www.coast.oaustech.edu.ng
COAST
JOURNAL OF THE SCHOOL OF SCIENCE
Volume 6, Issue 2. November 2024 ISSN: 2714-3716

Coast, J. Sch. Sci. 6 (2): 1021 - 1035

APPLICATIONS OF STATISTICS AND PROBABILITY TO ENHANCE THE RELIABILITY AND MAINTENANCE STRATEGIES FOR CORRODED PIPELINES

***Opeyemi, D. A.**

Department of Civil Engineering, Olusegun Agagu University of Science & Technology, Okitipupa, Nigeria.
Corresponding Author's Email: da.opeyemi@oaustech.edu.ng

https://doi.org/10.61281/coastjss.v6i2.2

Abstract

Pipeline load carrying capacity and safety are often reduced by corrosion and associated damage. The prediction of future defects and the pipeline's remaining lifetime are obtained by using consistent assessments of corrosion rates. However, its modelling often involves simplifications and assumptions to compensate a lack of data, imprecision and vagueness, which cannot be justified completely and may, thus lead to biased results. To overcome these issues, an imprecise probabilities approach is proposed for reliability analysis, decision-making, risk-based design and maintenance. It is shown how this approach can improve the practise using B31G, Modified B31G, DNV-101 and Shell-92 failure pressure models. In addition, a robust and efficient probabilistic framework for optimal inspection and maintenance schedule selection for corroded pipelines is proposed. Optimal solution is obtained through only one reliability assessment removing huge computational cost of reliability-base optimization and generalised probabilistic methods and in turn, making the analysis of industrial size problem feasible.

Keywords:- Probabilistic methods, reliability analysis, optimal inspection and maintenance, pipeline's remaining life, failure pressure models

Introduction

One of the most important degradation/deterioration mechanisms that affect the long-term reliability and integrity of metallic pipelines is corrosion (Ahammed and Melchers, 1997; Bazan and Beck, 2013; Nahal *et al.,* 2023). Corrosion which leads to metal loss both in type and section (length and depth) is the most prevailing time dependent threat to the integrity, safe operation and cause of failure for oil and gas pipelines (Caleyo *et al.,* 2002, Wang *et al.,* 2020, Okolie *et al.,* 2023, Fu & Yao, 2022). Unavoidable uncertainties make the assessment of pipelines a complex and challenging task (Ahammed, 1998; Bazan and Beck, 2013; Qian *et al.,* 2011, Nahal *et al.,* 2023). These uncertainties appear, such as in relation to operational data variation, as randomness of the environment, in form of imperfect measurement pipeline geometry, in the material strength, operating pressure and inspection tools, and in aging processes of the pipeline (Opeyemi *et al.,* 2015a & 2015b).

The remaining strength of a pipeline with corrosion defects can be assessed using one or all the international design codes viz: B31G (ASME, 1991), B31Gmod (ASME, 1995), Battelle (Leis and Stephens, 1997), DNV-

101(DNV, 1999) and Shell-92 (Klever and Stewart, 1995). The associated methods use deterministic values for load and resistance variables, thereby assuming no uncertainty. In the light of the existing inherent uncertainties in the corrosion process, the obtained results are obviously quite coarse approximations, which may deviate from reality significantly. A key challenge in this regard is the probabilistic modelling, which relies on substantial information and data required to define parameter distributions. However, the amount of data required to define univocally those distributions might not be available in practice, assumptions and simplifications are applied that cannot be justified completely. To solve this conflict, the use of imprecise probabilities (Beer *et al.,* 2013) is proposed to realistically reflect the vagueness of the available information in the probabilistic model. In fact, since these assumptions and simplifications can be quite decisive, an imprecise probabilities approach provides a promising pathway towards a robust maintenance strategy. This work therefore proposes the use of a novel reliability metrics redefined within the framework of imprecise probabilities.

Another challenging task is the identification of optimal inspection interval time to reduce the overall costs of pipelines including cost of inspection, repair and failure. For instance, areas needing repairs should be accurately pinpointed as to minimise excavations for verifications. Likewise, early observations of failure mechanisms, and determination of the likelihood of failure in association with the pipeline must be handy. The identification of optimal maintenance scheduling requires in turn the evolution of the model reliability that can be computational expensive to evaluate. Approximate methods – e.g. FORM may not be sufficiently accurate or applicable for large scale problems, and we must resort to Monte Carlo simulation-based methods. Efficient Monte Carlo simulation is one of the most useful approaches to scientific computing due to its simplicity and general applicability; required for analyzing complex real-world problems. In this work, an efficient computational technique is proposed for the identification of a robust maintenance scheduling considering uncertainty and imprecision. More specifically, the proposed approach allows determining the optimal inspection interval and the repair strategy that would maintain adequate reliability level throughout the service life of the pipeline obtained through only one reliability assessment. Hence, the proposed approach is applicable to the analysis of industrial size problem. The proposed reliability strategies are implemented in the general-purpose software OpenCossan (Patelli, 2016). Applications and numerical examples are presented to show the applicability of the proposed strategies.

Materials and Methods

Modelling of the Pipeline Corrosion Defect

One of the significant potential threats to existing structures and infrastructures is corrosion. Metal losses due to corrosion affect the ultimate resistance, safety and serviceability of the structure and cause changes in its elastic and dynamic properties. These are major concerns in structural reliability assessment of existing structures and infrastructures, also in the prediction of the safe and serviceable life for both new and existing structures.

The prediction of future defects and the pipeline's remaining lifetime are obtained by using consistent assessments of corrosion rates. Assessed corrosion rate models has been outlined in (Caleyo *et al.,* 2012; Valor *et al.,* 2012) following National Association of Corrosion Engineers - NACE's recommendation (Race *et al.,* 2007). It is a consensus that no single approach provides all the necessary information for a confident estimate of the corrosion rate in the pipeline industry.

