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Enhancing pipeline system resilience: a reliability-centric approach

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ABSTRACT

Pipelines are the most widely used system for transporting liquid and gaseous energy materials, but throughout their lifespan, they are exposed to various detrimental factors, such as corrosion and deviations in process variables. In recent years, the concept of resilience has gained significant attention as a means to analyze infrastructure behavior during failure states. This study introduces a novel metric for assessing pipeline resilience based on reliability. The proposed method involves an aging study of pipelines, considering the interaction of potential failures—such as corrosion, pressure variations, temperature fluctuations, and changes in fluid velocity—and subsequently analyzes ways to restore the system to its original conditions. The method offers an assessment approach for the three phases that constitute a resilience curve: absorption, adaptation, and restoration. This approach not only identifies the system's time to failure, but also through analysis of the resilience curve, facilitates the comparison of the effects of potential preventive, mitigative, and repair actions. A case study is presented to validate the method's efficacy. The results suggest that the proposed approach could be a valuable tool in the decision-making process within the asset integrity management (AIM) framework, aiming to optimize pipeline resilience by implementing the most effective safety solutions.

1. Introduction

Pipelines are the most widely used system for the transportation of liquid and gaseous energy materials. The oil and gas pipeline network is spread all over the world and nowadays, millions of kilometres of transportation pipelines extend across the globe (Kiefner et al., 2012). Pipelines have an extended lifetime of over 30 years, and during this timeframe they are subjected to many different detrimental factors, from both internal and external environment. The most common factors are corrosion, weather conditions and process variables deviations (Vishnuvardhan et al., 2023). These factors may lead to a decrease of the initial performance level or ultimately to pipeline failures, such as leakages, ruptures and pipeline bursts. The adoption of defects identification strategies and the introduction of safety measures became relevant in the asset integrity management (AIM) field, in order to find the best way to reduce losses and minimize failure consequences. In recent years, resilience concept spread all over the AIM field, focusing on the system's response behaviour after disturbances (Yang et al., 2023a).

Current research aims to create a measurable way of quantifying resilience. This process of quantification depends on a specific goal-based on the objective particular performance measure is selected (structural properties, economic effects, etc.) (Okoro et al., 2022). Various metrics and models have been defined in literature (Cheng et al., 2022; Hosseini et al., 2016). In general, most resilience metrics are based on system's performance and in terms of pipelines, performance belongs to pipeline's "availability" (Cheng et al., 2022; Poulin and Kane, 2021). System's performance have been defined variously, however it mainly rely on a set of data, which is affected by gaps in knowledge and information (Yang et al., 2023b). Most recent research is based on deterministic and/or probabilistic approach to quantify resilience (Yazdi et al., 2022; Yang et al., 2023c), but only few studies focus on risk-based models, which is more significant in terms of pipelines AIM (Yang et al., 2023b; Khan et al., 2016; Khan et al., 2021). Various attempts are available in literature, Abubakirov et al. (2020) use dynamic bayesian network (DBN) models to assess the optimal inspection interval of a buried pipeline, while Yang et al. (2023b) propose a framework for resilience quantitative assessment. Many of the present models adopt a static perspective or focus solely on resilience against unforeseen deviations in process variables from design conditions (due to external factors or changes in operating conditions, affecting pressure P,

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temperature T and flow rate Q), with only minimal efforts directed towards considering other critical factors, such as corrosion. Interacting hazards are less considered, leading to a decrease in system's performance over time and, consequently, affecting risk assessment integrity (Khan et al., 2021). This has led to significant gaps in developing a comprehensive model of pipeline resilience, which needs to be addressed:

1) Most resilience metrics rely only on a single parameter (e.g., burst pressure) and fail to consider the potential interdependences between various process variables and corrosion defects.
2) There is a lack of a definitive model for corrosion growth rate that is tailored to the specific type of service pipeline.
3) While there have been studies on quantifying pipeline resilience, there has been limited exploration of strategies to enhance this value effectively.
4) There is not an ultimate framework to follow in quantifying pipeline system resilience.

The primary goal of this work is to develop a pipeline resilience metric based on pipeline's reliability, using condition monitoring data, to calculate the resilience value of a corroded pipeline system, which is subjected to process variables deviations. The innovative metric aims to find the optimal solution in the pipeline AIM, avoiding overly conservative approaches and offering a more balanced and effective means of enhancing pipeline integrity. Adopting resilience in AIM enables a more dynamic, proactive, and comprehensive approach to maintain asset performance, particularly in environment prone to uncertain disruptions. First, reliability represents the probability that a system fulling desired system performance without failure; while resilience refers to the capability of the system to absorb, adapt and recover from disruptions. Reliability is reactive, dealing with failures when they occur and aiming at preventing the failures. Thus, reliability can be considered as the absorption ability of a system (i.e., as part of the system resilience). It may not fully capture the system's ability to adapt and continue functioning in a compromised functional state. Second, reliability focuses on the technical aspects of a system's performance; while resilience adopts a more holistic approach by considering the interdependency between technical, human, and organizational factors in AIM. Third, resilience, considering the broader environmental and operational uncertainties, helps to ensure the long-term sustainability of assets. Reliability often aims at maintaining operational and maintenance consistency. Fourth, resilience also encourages a learning culture, which emphasizes the importance of learning from past disruptive events and continually adapting strategies for AIM. Finally, reliability focuses on component-level failures while resilience considers how local disruptions or failures can impact the entire system.

To achieve the goal of this paper, several sub-objectives are set out:

1) To delineate the interdependency between local corrosion and deviations in process variables.
2) To quantify system's resilience through a new metric based on the pipeline's reliability.
3) To determine the most effective preventive and mitigative strategies for enhancing resilience of a pipeline and its life expectancy, through the modelling of AIM activities effects during a fixed period of time.

