrosion is a sub-objective factor which is further divided into external and internal corrosion. The selected crude oil and gas pipelines are the decision alternatives which will be prioritized for design, construction, inspection and maintenance.

In the methodology, AHP is used to estimate the probability of failure of pipelines by combining historical failure data of the pipeline with pairwise comparison carried out by experts. The expected values of consequences of pipeline failures are obtained from typical cost of failures. Risk is then estimated by the product of probability and consequences. Web-HIPRE version 1.22 (Mustajoki and Hämäläinen 2000), is used to analyze the results and to carry out a sensitivity analysis.

Scientifically, the approach will be valuable to oil and gas companies in prioritizing the inspection and maintenance activities of their oil and gas pipelines. The methodology could also prove valuable in arriving at a design, redesign, construction and monitoring decisions.

2 RESEARCH METHODOLOGY

2.1 *The analytic hierarchy process*

Analytic hierarchy process is used in the decision making to estimate the likelihood of an event, by establishing relative importance of each contributing factors. The analytical hierarchy process consists of the following basic steps:

2.2 *Procedures*

2.2.1 *Problem formulation*

The ultimate goal of the AHP is defined. In this paper, it is the determination of risk of failure of oil and gas pipelines. After the goal definition, contributing factors to the failure are then identified. If applicable, these factors are further divided into 1 or 2 sub factors.

2.2.2 *Selection of decision alternatives*

Identification of decision alternatives is very important in the AHP. The conclusion on the decision alternatives is the outcome of the AHP. In this paper, three oil and gas pipelines are selected as the decision alternatives. The goal of the AHP therefore is to compare these pipelines risk wise, and to rank them based on the level of risk expected.

2.2.3 *Collection of information*

Required features for the pipelines are divided into physical data, construction data, operational data, inspection data and Failure history. This information is documented for the hierarchical analysis.

2.2.4 *Hierarchy*

The next step is the development of an hierarchy (value tree), which consists of the goal of the risk assessment, the failure factors and sub factors, if applicable and the decision variables.

2.2.5 *Expert elicitation*

In the last step of the analytical hierarchy process, data of the pipelines are presented to a number of experts who will carry out a pairwise comparison of the pipelines with respect to each risk factor. The outcome of the comparison is a matrix that ranks the pipelines in order of likelihood of failure. The experts were required to rank each factor against another using the Saaty scale 1–9. Table 1 below gives an explanation of the Saaty scale.

For example, if two criteria are judged to have the same level of risk, the pairwise comparison score will be 1. A score of 9 is given if one criterion is assumed to be extremely stronger than the other. Intermediate judgments of 2, 4, 6 and 8 are selected when a conclusion cannot be reached from the scores of 1, 3, 5 and 7 as defined in Table 1.

2.2.6 *Consistency check*

AHP provides the possibility of checking the logical consistency of the pairwise matrix by calculating the Consistency Ratio (CR). AHP judgment is acceptable if CR is less than 0.1. Given a weight vector,

Table 1. Saaty scale of decision preference.

Judgment	Explanation	Score
Equally	Two attributes contribute equally to the objective	1
Moderately	Slightly favour one attribute over another	3
Strongly	Strongly favour one attribute over another	5
Very strongly	Strongly favour one attribute with demonstrated importance over another	7
Extremely	Evidence favouring one attribute over another is of the highest possible order of affirmation	9
Intermediate judgment	The intermediate values are used when compromise is needed	2, 4, 6, 8

$\vec{w} = \begin{bmatrix} w_1 \\ w_2 \\ w_n \end{bmatrix}$ Obtained from a decision matrix,

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{1n} \\ a_{21} & a_{22} & a_{2n} \\ a_{31} & a_{32} & a_{3n} \end{bmatrix}$$

The consistency of the decision matrix is calculated as follows:

