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DOI
10.1016/j.ress.2024.110792

Publication date
2025

Document Version
Final published version

Published in
Reliability Engineering and System Safety

Reliability Engineering and System Safety 256 (2025) 110792

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Dynamic quantitative assessment of service resilience for long-distance energy pipelines under corrosion

Yunfei Huang [a,b], Guojin Qin [c,d,*], Ming Yang [b,e,f,*], Maria Nogal [g]

[a] School of Mechatronic Engineering, Southwest Petroleum University, Chengdu, Sichuan 610500, PR China
[b] Safety and Security Science Group, Department of Values, Technology, and Innovation, Faculty of Technology, Policy, and Management, Delft University of Technology, 2628 BX Delft, The Netherlands
[c] School of Civil Engineering and Geomatics, Southwest Petroleum University, Chengdu, Sichua 610500, PR China
[d] School of Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[e] National Centre for Maritime Engineering and Hydrodynamics, Australian Maritime College (AMC), University of Tasmania, Launceston, TAS 7250, Australia
[f] Centre of Hydrogen Energy, Institute of Future Energy, Universiti Teknologi Malaysia (UTM), Johor Bahru 81310, Johor, Malaysia
[g] Department of Materials, Mechanics, Management, and Design, Delft University of Technology, Delft 2629, The Netherlands

A R T I C L E I N F O

Keywords:
Long-distance energy pipelines
Service resilience
Corrosion
Dynamic assessment
Repair strategies

A B S T R A C T

Corrosion is a deterioration phenomenon of buried long-distance pipelines involving complex dynamic processes. The complexity poses challenges to addressing the safety concerns caused by corrosion. In recent years, the concept of resilience has been introduced into the assessment of engineering systems. However, there is a limited effort in quantitatively assessing the resilience of a pipeline's response to corrosion. This work aims to develop a novel framework to quantify the resilience of pipelines against corrosion while considering the resilience evolution induced by future corrosion growth, dynamic in-line inspection (ILI) plans, and distinct repair strategies (re-coating, composite material reinforcements, and pipe replacement). *Pipeline Service Resilience* (PSR) is modeled as a function of absorption, adaptability, and restoration capabilities based on the time-dependent burst pressure metric. Dynamic Monte Carlo Simulation technique is employed to model the potential resilience evolution scenarios to predict the PSR. The proposed framework is demonstrated on an in-service pipeline. The case results show that the PSR value ranges from 0.8943 to 1 due to the uncertainty of the resilience evolution process. Noteworthy impacts on PSR include repair time, ILI intervals, anti-corrosion ability, decision-making time, corrosion depth growth rate, and corrosion length growth rate (in decreasing order of sensitivity). The proposed methodology can potentially emerge as a significant tool for evaluating pipeline resilience under corrosion.

1. Introduction

Long-distance energy pipelines play a vital role in the global economy, serving as the crucial lifeline for the transportation of oil, natural gas, and hydrogen energy resources [1]. However, the operation of energy pipelines faces a series of challenges and potential hazards owing to the flammable and explosive characteristics of transported media [2, 3]. Addressing these concerns is paramount to ensuring energy resources' safety and continual supply [4]. Pipelines are susceptible to various disruptions, including corrosion, third-party damage, material degradation, natural hazards, environmental impact, and geopolitical and security risks [5]. These undesirable events may threaten the integrity, safety, and continuous operation of energy pipelines, with the potential to cause ruptures, leaks, and devastating environmental disasters, thereby significantly endangering public safety and the environment [6]. For instance, in 2010, a rupture occurred in a natural gas pipeline in California, which caused the leakage and release of vast quantities of natural gas to the community surrounding the pipeline, leading to an explosion and fire [7]. Another notable incident is the 2013 Qingdao oil pipeline explosion in China, resulting in 62 fatalities, 136 injuries, and a direct economic loss of 750 million CNY [8].

In response to the threat of pipeline failure, pipeline owners commonly embrace risk mitigation strategies to prevent failure, including regular inspections, corrosion control programs, monitoring systems, and well-defined emergency response plans [9]. However, these strategies aim to design pipelines to avoid the occurrence of

* Corresponding authors.
E-mail addresses: guojinqin@swpu.edu.cn (G. Qin), m.yang-1@tudelft.nl (M. Yang).

https://doi.org/10.1016/j.ress.2024.110792
Received 7 October 2023; Received in revised form 23 December 2024; Accepted 24 December 2024
Available online 25 December 2024

disruptions, but the mentioned failure events indicate that not all unexpected events can be prevented [10]. Thus, the ability of pipelines to maintain and recover continuous operation following failures has attracted more attention. In this context, applying the resilience engineering concept, which aims to maintain the continuous operation and rapid recovery of systems under disruptions, to the pipeline safety and security field has led to greater interest [11]. The term "resilience" has its root in the Latin word "resiliere", meaning "act of rebounding" [12]. From a broad perspective, resilience is defined as the ability of the system to absorb the adverse effects of disruptive events, continue to operate in the degraded state and recover to a new or previous operation quality with minimal support [13]. This expansive definition has evolved in many disciplines, from ecology to social sciences, psychology, and economics [14]. Despite the rich history of the resilience concept, engineering resilience is still in its infancy.

There is a growing interest in better understanding and improving engineering systems' resilience under disruptive events. Wang et al. [15] examined the resilience of the air transport system by combining network science and operational dynamics. The findings demonstrated that while the system initially deteriorates after disruptive events, it eventually recovers to an acceptable level. A study from Bhattacharya and Goda [16] proposed that small wind farms that provide emergency backup power for nuclear power plants can form a robust and resilient system with nuclear power plants. Wang et al. [17] presented a resilience assessment approach for integrated electricity-gas systems adept at effectively addressing multi-type natural disasters. The case study demonstrated that the resilient strategy considering various natural disaster types can notably improve system resilience. Saikia et al. [18] proposed a governance-driven framework for city flood resilience in response to the shock of floods on cities. Through the case application, they provided evidence of the framework's effectiveness in improving urban resilience against floods. A novel framework by Jiang et al. [19] was introduced to assess the resilience of natural gas network systems when subjected to unpredictable leakage conditions. Their findings indicated the efficacy of the proposed approach in accurately evaluating the resilience of the natural gas network system. Minaie and Moon [20] developed a qualitative framework for analyzing and assessing bridge resilience. Two case studies of bridges affected by Hurricane Katrina illustrated the approach's potential in bridge resilience assessment. In the study from Chen et al. [21], the resilience of hazardous material storage plants against overpressure and fire incidents was assessed using a dynamic Monte Carlo Simulation (MCS) method. The evolution of resilience was modeled as a dynamic process comprising disruption, escalation, adaption, and restoration stages. Finally, a case study was presented to demonstrate the developed framework. Sun et al. [22] presented a novel approach that integrates resilience principles to assist practitioners in identifying cost-optimal measures. The optimal maintenance cost was determined by introducing the minimum acceptable resilience level and the maximum acceptable recovery time. The proposed approach was applied to the Chevron Richmond refinery crude unit and its upstream process. In another study by Sun et al. [23], they developed a dynamic approach based on a system-theoretic accident model and a process to assess system resilience. The application in the diesel oil hydrogenation system indicated the ability of the proposed method to quantify the resilience of chemical process systems. Hu et al. [24] introduced a framework to evaluate the time-dependent resilience of marine liquefied natural gas (LNG) offloading systems against severe climate disasters. The application in an LNG offloading system emphasized how the proposed framework supported decision-makers in integrating resilience considerations into system design and operation.

From the literature, many qualitative and quantitative methodologies have been proposed to assess the resilience of engineering systems subjected to various disruptive events (floods, hurricanes, overpressure, fires, etc.). However, discussions on evaluating the pipeline's resilience under corrosion are scarce, especially for long-distance energy pipelines. While some studies [17,19,25–27] have assessed the resilience of natural gas network systems, there are significant differences between natural gas network systems and long-distance pipelines regarding application areas, pressure levels, diameter sizes, transmission distances, and system structures. A key distinction lies in the structural difference between long-distance pipelines and gas network systems. Gas network systems typically feature a complex paralleling topology structure, designed with the consideration that shutting down specific pipe sections would not compromise the operation of the remaining sections in the event of a failure. Conversely, long-distance pipelines consist of numerous series of connected pipe segments that form a single, continuous pipeline. As a result, any pipe segment failure inevitably impacts energy transmission to downstream users. These structural disparities result in distinct emphases in the resilience assessment between the two. In the case of natural gas network systems, their resilience assessment primarily concerns the stability of the entire system and its ability to recover under disruptions from a system perspective. Conversely, for long-distance pipelines, their resilience evaluation focuses on the safety and the ability of the pipeline's own structure to recover from disruptions. Thus, the resilience assessment findings for gas network systems are not applicable to the resilience assessment of long-distance pipelines. Additionally, the pipelines' weakness is that they are prone to deteriorate due to various disruptions [28]. Therefore, long-distance pipelines must be designed to withstand these harmful factors and recover quickly after an undesirable event occurs. Corrosion, a time-dependent phenomenon, poses a safety concern and can potentially trigger operational disruptions [29]. As far as the authors are aware, a limited effort focused on introducing the concept of resilience to investigate a pipeline's response to a harmful factor such as corrosion.

This work aims to develop a quantitative framework to predict the resilience of pipelines against corrosion, considering the resilience evolution induced by both the corrosion growth and dynamic recovery process. Unlike the conventional risk-based approach focusing on pipeline failure, the proposed resilience-based approach assesses the pipeline system's capability of handling corrosion as a disruption to its operation and seeks to enhance this capability. This study's uniqueness emerges from its integration of pipeline corrosion prediction, mitigation, and repair decisions into the resilience framework.

The remainder of this paper is outlined as follows: Section 2 describes the definition of pipeline service resilience. Section 3 details the implementation of the proposed methodology, outlining each of the main steps in the approach. A case study in an in-service pipeline is presented in Section 4. Section 5 describes the results and discussion. Finally, this paper concludes in Section 6.