The organization of the remainder of this paper is provided as the following. In Section 2, the resilience concept in the safety engineering system and pipeline domains is discussed. In Section 3, the new methodology is proposed to assess the pipeline system's resilience. In Section 4, an application case study is studied. In Section 5, results are illustrated and analysed. Directions for future studies are provided in Section 6, and finally, a conclusion and further remarks are provided in Section 7.

2. Preliminaries of resilience assessment

Resilience is defined as "a system's ability to withstand, respond to and recover from disruptions" (Poulin and Kane, 2021). Initially, studies predominantly focused on system resilience after disruptive events like natural disasters. However, an increasing number of investigations are now dedicated to the development of resilient infrastructures (Khan et al., 2021). An effective representation of system resilience is given by the "resilience bathtub curve", represented in Fig. 1. It shows a function of performance over time, and it is characterized by three main stages between the normal operative conditions, i.e., absorption (i), adaptation (ii) and restoration (iii) phases (Yazdi et al., 2022). Resilience quantification is possible through several models, which includes a multiple indicators model, a performance at a time instant model and a performance over a time period model (Cheng et al., 2022). Specifically, the last method is the most common one, which evaluates the performance loss and recovery over the entire disruption time interval (t_0–t_3), as expressed in Eq. (1). This method is the most suitable in terms of resilience of pipelines subjected to long term disruptions, such as corrosion. A more detailed description of the three resilience phases is given:

i. Absorption capacity (t_0–t_1) is defined as the extent to which a system can absorb the adverse effect of disturbances, thereby minimizing their impact on system's functionality. Generally, it is an intrinsic feature of the system, depending on its characteristics (Yarveisy et al., 2020).
ii. Adaptation (t_1–t_2) is the reaction of the system to a disruption and its ability to continue its operations in a degraded state with an acceptable performance level characteristics (Yarveisy et al., 2020).

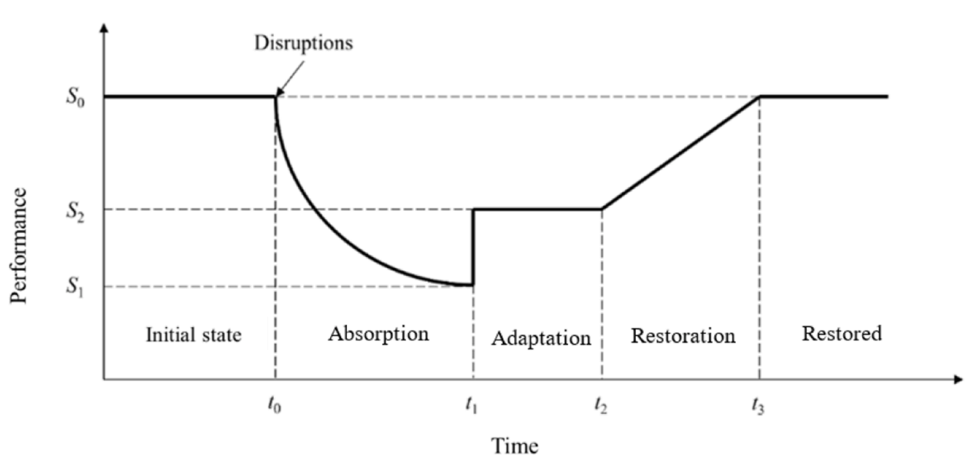


Fig. 1. Resilience bathtube curve (reprised and modified from Yang et al. (2023b)).

iii. Restoration (t_2–t_3) is defined as the phase in which the system is able to be repaired and return to either its original or a new steady state level, rapidly and requiring the minimal effort (Yarveisy et al., 2020).

In terms of pipeline resilience assessment, the most meaningful performance parameter is represented by transportation availability. For this reason, probabilistic approaches have to be considered, such as reliability-centric approaches.

$$R(t) = \frac{\int_{t_0}^{t_3} S(t)\mathrm{d}t}{S(t_0)(t_3 - t_0)} \quad (1)$$

3. The proposed methodology

In this section, a methodology is proposed to describe and evaluate pipeline resilience, based on the system's reliability. As shown in Fig. 2, the system's reliability $S(t)$ was firstly evaluated. This parameter depends on the joint probability of failure (PoF) between the main internal causes. For this reason, the interdependency between internal corrosion and variables deviation (in the solid line box) was considered. In particular, pressure (P), temperature (T) and flow rate (Q) were considered.