Some of the existing corrosion growth modelling in literature (see e.g. Caleyo *et al.,* 2012; Valor *et al.,* 2012) was designed to exclude the evolution of the corrosion defect lengths. The notion is that changes in the defect length do have little or no effect on the probability of failure estimation in association with the individual corrosion defects.

The corrosion model using linear growth is adopted in this research to include evolution of the corrosion defect lengths, measured maximum defect depth through the nominal wall thickness, and measured relative corrosion defect (ratio of defect depth to pipe wall thickness). This allows defining the failure criterion based on remaining pressure strength of corroded pipeline which depends on the length and depth of corrosion defects in addition with imprecise numbers, rather than maximum defect depth only. This is to realistically reflect the vagueness of the available information in the probabilistic model by utilizing imprecise probabilities, and to address the robustness of the same. The traditional probabilistic methods are used in practice, it is also clear that the corresponding probabilities are only known imprecisely.

For instance, corrosion growth rates are presumed traditionally to be constant values. The analysis of the future state of pipelines, such as failure probability, residual strength, etc., is based on the predicted sizes of the defects which were detected during in line inspection. The defect parameters at a given time t, for a linear growth rate of the length and depth of corrosion are assessed, the corrosion rates are expressed mathematically as $l(t) = l_0 + v_1 t$ and $d(t) = d_0 + v_d t$

The failure modes adopted here are the loss of structural strength of pipelines through reduction of the remaining pressure strength, and pipe wall thickness caused by corrosion defects. The failure pressure of the pipeline with corrosion defects at different elapsed times are assessed using four international design codes: Shell-92, B31G, DNV-101 and Modified B31G models. The summary of all the failure pressure models is shown in Table1.

In Table1,P_f, d and D are the failure pressure, defect depth, and outside diameter of pipe respectively. While w_t is the pipe wall thickness; L the longitudinal length of defect, σ_y is material yield stress, σ_u the ultimate tensile strength and M is the Folias' factor.

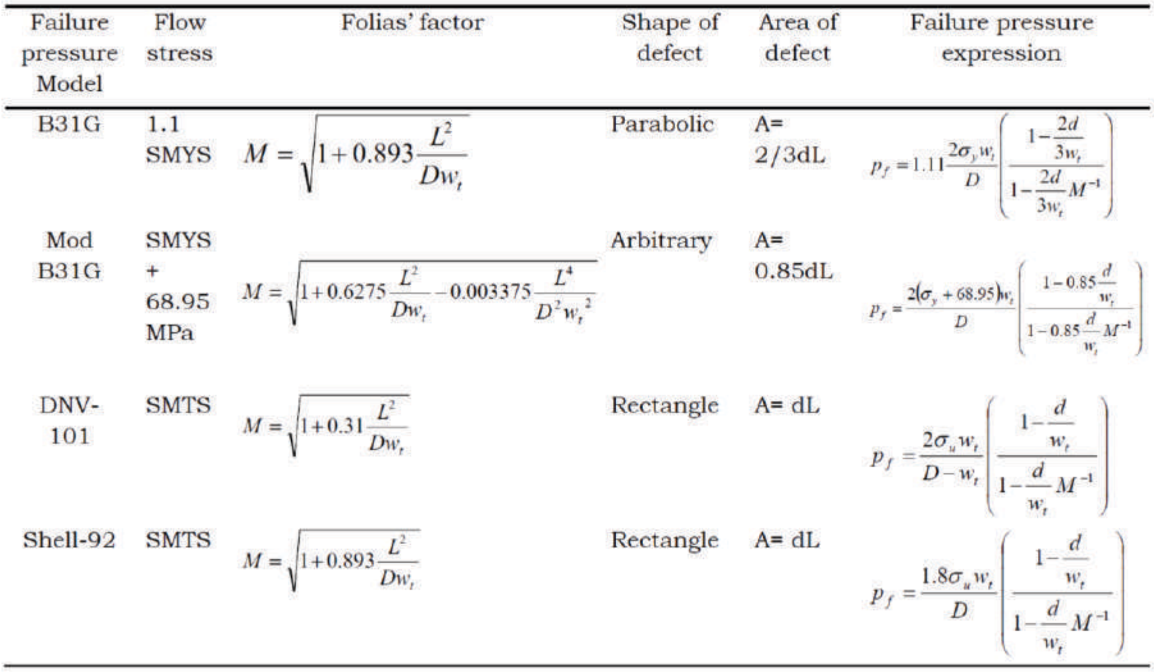
The assumption and limitation of these models are reflected on the individual flow stresses – which is the measure of the strength of steel in the presence of a defect. Failure is assumed to be because of the flow stress, defined by yield strength (in B31G and Modified B31G codes) or ultimate tensile strength (in DNV-101 and Shell-92) as their tensile properties. Then further consideration and assumption on different shapes and areas of corrosion defect; and different Folias' factors- the geometry correction factor - to account for the stress concentration due to radial deflection of the pipe surrounding a defect. These lead to variations in the obtained results based on different modifications.

Pipeline Reliability Assessments

Reliability is the probability of a structural system performing its intended function over its specified period of usage and under specified operating conditions. It is the measure of the probability of failure. The failure probabilities of the pipeline can be obtained from the models shown in Table 1.

In the level III analysis (or full probabilistic approach), the pipeline assessment has been modified with the integration of probabilistic values into the existing failure pressure models using limit state function equations as shown in Eq. (1).

