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A Comprehensive Failure Risk Analysis of Drainage Pipes Utilizing Fuzzy Failure Mode and Effect Analysis and Evidential Reasoning

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Abstract: Drainage pipes play a crucial role in maintaining the functionality of cities and ensuring the smooth flow of daily life for its inhabitants. However, due to their placement either in shallow ground or within building foundations, maintenance of these pipes can be challenging. At present, research in this field primarily focuses on evaluating the overall health of macroscopic pipeline systems. Moreover, there is a lack of decision algorithms that can effectively minimize the subjectivity of experts. To address this issue, a failure risk analysis method was developed that incorporates the principles of Failure Mode and Effect Analysis (FMEA), Evidential Reasoning (ER), and Fuzzy Set Theory (FST) (FACEF). Nineteen pipeline failures were analyzed by synthesizing information from five commonly used pipeline evaluation specifications. Ten experts were consulted to evaluate these failures, and the scores were calculated and ranked using the FACEF method. The results indicated that six types of failures, namely penetration, crack, deformation, mismatch, leakage, and obstruction, require the most attention. An analysis of the typical causes of failure was conducted based on the FACEF scores, and measures for prevention and control were recommended. This study provides novel perspectives and insights on the risk management of pipeline failures, with a focus on reducing the influence of expert subjectivity through the refinement of pipeline failure analysis.

Keywords: failure risk analysis; drainage pipe failure; failure mode and effect analysis; evidential reasoning; fuzzy set theory

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1. Introduction

Sewage overflow and groundwater leakage from drainage pipes severely affect urban aesthetics and environmental health [1,2]. Black smelly water bodies [3] and heavy metal pollution [4] pose health hazards and hinder urban development. Drainage pipes are usually buried in the shallow ground or shuttled in the infrastructure of buildings, which hinders maintenance work [5,6].

The health status analysis of drainage pipes is closely related to asset management and maintenance costs, etc. The scientific and efficient analysis of pipe failures has a very positive significance in evaluating the health status of drainage pipes, reducing the frequency of drainage system damage, and decreasing the property cost of pipeline maintenance. Many researchers have conducted a lot of research on pipeline failure risk in pipeline O&M management, mainly by adopting technical methods or management approaches to evaluate the current health status of pipeline systems and make targeted treatments. Typical applied technological methods are GIS systems [7,8] and experiment-based methods of pipeline status assessment [9,10]. Typical management approaches are the questionnaire method [11], a hybrid of bibliometric, scientometric, and meta-analysis approaches [12], etc. The above approaches provide important reference and technical support for solving safety risk problems in drainage systems, but still have some drawbacks:

(a) field data are difficult to collect; (b) the approaches used are relatively straightforward and simple, making it difficult to cut down the subjective factors in expert evaluation as much as possible; (c) most of the existing approaches analyze the pipeline system from the perspective of the macro level, and few studies have been conducted to study and judge the failures of the pipeline. In conclusion, it is of great practical significance and research value to develop an algorithm theory that can explore as objectively as possible the judgmental ideas in the expert evaluation in the absence of realistic data and analyze the pipeline failures from the level of the whole.

In this study, Failure mode and effect analysis (FMEA) is selected as the basic theory of the algorithm, which is a quantitative analysis method used for analyzing the potential failure modes of complex systems and the causes of failures [13]. FMEA comprises five stages: preparation, identification, prioritization, risk reduction, and re-evaluation [14]. The risk priority number (RPN) parameter is defined to specify the failure mode or cause. RPN values are expressed using the severity of the failure (S), the occurrence of failure modes (O), and the probability of not detecting the failure (D). The risk of failure with a higher RPN value causes severe damage to property and personnel and should be given sufficient attention by the management and maintenance staff. Numerous studies have proven that FMEA has many limitations in application, and the use of FMEA alone usually generates problems such as model complications and detachment from the real situation [15,16]. In order to weaken the influence of subjectivity in the expert evaluation and to reflect the tendency in expert judgment, this study cites ER as a supplement to FMEA theory and adopts FST to fuzzify the expert opinions to make the evaluation results closer to reality and more realistic in operation.

The remainder of this article is organized as follows. In Section 2, the basics of FMEA, ER, and fuzzy set theory (FST) are presented. In Section 3, drainage pipeline failure patterns and common pipeline evaluation specification methods are described. In Section 4, the ER and FST concepts are applied to construct evaluation models by using FMEA. In Section 5, the constructed model is used to evaluate and rank the pipeline failure patterns by expert scoring. In Section 6, the model evaluation results are discussed, and mechanistic explanation and avoidance suggestions for typical failures are presented; in addition, the advantages of the proposed method over the traditional failure mode and effect analysis (TFMEA) method are discussed.

