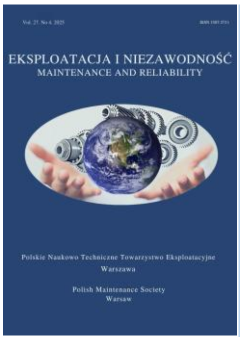

Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 27 (2025), Issue 4

journal homepage: http://www.ein.org.pl

Article citation info:
Wang Y, Xie M, Xu X, Gu M, Optimization of maintenance strategies for natural gas pipeline systems based on FFTA-BN, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2025: 27(4) http://doi.org/10.17531/ein/204611

Optimization of maintenance strategies for natural gas pipeline systems based on FFTA-BN

Indexed by: Web of Science Group

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Highlights

- The combination of Tω and FFTA can overcomes fuzzy accumulation and subjectivity.
- The hybrid maintenance model is established to optimize pipeline's cost.
- The proposed optimal model can better meet the actual needs of the project.

Abstract

Pipelines are vital for transporting oil and natural gas, which are always facing many security challenges during the transportation process. Pipeline failures can lead to significant economic losses and injuries, therefore risk assessment and maintenance are crucial. To address the lack of precise data and inherent uncertainty in evaluating pipeline risk, this paper proposes a new approach for assessing pipeline system reliability. This method integrates the weakest t-norm algorithm, fuzzy fault tree analysis, and Bayesian networks to compute the reliability of natural gas pipeline systems, mitigating the issues of fuzzy accumulation and bias found in traditional fault trees. Furthermore, research is conducted on optimizing maintenance strategies under hybrid maintenance. The maintenance optimization model fully considers the specific requirements of pipeline reliability in different risk areas. The proposed method can provide corresponding optimal maintenance solutions for different risk areas, which can better meet the actual needs of engineering.

Keywords

natural gas pipeline system, fuzzy fault tree analysis, the weakest t-norm, bayesian network, hybrid maintenance, system reliability assessment

1. Introduction

Due to the advantages of low cost and high safety, pipelines have been widely used to transport oil and gas resources. However, with the increase in service life and the impact of external environmental factors, the pipeline performance gradually deteriorates and eventually fails. The 2021 China Gas Accident Survey [1] details a significant gas explosion in Shiyan City, Hubei Province, leading to 26 deaths, 138 injuries, and approximately 53.95 million CNY in direct economic losses. It can be seen that it is crucial to scientifically assess pipeline risk and adopt reasonable maintenance strategies to avoid accidents.

For mechanical systems, risk assessment involves modules such as fault diagnosis and prediction based on detection data, reliability evaluation, etc. [2-3]. Up to now, the most common method for pipeline risk assessment include Fault Tree Analysis (FTA), Mond method, Kent method, etc. [4-6]. Wang et al. [7] used the FTA model to identify corrosion risk factors in the transportation process of submarine pipelines, and conducted a risk assessment of corroded submarine pipelines based on Bayesian networks (BN). Liang et al. [8] integrated the TOPSIS

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model and cloud reasoning to complete the risk assessment of polyethylene natural gas pipelines. Yin et al. [9] adopted an improved pipeline risk quantitative analysis method to address potential hazards in high-risk areas. Zhao et al. [10] proposed a bow-tie model combining an FT with an event tree to complete a dynamic risk assessment of buried gas pipelines. Considering the complexity of the external environment, Li et al. [11] used the Copula-Bayesian method to achieve risk assessment of submarine pipelines.

The basic feature of quantitative methods is to use quantitative indicators as the basis for judgment, and quantitatively analyze accident probability, accident consequences, and other risk evaluation indicators [12]. Therefore, obtaining effective quantitative evaluation data is the foundation and prerequisite of quantitative risk analysis methods. Expert knowledge can provide favorable supplements for quantitative risk assessment, but there are also fuzzy and random uncertainties [13]. In short, uncertainty analysis is crucial for risk assessment.

For natural gas pipelines, there are many old pipelines which lack early detection data and result in incomplete statistics of historical failure cases. Due to the rarity of major failure events, the reliability of statistical patterns is low. And the uncertainty of failure mode prediction under extreme working conditions significantly increases. Meanwhile, due to errors in detection tools and difficulty in accurately measuring fluctuations in external environmental factors, there is significant uncertainty in pipeline inspection and failure data. To mitigate this uncertainty, fuzzy theory is often utilized in the evaluation process. Singh et al. [14] combined fuzzy fault tree analysis (FFTA) with BN to calculate the probability of basic events occurring in pipeline systems. Among them, the weakest t-norm (T_ω) has strong robustness and it is suitable for handling fuzzy sets. Considering that existing risk assessments ignore fault correlation, Zhang et al. [15] combined fuzzy set theory with FTA to evaluate the risk of pipeline systems.

The scientific formulation of maintenance decisions based on risk assessment results to improve the reliability of pipeline operations has received increasing attention [16]. According to the effect of maintenance, maintenance can be divided into minimum repair, imperfect maintenance, perfect maintenance, and replacement [17-20]. Common pipeline maintenance measures include sleeve repair, composite material reinforcement, and replacement et al. Leoni et al. [21] used BN to quantify the risk of pipeline failures and their causal relationships, dynamically formulating and optimizing maintenance plans. Yu et al. [22] used interval analysis to quantitatively evaluate the risk of onshore pipelines, and the proposed method reduces the uncertainty caused by decision makers' preferences. Daas et al. [23] proposed a Pythagorean fuzzy cost-benefit safety analysis method to predict preventive maintenance strategies for fire water systems. The proposed method integrates PFFTA, an improved consistency aggregation method and fuzzy Dematel.

At present, research on pipeline maintenance optimization is mostly focused on a single maintenance method. However, the alternating use of different maintenance methods is of little consideration, which is somewhat different from reality. Meanwhile, due to various external constraints, most of the existing pipeline inspection data have small data volumes and high uncertainties. How to handle uncertainty correctly, conduct high-precision pipeline reliability assessment, and develop scientific and reasonable maintenance measures is of great significance for reducing the operating costs of pipeline enterprises and minimizing personnel casualties.

This paper proposes a method for evaluating the reliability of natural gas pipeline systems by integrating FFTA and BN. This method is applied to a natural gas pipeline system in Jiangsu Province. It addresses the significant uncertainties and fuzzy accumulation problems of pipeline inspection data in traditional FFTA. The main innovations of this article include: (1) Integrating theories such as T_ω, FFTA, and BN to evaluate the reliability of natural gas pipeline systems, which overcomes the problems of fuzzy accumulation and subjectivity in traditional fault trees; (2) Considering the differences in maintenance effectiveness of different maintenance methods during the actual maintenance process, research is conducted on optimizing maintenance strategies under hybrid maintenance. Compared with traditional single maintenance method optimization, the proposed method has more cost advantages while meeting reliability requirements; (3) The optimization of pipeline system maintenance under different corrosion rates and reliability constraints is studied. The optimization results can provide the most suitable maintenance plan for different risk areas, which can better meet the actual needs of the project compared to traditional maintenance strategies.

The rest of this paper is divided into five sections. Section 2 introduces relevant theories of maintenance optimization methods for natural gas pipeline systems, such as FTA, fuzzy sets, and BN. Section 3 establishes a FFTA model for the natural gas pipeline system, and evaluates the system reliability by BN theory. Section 4 considers the reliability requirements and corrosion rates of different risk areas, and studies the optimization of maintenance strategies. Section 5 concludes the study.

2. Theoretical basis for maintenance optimization of natural gas pipeline systems

2.1. Optimization method for maintenance of natural gas pipeline systems

The proposed method can be divided into two key steps, as shown in Fig. 1. The first step is the reliability assessment of natural gas pipeline systems. Firstly, construct a fuzzy fault tree model for the pipeline system. Secondly, classify the probability intervals and create a set of fuzzy numbers to determine different levels of probability risk. During the evaluation process, the consistency coefficient is determined using expert evaluation method. Using the $T\omega$ operator to integrate the viewpoints of all experts. In the process of defuzzification, the aggregated fuzzy numbers are converted into fuzzy probability scores, which are then transformed into fuzzy failure probabilities for each event. Thus, the failure probability of the top event and the importance of each bottom event can be calculated.

The second step is the research on optimizing maintenance strategies for pipeline systems. Using a hybrid failure rate model to describe the differences in effectiveness of imperfect maintenance. On this basic, establishing a maintenance optimization model. The genetic algorithm (GA) is used to solve the optimization model and the corresponding maintenance optimization models under different corrosion rates and risk areas is studied.