Table 1: Failure pressure models used for computing pipeline failure pressure (Bjornoy *et al.*, 1997; Cosham *et al.*, 2007)



Failure pressure Model	Flow stress	Folias' factor	Shape of defect	Area of defect	Failure pressure expression
B31G	1.1 SMYS	$M=\sqrt{1+0.893\frac{L^2}{Dw_t}}$	Parabolic	A= 2/3dL	$p_f=1.11\frac{2\sigma_y w_t}{D}\left(\frac{1-\frac{2d}{3w_t}}{1-\frac{2d}{3w_t}M^{-1}}\right)$
Mod B31G	SMYS + 68.95 MPa	$M=\sqrt{1+0.6275\frac{L^2}{Dw_t}-0.003375\frac{L^4}{D^2w_t^{\ 2}}}$	Arbitrary	A= 0.85dL	$p_f=\frac{2(\sigma_y+68.95)w_t}{D}\left(\frac{1-0.85\frac{d}{w_t}}{1-0.85\frac{d}{w_t}M^{-1}}\right)$
DNV-101	SMTS	$M=\sqrt{1+0.31\frac{L^2}{Dw_t}}$	Rectangle	A= dL	$p_f=\frac{2\sigma_u w_t}{D-w_t}\left(\frac{1-\frac{d}{w_t}}{1-\frac{d}{w_t}M^{-1}}\right)$
Shell-92	SMTS	$M=\sqrt{1+0.893\frac{L^2}{Dw_t}}$	Rectangle	A= dL	$p_f=\frac{1.8\sigma_u w_t}{D}\left(\frac{1-\frac{d}{w_t}}{1-\frac{d}{w_t}M^{-1}}\right)$

The limit state functiong is defined as the difference between the failure pressure, P_f, of the pipeline and the operating pressure, O_p, expressed mathematically as:

$$g = P_f - O_p, \tag{1}$$

The probability of failure, P_f for the pipeline is defined as:

$$P_f = P(g \leq 0) = \int_{g(\theta)\leq 0} f(\theta)\,d\theta \tag{2}$$

θ represents the vector of uncertainty and in realistic cases it might be composed of many variables. Hence, analytical and approximate like FORM and SORM methods result to be inadequate for solving Eq. (1). Simulation methods are required. Monte Carlo simulation-based methods are well known techniques that can be used to evaluate the integral of Eq. (1). When dealing with rare case events, plain Monte Carlo simulation might become infeasible due to the large number of the samples required to achieve a specific level of accuracy. To overcome this limitation, advanced Monte Carlo techniques such as Line Sampling (Pradlwarter *et al.*, 2007) and Subset simulations (Au and Beck, 2001) can be adopted for analyzing complex real-world problems. Line Sampling is applicable to cases where important directions can be evaluated, and for weakly nonlinear reliability problems. Subset simulations compute small failure probabilities encountered in reliability analysis of engineering systems.

Probabilistic approach aims at providing a realistic estimation of the risk presented by the pipeline system. This can also be used to confirm the validity of the deterministic safety assessment. The major advantage of the probabilistic approach is the integrative and quantitative approach which allows explicit consideration and treatment of all types of uncertainties. Furthermore, it enhances safety and operational management; results and decisions can be communicated on a clearly defined basis.

Imprecise probability is a powerful tool to consider imprecision and vagueness, also to address sensitivities of the failure probability with respect to the probabilistic model choice and the imprecision on the characterisation of the input parameters (Beer *et al.,* 2013). It provides another set of tools for analysing computational error, verifying sufficient conditions for existence and convergence, constructing upper and lower bounds on sets of solutions, and in providing natural stopping criteria for iterative methods. More specifically, the effect of imprecision on the most common models used to predict the effect of corrosion.

Imprecise analysis is helpful in identifying low-probability but high-consequence events for risk analysis. It controls modelling accuracy with high degree of flexibility in uncertainty quantification; improves design, performance and reliability of structures. For a defined confidence level, interval bounds may be easier to specify or to control than moments of the parameter distributions.

Maintenance Strategy

Inspection and monitoring of pipelines is necessary to ensure their continued fitness for purpose, which entails protection from any time-dependent degradation processes, such as corrosion. Also, pipeline failures have significant impact on the economic, environmental and social aspects of the society. Therefore, the proper assessment and maintenance of such structures are crucial; negligence will lead to serviceability loss, failure and might lead to catastrophic environmental and financial consequences (Ahammed and Melchers, 1997). On the other hand, maintenance is an expensive activity, and the availability of robust maintenance scheduling is of paramount importance. The premise for these decisions is supplied by reliability estimation inculcating the impact of inspection scheduling and reparation activities over the pipeline's service life.

Optimization problem

In reliability-based optimization of structures, the total expected costs in relation to maintenance and failure for the structure is the objective function that needs to be minimised (Enevoldsen and Sorensen, 1994). The time of inspection represents the design variable of the optimization problem. The monetary cost associated with the inspection, the cost of the repair and the expected cost of failure form the objective function that can be formulated as:

$$\underset{N_I,e,t_i}{\arg\min} C_T(N_I,e,t_i)=C_I(N_I,e,t_i)+C_R(N_I,e,t_i)+C_F(N_I,e,t_i) \qquad (3)$$

where N_I, e, and t_i denote the number of inspections, the qualities of inspection, and the time of inspection; C_T, C_I, C_R and C_F are the expected total cost of operation, expected costs of inspection, repairs and failure respectively. In addition, the optimisation problem must satisfy some constraints. For instance, it might be necessary to guarantee a minimum level of reliability:

$$\beta= 1 -P_f(t) \qquad (4)$$

Hence, the robust maintenance strategy is closely related to the evaluation of reliability and methods of structural reliability have been applied in the literature to evaluate expected costs (Valdebenito and Schuëller, 2010).

The probability of failure is calculated by evaluating the integral of Eq. (2).