Multiply matrix A by the weight vector $\vec{w}$ to give vector, $\vec{B}$

$$\vec{B} = \vec{A}.\vec{w} = \begin{bmatrix} b_1 \\ b_2 \\ b_n \end{bmatrix} \text{ where,}$$

$$\begin{aligned} b_1 &= a_{11}w_1 + a_{12}w_2 + a_{1n}w_n \\ b_2 &= a_{21}w_1 + a_{22}w_2 + a_{2n}w_n \\ b_n &= a_{31}w_1 + a_{32}w_2 + a_{3n}w_n \end{aligned} \tag{1}$$

Divide each element of vector, $\vec{B}$ with the corresponding element in the weight vector $\vec{w}$ to give a new vector

$$c = \begin{bmatrix} b_1/w_1 \\ b_2/w_2 \\ b_n/w_n \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_n \end{bmatrix} \tag{2}$$

$\lambda_{\max}$ is the average of the elements of vector $\vec{c}$:

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n} c_i \tag{3}$$

Consistency Index is then calculated using,

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

where n is order of the decision matrix and $\lambda_{\max}$ is obtained from equation (3) above.

Using equation (4), Consistency Ratio is calculated as,

$$CR = \frac{CI}{RI} \tag{5}$$

where RI is the random index and its value is obtained from Table 2 below.

Table 2. Random index table.

n	3	4	5	6	7	8	9	>9
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Other measures of consistency have been defined. For example, (Mustajoki and Hämäläinen, 2000) give a Consistency Measure (CM) of between 0 to 1 using the Multi Attribute Value Theory inherent in the Web-HIPRE software. A CM of 0.2 is considered acceptable.

Consistency Measure is calculated using,

$$CM = \frac{2}{n(n-1)} \sum_{i>j} \frac{\bar{r}(i,j) - \underline{r}(i,j)}{(1+\bar{r}(i,j))(1+\underline{r}(i,j))} \tag{6}$$

where $\bar{r}(i,j) = \max a(i,k)a(k,j)$, $k \in \{1, \ldots, n\}$ is the extended bound of the comparison matrix element $a(i, j)$, and $\underline{r}(i,j)$ is the inverse of $\bar{r}(i, j)$. CM gives an indication of the size of the extended region formed by the set of local preferences, when $w_i \le \bar{r}(i,j)w_j$ for all $i, j \in \{1, \ldots, n\}$.

3 CASE STUDY

3.1 *Background information*

The AHP methodology of Risk Management has been illustrated by a case study of oil and gas pipelines in Nigeria. A summary of the characteristics of the pipelines is given in Table 3 below. The goal of the research is to conduct a risk assessment of given pipelines using the AHP methodology. This is achieved by determining the relative contribution of different failure factors to the overall pipeline failure. The failure factors indentified for this study are: corrosion, external interference, structural defects, operational error and others. We arrived at these factors based on literature review, the historical record of failures from company database, and feedback from company experts.

Table 3. Summary of the attributes of pipelines.

	Pipeline		
Attribute	EL	AB	AZ
Primary service	Gas	Crude oil	Crude oil
Year of commission	1989	1996	2002
Type of coating	Concrete	Polykene	Polykene
Length	340 km	4 km	18 km
Diameter	24″	4″	6″
Design pressure	100 bar	207 bar	207 bar
Operating temperature	26.8°C	33.4°C	33.4°C
Material	Carbon steel	Carbon steel	Carbon steel
Climate	Tropical	Tropical	Tropical
Age of coating	21 yrs	25 yrs	25 yrs
Flowrate	600MCFd	1380bbls	1080bbls

A total of six pipeline experts participated in the expert judgment study on risk assessment of the pipelines. The affiliations of the experts are in the following organisations: Shell International, Chevron Exploration, BJ Services, Nigeria Petroleum Development Company, Nigeria National Petroleum Company, and SBM Offshore. Attributes of the pipelines and an historical failure records sheet containing defining characteristics of the pipelines were made available to the experts with a questionnaire.

3.2 *Construction of hierarchy*

A hierarchy tree of the three pipelines is constructed using Web-HIPRE software, version 1.22. The tree (Figure 1) contains information on the goal (failure of pipeline), criteria (failure factors) and sub-criteria (sub division of failure factors). The decision alternatives are the three pipelines under consideration.

