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A risk-based approach to inspection planning for pipelines considering the coupling effect of corrosion and dents

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ABSTRACT

RBI, referring to a risk-based approach to inspection planning, is an established pipeline integrity management method. Both corrosion and dents are the primary threats to pipeline integrity. However, they are often treated separately in RBI without considering their interactions. This coupling may lead to a synergic effect on integrity degradation. The present study proposes an RBI planning framework for pipelines considering external corrosion and dents. Time-dependent pipeline deterioration by dents and corrosion is modeled probabilistically using a Dynamic Bayesian Network (DBN), in-line inspection (ILI) data, and corrosion propagation knowledge. Two failure scenarios (leakage and burst) are considered. The hybrid method, integrating Monte Carlo Simulation (MCS) and Latin Hypercube Sampling (LHS) technique, estimates the pipeline's Probability of Failure (PoF) over time. The pipeline failure risk is quantified by monetizing the Consequence of Failure (CoF). An optimization model of loss-maintenance total expected cost is introduced to determine the optimum inspection period using maximum acceptable risk (MAR) and the lowest total expected cost. A cost-benefit analysis (CBA) is finally implemented to choose appropriate risk reduction measures. The proposed framework is robust and well-validated by a case study on an in-service pipeline.

1. Introduction

Pipelines serve as a crucial medium for long-distance transportation of oil and natural gas (Akhlaghi et al., 2023; Huang et al., 2021). However, pipeline failures, followed by the release of flammable materials, may cause fires and explosions and propagate severe accidents (Li et al., 2022a). An impressive incident is the 2013 Qingdao oil pipeline explosion in China, which caused 62 fatalities, 136 injuries, and a direct economic loss of 750 million CNY (Chen et al., 2022). Hence, pipeline integrity has to be effectively managed to prevent accidents (Ma et al., 2023). Pipeline integrity management (PIM), including testing and inspection, condition assessment, maintenance and repair, quality assurance procedure enforcement, and training, is conducted systematically to ensure the risk level is reasonable and acceptable (GB 7, 3216, 2015). A key element in PIM is inspection and maintenance (IM). The problem of achieving optimized IM strategies using mathematical models has received significant attention in the literature (Besnard and Bertling, 2010; Gölbaşı and Demirel, 2017a, 2017b). According to Khan et al (Khan et al., 2016)., IM strategies have undergone five stages: breakdown maintenance, preventive maintenance based on the detection of degraded components, reliability-based maintenance, reliability-based design, preventive maintenance based on mathematical modeling, and risk-based design and preventative maintenance. In particular, risk-based design and preventive maintenance can determine the frequency and plan of pipeline inspection according to the risk assessment results—the risk-based inspection (RBI) method

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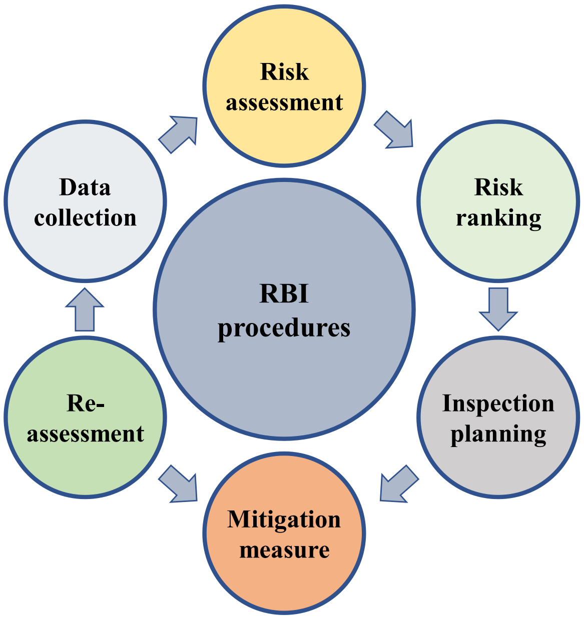

Fig. 1. Aim scope and planning process for RBI methodology.

(Abubakirov et al., 2020). As presented in Fig. 1, an RBI approach is used to assess the risk of equipment failure and prioritize inspection and maintenance activities, considering the likelihood and consequences of such failure (Sözen et al., 2022).

RBI methods have been standardized by standards-setting organizations, including the American Petroleum Institute (API) (API 581, 2008) and Det Norske Veritas (DNV) (DNV-RP-G101, 2010; DNV-RP-C210, 2019), etc. There is a growing body of research on their application to pipelines. These works typically consider factors such as corrosion, mechanical damage, and weld flaws and use techniques such as finite element analysis (FEA) and probabilistic methods to assess the risk of failure. Eskandarzade et al. (2022) proposed a risk assessment framework for subsea pipelines that combines the modified Kent method with the general failure frequency approach from AP 581 (API 581, 2008), which can comprehensively evaluate a pipeline integrity assessment. A framework for risk-based integrity assessment of unpiggable pipelines (where pigging cannot be practiced due to restricted access, pipeline fittings, diameter or wall thickness variations, no pig traps, and operational conditions, etc.) suffering from internal corrosion was developed by Melo et al. (2019) for maintenance cost optimization. In a separate study from Hameed et al. (2021), a modified RBI approach was proposed for offshore steel and flexible pipelines. Case studies found that the study's outcomes present uncertainties that may not be measurable when conducting traditional RBI schemes. Seo et al. (2015) proposed a risk assessment method for subsea pipelines that combines piping systems' design and inspection/maintenance planning aspects to improve existing methods for risk-based inspection of subsea pipelines. A framework by Febriyana et al. (2019) was proposed to address the focus on corrosion damage by applying the RBI approach to offshore pipelines in the South China Sea. Arzaghi et al. (2017) proposed a dynamic risk-based methodology for the maintenance scheduling of subsea pipelines subjected to fatigue cracks. Case studies demonstrated that the methodology could suggest the optimal maintenance technique among various options, such as welding or major repair. From the literature review, we learned that RBI methodologies were commonly applied to formulating pipelines with a single defect inspection and maintenance strategy. However, identifying inspection strategies for pipelines with combined defects remains an unsolved problem despite the advancements in RBI approaches.

Corrosion and dent are common pipeline defects (Huang et al., 2022a). Dent may result in local geometric deformations. This type of damage usually interacts with external corrosion, which may be introduced or developed due to the associated coating damage caused by the initiation of dents, as shown in Fig. 2 (Huang et al., 2022a, 2022b). The presence of dents would lead to local stress concentration and affect external corrosion growth (Gossard et al., 2016). Proper assessment and treatment of defects are crucial to ensure pipeline integrity (Heggen et al., 2014). Several popular assessment standards and codes for only corrosion or dents on pipelines have been proposed, such as ASME B31.8.8.8 (2022), ASME B31G (2012), CSA, Z662 (2020), API 579 (2021). The impact of corrosion or dents on pipelines has also been studied through theoretical, experimental, and numerical approaches. Mondal et al., (2022) numerically investigated the effects of corrosion on the burst pressure for pipe elbows. Wang et al. (2022) proposed a useful and reliable tool for predicting the failure time to corrosion-induced fracture of steel pipelines. A study from Huang and Zhang (2021) examines the strain response of an X80 steel pipeline with a constrained dent using FEA. Yu et al., (2022) studied the effect of dents on the collapse pressure of sandwich pipes under external pressure. Another paper from Gao et al. (2022) examined the effects of specimen span, corrosion, and dents on the transverse impact resistance through the drop weight impact test. However, the combination of dents and corrosion will synergistically affect pipeline integrity, increasing PoF and CoF, and the current methods cannot assess such combination defects. It is, therefore, of great challenge to plan the optimal inspection interval. As the authors know, none has proposed the RBI framework to guide the inspection planning for pipelines suffering the coupling of dents and corrosion.

The present study proposes a novel RBI framework to develop IM strategies for pipelines containing dent-corrosion defects. The framework incorporates a dynamic Bayesian network (DBN)-based model to predict the time evolution of dent-corrosion defects on the pipeline and an LHS-MCS technique to evaluate the time-dependent Probability of Failure (PoF) of the pipeline. The consequence of failure (CoF) is also monetized to quantify the pipeline's risk. An optimization model of loss-

Fig. 2. Dented pipe segment examples with corrosion (Huang et al., 2022a).

