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A Review on Failure Prediction Models for Oil and Gas Pipelines

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ABSTRACT: Over 10,000 failures have occurred in the US oil and gas pipelines in the past 15 years, highlighting the significance of safety measures for such facilities. Various models have been proposed by researchers with the aim of predicting different failure parameters. Despite such efforts, no comprehensive review has yet been conducted in this domain. The objective of this study is to provide a detailed review on the methodologies proposed to predict failure parameters for oil and gas pipelines. Such a review gathers, organizes, classifies and analyzes previous contributions in this domain and highlights the gaps associated with different failure prediction models. In addition, the current code-based methodologies for failure prediction of oil and gas pipelines and their corresponding limitations are discussed. As such, this study provides pipeline operators and researchers with a comprehensive overview of the research and practice in oil and gas pipeline failure and safety. In conclusion, several avenues for future research are discussed. In particular, a maintenance planning procedure directed by pipeline availability analysis is proposed to address the existing gaps and limitations.

Keywords: Oil and gas, pipelines, failure prediction, risk, probability, reliability, cause, asset management, inspection, condition assessment

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Introduction

Oil and gas pipelines are important assets of a society, transporting millions of dollars of wealth. Though pipelines are recognized as one of the safest means of transportation of oil and gas compared to rail and road transportation, the statistics show an increasing trend in occurrence of incidents. According to US department of transportation (US DOT 2016), around 10,000 failures have occurred in US since 2002 leading to considerable safety, environmental and economic consequences. Table 1 reports the statistics regarding number of failures and damages due to oil and gas pipelines malfunctioning (US DOT 2016). This highlights the importance of adopting failure prediction and maintenance planning in order to establish timely prevention and intervention strategies.

Different sources may threat pipeline integrity such as corrosion, natural hazards and third party activities. In order to minimize these threats, pipeline integrity programs are widely practiced. This program is composed of three main phases including defect detection, prediction and maintenance management (Xie and Tian 2018). Defect detection requires extensive in-line inspection (ILI) and monitoring of pipeline conditions. In this sense, anomalies (e.g. metal loss, dents, gouges and girth weld quality), length, width and location of the anomaly are reported by using smart devices such as magnetic flux and ultrasonic tools (Baker 2008). However, these techniques are considered as time consuming and expensive due to the necessity of performing frequent inspections with high-resolution tools to obtain accurate results and minimize the associated uncertainties. In the second step of integrity programs, defect prediction is carried out involving the development and implementation of failure prediction models based on historical data, experimental tests, or inspection results obtained from the first step (Xie and Tian 2018). In doing so, there has been a growing attention towards developing models that can ameliorate prediction of failure attributes of oil and gas pipelines. Such models could predict one or several parameters including risk, time of failure, probability of failure (POF) or reliability, consequence, source, pressure at time of failure, rate of failure and mode of failure. These models can be based on inspection, experimental, and historical records or use physical methods such as finite element analysis to predict failure. Considering the variety of the proposed models, there is a need to conduct a comprehensive literature review to distinguish these techniques in a classified manner, discuss their advantages in prediction of failure parameters, and highlight their gaps to present avenues for future research. In addition, the current code-based failure prediction methodologies practiced in the industry needs to be discussed identifying their limitations. Such a review could pave the path to connect the research and practice on failure prediction for oil and gas pipelines by informing the researchers and practitioners about the state-of-the-art contributions and developments in this area.

The aim of this paper is to present a comprehensive, classified review and analysis on the existing literatures on failure prediction models developed for oil and gas pipelines. In review of the literature, first a pool of related publications is collected. The selected publications are then meticulously analyzed and classified based on topic, predicted parameter and the applied techniques. Then, a detailed discussion and gap analysis of the reviewed methodologies is provided in line with the identified failure parameters. In addition, the current code-based methods practiced in industry for assessment of pipelines are discussed and analyzed, highlighting their limitations. The paper concludes by proposing a framework for practitioners towards an availability-based maintenance planning in oil and gas pipelines on the basis of the reviewed failure analysis and prediction models.

In summary, this study distinguishes the research and practice in failure prediction for oil and gas pipelines and discovers their shortcomings for advocating some future research directions. In addition, this study will provide insights for pipeline operators, project managers and standard institutions who quest to choose proper methods of failure prediction with the aim of integrating them into the current assessment measures.

