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A Review on Pipeline Condition Prediction Methods

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Abstract

Predictive maintenance is considered as cost-efficient and acts as an enabler for businesses to be more competitive. Maintenance of pipelines can be complex and costly especially when it is located underground or subsea. Based on the literature survey, many methods have been developed to predict pipeline conditions. To date, however, none have focused on the economic comparison of the various prediction methods. The paper reviews several common methods of pipeline prediction in order to facilitate future assessment of the economic costs of each method. These include Split System Approach, Artificial Neural Network, Reliability Analysis, Monte Carlo Simulation, Standard Data Structure Approach, Bayesian Network, Fuzzy Logic method and other probabilistic assessments that have produced promising results. The different types of machine algorithms are compared in terms of accuracy. Artificial Neural Network is seen as the most popular choice of methods and produced better accuracy compared to the rest of the machine learning algorithm.

Keywords: pipeline reliability; Machine Learning Algorithm; Artificial Neural Network

1 Introduction

The world is currently facing industrial revolution 4.0 where digitalization plays an important part in our daily lives. Businesses are racing to start using digitalization to their benefit as it is seen to improve performance and efficiency, leading to cost optimization, which in turn generates more revenues for the company in order to thrive in today's competitive environment. One area of interest is the application of digitalization for efficient maintenance of equipment. The maintenance of equipment is crucial for businesses as it eliminates or reduces the number of failures that may occur during production which may disrupt the supply chain.

Maintenance and diagnosis play an important role in promoting machine uptime, as well as the potentially impacting operating costs. Some data suggest that equipment maintenance can exceed 30 % of total operating costs, or between 60 and 75 % of equipment lifecycle cost (Dhillon, 2006). Machinery that is not functioning as per its design specification may negatively impact production yield (e.g. scrapped product). Equipment maintenance can have an overall positive impact on capital costs. The lifetime of machinery may be enhanced by limiting the number of times it enters a state of disrepair, while ongoing costs may be reduced by using predictive and preventive maintenance strategies to optimize the scheduling of maintenance activities (O'Donovan, Leahy, Bruton, & O'Sullivan, 2015). Predictive maintenance is favored due to its ability to predict failure and decrease hands-on tool time required to perform maintenance work in the field, making it an economical and cost-efficient approach.

Several methods for pipeline condition prediction have shown promising outcomes. However, studies conducted on these methods focus primarily on accuracy- either on improving the accuracy of the method in question or comparing the accuracy of various types of pipeline prediction methods. To date, none of the work involved cost analysis to evaluate the most economical and cost-efficient pipeline predictive maintenance method. This paper examines existing studies on methods of pipeline condition prediction and compares their areas of focus, objective of prediction, the types of data collected and the outcomes. This analysis can be used to conduct a future study on the economic cost of these methods. The methods in question are split system approach, reliability analysis, standard data structure approach, machine learning algorithms such as Artificial Neural Network, regression analysis, Decision Tree techniques, Monte Carlo simulation, Markov modeling, Stochastic model, Bayesian network and Fuzzy based model.

This paper first justifies the case for predicting pipeline conditions and then outlines the different types of methods that have been developed. Research work focusing on the same prediction methods are grouped together to demonstrate the adaptability of the method in solving different types of problem. Section 3 presents a comparison of the accuracy of the machine learning algorithm across different methods. The analysis of existing review of the methods is tabulated in section 4 and this paper concludes with an assessment of the most viable methods to be further analysed for economic cost assessment.

