An efficient computational strategy for robust maintenance scheduling: Application to corroded pipelines

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ABSTRACT: The ability to predict correctly the future remaining life time of components is of paramount importance to improve the safety and reliability of systems and networks via an effective maintenance policy. However, simplifications and assumptions are usually adopted to compensate 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 and risk-based maintenance strategy. A novel efficient computational approach is proposed for identifying robust maintenance strategies. The optimal solution is obtained through only one reliability assessment based on Advanced Line Sampling and reusing the outcome of maintenance activities in a force Monte Carlo approach. The proposed methodology remove the huge computational cost of reliability-base optimization making the analysis of industrial size problem feasible. The applicability of the approach is demonstrated by identifying the optimal maintenance policy of buried pipelines and it is shown how this approach can improve the current industrial practice.

1 INTRODUCTION

One of the most important degradation/deterioration mechanisms that affect the long-term reliability and integrity of metallic pipelines is corrosion. Corrosion which leads to metal loss 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). The corrosion process is affected by large uncertainty making the assessment of pipelines a complex and challenging task (Bazán and Beck 2013, Qian et al. 2011). For instance, uncertainties are in relation to operational data variation, associated to the randomness of the environment, form imperfect measurements of pipeline geometry, in the material strength and from the ageing processes of the pipeline.

The remaining strength of a pipeline with corrosion defects can be assessed using one or all of the international design codes viz: B31G (AMSE 1991), B31Gmod (ASME 2012), Battelle (Leis and Stephens 1997a, Leis and Stephens 1997b), DNV-101 (AS 2015) and Shell-92 (Klever et al. 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. Sahraoui et al. (2013) proposed a Bayesian modelling to take into account imperfect inspection results while Li et al. (2017) suggested using Bayesian network and Markov process approach to develop an optimal maintenance strategy for corroded subsea pipelines.

However, the amount of data required to define unequivocally those distributions might not be available in practice, assumptions and simplifications are applied and often they cannot be justified completely. To solve this conflict, the use of imprecise probabilities (Beer and Ferson 2013, Beer and Patelli 2015) 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 paper therefore proposes the use of a novel reliability metric redefined within the framework of imprecise probabilities.

Another challenging task is the identification of optimal inspection interval time in order to reduce the overall costs of pipelines including cost of inspection, repair and failure. For instance, areas needing repairs must 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 (Gomes et al. 2013). Approximate methods, e.g. FORM may not be sufficiently accurate or applicable for large scale problems, and we have to resort to simulation based methods.

In this paper, a novel and efficient computational technique is proposed for the identification of a robust maintenance scheduling taking into account 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. In turn, the reliability analysis is performed using Advanced Line Sampling (de Angelis et al. 2015). This allows to estimate reliability bounds with only one simulation and, in addition, it efficiency is independent of the reliability level. 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 et al. 2018, Patelli 2016, Patelli et al. 2012) and freely available.

2 MODELLING CORRODED PIPELINE

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.

2.1 Failure criteria

The failure modes considered 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 are assessed using four international design codes: Shell-92, B31G, DNV-101 and Modified B31G models, respectively. The summary of all the failure pressure models is shown in Tables 1 and 2. In Table 1 W is the pipe wall thickness; L is the longitudinal length of defect; D is the outside diameter of pipe and M is the Folias' factor. In Table 2, F_p is the failure pressure and d represents the defect depth. σ_y and σ_u are the material yield stress and the ultimate tensile strength, respectively.

The assumption and limitation of these models are reflected on the individual flow stresses which

Table 1. Flow stess and Folias' factor according different international design codes.

