XLIII
CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

# Optimal maintenance planning in pipelines with corrosion defects considering different types of steel.

Paulo Virginio da Silva Neto[1], Paulo Fernando Silva Sousa[2], Alamo DiTarso Sousa Pessoa[2], Savanna Cristina Medeiros D'aguiar[2], Silvana Maria Bastos Afonso Da Silva[2]

[1]*Dept. of Mechanical Engineering, Federal University of Pernambuco*
*Av. Prof. Moraes Rego, 1235 - Cidade Universitária, 50670-901, Recife - PE, Brazil.*
[2]*Dept. of Civil Engineering, Federal University of Pernambuco*
*Av. Prof. Moraes Rego, 1235 - Cidade Universitária, 50670-901, Recife - PE, Brazil.*
*paulo.virginio@ufpe.br, paulo.silvasousa@ufpe.br, alamo.pessoa@ufpe.br, savanna.cristina@ufpe.br, silvana.bastos@ufpe.br*

**Abstract.** Recent studies indicate that most of the world's fuel is composed of oil and gas, being transported by pipelines. In this scenario, corrosion is considered one of the main problems that affect the integrity of these elements, in which the risks associated with failures can have human, environmental and financial repercussions. Thus, planning its maintenance is essential to control the risk of failures and prevent accidents. In this context, the present work aims to evaluate the influence of the types of steel, considering different expressions for the calculation of the pressure of failure, in the cost and probability of failure of the optimal timeline for different numbers of inspections, not being restricted to the approach of fixed intervals. More than one failure mode is considered, the 'interior-point' algorithm is used in the optimization and the reliability analysis is performed with Monte Carlo simulations, commonly used in the literature. To determine the starting point of the optimization, the objective function is calculated on a sample constructed using the Latin Hypercube - LHS technique. Preliminary results shows that different types of steel have a significant effect on optimal costs and probability of failure for different numbers of inspections.

**Keywords:** corroded pipelines, maintenance planning, types of steel, reliability analysis, cost analysis.

## 1 Introduction

Maintenance planning in pipelines with defects caused by corrosion is very relevant, since the risks associated with pipeline failures are evident. In this context, the calculation of burst pressure is fundamental, and it is usually done through empirical calculation methodologies, as shown by Amaya et al. [1]. This work discusses several empirical methods for failure assessment, recommending the applicability of each one as a function of the degree of toughness of the steel.

In addition, recent works have used reliability analysis to define optimal maintenance planning for corroded pipelines, since from the design variables and their uncertainties it is possible to obtain the maintenance timeline that minimizes the operational costs of managing a pipeline (failure, inspection, repairs, etc.), as described in Liu et al. [2] and Liu et al. [3].

Thereby, the present work intends to develop the application of optimal maintenance planning, combining the methodologies described in Amaya et al. [1], with the empirical expressions available in Sousa et al. [4] and Sousa et. al [5] for consideration in different failure modes, as described by Gomes et al. [6].

## 2 Proposed methodology

Regarding material toughness, the standard API 5L [7] classifies pipelines based on their mechanical properties in order to ensure operational and environmental safety, regulating the production and proper use of pipelines transporting oil and natural gas.

The grades covered by the standard are based on the minimum yield stress and the defect shape idealization scheme. In the present work, the defects are idealized as rectangular, elliptical or mixed areas, depending on the applied methodology. Table 1 describes the shape of the defect and the degree of tenacity adopted for each methodology used, as indicated by Amaya et al. [1].

It should be noted that there are other methodologies that are indicated depending on the type of steel. The choice considered here is based on methodologies that depend on similar factors such as the diameter and thickness of the pipeline wall, length and depth of the defect, yield stress of steel, ultimate stress, among others.