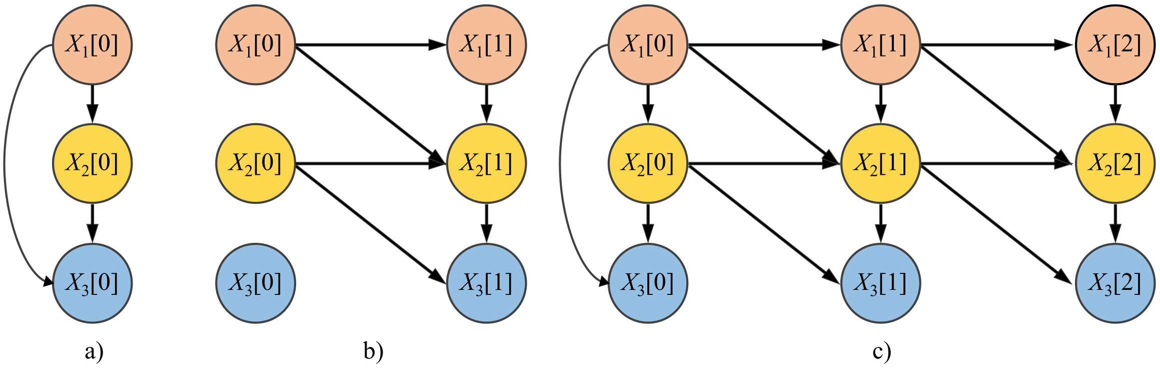

Fig. 3. A DBN example for different states: a) a prior network of DBN, b) a transition network of DBN, c) an unrolled network of DBN.

maintenance total expected cost is introduced to specify the most appropriate inspection period that satisfies the MAR and lowest total expected cost. A CBA is performed to identify risk reduction measures. A case study on an in-service pipeline verifies the feasibility and functionality of the proposed methodology. The uniqueness of this study lies in providing an RBI-based framework for determining inspection planning for pipelines with combined defects.

2. Mechanism of dented pipeline corrosion

Generally, external corrosion is an electrochemical process, typically accompanied by an anodic dissolution, in which electrons are transferred from the steel to the surrounding environment. It occurs when pipeline steel reacts with its laying environment and deteriorates (Vanaei et al., 2017). This corrosion process typically occurs in the absence of mechanical stress. According to Gutman's theory (Gutman, 1998), however, mechanical stress would affect the electrochemical process, thus accelerating the corrosion rate of the pipeline steel surface. This phenomenon is also named the mechano-electrochemical (M-E) synergistic effect (Xu and Cheng, 2013). The introduction of dents, accompanied by large mechanical stresses, often leads to the peeling off or damage of coatings, which induces the formation or development of corrosion. This has been remarked on in the study by the authors and many other researchers (Huang et al., 2022a, 2022b; Gossard et al., 2016; Heggen et al., 2014; Zhao et al., 2022).

Several models have been proposed to predict corrosion growth, including the linear corrosion growth rate (CGR), single-value CGR, and non-linear CGR models (Vanaei et al., 2017). These models may be more appropriate in certain situations, depending on the specific characteristics of the material and the corrosive environment. The power-law model is a widely accepted and commonly used non-linear model to predict the corrosion growth for pipelines and other metallic structures, as represented below (Valor et al., 2013):

$$d(T) = d_0 + k(T - T_0)^{\alpha} \tag{1}$$

$$l(T) = l_0 + k(T - T_0)^{\alpha} \tag{2}$$

where $d(T)$ and $l(T)$ refer to the time-dependent depth and length of corrosion defects, d_0 and l_0 represent the initial corrosion depth and length, T and T_0 are the pipeline exposure time and corrosion initiation time, respectively, k and α are the soil-pipe dependent factors. According to Eq. (1), the corrosion rate $v(T)$ over time can be calculated, as shown below, from the time derivative of the corrosion depth (Valor et al., 2013):

$$v(T) = k\alpha(T - T_0)^{\alpha - 1} \tag{3}$$

It should be noticed that Eqs. (1)–(3) are applicable to pipeline corrosion in the absence of mechanical stress (Zhao et al., 2022). According to the M-E effect, the mechanical stress caused by the external load would enhance the local corrosion rate of the pipeline. This effect can be represented as per an enhancement factor, k_σ defined below (Tang and Cheng, 2009; Xue and Cheng, 2010):

$$k_\sigma = \frac{R_{ct}^{\sigma=0}}{R_{ct}^{\sigma}} \tag{4}$$

where $R_{ct}^{\sigma=0}$and R_{ct}^{σ} are charge-transfer resistance, which is inversely proportional to corrosion rate, in the absence and presence of stress (σ), respectively. Accordingly, in this work, it is assumed that the corrosion depth $d_\sigma(T)$, longitudinal length $l_\sigma(T)$ and corrosion rate $v_\sigma(T)$ interacting with the dent are determined as per the following equations (Zhao et al., 2022):

$$d_\sigma(T) = d_0 + k_\sigma k(T - T_0)^{\alpha} \tag{5}$$

$$l_\sigma(T) = l_0 + k_\sigma k(T - T_0)^{\alpha} \tag{6}$$

$$v_\sigma(T) = k_\sigma v(T) = k_\sigma k\alpha(T - T_0)^{\alpha - 1} \tag{7}$$

3. DBN and its application to risk assessment of pipeline corrosion

DBN is an updated BN that can model temporal dependencies between nodes (Li et al., 2022b). DBN can be a system that changes or evolves evolve, and it can consider both external factors that influence the system and the internal relationships and correlations within the system. Under a probabilistic framework, a DBN could be employed to represent the relationships between the influence factors and the evolution of the corrosion with uncertainties. It can also demonstrate the interdependencies of various risk factors in corrosion phenomena. Combining Bayes' theorem with Markov Chain theory, DBN has two critical features in its structure (Palencia et al., 2019): a) the static model corresponding to each time slice is certain, which can be seen as a structure where multiple random variables (states) interact with each other; b) a specific state at each time T may depend on a certain state at the previous time and a certain state at the current time, i.e., at time $T - 1$. A DBN can be described by the probability distribution function (PDF) of implicit state variable $X = \{x_0, \dots, x_{T-1}\}$ and observation variable $Y = \{y_0, \dots, y_{T-1}\}$ at $T - 1$ moment, which is shown below (Mihajlovic and Petkovic, 2001):

$$P(X, Y) = P(x_0) \prod_{T=1}^{T-1} P(x_T | x_{T-1}) \prod_{T=0}^{T-1} P(y_T | x_T) \tag{8}$$

where $P(x_T|x_{T-1})$ is the state transition PDF that expresses the time dependence between states; $P(y_T|x_T)$ is the observed PDF that describes the dependence of observed data on other (unobserved) nodes within a time slice; $P(x_0)$ is the initial state's PDF that displays the state distribution at the beginning of the process. A DBN example is illustrated in Fig. 3.

