Open Access Journal

Journal of Sustainable Research in Engineering Vol. 2 (1) 2015, 17-22

Journal homepage: www.jkuat-sri.com/ojs/index.php/sri/index

Selecting an Appropriate Maintenance Policy for Petroleum Pipeline System using AHP: A case study

Mark E. Achilla*[1], Peter N. Muchiri[2] and Bernard W. Ikua[3]

[1]*Department of Mechanical Engineering, Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. BOX 62000-00200, Nairobi, Kenya.*

[2]*School of Engineering, Dedan Kimathi University of Technology (DKUT), P.O. BOX 657-10100, Nyeri, Kenya..*

[3]*College of Engineering and Technology, Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. BOX 62000-00200 Nairobi, Kenya.*

**Corresponding Author - Email: meachilla@yahoo.com.*

Abstract Petroleum pipelines are the most energy-efficient, safe, environmentally friendly, and economic way to transport oil and gas over long distances. Significant portions of many nations' energy requirements are now transported through pipelines. With the economies of many countries depending on the smooth and uninterrupted operation of these lines, it is increasingly important to sustain, preserve and prolong the operating lives of the pipelines through systematic maintenance efforts that ensure the safe and failure-free operation of pipelines.

This paper seeks to determine the appropriate maintenance policy for the pipeline system using analytic hierarchy process (AHP). A case study approach is adopted for the pipeline in Kenya. Several steps of the AHP approach are used in structuring the decision making process. Petroleum pipeline maintenance policy selection involves identifying the failure and risk factors that initiate pipeline failures and using them as criteria for selecting the appropriate maintenance policy. The pipeline system failure factors are: operational error, external interference, corrosion, structural defects and natural hazards. Four possible maintenance policy alternatives are considered: failure based maintenance, condition based maintenance, time based maintenance and design out maintenance. The AHP results suggest that condition based maintenance (CBM) is the most appropriate maintenance policy for the pipeline system.

Keywords Pipeline system, maintenance policy, pipeline failure factors, analytic hierarchy process (AHP).

---

1. Introduction

Petroleum pipeline equipment handle large volumes of flammable and hazardous hydrocarbons and a small accident involving the pipeline system equipment may lead to heavy losses. The Pipelines are subjected to several risks, which can cause failure of the line. These risks include corrosion, third party damage,operational errors, and construction defects.

Pipeline operators are continually developing inhouse maintenance policies to replace the rules-of-thumb inspection and maintenance practices. This is because even though these pipelines are known to be the safest way of transporting these flammable and volatile materials with much lower failure rates compared to railroads and highway transportation, their failure can be catastrophic.

In Kenya, the Sinai tragedy of 2011 occasioned by pipeline equipment failure and subsequent ignition of the fuel led to loss of one hundred people with several others sustaining serious degree burns. Venezuela lost fifty one people in 1993 as a result of gas pipeline failure and subsequent ignition of the escaping gas. The failure of a 914 mm pipeline in New Jersey in 1994 caused a loss of one life and injuries to over 50 people. Similar failures have occurred in the UK, Canada, Russia, Pakistan, and India as stated by Hopkins [1]. Given these incidents, there is need to select a proper maintenance policy for the pipeline system.

2. Review of Maintenance Policies

A maintenance policy is a set of activities which help keep plant, machinery and other activities in good condition. The maintenance policies described in this study are: failure based maintenance, condition based maintenance, time based maintenance and design out maintenance.

2.1. Maintenance Policies

Failure based maintenance (FBM) prescribes activation of maintenance in the event of failure [2], and no action is taken to detect or prevent failure [3].

Condition based maintenance (CBM) is a maintenance program that recommends maintenance decisions based on the information collected through condition monitoring [4]. CBM is considered as a management toolbox required for planning maintenance activities, such as data acquisition, analysis, scheduling and conducting maintenance actions cost-effectively [5].

Time-based maintenance (TBM) is maintenance performed on equipment based on a calendar schedule. This means that time is the trigger for this type of maintenance. TBM is planned maintenance and can be used with both preventative maintenance and predictive maintenance strategies. In TBM, a maintenance plan for a piece of equipment is drawn and maintenance is performed each time the calendar rolls over the specified number of days.

According to Gopalakrishnan and Banerji [6], DOM is a system that strives to eliminate, and if that is not possible, then to minimise the need for maintenance to the lowest possible level. It is therefore also known as eliminative maintenance. Hence it has to be thought of and applied to the product at the design stage itself, so that machinery, plant, and equipment are so designed as to require the least possible amount of attention or maintenance during their economic life-span.