Following an inspection, if a defect is detected, it can be repaired or not. A defect is repaired immediately after an inspection if the pipe defects are lower than the threshold based on the sizing of the inspection method (the pipeline must be excavated and repaired). On the other hand, when the pipe defects are above a predefined threshold the pipe will be left unrepaired, this indicates that the processed data collected from in-line inspection to identify defects are not critical to the pipeline integrity. The threshold is a typical value $1.25 \leq SF_{FP} \leq 1.5$ (see Eq. 5) where SF_{FP} is the failure pressure safety factor often that defines the repair criterion (Pandey, 1998).

$$SF_{FP} = \frac{Pf}{MAOP} \qquad (5)$$

P_f is the failure pressure as defined in Table 1 and *MAOP* is the Maximum Allowable Operating Pressure.

This value agrees for the level of integrity established by actual pipeline hydro testing and corresponds with the repair factor for a class 2 pipeline in Canadian code (CSA Z662-07) as its safety factor adopted in design.

The expected inspection cost is calculated as the product of the unit inspection cost, C_I, corrected by the discount rate, *r*, and the probability that inspection takes place (Enevoldsen and Sorensen, 1994). This expected cost is expressed in mathematical form as:

$$C_I = \sum_i \frac{c_I(q)}{(1+r)^{t_i}}.(1-P_f^{t_i}) \qquad (6)$$

The unit cost of performing inspection depends on the quality of inspection *q*, and P_f^t is the probability that failure occurs before the time of inspection t_i.

The evaluation of the expected cost associated with repair is quite challenging and depends on the probability of detection (i.e. the probability to detect a defect).

The expected repair costs are modelled as:

$$C_R = \sum_{i=1}^{N_I} C_{R_i}.P_{R_i}.\frac{1}{(1+r)^{t_i}} \qquad (7)$$

Where i-th term represents the capitalized expected repair costs at the i-th inspection; C_{Ri}, is the cost of a repair at the i-th inspection and P_{Ri} is the probability of performing a repair after the i-th inspection when failure has not occurred earlier.

The most common tools for metal loss and crack inspection are based on the Magnetic Flux Leakage or Ultrasonic techniques (Pipeline Operators' Forum, version 2009). Pigging data is gathered through in-line inspection activities using Magnetic Flux Leakage (MFL) intelligent pig, whereby the values of parameters in the model is because of the operations and inspection histories of the pipeline. Geometry tools are available for detecting and sizing of deformations and mapping tools for localization of a pipeline and/or pipeline features (Pipeline Operators' Forum, version 2009). The inspection activities may assess the damage incorrectly or may not even detect any damage at all based on the quality. Hence, a probability of detection (PoD) associated with the non-destructive inspection techniques is assigned.

The probability of detection (Pandey, 1998) is:

$$PoD = 1 - \exp^{-qd} \qquad (8)$$

where *d* represents the defect depth and *q* the quality of inspection.

The typical minimal detectable depth of a high-resolution Magnetic Flux Leakage (MFL) tool for uniform corrosion is $0.1wt$ with a PoD of 0.9 (POF, version 2009) as illustrated in Fig. 1. Using these values, and a typical value of the pipeline wall thickness w_t = 9.52 mm the quality of inspection can be estimated as q = 2.42.

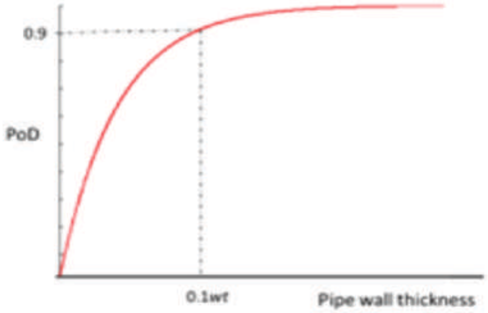


Figure 1: The PoD for minimal detectable for

uniform corrosion using MFL tool.

The total capitalized expected costs due to failure are determined from Eq. (9). It is the cost function associated with failure over the region of the corresponding demand functions (i.e. threshold based on the sizing of the inspection method) with the first, t_{i-1} and second failure criterion, t_i.

$$C_F = \sum_{i=1}^{N_{I+1}} C_F(t_i)\left(P_f(t_i) - P_f(t_{i-1})\right)\frac{1}{(1+r)^{t_i}} \qquad (9)$$

Computational Strategy

The estimation of the probability of failure requires in general significant computation effort, for highly reliable pipelines. In fact, the number of model evaluations increases with the reliability of the pipeline, and they easily exceed the computational resources available. For this reason, the Line Sampling method is adopted to estimate the probability of failure. Line Sampling (Pradlwarter *et al.,* 2007) proved to be quite robust and efficient for high dimensional problems particularly where an important direction towards the failure domain could be estimated. Line sampling employs lines instead of points to collect information about the probability content of the failure domain. It was shown that it always outperforms direct Monte Carlo (Pradlwarter *et al.,* 2007). The variance of the respective estimator depends on the deviation of the limiting hyper-surface from a hyper-plane, i.e., a single line suffices to obtain the exact value of the probability content of the failure domain. Likewise, the limit state functions which are far from plain can be accounted for in an efficient manner.

In addition, the presence of imprecision adds another level of complexity. The estimation of the bounds requires an optimization approach making the required computational cost quite challenge. Further, the identification of the optimal maintenance strategy requires a second optimization approach, making the analysis unfeasible. To overcome these computational issues the adoption of Advanced Line Sampling is suggested for the calculation of the reliability and a novel optimisation strategy is proposed for the solving the maintenance approach. The Advanced Line Sampling (de Angelis *et al.,* 2015), increases the efficiency of reliability analyses and the efficiency to estimate lower and upper bounds of the failure probability. It makes the computation of failure probabilities much faster compared with direct Monte Carlo, and most importantly because it eases the search procedure for lower and upper failure probabilities; it allows changing the important direction without re-evaluating the performance function along the processed lines.

