Decision Support System for Inspection and Maintenance: A Case Study of Oil Pipelines

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***Abstract*—The existing method of pipeline health monitoring, which requires an entire pipeline to be inspected periodically, is unproductive. A risk-based decision support system (DSS) that reduces the amount time spent on inspection has been presented. The risk-based DSS uses the analytic hierarchy process (AHP), a multiple attribute decision-making technique, to identify the factors that influence failure on specific segments and analyzes their effects by determining probability of occurrence of these risk factors. The severity of failure is determined through consequence analysis. From this, the effect of a failure caused by each risk factor can be established in terms of cost and the cumulative effect of failure is determined through probability analysis. The model optimizes the cost of pipeline operations by reducing subjectivity in selecting a specific inspection method, identifying and prioritizing the right pipeline segment for inspection and maintenance, deriving budget allocation, providing guidance to deploy the right mix labor for inspection and maintenance, planning emergency preparation, and deriving logical insurance plan. The proposed methodology also helps derive inspection and maintenance policy for the entire pipeline system, suggest design, operational philosophy, and construction methodology for new pipelines.**

***Index Terms*—Analytic hierarchy process (AHP), construction and operations improvement, design, inspection, insurance, maintenance, petroleum pipelines, probability analysis.**

I. INTRODUCTION

CROSS-COUNTRY pipelines are the most energy-efficient, safe, environmentally friendly, and economic way to ship hydrocarbons (gas, crude oil, and finished products) over long distances, either within the geographical boundary of a country or beyond it. A significant portion of many nations' energy requirements is now transported through pipelines. The economies of many countries depend on the smooth and uninterrupted operation of these lines, so it is increasingly importance to ensure the safe and failure-free operation of pipelines.

While pipelines are one of the safest modes of transporting bulk energy, and have failure rates much lower than the railroads or highway transportation, failures do occur, and sometimes with catastrophic consequences. A number of pipelines have failed in the recent past, with tragic consequences. In 1993 in Venezuela, 51 people were burned to death when a gas pipeline failed and the escaping gas ignited. Again in 1994, a 36-in (914-mm) pipeline in New Jersey failed, resulting in the death of one person and more than 50 injuries. Similar failures also have occurred in the U.K., Russia, Canada, Pakistan, and India [12]. While pipeline failure rarely cause fatalities, disruptions in operation lead to large business losses. Failures can be very expensive and cause considerable damage to the environment.

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A. Defining Failure

The use of the term *failure* in the context of pipelines varies from country to country and across organizations. For example, in Western Europe, any loss of gas/oil is considered a failure, while, in the U.S., an incident is considered to be a failure only when it is associated with the loss of commodity and also involves a fatality or injury, or damage over \$50 000 [2]. In India, generally any loss of commodity, however small, is considered to be a failure is defined as any unintended loss of commodity from a pipeline that is engaged in the transportation of that commodity.

B. Monitoring Pipeline Health

Traditionally, 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. Safety provisions are considered when selecting pipes and other fittings. To prevent corrosion, a pipeline is electrically isolated by providing a high resistance external coating materials. As a secondary protective measure, a low-voltage direct current is impressed in the pipe at precalculated distance to transfer any corrosion that occurs due to breaks in the coating caused by a heap of buried iron junk, rails, etc. This is called impressed current cathodic protection. The quality of the commodity that is being transported through the line is also ensured, and sometimes corrosion-preventing chemicals (corrosion inhibitors) are mixed with the commodity. To avoid deliberate damage of the pipeline in isolated locations, regular patrolling of the right-of-way from the air as well as on foot is carried out, and all third party activities near the route are monitored.

Various techniques are routinely used to monitor the status of a pipeline. Any deterioration in the line may cause a leak or rupture. Modern methodologies can ensure the structural integrity of an operating pipeline without taking it out of service [14].

C. Existing Inspection and Maintenance Practices

The existing inspection and maintenance practices commonly followed by most pipeline operators are formulated mainly on the basis of experience. However, operators are developing an organized maintenance policy based on data analysis and other in-house studies to replace rule-of-thumb based policies. The primary reasons for this are stringent environmental protection laws [23], scarce resources, and excessive inspection costs. Existing policies are not sharply focused from the point of view of the greatest damage/defect risk to a pipeline. The basis for selecting health monitoring and inspection techniques is not very clear to many operators. In many cases, a survey is conducted over an entire pipeline or on a particular segment, when another segment needs its more. Avoidable expenditures are, thus, incurred.

A strong reason exists, therefore, to derive a technique that will help pipeline operators select the right type of inspection/monitoring technique for segments that need it. A more clearly focused inspection and maintenance policy that has a low investment-to-benefit ratio should be formulated.

This paper introduces a decision support system (DSS) for predicting the risk factor for pipeline failures, analyze their effect, and develop responses through effective inspection and maintenance strategies. Risks are by nature subjective, so to analyze their potential of contributing to a failure, the analytic hierarchy process developed by Saaty [20] is used here.

This study reveals the effect of certain risk factors on the failure of pipelines/pipeline sections, and derives risk management strategies.

The objectives of this paper are to develop a DSS to perform the following functions:

1) predict the greatest risk factors;
2) analyze the effect of risk factors on pipeline failures;
3) respond to risk through an appropriate inspection and maintenance program;
4) analyze the costs and benefits to justify the investment in preparation;
5) rationalize insurance premium.

The remainder of the paper is classified into four sections. Section II elaborates DSS and analytic hierarchy process in general. Section III details the steps for developing DSS using the analytic hierarchy process (AHP) for inspection and maintenance strategy formulation. Section IV illustrates the application of DSS through a case study, and Section V draws the conclusion.

II. Decision Support System and the Analytic Hierarchy Process

A DSS assists management decision making by combining data, sophisticated analytical models and tools, and user-friendly software into a single powerful system that can support semi-structured or unstructured decision making. A DSS provides users with a flexible set of tools and capabilities for analyzing important blocks of data. In this study, AHP is used to develop the DSS for inspection and maintenance strategy selection.