Model	Flow stress	Folias' factor (M)
B31G	1.1 SMYS	$\sqrt{1+0.893\dfrac{L^2}{DW}}$
Modified B31G	SMYS + 68.95 MPa	$\sqrt{1+0.6275\dfrac{L^2}{DW}-0.003375\dfrac{L^4}{D^2W^2}}$ for $L \le \sqrt{50DW}$ $0.032*\dfrac{L^2}{DW}+3.3$ for $L > \sqrt{50DW}$
DNV-101	SMTS	$\sqrt{1+0.31\left(\dfrac{L}{DW}\right)^2}$
Shell-92	SMTS	$\sqrt{1+0.893\dfrac{L^2}{DW}}$

Table 2. Failure pressure of pipelines according different international design codes.

Model	Defect (area and shape)	Failure pressure expression (F_p)
B31G	2/3dL Parabolic	$1.11\dfrac{2\sigma_y W}{D}\left(\dfrac{1-\dfrac{2d}{3W}}{1-\dfrac{2d}{3W}M^{-1}}\right)$
Modified B31G	0.85dL Arbitrary	$\dfrac{2\left(\sigma_y+68.95\right)W}{D}\left(\dfrac{1-0.85\dfrac{d}{W}}{1-0.85\dfrac{d}{W}\cdot M^{-1}}\right)$
DNV-101	dL Rectangle	$\dfrac{2\sigma_u W}{D-t}\left(\dfrac{1-\dfrac{d}{W}}{1-\dfrac{d}{W}\cdot M^{-1}}\right)$
Shell-92	dL Rectangle	$\dfrac{1.8\sigma_u W}{D}\left(\dfrac{1-\dfrac{d}{W}}{1-\dfrac{d}{W}\cdot M^{-1}}\right)$

are the measure of the strength of steel in presence of a defect. Folias' factors, M, is the geometry correction factor to account for the stress concentration due to radial deflection of the pipe surrounding a defect. Failure is assumed to occur as a result 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. Further considerations and

assumptions on different shapes and areas of corrosion defect can also be made which might lead to different definition of failure critaria.

The failure criteria is defined as the difference between the failure pressure, F_p, of the pipeline and the maximum allowed operating pressure, ($MAOP$):

$$g = F_p - MAOP \qquad (1)$$

where g is the so-called limit state function.

The easiest way to estimate the reliability of pipelines is based on safety factors (also known as level I analysis) calculated using the capacity equations or codes presented in Table 2. Such analysis do not model explicitly the uncertainties that might have occurred and increased over the years of the pipeline service. The effects of the uncertainty are considered in terms of safety margins and factors. Worst-case scenario is used for loads and capacity of the structural system and in turn, this might leads to greater safety/reliability but also to huge costs associated with the overdesign or overmaintenance of pipelines.

Level II analysis based on partial safety factors includes the first and second moment of the parameter distributions. Partial safety factors take care of uncertainties for defect depth and failure pressure (burst) capacity. For instance, DNV-101 code uses analytical expression to derive the values of standard deviation of relative corrosion defect σ_{rd}, and the failure pressure.

In modern engineering systems and critical infrastructures to assure adequate level of safety and reliability an explicit quantification of the uncertainty must be performed. A full probabilistic approach (level III analysis) requires the evaluation of multidimensional integral shown in Eq. 2. The probability of failure, P_f, is defined as:

$$P_f = P\left(g \leq 0\right) = \int_{g(\theta) \leq 0} f\left(\boldsymbol{\theta}\right) d\boldsymbol{\theta} \qquad (2)$$

where $f\left(\boldsymbol{\theta}\right)$ represents the multivariate distribution function of the uncertainty vector $\boldsymbol{\theta}$. In realistic application a large number uncertainties need to be considered. Hence, analytical and approximate methods like FORM and SORM result to be inadequate for solving Eq. (2) (Valdebenito et al. 2010). Monte Carlo simulation methods are then required to evaluate the integral of Eq. (2). However, 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 (de Angelis, Patelli, & Beer

2015) and Subset simulations (Au & Patelli 2016) can be adopted for analysing complex real world problems.

2.2 Maintenance strategy

In order to understand the status of pipelines, different inspection tools can be used characterised by different quality and sensitivity. The inspection activities may assess the damage incorrectly or may not even detect any damage at all based on the quality and assiciated inspection costs.