2.2. Maintenance Policy Selection Criteria

A number of studies that focused on maintenance policy selection have been reported in literature. Azadivar and Shu [7] proposed some effective methods of selecting appropriate maintenance strategies for just in time production systems. Okumura and Okino [8] presented the maintenance selection method based on production loss and maintenance cost. Bevilacqua and Braglia [9] used an analytical hierarchy process (AHP) for maintenance selection in an oil refinery. In their study, four evaluation criteria (damages produced by a failure, applicability of the maintenance policy, added value created by the policy, and the cost of the policy) that influenced the primary goal were used.

Many different multiple criteria decision making (MCDM) methods were also adopted in maintenance strategy selection process. For instance, Al-najjar and Alsyouf [3] assessed the most popular maintenance strategies using the fuzzy inference theory and fuzzy MCDM evaluation methodology. A number of researchers identify the criteria using past data and technical analysis of processes, machines and components. Wang et. al [10] evaluated maintenance strategies based on the fuzzy AHP method. Authors used safety, cost, added-value and feasibility as main criteria. Bertolini and Bevilacqua [11] proposed a combined goal programming and AHP for maintenance selection through the use of the classic parameters occurrence, severity and detectability. In a more recent study by Zaim et. al [12], authors used AHP and ANP decision-making methodologies for the selection of the most appropriate maintenance strategy.

While drawing on prior studies related to the application of the AHP for maintenance policy selection, this paper utilizes AHP approach in selecting a maintenance policy for petroleum pipeline system. The criteria used will be based on past historical failure data, operational error, external interference, corrosion, structural defects and natural hazards.

2.3. Analytic Hierarchy Process

AHP, which was developed by Thomas L. Saaty [13] is a theory of measurement involving pairwise comparisons and relies on the judgements of experts to derive priority scales. The comparisons are made using a scale of absolute judgements that indicate how much more one element dominates another with respect to a given attribute [14]. AHP can be used in making decisions that are complex, unstructured, and contain multiple-attributes [15]. AHP provides a methodology for risk analysis, which, when applied to pipeline failure potential, creates a cost-effective, customized, flexible, and logical maintenance plan [16]. There are three basic principles of the AHP which include [17]:

1) **The principle of constructing hierarchies**
   A complex system is structured hierarchically by decomposing the elements into constituent parts according to essential relationships towards a desired goal which can make the whole system well understood.
2) **The principle of establishing priorities**
   The first step in establishing the priorities of elements in a decision problem is to make pairwise comparison that is to compare the elements in pairs against a given criterion. Table 1 shows the scale for pairwise comparison matrix. Saaty [17] pointed out that experience has confirmed that a scale of nine units is reasonable and reflects the degree to which the intensity of relationships between elements can be discriminated.

Table 1. Scale for pairwise comparison matrix [17]

Judgment	Explanation	Score
Equal importance of both elements.	Two criteria are of equal importance and equally contribute to the property or objectives.	1
Weak importance of one over another.	Experience and judgment slightly favour one criterion or element over another.	3
Essential or strong importance of one element over another.	Experience and judgment strongly favour one criterion or element over another.	5
Very strong and demonstrated importance of one element over another.	A criterion or element is strongly more important or favoured and its dominance is demonstrated in practice than the other.	7
Absolute importance of one element over another.	The evidence favouring one criterion over another is of the highest possible order of affirmation.	9
Intermediate values between adjacent scale values.	The intermediate values are used when compromise is needed.	2, 4, 6, 8

3) **The principle of logical consistency**: Logical consistency ensures that, elements are grouped logically and ranked consistently according to a logical criterion. The consistency of the comparison matrix is monitored by a consistency ratio (CR) calculated as:

$$CR = \frac{CI}{RI} \qquad (1)$$

Where CI is the consistency index and RI is the Random index.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (2)$$

Where n is the number of criteria or sub-criteria of each level and λ_{max} is the largest eigenvector in the matrix.
Table 2 shows Random Index (RI) for consistency index of a randomly generated reciprocal matrix within a scale of 1 to 9.

Table 2. Random index table [17]

n	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

AHP is an effective method for dealing with complex decision making and can assist in identifying and weighing criteria, analyzing data collected and advancing the decision making process. AHP method has received considerable attention among decision makers and has demonstrated its applicability in different fields such as maintenance policy selection, prioritizing and selecting suitable organizational structure.

3. Methodology

In this study, the AHP approach used entails: outlining the problem, structuring the decision hierarchy, pairwise comparison of criteria (failure cause factors) and alternatives (maintenance policies), and determining priorities for the alternatives. The following steps outline the methodology used:

Step 1: Defining the study objective or goal
The objective of the study was to select an appropriate maintenance policy for the pipeline system.