The AHP developed by Saaty [20] provides a flexible and easily understood way of analyzing complicated problems. It is a multiple criteria decision-making technique that allows subjective as well as objective factors to be considered in decision-making process. The AHP allows the active participation of decision-makers in reaching agreement, and gives managers a rational basis on which to make decisions. AHP is based on the following three principles: decomposition; comparative judgment; and synthesis of priorities.

The AHP is a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution [24]. AHP is a problem-solving framework and a systematic procedure for representing the elements of any problem [22].

Formulating the decision problem in the form of a hierarchical structure is the first step of AHP. In a typical hierarchy, the top level reflects the overall objective (focus) of the decision problem. The elements affecting the decision are represented in intermediate levels. The lowest level comprises the decision options. Once a hierarchy is constructed, the decision-maker begins a prioritization procedure to determine the relative importance of the elements in each level of the hierarchy. The elements in each level are compared as pairs with respect to their importance in making the decision under consideration. A verbal scale is used in AHP that enables the decision-maker to incorporate subjectivity, experience, and knowledge in an intuitive and natural way. After comparison matrices are created, relative weights are derived for the various elements. The relative weights of the elements of each level with respect to an element in the adjacent upper level are computed as the components of the normalized eigenvector associated with the largest eigenvalue of their comparison matrix. Composite weights are then determined by aggregating the weights through the hierarchy. This is done by following a path from the top of the hierarchy to each alternative at the lowest level, and multiplying the weights along each segment of the path. The outcome of this aggregation is a normalized vector of the overall weights of the options. The mathematical basis for determining the weights was established by Saaty [20].

Risk analysis is usually a team effort, and the AHP is one available method for forming a systematic framework for group interaction and group decision making [21]. Dyer and Forman [10] describe the advantages of AHP in a group setting as follows:

1) both tangibles and intangibles and individual values and shared values can be included in an AHP-based group decision process;
2) the discussion in a group can be focused on objectives rather than alternatives;
3) the discussion can be structured so that every factor relevant to the discussion is considered in turn;
4) in a structured analysis, the discussion continues until all relevant information from each individual member in a group has been considered and a consensus choice of the decision alternative is achieved.

A detailed discussion on conducting AHP-based group decision-making sessions including suggestions for assembling the group, constructing the hierarchy, getting the group to agree, inequalities of power, concealed or distorted preferences, and implementing the results can be found in Saaty [21] and Golden *et al.* [11]. For problems with using AHP in group decision making, see Islie *et al.* [13].

AHP was used for risk management because of the following:

1) risk factors are both objective and subjective;
2) factors are conflicting, achieving of one factor may sacrifice others;

3) some objectivity should be reflected in assessing subjective factors;
4) AHP can consider each factor in a manner that is flexible and easily understood, and allows consideration of both subjective and objective factors;
5) AHP requires the active participation of decision-makers in reaching agreement, and gives decision-makers a rational basis upon which to make their decision.

Researchers use AHP in various industrial applications. Partovi *et al.* [18] used it for operations management decision-making. Dey *et al.* [3] used it in managing the risk of projects. Korpela and Tuominen [15] and Dey [9] used AHP for benchmarking logistic operations and project management respectively. Mian and Christine [16] used AHP for evaluation and selection of a private sector project. Dey [8] described AHP as an effective tool for project selection. Dey *et al.* [7] used AHP for cross-country petroleum pipeline route selection. Mustafa and Ryan [17] used AHP for bid evaluation.

In this study, an AHP-based approach to develop a DSS for risk management has been demonstrated.

III. Methodology

The methodology adopted in this study involves the following steps.

A. Step 1

Cross-country petroleum pipeline passes through various terrain and requires originating and a few intermediates pumping stations for transporting petroleum products or crude oil. Therefore, the entire pipeline is classified into a few stretches (preferably in line with its natural stretch, i.e., pipeline sections in between two stations).

B. Step 2

All information related to the pipeline including the terrain detail under study is prepared and documented section wise.

C. Step 3

Step 3 is the identification of the risk factors that can cause failures. Generally, pipelines fail because of one of these reasons:

1) corrosion;
2) external interference;
3) construction and materials defects;
4) acts of God;
5) human and operational error.

One of the major causes of pipeline failure is corrosion [1], [19], an electrochemical process that changes metal back to ore. Corrosion generally takes place when there is a difference of potential between two areas having a path for the flow of current. Due to this flow, one of the areas loses metal.

External interference is another leading cause of pipeline failure [1], [19]. It can be malicious (sabotage or pilferage) or be caused by other agencies sharing the same utility corridor. The latter is known as third-party activity. In both cases, a pipeline can be damaged severely. External interference with malicious intent is more common in socio-economically backward areas, while in regions with more industrial activity, third-party damage is common.

All activities, industrial or otherwise, are prone to natural calamities, but pipelines are especially vulnerable. A pipeline passes through all types of terrain, including geologically sensitive areas. Earthquakes, landslides, floods, and other natural disasters are common reasons for pipeline failures.

Poor construction, combined with inadequate inspections and low-quality materials, also contributes to pipeline failures. Other reasons include human and operational error and equipment malfunctions [23]. Computerized control systems considerably reduce the chance of failure from these factors.

Human and operational errors are another sources of pipeline failure. Inadequate instrumentation, foolproof operating system, lack of standardized operating procedures, untrained operators, etc., are the common causes of pipeline failure due to human and operational errors.

D. Step 4

The next step of this methodology is the formation of a risk structure model in the AHP framework. Based on the identified risk factors, a hierarchical risk structure is formed (see Fig. 1). In the context of our study, the goal is to determine the relative the likelihood of pipeline failures. Level II is criteria (risk factors), level III is subfactors, and level IV is alternatives (the pipeline stretches). Fig. 1 shows the AHP model for analyzing risk from a failure perspective.