Once the system's reliability had been estimated, its variation over

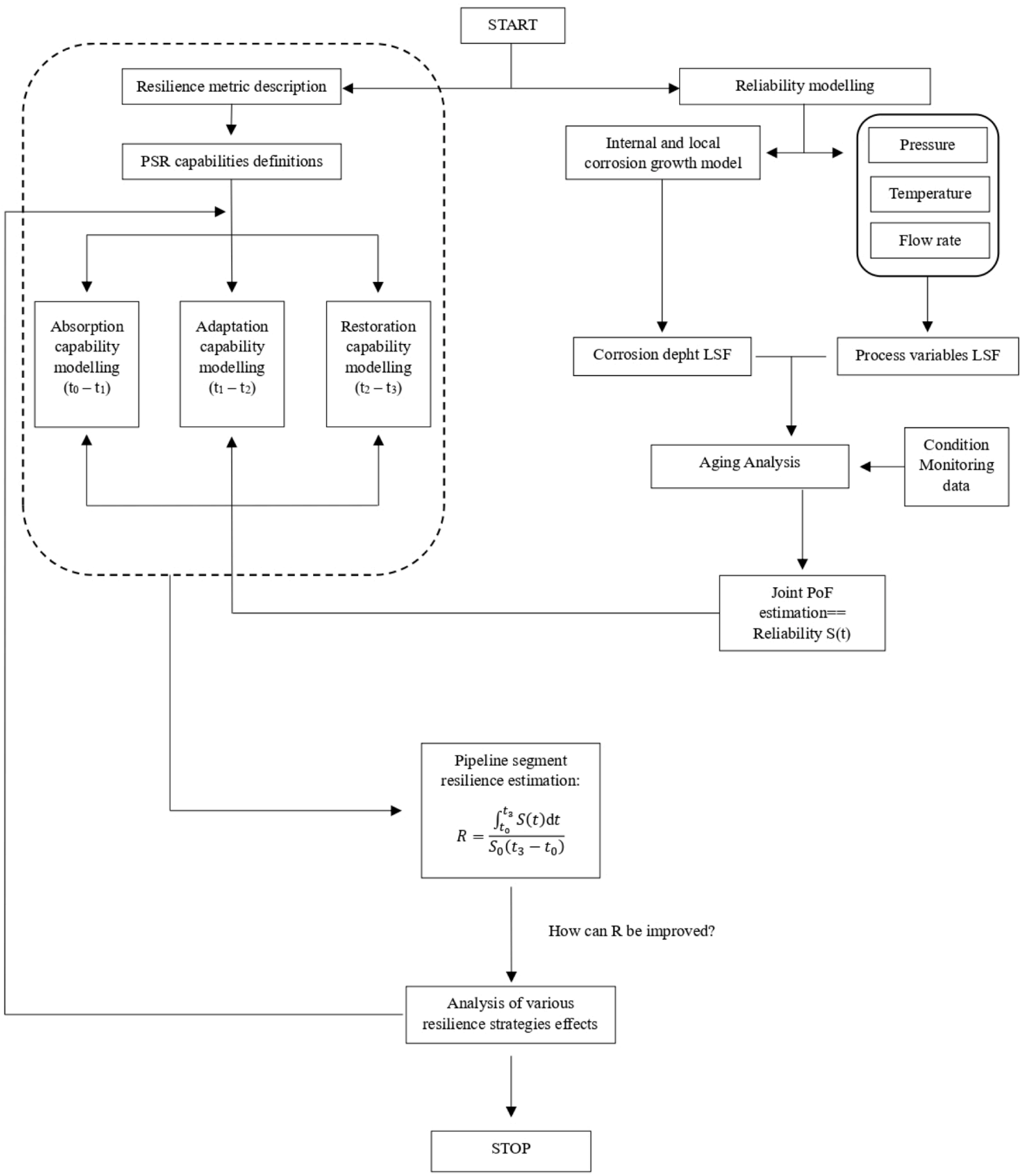


Fig. 2. Research methodology.

time was used as metric for the resilience evaluation. In particular, the dashed line box shows the three resilience phases. Each phase was modelled from $S(t)$ and its corresponding curve was plotted. Last, an analysis of the various resilience strategies effects on the resilience curve was conducted to detect the most reliability-affecting parameters, in order to enhance the resilience value. This approach allows to consider more than one damaging factor simultaneously, analysing the system's failure state over time.

3.1. System's reliability modelling

Reliability $S(t)$ is defined as the probability of the system operating in safe conditions or its capacity to function over a period of time (Yang et al., 2023b). Hence, it can be described even in terms of probability of failure (PoF), that is the probability of the system experiencing a failure state, expressed by a complementary function (Eq. 2).

$$S(t) = 1 - \mathrm{PoF}_{\mathrm{total}}(t) \tag{2}$$

In the Eq. (2), $\mathrm{PoF}_{\mathrm{total}}(t)$ represents the system's PoF which depends on the occurrence of one of the possible failure modes ($\mathrm{PoF}_{\mathrm{joint},\ k}$), expressed by corrosion in combination with the deviation of process variables *P, T, Q* (Okoro et al., 2022). In particular:

$$\mathrm{PoF}_{\mathrm{joint},\ k}(t) = \mathrm{PoF}_{\mathrm{CD}}(t) \cap \mathrm{PoF}_{l}(t) = \mathrm{PoF}_{\mathrm{CD}}(t) \cdot \mathrm{PoF}_{l}(t) \tag{3}$$

Where $l = P, T, Q$ and $k =$ (CD+P), (CD+T), (CD+Q). CD is the corrosion depth. Hence:

$$\mathrm{PoF}_{\mathrm{total}}(t) = \mathrm{PoF}_{\mathrm{CD}+P}(t) \cup \mathrm{PoF}_{\mathrm{CD}+T}(t) \cup \mathrm{PoF}_{\mathrm{CD}+Q}(t) = 1 - \prod_{k} \left[1 - \mathrm{PoF}_{\mathrm{joint},\ k}(t)\right] \tag{4}$$

Probability of failure of each variable are calculated from limit state functions (LSFs). LSFs are useful tools for evaluating structural reliability and can be expressed by functions like:

$$g = R_{\mathrm{f}} - D \tag{5}$$

Where, R_{f} represents resistance to failure, and D is for a demand (or load). When g falls below 0 ($g \leq 0$), the system is expected to fail, while $g > 0$ indicates a safe operational state (Amaya-Gómez et al., 2019; Zelmati et al., 2022). Once g_i expressions are calculated, PoF_j are consequently determined as

$$\mathrm{PoF}_j(t) = P[g_i(t)] < 0 \tag{6}$$

Where j=CD, *P, T, Q* and i=CD, *P*. As can be noted, only two types of LSF are developed, specifically for corrosion depth (CD) and pressure (*P*). Furthermore, the main failure mode is the local burst failure, due to a weakening of the pipeline (Zhang et al., 2019). This simplification derives from the fact that, for temperature and flow rate, specific LSFs are not much meaningful compared to the effect on operating pressure. Indeed, the two variables are important factors affecting flow parameters, such as flow density, flow viscosity and reynolds number, leading to a variation in the internal pressure drops. The calculation process is specified in detail in Section 3.1.2. Hence, PoF_j can be calculated using the specification of the following two paragraphs, which explain the development of the respective LSFs.