The most common tools for metal loss and crack inspection are based on the Magnetic Flux Leakage or Ultrasonic techniques (Version 2009). Pigging data is gathered through in-line inspection activities using Magnetic Flux Leakage intelligent pig, whereby the values of parameters in the model is as a result 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 (Version 2009).

In this paper the probability of detection (PoD) associated with the non-destructive inspection techniques is modelled as (Pandey 1998):

$$PoD = 1 - \exp^{-qd} \qquad (3)$$

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

Following an inspection, if a defect is detected, it can be repaired or not. In fact, repairing a buried pipeline is an expensive process because it requires the excavation and the replacement of part of the pipeline. For this reason, the repair is perform immediately after an inspection only if the pipe defects produce a failure pressure safety factor lower than a prescribed threshold otherwise the pipe is left unrepaired. In this case a useful remain life is estimated and a preventive maintanance can be scheduled. The threshold level of the safety factor is between 1.25 and 1.5 (Pandey 1998). These values are in agreement with the level of integrity established by actual pipeline hydro testing, and corresponds with the repair factor for a class 2 pipeline in Canadian code (Association 2007).

3 MODELLING THE UNCERTAINTIES

A full probabilistic analysis requires the proper characterisation of the uncertainties. In other words, each variable is associated with a proper probabilistic distribution function. For instance, it is practice to describe the variability of measurements as a Gaussian process characterised by its mean and standard deviation. A proper estimation

of the characteristic of the distribution (or even the shape of the distribution itself) requires the availability of data. When the amount of data is not enoughfor unambiguous characterisation of the uncertainties, expert judgement and often unjustified assumptions. This is the case in many practical situations where very limited data are available. To avoid the inclusion of subjective hypothesis, the imprecision and vagueness of the data can be treated combining probabilistic and set theoretical components in a unified construct allowing the identification of bounds on probabilities for the events of interest in order to give a different prospective to the resultss (Beer and Patelli 2015).

For the treatment of imprecise knowledge, non-consistent information and both epistemic and aleatory uncertainty multiple mathematical concepts can be used including intervals (Augustin 2004), probability boxes (Ferson et al. 2003), normalized fuzzy sets (also known as possibility distributions) (Verma et al. 2007), Dempster-Shafer structures (Dempster 1967, Shafer 1976), Bayesian frameworks (Faber 2005) and Random Set theory. In particular, Random Set theory is a general framework suited to model uncertainty represented as cumulative distribution functions (CDFs), without making any implicit or explicit assumption at all. Explanatory examples of such flexible frameworks are provided in (Patelli et al. 2015, Rocchetta et al. 2018).

In this paper, the concept of probabilistic boxes (P-boxex) is used (Ferson, Kreinovich, Ginzburg, Myers, & Sentz 2003). P-boxes can be seen as a generalization of the Dempster-Shafer structures where the sets are represented by distributions. Hence, P-boxes are sets of Cumulative Distribution Functions (CDFs) for which lower and upper bounds are assigned $\left[\underline{F}_X, \overline{F}_X \right]$. The probability distribution associated to the random variable x can be either specified or not. The former are generally named distributional P-boxes, or parametric P-boxes, the latter are named distribution-free P-boxes, or non-parametric P-boxes. In literature the upper bound on probability is referred as plausibility and the lower bound as belief.

Distributional p-boxes appear when there is indetermination in the representations of the parameters of a given CDF. These parameters are imprecisely specified as intervals. For instance, consider a quantity that is known to be Gaussian with mean within the interval [1,2] and standard deviation somewhere in [3,4]. All CDFs that are normal and have means and standard deviations inside these respective intervals will belong to this probability box. The upper and lower CDF bounds $\underline{F}$ and $\overline{F}$ of the p-box enclose many non-normal distributions, but these would be excluded from the p-box by specifying the normal CDF as the *parental distribution family*.