The robust maintenance is computed adopting a novel computational strategy that allows computing the reliability of the model only once. The idea is to first simulate the evolution of the pipelines without considering inspections and repairs by performing a Monte Carlo simulation of the model evolution (i.e. solving the equations in Table 1) till the time of interest. Then the solution of the optimisation problem formulated in Eq. (3) and (4) is performed within the OpenCossan software environment by simply combining all the algorithms.

Example Application

To demonstrate the usefulness and applicability of the approach discussed in this work, a real-life above ground oil pipeline with corrosion defects is analysed. First, the effect of parameter uncertainty and model uncertainty are analysed and then a robust maintenance scheduling is performed. The pipeline characteristics are shown in Table 2. The evaluation of remaining strength and reliability assessment of the pipeline with defect is carried out using both DNV-101 code for semi-probabilistic values and Shell-92, B31G and B31Gmod codes for full probabilistic analysis.

The corrosion defects were assigned an interval of 150 – 250 mm and 0 - 100% as defect length and measured defect depth through the nominal wall thickness based on professional judgements, respectively. In addition, imprecise values are added to the mean values of the parameters. The quality of inspection associated with PoD is 2.42 (from Eq. 8). Monte Carlo simulation is employed to simulate the evolution of the system over the time considering inspections and reparation. Simulations were completed using line sampling with 20 lines, varying the number of inspections from 1 to 25 in a period of 25 years.

Table 2: The pipeline characteristics

Transported substance	Crude oil
Pipe outlay	Above ground
Outside Diameter	609.6mm
Pipe material	Class X52: UTS 496MPa, SMYS358MPa, and MAOP 4.96MPa.
Pipe nominal wall thickness	9.52mm

Table 3: Stochastic model used for the corroded pipeline.

Variable	Symbol	Unit	pdf	Mean	CoV
Diameter	D	mm	N	609.6	0.02
Defect depth	d	mm	N	3	0.1
Wall thickness	w_t	mm	N	9.52	0.02
Ultimate Tensile Strength	σ_u	MPa	LN	496	0.07
Pipe Yield Stress	σ_y	MPa	N	358	0.07
Defect length	l	mm	N	200	0.1
Operating Pressure	O_p	MPa	LN	4.96	0.1
Radial corrosion rate	v_d	mm/yr	LN	0.5	0.10
Long. Corrosion rate	v_l	mm/yr	LN	0.5	0.10

The random variables involved in the analysis and their statistical parameters in Table 3 are numerical values based on practice and have been obtained from Spangler and Handy (1982) and Melchers (1999). The normal distribution has been adopted for some of the variables since only means and variances are available in this literature.

Table 4: The monetary unit cost for operation (multiplicative factor).

Cost of Inspection	0.018
Cost of Repairs	0.243
Cost of Failure	36.55
Discount Rate	0.05

The monetary unit costs for operation in the form of multiplicative factors in Table 4 are estimated based on the summary of unit costs.

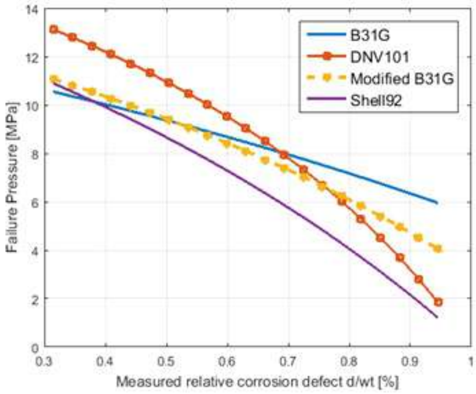


Figure 2: Failure pressure of the corroded pipeline in accordance with B31G, DNV-101, Shell-92, and Modified B31G codes as deterministic values.

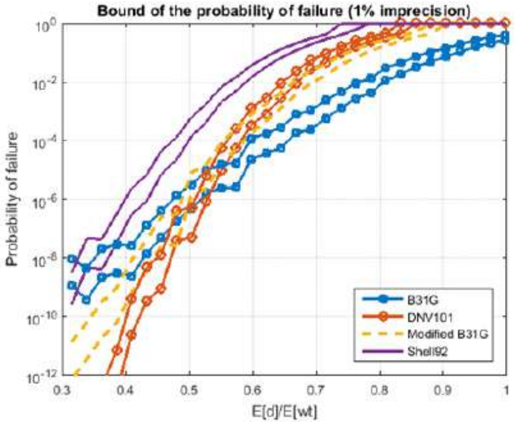


Figure 3: Lower and upper bounds of the probability of failure of a pipeline as a function of assigned 1% imprecision on the variables using Shell-92, B31G, Modified B31G and DNV-101 failure pressure models.

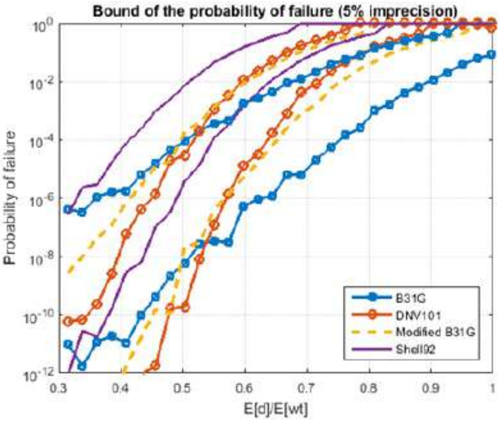


Figure 4: Lower and upper bounds of the probability of failure as a function of assigned 5% imprecision on the variables using Shell-92, B31G, Modified B31G and DNV-101 failure pressure models.