3.1.1. Corrosion LSF

In this work, the LSF utilized for corrosion defect is expressed as follows:

$$g_{\mathrm{CD}}(t) = \mathrm{SF} \cdot \delta - d(t) \tag{7}$$

Where δ is the initial pipeline wall thickness, mm; $d(t)$ is the defect depth over time, mm; SF stands for a safety factor (corrosion allowance, normally between 75 % and 85 %) (Han et al., 2023). The evaluation of the defect depth $d(t)$ is based on an empirical model, such as a power-law function. Few studies focused on the description of the corrosion mechanism, and this type of model (which uses probability theories) is widely used due to the fact that it can be employed in various forms of corrosion, and it depends on simple material-environmental parameters (Velázquez et al., 2017). However, it has some limitations regarding the randomness of corrosion. Specifically, the power-law function is expressed as:

$$d(t) = d_0 + k\,\alpha\,(t - t_0)^{\beta} \tag{8}$$

Where d_0 is the initial defect depth, mm; k, α, β are factors specific for the considered case; while t and t_0 are the time instant and the initial corrosion time, expressed in years. The additional coefficient k is a parameter representing the effectiveness of anti-corrosion measures taken on pipelines. Anti-corrosion measures are imperative to minimize the weakening effects of corrosion. However, there is a lack in literature quantifying the effectiveness of these measures on reducing pipeline corrosion. Therefore, this paper proposes to use a factor k, which can capture the uncertainty in the action's effectiveness, by varying its value between 0 and 1, where 1 represents the absence of any protective measure against corrosion, 0 is the ideal case where anti-corrosion measures can perfectly contrast corrosion. A uniform distribution was applied to these values.

3.1.2. Variables LSF

As previously said, LSFs related to *P, T, Q* are represented by the same expression as a function of *P*:

$$g_P(t) = F \cdot P_{\mathrm{b}}(t) - P \tag{9}$$

Where F represents a design factor, which is generally equal to 0.72 for oil pipeline (ASME B31.4, 2022), P is the internal pressure, MPa; $P_{\mathrm{b}}(t)$ is the burst pressure of the pipeline, MPa, which varies over time because it depends on the defect's growth. Significant considerations need to be made regarding internal pressure P and burst pressure P_{b}.

Fluctuations in operating pressure may lead to variations in the energy supplied by the pump to overcome the pressure drops. For this reason, pressure drops were calculated and added to the initial operating pressure in the definition of the PoF of T and Q. Considering variable P, fluctuations have been represented by random values from a set. Pressure drops ΔP (Pa) can be calculated through Bernoulli formula:

$$\Delta P = 4 f\, L_{\mathrm{s}} / D_i\, \rho\, u_{\mathrm{m}}^2 / 2 \tag{10}$$

Where L_{s} represents the pipeline section's length, m; f is the fanning friction factor, whose expression is specified for pipeline in turbulent regime in section 2.B.13.3.6 of API 581 (2016). u_{m} is the flow velocity. Once the pressure drops are calculated from the variation of each variable, worst case scenarios are selected, and they are utilized to calculate a new operating pressure (Table 1). Indeed, pumps must give enough energy to the fluid to overcome the drops, and for this reason operating pressure is affected and the estimated ΔP are added to the original operating pressure P_0. Specifically, LSF for T and Q were calculated by varying variable T and u_{m}, respectively, and by setting a fixed value of u_{m} and P_0 (for T-LSF) and a fixed value of T and P_0 (for Q-LSF), corresponding to the worst cases previously calculated. P_{b} represents burst pressure, which indicates the internal pressure limit after which pipeline's failure occurs. Many definitions of P_{b} are given in literature (Amaya-Gómez et al., 2019), and the most common model used is ASME B31 G, represented in ASME guideline and shown below in Eq. (11):

$$P_{\mathrm{b}}(t) = \begin{cases} \dfrac{2\,\delta}{D}(1.1\,\sigma_{\mathrm{y}}) \left\{ \dfrac{1 - \dfrac{2}{3}\left[\dfrac{d(t)}{\delta}\right]}{1 - \dfrac{2}{3}\left[\dfrac{d(t)}{\delta M(t)}\right]} \right\}, & \dfrac{L(t)^2}{D\delta} \leq 20 \\[2ex] \dfrac{2\,\delta}{D}(1.1\,\sigma_{\mathrm{y}}) \left[1 - \dfrac{d(t)}{\delta}\right], & \dfrac{L(t)^2}{D\delta} > 20 \end{cases}$$

With,

$$M(t) = \sqrt{1 + 0.8\left[\frac{L(t)^2}{D\delta}\right]} \tag{11}$$

Where, D is the outer diameter, mm; δ represents the wall thickness, mm; σ_y is the yield strength, MPa; and $L(t)$ and $d(t)$ are the corrosion defect's dimensions (length and depth, respectively), mm. This model was used in the calculation of pressure LSF.

3.2. Resilience modelling

The proposed approach is the employment of the system's failure probability (PoF) as a performance metric in the resilience assessment. PoF was converted to reliability $S(t)$ for this computation. Eq. (1) was employed for the resilience calculation. Indeed, the proposed model belongs to the performance over a time period type of metric, which is suitable for this study, since it focuses on a long-time disruption such as corrosion. The construction of the resilience curve was done by evaluating system's PoF over time, considering the system's properties every month of operation for a timeframe of decades (and system's $S(t)$, consequently). Firstly, PoF was calculated without any preventive or mitigative measure; therefore, absorptive capacity was studied. Then, the model was accurately modified (see below) in order to reflect applicable mitigative and restorative actions within the proposed mathematical model. The following paragraphs give an explanation of the main considerations:

1) Absorption

   In the context of this study, it represents the delayed time at which the failure occurs and the rate at which the system's reliability decreases. From the previously calculated $S(t)$, time to failure (t_0) can be determined as the time at which system's reliability starts decreasing. Absorption capacity mainly depends on the presence of anti-corrosion measures and two different values of k were considered (Eq. 8), 1 and 0.8 (Fig. 3).