3.3 *Results of pairwise comparison*

3.3.1 *Individual expert comparison*

Individual expert opinion on the pairwise comparison of factors responsible for pipeline failures are separately collected using a questionnaire that was made available to each expert. The outcome of the comparison is the pairwise matrix for the failure likelihood of the pipelines, based on the judgment of each expert. As expected, the outcome varied from one expert to another, since a consensus vote does not apply in this case.

3.3.2 *Group judgment*

The individual expert comparison is combined group wise using the geometric mean method (GMM), (Aczel and Saaty 1983). In the geometric mean method, the group judgment for the pairwise comparison is obtained by taking the geometric mean of the individual judgments. GMM is particularly suitable for aggregating group preference especially where conflicting responses could arise.

For n parties, the geometric mean of judgments from entries for the matrices of pairwise comparison is calculated as:

$$a^{G}_{ij\psi} = \left[\prod_{k=1}^{N} a^{k}_{ij\psi}\right]^{1/n}, i, j \in O_{\psi}, \psi \in \Psi,$$

Where:

$a^{G}_{ij\psi}$: The group judgment for criterion i with criterion j of issue ψ.
$a^{k}_{ij\psi}$: Judgment of individual k ($k = 1, \ldots, N$) for criterion i with criterion j of issue ψ.
O_{ψ}: Ordening of all criteria of issue ψ.

The result of the pairwise comparison for the group is shown in Table 4 below.

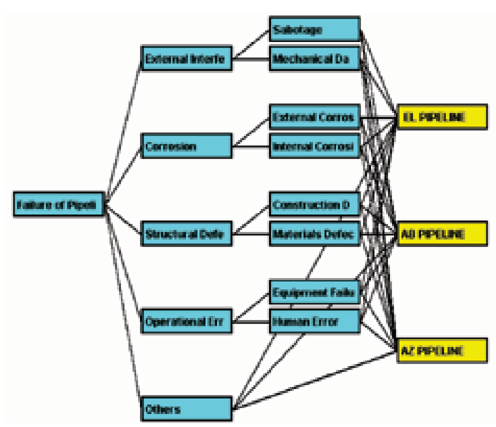

Figure 1. Hierarchy tree for EL, AB and AZ pipeline.

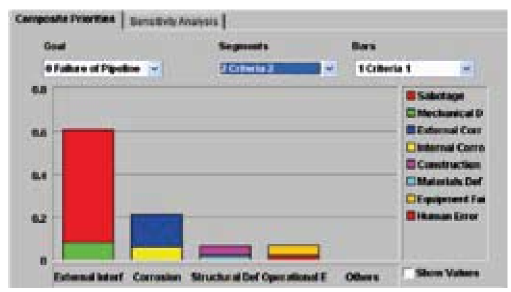

Figure 2. Distribution of factors responsible for pipeline failures. The figure shows external interference as the leading cause of pipeline failure followed by corrosion, with relative likelihood of failure of 0.607 and 0.214 respectively.

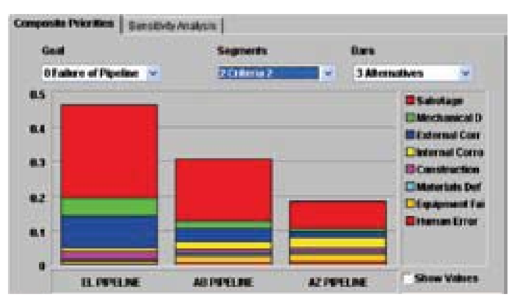

Figure 3. Factors responsible for failures of EL, AB and AZ pipelines. The figure shows EL as the most vulnerable among the three pipelines. The most pronounced failure factor for each pipeline is also shown. For example, for EL pipeline it can be seen that external corrosion is the next most significant failure factor after external interference. While for AZ pipeline it is internal corrosion.

Table 4. Pairwise ranking of failure criteria and likelihood of failure of EL, AB and AZ pipelines.