The calculation of the bounds of the quantity of interest such as the probability of failure requires significant computational resources. This because it will be necessary to estimate the integral of Eq. (2) for all the possible probabilistic model considered and then identify the bounds of the response. Fortunately in many engineering applications the response of the model is monotonic with respect to the imprecision of the input parameters. In general, this allows to estimate the bounds of the probability of failure with only 2 full probabilistic analysis (Rocchetta et al. 2018). Advanced Line Sampling (de Angelis et al. 2015) method can further reduce the computational cost allowing the estimation of the bonds of the probability of failure with only 1 efficient probabilistic analysis (de Angelis et al. 2014).

4 ROBUST MAINTENANCE STRATEGY

Inspection and monitoring of pipelines is necessary in order 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. 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.

4.1 *Optimization problem*

In reliability-based optimization, the total expected costs in relation to maintenance and failure is the objective function that needs to be minimised, see e.g. (Beer et al. 2014). The time and number of the inspections represents the design variables of the optimization problem while the expected monetary costs associated with inspection, repair and failure form the objective function that can be formulated as:

$$\underset{N_I, q, t_i}{\arg\min} \quad E\left[C_T \left(N_I, q, t_i \right) \right] \tag{4}$$

where N_I, q, t_i and C_T denote the number of inspections, the qualities of inspections, the i-th time of inspection and the expected total cost, respectively. The expected total costs are defined as:

$$E\big[C_T\big(N_I,q,t_i\big)\big] = E\big[C_I\big(N_I,q,t_i\big)\big] \\ + E\big[C_R\big(N_I,q,t_i\big)\big] \qquad (5) \\ + E\big[C_F\big(N_I,q,t_i\big)\big]$$

where C_I, C_R and C_F are the 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, i.e.:

$$R(t) = 1 - P_f(t) \geq \beta \qquad \forall t \in \big[0, T_m\big] \qquad (6)$$

where $P_f(t)$ is the probability of failure at time t and T_m represents the so-called mission time. Hence, reliability based maintenance strategy requires the evaluation of the reliability over the time as summarised in Section 2.1. Constrained optimisation techniques are then adopted to identify the minimum of the objective function, Eq. (4), satisfying the constrain of Eq. (6).

4.2 *Inspection costs*

The expected inspection costs $E(C_I)$ are calculated as the product of the unit inspection cost, c_I, that depends on the quality of inspection q, corrected by the discount rate, r, and the probability that inspection will take place at time t_i: $1 - P_f(t_i)$. In other words, the pipeline has not to be failed before the i-th inspection time scheduled at t_i. This expected costs are expressed in mathematical form as:

$$E\big[C_I\big] = \sum_i \frac{c_I(q)}{\big(1+r\big)^{t_i}} \cdot \big(1 - P_f(t_i)\big) \qquad (7)$$

4.3 *Repair costs*

The evaluation of the expected costs associated with repair, $E\big[C_R\big]$, is quite challenging since depends on the probability of performing a repair after the i-th inspection, $P_R(t_i)$. This, in turn depends on the probability of detection (POD) (i.e. the probability to detect a defect). The expected repair costs are modelled as:

$$E\big[C_R\big] = \sum_{i=1}^{N_I} c_R P_R(t_i) \frac{1}{\big(1+r\big)^{t_i}} \qquad (8)$$

where c_R, is the unit cost of a repair. The probability of repair is calculated by computing the reliability analysis of the pipeline where the repair threshold represents the limit state function weighted by the probability to detect the crack, i.e.

$$P_R(t) = \int\limits_{1.25 \leq g(\boldsymbol{\theta},t) \leq 1.5} f(\boldsymbol{\theta}) \cdot PoD(d,t) d\boldsymbol{\theta} \qquad (9)$$

4.4 *Failure costs*

The total capitalized expected costs, $E[C_F]$, due to failure are the costs associated with failure over the region of the corresponding demand functions. Hence, the calculation of the failure costs requires the estimation of the probability of failure of the pipeline over the time. Teh computational strategy proposed in the next Section allows to estimate these costs by performing a single reliability analysis and the reusing the results in the optimisation loop.