2. Definitions of pipeline service resilience

In general, resilience definition and assessment involve the following inquiries [11]:

1) What potential disruptions could affect the system?
2) If these disruptions occur, what would be their impacts on the system's functionality?
3) How effectively can the system manage and recover from these disruptions while maintaining an acceptable level of performance?

Concerning the first question, Carpenter et al. [30] stated that the operationalization of resilience depends on the answer to the "resilience of what to what?" This work aims to investigate the resilience of a pipeline to disruptive events. It is termed pipeline service resilience (PSR). With the US National Academy of Sciences' definition of resilience - "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" [31], in this work, PSR is defined as a pipeline's ability to anticipate, absorb, adapt to, and recover to maintain its material transportation performance subject to various types of disruptions (e.g., corrosion, natural hazards). This paper focuses on corrosion as a primary disruption to pipeline service.

The system's functionality in the second question is defined as the service provided by the system. Specifically, functionality in this paper refers to the functional service provided by a pipeline transporting liquid or gaseous energy materials, including oil, natural gas, hydrogen, or other hydrocarbons, from their production sites to end-users. Considering corrosion as a disruption, the pipeline's wall may undergo thinning, leading to a decrease in its pressure-bearing capacity and consequently compromising its transportation functionality.

Regarding the last question, performance is the measurement of functionality over time and captures how the system's functionality is affected by disruptions. The performance metric can take the form of a singular parameter representing the system's overall functionality, such as the medium temperature, flow rate or burst pressure of a pipeline, or a comprehensive list of parameters encompassing different aspects of the pipeline, including safety, media quality, economic considerations, and environmental concerns [32]. Note that burst pressure (P_b) is used to indicate the pipeline transportation performance in this work. With corrosion as a disruption to a pipeline, its burst pressure is expected to drop gradually [33]. As a result, employing burst pressure as a performance metric could be more meaningful to pipeline owners [33]. Repair activities can be implemented for the corroded pipe segment to maintain the pipe's burst pressure and prevent a decline. These repair actions facilitate the pipeline's performance recovery from the disruptive event. The burst pressure changes curve serves as the performance profile for quantitative resilience assessment in this study. Meanwhile, since the process safety of the pipeline operation is significantly dependent on the burse pressure (e.g., exceeding its threshold may lead to cracking, causing accidental release of hazardous material), safety is inherently considered in this resilience model.

3. Methodology

In this section, a quantitative framework is introduced to estimate the PSR, as shown in Fig. 1. The framework is divided into three distinct phases: Phase I involves resilience metric description, definitions of PSR capabilities and their modeling; Phase II introduces the procedure for burst pressure prediction of corroded pipelines; Phase III finally presents PSR quantification and how to enhance it.

3.1. Resilience metric description

Following the PSR definition in Section 2, a time-dependent pipeline transportation performance curve (or the resilience evolution process) subject to disruptions is presented in Fig. 2. It shows the pipeline transportation performance experiences five distinct stages after encountering a disruption (i.e., corrosion). In this work, disruption refers to the corrosion process causing the local wall thinning of pipelines, and the corrosion initiation time, t_0, refers to the point at which the pipe wall thickness begins to decrease. As shown in Fig. 2, the pipeline initially operates at its maximum performance (S_0) before encountering disruption. A corrosion-induced wall thinning of the pipeline then occurs at a time (t_0), leading to a reduction in the pressure-bearing capacity of the pipeline and consequent deterioration of its transportation performance. Over time, the corrosion growth exacerbates the wall thinning, further diminishing the pipeline's transportation capability. When the corrosion defect is detected during scheduled inspections like ILI, the disruption is considered to be prevented (t_1). At this time, the pipeline's remaining transportation performance reaches its minimum value (S_1). Pipeline owners can implement temporary activities to maintain or enhance the transportation performance of corroded pipelines. The ultimate recovery strategy involves the repair measures for damaged segments of the pipeline ($t_2 \sim t_3$). The pipeline's transportation

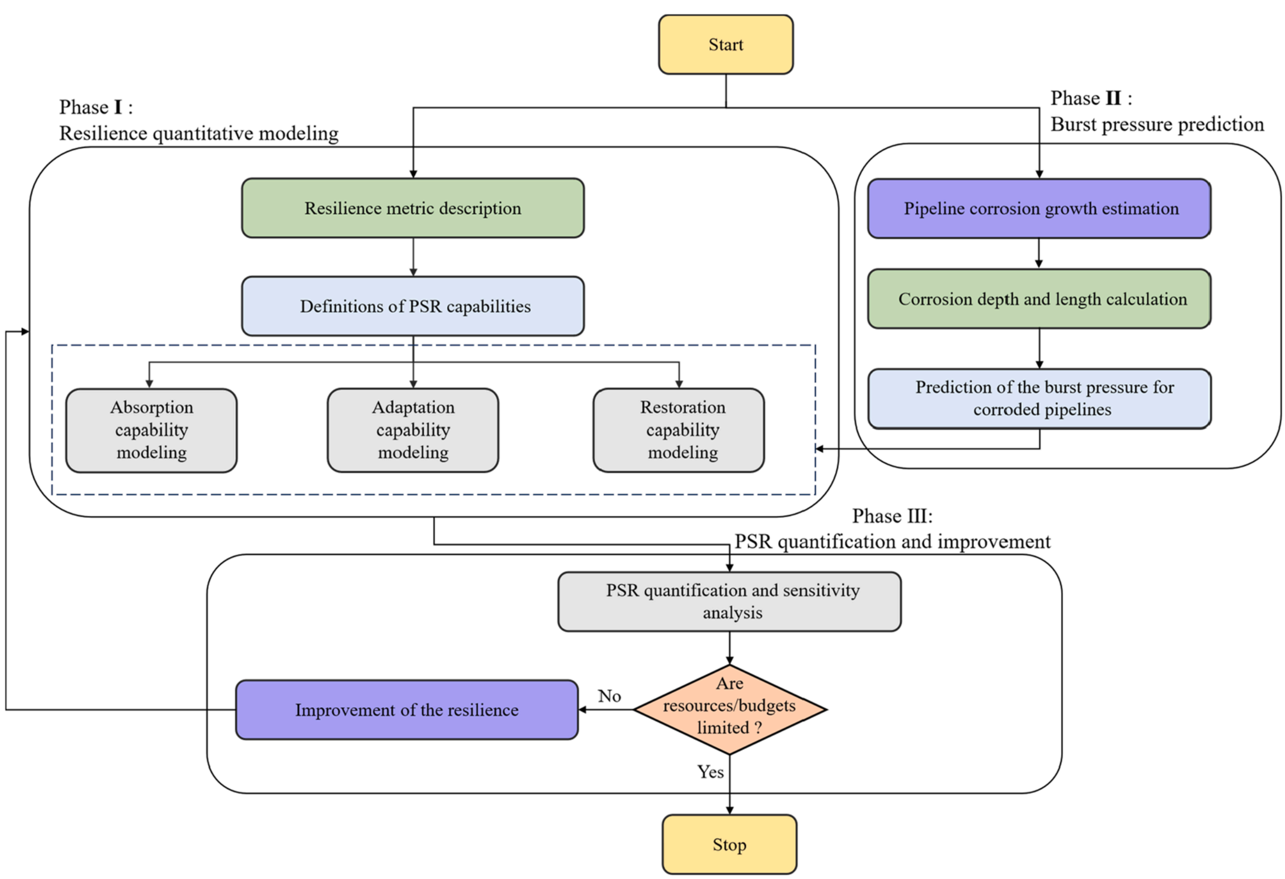

Fig. 1. Flowchart of resilience assessment framework for corroded pipelines.

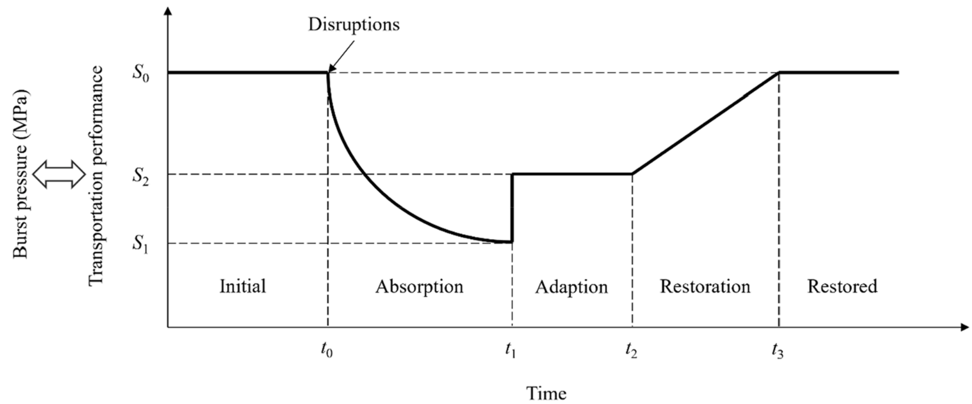

Fig. 2. Pipeline transportation performance curve over time.

performance is fully restored at t_3. Note that the performance of the restored pipeline may differ from that observed in the initial stage, reflecting practical considerations. The process of resilience evolution is intricate, time-dependent and stochastic, arising from uncertainties in pipeline vulnerability, corrosion prediction, and maintenance strategy.

Cheng et al. [34] summarized four types of metrics to quantify resilience. This work uses performance-based metrics to model resilience mathematically. Following the time-dependent performance curve in Fig. 2, the metric of PSR is described as the ratio of the average pipeline transportation performance S(t) between disruptions and complete recovery to the initial transportation performance S_0, as expressed in Eq. (1) [21]. Note that the anticipation phase of PSR is excluded since, at the present stage, it cannot be modeled using the performance curve [11].

$$R = \frac{\int_{t_0}^{t_3} S(t)\mathrm{d}t}{S_0(t_3 - t_0)} \tag{1}$$

where R denotes the PSR metric value; t_0 and t_3 represent the times when the pipeline experiences disruptions and completely recovers, respectively. It is worth noting that the defined resilience metric can be applied across diverse fields by substituting $S(t)$ with alternative performance functions.