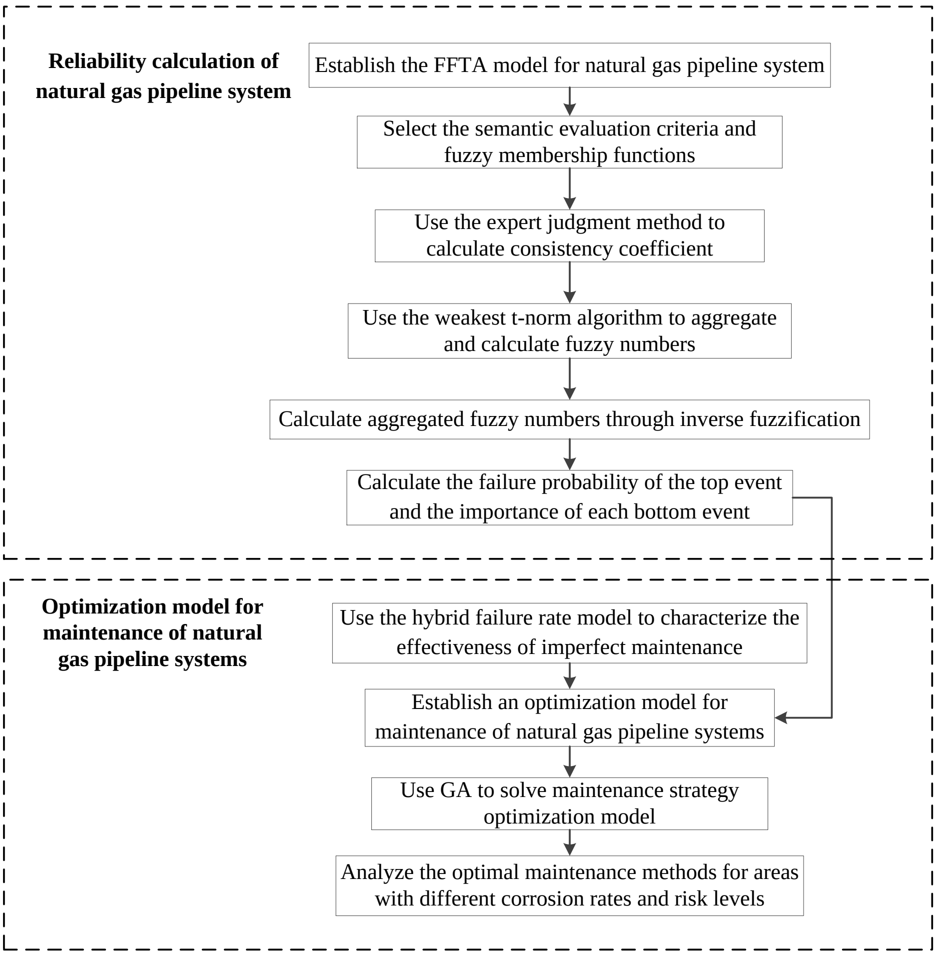


Fig. 1. Optimization process for maintenance of natural gas pipeline system.

2.2. FTA method

FTA is a widely used method in the fields of safety engineering and reliability engineering [24]. Specific graphical symbols are adopted to establish a system FTA model. The minimum cut set method is often used to describe the relationship between top and bottom events.

If all the minimum cut sets of the FT are known to be C_1、C_2、…、C_n, the probability of the top event T occurring is [25]:

$$P(T) = P\left(\overset{n}{\underset{i=1}{\cup}} C_i\right) \tag{1}$$

If the probability of each base event x_1, x_2, …, x_k occurring in the minimum cut set C_i is known, then the probability of the minimum cut set occurring is:

$$P(C_i) = P\left(\overset{k}{\underset{j=1}{\cup}} x_j\right) \tag{2}$$

If the $P(C_i)$ is known, $P(T)$ can be calculated as [26]:

$$P(T) = P\left(\overset{n}{\underset{i=1}{\cup}} C_i\right) = P(C_1 \cup C_2 \cup \cdots \cup C_n) = \sum_{i=1}^{n} P(C_i) - \sum_{i<j=2}^{n} P(C_iC_j) + \sum_{i<j<k=3}^{n} P(C_iC_jC_k) - \cdots + (-1)^{n-1}P(C_1C_2\cdots C_n) \tag{3}$$

2.3. Fuzzy set theory

（1）Fuzzy set definition

Assume that there exists a mapping from the domain U to the real interval [0,1] [27]:

$$\mu_A: U \to [0,1], \forall x \in U, x \to \mu_A(x) \tag{4}$$

Determine a fuzzy set A on U, μ_A is called the membership function of A, $\mu_A(x)$ is the degree of membership of x to A.

(2) Membership function

In fuzzy set theory, commonly used membership functions are shown in Table 1[28-29].

Table1. Common expression of membership function.

Common fuzzy distributions	Function expression form
Trigonometric membership function	$f(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-a}, & b < x \le c \\ 0, & c < x \end{cases}$
Trapezoidal membership function	$f(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b < x \le c \\ \dfrac{d-x}{d-c}, & c < x \le d \\ 0, & d < x \end{cases}$
Normal distribution membership function	$f(x) = e^{-(k-a)^2}$

① Language probability membership degree

Due to the limited data available for many basic events, it is difficult to convert them into fuzzy numbers. Therefore, this section introduces seven natural language variables: {extreme high (EH), high (H), relative high (RH), medium (M), relative low (RL), low (L), and extreme low (EL)}, for quantifying fuzzy numbers.

The language description of the possibility of event occurrence for the trapezoidal membership function and its fuzzy numbers are shown in Table 2.

Table2. Semantic values of event occurrence probability and corresponding trapezoidal fuzzy numbers.

Language evaluation indicators	Trapezoidal fuzzy number
EL	（0，0，0.1，0.2）
L	（0.1，0.2，0.2，0.3）
RL	（0.2，0.3，0.4，0.5）
M	（0.4，0.5，0.5，0.6）
RH	（0.5，0.6，0.7，0.8）
H	（0.7，0.8，0.8，0.9）
EH	（0.8，0.9，1，1）

① T_ω algorithm

$T\omega$ algorithm is one of the classic forms of t-norm algorithm, and its function expression is [30]:

$$T_\omega(x,y) = \begin{cases} x, & if\ y = 1 \\ y, & if\ x = 1 \\ 0, & otherwise \end{cases} \tag{5}$$

where x and y are independent variables.As for trapezoidal fuzzy numbers $\tilde{A}(a_1,a_2,a_3,a_4)$ and $\tilde{B}(b_1,b_2,b_3,b_4)$, the calculation formula of the weakest t-norm is as follows [31]:

$$\tilde{A} \oplus_{T_\omega} \tilde{B} = \begin{pmatrix} a_2 + b_2 - \max(a_2 - a_1, b_2 - b_1), a_2 + b_2, \\ a_3 + b_3, a_3 + b_3 + \max(a_4 - a_3, b_4 - b_3) \end{pmatrix} \tag{6}$$

② Fuzzy number aggregation processing

It is usually recommended to refer to the evaluation opinions of multiple experts to reduce uncertainty. This section adopts the consistency aggregation method to evaluate the fuzzy possibility of expert evaluation, and the basic steps are as follows [32]:

a. According to the language evaluation criteria, it is assumed that the evaluation of any bottom event b_j for the semantic values of different experts $E_u(u = 1,2,\cdots,N)$ and $E_v(v = 1,2,\cdots,N)$ can be expressed as trapezoidal fuzzy numbers $(e_{u1}, e_{u2}, e_{u3}, e_{u4})$ and $(e_{v1}, e_{v2}, e_{v3}, e_{v4})$ respectively. And the consistency of the opinions of any two experts is:

$$S\left(\tilde{E_u}, \tilde{E_v}\right) = 1 - \frac{1}{4}\sum_{i=1}^{4}|e_{ui} - e_{vi}| \quad (7)$$

where $S\left(\tilde{E_u}, \tilde{E_v}\right) \in [0,1]$.

b. Calculate the average consistency of expert E_u's evaluation opinions:

$$S_{AA}(E_u) = \frac{1}{N-1}\sum_{\substack{u\neq v\\ v=1}}^{4} S\left(\tilde{E_u}, \tilde{E_v}\right) \quad (8)$$

c. Calculate the relative consistency of expert E_u's evaluation opinions:

$$S_{RA}(E_u) = \frac{S_{AA}(E_u)}{\sum_{u=1}^{N} S_{AA}(E_u)} \quad (9)$$

d. Solve the consistency coefficient of expert E_u's evaluation opinions:

$$S_{CC}(E_u) = \beta\omega(E_u) + (1-\beta)S_{RA}(E_u) \quad (10)$$

e. Calculate the evaluation opinion aggregation fuzzy result of the bottom event bn by the weakest t-norm algorithm, which is:

$$\tilde{b}_n = S_{CC}(E_1)\tilde{E}_1 \oplus_{T\omega} S_{CC}(E_2)\tilde{E}_2 \oplus_{T\omega} \cdots \oplus_{T\omega} S_{CC}(E_u)\tilde{E}_u \quad (11)$$

③ Defizzification

The fuzzy probability score (P_{FPS}) is inverted by aggregated fuzzy results of the bottom event. The area center method can be used to solve the aggregation fuzzy number of basic events, as shown in Eq (12) [33]:

$$P_{FPS} = \frac{\int \mu_{\tilde{b}_n}(x)xdx}{\int \mu_{\tilde{b}_n}(x)dx} = \frac{1}{3}\frac{(r_4 + r3)^2 - r_4 r_3 - (r_1 + r_2)^2 + r_1 r_2}{r_4 + r_3 - r_2 - r_1} \quad (12)$$

where $\mu_{\tilde{b}_n}(x)$ represents the membership function of the fuzzy number of base events.