E. Step 5

In this step, risk factors and subfactors are compared pairwise to determine the likelihood of pipeline failure due to each factors and subfactors. Then, the alternative pipeline stretches are compared with respect to each risk subfactor, to determine the likelihood of failure for each pipeline stretch. Then, likelihood of failure of various pipeline stretches was determined through synthesizing the results of pairwise comparison across the hierarchy.

F. Step 6

In this step, specific inspection/maintenance requirements are determined for specific segments of pipelines from the likelihood of failure data, to mitigate risk.

G. Step 7

The last step demonstrates cost–benefit analysis of suggested inspection and maintenance strategy along with cost-effective insurance plan for pipeline.

IV. Application

The entire methodology has been illustrated through a case study. A crude oil pipeline (length 1500 km) in the western part of India was studied. The throughput of the pipeline is 9 million metric ton per annum (MMTPA) with augmentation capability of 12 MMTPA, having three intermediate booster stations and a offshore terminal. The schematic of the pipelines is shown in Fig. 2 and the work breakdown structure of a pipeline system has

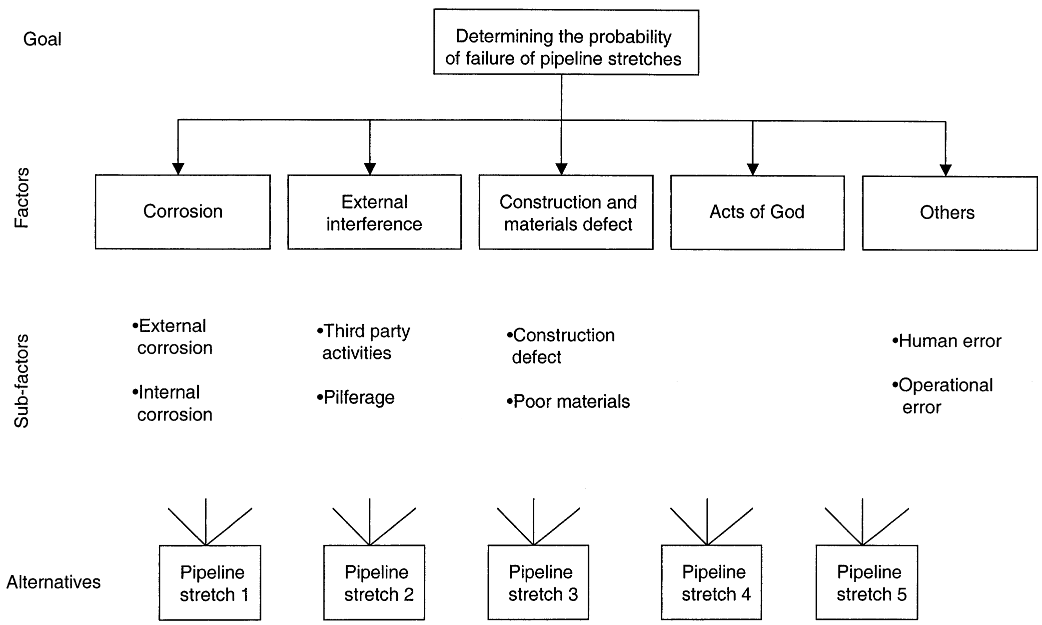

Fig. 1. Risk structure in AHP framework to determine failure characteristics of various pipeline stretches.

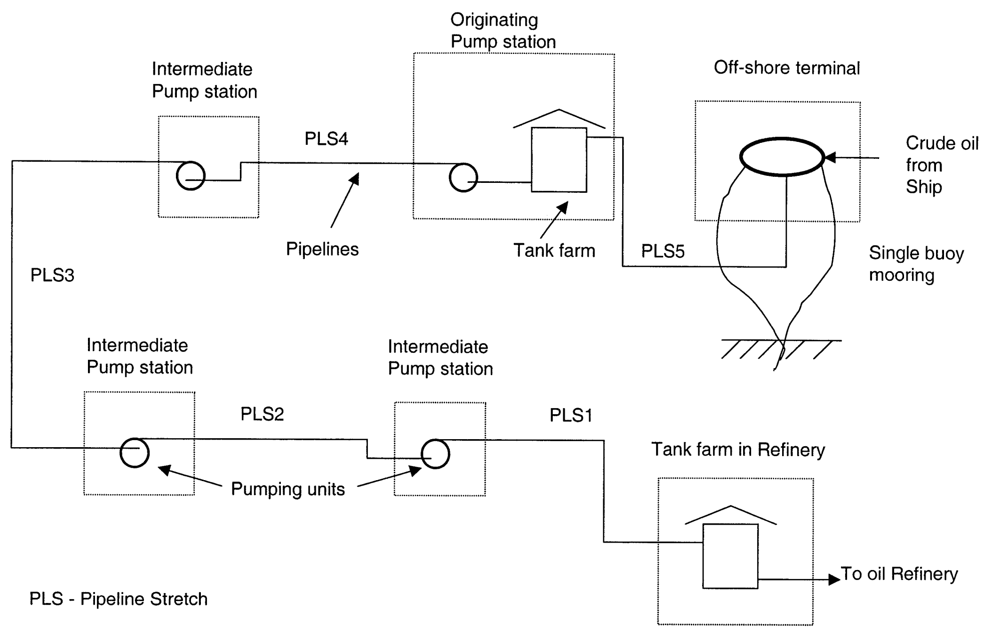

Fig. 2. Schematic of cross-country crude oil pipelines.

been depicted in Fig. 3. This pipeline is 19 years old and has a history of corrosion failure. The poor condition of the coating, as revealed during various surveys and an unreliable power supply to cathodic protection stations, are the reasons for this. The line passes through long stretches of socio-economically backward areas and is vulnerable to pilferage and sabotage. In some regions, the right-of-way is shared with other agencies, so the chance of external interference is high. Failure data revealed numerous precommissioning failures, raising doubts about the quality of construction. Detailed description of the pipelines is available in [4] and [5].