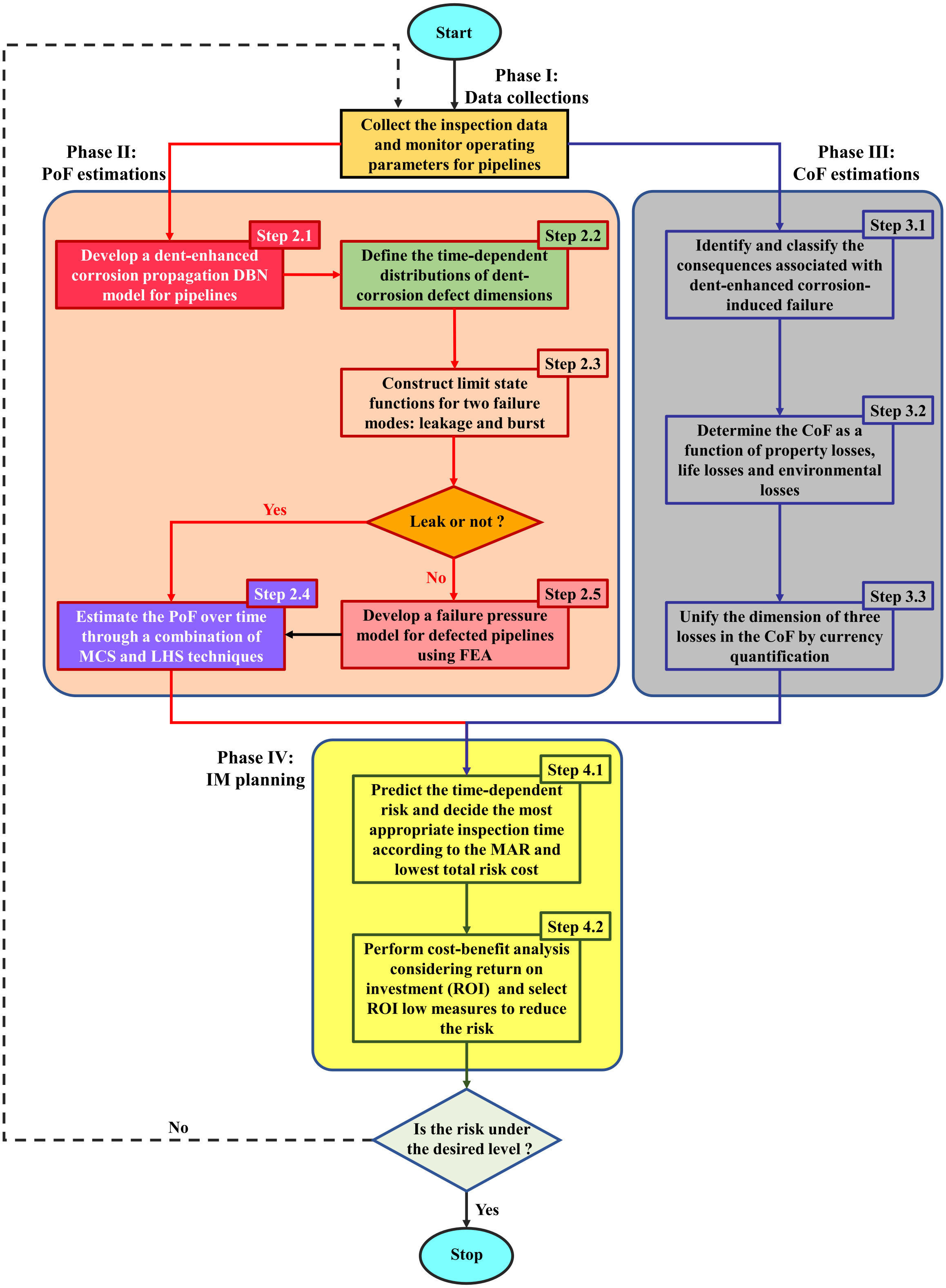

Fig. 4. Flowchart of the proposed methodology framework.

DBN has been widely used in planning RBI strategy for pipeline corrosion. Abubakirov et al. (2020) employed DBN to optimize inspection intervals for internally and externally corroded pipelines. Arzaghi et al. (2018) proposed a novel probabilistic methodology for modeling pitting and corrosion-fatigue simultaneous degradation phenomena of subsea pipelines using DBN. Adumene et al. (2021) presented a dynamic framework that combined DBN with a loss aggregation technique to predict the risk of microbiologically influenced corrosion (MIC). Similar work for MIC assessment from Yazdi et al. (2023) presented a multi-objective functional approach utilizing DBN and Genetic Algorithm (GA) to generate an optimal schedule for performing PIM actions. Through our review of the literature, it is observed that the use of DBN

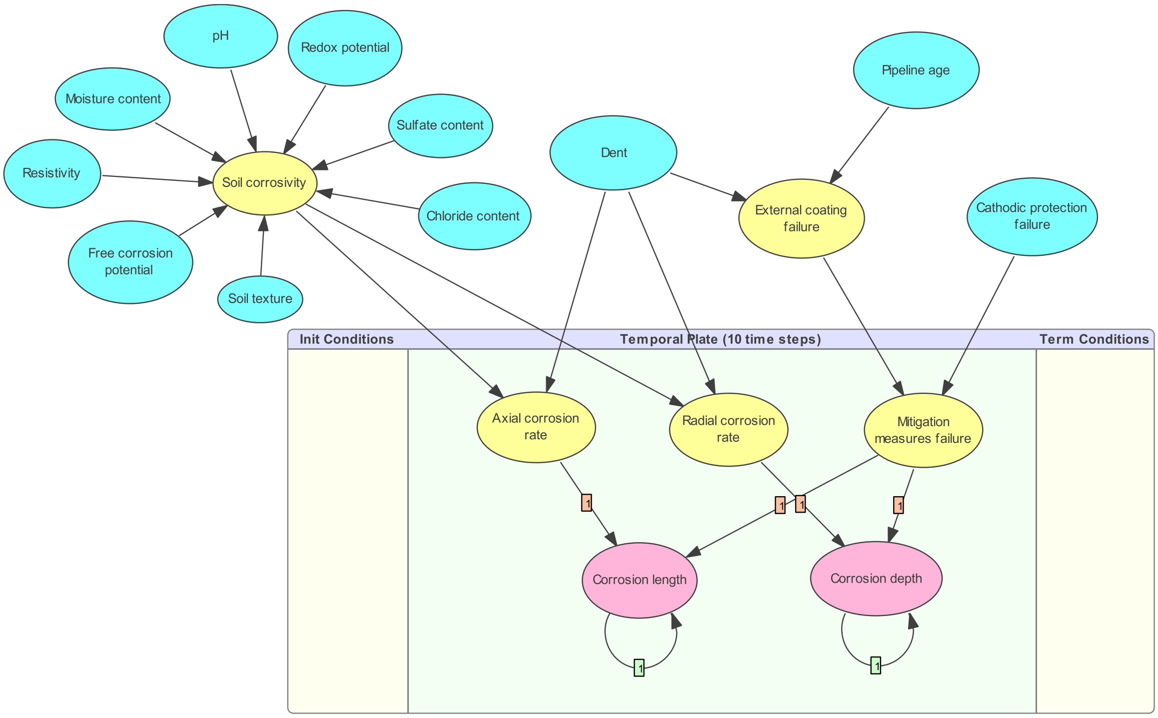

Fig. 5. Developed DBN model for dent-enhanced corrosion.

allowed for the dynamic modeling of corrosion processes and facilitated the incorporation of time-dependent information into the analysis.

4. Methodology development

The presence of dents can significantly increase the corrosion risk of the pipelines. The potential severity of dents associated with metal loss is greater than those of independent dents or corrosion. The complexity of dent-enhanced corrosion makes it challenging to predict the likelihood and rate of corrosion over time accurately. To better understand and manage the dented pipeline corrosion, an RBI-based methodology framework, as presented in Fig. 4, is developed to simulate the corrosion process and support decision-making in the maintenance. The framework comprises four distinct phases: phase I is the data collection; phase II and phase III detail the prediction techniques for PoF and CoF, respectively, but note that no order exists between them; Finally, IM planning is presented in phase IV.

4.1. Data collections

Inspection data and historical information on the monitoring operating parameters and environmental conditions are collected to identify corrosion, dents, or any other type of damage. This can be accomplished using various techniques, such as visual inspections, non-destructive testing techniques (Ultrasonic or radiographic detecting), or ILI tools (Pigs or smart balls). The collected operational data are processed into intervals to estimate their probabilities within a defined range, and the predicted probabilities are used as input data for DBN analysis.

4.2. Estimations of PoF

- **Step 2.1**: A DBN model is developed by GeNIe software (https://www.bayesfusion.com/) to model dent-enhanced corrosion growth, as illustrated in Fig. 5. This DBN model is developed with the idea that external corrosion of pipelines is initiated due to coating damage attributed to the generation of dents at the outer surface of the pipeline.

Table 1
Discretization table of the input parameters for the DBN model from (Abubakirov et al., 2020; Taghipour et al., 2016).

Nodes	States of nodes	Values
Resistivity	Low	> 5000 Ohm cm
	Medium	2000 ~ 5000 Ohm cm
	High	< 2000 Ohm cm
Moisture content	Low	> 40% or ≤ 7%
	Medium	30% ~ 40% or 7~10%
	High	25% ~ 30% or 10~12%
	Very high	12% ~ 25%
pH	Very low	> 8.5
	Low	7 ~ 8.5
	Medium	5.5 ~ 7
	High	4.5 ~ 5.5
	Very high	< 4.5
Redox potential	Low	> 400 mV
	Medium	0 ~ 100 mV
	High	200 ~ 400 mV
	Very high	< 100 mV
Sulfates content	Low	≤ 0.05%
	Medium	0.05% ~ 0.15%
	High	0.15% ~ 0.75%
	Very High	> 0.75%
Free corrosion potential	Low	> −300 mV
	Medium	-450 ~ − 300 mV
	High	-550 ~ − 450 mV
	Very High	< −550 mV
Chloride content	Low	≤ 0.0005%
	Medium	0.0005% ~ 0.01%
	High	0.01% ~ 0.05%
	Very High	> 0.005%
Soil texture	Sand	N/A
	Loam	N/A
	Clay	N/A
Pipeline age	Short	0 ~ 15 years
	Medium	15 ~ 30 years
	Long	30 ~ 50 years
Dent	Absent	N/A
	Present	N/A
Cathodic protection failure	Yes	N/A
	No	N/A

Table 2
State transition CPT example for the evolution of corrosion depths (Abubakirov et al., 2020).

Radial corrosion rate	State j					
Mitigation measures (Self) $[t-1]$	State k			State $k+1$		
	State i	State $i+1$	State I	State i	State $i+1$	State I
State i	$1-P(i,j,k)$	0	0	$1-P(i,j,k+1)$	0	0
State $i+1$	$P(i,j,k)$	$1-P(i+1,j,k)$	0	$P(i,j,k+1)$	$1-P(i+1,j,k+1)$	0
State I	0	$P(i+1,j,k)$	1	0	$P(i+1,j,k+1)$	1

The geometries of the defect are described by the "Corrosion Length" and "Corrosion Depth" nodes, which are the leaf nodes of the network and represent the geometries of the defect based on the probability distributions of a range of defect states. The probability of a dent-enhanced corrosion defect evolving to the next state in a unit time interval is determined by three factors (Abubakirov et al., 2020): a) external environmental influence (performed as time-dependent corrosion growth and evolution), b) anti-corrosion measure efficiency and c) the state of the defect in the current time slice.