   The duration of the absorption stage (t_0–t_1) is a consequence of the planned inspection time interval (ILI). Indeed, t_1 denotes the moment when the defect is identified. Various ILI are shown in literature (API 570, 2016; Abubakirov et al., 2020), hence a comparison of the effects of two different inspection time were considered, 7 years and 17 months (Table 2).

2) Adaptation

   During this stage (t_1–t_2), temporary adaptive measures are applied to the system, in order to continue its operability. Fix duration of this phase was considered, and two different strategies were studied: manipulation of operating parameters and the application of corrosion inhibitors.

   The first method entails a modification in the range of operating parameters, adjusted based on the results of ΔP calculation (Table 1), in order to avoid worst case scenarios.

   The second method is modelled by modifying the value of k after time t_1, in accordance with the effectiveness of the considered treatment (Yazdi et al., 2022).

3) Restoration

   Restorative capacity mainly depends on the type of strategy implemented to recover from disruption. Three different repair activities were analysed, the application of an external composite material reinforcement (CMR) (a), an internal recoating (b) and pipeline replacement (c).

   (a) CMR improves pipeline's strength, preventing from bursting. Hence, P_b was modified after time t_2 by increasing its value with a certain ratio of the burst pressure loss, in accordance with the values of repair effectiveness (Yazdi et al., 2022).

   (b) Internal re-coating allows a partial recovery of the corrosion defects. For this reason, $d(t)$ and $L(t)$ were modified considering a decrease of a certain ratio of their values, in accordance with the values of repair effectiveness (Yazdi et al., 2022). This approach may require the pipeline being out of function and a fixed time interval with parameters set at 0 was used.

   (c) Pipeline replacement allows the complete recovery of the initial conditions. Both defect dimensions and burst pressure return to their initial values, since a new pipe is installed. Also in this case, strategy requires pipeline's shutdown for a fixed time interval. In the computation context, PoF is calculated considering restarting the total number of events.

Restoration phase ends when the system's reliability reaches a new stable state (t_3).

Table 1
ΔP associated to variations in process variables T and u_m.

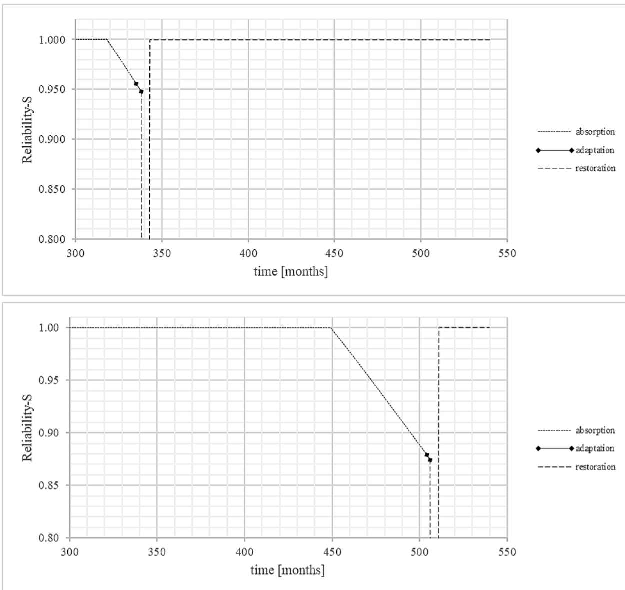
u_m (m/s)	T (°C)	ΔP (MPa)
1.0	20	0.45
1.0	30	0.45
1.0	40	0.44
1.0	50	0.44
1.0	60	0.43
1.1	20	0.55
1.1	30	0.54
1.1	40	0.54
1.1	50	0.53
1.1	60	0.52
1.2	20	0.65
1.2	30	0.64
1.2	40	0.64
1.2	50	0.63
1.2	60	0.62
1.3	20	0.76
1.3	30	0.76
1.3	40	0.75
1.3	50	0.74
1.3	60	0.73
1.4	20	0.88
1.4	30	0.88
1.4	40	0.87
1.4	50	0.86
1.4	60	0.85

4. Case study

The verification of the proposed methodology is achieved through a case study. The main objective is to obtain a resilience curve, with its three principal phases, using pipeline's reliability as metric. Hypothetical conditions were found on literature to generalize the obtained results (API 5L, 2024; Ossai et al., 2015; Zelmati et al., 2022). In particular, the study was conducted considering a buried pipeline and a timeframe of 45 years, subjected to internal local corrosion and process variables deviations. An oil pipeline was chosen, transporting a mixture of cyclohexane and water. Cyclohexane is a common hydrocarbon present in oil and water is the main responsible of pipeline's corrosion. Initial corrosion defect was set at 0, Table 3 gives the main parameters of the considered case.

5. Results and discussion

Representation of system's resilience requires a preliminary aging analysis, in order to obtain system's reliability over time without any preventive, mitigative or restorative strategy. Corrosion defect's dimensions and burst pressure over time were firstly calculated (as explained in Section 3.1.1 and 3.1.2). The obtained results are shown in Figs. 4 and 5. In Fig. 4 it is noticeable that the curves' slope is higher for the first months and then it decreases, because the corrosion mechanism follows a power-law function. The k-factor can vary between 0 and 1,



(a)

(b)

Fig. 3. Effect of varying k-factor from (a) 1 to (b) 0.8.