				Pipeline		
Factors	Likelihood	Sub-Factors	Likelihood	EL	AB	AZ
External interference	0.607	Sabotage	0.525	0.271	0.179	0.076
		Mechanical damage	0.081	0.051	0.019	0.011
Corrosion	0.214	External corrosion	0.153	0.093	0.041	0.018
		Internal corrosion	0.061	0.009	0.021	0.031
Structural defects	0.066	Construction defect	0.045	0.023	0.014	0.009
		Materials defects	0.021	0.006	0.007	0.008
Operational error	0.069	Equipment failure	0.050	0.009	0.018	0.024
		Human error	0.019	0.003	0.007	0.009
Others	0.044		0.044	0.023	0.011	0.010

3.4 *Sensitivity analysis*

The graphs below (Figures 4–8) show the sensitivity of each of the failure factors to the likelihood of failure of the pipelines. In the sensitivity analysis, the influence of changes on the overall model is investigated. The final priorities of the likelihood of failures of the pipelines depend greatly on the weights attached to the failure criteria. Similarly, the likelihood of failure of each pipeline is influenced by the weights attributed to each failure criterion. Hence, some changes in the relative weights of the failure criteria could lead to significant changes in the final ranking. Sensitivity analysis therefore gives good information on the robustness of the model.

The likelihood of failure due to external interference is increased by 20% to see how this affects the ranking of failures of EL, AB and AZ pipelines. This change results in about 3% increase and 10% decrease in the weights of EL and AZ pipeline respectively. AB pipeline has an increase of 2% in weight. The result is displayed in Figure 4. Similarly in Figure 5, a 70% decrease in the weight of operational errors leads to about 3% increase in the likelihood of failure of EL pipeline and a 5% decrease in the weight of AZ pipeline, with about 1% decrease in the weight of AB pipeline. In addition, the weight of corrosion and structural defect is further increased by 50% and 60% respectively, and the weight of minor failures (others) is decreased by 75% to capture the sensitivity. The outcomes are represented in Figures 6 to 8 below.

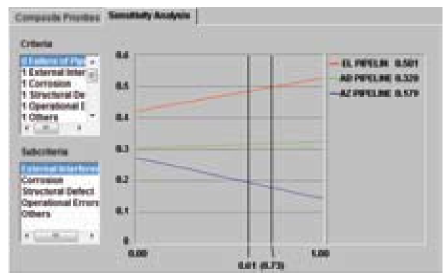

Figure 4. Sensitivity of pipeline failure to external interference when the likelihood of failure due to external interference is increased by 20%, from 0.61 to 0.73.

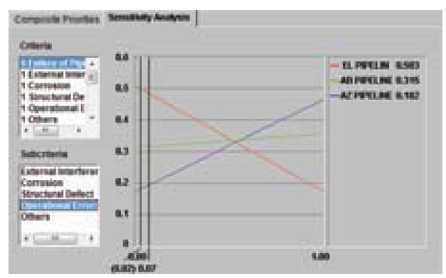

Figure 5. Sensitivity of pipeline failure to operational error when the weight of operational error is decreased by 70%.

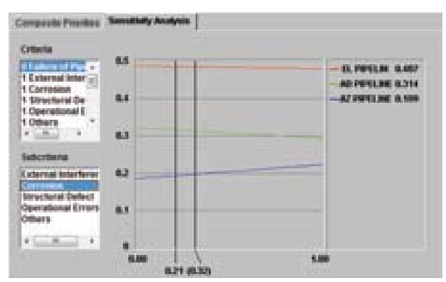

Figure 6. Sensitivity of pipeline failure for a 50% increase in the likelihood of failure due to corrosion.

4 RISK MANAGEMENT OF PIPELINES

4.1 *Inspection and maintenance strategy*

Part of the risk management strategies is to formulate an appropriate inspection and maintenance strategy for the three pipelines. Table 5 gives some possible strategy (ies) for each failure factor.