"Soil corrosivity" and "Dent" nodes are considered that would affect the external corrosion rate. Thus, these nodes are represented in the DBN model as the parent nodes of the "Axial corrosion rate" and "Radial corrosion rate" nodes. Several soil factors contribute to the external corrosion of onshore buried pipelines (Biezma et al., 2018). Thus, eight root nodes, "Resistivity", "Moisture content", "pH", "Redox potential", "Sulfate content", "Free corrosion potential", "Chloride content", and "Soil texture", are built to represent the physical and chemical properties of the environmental factor (soil) where the pipeline is exposed. The mitigation measures can be used to reduce the rate of corrosion development over time, and they can be considered control variables in the DBN model. Therefore, two child nodes of "Mitigation measures", that is, ''Cathodic protection" and "External coating" nodes, have been included as additional nodes in the DBN model. "Dent" and "Pipeline age" nodes are set to affect the properties of the external coating, i.e., coating damage impacted by the existence of the dents and the exposure duration of the pipeline. The discretization ranges for all root nodes are illustrated in Table 1, with the different ranges and their corresponding values. The CPTs between the root nodes and their child nodes can be established by experts in the field of pipeline corrosion based on their knowledge and experiences or built based on the models proposed by other researchers (Li et al., 2022b; Hong et al., 2023; Taghipour et al., 2016; Aulia et al., 2021).

The variability in the corrosion rate has been considered in the DBN model by incorporating the arcs from the "Corrosion Length" and "Corrosion Depth" nodes to themselves, which captures the temporal dependency of the defect state on its previous state. In Section 2, the evolution of dent-enhanced corrosion over time has been given in Eqs. (5)–(7). Therefore, the transition probability of a defect propagating into the next state is proportional to the corrosion growth rate at the current state of the defect. State transition CPTs can represent the probability of the defect being transferred with time. An example of state transition CPTs of the corrosion depth is presented in Table 2, where the defect depth is set to evolve through I states (Abubakirov et al., 2020). The state transition CPT has considered the corrosion rate, represented by the state j, and the efficiency of the mitigation measure, denoted by the state k. $P(i,j,k)$ describes the probability of the defect evolving from state i to state $i+1$ in a unit time interval. It is noted that the construction of the state transition CPTs and the definition of the states of the nodes in the DBN model may vary depending on the specific corrosion system being studied and the available data. The state transition CPTs are usually built based on expert knowledge, the results of the analytical models and the data.

- **Step 2.2:** The proposed DBN model has considered various factors that may affect the progression of pipeline corrosion, such as the time and surrounding environment of pipeline exposures and the mitigation measures. The result of the DBN model is obtained from the time-dependent probability distribution of pipeline corrosion geometries.
- **Step 2.3:** Pipeline failure scenarios due to corrosion can generally be classified into two categories: either a leak or a burst. A leak is a small opening or hole in a pipeline that allows fluids to escape, while a burst is a more severe form of damage involving a complete pipe failure. The leak failure scenario occurs when the time-dependent defect depth $d(T)$ owing to the dent-enhanced corrosion growth exceeds the maximum allowed corrosion depth d, 80% of the pipeline wall thickness t. While the burst failure scenario occurs when the operating pressure exceeds the burst pressure $P_b(T)$ of the dented corroded pipeline. Therefore, two limit state functions (LSF), g_1 and g_2, are developed for the two failure modes. Eq. (9) is defined to express the difference between the maximum allowed corrosion depth and the measured defect depth over time, while Eq. (10) represents the difference between the pipe's burst pressure and operating pressure (Yu et al., 2021; Aljaroudi et al., 2015):

$$g_1 = d(T) - 0.8 \times t \tag{9}$$

$$g_2 = P_b(T) - P \tag{10}$$

- **Step 2.4:** Using a hybrid method of MCS and LHS technique on the LSF determines the time-dependent PoF of the defected pipelines. Two distinct failure modes are considered: leak failure and burst failure. It is assumed that the failure due to leaks occurs only when $(g_1 \le 0) \cap (g_2 > 0)$, that is, the defect depth exceeds 80% of the pipeline wall thickness, and the operating pressure is less than the failure pressure. A burst failure occurs when the operating pressure equals or exceeds the failure pressure at a defect, but the defect depth is less than the maximum allowable defect depth, which can be expressed as $(g_1 > 0) \cap (g_2 \le 0)$.
- **Step 2.5:** There is no available failure pressure model with a dent-corrosion defect. The previous works of the authors and other researchers have proven that the presence of dents can reduce the failure pressure of corroded pipelines (Gossard et al., 2016; Heggen et al., 2014). Existing burst pressure models for pipelines with a single corrosion defect are not applicable for dented corroded pipelines (Huang et al., 2022a, 2022b; Zhao et al., 2022). Therefore, finite element analysis (FEA) is used to predict the failure pressure of pipelines containing a dent-corrosion defect and develop a mathematical equation between the variables in Step-1 and failure pressure. The modelling details and numerical results can be found in another work of the authors (Huang et al., 2022b). A deterministic prediction model for burst pressure, $P_b(T)$, of the dented corroded pipeline over time, T, can be written the as

$$P_b(T) = \frac{2t\sigma_{\mathrm{UTS}}}{D-t} S(T) \left(\frac{1-\frac{d(T)}{t}}{1-\frac{d(T)}{tM(T)}} \right) \tag{11}$$

$$M(T) = \sqrt{1 + 0.31\left(\frac{L^2(T)}{Dt}\right)} \tag{12}$$

$$S(T) = \frac{1}{\alpha + \beta e^{-\frac{\delta(T)}{t}}}, \frac{\delta(T)}{t} \ge 0.74 \tag{13}$$

Table 3
Several possible consequences of pipeline failures resulting from corrosion.

Consequence	Description
Environmental damage	Leaks or bursts in a pipeline can release harmful substances into the environment, potentially causing pollution or contamination of soil and water sources. This may have long-term impacts on the ecosystem and may require extensive cleanup efforts;
Public safety risk	Leaks or bursts can also pose a risk to public safety, particularly if the pipeline carries hazardous materials or is located in a populated area;
Financial costs	Repairs or cleanup resulting from corrosion-induced failures can be expensive, potentially costing millions of dollars depending on the severity of the damage;
Reputation damage	Incidents of corrosion-induced failures can damage a company's reputation and may result in fines or other regulatory consequences.

Table 4
Empirical and mathematical models of PL, LL and EL (10^3 \$) from (Taghipour et al., 2016), where D, P and V donate the pipe outer diameter, internal pressure and released volumes; VSL, ns, P_{ign}, δ_h, r, E, A, I and Q are statistical life value, casualty number, ignition probability, population density, distance from the fire center, surface flame emissivity, pool fire diameter and heat flux, respectively.

Medium	PL	LL	EL
Natural gas	PL $= 0.00167D^2P + 110.445$	LL $= VSL \times ns \times P_{ign}$ $\quad ns = \delta_h \times \frac{\pi}{3} \times \left(r_{1\%}^2 + r_{100\%}^2 + r_{1\%}r_{100\%}\right)$ $\quad r = 0.15\sqrt{D^2P}$ or $0.21\sqrt{D^2P}$, for gas $r = \begin{cases} \sqrt{\frac{EA^2}{16I}} \\ \sqrt{\frac{0.3}{4\pi}\frac{Q}{I}} \end{cases}$, for oil	-
Crude oil	PL $= 3.535V + 74.19$		EL $= 3.334V + 135.886$
Refined oil	PL $= = 0.392V + 269.97$		EL $= 4.567V + 241.95$

where D is the pipe's outer diameter; t is the pipe's wall thickness; σ_{UTS} is the ultimate tensile strength of the pipeline steel; $d(T)$ and $L(T)$ denote the time-dependent corrosion depth and length, respectively; $\delta(T)$ represents the dent depth evolving through time due to pressure fluctuations, but it is considered as constant in this work; α and β are undetermined coefficients with values equal to 1.09 and 0.19, respectively.

4.3. Estimations of CoF

- **Step 3.1:** Potential consequences of corrosion-induced pipeline failures may include (da Cunha, 2016): environmental damage, public safety risk, financial costs, reputation damage, etc. Table 3 displays a comprehensive description of each consequence.