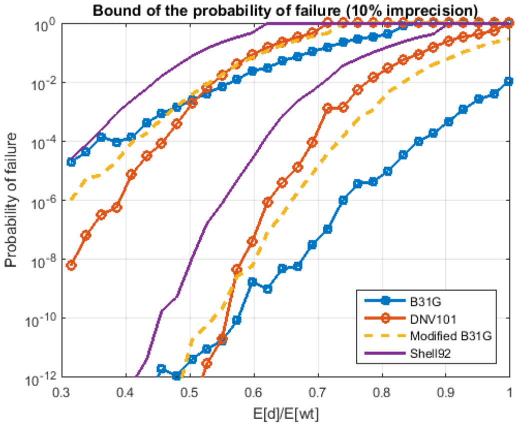


Figure 5: Lower and upper bounds of the probability of failure as a function of assigned 10% imprecision on the variables using Shell-92, B31G, Modified B31G and DNV-101 failure pressure models.

Model and parameter uncertainty

Figure 2 shows the model uncertainty and the corresponding variations in the failure pressure as a function of the relative corrosion defect. The failure pressure is calculated by the deterministic methods based on the Shell-92, B31G, Modified B31G and DNV-101 models. DNV-101 and Modified B31G models are the more conservative models, followed by the B31G model, while the Shell-92 model gives the most non-conservative result for the corroded pipeline. The reason behind the conservatism is because of the removal of several conservative simplifications (e.g. Folias' bulging factor, flow stress particularly in the Modified B31G model) to be a bit more accurate. Generally, and it is obvious that the failure pressure decreases with increasing measured relative corrosion defects for all the deterministic analyses.

In Figures 3 and 4, the probability of failure as a function of the expected values of the relative corrosion defect ($E[d]/E[w_t]$) is shown. The probability of failure has been calculated using the parameters shown in Table 3. Advanced Line Sampling simulation is adopted with 20 lines resulting in 120 model evaluations for each reliability analysis but independently of the reliability level. As expected, the probability of failure of the corroded pipeline increases with increase in measured relative corrosion defect. It is highly conservative in the Shell-92 and the DNV-101 models followed by Modified B31G model and the least in the B31G model. Considering a small level of imprecision in the parameter values (1%) the results in Fig. 3 show that the Shell-92 and the B31G models give the highest and the lowest failure probabilities (for a relative corrosion level greater than 0.6) respectively; and this is in accordance with obtained results from literature (Qian *et al.,* 2011; Caleyo *et al.,* 2002).

The results in Caleyo *et al.,* (2002) show that the failure pressure models used to predict failure pressure give similar pipeline failure probabilities for relatively short service time. For longer service times, the Shell-92 gives the highest failure probabilities while B31G gives the smallest. This agrees with the results obtained here in this study without considering imprecision in the model parameters.

To understand the effect of imprecision on the probabilistic model, imprecision has been included. The first moments of the distribution have been assumed to be known with a degree of imprecision. More specifically, a 1%, 5%, and 10% of variation around the mean values have been considered.

The uncertainty in the output predictions is dominated by the model uncertainty. While for an imprecision level of 5% in the parameter values, the uncertainty due to the model parameters become comparable with the model uncertainty, for small relative corrosion level. For imprecision of 10%, in a relative corrosion level of 0.6; the B31G model (lower bounds) and the Shell-92 (upper bounds) give the lowest and the highest failure probabilities respectively. DNV-101 and Modified B3iG models give the same levels of failure probabilities both for lower and upper bounds of imprecise values (see Fig. 5).

Considering the lower and upper probability bounds, DNV-101 and Modified B31G models could be quite relevant when dealing with unnecessary pipe repairs and for greater safe operating pressure in the pipelines. It will provide the operator with several options to manage both the present and future integrity of the pipeline at a minimum acceptable reliability level with limited resources.

In summary, the probabilistic procedures are required to evaluate pipeline integrity because of the inherent uncertainties associated with corrosion growth rate, inspection tools, pipeline geometry, material properties and operating pressure. Considering the effect of imprecision is of paramount importance. First, it allows accounting for the effect of such imprecision on the quantity of interest and secondly can allow identifying the maximum level of imprecision that can be tolerated. In fact, this has overcome the drawbacks in classical probabilistic methods with the consideration of an entire set of probabilistic models in one analysis; thereby making imprecise probabilities framework provide mathematical basis for dealing with problems which involve both probabilistic and non-probabilistic information.

The safety level of imprecision and uncertainty that can be tolerated according to this result, for a meaningful outcome or performance on the measured defect depth through the nominal wall thickness has been outlined. After having analyzed the pipeline probability a robust maintenance scheduling is performed to get an optimal solution as to remove huge computational cost of reliability-based optimization and making the analysis of industrial size problem feasible.

Optimal inspection and maintenance

Optimal maintenance strategy for the remaining lifetime of the pipeline is assessed using the failure pressure models in Table 1 and performed adopting a very efficient procedure requiring performing only a single reliability analysis.

Fig. 6 shows the results of the application of the imprecise probability to compute the pipeline failure probability at mission time against the number of inspections using the failure pressure models in Table 1. A mission time interval of 25 years from the last in-line inspection time was considered with numbers of inspections ranging from 1 to 10.

Considering imprecision in the failure pressure models, results in Fig. 6 show that the failure probability is lowest with the upper bound of imprecision in B31G model and highest with the lower bound of imprecision in Modified B31G model. Probability of failure increases with lesser numbers of inspections for a specified mission time but decreases with large numbers of inspections within the same mission time.