According to reference [14], the relationship between P_{FPS} and fuzzy failure probability (P_{FFP}) is as follows:

$$P_{FFP} = \begin{cases} \left\{10^{-\left[\frac{1-P_{FPS}}{P_{FPS}}\right]^{1/3}}\right\}^{-1}, (P_{FPS} \neq 0) \\ 0, \ (P_{FPS} = 0) \end{cases} \quad (13)$$

④ Calculate the failure probability

The failure probability of the top event is calculated by Eq(3).

2.4. Bayesian theory

Bayesian formulas are often used to update the reliability of pipelines under external environmental changes. Under the condition of known the prior probability, the posterior probability can be calculated using the Bayesian formula. The specific formula is as follows [34]:

$$p(B_i|A) = \frac{p(B_i)p(A|B_i)}{\sum_{i=1}^{n} p(B_i)p(A|B_j)} \quad (14)$$

3. Establishment of pipeline system model based on fuzzy fault tree

3.1. Establishment of fuzzy fault tree for natural gas pipeline system

This section takes the natural gas transmission pipeline in shale gas fields as the research object, and establishes a corresponding FT model using the above method [35]. The symbols and names of relevant risk events are shown in Table 3 [36].

Table3. Symbols and events in the fault tree of natural gas pipeline systems.

Symbol	Event	Symbol	Event	Symbol	Event
A_1	Perforate	C_5	Poor mechanical performance	X_{11}	Mechanical damage
A_2	Crack	C_6	The existence of cracks	X_{12}	Illegal building
B_1	Severe corrosion	X_1	Soil corrosion	X_{13}	Moving soil layer
B_2	Severe pipeline defects	X_2	Cathodic protection failure	X_{14}	Illegal construction
B_3	Third-party damage	X_3	Anti-corrosion insulation coating	X_{15}	Poor corrosion resistance
B_4	Low pressure bearing capacity	X_4	High H_2S	X_{16}	Unreasonable strength design
B_5	Corrosion cracking	X_5	High CO_2	X_{17}	Poor mechanical performance
B_6	Human error operation	X_6	Corrosion inhibitor failure	X_{18}	Greater force
C_1	External Corrosion	X_7	Thinning of inner coating	X_{19}	Existence of residual stress
C_2	Internal corrosion	X_8	Manufacturing defects	X_{20}	Stress concentration
C_3	Initial defects	X_9	Material defects	X_{21}	Improper maintenance methods
C_4	Construction defects	X_{10}	Improper installation	X_{22}	Insufficient employee training

This section categorizes pipeline failures into two types: perforation and cracking. Among them, the failure of system (T) is the top event, and intermediate events include severe corrosion, defects, third-party damage, low pressure bearing capacity, corrosion cracking, and human error operation. Fig. 2 shows the FT model corresponding to the pipeline system.

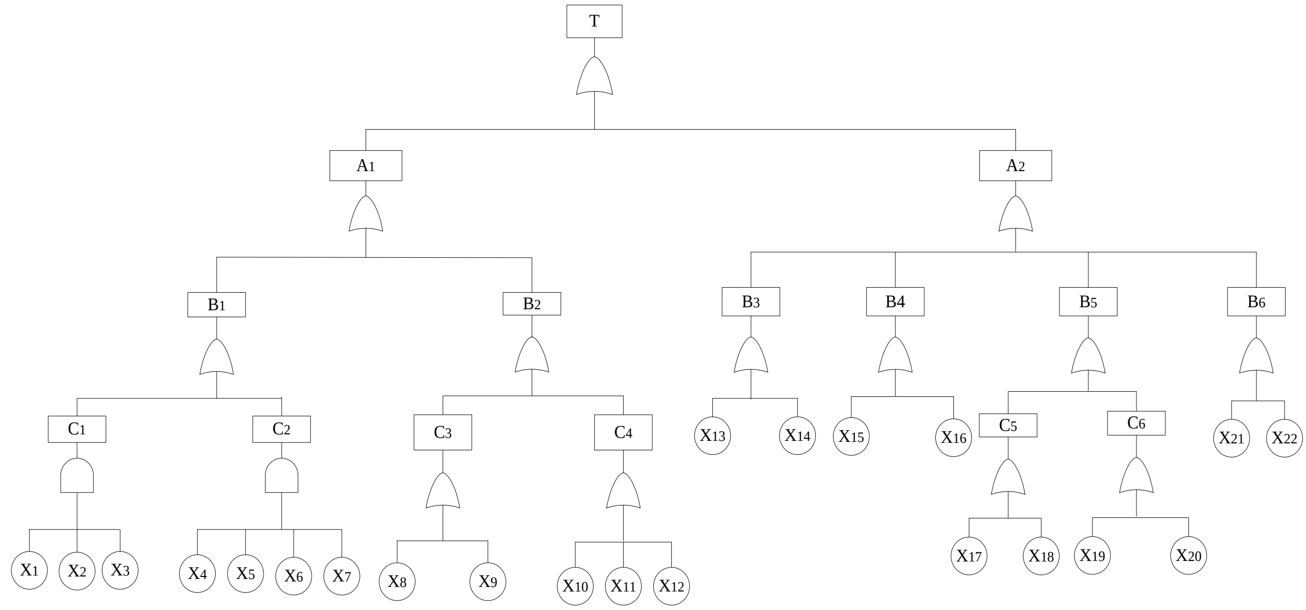


Fig. 2. FT of natural gas pipeline system.

After establishing the FT model, the P_{FFP} of the root node can be calculated. The specific process is as follows:

(1) Select 4 pipeline experts from different fields of work and assign different weights to them. The expert weights are shown in Table 4.

Table 4. Expert weights.

Expert	Job title	Weight coefficient
E_1	Professor	0.30
E_2	Senior technician	0.25
E_3	Engineer	0.20
E_4	Technician	0.25

(2) The $T\omega$ algorithm and inverse fuzzy method are used to obtain the P_{FFP} of the basic event.

To make reliable empirical judgments on each basic event, experts from a pipeline inspection and testing company under Sinopec were invited to provide their evaluations on the basic events. Before the questionnaire survey, each expert will be informed of the mapping relationship between the value space of probability scales and confidence levels and language terms to ensure consistency in language assessment. Table 5 summarizes the results of the questionnaire survey and the calculation of fuzzy failure probability.

Table 5. Trapezoidal aggregation fuzzy numbers, fuzzy possibility, and fuzzy failure probability.

Basic event	E1,E2,E3,E4	Trapezoidal aggregation fuzzy number	Fuzzy possibility	Fuzzy failure probability
X1	M,H,RH,RL	(0.52,0.55,0.59,0.62)	0.5675	7.9×10^{-3}
X2	RH,RH,EH,L	(0.53,0.56,0.64,0.67)	0.5975	9.6×10^{-3}
X3	M,RH,EH,L	(0.50,0.53,0.58,0.61)	0.5525	7.2×10^{-3}
X4	RL,RL,RH,RH	(0.41,0.44,0.54,0.57)	0.4850	4.5×10^{-3}
X5	RL,EL,RL,L	(0.17,0.20,0.28,0.31)	0.2375	4.0×10^{-4}
X6	M,RL,M,RL	(0.37,0.4,0.45,0.48)	0.4250	2.9×10^{-4}
X7	RH,M,RL,RL	(0.41,0.44,0.52,0.55)	0.4775	4.3×10^{-3}
X8	RH,EH,RH,H	(0.70,0.73,0.80,0.83)	0.7625	2.8×10^{-2}
X9	H,EH,RH,H	(0.76,0.79,0.83,0.86)	0.8075	3.7×10^{-2}
X10	M,H,RL,RL	(0.46,0.49,0.53,0.56)	0.5075	5.3×10^{-3}
X11	M,RH,L,M	(0.44,0.47,0.49,0.52)	0.4775	4.3×10^{-3}
X12	RL,H,L,L	(0.35,0.38,0.41,0.44)	0.3950	2.2×10^{-3}

Basic event	E1,E2,E3,E4	Trapezoidal aggregation fuzzy number	Fuzzy possibility	Fuzzy failure probability
X13	RL,RL,M,RL	(0.31,0.34,0.42,0.45)	0.3800	2.0×10^{-3}
X14	M,EH,RL,RL	(0.48,0.51,0.58,0.61)	0.5450	6.8×10^{-3}
X15	RH,H,H,RH	(0.66,0.69,0.75,0.78)	0.7175	2.1×10^{-2}
X16	H,H,RH,RH	(0.68,0.71,0.76,0.79)	0.7325	2.3×10^{-2}
X17	RH,RL,M,RH	(0.48,0.51,0.59,0.62)	0.5450	6.8×10^{-3}
X18	H,RH,RH,M	(0.61,0.64,0.68,0.71)	0.6575	1.4×10^{-2}
X19	M,M,M,M	(0.47,0.50,0.50,0.53)	0.5000	5.0×10^{-3}
X20	H,M,H,M	(0.61,0.64,0.64,0.67)	0.6400	1.3×10^{-2}
X21	L,EH,RL,M	(0.44,0.47,0.52,0.55)	0.4925	4.7×10^{-3}
X22	L,RH,H,M	(0.47,0.50,0.52,0.55)	0.5075	5.3×10^{-3}

3.2. BN model construction

The FTA is used to calculate the failure probability of pipeline system. Subsequently, the FTA model is converted a BN model through relevant theoretical analysis. In this conversion, each node in the network corresponds directly to a fault event, with the conditional probability table for the BN established using the expert investigation weighting method. Fig. 3 illustrates the developed BN model. Using Genie® software, the failure probability for natural gas pipeline systems is calculated as 6.3×10^{-2}.