- **Step 3.2:** According to the pipe's possible failure modes and potential consequences, the reference CoF of the pipelines is considered in three aspects (Zhang et al., 2018): property losses, life losses, and environmental losses. Property losses (PL) refer to the economic losses due to pipeline failure, such as the cost of lost production, typically represented in terms of the monetary value of the damages, or c (USA\$). Life losses (LL) are the number of deaths or injuries resulting from a pipeline failure and are typically expressed in the number of people killed or injured as n (person). Environmental losses (EL) are the impact of a pipeline failure on the environment, including the volume of any contaminated media and the potential impact on soil and water. These losses may be expressed in terms of the volume of the contaminated environment as v (m^3). The reference CoF of a pipeline is, therefore, a function of c, n, and v, as presented below, and can be used to evaluate the potential consequences of distinct failure scenarios and to prioritize risk-mitigation efforts:

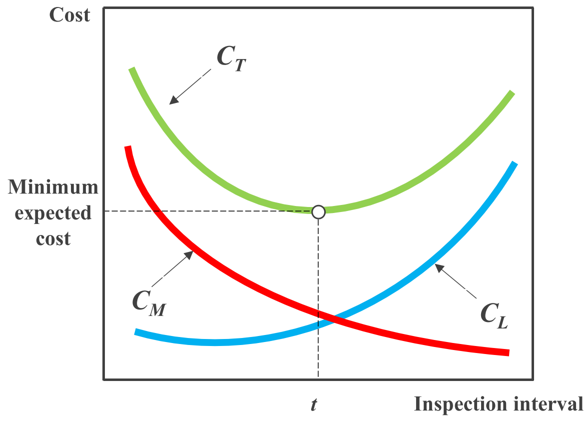

Fig. 6. The optimization model of the loss-maintenance total expected cost.

$$\text{CoF}_i = C(c_i, n_i, v_i) \quad i = 1, 2 \tag{14}$$

where $i = 1$ or 2, refer to leak or rupture failure scenarios, respectively.

- **Step 3.3:** A monetary quantification metric is employed to deal with the problem that each parameter dimension in the consequence function differs. PL can be expressed in terms of the monetary value of the damages; LL can be defined in terms of the number of casualties and the corresponding compensation; EL can be determined in terms of the cost of pollution control and government fines or estimated based on the quantity of any leaked materials and the degree of environmental damage. Estimating these costs can be based on historical data or empirical formulas in Table 4. Afterwards, considering the influence of inflation, the CoF can be derived as a function of the monetary values associated with PL, LL, and EL, as well as interest rates and time, as expressed below (Aljaroudi et al., 2015):

$$\text{CoF}(T) = \frac{C(c, n, v)}{(1+r)^T} = \frac{(S_{PL} + S_{LL} + S_{EL})}{(1+r)^T} \tag{15}$$

where S_{PL} donates the quantified economic loss; S_{LL} and S_{EL} represent the loss of life and environment in terms of monetary metrics; r refers to the annual interest rate.

4.4. Inspection planning

- **Step 4.1:** The risk associated with a pipeline failure can be calculated by multiplying the PoF and CoF, as following:

$$\begin{aligned} \text{Risk}(T) &= \sum\nolimits_{i=1}^{2} \text{PoF}(T)_i \times \text{CoF}(T)_i \\ &= \text{PoF}(T)_1 \times \text{CoF}(T)_1 + \text{PoF}(T)_2 \times \text{CoF}(T)_2 \end{aligned} \tag{16}$$

Following the risk estimation, a comprehensive optimization model that considers the relationship between the maintenance cost (C_M), loss cost (C_L) associated with a failure and total expected cost (C_T) is adopted to manage this risk and make informed maintenance decisions, as demonstrated in Fig. 6. C_M includes maintenance/repair cost C_R, and inspection expenses C_I. This work considers various maintenance/repair measures to reduce pipeline risk. Thus, distinct C_R is obtained. On the other hand, C_L involves direct costs, such as the cost of lost production, and indirect costs, such as potential fines or legal costs. Only the cost of lost production, i.e., property damage expense, is considered, and indirect costs are not included due to the lack of data. Eventually, the optimization model of loss-maintenance total expected cost can be employed to determine the most appropriate times for periodic inspections based on the point at which C_T, which is the sum of C_M and C_L, is minimized (Sahraoui et al., 2013):

Table 5
Case pipeline information input into the DBN model.

Parameters	Values	Parameters	Values
Resistivity	80.63339 Ω·m	Sulfates content	0.02496%
Moisture content	16.95%	Free corrosion potential	-688.72 mV
pH	6.83	Chloride content	0.01254%
Redox potential	166.152 mV	Soil texture	Loam

$$\min C_T = C_M + C_L = \frac{C_R + C_I + \sum_{i=1}^{2} \mathrm{PoF}(T)_i \times C_{Li}}{(1+r)^T} \tag{17}$$

- **Step 4.2:** CBA is commonly used to evaluate the feasibility of various measures. In this approach, the return on investment (ROI) is used as a metric to represent the cost required to take measures to reduce the unit risk value (Zhang et al., 2018). As shown in Eq. (18), the ROI is typically expressed as a ratio, with the input cost (measure cost, $) on the numerator and the benefit (risk reduction value, $) on the denominator. According to the CBA, pipeline operators should select measures with a low ROI to minimize the cost of risk reduction.

$$\mathrm{ROI} = \frac{\text{Measure cost}}{\text{Risk reduction value}} = \frac{C_{mi}}{\Delta R} \tag{18}$$

where ΔR is the difference between the current risk value of the pipeline and MAR, C_{mi} is the cost of the ith measure.

5. Application of the methodology

5.1. Case description

To describe the proposed approach, a case study of a 20-inch pipeline carrying refined oil products installed in 2002 and located in Western China has been implemented in this section. The case pipeline is made of API X60 pipeline steel with an outer diameter equal to 508 mm, a wall thickness of 7.9 mm, and a length of 193.3 km. The design pressure for the pipeline is 10.1 MPa, while the operating pressure is 6.38 MPa. The mechanical damage activities on the pipeline were observed, and the cathodic protection system failed. A DBN model is built to predict the corrosion depth and length probability distributions over time. Table 5 tabulates the input values of the operating environment parameters in the DBN model. The CPTs are constructed according to expert opinions, field data, experimental results, and analytical models. For instance, the CPT for the "Soil corrosivity" node is developed according to the assessment model from GB 19285 code (GB 19285, 2014), as written in Table 6.

5.2. Collected ILI data

A total of 327 dent features with various sizes and dimensions were detected in the inspection, most of which are located at the bottom of the pipeline. It is noted that 55 dent features are associated with external metal loss, which presents distinct degrees of corrosion features. The distribution of identified dents associated with corrosion is displayed in Fig. 7. It is shown that the majority of the corrosion defects related to dents are distributed in the lower left corner of the figure, i.e., the corrosion depth is less than 20% of the wall thickness, and the corrosion length is less than 100 mm. The distributions of depth and length of corrosion defects are discretized into nine states as increasing the defect geometries. It is assumed that the case pipeline is intact with no indication of defects when installed in 2002. The ILI-reported defect probability information in 2012 serves as evidence for the DBN model to update the time-dependent distributions of corrosion lengths and depths. Thus, the pipe's PoF over time can be predicted.

5.3. Results and discussions

Fig. 8 shows the results from the DBN model, and then the discrete distributions of the corrosion depth and length evolving over multiple time-slices from the DBN model are brought into LSF equations (g_1 and g_2) as the input data. The stochastic testing of the LSF equations for a leak or burst failure mode is performed via MATLAB codes to evaluate the progression of the pipe's PoF over time, given the distributions of defect depth and length. Fig. 9 shows the results of the annual PoF as a function of time for the pipeline with dent-corrosion damage. The reliability of LHS-MCS results has been well-validated by conventional MCS calculations.

The historical data of pipeline accidents and the records from previous incidents quantify the consequences of the pipeline due to leak and

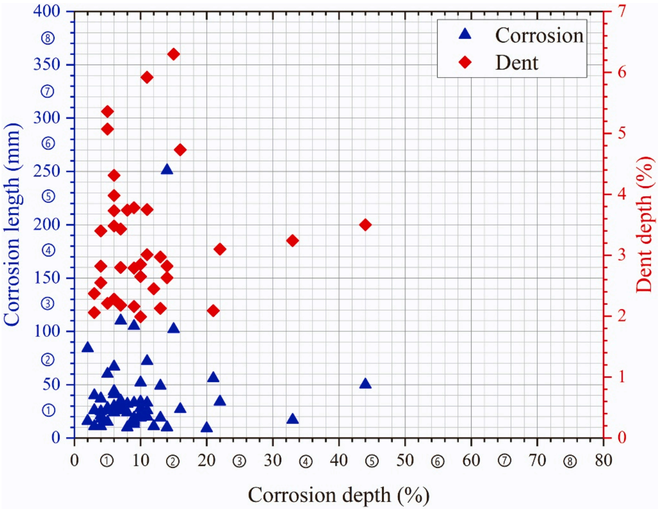

Fig. 7. Schematic view of dent-corrosion combined defects inspected via ILI (corrosion depth in % of wall thickness and corrosion length in mm as well as dent depth in % of pipe diameter).