Background

In order to conduct a detailed review on developed models for oil and gas pipeline safety, a structured methodology is followed. This methodology consists of three main phases. In the first step, the papers focusing on model development for oil and gas pipeline safety are identified. In the second phase, the selected papers are classified according to different criteria. In the third phase, research and code-base methods are analyzed and discussed according to their classifications. Figure 1 presents a summary of the framework adopted in this study. The details of the above mentioned phases are provided as follows:

Phase I: In this phase, a search was performed by keywords which were accessible through web-search facilities. Keywords of “pipeline”, “oil”, “gas”, “model”, “prediction” and “assessment” were chosen within titles and abstracts in the search tool. After extracting the resulting publications and squinting abstracts, they were further assessed individually regarding to their relevance to oil and gas pipeline safety. This step led to a final selection of more than one hundred journal publications and conference proceedings that propose assessment models to defer oil and gas pipeline failure. It should be mentioned that in collection and classification of the literature, the focus is first directed towards academic journal publications and conference proceedings. Then, an overview of practical contributions (including industry reports, standards, etc.) is provided. This approach facilitates the investigation of the gaps and limitations from both research and practical perspectives.

Phase II: A framework for classifying the selected publications is then explored. After gathering the related journal publications and conference proceedings, they were classified according to different criteria including predicted failure parameter and the applied techniques. Figure 2 illustrates taxonomy of failure prediction parameters in the reviewed research including risk, time of failure, probability of failure (POF) or reliability, consequence, source, pressure at time of failure, rate of failure and mode of failure. This step provides answers to questions such as, what failure parameters are predicted and which techniques are applied.

Phase III: Due to the vast number of contributions in development of safety models for oil and gas pipelines, a more focused analysis is provided for the models proposed to predict the failure parameters shortlisted from the previous phase. In order to predict these failure parameters in oil and gas pipelines, different methods have been investigated in the literature. The most common types of these methods include fuzzy technique, analytic hierarchy process (AHP), bow tie analysis, fault trees, event trees, neural networks, Monte Carlo simulation, regression analysis and Bayesian network. Table 2 presents a summary of the predicted failure parameter and the applied techniques for the reviewed researches published in the past 5 years.

The next section provides a more detailed overview of the prediction models, techniques used, and their advantages and shortcomings. This will be followed by a review of the practical implications of failure prediction for oil and gas pipelines and the existing practices in industry.

Failure Prediction Models

This section provides detailed information on the extent of the efforts directed towards predicting different failure parameter, their corresponding limitations, and avenues for future research.

Risk of failure

In oil and gas failure prediction domain, risk of failure is considered as the first most studied failure parameters. Risk of an undesired event is a function of its likelihood of occurrence and the magnitude of its consequences. The purpose of risk assessment is to highlight potential accidents and analyze their impact to identify and prioritize prevention and intervention strategies (Jonkman et al. 2003; Shahriar et al. 2012). Risk assessment methods can be classified into quantitative, qualitative or semi-quantitative. In qualitative assessments, risk is evaluated using a qualitative score, while in quantitative methods; risk is assessed through estimation of probabilities of failures and their corresponding consequences. Also, semi-quantitative methods, also known as score index methods are widely used where partial data is accessible, and the missing data will be presented through subjective (qualitative) scores provided by experts (Xie and Tian 2018).

Different methodologies and techniques have been applied to predict risk of failure for oil and gas pipelines. Chen et al. (2009) identified the hazards limited to geological risk assessment of gas pipelines. Lu et al. (2014), Guo et al. (2016), Khaleghi et al. (2014), Shahriar et al. (2012), Jamshidi et al. (2013), Lu et al. (2015) and Markowski and Mannan (2009) developed risk evaluation methods for oil and gas pipelines through fuzzy logic and fuzzy rule-based systems. Guo et al. (2016) obtained weights of risk factors for oil and gas pipelines applying AHP method. Li et al. (2016b), Dziubiński et al. (2006) , Shahriar et al. (2012) and Lu et al. (2015) developed a risk assessment method by presenting failure types and consequences through a bow-tie graphical model. Fault tree analysis is also employed by Liang et al. (2012) to develop an index-based risk assessment system. Self-organizing map (SOM) neural network was applied to classify risk patterns (Liang et al. 2012). A Bayesian method was applied by Li et al. (2016b) in order to assess risk of failure for oil and gas pipelines to model uncertainties and conditional dependencies.