2 Cases for Pipeline Prediction and Methods Used.

2.1 Split System Approach.

The problem areas widely focused in the literature are the influences of corrosion and creep on the pipeline failures (Sun, Ma, & Morris, 2009). Sun et al, however, considers the impact of preventive maintenance (PM) on the system reliability of pipelines. In their research work, they highlight the need for meeting an effective model that can accurately improve the overall reliability of the entire pipeline and cost-effective preventive maintenance strategy. They emphasize that pipelines are a complex system and imperfect repairs would need to be considered since most of the assets are assumed to be subjected to PM actions periodically, based on time-based preventive maintenance method (TBPM). TBPM cannot model the effect of different PM actions on the system reliability nor does it consider system configuration. When modeling imperfect maintenance, it uses a method similar to the improvement factor method. To make an optimal decision, the reliability changes of the entire pipeline with different PM strategies have to be predicted accurately. However, the existing models/methodologies cannot meet industrial need for the explicit prediction of the reliability improvement and the consideration of multiple imperfect repairs because only partial pipeline will be repaired during a PM action. Therefore, to address this issue, their research aims to predict the reliability of pipelines with multiple imperfect PM actions using split system approach (SSA) by considering both TBPM and RBPM. They developed a model for the effects of PM activities from pipeline repair history and inspection results using reliability function (Sun et al., 2009).

2.2 Reliability Analysis Method

Ahammed (1998) addresses the problem of estimating the remaining strength of corroded pipelines based on deterministic approaches that are free of any uncertainty. In his research, he carried out reliability analysis which can be used to assess the safety and integrity, and also to predict the remaining life of a corroded pipeline with further corrosion growth. The resulting information can be used to predict safe operating pressure at any time and to prepare an effective and economic inspection, repair and replacement schedules (Ahammed, 1998).

Hallen et al proposed structural reliability analysis in their research work to evaluate the integrity of in-service corroded pipelines in Mexico using high-resolution magnetic flux leakage (MFL) or ultrasonic technology-based (UT) in line inspection tool (Hallen, Caleyo, González, & Fernández-Lagos, 2003).

Pandey deals with uncertainties in the decision-making regarding pipeline maintenance, the frequency of future inspections, and the estimation of associated costs involved with the assessment of condition. The primary objective was to formulate a quantitative probabilistic approach with the aim of determining the optimal inspection interval and the repair strategy that would maintain adequate reliability over the remaining service life of the pipeline (Pandey, 1998).

2.3 Bayesian Network Method

Reza et al focus on dynamic modeling for predicting pipeline performance. This research was driven by the fact that a majority of studies rely on static models to analyze the failure prediction based on corrosion rates, historical data and/or expert judgment. The main objective of their research work was to propose a preliminary dynamic reliability model for aging pipeline performance prediction, by analyzing the pipeline residual life based on internal and external corrosion rates and several other variables that influence the performance of the system. The initial model of their research was to utilize qualitative inputs such as experts' judgment and assumptions in the model to fill the data gap. As such, the Bayesian Network method was the preferred choice to build dynamic probabilistic models for its ability to manage and overcome uncertainties. The network diagram developed in the study was based on the causality of each variable, from the cause of the corrosion to the effect of the failures. It takes into consideration that corrosion failure is a time-dependent process as the analysis utilizes inspection history data from several years (Aulia, Tan, & Sriramula, 2019).

Amit et al address the challenges of locating the internal corrosion damage in oil and gas pipelines that are hundreds of miles long due to the presence of large uncertainties in flow characteristics, pre-existing conditions, corrosion resistance, elevation data and test measurement despite recent advances in inline inspection technology In their research, they have considered probabilistic methodology based on internal corrosion direct assessment (ICDA). Bayesian Network was used to predict the most probable corrosion damage location along the pipelines using physical models for flow, corrosion rate, and inspection information as well as uncertainties in elevation data, pipeline geometry and flow characteristics (Kale, Thacker, Sridhar, & Waldhart, 2004).