The cost of failure at a specific inspection time is calculated as the cost of the failure of i-th time t_i (that is proportional to $P_F(t_i)$ minus the cost of failure at previous time t_{i-1}: $\propto P_F(t_{i-1})$. This allows to take into account the fact that the system has survived till the time t_{i-1}. Taking into account all the inspection times and the discount costs, the expected failure cost becomes:

$$E\big[C_F\big] = \sum_{i=1}^{N_I} c_F \frac{\big(P_f(t_i) - P_f(t_{i-1})\big)}{\big(1+r\big)^{t_i}} \qquad (10)$$

5 COMPUTATIONAL STRATEGY

5.1 *Reliability analysis*

The estimation of the probability of failure requires in general significant computation efforts. In particular for highly reliable pipelines, the number of model evaluations easily exceed the computational resources available. In addition, the presence of imprecision adds another level of complexity because the propagation of intervals and p-boxes requires the adoption of an additional optimization loop making the required computational cost quite challenge. For this reason, the Advanced Line Sampling (de Angelis et al. 2015) method is adopted to estimate the bounds of the probability of failure. One of the key feature of this approach is the ability to estimate different probabilities of failure (associated to different levels of the performance function) with only one analysis. For instance this can be used to estimate with only one reliability analysis the bounds of probability of failure due to imprecision in the inputs and the probability of repairs as well.

5.2 *Robust maintenance*

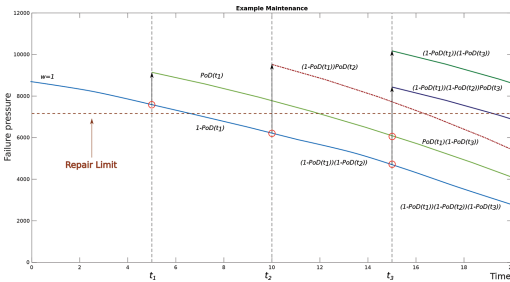The robust maintenance is computed adopting a novel computational strategy that allows to reuse

Figure 1. Effect of maintenance (repairs) on the weights associated with realisations of evolution on the time of the failure pressure.

the results of the reliability analysis in the optimisation problem.

In order to explain the simulation approach, we first consider a simplified model without imprecision and solved using plain Monte Carlo method. The idea is to first simulate the evolution of defects/cracks in pipelines without considering inspections and repairs. This is performed by sampling the parameters of the model and then solving the equations in Tables 1–2 till the time of interest. At this point we have a number of possible cracks evolution (or failure pressures) over the time. Then, we add the effect of maintenance and update the corresponding pipeline reliability as shown in Figure 1 by calculating the weights associated to each possible event outcome. The procedure is repeated for all the simulated cracks evolution. The computed weights are then used to calculate the probability of failure at time of interest. For instance, the probability of failure at time t_i is estimated by the summation of the weights associated to the failure events divide by the total numberof simulations.

Finally an optimisation tools is used to identify the number and time of inspections that minimise Eq. (4). When a new inspection time is proposed, it is necessary to recompute the weights starting from the original simulation but thisstep does not require the re-analysis of the model (i.e. evaluating the evolution of the crack/defect till the time of interest).

6 EXAMPLE APPLICATION

The optimal maintenance scheduling of a pipeline with characteristics shown in Table 4 is performed.

6.1 *Reliability analysis of pipelines*

First, the probability of failure of the pipeline as a function of time has been computed using the DNV-101, Shell-92, B31G and B31Gmod codes

without considering inspection and maintenence. The uncertainties are modelled as shown in Table 5. Different level of imprecision on the parameter vaules has also been condidered.