Index-based risk assessment is one of the semi-quantitative risk assessment methods applied for oil and gas pipelines. The index system developed by Han and Weng (2011) consists of causation, inherent risk and consequence with their corresponding weights. Bonvicini et al. (2015) defined an environmental risk index for spills from oil and gas pipelines. Jamshidi et al. (2013) developed a risk assessment model for oil and gas pipelines involving a relative risk score obtained from indices of pipeline failures. These indices include index sum and leak impact factors. Zhou et al. (2014) assessed individual risk associated with gas pipeline failure with the corresponding risk-index. Lu et al. (2015) evaluated the severity of an accident through an index system that includes personal casualties, economic losses and environmental disruptions. Finally, Khaleghi et al. (2014) computed relative risk scores of gas pipelines through gathering risk indices.

Matrix-based risk assessment is another method in which a hazard is presented by a matrix comprised of probability and consequence of failure. Kamsu-Foguem (2016), Henselwood and Phillips (2006), Lu et al. (2014) and Pasquarè et al. (2011) developed integrated matrix-based risk assessment approaches for oil and gas pipelines. In addition, Lu et al. (2015) and Zeng and Ma (2009) and Tajallipour et al. (2014) proposed a risk matrix consisting of probability and consequence ranking criteria. In some cases, simulation and statistical analysis, theoretical quantitative methods and data analysis were proposed to assess risk parameters. Aljaroudi et al. (2015; 2016), Ma et al. (2013b), Jo and Ahn (2005), Han and Weng (2010; 2011) and Jo and Crowl (2008) estimated risk of failures in petroleum pipelines through developing empirical equations for consequence, rate or probability of failure.

Though risk is considered as one of the most studied parameters in the researches reviewed, some research gaps and limitations were identified in the current state of the art. As previously discussed, pipeline failure may occur due to different failure sources. In addition, these failures can lead to three types of consequences including financial, safety and environmental aspects. A review of the proposed risk prediction methodologies for oil and gas pipelines indicates that they are not comprehensive regarding to these criteria. From consequence point of view, Lu et al. (2014), Guo et al. (2016), Khaleghi et al. (2014), Jamshidi et al. (2013), Li et al. (2016b), Dziubiński et al. (2006), Liang et al. (2012), Han and Weng (2010; 2011), Bonvicini et al. (2015), Zhou et al. (2014), Kamsu-Foguem (2016), Henselwood and Phillips (2006), Pasquarè et al. (2011), Aljaroudi et al. (2015; 2016), Ma et al. (2013b), Jo and Ahn (2005), Jo and Crowl (2008) and Zeng and Ma (2009) evaluated risk with respect to either one or few types of consequences (individual, societal or monetary). Regarding to type of failure, Jamshidi et al. (2013), Khaleghi et al. (2014), Aljaroudi et al. (2015; 2016), Chen et al. (2009) and Tajallipour et al. (2014) accounted for either one or few failure causes, while Zeng and Ma (2009) did not consider type of failure in their studies. In addition, some of these studies relied on the use of subjective measures such as expert opinion which can lead to inaccurate results. Shahriar et al. (2012), Jamshidi et al. (2013), Markowski and Mannan (2009), Lu et al. (2015), Dziubiński et al. (2006), Guo et al. (2016) and Khaleghi et al. (2014) proposed risk assessment models based on expert judgment surveys.

Probability of failure and reliability

Probability of failure (POF) defined as the likelihood of failure occurrence, is ranked as one of the most studied failure parameters in this domain. POF plays an integral role in design and planning of pipeline maintenance strategies addressing the inefficiencies associated with in-line inspections (Sinha and Pandey 2002). Different methodologies and techniques are applied to estimate this parameter including, fuzzy expert systems, AHP method, bow-tie and fault tree analysis, artificial neural networks, Monte Carlo simulation, Bayesian theory and finite element numerical methods.