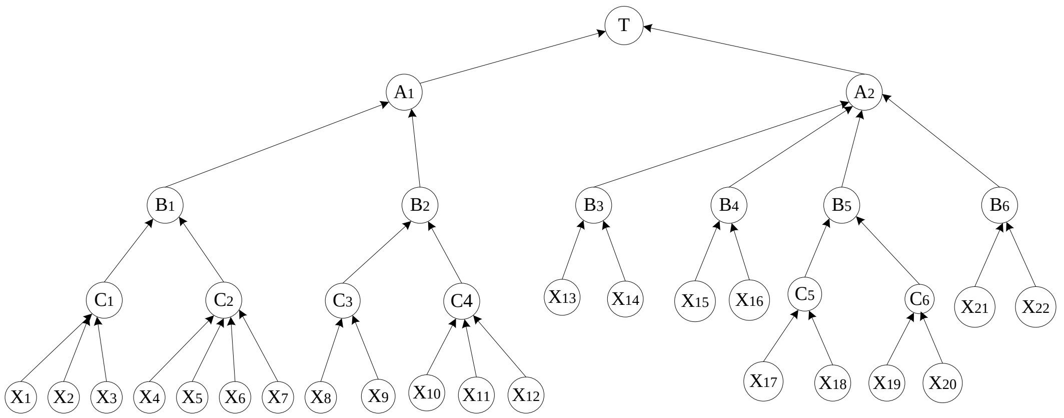


Fig. 3. BN model for natural gas pipeline system.

3.3. Parameter sensitivity analysis

Usually, the proportional change in failure probability (η) is used to quantity the dependency of root nodes on leaf nodes, expressed as Eq. (15) [37]:

$$\eta(X_i) = \frac{\varphi(X_i) - \theta(X_i)}{\theta(X_i)} \tag{15}$$

where $\varphi(X_i)$represents the prior probability of the root node X_i; $\theta(X_i)$represents the posterior probability of the root node X_i.

Fig. 4 shows the sensitivity analysis results of 22 root nodes. Among them, X_8-X_9, X_{15}-X_{17}, and X_{19}-X_{20} have larger η values. X_8 and X_9 respectively indicate manufacturing defects and material defects, X_{15} indicates severe corrosion, X_{16} and X_{17} respectively indicate unreasonable strength design and poor mechanical properties of the pipeline, X_{19} and X_{20} respectively indicate residual stress and stress concentration. When maintenance resources are limited, priority should be given to anti-corrosion measures for pipelines.

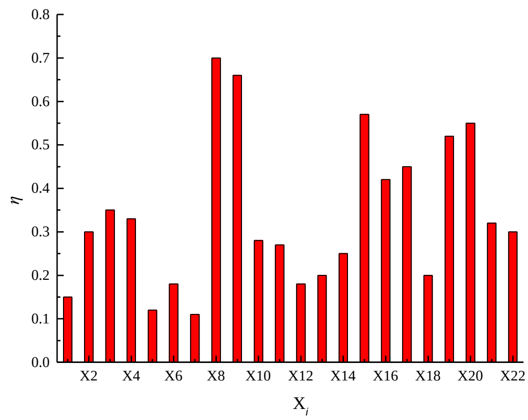


Fig.4. The η values corresponding to different nodes.

As for the problem of defects (X_8-X_9), scientific and reasonable construction is helpful to reduce the occurrence of defects. To address the specific causes of severe pipeline corrosion (X_{15}), measures such as adding anti-corrosion insulation layers can be taken to prevent corrosion failure. Considering the effect of low pressure capacity (X_{16}-X_{17}) on pipelines, the use of corrosion inhibitors can prolong the safe operation time of pipelines. As for the effect of external forces (X_{19}-X_{20}) to pipelines, increasing the inspection frequency of pipelines and adopting effective warning techniques are very important.

4. Optimization of natural gas pipeline system maintenance

4.1. Modeling of natural gas pipeline system maintenance

Using a hybrid failure rate model to characterize imperfect maintenance, as shown in Eq (16) [38]:

$$\begin{cases} Y_k = a_k Y_{k-1} + T_k \\ \lambda_k(t) = \prod_{k-1}^{i=1} b_i \lambda_1(t + a_{k-1} Y_{k-1}) \end{cases} \tag{16}$$

where Y_k is the effective age of the k-th maintenance; $\lambda_k(t)$ is the failure rate of the k-th maintenance; a_k is the age reduction factor of the k-th maintenance; b_i is the failure rate increasing factor of the i-th maintenance;

Due to the limited failure data of natural gas pipelines, this paper introduces the failure rate function from the literature in constructing the maintenance strategy optimization model, as shown in Eq (17) [20]:

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t-\gamma}{\theta}\right)^{\beta-1}, \theta > 0, \beta > 0, t \geq \gamma \tag{17}$$

where β=1.281,θ=0.7987,γ=1.1.

The optimization objective of maintenance strategy is the total cost (C_T), which can be expressed as [39]:

$$\text{CT=CI+CM+CF} \tag{18}$$

where C_T is the total cost; C_I is the inspection cost; C_M is the maintenance cost; C_F is the failure cost.

$$C_I = \sum_{j=1}^{n} c_I \left(1 - P_F(T_j)\right) \frac{1}{(1+\alpha)^{T_j}} \tag{19}$$

$$C_M = \sum_{j=1}^{n} c_M \left(1 - P_M(T_j)\right) \frac{1}{(1+\alpha)^{T_j}} \tag{20}$$

$$C_F = \sum_{j=1}^{n+1} c_F \left(P_F(T_j) - P_F(T_{j-1})\right) \frac{1}{(1+\alpha)^{T_j}} \tag{21}$$

where c_I is the inspection cost per time; c_M is the maintenance cost per time; c_F is the failure cost per time; n is the number of inspections; T_j is the time for the jth inspection; P_F is the failure probability; P_M is the maintenance probability; and a is the annual interest rate.

The failure probability of top events in natural gas pipeline systems can be calculated through FFTA and BN calculations. Then, the failure probability can be updated based on BN's inference function to obtain the change curve of pipeline failure probability and then fit the failure probability function. The failure probability of pipeline system is shown in Fig. 5.

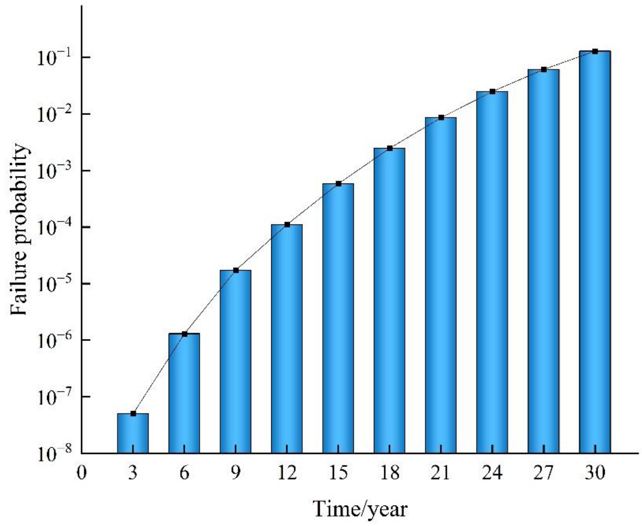


Fig.5. The failure probability of pipeline system.

Based on the data analysis of pipeline operation time and failure probability, it is found that the cumulative distribution function using the Weibull distribution provided the best fitting effect. The evaluation metrics show that R^2 is 0.99907 and RMSE (Root Mean Square Error) is 0.001. After parameter estimation, the following relationship is obtained:

$$P(t) = 1 - exp(-\left(\frac{t}{\eta*}\right)^{\beta*}) \tag{22}$$

where β^*=7.2, η^*=39.6.