Step 2: Identifying criteria for selecting maintenance policy
In this study, the criteria identified for maintenance policy selection are corrosion, structural defects, natural hazard, operational error and external interference. These are the factors attributed to the pipeline system failures.

Step 3: Determining the alternative maintenance policies
The maintenance policies analyzed in this study were FBM, CBM, TBM, and DOM.

Step 4: Construction of a hierarchy framework for analysis
The criteria were structured into a hierarchy descending from the overall objective to the alternatives. The first level of the hierarchy represents the objective/goal, while the second level consists of the criteria (pipeline failure cause factors), the third level represents the alternative maintenance policies as illustrated in figure 1.

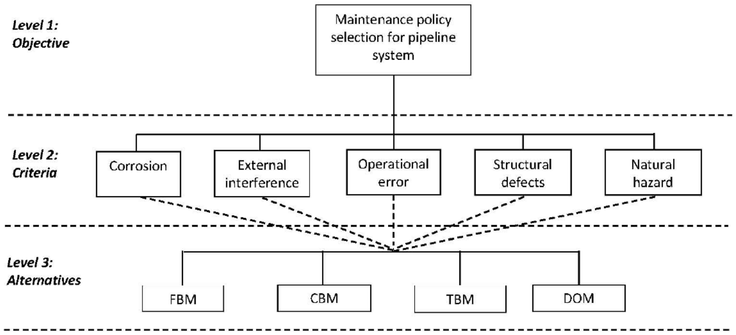

Fig. 1. Maintenance policy selection model for pipeline system

Step 5: Performing pairwise comparisons for each level of the hierarchy model
The pairwise comparison judgement matrices were obtained from the mean of the data collected through the expert questionnaire. The comparisons were entered in a pairwise comparison matrix. After developing the matrix, priority vectors or weights of the elements in the matrix were calculated, then the consistency ratios were determined. The consistency of the judgmental matrix was determined using equation 1.
A CR of 0.10 or less is considered acceptable, if the CR of the matrix is high, it means that the input judgments are not consistent and hence are not reliable. Table 1 and 2 were instrumental in this analysis.

Step 6: Ranking of the alternatives (maintenance policies)
After calculating priorities for the criteria and decision alternatives, the ranking of the alternatives is calculated

using equation 3:

$$P_j = \sum_{i=1}^{N} P_{j,i}.w_i \qquad (3)$$

where P_j is the priority assigned to the alternative *j*; $P_{j,i}$ is the priority assigned to the alternative *j* for the criteria *i*; w_i is the priority assigned to the criteria *i* in respect to the goal.

4. Results and Discussion

4.1. Pairwise Comparison of Failure Factors

Table 3 shows the results of the pairwise comparison of criteria used in the selection of the pipeline system maintenance policy. Corrosion, structural defects, natural hazard, operational error and external interference are the criteria used in the policy selection.

From table 3, it can be seen that operational error is the most prevalent cause of pipeline failure with a priority vector of 0.461. Operational error is equipment failure or human error related. Operational errors occur during the operation of the pipeline and are basically human related, occurring due to the negligence or lack of knowledge on the equipment by the operator. Lack of standardized operating procedures, equipment malfunction or inadequate instrumentation may as well result to operational errors.

External interference is the second prevalent failure factor due to the fact that 29 mechanical damage and sabotage/vandalism cases have been reported during the period under study. Most of the mechanical damage incidents are due to interference from earth moving operations, particularly by earth digging excavators. Sabotage/vandalism incidents are due to line puncture and product theft attributed to lack of employment and economic backwardness on the part of the youth.

Corrosion is the third prevalent failure factor with a priority vector of 0.159. Corrosion attacks on pipeline are classified as either internal or external. Internal corrosion takes place within the walls of the pipeline whereas external corrosion attacks the surface of the pipeline burried on corrosive soil.

Structural defect related incidents are the fourth most prevalent failure factor. These defects occur mostly due to deformation in the pipeline material or as a result of construction defects that occur during the fabrication process. Material defects originate during the fabrication of the pipeline and may lead to metal loss and thinning of pipe walls. Construction defects are primarily scratches, gouges and dents which create avenues for corrosion attack due to the irregular surface or pores created which allow entrapment of air that react with water or moisture to form corrosion.

Natural hazard is the least prevalent failure factor. Natural hazard occurs as a result of heavy rains washout, landslide, lightning, earthquakes and other nature related calamities. During the period under study only one incident of a washout was reported which was attributed to heavy rains.

It can also be seen that the information contained in this table is consistent since it has a consistency ratio of 5.72% which is less than 10%. According to Saaty [13], data with a consistency ratio less than 10% is said to be consistent and vice versa.