Kabir et al. (2016), Bertuccio and Moraleda (2012), Yuhua and Datao (2005), Zhou et al. (2016) and Li et al. (2016a) applied a fuzzy evaluation technique to estimate probability of failure for oil and gas pipelines. Li et al. (2016a), Kabir et al. (2016) and Hasan (2016) determined expert weights based on expert credibility and evaluation ability and generated a hierarchical risk structure to estimate probability of failure through an AHP method. Using fault trees, Omidvar and Kivi (2016), Yuhua and Datao (2005) and Li et al. (2016a) predicted probability of failure to specific causes including accidents, corrosion, operational failure. Nessim et al. (2009), obtained probability of equipment impact failure through development of a fault tree in order to set a reliability target for natural gas pipelines. By generating a back propagation artificial neural network, Bersani et al. (2010) estimated probability of failure due to third party activities. Chou et al. (2010) developed a damage detection model through application of neural networks to strain patterns obtained from finite element analysis and experimental results assessing pipeline local buckling. Using Monte Carlo simulation, Aljaroudi et al. (2014), Pognonec et al. (2008), Li et al. (2009), Oliveira et al. (2016) and Witek (2016) estimated probability of failure using experimental equations of burst pressure due to corrosion failure. In a similar research, Dundulis et al. (2016) predicted this probability by linking Monte Carlo simulation with hoop stress values obtained from finite element numerical results. Wen et al. (2014) estimated probability of failure using Monte Carlo simulation from limit state functions for several types of failures including corrosion, equipment impact and weld defects. Through Bayesian belief network, Kabir et al. (2016) proposed a method to transform fault tree into Bayesian network in order to predict probability of failure for oil and gas pipelines by presenting different hazard dependencies. Dundulis et al. (2016)

integrated Bayesian method with Monte Carlo simulation and finite element analysis to estimate probability of failure in gas pipelines due to corrosion. Using Bayesian Networks, Guan et al. (2016) estimated probability of internal corrosion failure for a case study of Chinese oil pipeline.

Besides probability of failure, several researches were identified in the domain of reliability analysis. These studies focus on time-dependent failures such as corrosion. Through iterative numerical analysis, Weiguo et al. (2014) predicted remaining life of buried gas pipelines under corrosion and cyclic loads. Similarly, Kucheryavyi and Mil'kov (2011) performed reliability assessment of corrosion failure in a defective gas pipeline with cracks using mechanical equations of pipeline strength. A Monte Carlo simulation was performed by Teixeira et al. (2008) proposing a first order reliability method for oil and gas pipelines to predict corrosion failure based on burst pressure estimations obtained from a finite element analysis and experimental tests. Similarly, Ossai et al. (2015) applied this technique in conjunction with Weibull probability function to assess reliability of oil and gas pipelines subject to corrosion failure with respect to maximum pit depth. Cobanoglu et al. (2014) estimated reliability of gas transmission pipelines subject to internal and external corrosion by application of homogeneous and nonhomogeneous Poisson processes (HPP and NHPP). Regarding to other types of failures, Ismail et al. (2015) estimated reliability of a petroleum pipeline to buckling failure resulting from soil vertical loads using Monte Carlo simulation. Liu et al. (2009) obtained reliability of a gas pipeline network to seismic damages using a fuzzy evaluation technique to evaluate seismic fortification intensity. On that basis, a Monte Carlo simulation is then used to estimate a damage state score for the network. Similarly, Liu et al. (2018) used Mont Carlo simulation to obtain the reliability function of a gas pipeline, subject to design failures, based on finite element results and field data.

Although considerable efforts are dedicated to estimating probability of failure for oil and gas pipelines, the review of the literature highlights some remaining gaps. In several studies, the proposed models are only capable of estimating the likelihood of only a specific failure rather than different failure types. Bertuccio and Moraleda (2012), Li et al. (2016a), Hasan (2016), Omidvar and Kivi (2016), Dundulis et al. (2016), Weiguo et al. (2014), Witek (2016), Ossai et al. (2015), Cobanoglu et al. (2014), Liu et al. (2009), Liu et al. (2018) and Wen et al. (2014) estimated the POF or reliability of pipes due to either corrosion, natural hazard, mechanical or third party sources. Yuhua and Datao (2005) and Li et al. (2016a) proposed methods which rely on expert judgment and are therefore subjective. In some studies, the generalization of the results are questionable as these models are developed based on only a limited number of failure records (Zhou et al. (2016), Cobanoglu et al. (2014), Chou et al. (2010), Liu et al. (2009) and Bersani et al. (2010)). Also, the methods proposed by Zhou et al. (2016), Li et al. (2009), Teixeira et al. (2008), Witek (2016) and Ossai et al. (2015) require performing expensive and time intensive in-line inspections such as magnetic flux and ultrasonic techniques.