Table 1. Defect form and material restriction. Adapted from Amaya et al. [1]

| Methodology | Defect Form | Material Restriction - Tenacity |
|---|---|---|
| ModB31G | Mixed | Low to moderate (below X65) |
| DNV | Rectangular | Excluding high tenacity tubes (all but above X80) |
| PCORRC | Elliptic | Moderate to high (X65 to X80) |
| ZHU | Rectangular | Moderate to high (X65 to X80) |
| CHOI | Elliptic | High (bigger than X65) |
| MA | Elliptic | Excluding low tenacity tubes (all but below X52) |

Another determining factor for the overall pipeline timeline is its costs. The calculations of these costs are based on eq.(1), adapted from Sousa et al. [4], where $C_{REF}$ is the total cost of installing the pipeline, $C_{INSP}$ is the cost of carrying out an inspection of the pipeline, $C_{REP}$ is the cost of each necessary repair (by failure or failure criteria), $C_{SMALL}$ and $C_{BURST}$, referring to the costs associated with the small leak and burst failure mode, respectively. The sum of all these costs results in the $C_{ET}$ (eq.1), which represents the total cost during a life cycle.

$$C_{ET} = C_{REF} + N_{INSP}.C_{INSP} + EnR.C_{REP} + EnF1.C_{SMALL} + EnF2.C_{BURST}. \tag{1}$$

In Equation (1), the $N_{INSP}$ factor represents the number of inspections, EnR the expected number of repairs and EnF the expected number of failures. While the number of inspections and their inspection times are deterministic values, defined by the engineers, the expected number of repairs and the expected number of failures are directly linked and are calculated according to the methodology of Sousa et al. [4].

Inspection, repair and failure costs are obtained from a cost factor multiplied by the reference cost $C_{REF}$. The values of the cost factors associated with these costs are shown in Table 2.

Table 2. Cost factor and its values. Adapted from Sousa et al. [4]

| Event | Cost Factor | Value |
|---|---|---|
| Inspection | $C_{INSP}$ | 0.0177 |
| Repair | $C_{REP}$ | 0.243 |
| Failure | $C_{SMALL}$ | 0.243 |
|  | $C_{BURST}$ | 25.0 |

A non-linear reliability constraint is imposed, according to the methodology of Mishra et al. [8]. The restriction for the probability of failure adopted was 0.001 as described in Sousa et al. [4].

With the previous definitions well structured, the optimization is solved with a combination of scripts in Matlab [9] language, using interior-point algorithm. To determine the starting point of the optimization, samples were generated with the LHS method, described in McKay et al. [10], and from these samples the starting point was chosen as the one with the lowest cost. In addition, the number of samples for Monte Carlo was used within a size equal to $10^4$.

# 3 Results

The analyzes are carried out for the number of inspections varying from 1 to 4, obtaining the values of optimized costs, failure probability and optimal maintenance timeline, considering only the burst failure mode, in a first case, and small leak, large leak and rupture in a second study. The geometric data of the pipeline and the defect were the same used by Sousa et al. [4], highlighting the pipeline's 30-year lifespan. Thus, the results obtained, taking as a reference the probability of failure and costs, can be seen in Fig. 1.

In this presentation of results, the B31Gmod and DBV methodologies, in blue, represent the low tenacity pipelines, while PCORRC and ZHU, in red, symbolize the moderate tenacity pipelines and, finally, CHOI and MA, in black, refer to high tenacity ducts.