Advanced Line Sampling (de Angelis et al. 2015) is adopted to estimate the reliability of the pipelines with 20 lines resulting in 120 model evaluations. Advance Line Sampling is able to deal with imprecision in the parameter values and it allows to compute the bounds of the reliability. In addition, the number of model evaluations are independent of the reliability level. As expected, the probability of failure of the corroded pipeline increases with time as shown in Figure 2. The Figures shows lower and upper bounds of the probability of failure when 10% of imprecision is considered on the input variables. Shell-92 and the DNV-101 are the most conservative models followed by Modified B31G and the least conservative is the B31G model. than 0.6) respectively. This is in accordance with results from literature obtained without considering imprecision (see e.g. Caleyo et al. (2002)). The results of the analysis are also summarised in Table 3.

6.2 *Robust maintenance*

Maintenance is a very effective way to improve the safety of corroded pipelines. The aim of this section is to identify the optimal number of inspections that are able to minimise the overall costs. Maintenance is only performed is a defect is detected. The typical minimal detectable depth of a high resolution Magnetic Flux Leakage tool for uniform corrosion is 0.1 W with a *POD* of 0.9 (Version 2009). Using these values and the pipeline wall thickness $W = 9.52\ mm$, the quality of inspection can be estimated as $q = 2.42$ (from Eq. 3). However, if the length of the defect is $l < 30mm$ we have a pitting defect. In this case the quality of inspection is reduced to $q = 1.61$.
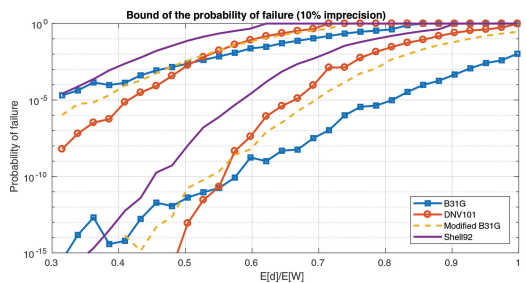

Figure 2. Lower and upper bounds of the probability of failure of a pipeline with 10% of imprecision on the variables using Shell-92, B31G, Modified B31G and DNV-101 failure pressure models.

In this example, it is assumed that the inspection time are equally spaced from the initial time till the final time of 50 years (mission time). Figure 3 shows the pipeline failure probability at mission time against the number of inspections for different models and parameter imprecision. From the results presented in the Figure 3, it can be deduced that using B31G model and 3 inspections suffice reducing the probability of failure of the pipeline below 10^{-6}. However, when the modified B31G model is used more than 6 inspections are required (using the upper bounds of the parameters). These results allows to identify the minimum number of inspections required to guarantee a prescribed level of safety. The very small probability of failure have been calculated adopting the approach presented in Section 5.

Figures 4 and 5, show the total expected cost as a function of the number of inspection obtained using DNV-101 model. Obviously, the costs of inspection increases with the number of inspections performed during the lifetime of the pipeline. Costs of failure decreased with the number of inspections. For very small number of inspections the total costs are governed by the costs associated with failure while for large number of inspections, the total maintenance costs are due to the costs associated with repairs. The optimal number of inspection is always a trade-off between costs of failure and costs of repairs. Using the DNF-
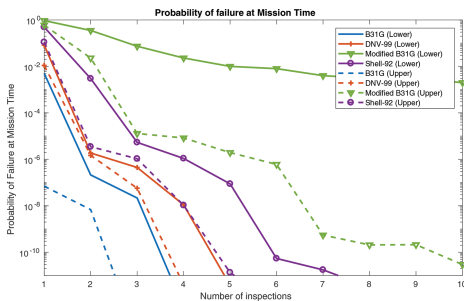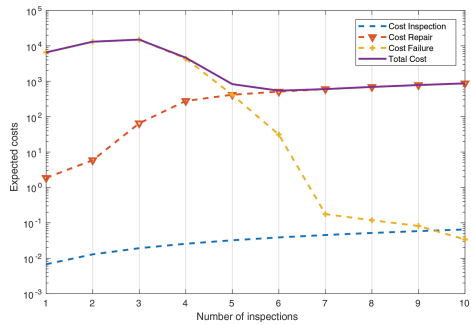