Consequence of failure

For oil and gas pipelines, consequence of failure corresponds to individual, social, environmental and property damages. This parameter is considered as a component of risk assessment in oil and gas pipelines. Several researches contributed to predicting consequence of failure in oil and gas pipelines. Parvizsedghy and Zayed (2015a) predicted financial consequences of gas pipelines through a neuro-fuzzy technique and bow-tie model for different failure sources. In another study, Parvizsedghy and Zayed (2013b) estimated the financial consequences from external corrosion through application of neural networks. Restrepo et al. (2009) estimated probability of failure consequences of oil pipelines using binary logistic and least square regression models. Zhang et al. (2014b) coupled monetary and safety consequences obtained from experimental equations to develop a failure consequence severity index. Through consequence modeling of two case studies, Pettitt et al. (2014) highlighted the problem of over-prediction of pipeline failure and its consequences using common industry methods. They used the PHAST consequence modeling program for two consequence types of thermal radiation ellipse and fatal injuries. In two other studies, Duncan and Wang (2014) and Wang and Duncan (2014) analyzed gas pipeline failure records reported in PHMSA (US DOT 2016) and derived rate of injury, fatality and failure rate for these pipelines till 2010.

In this context, however, the methodologies proposed by Parvizsedghy and Zayed (2015a; 2013b) and Restrepo et al. (2009) only considered financial consequences. The research performed by Zhang et al. (2014b) is limited to specific cases of jet fire leakages. The studies pursued by Duncan and Wang (2014) and Wang and Duncan (2014) don not provide implications or estimations about future failure consequences.

Failure types

Failures of oil and gas pipelines may originate due to different sources including mechanical, operational, natural hazard, third party and corrosion failures. These failure sources are classified as follows (Davis et al. 2010; US DOT 2016; EGIG 2015):

(i) Mechanical: Failures resulting from design, material or construction defects.

(ii) Operational: Failures resulting from operational errors and safeguarding deficiencies due to system malfunction, human errors and excessive pressure.

(iii) Natural hazard: Failures resulting from land movement, flooding, earthquakes, erosion, frost and lightning.

(iv) Third party: Intentional or accidental actions representing damages by others in pipeline vicinity and not related to management. This failure source is ranked as one of the most frequent (Muhlbauer 2004; Davis et al. 2010).

(v) Corrosion: Corrosion is a time-dependent failure resulting from deterioration of a material (usually metal) due to interaction of pipe with the environment. Corrosion leads to wall metal loss and can be classified as either internal, external or stress corrosion cracking. Corrosion failure is ranked as one of the most frequent failure sources in oil and gas pipelines (Muhlbauer 2004; Davis et al. 2010).

Few studies are identified in prediction of failure types in oil and gas pipeline domain. Senouci et al. (2014a) developed and compared two approaches using neural networks and regression techniques to estimate source of failure in oil pipelines. Similarly, Senouci et al. (2014b) predicted failure type in oil pipelines through applying fuzzy expert systems. Breton et al. (2010) proposed a Bayesian probabilistic approach that can identify failure modes of leakage and rupture for oil and gas pipelines. Bertolini and Bevilacqua (2006) developed a multi regression model using a classification and regression tree (C&RT) approach that estimates source of a failure from available records reported in CONCAWE database (Davis et al. 2010). However, all these models were developed based on limited number of historical data on certain pipes that cannot be generalized for oil and gas pipelines. In addition, the method proposed by Breton et al. (2010) relies on performing in-line inspections which is costly and requires a considerable amount of time.

Rate, pressure and time of failure

Several publications were identified on prediction of rate of failure, pressure at time of incident or time of failure. However, most of the identified publications concentrate on prediction of failure rate. Liao et al. (2012) and Peng et al. (2009) predicted corrosion rate in a gas pipeline using artificial neural networks. In similar studies, Caleyo et al. (2009) and Engelhardt et al. (2013) predicted pitting corrosion depth and rate in underground pipelines by applying Monte Carlo simulation. Zhang et al. (2014a) developed a predictive model for rate of corrosion failure from in-line inspection data. This model is based on Bayesian networks and Monte Carlo simulation to take account of variable interdependencies and probability distributions. Velázquez et al. (2008) developed a regression model to predict rate of corrosion by considering soil and pipe characteristics. Similarly, Luo et al. (2013) predicted corrosion rate of natural gas pipelines through application of support vector machine (SVM) regression using historical records. Kaewpradap et al. (2017) validated the mechanistic internal corrosion rate prediction model previously developed by Zhang et al. (2007) through a simulation using in-line inspection field data. Papavinasam et al. (2010) predicted internal corrosion pitting rate of oil and gas pipelines using an empirical approach. Tronskar et al. (2005) determined Gumbel distribution as the best cumulative probability description for corrosion damage using statistical data fitting of inspection data. Seneviratne and Ratnayake (2014) proposed a two-phase methodology to estimate patterns of visible degradations observed in oil and gas pipelines. This methodology is composed of parameter identification and clustering using artificial neural networks and fuzzy clustering approach.