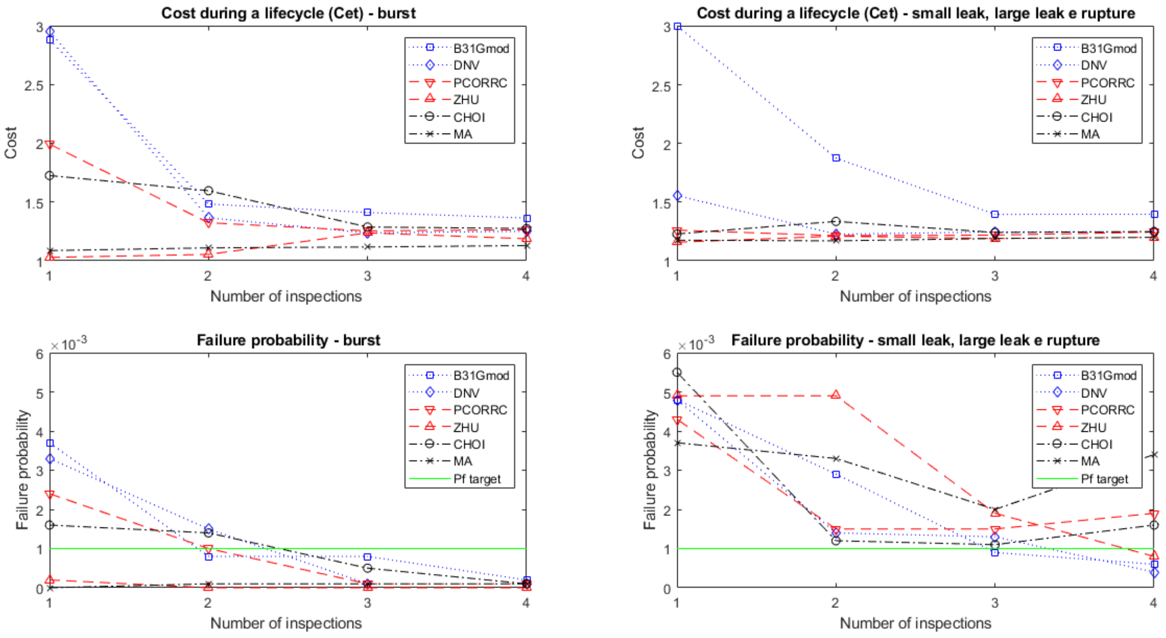

Figure 1. Costs and failure probabilities considering small leak, large leak, rupture and only burst

When analyzing the failure probabilities, it can be seen that changing the failure mode significantly changes its value. Considering only the burst failure mode, it can be seen that with 4 inspections all methodologies converge to a value between 0 and 2e-4, showing that with this number of inspections the probability of failure is relatively low, regardless of the type of steel. It is noticed that when doing 3 and 4 inspections, the difference between the costs, when considering different failure modes, is not significant. Added to this, it is verified that, for the DNV, PCORRC and CHOI methods, considering different failure modes in the analysis reflects in a cost reduction, mainly for the DNV and PCORRC methods.

When analyzing only failure mode burst, it can be seen that ZHU and MA satisfy the failure probability conditions for all inspections, while B31Gmod and PCORRC can only satisfy this condition with 2 inspections. The other cases, after 3 inspections, already fall within the established limit.

In addition, when considering small leak, large leak and rupture, no methodology adopted presented viable results for 1 and 2 inspections. It is noticed that between 2 and 3 inspections, PCORRC, DNV and CHOI, maintain a constant, but not acceptable, failure probability.

Still considering the failure modes, small leak, large leak and rupture, we have B31Gmod, satisfying the constraint only when considering 3 inspections. Cith 4 inspections, both methods adopted for low tenacity (B31Gmod and DNV) and the ZHU methodology (moderate tenacity) satisfying the constraint. The other methodologies do not present viable results even if the number of inspections is increased.

Subsequently, the optimal maintenance timeline is obtained for the burst, small leak, large leak and rupture defects, considering up to 4 inspections, as can be seen in Fig. 2 and Fig. 3.