Table 6
The partial CPT of the "Soil corrosivity" node.

Moisture content		Very high								
……		……								
Chloride content		Very high								
Resistivity		High			Medium			Low		
Soil texture		Sand	Loam	Clay	Sand	Loam	Clay	Sand	Loam	Clay
Soil corrosivity	Strong	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625
	Medium	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
	Weaker	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
	Weak	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125

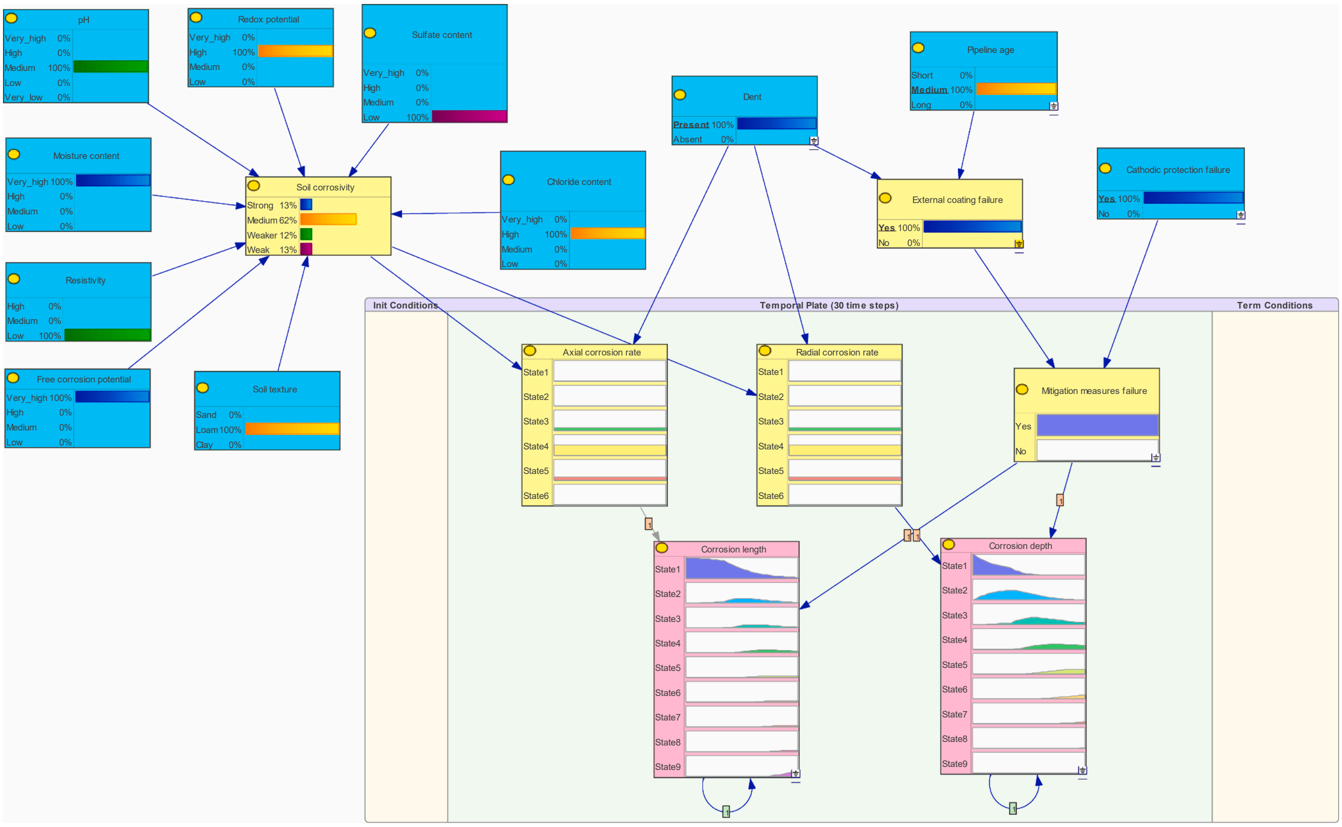

Fig. 8. The distribution of the corrosion defect over time from the developed DBN model.

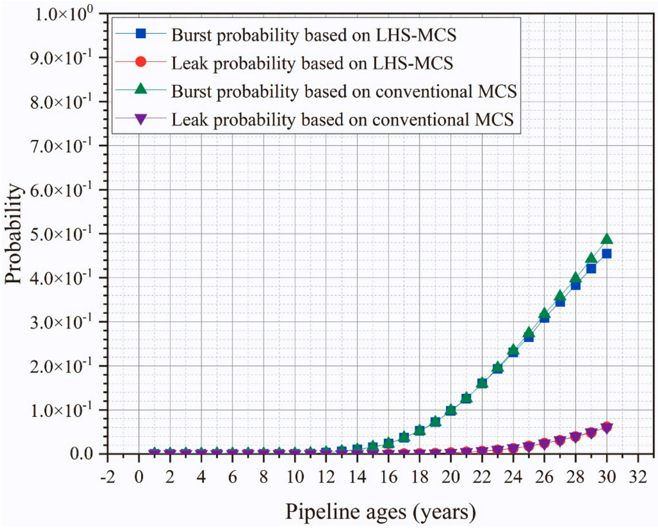

Fig. 9. Time-dependent PoFs of the case pipeline for burst and leak modes.

burst failure scenarios. In the case of a leak failure scenario, the CoF is exclusively comprised of the property damage costs and environmental dispute expenses. As a result, the leak-induced reference CoF is estimated to be $889,560. In a burst-induced failure, the associated CoF encompasses the loss caused by the released volume of refined oil from the damaged pipe segment, compensation for any resulting injuries or fatalities, and environmental damage reparation costs. Thus, the burst-induced reference CoF is assessed at $2,064,350. The corresponding sub-divided and total CoF for distinct failure modes is illustrated in Table 7. The estimation of the property damage, life loss, and

Table 7
The values of reference CoF for two failure modes (Aljaroudi et al., 2015).

Scenario	PL ($)	LL ($)	EL ($)	CoF ($)
Leak	583,730	-	305,830	889,560
Burst	1641,690	140,200	282,460	2064,350

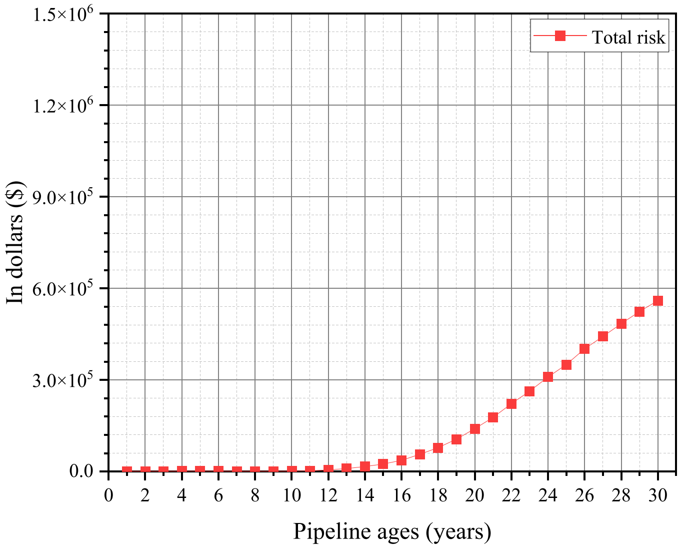

Fig. 10. The total risk of the pipeline over time.

Table 8
The cost assumptions of repair measures employed in the optimization model (Parvizsedghy et al., 2015).

Repair measures	Cost ($)
Recoating	200,000
Type-B sleeves	392,352
Replacement	750,000

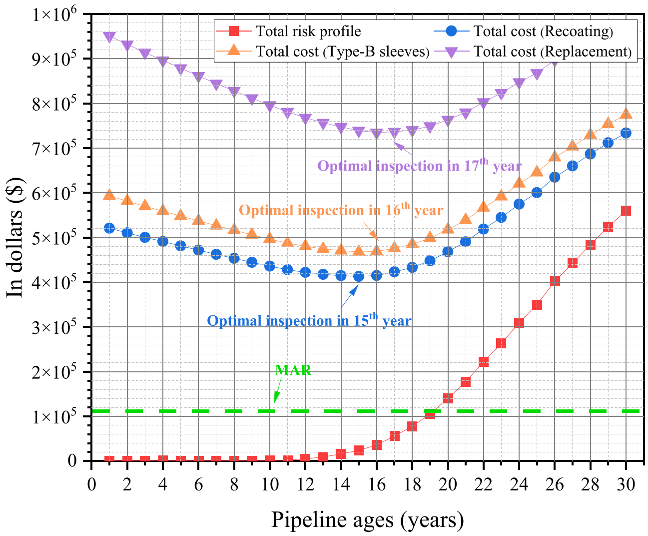

Fig. 11. The pipe's risk profile and total expected cost.

environmental impact of onshore pipelines without available historical data is discussed in Cunha (da Cunha, 2016) through mathematical and empirical approaches. The reference CoFs are brought into Eq. (15) to define the CoF over time, considering inflation. Further multiplied by the time-dependent PoF, the monetization values of the CoF derive the associated pipe's risk over time according to Eq. (16). Fig. 10 shows the results. The total risk of the pipeline presents a nonlinear increasing trend as the pipeline age increases.