Considering the potential existence of multiple resilience evolution scenarios $S_i(t)$ in different pipe segments, wherein distinct performance curves may arise, the PSR metric can be updated as below:

$$R = \frac{1}{N}\sum_{i=1}^{N} \frac{\int_{t_0}^{t_3} S_i(t)\mathrm{d}t}{S_0(t_3 - t_0)} \tag{2}$$

where N represents the number of resilience evolution scenarios, $i = 1, 2, 3, \ldots, N$.

3.2. Definitions of PSR capabilities

As demonstrated in Fig. 3, the PSR involves three properties: absorption capability, adaption capability (*Ad*), and restoration capability (*Res*). These capacities serve as the fundamental components for quantifying the PSR. To improve the PSR, pipeline owners should take resilience measures at different stages to resist the impact of disruptions. Resilience measures refer to measures that can enhance the system's ability to absorb disruptions, as well as its ability to adapt to and recover from them. Herein, we present the definitions of three resilience capabilities.

The absorption capability is a system's ability to mitigate the detrimental impact of disruptions and maintain its continuous operation. In this work, the PSR's absorption capability refers to the capacity of pipelines to prevent failure due to corrosion. Diverse protective measures can increase the system's absorption capacity, such as the application of anti-corrosion coatings on the external surface of pipelines to

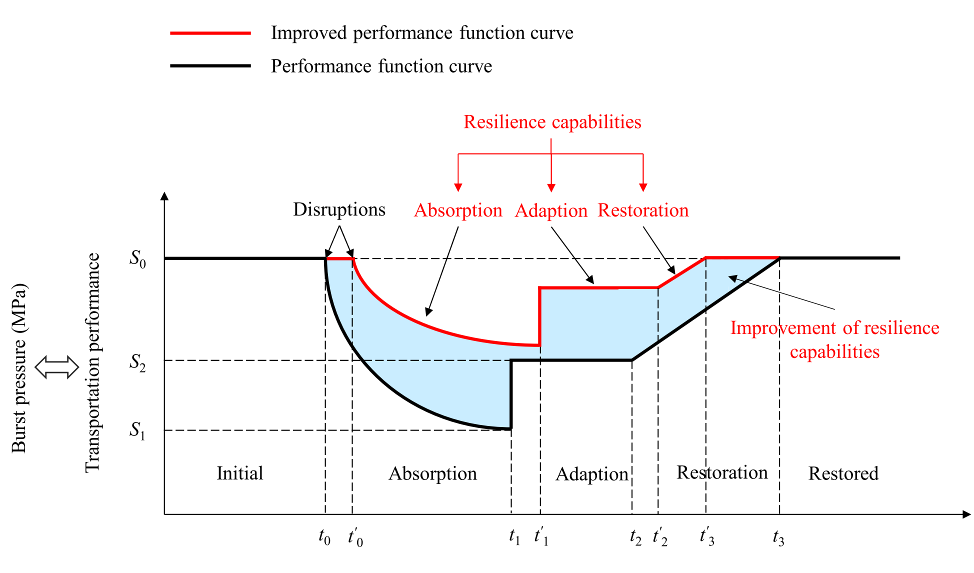

Fig. 3. Increased pipeline transportation performance by resilience capabilities.

shield them from direct exposure to the surrounding corrosive environment. Commonly employed coating materials include epoxy resin, polyethylene, and polyurethane, which act as physical barriers against corrosion [35]. Cathodic protection, an electrochemical technique, represents another approach utilized to manage pipeline corrosion. It employs sacrificial anodes or impressed current to control the corrosion process of pipelines. Furthermore, chemical corrosion inhibitors can be introduced into the internal medium of pipelines to establish a protective film on their inner surfaces, thereby averting the corrosive effects of transported substances [36]. Regular pipeline maintenance, appropriate pipe material selection, and pipeline design considerations are additional prevalent anti-corrosion measures in the pipeline industry [37]. By implementing these measures, the absorption capacity can be established, thus delaying the corrosion initiation time t_0 to t_0' and increasing S_1 in Fig. 3. This leads to a decrease in the transportation performance loss and an improvement in the PSR.

The adaption capability involves the capacity of a system to accommodate the disruptive event and continue operation in the degraded state with acceptable performance. It allows the partial recovery or maintain performance prior to restoration. After conducting ILI at time t_1 or t_1', pipeline owners typically assess the data collected by experts and specialized software. Each identified corrosion is carefully evaluated to determine its severity and potential impact for helping prioritize repair activities. During this period, temporary corrosion protection measures (Adaption strategies), including cathodic protection, or inhibitors, can be implemented in the defected section to temporarily slow the corrosion process. In this way, adaptation capability can be achieved. The improvement of adaption capability contributes to an increase of the S_2 value in Fig. 3 and enhances the transportation performance preceding the restoration of the pipeline.

The restoration capability is the ability to completely restore pipeline transportation performance through repair strategies. Based on the outcomes of data analysis and defect assessment after ILI, the restoration capacity can be attained by implementing repair strategies in the pipeline, such as the installation of sleeves or clamps, composite material reinforcements (CMR), and replacements to repair corroded pipe segments, thereby partially or entirely enhancing the transportation performance of the pipeline. At this stage, the restoration capacity mainly depends on the recovery time, i.e., the duration between the start (t_2 or t_2') and end (t_3 or t_3') of the pipe repair process. The reduction of the recovery time, from t_2-t_3 to t_2'-t_3', can significantly mitigate performance losses and yield pipelines with heightened resilience.

3.3. PSR capability modeling using burst pressure metric

This step focuses on modeling the three resilience capacities to quantify the PSR.

3.3.1. Absorption capability modeling

The absorption capability is the pipeline's ability to mitigate the deterioration of disruptions and maintain the continuous pipeline operation. The corrosion-induced wall thinning is the main threat to pipelines. Hence, the initial step of absorption capability modeling is estimating the corrosion growth rate (CGR) over time. Empirical models derived from experimental data are extensively employed to forecast CGRs. Utilizing an appropriate CGR model that suits the pipeline conditions can minimize the uncertainty arising from corrosion behavior intricacies, environmental variability, or data deficiencies. In recent years, various CGR models have emerged, including the single-value CGR model, linear CGR model, nonlinear CGR model, Markov model, time-dependent (TD) and -independent (TI) generalized extreme value distribution (GEVD) models [38]. These models cater to specific material characteristics and corrosive environments, making them more suitable for particular situations. Among them, the power-law model [39] stands as a widely accepted and commonly utilized probabilistic model, enabling the prediction of CGR in buried pipelines, as shown below:

$$v_d(t) = k\alpha\beta(t - t_0)^{\beta-1} \tag{3}$$

where $v_d(t)$ is the CGR over time; the dimensionless parameters α and β are the soil-pipe dependent factors, both of which are random variables; t and t_0 are the pipeline exposure time and corrosion initiation time, respectively; k represents the effect of protective activities on pipeline corrosion, varying stochastically between 0 and 1. A value of 1 signifies the absence of any anti-corrosion measures, while a value of 0 indicates complete protection against corrosion—an ideal scenario.

According to Eq. (3), the time-dependent corrosion sizes can be derived, as represented below, from the time integration of the CGR [39]:

$$d(t) = d_0 + k\alpha(t - t_0)^{\beta} \tag{4}$$

where $d(t)$ is the corrosion depth over time; d_0 represents the initial corrosion depth.

Since there is no available empirical model for corrosion length growth, a linear CGR model from Zhou and Nessim [40] has been embraced in this study. It is posited that the corrosion length experiences growth at a consistent rate, as expressed below:

$$L(t) = L_0 + kv_L(t - t_0) \tag{5}$$

where $L(t)$ is the time-dependent corrosion length, while L_0 is the initial corrosion length; v_L refers to the corrosion length rate, which is a random variable in this study.

After estimating corrosion depth and length, they can be used to predict the burst pressure of the pipeline under corrosion. Numerous industry-accepted burst capacity models have been proposed to assess the internal pressure threshold at which pipeline failure occurs due to corrosion-induced weakening. Notable examples of these models include PCORRC [41], DNV RP-F101 [42], CSA-Z662 [43], ASME B31 G, and its modified version [44], as presented below: i) PCORRC model

$$P_b(t) = \frac{2\delta\sigma_u}{D}\left(1 - \frac{d(t)}{\delta}M(t)\right) \tag{6}$$

$$M(t) = 1 - \exp\left(-0.157\frac{L(t)}{\sqrt{\frac{D}{2}(\delta - d(t))}}\right) \tag{7}$$

ii) DNV RP-F101 model

$$P_b(t) = \frac{2\delta\sigma_u}{D - \delta}\left(\frac{1 - \frac{d(t)}{\delta}}{1 - \frac{d(t)}{\delta M(t)}}\right) \tag{8}$$

$$M(t) = \sqrt{1 + 0.31\left(\frac{L(t)^2}{D\delta}\right)} \tag{9}$$

iii) CSA-Z662 model

$$P_b(t) = \begin{cases} \dfrac{2\delta(0.9\sigma_u)}{D}\left(\dfrac{1 - \dfrac{d(t)}{\delta}}{1 - \dfrac{d(t)}{\delta M(t)}}\right), & \sigma_u > 241\text{MPa} \\ \dfrac{2\delta(1.15\sigma_y)}{D}\left(\dfrac{1 - \dfrac{d(t)}{\delta}}{1 - \dfrac{d(t)}{\delta M(t)}}\right), & \sigma_u \le 241\text{MPa} \end{cases} \tag{10}$$

$$M(t) = \begin{cases} \sqrt{1 + 0.6275\left(\frac{L(t)^2}{D\delta}\right) - 0.003375\left(\frac{L(t)^2}{D\delta}\right)}, & \frac{L(t)^2}{D\delta} \leq 50 \\ 3.3 + 0.032\left(\frac{L(t)^2}{D\delta}\right), & \frac{L(t)^2}{D\delta} > 50 \end{cases} \tag{11}$$