Common pipeline maintenance methods include casing, welding, and composite material reinforcement, each with varying repair effects. According to reference [40], imperfect maintenance can be classified into major maintenance (M_1) and minor maintenance (M_2), shown as:

$$\begin{cases} M_1 = M(x)\ (a = 0.2, b = 1.2) \\ M_2 = M(x)\ (a = 0.3, b = 1.3) \end{cases} \tag{23}$$

The maintenance plan optimization model is:

$$\min C_T(K, T_k, M_i) \text{ s.t. } K \in N^*; T_k > 0 \quad i\text{=1or 2} \tag{24}$$

4.2. Solving algorithm for the optimal model

Considering the inefficiency of enumeration method in solving optimization problems, this section adopts GA to solve the optimization model. GA is an evolutionary optimization algorithm inspired by biological evolution principles, which iteratively optimizes candidate solutions through simulated selection, crossover, and mutation operations mimicking natural genetic processes [40]. The algorithm begins with a randomly generated initial population and evaluates individuals based on their fitness function values. High-quality genes are preserved through selection operators, while population diversity is balanced via crossover and mutation operators to simultaneously explore and exploit the solution space. This iterative process converges to a global optimum or near-optimal solution, making GA particularly effective for complex nonlinear optimization problems.

4.3. Case analysis

4.3.1. Research on periodic pipeline maintenance plans

This section takes a natural gas pipeline system in Jiangsu Province as the research object. In order to facilitate maintenance modeling research, relative cost is adopted to quantify different types of operating costs. The relative cost of pipeline system operation is shown in Table 6.

Table 6. Relative costs of pipeline operations.

Different types of operating costs	Relative value
Inspection cost	0.6
Major maintenance cost	1.5
Minor maintenance cost	1.0
Failure cost	200

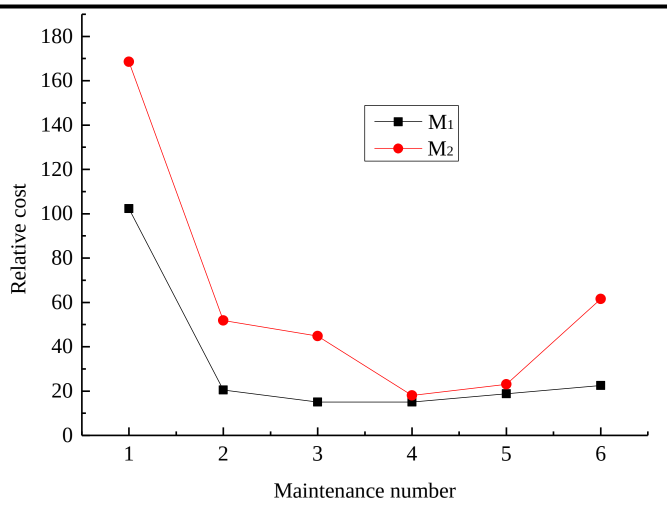


Fig. 6. Changes in relative cost of pipeline systems under different maintenance numbers.

The relative cost change curves of M_1 and M_2 are illustrated in Fig. 6. (1) When all M_1 maintenance strategies are adopted, the maintenance cost of the pipeline is highest at one repair. With the maintenance numbers increasing, the relative cost begins to decrease, it will reach the minimum at 3 repairs. Subsequently, as the number of repairs further increases, it will lead to an increase in relative costs; (2) When all M_2 maintenance strategies are adopted, the trend of relative cost change is similar to that of all M_1 maintenance strategies as the number of repairs increases, and the relative cost is the lowest when the number of repairs is 4.

A primary reason for this situation is that while reduced maintenance frequency results in lower direct inspection and upkeep expenses, the risk of pipeline failure escalates due to inadequate maintenance, thus leading to higher failure costs. Therefore, the pipeline with one repair has the highest relative cost. Afterward, the failure probability continued to decrease, but the failure cost gradually stabilized. At this point, the inspection and maintenance costs begin to exceed the failure cost, and the relative cost begins to increase. As the number of inspections and repairs further increases, the above phenomenon becomes more apparent, and the relative cost will continue to increase.

Taking the medium risk area and high corrosion rate as an example, the probability of pipeline failure varies with different hybrid maintenance numbers in equal period, as shown in Fig.7. It can be observed that: (1) If 3 hybrids repairs are used, the probability of pipeline failure will exceed the maximum acceptable failure probability (MAFP) in medium risk areas by 10^{-3}. (2) If 4 or 5 hybrid repairs are used, the MAFP is not exceeded.

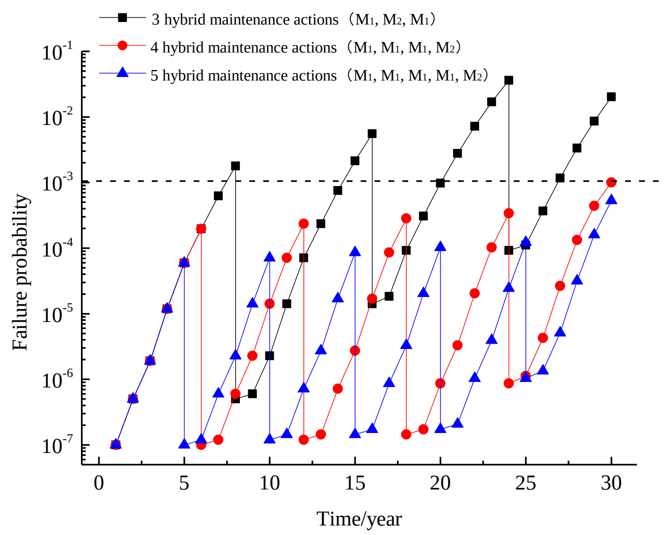
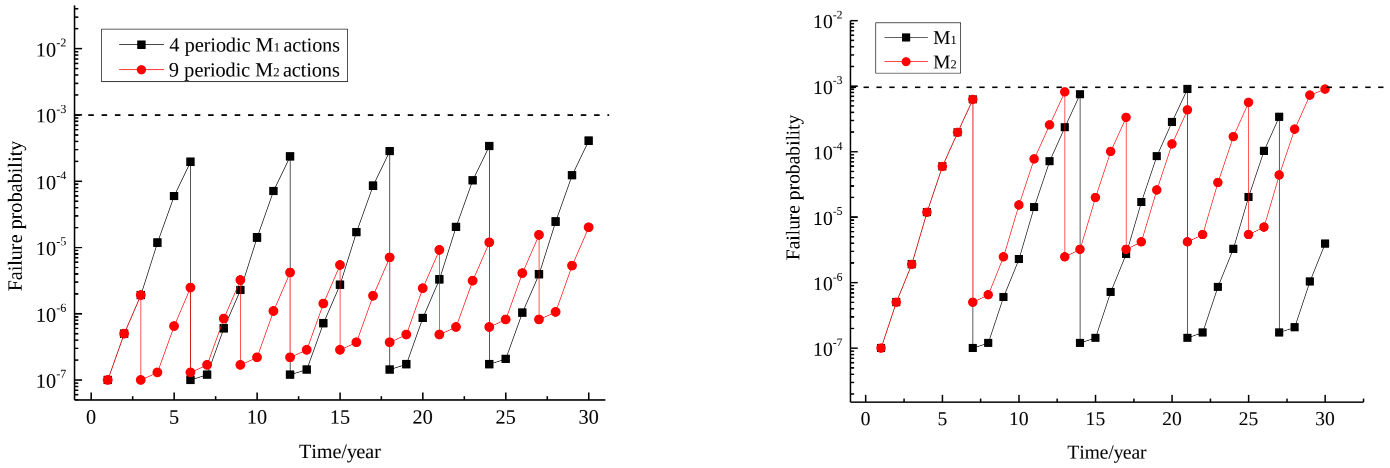


Fig. 7. Change in failure probability of different hybrid

maintenance numbers.

Scenario 1: Optimization study of equal periodic single maintenance strategy

Under the condition of probability constraints, the failure probabilities of using all M_1 and all M_2 for equal periods are shown in Fig. 8(a). The failure probability after 4 equal periods M_1 or 9 equal periods M_2 meets the requirements of medium-risk areas, and maintenance optimization research can be carried out in the future. To meet the failure probability requirements during pipeline operation, simply using all M_1 or all M_2 has the problem of high cost. Therefore, it is necessary to consider hybrid maintenance solutions.



(a) (b)

Fig. 8. Comparison of failure probabilities among different maintenances: (a) equal periods maintenance; (b) non-equal periods maintenance.

In the process of formulating pipeline maintenance strategies, it is necessary to choose appropriate maintenance methods and numbers. For the convenience of research, take the example of pipelines crossing medium-risk areas with high corrosion rates. Fig. 8(b) shows the change in failure probability of pipelines under a single maintenance method (M_1 or M_2). From Fig. 8(b), the minimum number of all M_1 is 4, and the minimum number of all M_2 is 5. Based on the above research work, the minimum number of hybrid maintenance should be between 4-5 numbers.