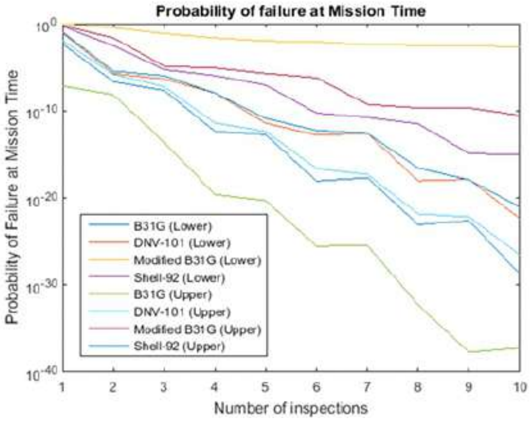


Figure 6: Pipeline probability of failure at mission time as a function of the number of inspections using Shell-92, B31G, Modified B31G and DNV-101 failure pressure models.

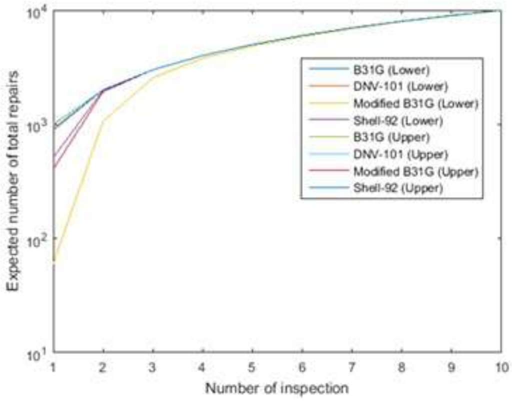


Figure 7: The expected number of total repairs as a function of the number of inspections using Shell-92, B31G, Modified B31G and DNV-101 failure pressure models.

The expected number of total repairs action is shown in Fig. 7. The lower bound of imprecision in Modified B31G model predicts the lowest number of repair actions and highest was in the lower bounds of imprecision in B31G, DNV-101 and upper bounds of imprecision in Shell-92, DNV-101, and B31G models. The increase in expected number of repairs with an increase in the inspection numbers signifies that increase in numbers of inspection increases the chances of failures to be detected, in addition to the possible damage to the system during each inspection thereby increasing the total cost of operation.

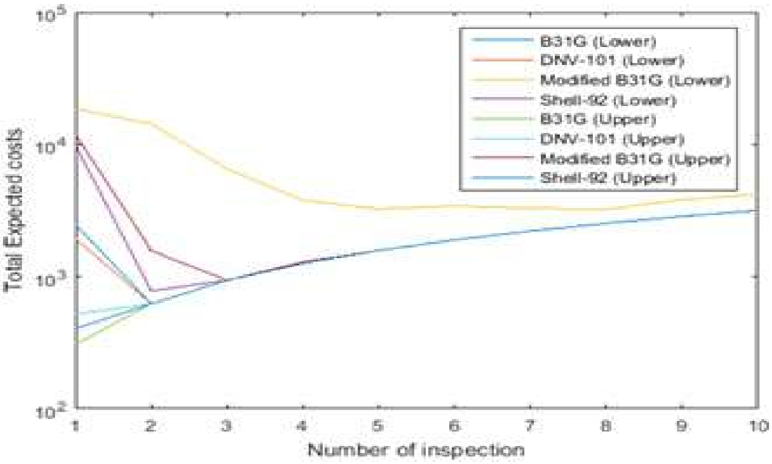


Figure 8: Pipeline expected costs as a function of the number of inspections using Shell-92, B31G, Modified B31G and DNV-101 failure pressure models.

The optimal inspection time is usually between when inspections are performed too early (e.g. for 10 inspections carried out in a mission time of 25 years, i.e. every 2.5 years an inspection is carried out), and when inspections are undertaken too late (e.g. for 1 inspection carried out in a mission time of 25 years, i.e. only one inspection in 25 years). Almost no damage will be found, and no repair will take place for early inspections resulting in marginal or no improvement in the pipeline reliability. While for too late inspections, in relation to the level of defect damage, the detection probability will be large. In this case, it is most likely that the pipeline system will have failed already.

In Fig. 8, the total expected costs as a function of the number of inspections with eventual repairs shows similar results for all the failure pressure models (particularly from 3 to 10 numbers of inspections), and only the lower bound in Modified B31G differs notably from the rest. It can be deduced here also that the optimal inspection time for both lower and upper bound of imprecision in all the failure pressure models is 3 inspections with eventual repairs (i.e. about 8 years), except for the lower bound in Modified B31G. Furthermore, the optimal solution is dependent on the number of inspections for different mission times.

Conclusion

In this work the importance of the model uncertainty on a proper characterisation of uncertainty has been shown. The proposed imprecise probabilities approach can be applied for the design of new systems as well as for assessing existing pipelines in operation, its inspection and repair for scheduling maintenance. It has been shown how this approach can improve the practise using B31G, Modified B31G, DNV-101 and Shell-92 failure pressure models.

In addition, an efficient numerical approach for robust optimal pipeline inspection time has been proposed. The procedure allows minimization of expenditures incurred when conducting maintenance activities, and at the same time keeping the pipeline in safe operation mode. The probabilistic framework presented is well suited for use to determine the optimal inspection interval and the repair strategy that would maintain adequate reliability throughout pipeline service life due to its simplicity, general applicability and singular reliability estimation for the whole optimization procedures.

References

Ahammed, M. (1998). Probabilistic estimation of remaining life of a pipeline in the presence of active corrosion defects. *International Journal of Pressure Vessels and Piping, 75*, 321-329.

Ahammed, M. and Melchers, R. E. (1997). Probabilistic analysis of underground pipelines subject to combined stresses and corrosion. *Engineering Structures, 12*, 988-994.

ASME. (1991). *Manual for determining the remaining strength of corroded pipelines. A supplement of ASME B31G code for pressure piping.* New York: ASME.

ASME. (1995). *Manual for determining the remaining strength of corroded pipelines. A supplement of ASME B31G code for pressure piping.* New York: ASME.