iv) ASME B31 G model

$$P_b(t) = \begin{cases} \frac{2\delta}{D}(1.1\sigma_y)\left[\frac{1 - \frac{2}{3}\left(\frac{d(t)}{\delta}\right)}{1 - \frac{2}{3}\left(\frac{d(t)}{\delta M(t)}\right)}\right], & \frac{L(t)^2}{D\delta} \leq 20 \\ \frac{2\delta}{D}(1.1\sigma_y)\left[1 - \frac{d(t)}{\delta}\right], & \frac{L(t)^2}{D\delta} > 20 \end{cases} \tag{12}$$

$$M(t) = \sqrt{1 + 0.8\left(\frac{L(t)^2}{D\delta}\right)} \tag{13}$$

v) ASME B31 G modified model

$$P_b(t) = \frac{2\delta}{D}(\sigma_y + 69)\left(\frac{1 - 0.85\frac{d(t)}{\delta}}{1 - 0.85\frac{d(t)}{\delta M(t)}}\right) \tag{14}$$

$$M(t) = \begin{cases} \sqrt{1 + 0.6275\left(\frac{L(t)^2}{D\delta}\right) - 0.003375\left(\frac{L(t)^2}{D\delta}\right)}, & \frac{L(t)^2}{D\delta} \leq 50 \\ 3.3 + 0.032\left(\frac{L(t)^2}{D\delta}\right), & \frac{L(t)^2}{D\delta} > 50 \end{cases} \tag{15}$$

where D is the pipe's outer diameter; δ is the pipe's wall thickness; σ_u and σ_y are the ultimate tensile strength and yield strength of the pipeline steel, respectively; $M(t)$ is the time-dependent bulging stress magnification factor.

Each model incorporates its own methodologies and assumptions, considering factors such as the degree of corrosion, corrosion morphology (e.g., uniform corrosion, pitting corrosion), residual wall thickness, material properties, and pipeline operating conditions (e.g., internal pressure, temperature). The burst pressure ($P_b(t_1)$) when the corrosion is detected (t_1) can be obtained according to the corrosion depth $d(t_1)$ and corrosion length $L(t_1)$. Notably, t_1 is influenced by the stochastic nature of the ILI interval. Once the time, t_1, is determined, it becomes possible to predict the pipe's absorption capability by calculating the integral of $P_b(t)$ over the interval from t_0 to t_1, as illustrated below:

$$Ab = \int_{t_0}^{t_1} P_b(t)\mathrm{d}t \tag{16}$$

where Ab denotes the absorption capability.

3.3.2. Adaption capability modeling

The adaption capability refers to the pipeline's capacity to adapt to the disrupted state. This capacity can be achieved by utilizing corrosion protection strategies to maintain or partially recover the performance. However, it is challenging to predict and model the effect of adaptive measures on the change of burst pressure. Detailed quantification methods are described in Section 3.4.

Once corrosion defects are identified through ILI and their geometric data is collected, it is essential to wait for pipeline companies to assess the data and determine the severity of the defects. The duration of this evaluation process, which involves decision-making, is a random variable. The evaluation results enable to plan repair activities accordingly. Based on the extent of corrosion depth, the repair plan encompasses three types: no repair required, limited-time repair, and immediate repair, as follows [45]:

i) No repair is needed if the maximum corrosion depth (d_{max}) is less than or equal to 10 %δ;
ii) In cases when d_{max} surpasses 10 %δ but remains within 40 %δ, no repair is necessary if the longitudinal corrosion length (L) does not exceed the acceptable length from Eq. (17), or the pipeline's maximum operating pressure (MOP) meets Eq. (18):

$$L_a = 1.12\sqrt{D\delta\left[\left(\frac{\frac{d_{max}}{\delta}}{1.1 \times \frac{d_{max}}{\delta} - 0.11}\right)^2 - 1\right]} \tag{17}$$

$$\mathrm{MOP} \leq K \cdot P_b \tag{18}$$

where L_a is the acceptable longitudinal corrosion length; K refers to the design factor.

i) If d_{max} exceeds 40 %δ, a deadline is set for repair;
ii) Immediate repair is required in the event that d_{max} exceeds 80 %δ or if d_{max} surpasses the critical corrosion depth d_c written below [46]:

$$d_c = \delta - \frac{F \times \mathrm{MOP} \times D}{2 \times \mathrm{SMYS}} \tag{19}$$

$$F = \frac{2\delta \times \mathrm{SMYS}}{P_{design} \cdot D} \tag{20}$$

where d_c represents the critical corrosion depth; F is the safety factor, while SMYS is the specified minimum yield strength of pipeline material; P_{design} donates the design pressure of pipelines. Once the repair threshold is determined, the next step involves planning specific repair strategies for corrosion with various severity. After planning the repair activities, the pipe's burst pressure, $P_b(t_2)$, at time t_2 can be predicted. Note that the value of t_2 is influenced by the decision-making duration. By integrating $P_b(t)$ during $t_1 \sim t_2$, the adaption capability can be obtained as shown below:

$$Ad = \int_{t_1}^{t_2} P_b(t)\mathrm{d}t \tag{21}$$

where Ad is the adaption capability.

3.3.3. Restoration capability modeling

Restoration capability is the ability to restore pipeline transportation performance entirely using repair actions. Such strategies involve re-coating, installation of sleeves or clamps, and CMR in corroded pipe segments [45]. *Re*-coating involves the application of a fresh protective coating onto the exterior surface of the pipeline. This practice serves to prolong the operational lifespan of the pipeline by impeding the advancement of corrosion and deterioration. Installing sleeves is a prominent method for repairing corroded pipelines and is typically classified into A-type sleeves, B-type sleeves, and steel sleeves filled with epoxy resin [47]. Fabricated from corrosion-resistant materials, these sleeves are designed to be installed over the corroded parts, acting as protective layers that prevent further corrosion and reinstate the pipeline's structural integrity. Bolt-on clamps can also be utilized for localized corrosion. These clamps, crafted from durable materials, are applied around the corroded areas to support and inhibit further deterioration. An emerging trend involves the use of composite materials like fiberglass-reinforced polymers (FRP) for pipeline repair [48]. These materials boast high strength-to-weight ratios and excellent corrosion resistance, offering additional structural support to the damaged pipelines. In severe corrosion cases, a simple repair strategy may not be sufficient, necessitating the replacement of the corroded pipe segment. This process involves the removal of the damaged part and the installation of a new pipe segment. Replacement time serves as a quantitative indicator. Pipeline replacement is inherently time-consuming, contingent on factors such as pipeline size, replacement costs, the number of personnel, and allocated resources. In general, the restoration capability exhibits a negative correlation with repair time. In this work, the repair time is a stochastic variable that varies depending on the chosen repair measures. Increasing repair funds can effectively shorten the repair time and enhance the transportation resilience of the pipeline system. Investing in adequate resources substantially improves the pipeline's ability to recover from disruptions. Once the repair time ($t_2 \sim t_3$) is determined based on various repair measures, the recovery ability can be calculated by integrating $P_b(t)$ over the interval $t_2 \sim t_3$:

$$Res = \int_{t_2}^{t_3} P_b(t)\mathrm{d}t \tag{22}$$

where *Res* is the restoration capability.

3.4. PSR quantification and improvement

After the determination of the pipe's absorption, adaption, and restoration capabilities, the resilience expressions from Eqs. (1) and (2) transform into those shown in Eqs. (3) and (4) to assess the pipeline's resilience.

$$R = \frac{\int_{t_0}^{t_3} S(t)\mathrm{d}t}{S_0(t_3 - t_0)} = \frac{\int_{t_0}^{t_1} P_b(t)\mathrm{d}t + \int_{t_1}^{t_2} P_b(t)\mathrm{d}t + \int_{t_2}^{t_3} P_b(t)\mathrm{d}t}{P_b(t_0)(t_3 - t_0)} = \frac{Ab + Ad + Res}{P_b(t_0)(t_3 - t_0)} \tag{23}$$

$$R = \frac{1}{N}\sum_{i=1}^{N}\frac{\int_{t_0}^{t_3} S_i(t)\mathrm{d}t}{S_0(t_3 - t_0)} = \frac{1}{N}\sum_{i=1}^{N}\frac{\int_{t_0}^{t_1} P_{bi}(t)\mathrm{d}t + \int_{t_1}^{t_2} P_{bi}(t)\mathrm{d}t + \int_{t_2}^{t_3} P_{bi}(t)\mathrm{d}t}{P_{bi}(t_0)(t_3 - t_0)} = \frac{1}{N}\sum_{i=1}^{N}\frac{Ab_i + Ad_i + Res_i}{P_{bi}(t_0)(t_3 - t_0)} \tag{24}$$

The resilience value is ranging between 0 and 1. A perfectly resilient system ($R = 1$) corresponds to an ideal condition where disruptions exert no adverse effect on pipeline transportation performance, with the pipeline promptly absorbing disruption impacts. Conversely, if the pipeline sustains irreparable damage, R equates to zero. Moreover, analyzing the sensitivity of resilience parameters allows for a deeper understanding of how resilience varies with changes in input parameters. The improvement of PSR can be achieved by considering maintenance costs and various combinations of repair measures.

4. The proposed algorithm

This section provides a stochastic dynamic algorithm with the dynamic Monte Carlo Simulation (MCS) method to predict the PSR. Fig. 4 shows a flowchart of the algorithm, an iterative process in which the uncertainty of PSR is modeled. As shown in Fig. 4, the algorithm consists of three main steps:

The first step is to model the absorption capability. The initial iteration is set to 1, along with the disruption initiation time set to t_0=0. Given the presence of corrosion as the disruption, we utilize Eqs. (3)-(5) in Section 3.3.1 to estimate the CGR, and the dimensions (depth and length) of corrosion defects. These estimations are then employed to predict the burst pressure of pipelines subject to corrosion. A random dataset (0∼1) is generated to express the efficacy of anti-corrosion measures (k). If the ILI period (t_1) is determined, we can acquire the pipe's burst pressure at time t_1.