Table 3. Results of pairwise comparison of failure factors

Criteria	Corrosion	Structural defects	Natural hazard	Operational error	External interference	Priority vector
Corrosion	1	1	3	1/3	1	**0.159**
Structural defects	1	1	3	1/5	1/3	**0.122**
Natural hazard	1/3	1/3	1	1/5	1/3	**0.061**
Operational error	3	5	5	1	3	**0.461**
External interference	1	3	3	1/3	1	**0.197**
Sum	**19/3**	**31/3**	**15**	**31/15**	**17/3**	**1.00**
CR=5.72%						

4.2. Pairwise Comparison of Maintenance Policies with Respect to Failure Factors

i. Corrosion

The pairwise comparison of maintenance policies with respect to corrosion indicates that in order to reduce the number of failures of the pipeline system, priority is given to CBM. This entails performing maintenance based on the equipment condition. Failure based maintenance is the least prefered because running the equipment until it fails could be catastrophic and also costly to the organization as it could mean a major overhaul of the system. Table 4 illustrates this scenario.

Table 4. Pairwise comparison of maintenance policies with respect to corrosion

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	1/9	1/7	1/3	**0.050**
CBM	9	1	1	3	**0.418**
TBM	7	1	1	3	**0.393**
DOM	3	1/3	1/3	1	**0.139**
Sum	**20**	**22/9**	**52/21**	**22/3**	**1.000**
CR=0.39%					

ii. Structural defects

Table 5 illustrates the pairwise comparison of maintenance policies with respect to structural defects. From this table, it is seen that DOM is given priority with respect to structural defects. In order to avoid structural defects related failure, it is preferred that the equipment is redesigned and a completely new design is put in place.

Table 5. Pairwise comparison of maintenance policies with respect to structural defects

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	1/3	5	1/3	**0.164**
CBM	3	1	5	1	**0.368**
TBM	1/5	1/5	1	1/9	**0.050**
DOM	3	1	9	1	**0.418**
Sum	**36/5**	**38/15**	**20**	**22/9**	**1.000**
CR=5.34%					

iii. Natural hazard

Table 6 illustrates the pairwise comparison of maintenance policies with respect to natural hazard. Natural hazard was due to heavy rains resulting to a washout. The preferred maintenance policy for natural hazard is CBM because the maintenance on the pipe system has to be performed based on its condition at that particular moment. The least preferred maintenance policy is FBM because running the pipeline till failure may result into more catastrophic incidents that may lead to product losses and environmental degradation.

Table 6. Pairwise comparison of maintenance policies with respect to natural hazard

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	1/7	1/5	1/3	**0.057**
CBM	7	1	3	5	**0.588**
TBM	5	1/3	1	3	**0.263**
DOM	3	1/5	1/3	1	**0.122**
Sum	**16**	**176/105**	**68/15**	**28/3**	**1.000**
CR=6.57%					

iv. Operational error

Table 7 illustrates the pairwise comparison of maintenance policies with respect to operational error. From this table, it can be seen that CBM is the most prefered maintenance policy with a priority vector of 0.566. This is due to fact that in order to reduce equipment failures the condition of the equipment has to be monitored and maintenance action initiated based on the condition. FBM is the least preferred maintenance policy. This is because pipeline system equipment are very sensitive in terms of accidents that are bound to occur if they fail, therefore it would not be economical to run a pipeline equipment till it fails.

Table 7. Pairwise comparison of maintenance policies with respect to operational error

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	1/5	1/3	1	**0.101**
CBM	5	1	3	5	**0.566**
TBM	3	1/3	1	1	**0.201**
DOM	1	1/5	1	1	**0.132**
Sum	**10**	**26/15**	**16/3**	**8**	**1.000**
CR=4.34%					

v. External interference

Table 8 illustrates the comparison of maintenance policies with respect to external interference. The pairwise comparison of the maintenance policies gives preference to FBM. This means that external interference which is as a result of either mechanical damage or sabotage/ vandalism initiates maintenance action based on the incident occurrence. Maintenance is immediately initiated at the occurence of an incident in order to reduce massive losses associated with these incidents. CBM is the second most preferred maintenance policy with regard to this factor. When a breakage/damage is detected on the pipeline system equipment, maintenance is initiated on the equipment based on its condition at that particular time.