Ma et al. (2013a) and Netto et al. (2007; 2005) developed models to estimate failure pressure of oil and gas pipelines using the results obtained from finite element numerical analysis. Parvizsedghy and Zayed (2013a and 2015b) developed nonlinear regression models for prediction of time of failure in oil and petroleum pipelines. However, these methods do not link these timings to failure sources which limit their applications and usefulness.

Some studies compared effectiveness of failure prediction according to different design codes. Kim et al. (2013) identified the empirical design code closest to the results of finite element analysis for corrosion burst pressure. Similarly, Ma et al. (2011) compared effectiveness of several design assessment codes for pipelines with different mechanical characteristics by application of limited experimental data. In addition, Stefani and Carr (2010) proposed application of modification factors to take account of some failure attributes that are not typically highlighted in historical records. Using a semi-probabilistic method and experimental equations reported in DNV-RP-F101 (D.N. Veritas 2004) for corroded pipelines, Noor et al. (2010) presented the potential future variations in corrosion defects. Their model was validated using in-line inspection data of a transmission pipeline.

The studies performed by Liao et al. (2012), Velázquez et al. (2008), Tronskar et al. (2005), Kim et al. (2013), Peng et al. (2009) Luo et al. (2013) and Papavinasam et al. (2010) are limited to failures due to corrosion. Regarding to subjectivity, the studies conducted by Peng et al. (2009) and Seneviratne and Ratnayake (2014) rely on expert judgments for generation of fuzzy membership functions used in the evaluation of failure parameters. Furthermore, the methods conducted by Caleyo et al. (2009), Engelhardt et al. (2013), Luo et al. (2013), and Papavinasam et al. (2010) relied on performing expensive in-line inspection or limited historical records.

Practical implications

In this section, a review of failure prediction measures applied in industry is provided, highlighting their applications as well as limitations. For risk assessment of oil and gas pipelines, quantitative risk assessment procedures are specified in standards codes (ASME B31.8 2018; PD 8010 2015) with a special attention directed towards external failures (i.e. not related to design and operation of pipelines) cited as the most significant failure sources. Accordingly, for individual and societal risks, tolerable risk levels are specified (Goodfellow et al. 2014; Nessim et al. 2009). These risk levels are dependent upon parameters including location type, wall thickness, population density, maximum stress and proximity of population to the studied pipeline (Goodfellow and Haswell 2006). In the corresponding equations, the fracture equations employed as criteria for such failures are considered semi-empirical and conservative (Seevam et al. 2008; Lyons et al. 2008; Cosham et al. 2008). In addition, occurrence of dent damage is supposed to be only dependent upon the force applied by indenter not the pipeline itself (Goodfellow et al. 2018).

Regarding to assessment of remaining strength of pipelines, this parameter is evaluated according to specified design codes for metal loss due to corrosion. These design codes are NG-18 equation (Kiefner et al. 1973), DNV-RP-F101 (LPC) (D.N. Veritas 2004; D.N. Veritas 1999), SHELL92 (Ritchie and Last 1995), ASME B31G (A.N.S. Institute 1991), modified B31G (Kiefner and Vieth 1989), RSTRENG (Kiefner and Vieth 1989), CPS (Cronin and Pick 2000), and SAFE (Wang et al. 1998) (Kim et al. 2013). These evaluation techniques used in these codes are different from one another in defect shape and bulging factors and are mainly based on are deterministic and experimental approaches with simplified assumptions for metal loss with two main limit states for depth of corrosion and failure pressure (Xie and Tian 2018; Timashev and Bushinskaya 2016; Noor et al. 2010; Aljaroudi et al. 2014). In corrosion assessment, a threshold for depth of corrosion defect is considered relative to pipe wall thickness, while in failure pressure approach the difference between operating and failure pressures is used (Aljaroudi et al. 2014). In comparison with data from actual pipelines with corrosion failure, such methodologies tend to provide considerably conservative results leading to economic loss and under maintenance of the pipes, mainly due to ignoring the probabilistic nature of corrosion (Ma et al. 2011; Kim et al. 2013). In this sense, use of probabilistic measures which take into account the randomness of pipeline parameters (geometry, material, loading, defect parameters) could provide more realistic estimations (Timashev and Bushinskaya 2016; Aljaroudi et al. 2014).