The second step involves modeling the adaption capability, with the key aspect being the determination of decision-making duration t_2. This step allows for the prediction of the pipe's burst pressure from t_1 to t_2. Note that the deterioration effect of corrosion on pipeline burst pressure during the period of decision-making is presumed to be negligible.

The final step is to model the restoration capability, entailing the evaluation of the estimated corrosion depth obtained in the first step to determine the corresponding repair interval it falls into. The process for determining the repair interval involves first acquiring d_c utilizing Eq. (19), and then comparing this value with 40 % of the wall thickness. If d_c is $<0.4\delta$, the repair interval is assigned as follows: [0, 0.1δ]; (0.1δ, d_c/δ]; (d_c/δ, 0.8δ]; (0.8δ, δ]. On the other hand, if the critical corrosion depth is equal to or greater than 40 % of the wall thickness, the repair interval is set to: [0, 0.1δ]; (0.1δ, 0.4δ]; (0.4δ, 0.8δ]; (0.8δ, δ]. Defects in the first two intervals do not require immediate repair but should be subject to re-coating at a suitable moment. For the defect in the third interval, one of the following repair activities needs to be implemented: CMR, B-type sleeves, and bolt-on clamps. For corrosion defects falling within the interval of (0.8δ, δ], the necessary action involves the pipe replacement. Random variations are employed to determine the time, t_3, required for pipeline repairing.

Following the three steps, the complete performance curve ($t_0 \sim t_3$) can be derived. These steps must be repeated until the number of iterations surpasses the desired number of iterations N. During each iteration, the resilience is calculated using Eq. (1). Eventually, PSR is determined by employing Eq. (2), which considers the uncertainties arising from the dynamic resilience evolution process as well as corrosion growth over time.

5. Case study

In this section, a case study of a 20-inch refined oil pipeline serves to illustrate the proposed framework. The pipeline material is API X60 pipeline steel, with a SMYS of 413.7 MPa. The pipeline has an outer diameter of 508 mm and is composed of sections with a wall thickness equal to 7.1 mm. P_{design} of the pipeline is 11.8 MPa, while its MOP is 6.8 MPa. The soil category for pipeline crossing terrain includes clay, clay loam, and sandy clay loam. Thus, α and β in Eq. (3) follow a Gamma distribution and a Lognormal distribution, respectively [44]. Adjusting these parameters allows for the simulation of various degrees of pipeline corrosion caused by different soil types. Their mean values (μ) are 0.475 and 0.592, while their standard deviations (σ) are 0.13 and 0.023, respectively [49]. The corrosion length growth rate is treated as a lognormal random variable [50]. The anti-corrosion ability coefficient k is assumed as a uniform random variable ranging from 0 to 1. The application of a uniform distribution is due to the fact that there is no quantitative data available to justify a more specific probability distribution. By assigning equal probabilities to all values within the range of 0∼1, we assume no prior knowledge or preference for any specific anti-corrosion actions. It is assumed that the minimum interval between two ILIs should be at least 3 years, while the maximum interval should not exceed 8 years. According to information provided by the ILI service provider, following the completion of an ILI, it is anticipated that the average duration for data analysis and the development of a repair plan will be 3 months, with a standard deviation of 10 days. There are no available temporary corrosion protection measures in the given case. Turning to repair activities, the re-coating process is assumed to follow a uniform distribution. Based on the estimation of the ILI service provider, the average time required for re-coating is 6 months, with a standard deviation of 15 days. CMR demonstrates a highly effective repair effect on pipeline corrosion. They can essentially restore the corroded pipe to its original strength, providing a cost-effective solution without the need for hot work [51]. Thus, this study has selected CMR as the preferred repair activity for the defects falling within the repair interval of (0.4δ, 0.8δ]. Assuming a uniform distribution for the CMR process, the

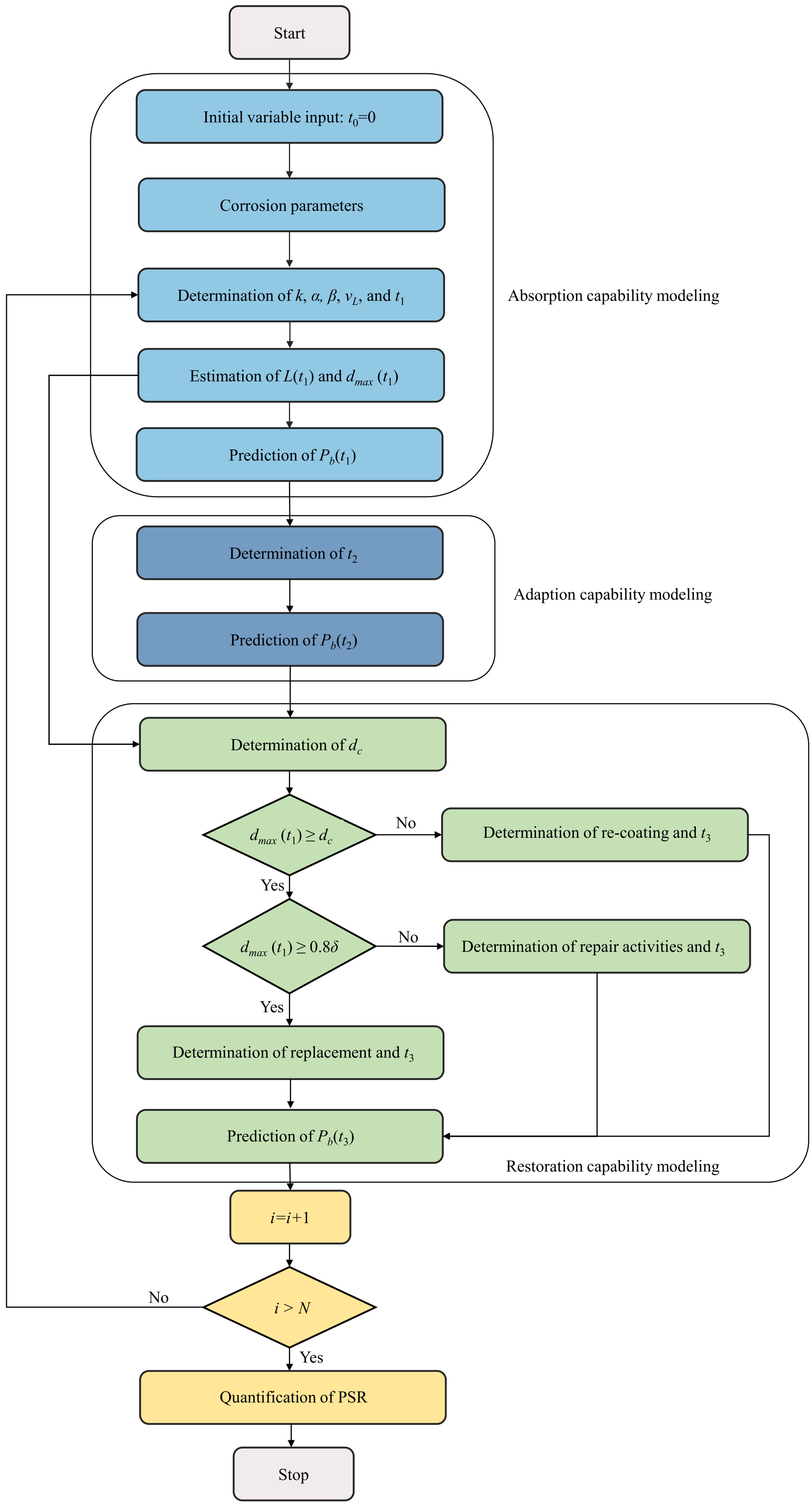

Fig. 4. Flowchart of the designed algorithm for PSR.

estimated average duration is 3 months with a standard deviation of 10 days. Finally, it is also assumed that the pipe replacement follows a uniform distribution. Its mean time is 4 months while its standard deviation is 10 days. The basic attributes and variables of the case pipeline are tabulated in Table 1. Notably, the repair time in this table denotes the duration between the conclusion of the decision-making process and the successful completion of repairs. This period includes the preparation of necessary materials, the assembly of personnel, safety training sessions, and any other preliminary activities required for the repair process.

6. Results and discussion

6.1. PSR evolution scenarios

The designed algorithm described in Section 4 is implemented using the MATLAB® 2020b software package. Truncated normal distributions have been assumed to avoid negative values for the stochastic times (Table 1). The ILI service provider recommended the burst pressure model in the ASME B31 G empirical design code. Therefore, in this study, the ASME B31 G model is employed to predict the burst pressure of corroded pipelines. The total number of iterations N is 105. In this work, the uncertainties surrounding resilience have been taken into account. Hence, a multitude of (10^5) resilience evolution scenarios have been generated, each accompanied by a distinct PSR value.

Fig. 5 shows 3 PSR evolution scenarios. As is clear, the red curve signifies the optimal PSR scenario. The black curve shows a PSR evolution scenario with an average value; while the blue curve represents the evolution scenario with the lowest PSR value. The mean PSR value is 0.9987, ranging from a minimum of 0.8943 to a maximum of 1. The scenario involving a PSR value of 1 signifies that there is virtually no corrosion, resulting in no performance degradation. In the scenario with a minimum PSR value of 0.8943, the timing for the initial ILI is stochastically set as the 84th month (7th year) after the pipeline's service. In this situation, the anti-corrosion ability is assigned a random value of 0.7252, indicating inadequate protection against corrosion. This leads to corrosion depths exceeding 0.8δ. Following 3 months of data analysis, a decision is made to replace the corroded pipe segment. This replacement process extends over 4 months and necessitates a pipeline shutdown, resulting in the pressure of the pipeline dropping to zero. Subsequent to the successful replacement, the burst pressure is restored to its initial value of 12.72 MPa. In the scenario where the PSR value equals the average of 0.9987, the initial ILI is randomly scheduled for the 69th month post-pipeline operation. At this moment, the depth of the corrosion defect is measured at 0.0547δ with a length of 6.23 mm. Given that the corrosion depth is below the critical depth of 0.1833δ, as calculated by Eq. (5), the decision is made to apply a re-coating to the corroded pipe segment. Assuming that the burst pressure would remain constant throughout the repair period. This 3-month rehabilitation program ultimately achieves a successful repair, reinstating the initial burst pressure. Given the wide range between minimum and maximum PSR values, the stochastic nature of resilience is evident. In the scenario with minimal PSR value, resilience loss arises not only due to wall-thinning but primarily from pipeline shutdowns during replacement. Although the replacement operation is relatively short, its resilience loss cannot be underestimated.