2.4 Stochastic Method

Mahmoodian and Li conducted research on a reliability-based methodology for assessment of corroded steel pipes. A stochastic model for strength loss was developed which is related to key factors that affect the residual strength of a corroded pipe. A pipeline system fails when its residual strength falls below its operating pressure. An analytical time-variant method is employed to quantify the probability of failure due to corrosion, so as to determine with confidence the time in which the pipeline may fail and hence require repairs. To deal with the assessment of pipelines with have more than one corrosion pit, system reliability analysis method is employed. The proposed methodology provides a rational and consistent approach to conduct a quantitative assessment of pipeline failures. The methodology proposed in this study can also be extended to other aging structures and infrastructures subjected to localized deterioration. Monte Carlo simulation technique was applied to verify the results of the analytical method (Mahmoodian & Li, 2017).

2.5 Monte Carlo Simulation

Shuai et al conducted a study to define an alternative to the conservative model used to predict burst capacity which is costly in terms of maintenance. In their research, Shuai et al developed a new burst prediction model that has a good precision for corroded pipelines Based on this model, a probabilistic method is presented to predict the failure probability of corroded pipeline by using the Monte Carlo (MC) simulation method. The parameter sensitivity and model sensitivity of uncertainties are analyzed to find the parameters which have the most influence on the safety of corroded pipelines (Shuai, Shuai, & Xu, 2017).

Shu Xin li et al used the cumulative distribution function (CDF) to estimate cumulative probable failure for a pipeline, calculated using the Monte Carlo simulation technique (Li, Yu, Zeng, Li, & Liang, 2009).

Ossai et al examine the problem of having limited information on failure probability estimation of corroded pipelines. The work aims to predict the failure probability and estimate the reliability of corroded pipelines using pipeline corrosivity index (PCI) in consideration of the retained pipe-wall thickness of the corroded pipeline at a given time. Monte Carlo simulation was used along with Markov modeling to predict the survival probability of corroded pipelines at a given time for different corrosion wastage rates. Weibull probability function was used to calculate the time-lapse for a pipeline leakage. Markov modelling and Monte Carlo simulation were chosen because they were used for estimating the failure probability of corrosion defect growth of corroded pipelines and other structures by numerous researchers(Ahammed, 1998; Breton, Sanchez-Gheno, Alamilla, & Alvarez-Ramirez, 2010; Keshtegar & Miri, 2014; Pandey, 1998; Zhang et al., 2012). The expectation from the model developed in this research is that it would be a viable tool for managing the integrity of corroded aging pipeline (Ossai, Boswell, & Davies, 2016).

2.6 Standard Data Structure Approach

Alison et al research mainly focus on developing an understanding of the failure modes and mechanisms of buried pipe infrastructure systems that are used in a municipal water system. Their research also considers the pipe material's advantages and disadvantages as well as to understand all the parameters affecting water pipe infrastructure systems (St. Clair & Sinha, 2014). In order to develop this understanding, they established a standard data structure for predicting the remaining physical life and consequence of failure of water pipes through physical or structural parameters, operational or functional parameters and environmental parameters. Correlating the various pipe material types with their pipe life cycle failure modes and mechanisms are crucial in defining the various parameters that affect the water pipelines (St. Clair & Sinha, 2014).

2.7 Artificial Neural Network

Najafi et al in their research address the challenge of completing more than 304 miles of inspection on 2200 miles of local sewers for cracks, collapses and blockages as part of their sewer system evaluation survey (SSES) effort. They developed a pipeline condition prediction model based on the neural network algorithm which can identify pipelines at risk of failure so that inspections can be prioritized (Najafi, M., and Kulandaivel, 2005).

Kexi Liao et al came up with an alternative approach for internal corrosion direct assessment of wet gas pipeline and developed a model using ANN (Artificial Neural Network) based on 116 groups of data from wet gas gathering pipelines (Liao, Yao, Wu, & Jia, 2012).