Table 2
Summary of the resilience values considering the same timeframe for each scenario.

Scenario	Resilience value $R(t)$: 319th–720th month
(i) $k = 1$; 7y ILI; internal re-coating	0.960
(ii) $k = 0.8$; 7y ILI; internal re-coating	0.933
(iii) $k = 0.8$; 17m ILI; internal re-coating	0.971
(iv) $k = 1$; 7y ILI; pipeline replacement	0.980
(v) $k = 0.8$; 7y ILI; pipeline replacement	0.981
(vi) $k = 0.8$; 17m ILI; pipeline replacement	0.989

and as can be seen, the steepest trend refers to the case study ($k = 1$), while the defect depth tends to increase slower when k approaches to 0. This behaviour means that more efficient anti-corrosion measures allow a more durable integrity of the pipeline. Looking at the curve with $k = 1$ (which was considered for the aging analysis), at the 449th month, the trend becomes steady since the corrosion depth has reached the same thickness of the pipeline's wall, and it stops growing. Finally, pressure drops related to each velocity and temperature's deviation were determined using Eq. (10), obtaining Table 1.

Results in Table 1 show that the worst case is represented by lower temperatures and higher flow velocities. For this reason, $T = 20$ °C and $u_m = 1.4$ m/s were used as fixed operating parameters for the flow rate LSF and the temperature LSF, respectively, in combination with the initial internal pressure P_0 of 6.8 MPa.

Overall, the system's total PoF and reliability can be obtained by following the method explained in Section 3.1. Results are shown in Fig. 6.

The preliminary aging analysis allows the determination of time to failure t_0, which indicates the beginning of absorption stage. In this case it is after 319 months. This prior curve corresponds to the first part of resilience curve, which is the absorption phase.

Table 3
Case study parameters.

Outer diameter (D) (mm)	Wall thickness (δ) (mm)	Yield strength, minimum (σ_y) (MPa)	$P_{d,max}$ (MPa)	Pipeline segment length (L_s) (km)	Pipeline depth of cover (m)	Corrosion length growth rate (v_L) (mm/a)	Proportionality factor (α)	Exponential factor (β)	Decision-making duration (month)	Replacement time (month)	Operating pressure (P) (MPa)	Operating temperature (T) (°C)	Operating flow rate (u_m) (m/s)
609.6	7.30	414	10.2	10	1.4	1.354	0.693	0.65	3	4	6.8-7.5	20-60	1.0-1.4

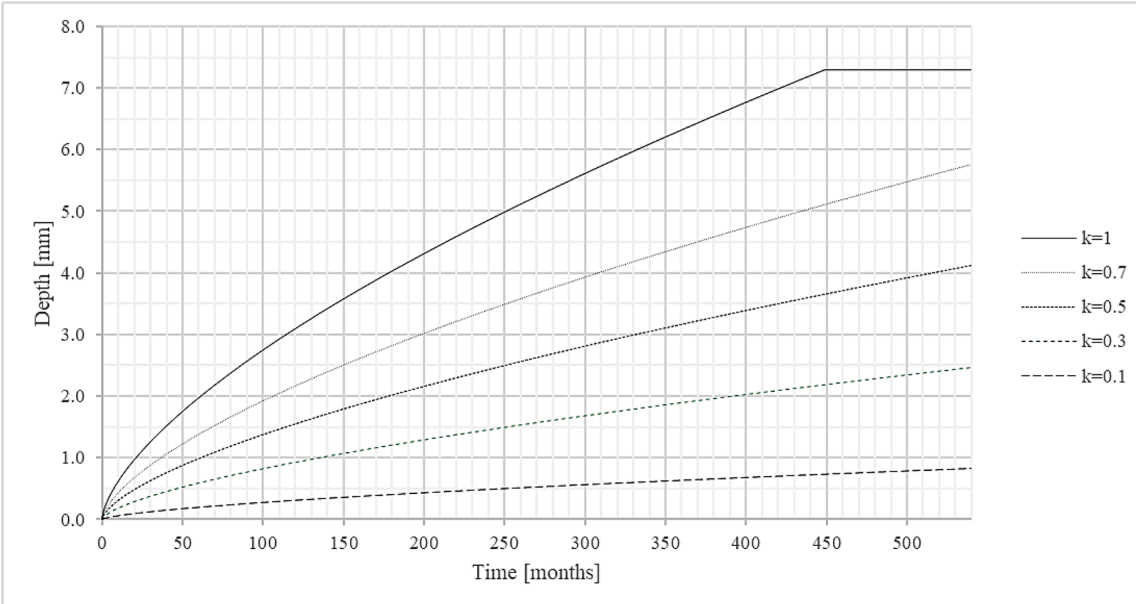


Fig. 4. Cumulative depth with different values of *k*.