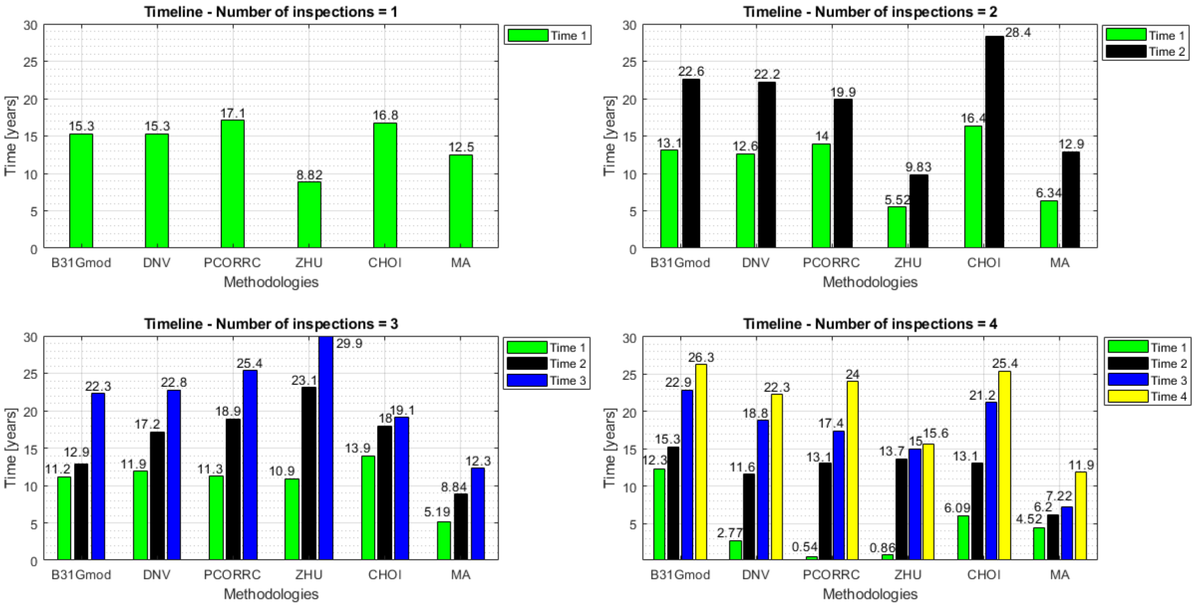

Figure 2. Maintenance timeline considering only burst

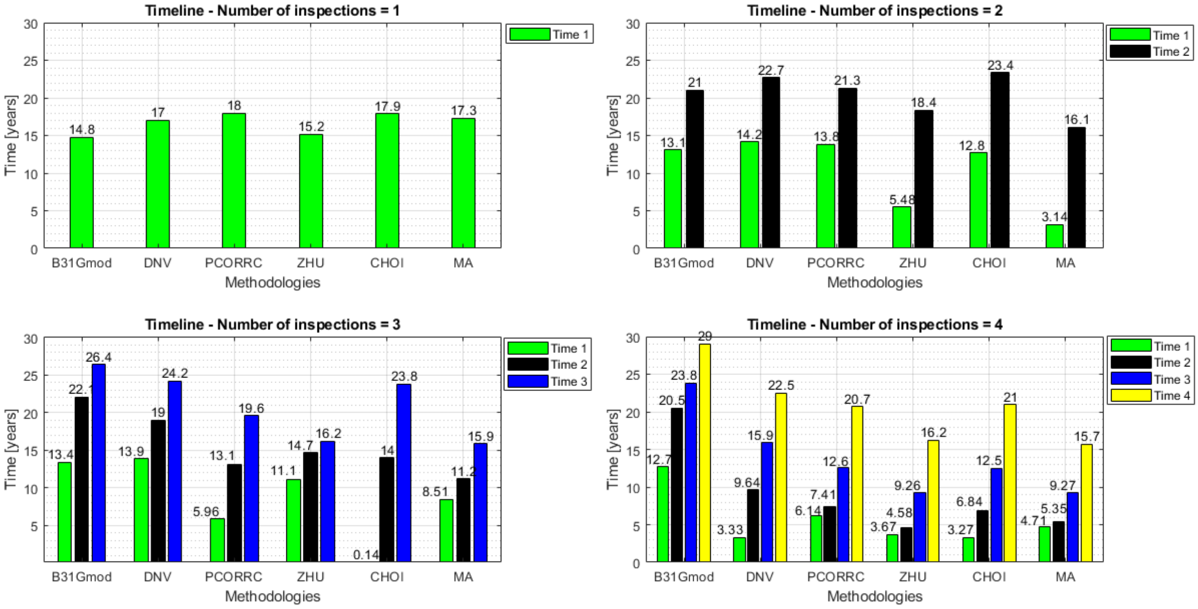

Figure 3. Maintenance timeline considering small leak, large leak and rupture.

In general, it is observed that the B31Gmod method tends to perform the first inspection with more than 10 years of useful life, regardless of the number of inspections and failure modes considered, and this method defines the times for the highest maintenance timeline when considering 4 inspections. The other methods are more sensitive to imposed variations.

When analyzing only burst, the methods for moderate tenacity (PCORRC and ZHU), with 4 inspections, present a first inspection with less than 1 year, a fact that is only repeated in CHOI with 3 inspections considering small leak, large leak and rupture.