El Abbasy et al conducted several studies on the prediction model for pipeline using the Artificial Neural Network method. In 2014, they studied condition assessment and prediction models in order to develop expected deterioration curves for offshore oil and gas pipelines based on several factors besides corrosion (El-Abbasy, Senouci, Zayed, Mirahadi, & Parvizsedghy, 2014a). In 2016, they developed forecasting models using ANN, regression analysis and decision tree techniques to predict the different types of pipeline failure by studying the critical factors affecting the condition of oil and gas pipelines and the design condition forecasting models for unpiggable oil and gas pipelines. They also developed expected deterioration curves for the pipelines considered in their research exercise. The models were tested, validated and compared with their previously developed models for piggable offshore pipeline (El-Abbasy, Senouci, Zayed, Parvizsedghy, & Mirahadi, 2016).

Ren et al considered the use of back propagation (BP) neural network to predict the corrosion rate in long distance natural gas pipeline. The input parameter was based on natural gas pipeline mileage, elevation difference, pipe inclination, pressure, and Reynolds number, whereas the maximum average corrosion rate of the pipeline was used as an output parameter, to predict natural gas pipeline internal corrosion rate (Ren, Qiao, & Tian, 2012).

Achim et al explored the possibility of using neural networks with the aim of improving failure predictions for CWW (City West Water Ltd), replacing regression analysis on past failure histories. The models were based on age only and are considered unsatisfactory, due to relatively low correlations between predicted and actual failure rates (Righetti 2001). The neural network developed was compared against previous modeling STPM (shifted time power model) and STEM (shifted time exponential model) (Achim, Ghotb, & McManus, 2007).

2.8 Fuzzy Based Model

Senouci et al developed a fuzzy-based model for oil and gas pipeline prediction in extension to their previous research activity on the same subject that involved regression and artificial neural network (ANN). The model took into consideration the prediction of failure types such as corrosion, mechanical, third-party, natural hazard, and operational. The model was built based on historical data collected from a report prepared by CONCAWE (Davis et al. 2010).

However, the developed models using regression analysis and ANN suffered from certain shortcomings, such as the precision incorrectly predicting the natural hazard type of failure. The data set was also subjective in nature, which led to many assumptions. They believed a fuzzy-based model will tackle the problems of uncertainties and subjectivity in the available variables. The main objectives of the study conducted were to identify and study the critical failure causes of oil pipelines, and to design a failure type prediction model for such pipelines (Senouci, El-Abbasy, & Zaye, 2014).

Maneesh and Tore considered the fuzzy logic method to come up with risk-based inspection planning. They realized that an important feature of plant operation is the availability of a considerable amount of information regarding the corrosion of pipelines, which are qualitative and imprecise knowledge. This knowledge cannot be easily applied using traditional mathematics such as differential and algebraic equations. Hence, the incorporation of the subjective knowledge along with the objective information is crucial in order to develop a practical model that is simple to use and flexible enough to be modified according to the requirement of plant section and field data. The fuzzy logic approach is an attractive option when (a) the available data is not precise enough to allow conventional methods of computing; (b) there is a significant tolerance to the imprecision, allowing the development of a simple and robust model; (c) the available information is too incomplete to allow the development of a proper model; and (d) the model is too difficult to allow easy computation [1–5]. The intent of their research was to develop an optimal inspection plan considering various sources of information like recommended models, standards and their own plant experience (Singh & Markeset, 2009).

3 Machine Learning Algorithm Methods Comparison

The literature review indicates that most pipeline condition prediction methods utilize machine learning algorithms. The algorithm is widely used, not only for predictive maintenance but also for data mining in other areas such as cloud computing, medical and banking sectors. The table below compares the accuracy of the methods as per gathered from the literature survey.