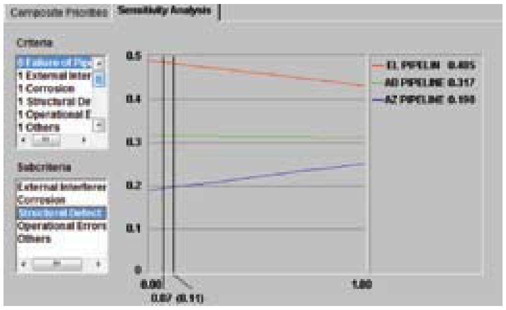

Figure 7. Sensitivity of pipeline failure due to structural defect when the weight is increased by 60%.

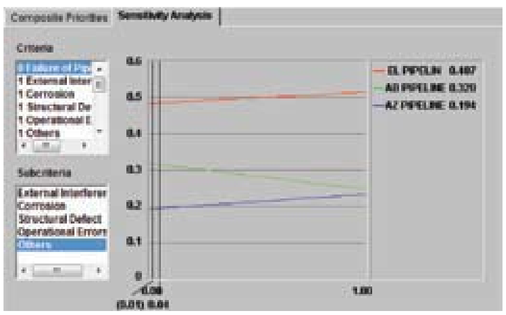

Figure 8. Sensitivity of pipeline failure for a 75% decrease in the weight of failure for other minor failures.

Table 5. Maintenance strategy for pipeline failures.

Sub-Factors	Maintenance strategy
Sabotage	Patrolling
Mechanical damage	Pipeline Marking/Improved Right of Way (ROW)
External corrosion	Pipe coating
Internal corrosion	Intelligent pigging survey
Construction defect	Reconstruction/ Replacement
Materials defects	Replacement of pipelines
Equipment failure	Replacement of faulty equipments
Human error	Operator training

EL pipeline is undoubtedly the most vulnerable among the 3 pipelines, having the highest likelihood of failure. The expected vulnerability of EL pipeline to external interference and external corrosion is much higher than expected for AB and AZ pipelines. EL pipeline is located in the Niger-Delta region of Nigeria, with a high likelihood of third party interference and sabotage due to the restive nature of the region. The high tendency to external corrosion could also be explained by the poor coating condition of the pipeline. The result presented in Figure 9 shows EL pipeline as the most vulnerable pipeline among the three pipelines. To reduce the likelihood to external interference more patrolling is suggested, while efficient pipe coating is recommended in order to reduce external corrosion.

The study reveals that AB pipeline is more liable to "external interference" than AZ pipeline, but not as liable as EL pipeline. Also, on "internal corrosion", AB seems to be more liable than EL pipeline, but better than AZ pipeline. On "Materials defect", the three pipelines generally have the same level of failure expectation. The similarity on the expected failure due to materials defect is expected because the three pipelines are all made of the same material, carbon steel. For AB pipeline, an intelligent pigging survey (IPS) is recommended to reduce its high likelihood to internal corrosion, and regular patrolling is also recommended to reduce its likelihood to external interference.

AZ pipeline has the highest likelihood of "internal corrosion", "equipment failure" and "human error". The investigation from the pipeline operator confirmed that the pipeline has suffered previously from internal corrosion and human failure. It is however interesting to note that if all the failure factors are considered, the likelihood of failure of pipeline AZ is much better than that of EL and AB pipelines. Therefore, AZ pipeline can be considered the least vulnerable among the three pipelines, as represented in Figure 9 and Table 4. This is due partially to the least likelihood of AZ pipeline to external interference, which has very high consequences. To reduce its operational error, immediate replacement of faulty equipments and retraining of operators is recommended. Intelligent pigging survey is also recommended to mitigate internal corrosion.

