Effect of repair factors on multi-level optimization of maintenance planning for corroded pipelines considering different failure modes

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Abstract. This paper explores the impact of repair factors on the costs of optimized inspection schedules, considering both single failure mode and combinations of modes (small leak and burst). Using validated methodologies and Monte Carlo simulations for reliability analysis, it finds that the type of failure mode significantly influences total costs.

Keywords: Pipelines, Maintenance Planning, Corrosion.

1 Introduction

The use of pipelines for fluid transportation is crucial and has seen substantial growth in the oil and gas industry. While pipelines are among the safest methods for transporting these materials, it is essential to account for the risks of failures in their design, as such events can significantly harm the population, environment, and infrastructure. Consequently, the aging consequences of pipeline networks has been extensively studied, with corrosion being a major concern regarding structural integrity.

In this context, inspection and maintenance planning research has proven to be highly relevant. Effective pipeline integrity management can reduce costs and maintain safety levels throughout the pipeline's lifespan. Recent studies [1-4] have used reliability analysis with Monte Carlo simulations to develop optimal maintenance plans for corroded pipelines, aiming to minimize operational costs related to pipeline management (failures, inspections, repairs, etc.).

This paper integrates methodologies proposed by Sousa et al. [1], Pessoa et al. [2] and D'Aguiar et al. [3] to assess the influence of a) the fraction of the pipeline's wall necessary for repair post-inspection (Repair Factor 1 - f_{rep1}) and b) the multiplicative factor of the pipeline's internal pressure for repair post-inspection (Repair Factor 2 - f_{rep2}) on the optimized schedule's total cost. Two cases are assessed: one where only small leak failure is taken into account (Case 1) and another one where only burst failure is considered (Case 2).

2 Problem description

In this research, corrosion is treated as a single idealized defect on the outer surface of the pipe. This defect is characterized by two variables: longitudinal length $L(t)$ and depth $d(t)$. Both variables follow a random linear growth corrosion model, as described in Equations 1 and 2 [1-4].

$$d(t) = d_0 + R_d \times t \tag{1}$$

$$L(t) = L_0 + R_L \times t \tag{2}$$

where $d(t)$ and $L(t)$ denote the defect's depth and length over time (t) in millimeters; d_0 and L_0 are the initial defect depth and length in millimeters; R_d and R_L are the annual growth rates of the defect's depth and length in millimeters per year.

The statistical parameters presented in Table 1 used in this study were adapted from Bazán and Beck [4].

Table 1 - Growth model: variables, statistics, and distribution.

Variable	Mean	COV	Distribution
d_0 (mm)	2,64	0,83	Normal
R_d (mm/year)	0,082	0,65	Gamma
L_0 (mm)	90	-	Deterministic
R_l (mm/year)	0	-	Deterministic
t_0 (year)	2,88	-	Deterministic

2.1 Failure probability

According to Mishra et al. [5], limit state equations for failure modes are crucial for evaluating pipeline reliability as corrosion reduces structural strength. The failure probability $Pf(t)$ is calculated, accounting for uncertainties in all related variables. Corrosion failures can manifest as small leaks, large leaks, or ruptures. Small leaks occur when corrosion penetrates the pipeline wall, while burst result from plastic collapse due to local strength reduction.

The limit state equation for a small leak is determined by the maximum defect depth ($d_{max}(t)$) and the pipeline wall thickness (w_t), as illustrated in Equation 3 [6].

$$g_1(t) = 0.8 \times w_t - d_{max} \tag{3}$$

The limit state of the burst failure is described according to Equation 4. This failure mode occurs when the internal pressure (P_0) exceeds the burst pressure (r_b) before the defect penetrates the pipeline wall [7].

$$g_2(t) = r_b(t) - P_0 \tag{4}$$

The burst pressure (r_b) is obtained here from the empirical method PCORRC developed by Leis and Stephens [8], shown in Equation 5.

$$r_b(t) = \frac{2\times\sigma_u\times w_t}{D}\left[1-\frac{d_{max}(t)}{w_t}\times\left(1-exp\left(-\frac{0.157\times L(t)}{\sqrt{0.5\times D\times(w_t-d_{max}(t))}}\right)\right)\right] \tag{5}$$

where σ_u is the ultimate material stress of the pipeline in MPa; w_t is the wall thickness of the pipe, in mm; D is the pipeline diameter in mm, and L is the defect length in the longitudinal direction of the pipe in mm.