The risk analysis model for the pipeline is formulated by applying the methodology described previously. The entire pipeline was classified into five stretches. The risk structure and pair wise comparisons were established through a workshop of the executives who operate various pipelines. About 30 executives participated. They have more than 15 years of experience in pipeline operations.

Before formulating the model, they were given full knowledge of pipeline conditions through the database of various pipeline stretches (Table I) and pipeline record sheet (Fig. 4).

A decision-maker can express a preference between each pair as equal, moderate, strong, very strong, and extremely preferable (important). These judgements can be translated into numerical values on a scale of 1 to 9 (Table II). Elements at each level of hierarchy are compared with each other in pairs, with their respective "parents" at the next higher level. With the hierarchy used here, matrices of judgements are formed.

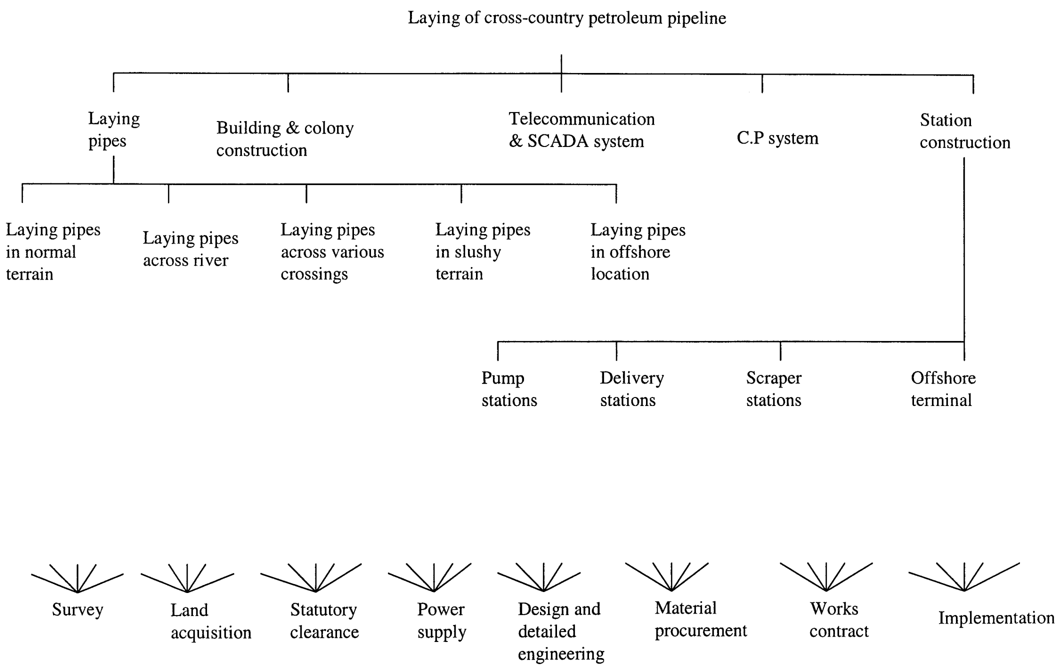

Fig. 3. Work breakdown structure of "Cross-country petroleum pipeline" project.

TABLE I
DATABASE OF PIPELINE STRETCHES (FIGURES IN KILOMETERS)

Descriptions	Pipeline stretches 1	Pipeline stretches 2	Pipeline stretches 3	Pipeline stretches 4	Pipeline stretches 5
Length	260	210	180	230	25
Terrain detail:					
Normal	170	95	35	169	7
Slushy	36				
Rocky (hilly)			115	20	
River & canal crossings	4	2		6	
Populated	50	88		35	
Offshore					18
Coal belt		25			
Forest			30		
Desert					
Soil condition	corrosive	corrosive	Less corrosive	Less corrosive	Less corrosive
3rd party activities		More due to coal belt			
Chances of pilferage	Higher due to populated area	Higher due to populated area		Higher due to populated area	
Construction complexity			More due to rocky and forest	More due to river crossing	More due to offshore piping
Operational complexity					More due to offshore terminal

A brainstorming session was held to compare the risk factors. The pipeline executives established a common consensus for the AHP hierarchy, pair wise comparison in factors, subfactors, and alternative levels through group decision making. Disagreements were resolved by reasoning and collecting more information. Their hierarchy contained the detail necessary for risk analysis. Table III shows the matrix of judgements that resulted.

The final outcomes of each of the pipeline stretch against the risk factors are summarized in Table IV. Both local probability and global probability for each of the five stretches are summed up to derive the probability of a pipeline stretch failure and its position with respect to other stretches. The results of the analysis (Table IV) reveal that the chances of pipeline failure due to corrosion and external interference are greater than other factors.

The following additional observations were made from the risk analysis study.

1) Pipeline stretches 1 and 2 are vulnerable from external corrosion due to slushy terrain, whereas pipeline stretches 4 and 5 are vulnerable to internal corrosion due to long submerged pipe sections.
2) External interference due to the third party activities are major problem in pipeline stretch 2 because of coal mining activities, whereas in stretch 4, it is due to major river crossings and canal crossing.
3) External interference due to malicious reasons are prevailing in stretches 1 and 2 because it passes through a long and highly populated industrial areas.
4) The pipeline stretch 3 is passing through mostly rocky terrain, exposing the pipe to various types of failure due to construction and poor materials. As this stretch is vulnerable to subsidence problem, the likelihood of pipeline failure from acts of God is quite high along with high chance of failure due to construction defect and poor materials.
5) The stretch 5, i.e., the offshore pipeline, is very sensitive to operational and human errors as well as failure due to various natural calamities.
6) All pipeline stretches are ranked with respect to their failure chances—pipeline stretch 5 comes first, pipeline stretch 1 comes second and pipeline stretch 2, 4, and 3 come third, forth, and fifth respectively.