With 4 inspections and burst only, all methodologies, except MA, predict the second inspection above 10 years, considering the other failures, both the first and second inspections occur below 10 years, with the exception of B31Gmod.

It was noted that the different methods are in fact predicting significantly different timelines, regardless of the indication according to the type of steel. Considering only burst, the methodologies for low tenacity (B31Gmod and DNV), up to 3 inspections, provide similar timelines, which changes with the increase in inspections. Another important factor is that only the ZHU (Ninsp = 3 and burst only) and B31Gmod (Ninsp = 4 considering small leak, large leak and rupture) methodologies provide timelines with final maintenance close to the pipeline's useful life.

## 4 Conclusions

This paper evaluated the influence of steel types on the maintenance cost and probability of failure of the optimal timeline for different numbers of inspections, considering six different methodologies, two for each type of toughness.

It is concluded that, although doing 3 and 4 inspections does not result in significant differences between the costs, this increase in the number of inspections has a considerable impact on the probability of failure. In this same analysis, even with the different failure modes, the costs remain in similar value, with a range of 1.13 from 1.40.

When analyzing the failure probability, considering only the burst failure mode, it appears that as the number of inspections increases, the failure probability tends to zero, regardless of the type of steel. However, when considering more than one failure mode (small leak, large leak and rupture) there is an increase in the probability of failure, especially when performing only 1 inspection.

As far as timelines are concerned, it was observed that the different methods are actually predicting significantly different timelines, regardless of the toughness of the steel. However, some methodologies provide similar timelines depending on the number of inspections.

**Acknowledgements.** The financial support for this research, provided by FACEPE, Grant Program IBPG-1295-3.01/20, IBPG-1303-3.01/20, IBPG-0959-3.01/17, is acknowledged, as well as CAPES and CNPq, through process 309727/2017-0. ID 210316895, for the financial support of various research projects developed in this area by the PADMEC Research Group.

**Authorship statement.** The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

## References

[1] - Amaya-Gómez, R.A.; Sánchez-Silva, M.; Bastidas-Arteada, E.; Schoefs, F.; Muñoz, F. Reliability assessments of corroded pipelines based on internal pressure – a review. Engineering Failure Analysis, vol.98, p.190-214, 2019.
[2] - Liu, X.; Zheng, J.; Fu, J.; Ji, J.; Chen, G. Multi-level optimization of maintenance plan for natural gas pipeline systems subject to external corrosion. Journal of Natural Gas Science and Engineering, vol.50, p.64-73, 2018.
[3] - Liu, X.; Zheng, J.; Fu, J.; Nie, Z.; Chen, G. Optimal inspection planning of corroded pipelines using BN and GA. Journal of Petroleum Science and Engineering, vol.163, p.546-555, 2018.
[4] - Sousa, P.F.S.; Afonso, S.M.B.; Willmersdorf, R.B. Multi-level strategy in optimal maintenance planning for corroded pipelines. In: Proceedings of the Rio Oil & Gas Expo and Conference 2020, Rio de Janeiro, RJ, pp. 1 – 10, 2020.
[5] - Sousa, P.F.S.; Afonso, S.M.B.; Willmersdorf, R.B. Reliability based preventive maintenance for corroded pipelines. In: Proceedings of the XL Ibero-Latin American Congress on Computational Methods in Engineering, Natal, RN, pp. 1 – 16, 2019.
[6] - Gomes, W.J.S.; Beck, A.T.; Haukaas, T. Optimal inspection planning for onshore pipelines subject to external corrosion. Reliability Engineering and System Safety, vol.118, p.18-27, 2013
[7] - American petroleum institute. API Specification 5L: Specification for Line Pipe, 2013.
[8] - Mishra, M.; Keshavarzzadeh, V.; Noshadravan, A. Reliability-based lifecycle management for corroding pipelines. Structural Safety, vol.76, p.1-14, 2019.
[9] - The mathworks, INC. Matlab and Statistics Toolbox Release 2016b. Natick, Massachusetts, United States, 2016.
[10] - Mckay, M. D.; Beckman, R. J.; Conover, W. J. A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code Technometrics, v. 21, n. 2, p. 239-245, 1979.