2.2 Description of optimization problem

The inspection schedule for pipeline maintenance planning includes the number of inspections and the intervals between them. The total cost (C_{ET}) of the inspection schedule consists of inspection costs (C_{insp}), failure costs (C_{small} and C_{burst}), and repair costs (C_{rep}). The objective is to minimize the total cost (C_{ET}), as defined by Equation 6, with x representing the design variable, which is the vector containing the inspection times for a specified number of inspections.

$$\begin{gathered}\text{Minimize: } C_{ET}(x) \\ \text{where: } x = [t_1, t_2, \dots t_n] \\ \textit{subject to:} P_{f,max} \leq P_{f,target} \\ t_1 < t_2 < \dots < t_n\end{gathered} \tag{6}$$

As mentioned, the total cost over the pipeline's lifecycle is obtained by summing the inspection, repair, and failure costs according to Equation 7.

$$C_{ET} = C_{ref} + N_{insp} \times C_{insp} + EnR \times C_{rep} + EnF1 \times C_{small} + EnF2 \times C_{burst} + \cdots \tag{7}$$

where N_{insp}, EnR, $EnF1$ and $EnF2$ correspond to the number of inspections, number of repairs, number of small leak failures and number of burst failures, respectively.

The inspection, repair, and failure costs are determined by multiplying a factor (f_i) by the unit of the reference cost (C_{ref}). ([7]).

The inspection, failure, and repair costs are based on Zhou and Nessim [9]. For the burst scenario, the factor considers various elements, including defects per kilometer, the number of injuries, and the population density in the pipeline's region, among others. For small leaks, only the costs of excavation and repair are considered. The values of these multiplicative factors are shown in Table 2.

Table 2 – Cost factor

Event	*Cost factor*	*Value*
Inspection	C_{insp}	*0.0177*
Repair	C_{rep}	*0.243*
Failure	C_{small}	*0.243*
	C_{burst}	*25*

According to the methodology, a repair is necessary either in the event of a failure or when certain conditions, verified during each inspection, are met. This approach, used by Gomes et al. [7], Liu et al. [6], and Sousa et al. [1], is based on the methodology proposed by Zhou and Nassim [9]. These conditions are expressed in the following equations:

$$d(t) \geq f_{rep1} \times w_t \tag{8}$$

$$f_{rep2} \times P_{int} \geq r_b(t) \tag{9}$$

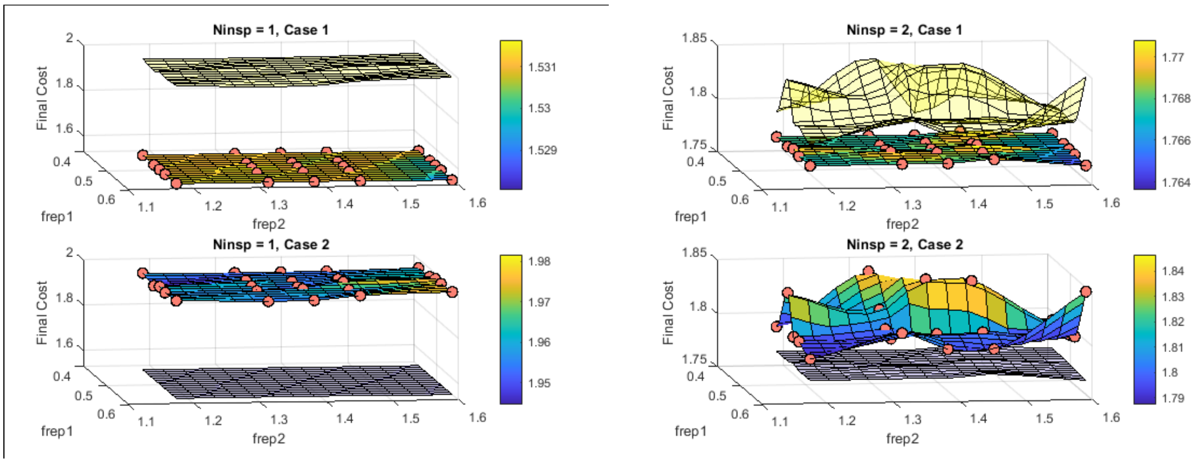
where w_t is the wall thickness of the pipe, in mm; $d(t)$ is the depth of the corrosion defect at a given instant in time, in mm; P_{int} is the internal pressure, in MPa; $r_b(t)$ is the burst pressure at a given instant in time, in MPa. The factors f_{rep1} and f_{rep2} characterize the limit state equations for inspection [1-4].