Machine Learning Algorithm Methods	**Accuracy Rate**					
	Tahyudin (Tahyudin, Utami, & Amborowati, 2013)	**Caruana** (Caruana & Niculescu-Mizil, 2006)	**Kalanaki** (Kalanaki & Soltani, 2013)	**Mollaza de et al** (Mollaza de, Omid, & Arefi, 2012)	**Ahmed Senouci** (Senouci et al., 2014)	**Correa** (Correa, Bielza, & Pamies-Teixeira, 2009)
Artificial Neural Network	100%	Average	99.92%	96.33%	92%	96.35%
Regression Analysis	100%	Poor		-	90%	
Support Vector Machine	100%	Excellent	100%	95.67%		
Bayesian Network	75.16%	Poor		94.33%		94.84%
Decision Trees	80.01%	Poor		94.67%		
Neuro Fuzzy			99.80%		93%	

Table 1 Comparison of machine learning algorithm (El-Abbasy et al., 2014a)

From the table below, it can be summarized that ANN is widely used in most research activities, and has a good accuracy rate. Although Support Vector Machine (SVM) is not discussed in this literature survey, from the table above it can be seen that SVM has an excellent outcome and outperforms ANN in terms of accuracy.

4 Summary of Literature Review

This literature survey paper reviews 19 articles, forming a data bank or database of information on various prediction methods of pipeline condition assessment. The information is summarized and tabulated below (Table 2).

5 Conclusion

Based on the literature review, there are many methods that can be used for the prediction of pipeline condition and each method has its own limitations. Artificial Neural Network (ANN) is widely used for pipeline prediction and the extent of the prediction can go beyond the internal corrosion based on pipeline failure history. The fuzzy model is also seen as the next promising method after ANN. Fuzzy logic can outperform ANN, but it can be inaccurate if the models are not trained enough. For probabilistic analysis, Monte Carlo simulation is generally used to calculate or analyze the reliability of the pipeline.

Most of the methods above are using machine learning algorithm to process, train and analyze data to predict pipeline failure. In this literature review, the effort is also extended to determine the accuracy of various machine learning algorithms as used in other applications. Based on the outcome, ANN is frequently used and has a good accuracy rate in general. Although Support Vector Machine (SVM) outperformed ANN in some of the studies conducted, not many pipeline predictions utilize the SVM method.

The common methods that have been identified here would be used for future works on economics assessment to determine the most viable method technically and economically. This would help the pipeline operator in selecting the best methods for their pipeline predictive maintenance program in the long run.

Table 2 Summary of Literature Survey

Method	Paper	Problem addressed	Objective	Data Collected	Outcome
Split System Approach	(Sun et al., 2009)	Assets are assumed to have PM actions periodically based on time-based preventive maintenance (TBPM) method. This method cannot model the effects of different PM actions on system reliability.	To predict the reliability of pipelines with multiple imperfect preventive maintenance actions.	Pipeline repair history	The prediction model can deal with multiple imperfect repairs more effectively and more accurately.
Bayesian Network	(Kale et al., 2004)	Locating internal corrosion damage in gas pipelines is challenging due to the presence of large uncertainties in flow characteristics, pre-existing conditions, corrosion resistance, elevation data, and test measurement.	To predict the most probable corrosion damage location along the pipelines, and then update this prediction using inspection data.	Pipeline Inspection data	The developed model was able to focus on locations with a high probability of damage.
Reliability Analysis	(Ahammed, 1998)	For a pipeline containing live corrosion defects.	To quantify the reduction in safety and hence the remaining life for deteriorating corroded steel pressurized pipelines at any point in time.	Depth of metal loss and axial length	This methodology allows calculation of the reliability index, failure probability, relative contribution of the random variables and also allows the study of the effect of variation of the variance of the random variables on the overall pipeline reliability.
Structural Reliability Analysis	(Hallen et al., 2003)	Significant effort required to assess the corroded pipeline using data obtained from high-resolution magnetic flux leakage (MFL) or ultrasonic technology-based (UT) ILI tools also known as ‘smart pigs’	To formulate operating and maintenance strategies for the safe operation of this pipeline over its targeted service life.	Inspection data	The method produced cost-effective maintenance strategies and target reliability levels are used as reference to assess the condition of the pipeline as measured by its failure probability.
Monte Carlo Simulation	(Li et al., 2009)	The traditional design code is unable to predict the failure probability of corroded pipelines at a given time.	To employ Cumulative Distribution Function (CDF) in a probabilistic model to predict pipeline failure for the underground pipeline.	Pipeline data	CDF is more appropriate to characterize the pipeline failure probability compared to Probability Density Function (PDF) and reliability index since the cumulative effect will be more obvious as exposure period of pipeline increases. Further effort is required for more precise predictions.