Regarding to consequence modelling, by comparing the results obtained from industry methods such as DNV PHAST with actual pipeline accidents, Pettitt et al. (2014) concluded that industry techniques are conservative in estimation of thermal radiation and fatal injuries. These limitations highlight the importance of integrating procedures that take into account the random nature of pipeline failure into current industry codes and methodologies in assessing risk and consequence of failure. In industry, maintenance measures and interventions applied to oil and gas pipelines are mostly in accordance with scheduled in-line inspections. Due to conservative nature of current design codes, such scheduled maintenance procedures lead to under/over maintenance of pipeline components which eventually have a negative impact on a pipeline uptime.

In this regard, adopting an availability-based maintenance planning, as practiced in power industry (Bose et al., 2012), would be beneficial due to criticality of oil and gas pipeline availability and importance of their operation on economy. This maintenance procedure is a branch of reliability-centered maintenance planning and is applied for maintenance planning of critical facilities such as power plants for which availability of the system is critical. The objective of performing availability-based maintenance scheduling is to provide a maintenance plan, which results in high availability and high level of safety (Zhang et al. 2002). In this method, the components with bigger effects in system availability are selected to be maintained more frequently and the ones with less impact on the system availability will be maintained less frequently (Pourhosseini and Nasiri 2017), helping to avoid over/under maintenance of components by considering their availability priorities. In this domain availability is defined as a function of mean time to repair, *MTTR*, and mean time to failure, *MTTF* (i.e.

MTTF/[MTTF+MTTR]) (Zhang et al. 2002). The first step in this method is to develop a comprehensive failure prediction model which considers probabilistic nature of pipeline failure for different sources (in contrast with current design codes). Based upon the developed prediction models, the reliability profiles can be obtained, and maintenance planning can be performed as directed by the expected improvements in availability of pipelines. The proposed availability-based approach, and its link to failure prediction models of pipelines, is presented in Figure 3.

Gap analysis

After reviewing the literature on oil and gas pipeline failure prediction models, some limitations and gaps were identified. These limitations are classified and discussed as follows:

(i) Regarding to failure risk and consequence assessment of oil and gas pipelines, the majority of the studies did not consider multiple consequences. The reviewed studies evaluated risk with respect to only one or two specific consequences (individual, societal or monetary).

(ii) Most studies considered few failure types and did not differentiate between failure sources. Failures due to corrosion are considered as the most highlighted failure type in the reviewed publications. Most studies predicted failure of oil and gas pipelines by considering only one failure type. Some studies (Parvizsedghy and Zayed, 2013a and 2015b) developed prediction models for time of failure; however, they did not consider any differentiation on failure types.

(iii) Applicability and generalization of some of the reviewed publications are limited since they are based on limited inspection or experimental data or they are proposed for a particular case study. Most studies developed failure prediction models based on inspection and experimental results from a particular case study pipeline.

(iv) Some of the models developed from available historical data are not considered as comprehensive models due to their reliance on limited historical data records. Bertolini and Bevilacqua (2006), Senouci et al. (2014b; 2014a), Bersani et al. (2010), Cobanoglu et al. (2014), Luo et al. (2013) and Zhou et al. (2016) developed failure prediction models from different available historical data with limited number of records.

(v) Use of subjective approaches such as conducting expert surveys, which highly depend on human judgments and experience, can be considered as another limitation. There were several studies that developed failure prediction models solely based on expert judgments in the absence of historical data.

(vi) The current code-based procedures, widely practiced in industry, mainly consider corrosion and third party activities in pipeline failure prediction. This is an over simplification which leads to conservative predictions (underestimation) of failures that could lead to higher economic loss.

Conclusions

In this paper, a comprehensive literature review is conducted on failure prediction models developed specifically for oil and gas pipelines. First, a pool of relevant publications on failure prediction models for oil and gas pipelines consisting of more than one hundred publications was extracted. Then, the selected publications were analyzed and classified according to different criteria including predicted parameter and the applied technique.