TYPICAL PIPELINE DATASHEET

1. Name of pipeline
2. Nominal diameter (inches)
3. Wall thickness (inches)
4. Pipe grade
5. Specific minimum yield stress
6. Operating pressure (kg/cm^2)
7. Age (years)
8. Age of oldest section (years)
9. Age of coating (years)
10. Length of pipeline (km)
11. Number of pipeline sections
12. Length of longest pipeline section (km)
13. Product type
14. Coating type
15. Type of soil
16. Discharge temperature
17. Population density
18. Number of crossings
19. Surveillance level
20. Inhibitor efficiency
21. Corrosion rate
22. History of leaks due to internal corrosion
23. History of burst due to internal corrosion
24. Number of cathodic protection (CP) station
25. CP availability
26. Efficiency
27. CP interface
28. Coating condition
29. Soil aggression
30. Instrumented pig surveying (IPS) conducted, if any
31. Major findings of IPS (in brief)
32. History of leaks due to external corrosion
33. History of burst due to external corrosion
34. Average metal loss due to external corrosion
35. Number of hydro-test failures
36. Number of years since last hydro-test
37. Number of pressure cycles per month
38. History of bursts due to fatigue
39. History of leaks due to fatigue
40. Evidence of stress corrosion cracking
41. History of bursts due to stress corrosion cracking
42. History of leaks due to stress corrosion cracking
43. History of bursts due to 3rd party damage
44. History of leaks due to 3rd party damage
45. History of sabotage/pilferage
46. History of bursts due to sabotage/pilferage
47. History of leaks due to sabotage/pilferage
48. Mining activities
49. Soil stability
50. Earthquake/fault zone
51. History of floods
52. History of failure due to natural calamity
53. History of failure due to equipment failure
54. History of failure due to human error
55. Failure cost (details against each item)
56. Number of employees
57. SCADA systems installed
58. Leak-detection mechanism available (software)
59. Training level of employees (from training history card)
60. Availability of equipment (maintenance history record)
61. Existing CP and coating survey schedule
62. Other health-monitoring survey schedule.

Fig. 4. Areas covered in the data forms.

TABLE II
SCALE OF RELATIVE IMPORTANCE FOR PAIR-WISE COMPARISON

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the object
3	Moderate importance	Slightly favors one over another
5	Essential or strong importance	Strongly favors one over another
7	Demonstrated importance	Dominance of the demonstrated in practice
9	Extreme importance	Evidence favoring one over another of highest possible order of affirmation
2, 4, 6, 8	Intermediate values	When compromise is needed

A. Selection of Inspection and Maintenance Strategy

The output of the analysis helps in deciding specific inspection and maintenance programs for each pipeline stretch. Instrument pig survey has been suggested for pipeline stretches 4 and 5 to detect internal corrosion. A survey technique chosen to reveal areas effected by external corrosion. One technique is a current attenuation survey or pearson survey (these surveys detect breaks in pipeline coating, i.e., areas where the pipeline is exposed to soil). Survey techniques that can identify both internal and external corrosion are not needed and are not cost effective.

Pipeline stretches 1, 2, and 3 are prone to external interference (pilferage and sabotage), so they require frequent patrolling. Stretches 2 and 4 are susceptible to third-party damage. Therefore, more publicity about the route among agencies working near it could be a solution. Cooperation with these agencies needs to be improved. However, a few contingency plans for handling the situations of failure incidents are to be kept ready for the above two stretches.

Pipeline stretches 3 and 5 are vulnerable from normal and abnormal natural calamities. Although various measures were

TABLE III
PAIR WISE COMPARISON IN FACTOR LEVEL

Factors	Corrosion	External Interference	Construction & materials defect	Acts of God	Others	**Likelihood**
Corrosion	1	2	3	7	3	**0.40**
External Interference	1/2	1	3	5	3	**0.29**
Construction & materials defect	1/3	1/3	1	3	2	**0.14**
Acts of God	1/7	1/5	1/3	1	1/4	**0.05**
Others	1/3	1/3	1/2	4	1	**0.12**

TABLE IV
LIKELIHOOD OF FAILURE OF VARIOUS PIPELINE STRETCHES

Factors	**Likelihood**	**Sub-factors**	**Likelihood**	**PLS$_1$**	**PLS$_2$**	**PLS$_3$**	**PLS$_4$**	**PLS$_5$**
Corrosion	0.40	External	0.221	0.108	0.064	0.007	0.011	0.031
		Internal	0.181	0.038	0.022	0.020	0.042	0.060
External Interference	0.29	3rd party activities	0.186	0.030	0.078	0.011	0.061	0.006
		Malicious	0.100	0.033	0.039	0.005	0.018	0.005
Construction & mat. defect	0.14	Construction defects	0.072	0.012	0.007	0.028	0.007	0.018
		Poor mats.	0.072	0.006	0.007	0.027	0.016	0.017
Acts of God	0.05		0.05	0.006	0.001	0.014	0.006	0.020
Others	0.12	Human error	0.048	0.001	0.005	0.003	0.008	0.030
		Operational error	0.072	0.001	0.003	0.009	0.003	0.056
Likelihood of failure of various pipeline stretches				**0.236**	**0.227**	**0.123**	**0.172**	**0.242**
Ranking				**2**	**3**	**5**	**4**	**1**

PLS – Pipeline stretch

TABLE V
INSPECTION AND MAINTENANCE COST* (FIGURES ARE IN RUPEES IN MILLION) WITH THE APPLICATION OF RISK-BASED INSPECTION MODEL U.S.$ 1 = Rupees 47

Inspection and maintenance strategy	**Problems**	**PLS$_1$**	**PLS$_2$**	**PLS$_3$**	**PLS$_4$**	**PLS$_5$**
Instrument pig survey	Internal corrosion				25	5
Cathodic protection survey	External corrosion	4	4			
Contingency plans	3rd party activities		1		1	
More patrolling	Malicious	2	2		2	
Contingency plans	Acts of God			1		1
Improved instrumentation						5
Pipe coating	External corrosion	3	2			
Pipe replacement	Construction defect and poor pipe materials			3		
Total cost (Rupees 61 million for five years)		**9**	**9**	**4**	**28**	**11**

* The Cost figures are estimated from the budgetary offers of the vendors.