Monte Carlo Simulation	(Shuai et al., 2017)	Various models were used to predict the burst capacity of corroded pipelines that are conservative and may cause many defects that need to be repaired which lead to more costs.	To develop a new burst prediction model that has a good precision for corroded pipelines using the Monte Carlo (MC) simulation method.	Pipeline data	The comparison results indicated that the proposed model shows good precision when compared with commonly used codes.
Probabilistic method	(Pandey, 1998)	The assessment of the extent of corrosion for underground pipelines carrying oil and gas that are inaccessible for direct inspection.	To determine the optimal inspection interval and the repair strategy that would maintain adequate reliability over the remaining service life of the pipeline.	Inspection data	The probabilistic analysis results are able to determine the optimal inspection interval and the repair strategy that would maintain adequate reliability throughout the service life. The method was validated using Monte Carlo simulation. The proposed approach can minimize the overall cost of inspection and repair of existing pipelines.
Dynamic modeling using Bayesian Networks	(Aulia et al., 2019)	Pipeline corrosion - pipeline reliability studies rely on static models to analyze the failure prediction based on corrosion rates, historical data and/or expert judgments.	To propose a preliminary dynamic reliability model for aging pipeline performance prediction.	Operational data and inspection results	Bayesian networks were seen effective for analyzing the corroded pipeline performance. The dynamic model produced a realistic result of the pipeline residual life, which lead to an efficient estimate of the future condition of the pipeline based on the current and historical data.
Reliability deterministic prediction	(Noor, Ozman, & Yahaya, 2011)	The inherent uncertainties embedded within metal-loss data play significant roles in reducing the accuracy of pipeline future assessment.	To manipulate the polynomial equation of safety factors in the DNV RP-F101 to make the capacity equation capable of predicting the future growth of defects by deriving a time-function standard deviation equation of the inspection tool.	Metal Loss Information;	The method has improved the capability of predicting the future growth of corrosion defects deterministically. The new equation is derived so that the partial safety factors can be recalculated to consider the growth of uncertainties as corrosion progresses.
Markov Modelling and Monte Carlo Simulation	(Ossai et al., 2016)	Limited information on failure probability estimation of corroded pipelines using the Pipeline Corrosivity Index (PCI).	To predict the survival probability of corroded pipelines at a given time for different corrosion wastage rates whilst using Weibull probability function to calculate the time-lapse for pipeline leakage.	Inline inspection data of X52 grade onshore transmission pipeline was used.	The probability of failure of internally corroded pipelines that are expected to fail by small leakage, burst and rupture are considered.