Under equal periodic maintenance, there are 14 combination schemes for 4 hybrid maintenances, as shown in Table 7. It should be noted that the M_1 in this article mainly refers to composite material repair (such as fiber-reinforced composite materials), while the M_2 mainly refers to welding repair and local coating repair. Faced with multiple combinations of four hybrid maintenances, MAFP is used as an evaluation indicator for selecting. In the case of using 1 M_1 and 3 M_2, the failure probability for the corresponding combinations will exceed the maximum allowable value, which does not meet the engineering requirements. 2 M_1, 2 M_2, and 3 M_1, 1 M_2 all meet the probability requirements for failure in the risk area. From a cost perspective, the hybrid maintenance strategy of 2 M_1 and 2 M_2 has a cost advantage compared to 3 M_1 and 1 M_2. Therefore, future research will focus on the hybrid maintenance strategy under 2 M_1 and 2 M_2 scenarios.

Table 7. Specific combination plans for 4 hybrid maintenances.

Combination of different maintenance plans	Specific maintenance plan
$1M_2$, $3M_1$	M_2, M_1, M_1, M_1; M_1, M_2, M_1, M_1; M_1, M_1, M_2, M_1; M_1, M_1, M_1, M_2
$2M_2$, $2M_1$	M_2, M_2, M_1, M_1; M_2, M_1, M_2, M_1; M_2, M_1, M_1, M_2; M_1, M_1, M_2, M_2; M_1, M_2, M_1, M_2; M_1, M_2, M_2, M_1
$3M_2$, $1M_1$	M_1, M_2, M_2, M_2; M_2, M_1, M_2, M_2; M_2, M_2, M_1, M_2; M_2, M_2, M_2, M_1

Scenario 2: Optimization study of hybrid maintenance strategy

The variation of pipeline failure probability for the hybrid maintenance strategy of 2 M_1 and 2 M_2 is shown in Fig. 9. Among them, there are a total of 6 combinations of hybrid maintenance strategies. According to the probability requirements for medium-risk areas, the two maintenance strategies: M_1, M_1, M_2, M_2 and M_1, M_2, M_1, M_2 can meet the requirements.

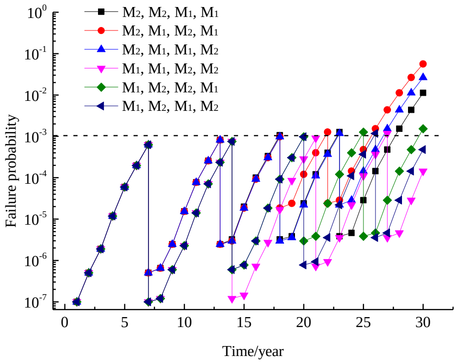


Fig. 9. Changes in pipeline failure probability under different hybrid maintenance methods.

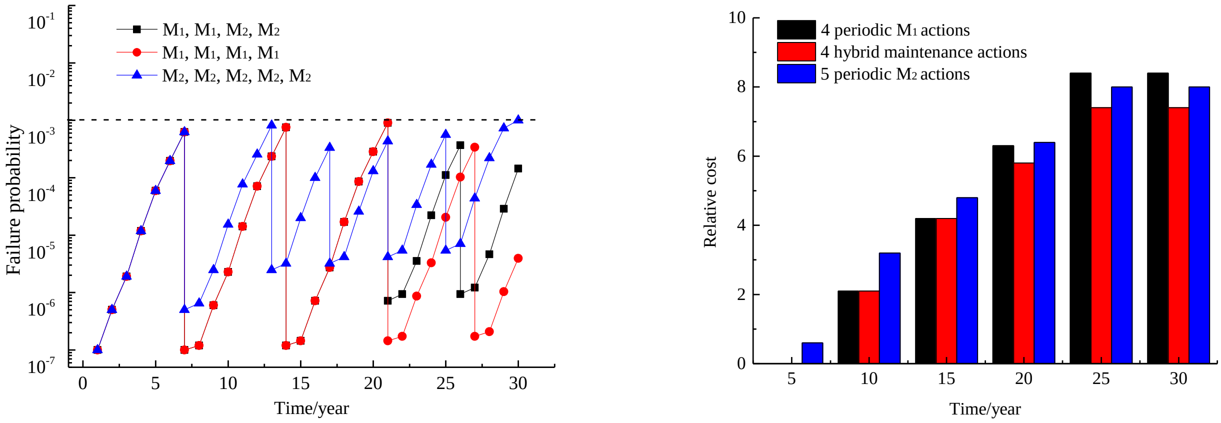


Fig.10. Comparison of failure probabilities among different maintenances: (a) optimal equal periods maintenance; (b) optimal non-equal periods maintenance.

The relative costs corresponding to the optimization results of single maintenance and hybrid maintenance are shown in Fig. 10(b). (1) In the 5th year, due to periodic inspection, the relative cost of using all M_2 is higher than using all M_1 and hybrid maintenance. (2) With the increase in pipeline operation time and the adoption of corresponding maintenance measures, in the 10th year, the relative cost of using all M_1 and hybrid maintenance exceeds that of using all M_2. As time goes on, the relative cost of using all M_2 gradually exceeds that of using all M_1 and hybrid maintenance. (3) In the 30th year, the relative cost of 4 M_1 repairs is the highest, followed by 5 M_2 repairs and 4 hybrid repairs, which had the lowest relative cost. In general, the hybrid maintenance strategy can better adapt to the system maintenance needs.

Scenario 2: Research on non-equal periodic single and hybrid maintenance strategies

The GA is used to optimize a hybrid maintenance strategy. The independent variables include the initial maintenance time, the number of maintenance actions, and the maintenance interval, while the dependent variable is the relative cost. The

4.3.2. Research on optimization of pipeline maintenance plans

There are various maintenance methods during pipeline operation, and the corresponding maintenance intervals are also different. This section investigates the optimization problem of pipeline maintenance plans under the conditions of equal periodic single and hybrid maintenance strategies, as well as non-equal periodic single and hybrid maintenance strategies.

Scenario 1: Research on equal periodic single and hybrid maintenance strategies

Fig.10(a) shows the failure probability of optimization results for single maintenance and hybrid maintenance. When the number of optimizations using M_1 is 4, and the failure probability remains at the lowest level; when the total number of optimizations using M_2 is 5, the failure probability is at a high level, approaching the MAFP in the 30th year. The optimization number for hybrid maintenance is 4, and the failure probability of pipeline is between using all M_1 and using all M_2.

constraint is the failure probability. The pipeline lifetime is set to 30 years, and the minimal search precision for the optimal inspection plan is defined as 1 year. The total cost is defined as the fitness function. Additionally, the population size is set to 100, the crossover rate is 0.8, the mutation rate is 0.1, and the number of iterations is set to 200.

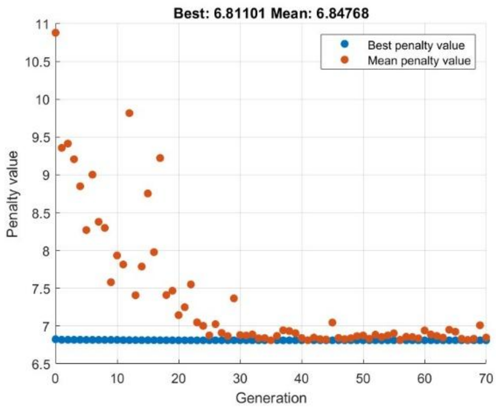
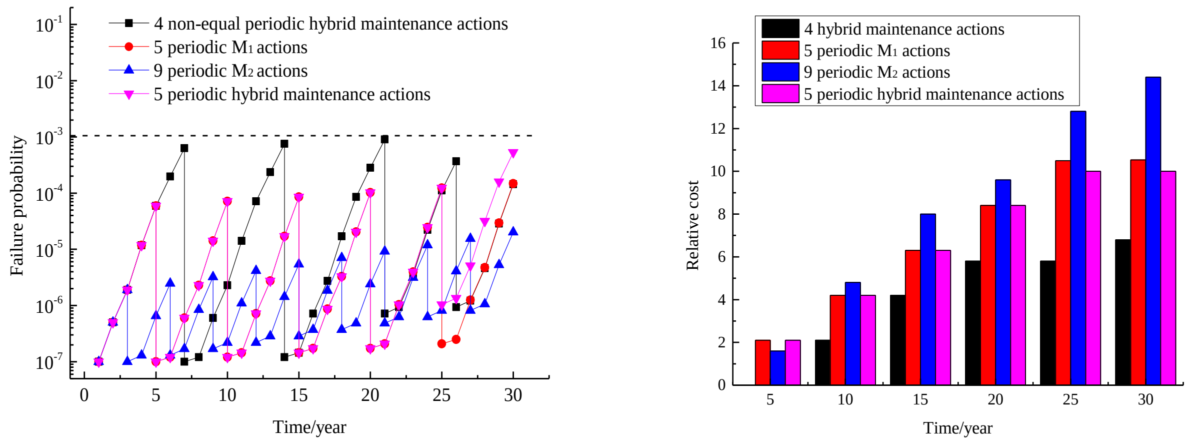


Fig. 11. Iterative process of GA optimization.

The optimization iteration process of the GA is illustrated in Fig. 11. As shown in Fig. 11, the optimal result converges gradually with an increasing number of iterations. When the iteration count reaches 30, the fitness function value stabilizes. Using the GA, the maintenance strategy optimization results can be obtained. The total cost of the pipeline system is minimized at 6.85 when maintenance measures are implemented in the 7th year (M_1), 14th year (M_1), 21st year (M_2), and 26th year (M_2).