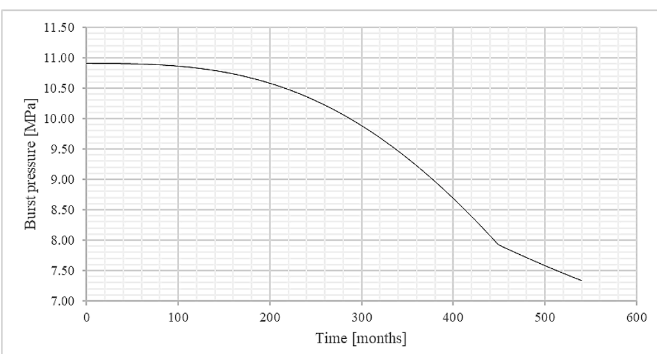
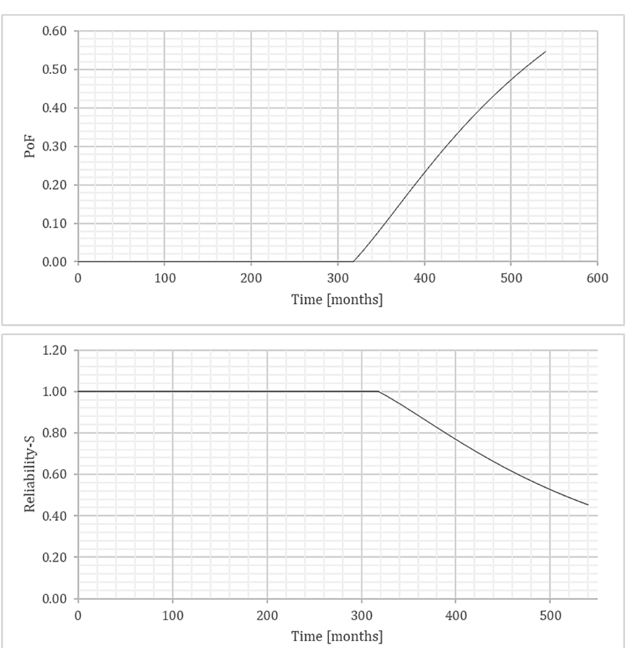


Fig. 5. Burst pressure variation with time.

As explained in Section 3.1.1 for Eq. (8) and for “absorption” paragraph, absorptive capacity of the system can be studied focusing on the presence or absence of anti-corrosion factors (k), which can minimize the effect of corrosion avoiding weakening of the pipeline. Fig. 3 highlights that the addition of an anti-corrosion agent leads to a delay in time to failure t_0, from 319 months to 450 months, increasing absorptive capacity of the system. Indeed, this factor allows a decrease in corrosion rate, as noticeable from Eq. (8). Furthermore, the failure process is shifted in later time period and the potential lifetime of the pipeline is increased. In this first example (Fig. 3), restoration process is represented by replacement of the pipeline, consequently recovery time is represented by the time needed to replace the pipe, as indicated in Table 3. A focus on the restoration process is explained below and shown in Fig. 7.



(a)

(b)

Fig. 6. (a) Total PoF and (b) system’s reliability over time.

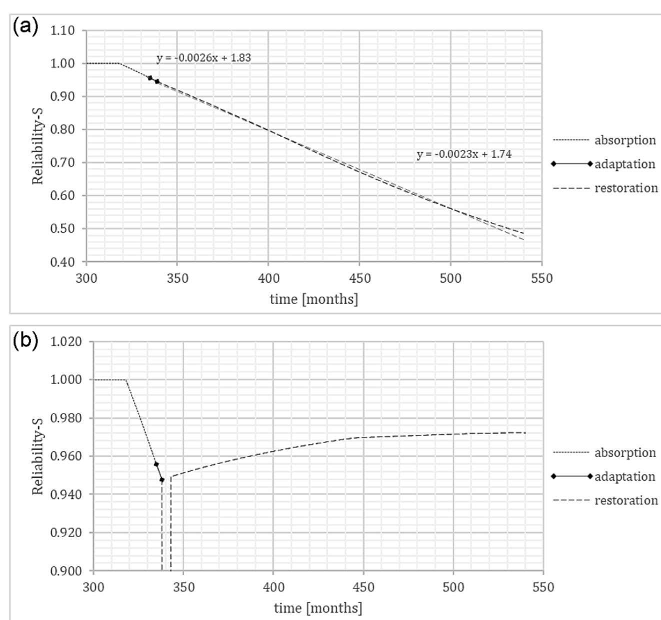


Fig. 7. Effect of different restoration strategies-application of (a) CMR and (b) internal re-coating.

The second stage of resilience curve, i.e., the adaptation stage (t_1–t_2) represents only a transitory phase between the disruption and the application of restorative measures. A duration of 3 months was chosen, during which the decision-making process takes place. Possible temporary measures applicable to the system do not have a noticeable effect on it. Table 4 shows that the two suggested methods (change of operating parameters and application of corrosion inhibitors) have almost the same results on system's reliability, which tends to decrease slower than in the absorption phase.

Table 4
Comparison of the effects on system's reliability between (a) changing operating parameters and (b) applying corrosion inhibitors.

Time (month)	PoF_{total} (a)	$S(t)$ (a)	PoF_{total} (b)	$S(t)$ (b)
336	0.0467	0.9533	0.0469	0.9531
337	0.0495	0.9505	0.0496	0.9504
338	0.0522	0.9478	0.0524	0.9476

In terms of restoration, the capacity of a pipeline to recover from disruption and to find a new stable state depends on the type of restorative strategy applied. Fig. 7 shows how the application of a CMR (a) or an internal re-coating (b) affect the system. Slopes highlight that CMR guarantees a slowdown in the failure process, but there is not an effective restoration. Indeed, it affects the value of $P_b(t)$, which has an influence on PoF_j, but it is not sufficient to induce a change in PoF_{total}. A different method was then compared. In this second case, the resilience curve exhibits its typical trend, with a noticeable restoration phase. As mentioned above, internal re-coating affects the corrosion defect's depth, and allows its partial recovery. Variations in defect's depth significantly influence P_b values, resulting in a positive effect on LSFs results. From the obtained result, an accurate selection of the best repair strategy can be performed (in this case by excluding CMR application). In terms of resilience, system's reliability reaches a new stable state at the 531st month (t_3), when the system is partially restored.

In Table 2, a list of resilience values obtained with the presented methodology, for various scenarios, is presented. To facilitate a meaningful comparison among each case, it is necessary to analyse them within the same time interval. Due to the different disrupted states which characterize the various cases delayed in cases with $k = 0.8$ and early initiation in the cases with $k = 1$ – a comprehensive timeframe was selected for a reasonable evaluation. For this reason, the estimation of the resilience value considers t_0 at the 319th month, and t_3 at the 720th month.