Following the pipe's risk determination, the pipeline operator is

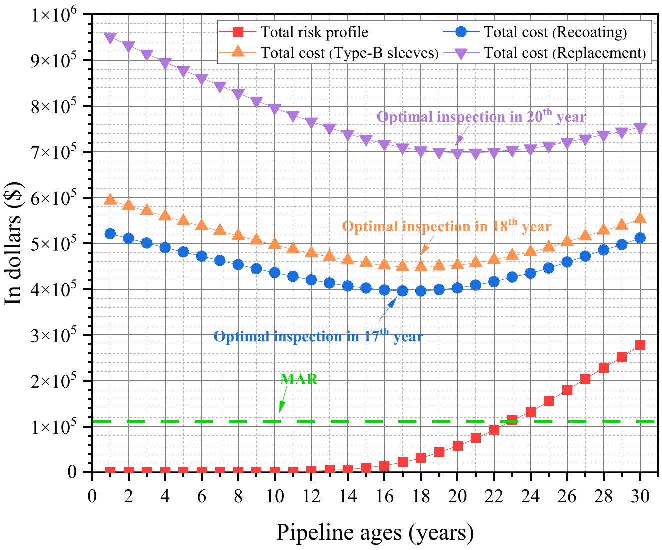

Fig. 13. The pipe's risk profile and total expected cost of treating the dent and corrosion separately.

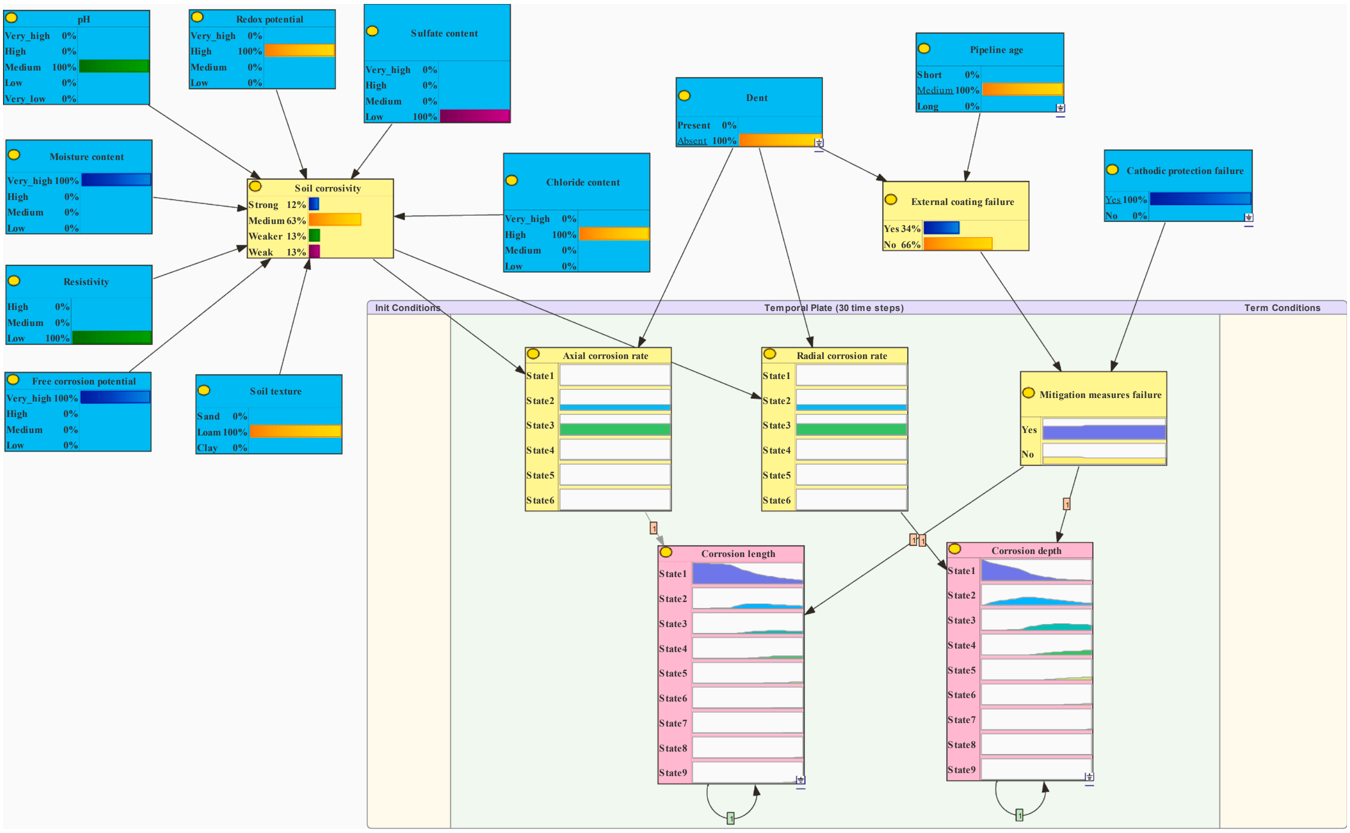

Fig. 12. The corrosion distribution of the developed DBN model neglecting the dents impact.

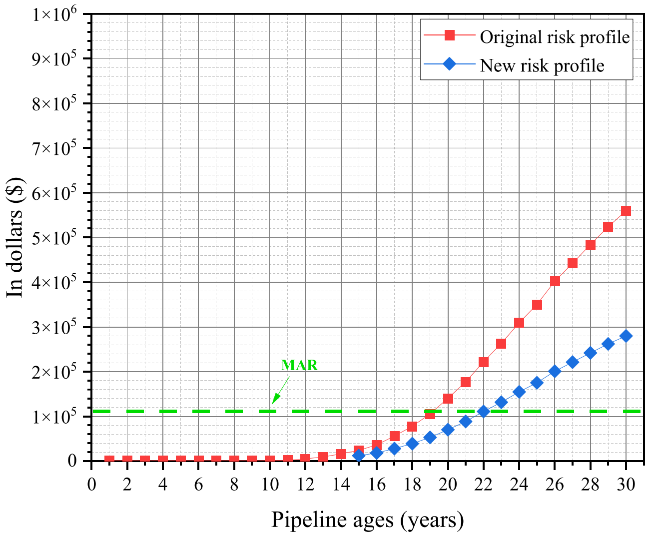

Fig. 14. The pipe's risk profile after the planned inspection and recoating.

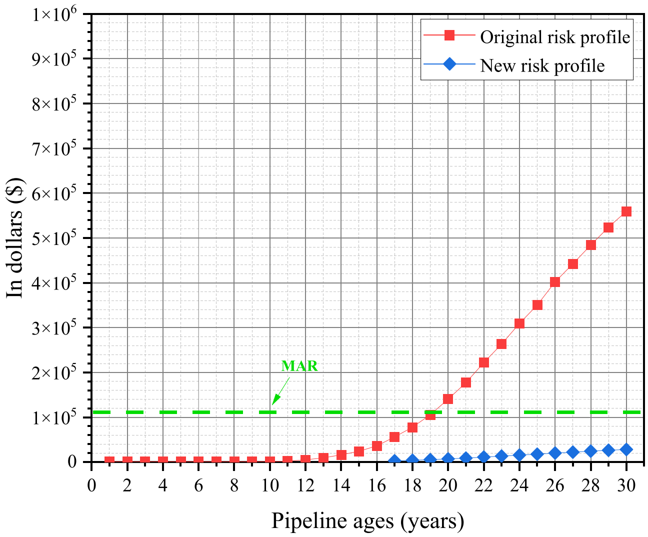

Fig. 16. The pipe's risk profile after the planned inspection and replacement.