The failure probability corresponding to the maintenance plan is illustrated in Fig.12(a). (1) When using a periodic single maintenance method, to meet the requirement of not exceeding the MAFP, the M_1 number is 5 and the M_2 number is 9. (2) For periodic hybrid maintenance methods, a reliability requirement can be met when the number of repairs is 5; when using non periodic hybrid maintenance methods, a minimum of 4 repairs are required.



(a) (b)

Fig. 12. The failure probability and relative cost corresponding to single and hybrid maintenance: (a) failure probability; (b) relative cost.

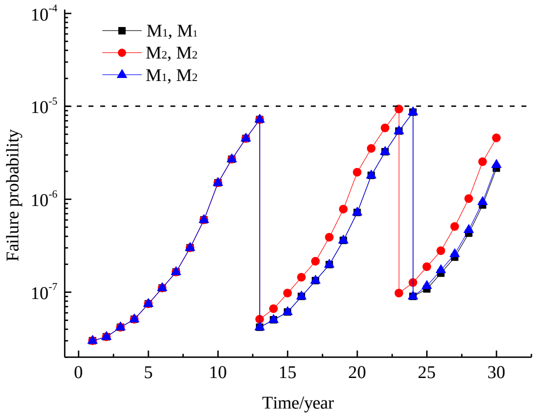
The relative costs corresponding to the above maintenance plan are illustrated in Fig.12(b). We can find that: (1) in the 5th year, the relative cost of 4 hybrid repairs is the lowest, followed by 9 equal periodic M_2, 5 equal periodic M_1, and 5 equal periodic hybrid repairs. With the increase in pipeline operation time and maintenance times, the relative cost of pipelines will begin to increase. (2) During the operating period, the relative cost of 4 hybrid repairs remained at a relatively low level; The relative cost of 5 non-equal periodic hybrid repairs and 5 equal periodic hybrid repairs is at an intermediate level; The relative cost of 9 equal periodic hybrid repairs is the highest, mainly due to excessive frequency of inspection and maintenance, which increases the relative cost of inspection and maintenance.

4.3.3. Research on pipeline maintenance plans under different corrosion rates

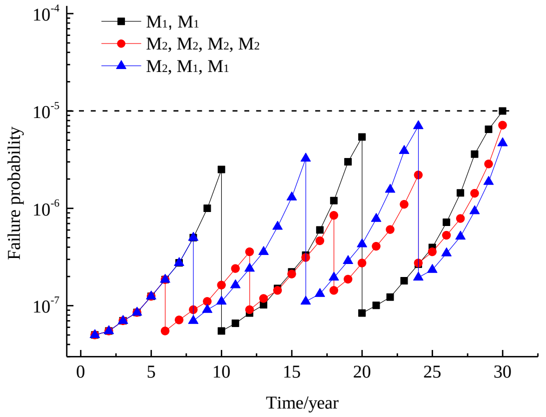
This section investigates the optimal maintenance strategies for pipelines under different corrosion rates.

(1) Low corrosion rate, different risk areas

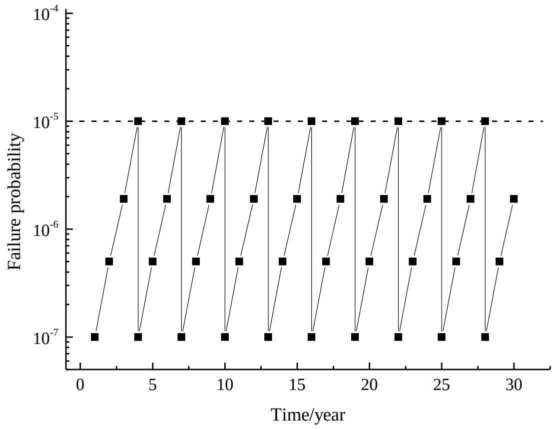
Under low corrosion rates, the performance degradation of pipelines is relatively slow, and the failure probability is relatively small. If the pipeline meets the failure probability requirements for high-risk areas, it can naturally meet the operational requirements for low to medium-risk areas. In high-risk areas, the failure probability of pipeline under different maintenance methods varies as shown in Fig. 13(a).



(a)



(b)



(c)

Fig. 13. Changes in pipeline failure probability under different maintenance methods: (a) low corrosion rate; (b) medium corrosion rate; (c) high corrosion rate.

From Fig.13(a), (1) when the number of repairs is 2, the failure probability under periodic M_1, M_2, and hybrid repairs meets the requirements for failure probability in high-risk areas. (2) The relative cost of 2 M_1> 2 hybrid repairs>2 M_2. Therefore, under the condition of meeting the requirement of failure probability, 2 M_2 is the optimal maintenance plan.

(2) Medium corrosion rate, different risk areas

Under medium corrosion rates, the degradation rate of pipeline performance increases, and correspondingly, the failure probability also rises. When the pipeline meets the failure probability requirements for high-risk areas, it is bound to meet the requirements for low to medium-risk areas. The failure probability of pipeline under different maintenance methods in high-risk areas is illustrated in Fig.13(b). (1) The maintenance plans of 2 M_1, 3 M_2, and 3 hybrid maintenance all meet the failure probability requirements of high-risk areas. (2) The failure probability of 3 hybrid maintenance is the highest, followed by 2 M_1 and 3 M_2 repairs. At this point, the relative cost of 3 hybrid maintenance is greater than the relative cost of 3 M_2 and the relative cost of 2 M_1. Therefore, under the condition of meeting the requirement of failure probability, 2 M_1 is the optimal maintenance plan.

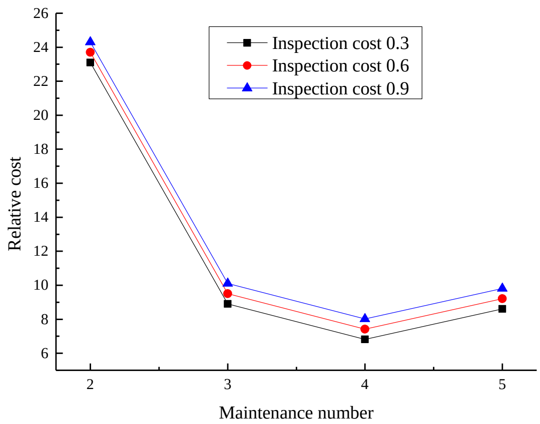
(3) High corrosion rate, different risk areas

Under high corrosion rates, the performance of pipelines deteriorates rapidly, and the corresponding probability of pipeline failure increases rapidly. If maintenance measures are not taken on time, it is easy to reach the MAFP in the risk area. For high-risk areas, the MAFP is 10^{-5}. Regardless of whether M_1 or M_2 is used, the pipeline will quickly reach its MAFP. In response to this situation, periodic perfect maintenance will be adopted, and the corresponding changes in pipeline failure probability are shown in Fig.13(c).

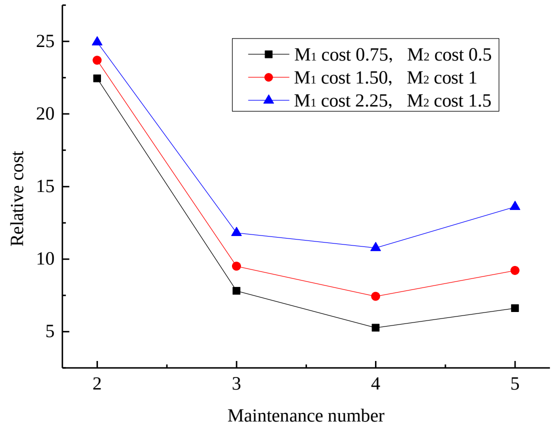
If maintenance measures are not taken, the pipeline will exceed the MAFP in the 4th year. Therefore, by taking perfect maintenance measures for pipelines in the 4th year, it can be restored to its original state. Subsequently, continuous perfect maintenance will be carried out on the pipeline.

4.4. Sensitivity analysis

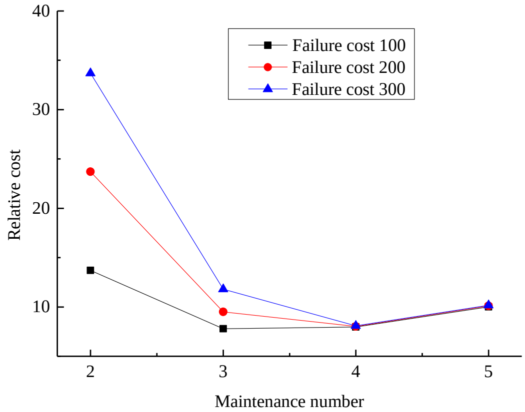
This section investigates the effect of different maintenance costs (C_I, C_M, and C_F) and failure rate parameters (a and b) on the optimization results under a hybrid maintenance strategy. Among them, the variation range of hybrid maintenance numbers is 2-5.