TABLE VI
INSPECTION AND MAINTENANCE COST* (FIGURES ARE IN RUPEES IN MILLION) WITHOUT USE OF RISK-BASED INSPECTION MODEL U.S.$ 1 = Rupees 47

Inspection and maintenance strategy	**Problems**	**PLS$_1$**	**PLS$_2$**	**PLS$_3$**	**PLS$_4$**	**PLS$_5$**
Instrument pig survey	Internal corrosion	25	25	25	25	5
Cathodic protection survey	External corrosion	4	4	4	4	1
Contingency plans	3rd party activities	1	1	1	1	1
More patrolling	Malicious	2	2	2	2	
Contingency plans	Acts of God	1	1	1	1	1
Improved instrumentation						5
Pipe coating	External corrosion	3	2			
Pipe replacement	Construction defect and poor pipe materials			3		
Total cost (Rupees 153 million for 5 years)		**36**	**35**	**36**	**33**	**13**

- The Cost figures are estimated from the budgetary offers of the vendors.

taken in designing and constructing the pipelines in both the stretches for minimizing failure, a few contingency plans are also to be formulated in line with the anticipated incidents.

Table V indicates the inspection and maintenance programs for pipeline under study *vis-à-vis* cost for each program. Table VI indicates the conventional inspection and maintenance programs *vis-à-vis* cost in absence of the proposed risk-based model. This establishes the advantage of using the risk-based model in designing inspection and maintenance of cross-country petroleum pipeline.

The inspection and maintenance cost has two components—fixed cost and variable cost. The variable cost depends on the length of pipeline. However, the fixed cost depends on design and consulting charge and apportionment of the overhead cost for the inspection tools. The fixed cost for specific inspection is very high compared to the variable cost. Therefore, the inspection cost for all most all pipeline section is approximated as same. The following calculations show the computation for inspection and maintenance of pipelines:

1) *Instrument pig survey:*

Consulting charge (fixed cost)	=5
Design (fixed cost)	=7
Overhead charge for tools (fixed cost)	=10
Survey (variable cost)	=3
Total	=25 (Rupees in million)

2) *Cathodic protection survey:*

Consulting charge (fixed cost)	= 0.5
Design (fixed cost)	= 1.0
Overhead charge for tools (fixed cost)	= 2.0
Survey (variable cost)	= 0.5
Total	= 4 (Rupees in million)

3) *Pipe coating for stretch 1:*

Coating materials and application	= 2.5
Overhead	= 0.5
Total	= 3.0 (Rupees in million)

TABLE VII
COST OF A PIPELINE FAILURE

Result	Cost (in million Rupees)
Loss of production	10
Loss of commodity	5
Loss of life and property	10
Loss of image	30
Environmental damage	50
Total	**105**

* The costs are estimated by simulating various situations of pipeline failure in Indian context
US$ 1 = Rupees 47

4) *Pipe replacement in stretch 3:*

$$\begin{aligned} &\text{Pipe materials} &&= 2.0\\ &\text{Pipe laying} &&= 0.4\\ &\text{Overhead} &&= 0.6\\ &\text{Total} &&= 3.0\ (\text{Rupees in million}) \end{aligned}$$

Selection of a particular inspection technique depends on the owner's experience. However, this approach will give a rational basis to the owner when selecting the most appropriate survey technique as well as the pipeline stretch where the survey is most needed.

TABLE VIII
SEVERITY OF FAILURE OF VARIOUS PIPELINE STRETCHES

Risk factors	PLS_1		PLS_2		PLS_3		PLS_4		PLS_5	
	Likelihood	Severity *	Likelihood	Severity *	Likelihood	Severity *	Likelihood	Severity *	Likelihood	Severity *
External	0.108	40	0.064	25	0.007	40	0.011	40	0.031	105
Internal	0.038	25	0.022	25	0.020	40	0.042	40	0.060	105
3rd party activities	0.030	105	0.078	105	0.011	105	0.061	105	0.006	105
Malicious	0.033	25	0.039	25	0.005	40	0.018	40	0.005	105
Constn. defects	0.012	25	0.007	25	0.028	40	0.007	40	0.018	105
Poor mats.	0.006	25	0.007	25	0.027	40	0.016	40	0.017	105
	0.006	105	0.001	105	0.014	105	0.006	105	0.020	105
Human error	0.001	25	0.005	25	0.003	40	0.008	40	0.030	105
Operational error	0.001	25	0.003	25	0.009	40	0.003	40	0.056	105
Likelihood of no failure	0.764	0	0.773	0	0.877	0	0.828	0	0.758	0
Expected failure cost		10.35		12.04		6.56		11.28		25.44

Total expected cost of pipeline failure = Rupees 66 million per year

* Severity figures are in Rupees in million;
PLS – Pipeline stretch
US$ 1 = Rupees 47
Assumptions:

- The pipeline failure in each stretch is an independent event.
- With one failure in specific pipeline stretch and subsequent maintenance, the pipeline stretch will be vulnerable for failure in the subsequent years with equal likelihood.
- Each risk factor causes failure of pipeline system upon occurrence, the degree of which is measured by small, medium, large and very large failures. Accordingly, cost is incurred for its rectification. As for example, external corrosion will cause medium to large failure. In order to rectify the failure, 40 million Rupees is required to be spent.