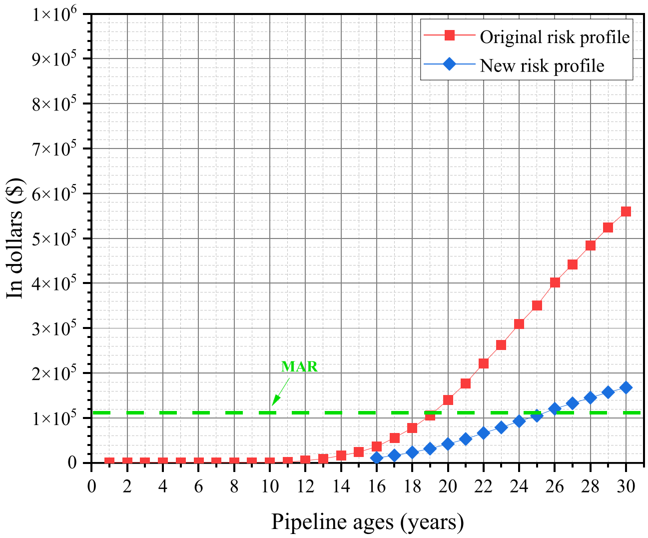

Fig. 15. The pipe's risk profile after the planned inspection and adding Type B sleeves.

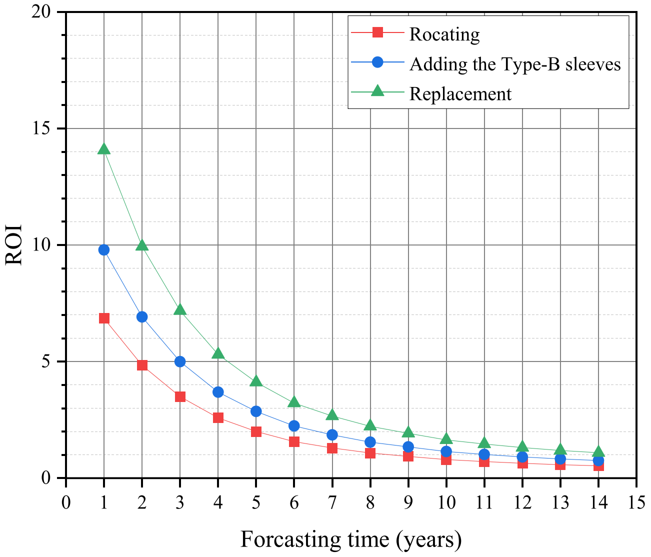

Fig. 17. The ROIs of the three repair measures.

faced with a crucial decision regarding the types of corrective maintenance. The optimum option depends on the severity and location of the identified defect, the pipeline's overall condition, and the operator's priorities, such as the cost-benefit ratio. In this work, three corrective maintenance/repair options are selected: the first measure is recoating to repair the pipeline coating peeled off by dents; the second measure is repairing the defect by adding a sleeve to the damaged area; the last measure is replacing the defected segment altogether (Parvizsedghy et al., 2015). The assumed cost values of these maintenance measures are tabulated in Table 8. The total expected cost curve differs owing to the different repair options available, as presented in Fig. 11. As demonstrated in the figures, the pipe's optimal inspection time point is at the 15th, 16th and 17th year, respectively, which is determined based on the minimization of the total expected cost associated with distinct maintenance measures as the pipe's risk at the inspection point does not exceed the defined MAR with a value of $112,114 per year set by the pipeline operators (da Cunha, 2016). When dents and corrosion are treated independently, i.e., neglecting the dent-enhancement effect on the corrosion growth, the corresponding DBN model results are shown in Fig. 12. The total expected cost curves are illustrated in Fig. 13. Notably, the optimum inspection time is observed to shift to the 17th, 18th, and 20th year, respectively, in comparison to the inspection period recommended when considering the synergistic effect between dents and corrosion. These observations reveal a delay of 2, 2, and 3 years in the optimal recoating, adding sleeves, and replacement inspection time. The findings highlight the importance of accounting for potential interactions between corrosion and dents in decision-making.

Upon completion of the planned inspection and selected maintenance option, the pipe's risk is expected to decrease. The reduction value of risk is dependent on the type and implementation quality of maintenance measures. Figs. 14–16 illustrate the risk profile of the pipeline after the conduction of the planned inspection and repair measures. The figures show that the risk of exceeding the defined MAR for recoated pipes is delayed to the 22nd year, 3 years later than the MAR for unrepaired pipes. Thus, recoating can be moderately effective but the least expensive of the three maintenance measures. After the implementation of adding Type-B sleeves, the pipe's risk reaches MAR in the 25th year. It is believed that adding sleeves increases the service life of the pipeline. Replacement measures can restore the pipeline to an undamaged condition, reducing the risk to a low level but not zero. As is clear from

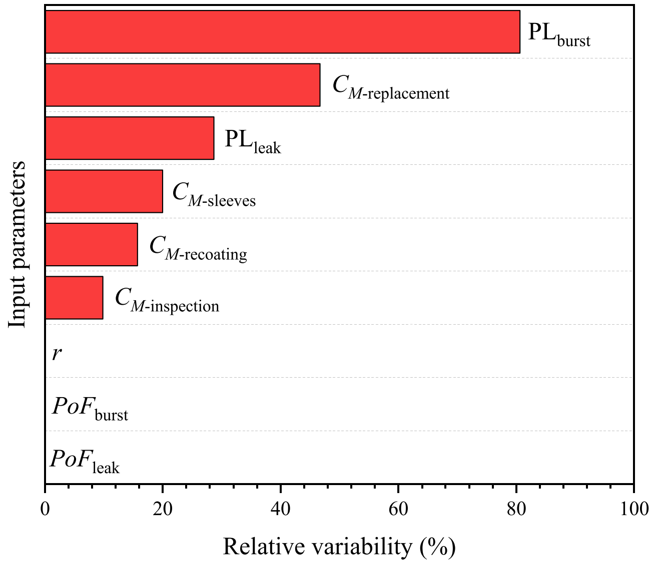

Fig. 18. Sensitivity analysis results of the input parameters.

Fig. 16, after pipeline replacement is implemented, the pipeline risk is always lower than the MAR as the pipeline age increases. Still, the replacement cost is also the highest among the three maintenance measures.

The ROIs of recoating, adding Type-B sleeves, and replacement in terms of Eq. (18) are depicted in Fig. 17. The ROIs of the three maintenance measures in descending order are a replacement, adding sleeves, and recoating. According to the principle of selecting measures with low ROI, recoating can be considered the most economical option for pipeline companies. Still, paying attention to the pipeline status is necessary to prevent the operational risk from exceeding the MAR. Adding and replacing sleeves are more appropriate for pipelines with deep or multiple defects.

Fig. 18 illustrates the sensitivity of input parameters to the total expected cost. It shows that the C_L is most sensitive to property damage by burst failure, and the replacement-based maintenance cost and leak-induced property damage also significantly influence the total expected cost. To increase the accuracy of C_L predictions, precisely estimating the release volume by pipeline failure may be beneficial. Furthermore, the company's budget and market price should justify the assumed maintenance cost.

6. Conclusions

The vulnerability of onshore pipelines to corrosion and dent poses a considerable risk of failure. However, developing a periodic inspection and maintenance strategy that is cost-effective remains a challenging task. This work presents an integrated RBI framework for pipelines affected by external corrosion and dents. The advantages of the proposed methodology involve three novel contributions: the first contribution is the consideration of the accelerating effect of dents on the local corrosion rate when determining the pipeline periodic inspection planning; the second contribution is a DBN-based probabilistic model that describes the possible defect states, even extreme defect states that may cause pipeline failure; the third contribution is the determination of the optimum inspection period and maintenance strategy for the pipeline containing dent-corrosion combined defects in the RBI frameworks. The results show that the pipe's optimal inspection interval is highly sensitive to the selected maintenance measure and cost. Neglecting the potential impact of dents on corrosion growth may lead to a delay of 2–3 years in the optimum inspection time. This means considering potential joint effects between different damage mechanisms in developing RBI strategies is critical.

However, there exist some uncertainties in the analysis. These uncertainties may considerably impact the results and affect the decision-making process. Two primary types of uncertainties, aleatory and epistemic, should be considered. Aleatory uncertainties stem from the natural randomness of measured parameters, and probabilistic distributions can be employed to mitigate them. On the other hand, epistemic uncertainties arise from a lack of information, such as limited data or imperfect inspection results, which may significantly impact obtained results. Additional knowledge of dent-enhanced corrosion causation can be introduced into the developed DBN model, or updated ILI data can be used as input to the DBN analysis to minimize their impact. Furthermore, as done in this work, using FEA to derivate the burst pressure model is another way to alleviate the uncertainties.

Declaration of Competing Interest

The research being report in this paper titled "A risk-based approach to inspection planning for pipelines considering the coupling effect of corrosion and dents" was supported by Southwest Petroleum University and Delft University of Technology. The authors of this paper have the IP ownership related to the research being reported. The terms of this arrangement have been reviewed and approved by the university in accordance with its policy on objectivity in research.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psep.2023.10.025.

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