(a)



(b)



(c)

Fig. 14. Sensitivity analysis of maintenance cost parameters: (a) different inspection costs; (b) different maintenance costs; (c) different failure costs.

(1) Sensitivity analysis of inspection cost

The effect of inspection cost changes on the relative cost of pipeline operation is illustrated in Fig. 14(a). From Fig. 14(a), (1) as the number of repairs increases, the relative cost first decreases and then increases. (2) When the inspection cost decreases from 0.6 to 0.3, the relative cost begins to decrease. When the number of repairs is 2, the relative cost decreases from 23.7 to 23.1 with a decrease of 2.53%. Afterward, as the number of repairs increased, the relative cost first decreased and then increased, reaching a minimum of 6.82 at 4 repairs. When the number of repairs is 5, the relative cost begins to increase again. (3) The inspection cost increased from 0.6 to 0.9, and the change in relative cost is similar to the cost curve under an inspection cost of 0.3. It is also the lowest relative cost during the 4 repairs, with a corresponding relative cost of 8.02, with an increase of 8.08%. When the number of repairs is 5, the increase in relative cost increases. In summary, changes in inspection costs have a certain impact on the relative cost of pipelines.

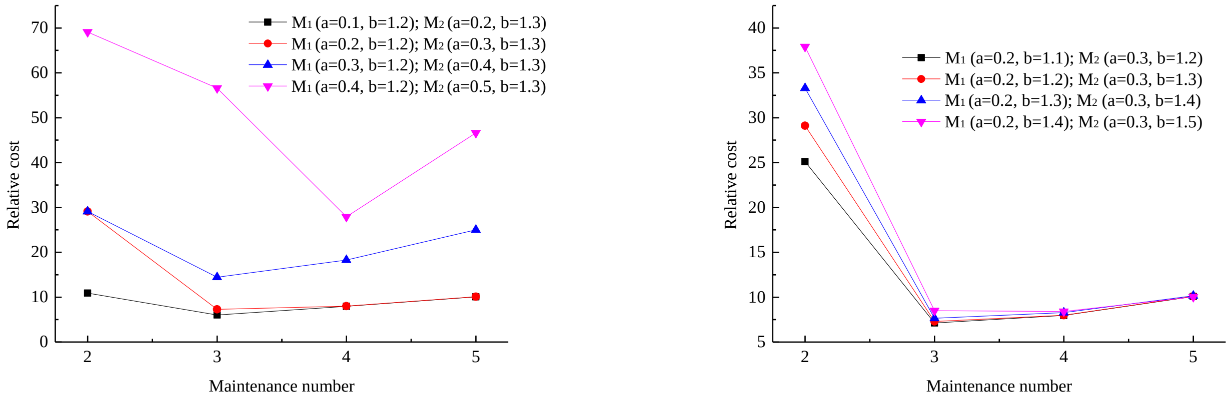
(2) Sensitivity analysis of maintenance cost

The effect of changes in maintenance costs on the relative operating costs of pipelines is illustrated in Fig. 14(b). From Fig. 14(b), (1) when the number of repairs increases from 2 to 5, the relative cost first decreases, reaches its lowest value at 4 repairs, and then begins to increase. (2) When the cost of M_1 decreases from 1.5 to 1 and the cost of M_2 decreases from 1 to 0.5, the relative cost begins to decrease. When the number of repairs is 2, the relative cost decreases from 23.7 to 22.45 with a decrease of 5.27%. Afterward, as the number of repairs increased, the relative cost first decreased and then increased, reaching a minimum of 5.27 at 4 repairs. When the number of repairs is

5, the relative cost begins to increase again. (3) When the cost of major repairs increased from 1.5 to 2.25 and the cost of minor repairs increased from 1 to 1.5, the change in relative cost was similar to the cost curve under major repair cost 1 and minor repair cost 0.5. The relative cost was the lowest during the 4 repairs, with a relative cost of 10.77 and an increase of 45.15%. When the number of repairs is 5, the relative cost increase is greater. In short, maintenance costs have a significant effect on the relative cost of pipelines.

(3) Sensitivity analysis of failure cost

The effect of changes in failure costs on the relative cost of pipeline operation is illustrated in Fig. 14(c). From Fig. 14(c), (1) when the maintenance number is 2 and the failure cost is reduced from 200 to 100, the relative cost decreases from 23.7 to 13.7, with a decrease of 42.19%; When the number of repairs is 3, the relative cost decreases from 9.5 to 7.8, with a decrease of 17.89%; Afterwards, when the number of repairs is 4-5, the relative cost remains basically unchanged. (2) When the failure cost increases from 200 to 300, the trend of change is similar to the previous analysis results, and the relative cost increases significantly during 2 or 3 repairs. When the number of repairs is 4-5, the relative cost remains basically unchanged. In addition, the increase or decrease in the cost of a single failure will cause a significant change in the cost of failure, thereby affecting the relative cost. When the repair numbers is 4-5, the change in failure cost has almost no effect on the relative cost change. The main reason is that the probability of pipeline failure is at a low level at this time, and the change in single failure cost will not cause a significant change in failure cost, so there will be no significant change in relative cost. In short, when the number of repairs is low, the impact of changes in failure costs on the relative cost of pipelines cannot be ignored; when the number of repairs is high, the impact of changes in failure costs on the relative cost of pipelines can be ignored.



(a) (b)

Fig. 15. Sensitivity analysis of parameters: (a) parameter a; (b) parameter b.

(4) Sensitivity analysis of failure rate parameters

The sensitivity analysis results of the failure rate parameters *a* and *b* are shown in Figs.15(a)-(b), respectively.

Among them, the variation range of *a* is from 0.1 to 0.5, and the variation range of *b* is from 1.1 to 1.5. From Fig. 15(a), (1) as *a* gradually increases, the relative cost changes significantly. (2) When the number of repairs is 2, the relative cost increases rapidly from 11 to 70 as *a* increases. As the number of repairs further increases, the relative cost first decreases and then increases.

From Fig. 15(b), (1) When the number of repairs is 2, the relative cost increases from 25 to 36 as *b* increases. As the number of repairs further increases, the relative cost first decreases and then increases. (2) When the maintenance numbers are 3-5, the increase in *b* has little effect on the relative cost. It can be inferred that when the number of repairs is small, *b* has important influence on the relative cost; as the number of repairs increases, the impact of *b* on relative costs decreases noticeably.

Compared with Figs. 15(a)-(b), it can be found that the effect of *a* on relative costs is greater than *b*. Therefore, when formulating maintenance plans, *a* is more important than *b*.

5. Conclusions

Formulating scientific maintenance strategies is crucial for ensuring the safe operation and enhancing the reliability of natural gas pipeline systems. By solving the maintenance optimization model, several conclusions are drawn:

(1) This paper explores the reliability assessment of natural gas pipeline systems under uncertain conditions. An integrated FFTA and BN method is proposed to calculate the top event failure probability of the pipeline system. Through sensitivity analysis, key basic events with significant impacts on the system are identified. On this basis, failure probabilities at different nodes are calculated and updated by BN. This approach reduces uncertainty due to limited data and enhances the precision of failure probability predictions.

(2) The optimization of maintenance strategies under hybrid and single maintenance methods is studied considering the differences in maintenance effectiveness among different maintenance methods. The results show that under low corrosion rates, the maintenance strategy of periodic minor repairs (M_2) can meet the reliability requirements of different risk areas; For medium corrosion rates, the maintenance strategy of periodic major repairs (M_1) can meet the reliability requirements of different risk areas; For high corrosion rates, a hybrid maintenance approach is effective in low to medium risk areas, whereas high-risk zones demand periodic perfect maintenance.

(3) A sensitivity analysis concerning cost factors reveals that inspection costs have minimal impact on the relative operational costs of the pipeline. In comparison, maintenance costs significantly influence these relative costs, with the effect becoming more pronounced as the frequency of maintenance increases. Furthermore, the effect of variations in failure costs on relative operational expenses is closely associated with the number of repairs performed. Specifically, when repair occurrences are limited, changes in failure costs notably affect operational costs; however, as the frequency of repairs rises, their impact on relative operational costs diminishes.

Due to the limited size of the collected data, this paper mainly uses expert opinion methods to calculate the probability of pipeline system top events, which may lead to certain inaccuracies. When pipeline companies establish a comprehensive database of oil and gas pipeline failures, the accuracy of model calculations will be further improved. In addition, the maintenance strategy optimization model mainly aims to minimize the total cost, and availability is also an important performance indicator in certain environments. In the future, when constructing maintenance optimization models, it is possible to consider establishing a maintenance strategy optimization model that incorporates cost and availability as the optimization objectives.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No.72471054; No.72001039; No. 52175257); ZhiShan Scholar Program of Southeast University (2242023R40037); the National Key R&D Programs (No. 2021YFC3340400); the Active Design Projects of Key R&D Plans of Zhejiang Province (No.2021C01053); the Science and Technology Plan Project of Zhejiang Provincial Government Market Supervision Administration (ZD2024005); Research start-up funds of China Jiliang University (01101- 241154).

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