B. Expected Failure Cost

Generally, a pipeline failure involves various costs that are difficult to compute. Each cost component is unique to specific failure and depends upon factors such as the magnitude, area, and time of the failure, where it happens, and others. A broad classification involving the factors shown in Table VII is possible. The amounts shown in each of these categories are the estimated maximum failure costs.

These factors depend on various subfactors and parameters. For the purpose of this paper, a typical pipeline was considered. The cost encountered in this case (maximum) was estimated for India. An analysis of 20 years of failure expenditure data for the pipeline was conducted, and suitable escalation was applied wherever necessary, on the basis of published literature and increases in the cost of various commodities. The failure are classified (on the basis of cost incurred) into four categories:

1) small failures: up to 25 million Rupees;
2) medium failures: between 25 and 40 million Rupees;
3) large failures: between 40 and 70 million Rupees; and
4) very large failures: up to 105 million Rupees.

The probability of failure in each of these four categories is taken into consideration, along with the cost of failure. The severity of failure of various pipeline stretches was estimated in brainstorming session by the executives. The outcomes are tabulated along with the likelihood of occurrences of various risk factors (previously determined) as shown in Table VIII. A Monte Carlo simulation was performed using the PC-based software Micro-Manager. The expected cost of failure of each stretch has been shown in Table VIII. Skilled personnel are needed to compute costs against each of the factors shown in Table VII. The cost of environmental damage varies from place to place, so readers are cautioned to use their own experience and expertise when estimating the cost of a pipeline failure. Table VI shows the conventional inspection and maintenance cost without using risk-based model. Our proposed method has the potential to reduce costs and is thus preferred over conventional method.

C. Pipeline Insurance Plan

This study establishes a cost-effective insurance plan for the pipeline under study. The basis of the insurance premium depends on likelihood of its failure, expected failure cost in a given period, risk perception of the management/organization, and inspection/maintenance programs undertaken.

In this case study, the maximum amount of insurance premium for the pipeline under study would be the expected failure cost per year, i.e., Rupees 66 million without any inspection and maintenance as indicated in Table VIII. If the pipeline operators undertake the inspection and maintenance program in line with as indicated in Table V, the likelihood and severity both decreases considerably. The expected cost of failure would reduce to Rupees13 million as shown in Table IX. Hence, the annual insurance premium would lie between Rupees 66 and 13 million in line with management risk perception.

TABLE IX
COMPUTATION OF EXPECTED FAILURE COST OF PIPELINE IN THE EVENT OF PROPOSED INSPECTION AND MAINTENANCE PROGRAM

Risk factors	PLS_1		PLS_2		PLS_3		PLS_4		PLS_5	
	Likelihood	Severity *	Likelihood	Severity *	Likelihood	Severity *	Likelihood	Severity *	Likelihood	Severity *
Likelihood of failure	0.118	25	0.114	25	0.062	25	0.086	25	0.121	25
Likelihood of no failure	0.882	0	0.887	0	0.939	0	0.914	0	0.879	0
Expected failure cost		2.95		2.85		1.55		2.2		3.1

Total expected cost of pipeline failure = Rupees 13 million per year

* Severity figures are in Rupees in million;
PLS – Pipeline stretch
US$ 1 = Rupees 47

Assumptions:
- With the implementation of proposed inspection and maintenance program the probability of failure of each pipeline stretch would reduce to half of the previously computed figure.
- Severity of the failure would be the minimum computed failure cost i.e. Rupees 25 million.

V. SUMMARY AND CONCLUSION

Petroleum pipelines are the nervous system of oil industry, as this transports crude oil from sources to refineries and petroleum products from refineries to demand points. Therefore, the efficient operations of these pipelines determine the effectiveness of the entire business.

As pipelines pass through varied terrain, the condition of pipelines varies widely across their entire length and throughout their life cycle. However, inspecting the entire pipelines through specific inspection methodology/tool cannot detect pipeline problems for the entire length as inspection tools are designed to detect specific problems only. On the other hand, inspecting the entire pipeline by various tools to detect the entire associate problems are not cost effective.

This study presents a DSS model in AHP framework, which determines the likely problems associated with each stretch with the involvement of the experienced pipeline operators. This leads to develop a cost-effective inspection and maintenance strategy for the pipelines.

This methodology has been applied in an Indian cross-country petroleum pipelines case. This study shows that the cost of inspection and maintenance after using the proposed risk-based DSS is Indian Rupees (INR) 61 million (U.S.$ 1 = INR 47) for five years as compared to INR 153 million for five years using conventional method. The expected failure cost also would be reduced to INR 13 million per year with the proposed inspection and maintenance strategy using risk-based DSS as compared to INR 66 million per year without any inspection and maintenance. These show the rational for using risk-based DSS for risk management.

The same methodology can be used for any operating unit to develop strategic DSS for inspection and maintenance.

Advantages of this method of analysis described here include the following:

1) reducing subjectivity in the decision making process when selecting an inspection technique;
2) identifying the right pipeline or segment for inspection and maintenance;
3) formulating an inspection and maintenance policy;
4) deriving the budget allocation for inspection and maintenance;
5) providing guidance to deploy the right mix of labor in inspection and maintenance;
6) enhancing emergency preparations;
7) assessing risk and fixing an insurance premium;
8) forming a basis for demonstrating the risk level to governments and other regulatory agencies.

If a productive system is designed, constructed, and operated ideally, many inspection and maintenance problems will not crop up. The overall performance of pipeline operations and maintenance would be improved through the following actions.