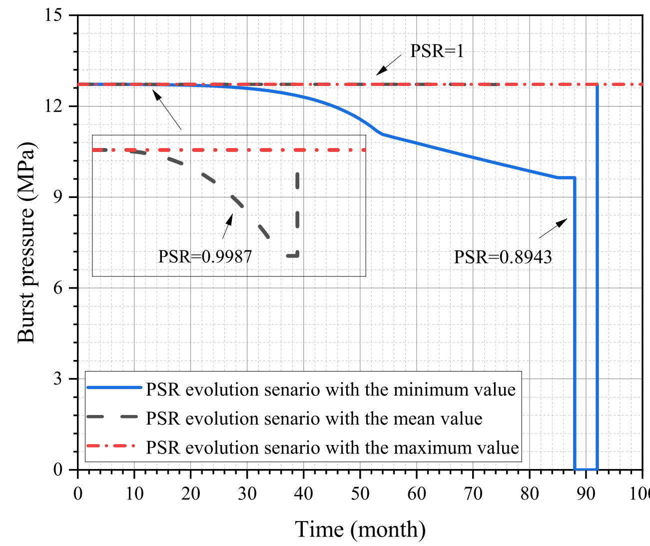

Fig. 5. PSR evolution scenarios exposed to corrosion.

Table 1
Basic attributes and variables of the case pipeline [49,51].

Variable	Mean	COV	Distribution
Diameter (D)	508 mm	–	Deterministic
Wall thickness (δ)	7.1 mm	–	Deterministic
Corrosion initiation time (t_0)	0	–	Deterministic
Initial corrosion depth (d_0)	0 mm	–	Deterministic
Initial corrosion length (L_0)	0 mm	–	Deterministic
Corrosion length growth rate (v_L)	1.698 mm/year	50 %	Lognormal
Proportionality factor (α)	0.475	27 %	Gamma
Exponent factor (β)	0.592	3.9 %	Lognormal
Maximum operating pressure (MOP)	6.8 MPa	–	Deterministic
Design pressure (P_{design})	11.8 MPa	–	Deterministic
Specified minimum yield strength (SMYS)	413.7 MPa	–	Deterministic
Anti-corrosion ability (k)	0.5	58 %	Uniform
ILI interval	5.5 years	26 %	Uniform
Decision-making duration	3 months	16 %	Truncated Normal
Re-coating time	6 months	8 %	Truncated Normal
Composite material reinforcement time	3 months	11 %	Truncated Normal
Replacement time	4 months	8 %	Truncated Normal

6.2. Absorption capability analyse

The absorption capability of pipelines against corrosion depends heavily on the efficacy of anti-corrosion measures and the implementation time of ILI. The effect of anti-corrosion ability on the PSR is depicted in Fig. 6. The mean value of the variables in Table 1 is chosen as the input data. Fig. 6**a** illustrates the PSR evolution scenario as the anti-corrosion ability k varies from 0.1 to 1 (strong to weak corrosion resistance). Since $k = 0$ represents an ideal scenario, it is not considered. Fig. 6**a** shows that with an escalating value of k, the decrement in the burst pressure curve becomes more pronounced, leading to heightened performance losses and a reduction in PSR from 0.999 to 0.997 (Fig. 6**b**). The results indicate the correlation between weakening anti-corrosion efficacy and the pipeline's diminished resilience against corrosion. As mentioned earlier, various protective strategies, including anti-corrosion coatings, cathodic protection, and chemical inhibitors, can be employed to augment pipeline resistance to corrosion. In this work, the anti-corrosion technique employed is not specified, but the effectiveness of the protective measures is simplified to a value between 0 and 1. Hence, future directions could focus on the impact of distinct protective measures on a pipeline's absorption capability against corrosion.

On the other side, the ILI timing also exerts an influence on the pipe's absorption capability, as shown in Fig. 7. Fig. 7**a** demonstrates the PSR's trajectory as the implementation time of ILI extends from the 3rd year to the 8th year. It is evident that as the ILI is delayed, the pipeline's burst pressure continues to decrease, and the magnitude of performance loss

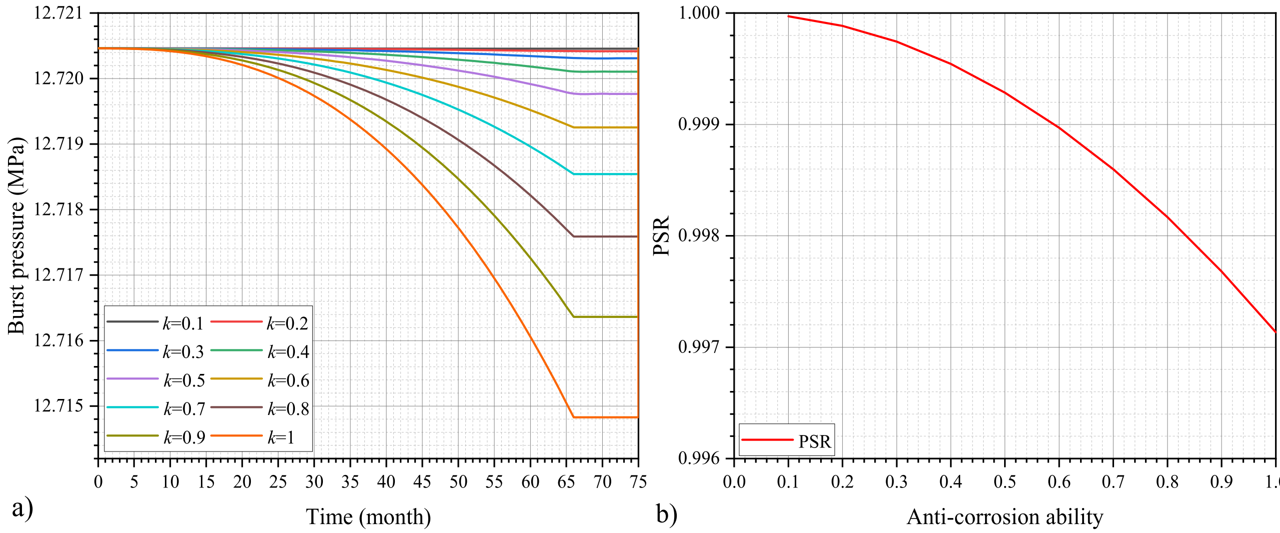

Fig. 6. Effects of anti-corrosion ability on the PSR: a) PSR evolution scenarios; b) PSR values.

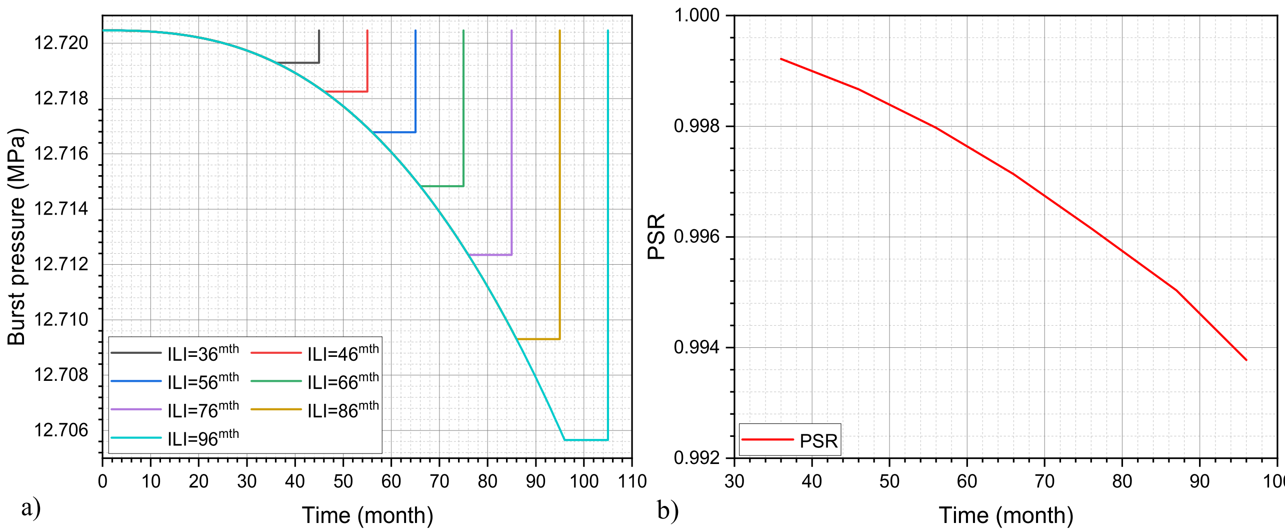

Fig. 7. Effects of ILI timing on the PSR: a) PSR evolution scenarios; b) PSR values.