Table 8. Pairwise comparison of maintenance policies with respect to external interference

Maintenance policy	FBM	CBM	TBM	DOM	Priority vector
FBM	1	3	7	5	**0.549**
CBM	1/3	1	5	5	**0.300**
TBM	1/7	1/5	1	1	**0.071**
DOM	1/5	1/5	1	1	**0.080**
Sum	**176/105**	**22/5**	**14**	**12**	**1.000**
CR=7.34%					

4.3. Priorities for the Maintenance Policies

Table 9 illustrates the priorities for the maintenance policies. In this table, it can be seen that CBM is the most preferable maintenance policy with a priority vector of 0.467. This could be due to the fact that the use of CBM techniques ensures that maintenance is done based on the state of the equipment at a particular time. CBM approach also helps predict equipment failures and this therefore makes it suitable for the pipeline system.
DOM is the least preferred because it entails redesigning the system. Redesigning the system could be costly to the pipeline operator as it implies coming up with a new system.

Table 9. Priorities for maintenance policies

Maintenance policy	Priority
FBM	0.187
CBM	0.467
TBM	0.191
DOM	0.157

5. Conclusions

In this study, an AHP approach has been provided to select the most appropriate maintenance policy for a pipeline system. Four kinds of maintenance policy were considered. It is seen that the proposed AHP method is applicable as an evaluation technique. CBM was identified as the most appropriate maintenance policy. CBM is a policy focused on maintaining equipment based on its condition.

Acknowledgement

The Corresponding author expresses sincere gratitude to the management, operations and engineering staff of the Kenya pipeline company for their support in giving information towards the success of the case study.

References

[1] P. Hopkins, “Ensuring the safe operation of older pipelines and off-shore contractors associations,” in *28th Convention*, September,1994.

[2] G. C. W., "Structuring maintenance control systems," *International journal of operations and production management*, vol. 14(7), pp. 5–17, 1994.

[3] B. Al-najjar and I. Alsyouf, "Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making.," *Journal of Production Economics*, vol. 83(3), pp. 81–96, 2003.

[4] A. K. S. Jardine, D. Lin, and D. Banjevic, "A review on machinery diagnostics and prognostics implementing condition-based maintenance.," *Mechanical Systems and Signal Processing*, vol. 20(7), pp. 1483–1510, 2006.

[5] B. Al-najjar, "On establishing cost-effective condition-based maintenance: Exemplified for vibration-based maintenance in case companies.," *Journal of Quality in Maintenance Engineering*, vol. 18(4), pp. 401–416., 2012.

[6] A. K. Gopalakrishnan, P. & Banerji, *Maintenance and spare parts management*. PHI Learning Private Limited, Delhi, 2^{nd} ed., 2013.

[7] F. Azadivar and V. Shu, "Maintenance policy selection for jit production systems," *International Journal of Production Research,*, vol. 37(16), pp. 3725–3738, 1999.

[8] . O. N. Okumura, S., "A maintenance policy selection method for a critical single-unit item in each workstation composing a fms with cbm optimization," *International Journal of COMADEM*, vol. 6(2), pp. 3–9., 2003.

[9] M. Bevilacqua and M. Braglia, "The analytic hierarchy process applied to maintenance strategy selection," *Reliability Engineering and System Safety*, vol. 70(1)), pp. 71–83, 2000.

[10] L. Wang, J. Chu, and J. Wu, "Selection of optimum maintenance strategies based on a fuzzy analytical hierarchy process," *International Journal of Production Economics*, vol. 107(1), pp. 151–163, 2007.

[11] M. Bertolini and M. Bevilacqua, "A combined goal programming-ahp approach to maintenance selection problem," *Reliability Engineering and System Safety*, vol. 91(7), pp. 839–848, 2006.

[12] S. Zaim, A. Turkyilmaz, M. F. Acar, U. Al-Turki, and O. F. Demirel, "Maintenance strategy selection using ahp and anp algorithms: a case study," *Journal of Quality in Maintenance Engineering*, vol. 18(1), pp. 16–29, 2012.

[13] T. L. Saaty, *The Analytic Hierarchy Process*. New York, NY: McGraw-Hill, 1980.

[14] T. L. Saaty, "Decision making with the analytic hierarchy process," *International Journal of Services Sciences*, vol. 1(1), pp. 83–98, 2008.

[15] F. Partovi, "Determining what to benchmark: An analytic hierarchy process approach," *International Journal of Operations and Project Management*, vol. 14, pp. 25–39, 1994.

[16] P. K. Dey, S. O. Ogunlana, S. S. Gupta, and M. T. Tabucanon, "A risk-based maintenance model for cross-country pipelines," *Cost Engineering*, vol. 40(4), pp. 24–30, 1998.

[17] T. L. Saaty, *Decision making for leaders: the analytical hierarchy process for decisions in a complex world*. United States of America: Lifetime Learning Publication, 1982.