1) Pipeline routes are to be decided on the basis of life cycle costing approach, not on the basis of shortest route. Dey and Gupta [6] have shown one of such approaches.
2) The maintenance characteristics of the pipeline are to be considered along with pressure and temperature parameters while designing pipe thickness for various stretches of pipeline.
3) Pipeline coating shall be selected on the basis of terrain condition, environmental policy of the organization, cost of coating materials, construction methodology, inspection and maintenance philosophy.
4) Construction methodology of pipeline in critical section to be formulated during feasibility stage of the project and this shall commensurate with design and operational philosophy of the pipeline as a whole. The factors like availability of technology, availability of consultants, contractors and vendors, experience of owner project group, government regulations, and environmental requirements through out the life of pipeline to be rationally considered during selecting the best construction methodology.
5) Networking in pipeline operations demand a foolproof mechanism in the system for minimizing operational and human errors. Improved instrumentation shall be designed which commensurate with the design philosophy of entire pipeline system.
6) All pipeline operators are to be suitably trained in pipeline operation before taking charge of working in specific pipelines. Pipeline simulation training may be one of these kinds. Criticality of pipelines and expertise of personnel to be considered for manning pipeline operations.

The technique does have limitations, because subjectivity is not totally eliminated. For instance, the weightage against each of the failure factors is based upon experience, available data and perception of the pipeline executives and decision-makers. Despite these limitations, a cross-country petroleum pipeline inspection and maintenance policy formed on the basis of our methodology is an effective tool to mitigate risk. It is cost effective and environmentally friendly.

The established DSS will help the pipeline operators to dynamically evaluate pipeline health and to make decision on types of inspection and maintenance program for specific stretch any time they desire. Therefore, all the pipeline sections will get attention with respect to health, although inspection and maintenance may be exempted for specific sections during a given period because of better condition of pipeline during risk analysis study.

Although the model developed in this paper is related to cross-country petroleum pipelines, the similar methodology can be applied to develop a risk-based inspection and maintenance model for any productive system. However, considerable research would be involved in such a study.

References

[1] "Conservation of clean air and water, Europe," Annual Report of CONCAWE, Brussels, Belgium, 1994.

[2] B. L. Payne, "California hazardous liquid pipeline risk assessment," in *Proceedings of the 1993 International Pipeline Risk Assessment, Rehabilitation and Repair Conference*. Houston, TX: Gulf, 1993.

[3] P. K. Dey, M. T. Tabucanon, and S. O. Ogunlana, "Planning for project control through risk analysis: A case of petroleum pipeline laying project," *Int. J. Proj. Manage.*, vol. 12, no. 1, pp. 23–33, 1994.

[4] ——, "Petroleum pipeline construction planning: A conceptual framework," *Int. J. Proj. Manage.*, vol. 14, no. 4, pp. 231–240, 1996.

[5] P. K. Dey, "Symbiosis of organizational re-engineering and risk management for effective implementation of large-scale construction project," Ph.D. dissertation, Jadavpur University, Calcutta, India, 1997.

[6] P. K. Dey and S. S. Gupta, "Decision support system for pipeline route selection," *Cost Eng.*, vol. 41, no. 10, pp. 29–35, Oct. 1999.

[7] P. K. Dey, S. O. Ogunlana, M. T. Tabucanon, and S. S. Gupta, "Multiple attribute decision making approach to petroleum pipeline route selection," *Int. J. Serv. Technol. Manage.*, vol. 2, no. 3/4, pp. 347–362, 2001.

[8] P. K. Dey, "Integrated approach to project feasibility analysis: A case study," *Impact Assess. Proj. Appraisal*, vol. 19, no. 1, pp. 135–245, Sept. 2001.

[9] ——, "Benchmarking project management practices of caribbean organizations using analytic hierarchy process," *Benchmarking: Int. J.*, vol. 9, no. 3, pp. 326–356, 2002.

[10] R. F. Dyer and E. H. Forman, "Group decision support with the analytic hierarchy process," *Decision Support Syst.*, no. 8, pp. 99–124, 1992.

[11] B. L. Golden, E. A. Wasli, and P. T. Harker, *The Analytic Hierarchy Process: Applications and Studies*. New York: Springer-Verlag, 1989.

[12] P. Hopkins, "Ensuring the safe operation of older pipelines," in *Proc. Int. Pipelines and Offshore Contractors Assoc., 28th Convention*, Sept. 1994.

[13] G. Islei, G. Lockett, B. Cox, and M. Stratford, "A decision support system using judgmental modeling: A case of R&D in the pharmaceutical industry," *IEEE Trans. Eng. Manage.*, vol. 38, pp. 202–209, Aug. 1991.

[14] R. M. Jamieson, "Pipeline integrity monitoring," in *Proc. Pipeline Integrity Conf.*, Aberdeen, Scotland, Oct. 29–30, 1986.

[15] J. Korpela and M. Tuominen, "Benchmarking logistic performance with an application of the analytic hierarchy process," *IEEE Trans. Eng. Manage.*, vol. 43, pp. 323–333, Aug. 1996.

[16] S. A. Mian and N. D. Christine, "Decision-making over the project life cycle: An analytical hierarchy approach," *Proj. Manage. J.*, vol. 30, no. 1, pp. 40–52, 1999.

[17] M. A. Mustafa and T. Ryan, "Decision support for bid evaluation," *Int. J. Proj. Manage.*, vol. 8, no. 4, pp. 230–235, 1990.

[18] F. Y. Partovi, J. Burton, and A. Banerjee, "Application analytic hierarchy process in operations management," *Int. J. Oper. Prod. Manage.*, vol. 10, no. 3, pp. 5–19, 1990.

[19] "Oil industry pipeline leakage survey," Pipes and Pipelines International, Jan./Feb. 1993.

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

[21] ——, *Decision Making for Leaders*. New York: Lifetime Learning, 1982.

[22] ——, "Priority setting in complex problems," *IEEE Trans. Eng. Manage.*, vol. EM-30, pp. 140–155, Aug. 1983.

[23] "Pipeline safety regulations," U.S. Dept. Transportation, 1995.

[24] L. G. Vargas, "An overview of the analytic hierarchy process and its applications," *Eur. J. Oper. Res.*, vol. 48, no. 1, pp. 2–8, 1990.

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