4.2 *Expected failure cost*

For the three pipelines, the severity of failure was estimated from historical failure costs available from database of the pipeline company. In addition,

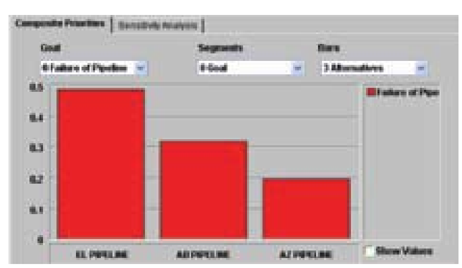

Figure 9. Ranking of pipelines according to likelihood of failure. Likelihood: EL = 0.488, AB = 0.317, and AZ = 0.196.

Table 6. Inspection and maintenance strategy for failure factors.

		EL pipeline		AB pipeline		AZ pipeline	
	Sub-Factors	Likeli-hood	Severity of failure ('$000 m)	Likeli-hood	Severity of failure ('$000 m)	Likeli-hood	Severity of failure ('$000 m)
External interference	Sabotage	0.271	2,200	0.179	800	0.076	1,000
	Mechanical damage	0.051	1,000	0.019	400	0.011	500
Corrosion	External corrosion	0.093	300	0.041	120	0.018	120
	Internal corrosion	0.009	200	0.021	80	0.031	100
Structural defects	Construction defect	0.023	80	0.014	30	0.009	35
	Materials defects	0.006	20	0.007	10	0.008	15
Operational error	Equipment failure	0.009	800	0.018	400	0.024	400
	Human error	0.003	400	0.007	200	0.009	200
Others		0.023	100	0.011	55	0.010	55
Likelihood of no failure		0.512	0	0.683	0	0.805	0
Expected failure cost		$689,560		$167,095		$99,145	

pipeline experts that participated in the AHP were asked to utilize their previous experience to estimate the severity of failure based on the unique characteristics of each pipeline.

In Table 6, the likelihood of failure obtained from the AHP result in Table 4 is combined with the severity of failure to calculate the expected failure cost for each pipeline.

It can be concluded from the results that the expected failure cost of EL pipeline is much higher than for AB and AZ pipeline. Moreover, AB pipeline has a higher likelihood of failure as compared to AZ pipeline. The expected failure cost calculation further indicates that allocating equal maintenance resources to the three pipelines will be a wrong and ineffective maintenance strategy. Therefore, in the allocation of maintenance resources, EL pipeline; with the highest expected failure cost should receive more attention than the other two pipelines. In addition, AB pipeline will require more maintenance resources than AZ pipeline.

5 CONCLUSIONS

A decision based model has been presented for risk management of oil and gas pipelines. The model uses available data and structured expert judgment to predict the probability of failure and severity of failure of oil and gas pipelines. The work has made a unique contribution to the application of Analytic hierarchy process in prioritizing oil and gas pipelines for maintenance. The geometric mean method is applied to arrive at a group consensus by combining individual responses of experts on pipeline failures. The software, Web-HIPRE used was found suitable to model the case study, and to express the sensitivity of the failure factors. The case study of petroleum pipelines in Nigeria revealed some interesting conclusions, which shows that location plays a significant role in pipeline integrity. Similar works (Dey *et al*. 2004 & Al-Khalill *et al*. 2005) have concluded that corrosion is the most significant failure criterion of petroleum pipelines in India and Saudi Arabia. However, for the Nigerian case study, external interference is found to be the most important failure criterion, representing 60% of the entire failure criteria. The high likelihood of failure by external interference obtained is due to the influence of sabotage acts on the petroleum pipelines. Therefore, increasing security around the pipelines would help to improve their reliability.

Concentrating on most relevant failure factors is cost efficient as it helps the concentration of maintenance resources on most relevant failure factors. The management will also find this approach to be beneficial in formulating an inspection and maintenance policy for the company's assets. For the pipelines, the outcome of the decision analysis could also prove useful in formulating individual and societal risk acceptance criteria (Vrijling *et al*. 2004).

The participation of experts with working knowledge of the pipelines reduces the subjective nature of the AHP method, although subjectivity has not been totally eliminated. In future work, a structured expert calibration technique will be applied to further reduce subjectivity. Also, the accuracy of the severity of failure estimated could be further improved with more data from the pipeline operator.

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