2.3 Reliability analysis

Reliability analysis is performed by calculating the failure probability over the pipeline's lifespan ($T = 50\, years$), using a time interval of $d_t = 0.125$ years, a typical value from literature [1,2,3]. Furthermore, the expected numbers of repairs and failures are determined through Monte Carlo simulation with $N = 10^6$ samples for the optimization process and $N = 10^5$ for the initial schedule.

3 Case study

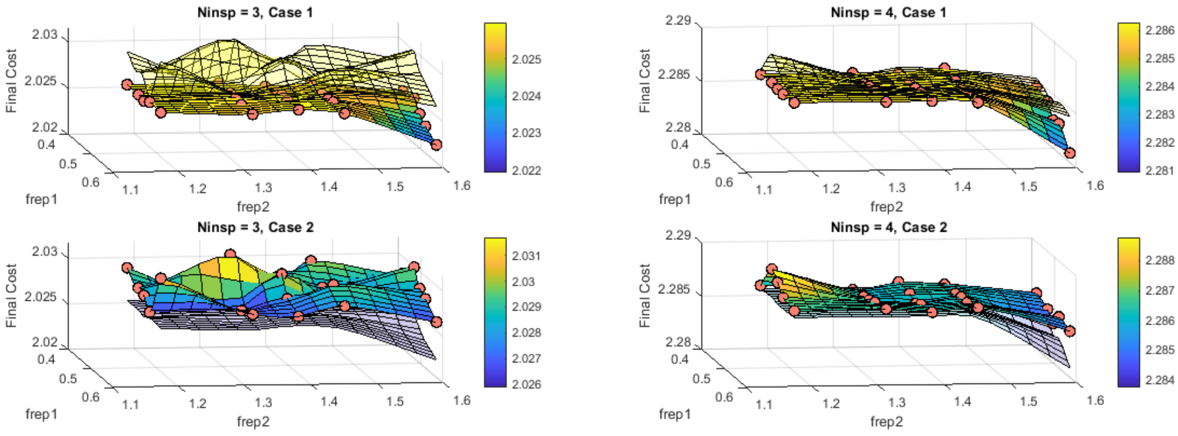
This study evaluates the impact of two failure modes acting separated (either small leak- Case 1 or burst-Case2) on the optimal schedule's final cost when considering different values for repair factors (f_{rep1} and f_{rep2}). The surfaces below show the final cost as a function of repair factors. The analyses are performed for the range of 1 to 4 inspections.



(a) 1 inspection

(b) 2 inspections

Figure 1. Final cost for 1 and 2 inspections.



(a) 3 inspections

(b) 4 inspections

Figure 2. Final cost for 3 and 4 inspections.

The surfaces shown in Figure 2 converge as the number of inspections increases, i.e., the final cost of the optimal schedule becomes increasingly independent of the failure mode considered. The increase in the number of inspections result in fewer failures. Therefore, there is a predominance of costs associated with inspections and their repairs.

In addition, Figure 2 shows a more significant variation in the final cost for Case 2 (Burst Only), especially when considering 2 and 3 inspections throughout the useful life. A possible explanation for this behavior is the non-linear nature of the expression for calculating the burst pressure (Equation 5).

4 Final remarks

This study examined the impact of repair factors on the cost of inspection schedules for pipelines, considering two failure modes. The results show that as the number of inspections increases, the final cost becomes less dependent on the failure mode. Furthermore, in the scenario where only the burst is considered (Case 2), the final cost showed more significant variation depending on repair factors.

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