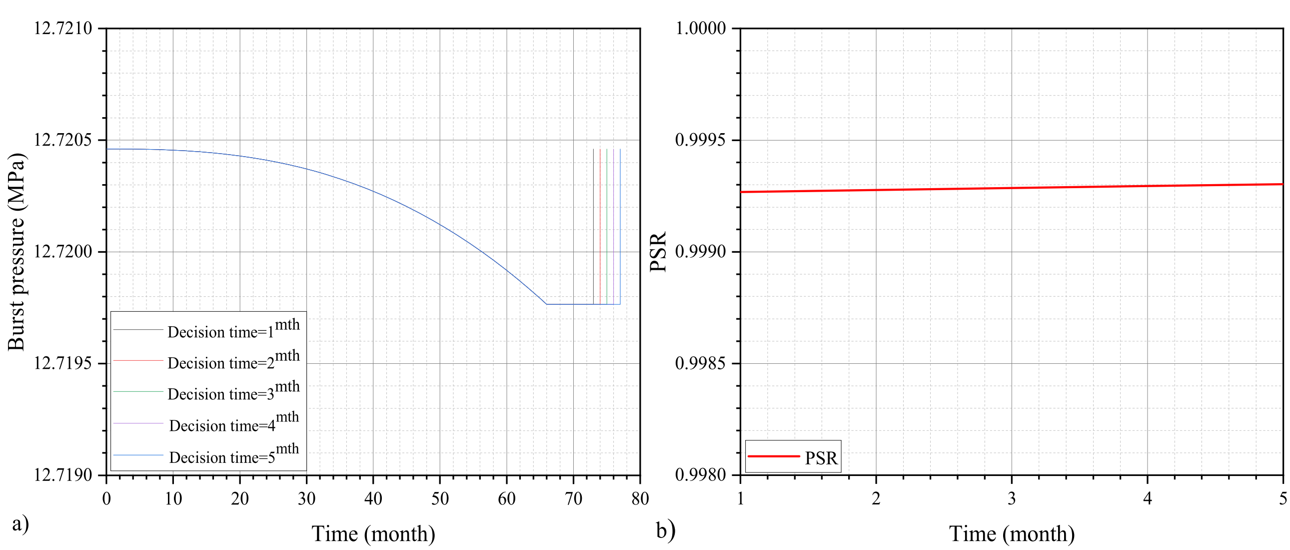

Fig. 8. Effects of decision-making duration on the PSR: a) PSR evolution scenarios; b) PSR values.

increases. This causes a reduction of PSR from 0.999 to 0.993 (Fig. 7**b**). The findings highlight the efficacy of early ILI in hastening the detection of corrosion-related defects, thereby decreasing performance loss and elevating PSR. Nonetheless, the economic implications of implementing ILI should be considered. Frequent ILI necessitates shorter intervals but also entails greater expenses. While early-stage ILI enables timely maintenance/repairs in the face of corrosion, the increased cost can pose challenges for pipeline owners. Therefore, future research could explore strategies for optimizing pipeline resilience by striking a balance between the interval and cost of ILI.

6.3. Adaption capability analysis

Fig. 8**a** shows the impact of the decision-making duration for repair plans following ILI on PSR. As illustrated in the figure, the performance curve remains unaltered during the absorption stage. In the subsequent adaption stage, there is a slight escalation in the loss of pipeline transportation performance corresponding to lengthening decision duration; however, this difference remains marginal, as illustrated by the PSR evolutions in Fig. 8b. This is attributed to the negligible duration of repair decisions (In days) compared with the service time (In years) preceding the ILI. Despite this limitation, the prompt development and execution of a repair plan can mitigate the performance loss and enhance the PSR. Therefore, decreasing the adaption period and initiating early restoration also constitute adaption actions to improve the PSR.

6.4. Restoration capability analyses

The restoration capability predominantly depends on the implementation time of repair activities, i.e., the complete recovery time. Figs. 9-11 demonstrate the effects of the three distinct repair measures' completion durations (re-coating, CMR, and pipe replacement) on the PSR. It becomes evident from Figs. 9**a** and 10**a** that as increasing durations of re-coating and CMR, the pipeline's performance loss gradually increases. However, their impact on the PSR remains almost inconsequential (Figs. 9**b** and 10**b**). On the other side, Fig. 11**a** illustrates the PSR evolution scenario under different pipe replacement time. Evidently, as the pipe replacement time extends, the pipeline's performance loss becomes more pronounced. Notably, Fig. 11**b** shows that the PSR declines from 0.97 to 0.92. The discrepancy in PSR between Figs. 9 and 10 and Fig. 11 arises due to the operational feasibility of re-coating and CMR, both of which can be executed without pipeline shutdown. As a result, the pipe's transportation performance is assumed to remain unaffected during the implementation. In these scenarios, PSR is exclusively tied to the implementation time of the measures. However, the replacement of a pipe necessitates a temporary shutdown, followed by the removal of the corroded segment and substitution with an intact one. During this period, the pipe's transportation performance drops to 0 [52]. Hence, in this scenario, PSR is not solely tied to the duration of repair measures but is also influenced by the pipeline's suspension time due to the pipe replacement. The restoration capability analyzed in this section has a limitation: the duration of re-coating and CMR in days is insignificant compared to the pipeline service time (In years) before ILI, leading to minor changes in the PSR and burst pressure values in Figs. 9**b and** 10**b**.

Overall, recovery time is a critical factor influencing restoration capability, and there is an inverse relationship between them. To reduce recovery time during the restoration stage, it becomes imperative to avert the need for pipe replacements due to excessive corrosion. This requires enhancing the pipeline's absorption capability during the absorption stage and shortening the time to detect corrosion. Hot tapping/plugging [53] can improve the pipeline's resilience. This measure allows the safe removal of corroded pipe segments without system shutdown, thereby reducing performance loss.

6.5. Sensitivity analysis

Fig. 12 shows the sensitivity of input variations to the PSR. As is apparent, repair time exhibits the highest sensitivity to PSR. The ILI time and anti-corrosion ability also notably influence the PSR, followed by decision time, proportionality factor, exponent factor, and corrosion length growth rate. The results indicate that the pipeline service resilience is predominantly impacted by its absorption and restoration capabilities. Reducing the absorption and recovery time can significantly enhance the pipeline's resilience. However, it is worth noting that this work does not account for the costs associated with different repair strategies and ILI plans. Therefore, a future direction involves integrating the proposed framework with economic tools like cost-benefit analysis. This study focuses on corrosion as a disruption to pipelines, given that corrosion is the primary cause of failure for steel energy pipelines, which sets it apart from other crucial infrastructures. Besides corrosion, external factors such as geological disasters, third-party damage, and even terrorist attacks could compromise the pipeline's service resilience [54,55]. Thus, future research can examine the pipeline's service resilience against other disruptions. The investigation of the influence of diverse repair strategies and inspection plans on the pipeline's resilience could also be a focus of future research.

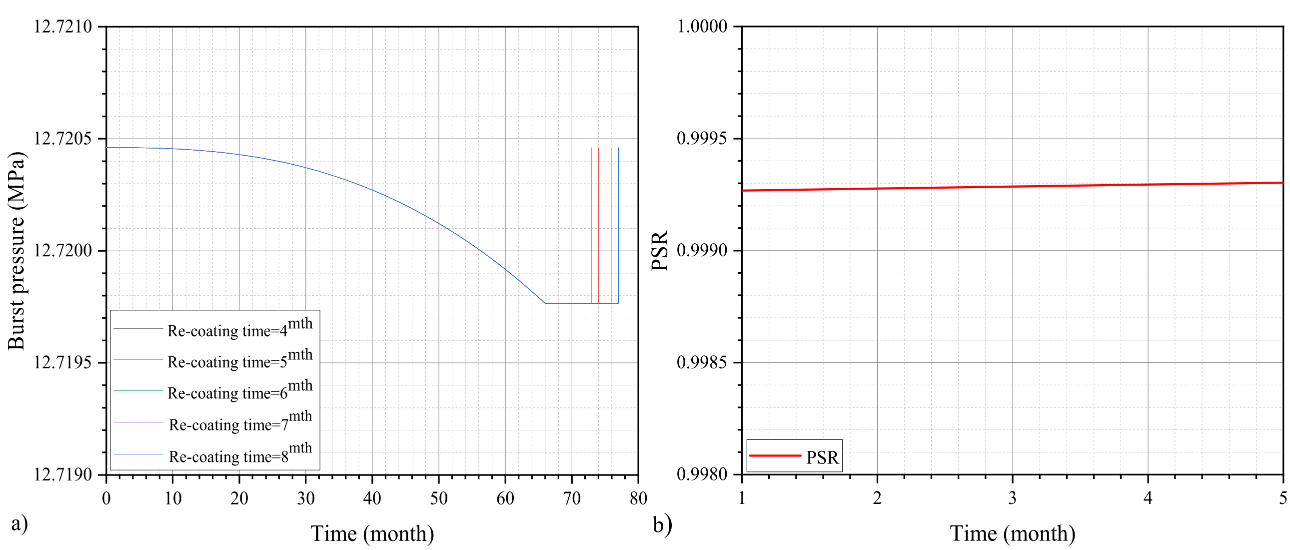

Fig. 9. Effects of re-coating time on the PSR: a) PSR evolution scenarios; b) PSR values.