The first three scenarios highlight that anti-corrosion measure have to be combined with an optimum inspection time interval, in order to obtain a resilient system. Indeed, ii has a lower resilience value than iii, due to the fact that anti-corrosion measures help in decelerating the corrosion process, leading to a safer system; however, in this case the restoration process starts late, and the system keeps degrading until the initiation of the repair activities. Overall, the system stands in safer conditions without an anti-corrosion agent if the inspection occurs earlier than the case with the anti-corrosion measures. This means that the ILI time interval has a great influence on the absorption capacity of the system. Indeed, a shorter ILI timeframe allows the system to keep a high integrity for its entire lifetime (cases iii and vi).

From the observation of the last three cases, the outcomes underline that pipeline replacement guarantees the most resilient system, in particular, if combined with the application of anti-corrosion measures and a short ILI time interval.

5.1. Advantages and limitations

The proposed model enables the calculation of the system's resilience value, along with establishing a failure initiation time (t_0) and a restoration time (t_3). It focuses on the pipeline's integrity status through its reliability, and it consequently supports the decision-making process, by finding the optimal solutions. The method also demonstrates that any intervention prior to t_0 is unnecessary, enhancing efficiency in maintenance planning. Using resilience metrics to support maintenance decisions offer several advantages, presented below:

1) Cost savings: resilience assessment directs maintenance efforts towards where they are necessary. Calculation of system's PoF due to several variables allows the determination of t_0, avoiding hastened ILI and repair activities until the system remains in a safe state.
2) Proactive maintenance planning: understanding the degradation process of the system, maintenance can be proactively scheduled.
3) Optimized resource allocation: the metric choice ensures that efforts are invested in the most vulnerable sections of the pipe, by understanding the most affected parameters.
4) Comprehensive analysis of the system: reliability-based AIM permits to analyse every phase of the considered pipeline, while a resilience-based approach focuses on the entire system's lifetime.
5) Enhanced safety and reliability.
6) Extended asset life.
7) Improved response to emergencies.
8) Wide applicability: the proposed model aspires to be a useful tool employed by industries in the AIM process. The utilized framework is general, and it is built on parametric equations. These expressions depend on operating parameters, pipeline's material, and other specific data, which can be easily substituted depending on the analysed case.

However, the proposed resilience assessment methodology has some limitations:

1) Lack of pre-disruption information: The methodology considers that the disrupted state begins after the first positive value of the composite PoF. Actually, the system starts degrading since the first month of operation, and different preventive measures may be actuated before the calculated t_0. However, it remains safe until t_0.
2) Lack of economic considerations: The previously obtained resilience results were utilized as an indicator to establish the best combination of maintenance activities. Actually, one of the most important contributions in the decision-making process is also represented by the monetary aspect. Indeed, the system's performance and quality are measured not only in terms of reliability or safety, but also in terms of productivity and economics. The proposed methodology is more focused on the quality of the system.

6. Future developments

Few studies were conducted to find the optimal inspection time interval, which is one of the main factors affecting the resilience value (Abubakirov et al., 2020). The optimization of the ILI time interval is found by introducing a utility function (UF), which incorporates the risk associated with the working pipeline at time t, and the costs associated to the inspection and maintenance programme to be performed within the same time interval. The optimal ILI time interval corresponds to:

$$\frac{d[UF(t)]}{dt} = 0 \tag{12}$$

Other approaches suggest an optimal combination of each factor which affects resilience value (Opeyemi et al., 2016). Each contribution can be expressed by a function, where each variable is a coefficient. The minimization of the cost is feasible through a large number of iterations, changing the inspection time and the reparation coefficients, until the best combination is found.

By following this suggested approach, a composite indicator that includes both reliability and costs may be used as new resilience metric. Pipeline productivity may represent a valid option for this purpose, and it can be expressed as an integrated efficiency, such as:

$$\text{Efficiency } (E) = \frac{\text{Reliability } (S)}{1 + \text{Normalized Operational Costs } (C)} \quad (13)$$

Furthermore, dynamic bayesian networks (DBN) can represent a useful tool in the determination of the system's reliability over time, to be then utilized in the construction of resilience curve. These networks are based on a large amount of data and can consider multiple affecting factors.

7. Conclusions

The present study introduces an innovative way to assess pipeline's resilience, through a new metric, based on the system's reliability. In particular, reliability represents a comprehensive metric, which is able to combine more than one parameter (corrosion and process variables), addressing the insufficiency of the previous metrics.

A composite PoF model which can describe system's integrity over time was modelled through suitable correlations. Subsequently, resilience curve was constructed, based on the application of absorptive, adaptive, and restorative strategies on the previous model, reflecting real cases. The understanding of the effects of these strategies on system's failure probability is a main aspect. Lastly, the application of the methodology on a case study led to an optimization of the suggested recover strategies and to a maximization of the resilience value.

In summary, this study outlined that the proposed approach represents a useful tool during the decision-making process. It allows to understand the correct time to failure and gives an insight into the degrading and restorative process. Consequently, it facilitates to establish which is the most appropriate strategy to be employed during the AIM planning process. Furthermore, it enhances the safety and reliability of the system, allowing a cost-saving effect with an optimization of the response strategies. However, the proposed approach does not take into account the economic aspect of the eventual maintenance activities. Moreover, the system's state of integrity before the actual failure time (t_0) is not comprehended by the methodology. Future research may focus on the possibility to find a more detailed reliability model, which includes both the economic and the structure's integrity aspect.

In conclusion, the proposed approach for resilience assessments appears as a new, valid and useful tool to be employed in pipeline system's safety analysis. However, it still comprises some gaps to be fulfilled, and further validations have to be carefully completed to extend this investigation to different cases.

CRediT authorship contribution statement

Federica Antonelli: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ming Yang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Valerio Cozzani:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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