Au, S. K. and Beck, J. L. (2001). Estimation of small failure probabilities in high dimensions by subset simulation**.** . *Probab Eng Mech, 16*(4), 263-277.

Battelle Columbus Laboratories. (1982). The Economic Effects of Fracture in the United States, National Bureau of Standards, U.S. Department of Commerce, Gaithersburg, MD, Special Publication 647-2, 1983.

Bazan, F. A. V. and Beck, A. T. (2013). Stochastic process corrosion growth models for pipeline reliability. *Corrosion Science, 74*, 50-58.

Beer, M., Ferson, S. and Kreinovich, V. (2013). Imprecise probabilities in engineering analyses. *Mechanical Systems and Signal Processing, 37*, 4-29.

Bjornoy, O. H., Cramer, E. H. and Sigurdsson, G. (1997). Probabilistic calibrated design equation for burst strength assessment of corroded pipes. *The Seventh International Offshore and Polar Engineering Conference, Honolulu, USA, Vol. IV,* pp. 160-166.

Caleyo, F., Valor, A., Venegas, V., Hernandez, J. H. E., Velazquez, J. C. and Jose Manuel Hallen, J. M. (2012). Pipeline Integrity—1: Accurate corrosion modeling improves reliability estimations. . *Ogj, 10*.

Cosham, A., Hopkins, P. and Macdonald, K. A. (2007). Best practice for the assessment of defects in pipelines. *Corrosions Engineering Failure Analysis,* (14), 1245-1265.

de Angelis, M., Patelli, E. *and* Beer, M. (2015). Advanced line sampling for efficient robust reliability analysis *Structural Safety, 52*, 170-182.

DNV. (1999). *Corroded pipelines. Recommended practice RP-101, det norske veritas.* Elendom AS.: Det Norske Veritas.

Enevoldsen, I. *and* Sorensen, J. D. (1994). Reliability-based optimization in structural engineering. *Structural Safety, 15*, 169-196.

Fu, Y. *and* Yao, X. (2022). A review on manufacturing defects and their detection of fiber reinforced resin matrix composites, Composites Part C: Open Access 8 (2022) 100276.

Klever, F. J. *and* Stewart, G. (1995). New developments in burst strength predictions for locally corroded pipes. *Shell Int. Res.*

Leis, N. *and* Stephens, D. R. (1997). An alternative approach to assess the integrity of corroded line pipe. Part I current status and II alternative criterion. *Proceedings of the Seventh International Offshore and Polar Engineering Conference.* pp. 624-641.

Melchers, R. E. (1999). *Structural reliability analysis and prediction***.** (2nd ed.). West Sussex, England: John Wiley & Sons.

Nahal, M., Sahraoui, Y., Khelif, R. *and* Chateauneuf, A. (2023). System reliability of corroded pipelines considering spatial and stochastic dependency in irregular zones, *Gas Science and Engineering*, Volume 117, September 2023, 205083

Okolie, O., Latto, J., Faisal, N., Jamieson, H., Mukherji, A. and Njuguna, J. (2023). Manufacturing defects in thermoplastic composite pipes and their effect on the in-situ performance of thermoplastic composite pipes in oil and gas applications, Appl. Compos. Mater. 30 (1) (2023) 231–306.

Opeyemi, D. A., Patelli, E., Beer, M. *and* Timashev, S. A. (2015a). Reliability of arctic pipelines taking into account the global change of temperatures: Wind loads case study. *International Conference on Economic and Technical Aspects of Safety of Civil Engineering Critical Infrastructures. Yekaterinburg, Russia.*

Opeyemi, D. A., Patelli, E., Beer, M. *and* Timashev, S. A. (2015b). Reliability assessments and remaining life of pipelines subject to combined loadings using imprecise probabilities. Safety and reliability of complex engineered systems – Podofilini et al. (eds). Taylor & Francis Group, London, ISBN 978-1-138-02879-1, pp. 2789 – 2796.

Pandey, M. D. (1998). Probabilistic models for condition assessment of oil and gas pipelines. *NDT and E International, 31*, 349-358.

Patelli, E. (2016). COSSAN: A multidisciplinary software suite for uncertainty quantification and risk management**.** In R. Ghanem, D. Higdon & H. Owhadi (Eds.), *Handbook of uncertainty quantification* (pp. 1-69) Springer International Publishing.

Pradlwarter, H. J., Schueller, G. I., Koutsourelakis, P. S. *and* Charmpis, D. C. (2007). Application of line sampling simulation method to reliability benchmark problems. *Structural Safety, 29* (3), 208-221.

Qian, G., Niffenegger, M. *and* Li, S. (2011). Probabilistic analysis of pipelines with corrosion defects by using FITNET FFS procedure. *Corrosion Science, 53*, 855-861.

Race, J. M., Dawson, S. J., Stanley, L. M. *and* Kariyawasam, S. (2007). Development of a predictive model for pipeline external corrosion rates. *Journal of Pipeline Engineering, 6*(1), 15-29.

Spangler, M. G. *and* Handy, R. L. (1982). *Soil engineering.* (4th ed.), Harper & Row, New York.

Valdebenito, M. A. *and* Schueller, G. I. (2010). Design of maintenance schedules for fatigue-prone metallic components using reliability-based optimization. *Computer Methods in Applied Mechanics and Engineering, 199:* 2305-2318.

Valor, A., Caleyo, F., Hallen, J. M. *and* Velazquez, J. C. (2012). Reliability assessment. *Ogj, 10.*

Wang, B., Zhong, S., Lee, T.L., Fancey, K.S. and Mi, J. (2020). Non destructive testing and evaluation of composite materials/structures:Astate-of-the-artreview,Adv.Mech. Eng. 12 (4) 1687814020913761.