Figure 4. Expected total maintenance cost as a function of the number of inspection using the DNF-99 model, with a mission time of 50 year and upper bounds of imprecise parameters.
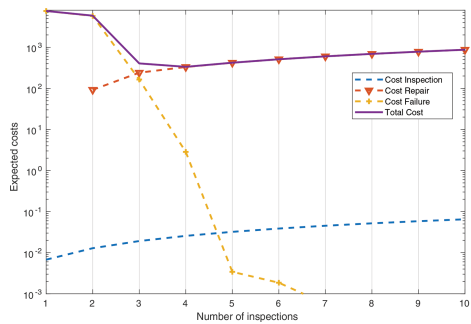

Figure 5. Expected total maintenance cost as a function of the number of inspection using the DNF-99 model, with a mission time of 50 year and lower bounds of imprecise parameters.

Table 4. Pipeline characteristics.

Parameter	
Transported substance	Crude oil
Pipe outlay	Below ground
Outside Diameter	609.6 mm
Material Class X52	SUTS 496 MPa, SMYS 358 MPa, MAOP 4.96 MPa.
Nominal wall thickness	9.52 mm

Figure 3. Probability of failure (at mission time) for a pipeline as a function of the number of inspections.

Table 3. Bounds of the relative corrosion defect for different safety levels with 10% imprecision on model parameters.

Safety level	B31G	DNV-101	Mod-B31G	Shell-92
10^{-3}	[0.4799, 0.9273]	[0.5035, 0.7389]	[0.4799, 0.7860]	[0.4093, 0.6683]
10^{-4}	[0.4093, 0.8566]	[0.4564, 0.7154]	[0.4328, 0.7389]	[0.3622, 0.6212]
10^{-5}	[0.3151, 0.8095]	[0.4328, 0.6683]	[0.3858, 0.7154]	[0.3151, 0.5977]
10^{-6}	[0.3151, 0.7625]	[0.4093, 0.6447]	[0.3151, 0.6683]	[0.3151, 0.5741]
10^{-7}	[0.3151, 0.7154]	[0.3622, 0.6212]	[0.3151, 0.6212]	[0.3151, 0.5270]

Table 5. Stochastic model used for the corroded pipeline and monetary unit cost for operation (i.e. multiplicative factors).

Parameter	Symbol & unit	Distribution	Mean	CoV	Parameter	Symbol	Value
Diameter	$D\,[mm]$	Normal	609.6	0.02	Inspection cost	c_I	0.018
Defect depth	$d\,[mm]$	Normal	3	0.10	Repairs cost	c_R	0.243
Wall thickness	$W\,[mm]$	Normal	9.52	0.02	Failure cost	c_F	36.55
Ultimate Tensile Strength	$\sigma_i\,[MPa]$	Log-Normal	496	0.07	Discount Rate	r	0.05
Pipe Yield Stress	$\sigma_y\,[MPa]$	Normal	358	0.07			
Defect length	$l\,[mm]$	Normal	200	0.1			
Operating Pressure	$Op\,[Mpa]$	Log-Normal	4.96	0.10			
Radial corrosion rate	$vd\,[mm/yr]$	Log-Normal	0.5	0.10			
Long. Corrosion rate	$vl\,[mm/yr]$	Log-Normal	0.5	0.10			

99 model the optimal number of inspections is between 4 an 6.

7 CONCLUSIONS

In this paper, an efficient numerical approach for robust optimal pipeline inspection time scheduling has been proposed. This allows to determine the optimal inspection interval and the repair strategy that would maintain adequate reliability throughout pipeline service life. The computational framework allows to take into account the uncertainties of the model and imprecisions on the knowledge of model parameters. The proposed approach is efficient since allows to perform reliability based optimisation with only one reliability analysis.

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