The review of state of art reveals that despite large contributions in this domain, several limitations are remaining. Subjectivity due to reliance of models on expert judgment, need to expensive inspection/experiments, limited historical data, and inclusion of a limited number of failure types or consequences are identified as the main shortcomings in the literature. The review of current code-based procedures practiced in industry for failure prediction of oil and gas pipelines revealed that such methodologies are mainly limited to corrosion and third party failures. In addition, these procedures are over simplified and conservative when it comes to failure prediction. This highlights the current gap between research and practice in oil and gas pipeline failure prediction.

This review provides a reference for pipeline operators, researchers and standards associations on the state-of-the-art literature on oil and gas pipeline safety and failure prediction. It distinguishes the different models proposed for predicting failure parameters of pipelines as reported in the literature and as practiced in industry through code-based methods. As such, the focus was to provide a balanced review of the models presented in the literature to identify and classify their limitations as well as the gaps in the literature, practice and the standards.

The review also advocated the adoption of an availability-based maintenance management approach for oil and gas pipeline in order to overcome the limitations associated with the current methods practiced in industry. The key step in establishing such a maintenance procedure is to develop a failure prediction model. In summary, this survey of the state-of-the-art literature serves as a comprehensive and classified source for pipeline failure prediction models.

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List of Figures

Table 1. Records of Oil and gas pipeline failures since 2002

Pipeline commodity	No. of failures	Damage ($)
Gas	3,869	2,684,699,818
Oil	5,528	3,431,943,554
Total	9,217	6,116,643,372

Table 2. Summary of the recent literature

Literature	Predicted parameter								Approach														
	Risk	POF/reliability	Consequence	Rate of failure	Type of failure	Failure pressure	Time of failure	Numerical	Empirical / experimental	Expert opinion	Fault/fault tree	Bayesian	AHP	Fuzzy	Monte Carlo/simulation	Matrix-based	Index-based	Bow-tie	Entropy method	NPP/NHPP	Neural network	SVM	Regression
Aljaroudi et al. (2014)		Y							Y														
Aljaroudi et al. (2015)	Y								Y														
Aljaroudi et al. (2016)	Y								Y														
Bonvicini et al. (2015)	Y										Y						Y						
Cobanoglu et al. (2014)		Y																		Y			
Dundulis et al. (2016)		Y						Y				Y			Y								
Engelhardt et al. (2013)				Y											Y								
Guan et al. (2016)		Y										Y											
Guo et al. (2016)	Y									Y			Y	Y					Y				
Hasan (2016)		Y											Y										
Ismail et al. (2015)		Y													Y								
Jamshidi et al. (2013)	Y													Y			Y						
Kabir et al. (2016)		Y								Y	Y	Y	Y	Y									
Kaewpradap et al. (2017)				Y											Y								
Kamsu-Foguem (2016)	Y															Y							
Khaleghi et al. (2014)	Y									Y				Y			Y						
Li et al. (2016a)		Y								Y	Y		Y	Y									
Li et al. (2016b)	Y											Y						Y					
Liao et al. (2012)				Y																	Y		
Liu et al. (2018)		Y													Y								
Lu et al. (2014)	Y									Y				Y		Y							
Lu et al. (2015)	Y													Y			Y	Y					
Luo et al. (2013)				Y																		Y	
Ma et al. (2013a)						Y		Y	Y														
Ma et al. (2013b)	Y								Y														

Literature	Predicted parameter								Approach														
	Risk	POF/reliability	Consequence	Rate of failure	Type of failure	Failure pressure	Time of failure	Numerical	Empirical / experimental	Expert opinion	Fault/fault tree	Bayesian	AHP	Fuzzy	Monte Carlo/simulation	Matrix-based	Index-based	Bow-tie	Entropy method	NPP/NHPP	Neural network	SVM	Regression
Oliveira et al. (2016)		Y							Y														
Omidvar and Kivi (2016)		Y						Y			Y												
Ossai et al. (2015)		Y						Y	Y														
Parvizsedghy and Zayed (2013a)							Y																Y
Parvizsedghy and Zayed (2013b)			Y																		Y		
Parvizsedghy and Zayed (2015a)			Y											Y				Y					Y
Parvizsedghy and Zayed (2015b)							Y																Y
Senouci et al. (2014a)					Y																Y		Y
Senouci et al. (2014b)					Y									Y									
Tajallipour et al. (2014)	Y															Y							
Weiguo et al. (2014)		Y						Y															
Wen et al. (2014)		Y													Y								
Witek (2016)		Y							Y														
Zhang et al. (2014a)				Y								Y			Y								
Zhang et al. (2014b)			Y														Y						
Zhou et al. (2014)	Y																Y						