Stochastic model and Monte Carlo Simulation	(Mahmoodian & Li, 2017)	Metal corrosion is a common threat to the structural integrity of aging oil and gas pipelines.	To provide a rational and consistent approach to make a quantitative assessment of pipelines failures to be extended to other aging structures and infrastructures subjected to localized deterioration.	Pipeline data	The effect of yield strength of the pipe material on failure probability is not significant, while the effect of operating pressure on the service life of the pipe is remarkable. The proposed time-variant reliability method can be used as a rational tool for failure assessment of corrosion affected oil and gas pipelines with a view to determining the service life of the pipeline system.
Artificial Neural Network	(Najafi, M., and Kulandaivel, 2005)	Unable to prioritize inspection plan for rapidly deteriorating sewer system that is 2200 miles long.	To develop a pipeline condition prediction model to identify pipelines at risk of failure so that inspections can be prioritized.	Sewer System Evaluation Survey	The neural network is capable of learning the deterioration trends
Artificial Neural Network	(El-Abbasy et al., 2014a)	Most of the models developed have used corrosion features alone to assess the condition of pipelines.	To design a condition assessment and prediction models and develop expected deterioration curves for offshore oil and gas pipelines based on several factors besides corrosion.	Pipeline Inspection data	Based on the comparison between ANN and the regression model, ANN technique provided better results. The models are expected to help pipeline operators to assess and predict the condition of existing oil and gas pipelines and hence prioritize their inspections and rehabilitation planning.
Artificial Neural Network	(Liao et al., 2012)	The calculated corrosion rate using the internal corrosion prediction model (ICPM) may deviate from the realistic corrosion rates when the internal environmental parameters of the inspection segments are not within the scope of the prediction model.	To develop an effective numerical method to evaluate the corrosion rate of wet gas gathering pipelines.	Pipeline detail; The internal corrosion inspection data	The test results show a satisfactory degree of matching between the prediction corrosion rate and the inspection data. This model was selected as the best model for the prediction of corrosion rates.
Artificial Neural Network	(Ren et al., 2012)	To predict the corrosion rate on long natural gas pipeline	BP neural network is applied to predict the corrosion rate of long-distance pipeline based on natural gas pipeline mileage, elevation difference, pipe inclination, pressure, and Reynolds number.	Pipeline data	BP neural network model can be used to describe the natural gas pipeline in different corrosive environments the maximum corrosion rate.

Artificial Neural Network	(Achim et al., 2007)	Regression analysis to predict future failure rates are based on age only and are considered unsatisfactory, due to relatively low correlations between predicted and actual failure rates (Righetti 2001).	To improve failure predictions by comparing the neural network method against previous modeling STPM (Shifted Time Power Model) and STEM (Shifted Time Exponential Model).	Historical data	The neural network outperforms the statistical models. However, some improvement is required due to databases that are relatively large and noisy.
Regression Analysis	(El-Abbasy, Senouci, Zayed, Mirahadi, & Parvizsedghy, 2014b)	Majority of developed condition assessments or failure prediction only deal with one failure causes such as corrosion. No standard condition assessment scale for oil and gas pipelines (condition rating system and its associated rehabilitation actions) has been developed.	The main objective of the study is to develop expected condition deterioration curves for pipelines with respect to age.	Historical inspection data collected from three different pipelines in Qatar.	The model developed is expected to help decision-makers assess and predict the condition of existing oil and gas pipelines and hence prioritize their inspections and rehabilitation planning.
Fuzzy Logic	(Singh & Markeset, 2009)	The traditional modeling approaches – semi-empirical and mechanistic have been successful in making accurate predictions only to a limited degree.	To develop an optimal inspection plan considering various sources of information like the recommended models, standards and their own experience of the plant.	Operating condition of the pipe, wall thickness, and corrosion rate	Flexible and easy calibration/modification It is based on a combination of expert knowledge, objective measurements and quantifiable objective which are more easily available.
Fuzzy Logic	(Senouci et al., 2014)	The majority of developed condition assessment and failure prediction models are either subjective (i.e., depending only on expert opinion considering no historical data), or are not comprehensive (i.e., dealing with only one failure cause). Therefore, there is a need for the development of a more objective failure prediction model for oil and gas pipelines to allow pipeline operators to take the necessary actions to prevent catastrophic failures	The main objectives of the present study are: (1) to identify and study the critical failure causes of oil pipelines, and (2) to design a failure type prediction model for such pipelines.	Historical pipeline data	The results showed that the fuzzy model outperformed regression and ANN techniques. However, as a model limitation, it is concluded that the model is not always capable of accurately predicting the natural hazard failure types due to limited details in database. As a result, the model was not trained enough to predict such type of failure.

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