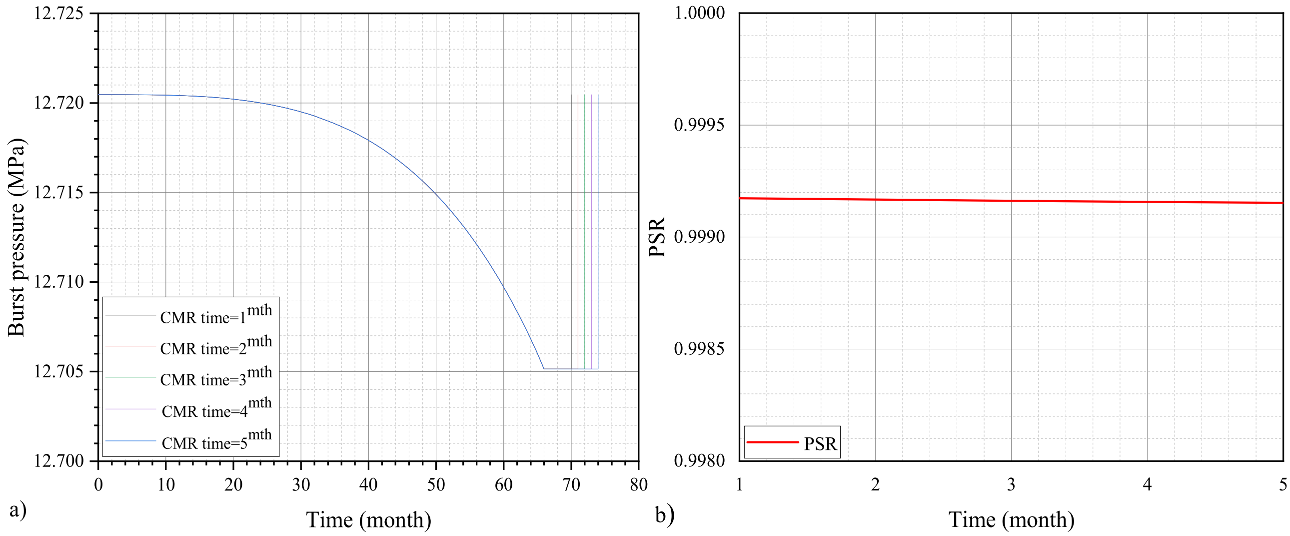

Fig. 10. Effects of CMR time on the PSR: a) PSR evolution scenarios; b) PSR values.

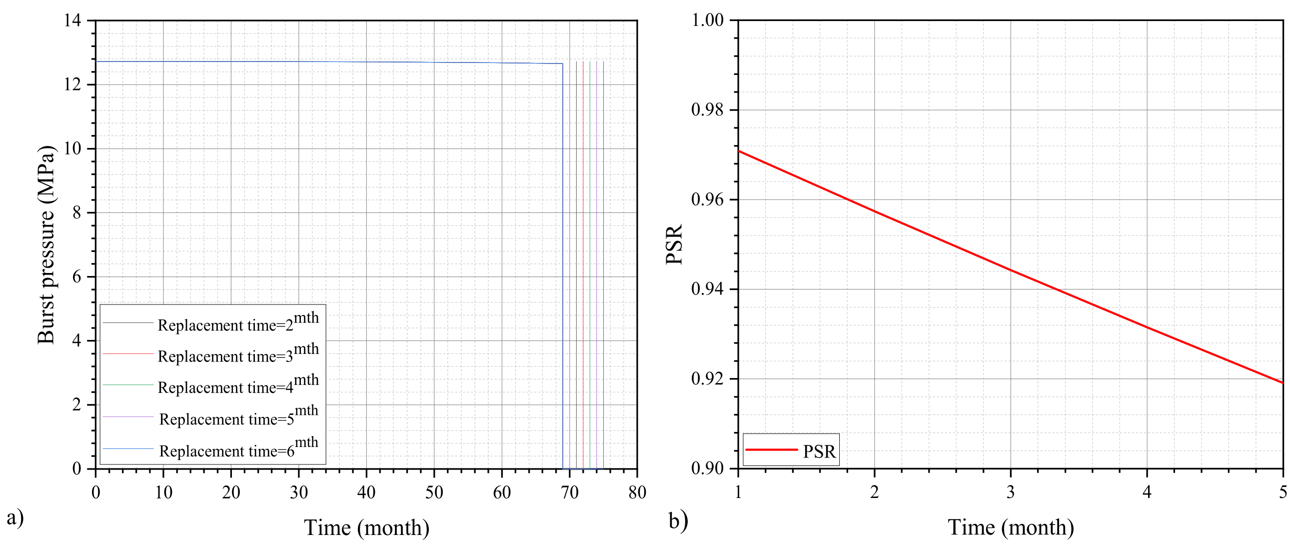

Fig. 11. Effects of replacement time on the PSR: a) PSR evolution scenarios; b) PSR values.

6.6. *Discussion*

This paper marks the first definition of service resilience of long-distance energy pipelines against corrosion. It introduces a quantitative framework for resilience that combines future corrosion growth with dynamic repair processes. Prior studies mainly concentrated on the resilience of gas networks, emphasizing system-level restoration and optimization following disruptions [17,19,25–27]. The proposed framework shifts the focus to assessing and enhancing the transportation capacity of individual long-distance pipelines from an inspection and repair perspective. In this work, pipeline service resilience is defined as the capacity of the pipeline to absorb, adapt, and recover from disruptions to maintain its transportation performance. The absorption capability concerns counteracting the impact of disruptions, while adaption and restoration capacities consider the ability to sustain and recover from such disruptions. This study models these three capabilities. Eqs. (1) and (2) are typical methods for resilience quantification; however, their potential limitation is that the resulting resilience values may be associated with different restoration processes [13]. Future efforts should be directed at refining the modeling of absorption, adaption, and restoration capacities while also employing additional metrics to indicate the transportation performance of pipelines. For instance, the Center of Resilience and Resilience Bandwidth can be metrics to assess resilience and mitigate potential limitations [13,28,56]. Apart from acquiring the temporal changes in the recovery process, spatial variability can be captured through spatial resilience measures, thereby refining the resilience modeling [57,58]. Moreover, due to the absence of corrosion history data for the case pipeline, this paper solely addresses resilience quantification in the initial ILI cycle, leading to minor changes in the PSR and burst pressure values. However, this limitation does not impede the proposed framework's applicability and reliability for resilience quantification in other different ILI cycles, with the exception that pipe's corrosion history data should be considered under these situations. In the case of abundant data, other case studies can also be employed to validate our proposed framework. Moving forward, a holistic approach could involve assessing resilience across the pipeline's life cycle and encompassing more factors such as corrosion growth, inspection planning, and repair strategies.

7. Conclusions

Corrosion deteriorates pipeline integrity, reduces transportation

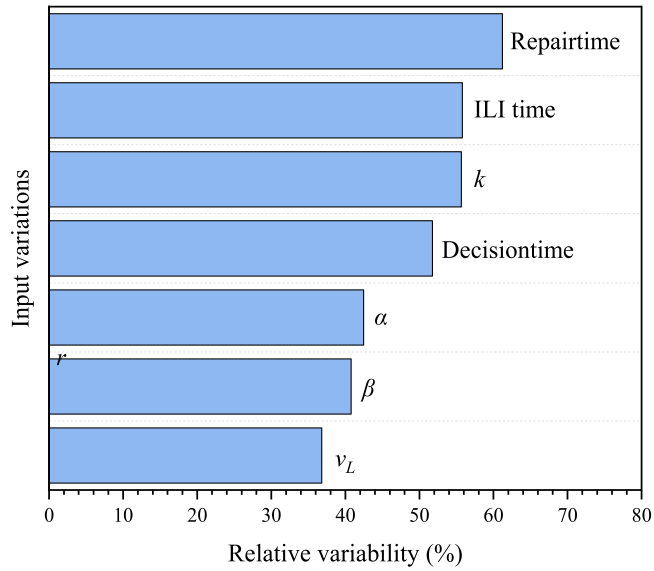

Fig. 12. Sensitivity analysis outcomes of the input variables.

performance, and affects service resilience. In response, a dynamic stochastic approach is proposed to quantify the resilience of pipelines against corrosion. This method effectively considers the uncertainty related to PSR regarding future corrosion growth, dynamic ILI plans, and distinct repair strategies (re-coating, CMR, and pipe replacement). Within this framework, PSR is modeled as a function of absorption, adaption, and restoration capabilities through the pipe's burst pressure metric. Dynamic MCS technique is employed to model the potential resilience evolution scenarios to predict the PSR. The proposed methodology and algorithm were validated on an in-service pipeline. Unlike the conventional risk-based approach focusing on pipeline failure, the proposed resilience-based approach boasts the advantage of zooming into the pipeline system's capability of handling corrosion as a disruption to its operation and seeking to enhance this capability. This work involves three primary contributions: i) the definition of resilience for long-distance energy pipelines against corrosion is the first one of its kind; ii) a quantitative resilience modeling approach for pipe service resilience is established, combining future corrosion growth with dynamic recovery process; iii) the integration of pipeline corrosion prediction, mitigation, and repair decisions into the framework of resilience, which is an innovative way to manage pipeline service performance and safety.

The results show that the PSR value ranges from 0.8943 to 1 due to the uncertainty of the resilience evolution process. The noteworthy impact on PSR includes repair time, ILI intervals, anti-corrosion ability, decision-making time, proportionality and exponent factors (corrosion depth growth rate), and corrosion length growth rate (in decreasing order of sensitivity). It is suggested that pipe replacement should be avoided due to its detrimental effect of over 5 % on PSR compared to re-coating and CMR due to a required temporary shutdown. Therefore, it is imperative to enhance the anti-corrosion ability in the absorption stage and shorten the time needed to detect corrosion. The proposed framework can potentially be applied in software systems designed for pipeline integrity management and corrosion monitoring control. By incorporating this framework, the pipeline industry can achieve a more intelligent and proactive approach to maintenance, thus contributing to its overall development and efficiency. Common approaches in validating the PSR quantitative framework involve historical data comparison, experimental testing through additional inspections, and seeking expert assessment. These methods can evaluate the accuracy of our proposed framework. However, their application is currently hindered by data insufficiency, prompting our consideration for validation efforts in future work. The limitation of this paper is the neglect of costs associated with different repair strategies and ILI plans. Therefore, a future direction involves integrating our proposed framework with economic tools like cost-benefit analysis. Besides corrosion, future research can also examine PSR against other external factors, such as geological disasters, third-party damage, and even terrorist attacks.

CRediT authorship contribution statement

Yunfei Huang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Guojin Qin:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation. **Ming Yang:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Maria Nogal:** Writing – review & editing, Validation, Supervision, Methodology, Investigation.

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.

Acknowledgement

This work was supported by China Scholarship Council (CSC No 202209225016), Natural Science Foundation of Sichuan Province (No. 24NSFSC6741), Natural Science Starting Project of Southwest Petroleum University (SWPU No 2022QHZ016).

Data availability

The data that has been used is confidential.

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