2. Materials and Methods

2.1. FMEA

FMEA can be described quantitatively by using the RPN parameter as follows:

$$RPN = S \times O \times D, \tag{1}$$

where S denotes the severity of the failure, O denotes the occurrence of failure modes, and D denotes the probability of not detecting the failure.

The traditional RPN calculation is to assign S, O, and D as single values and multiply them together to obtain the product value, which is then used for qualitative and semi-quantitative analyses. Some measures are required to prevent the occurrence of failure if the RPN value exceeds the threshold value. In long-term practical applications, although FMEA is widely used, it has many drawbacks [17]:

a) Discrete RPNs usually take values between 0 and 1000, a significant fraction of which is rarely used.
b) The same results can be obtained using different S, O, and D values; however, the different combinations do not correspond to the same real-world scenario (e.g., S = 1, O = 2, $D = 10$ has a completely different meaning in practice than $S = 4$, O = 5, D = 1).
c) The traditional RPN calculation method defaults to equal weights for the three dependent variables; however, this is not the case in practical applications.

d) Obtaining sufficiently representative and meaningful values for the dependent variables is difficult.
e) The use of discrete values in the assignment and calculation processes makes it difficult to avoid the problem of subjectivity.

2.2. ER

ER is an algorithmic theory proposed by Dempster [18] and developed by Shafer [19] and is widely used in logical analysis and engineering practice. In the theory of ER, all possible outcomes of a problem are assumed to be represented by a set $\Theta = \{H_1,\ H_2, \ldots, H_n\}$, and the subsets in the set Θ are mutually exclusive. The basic probability assignment (BPA) is expressed as follows [20]:

$$\begin{cases} m(\Phi) = 0 \\ \sum\limits_{A \subseteq \Theta} m(A) = 1 \end{cases}, \tag{2}$$

where Φ is an empty set, A is an arbitrary subset of Θ, and 2^Θ is the power set of Θ and is denoted as $2^\Theta = \{\varnothing,\ H_1, H_2, \ldots, H_N, \{H_1, H_2\}, \ldots, \{H_1, H_2, \ldots, H_i\} \ldots, \Theta\}$. When $m(A) > 0$, A is called the focal element; when there are two independent BPAs, the combination rule is expressed as follows [21]:

$$\begin{cases} 0,\ A = \varnothing \\ \frac{1}{1-K} \sum\limits_{B \cap C = A} m_1(B) m_2(C),\ A \neq \varnothing \end{cases}, \tag{3}$$

where K is the traditional conflict coefficient and reflects the degree of conflict between the pieces of evidence: a large K indicates a greater degree of conflict, and $K = 1$ indicates that the evidence is completely conflicting and is thus not suitable.

To enable simple and fast decision-making in the ER framework, Smets and Kennes established the pignistic probability transformation (PPT) method [22]. Assuming that m is a set of BPA structures, PPT deconstruction methods can be expressed as follows:

$$BetP_m(x) = \sum_{x \in A,\ A \subseteq \Theta} \frac{1}{|A|} \times \frac{m(A)}{1 - m(\varnothing)}, \tag{4}$$

where $|A|$ is the cardinality of set A, and $\Theta \in [0,\ 1]$.

2.3. FST

FST is a method proposed by Zadeh in 1965 to solve the problem of uncertainty in practical applications [23]. A fuzzy set $\widetilde{A}$ in a universe X can be expressed as follows:

$$\widetilde{A} = \{\langle x,\ \mu_{\widetilde{A}}(x)\rangle | x \in X\}, \tag{5}$$

where $\mu_{\widetilde{A}}$ is between $[0,\ 1]$, and $\mu_{\widetilde{A}}(x)$ is the degree of subordination to $\widetilde{A}$ among the values of $x \in X$.

Fuzzy sets are usually described using the triangular fuzzy number (TPN), trapezoidal fuzzy number, and Gaussian fuzzy number. In this study, we used the triangular fuzzy number $\widetilde{A} = (l,\ m,\ u)$ for expressing fuzzy relations, where m is a value located in the middle of l and u, as shown in follows, and the triangular fuzzy number is represented by the graph shown in Figure 1 [24]:

$$\mu_{\widetilde{A}}(x) = \begin{cases} \frac{x-l}{m-l},\ l \leq x \leq m \\ \frac{u-x}{u-m},\ m \leq x \leq u \\ 0,\ else \end{cases}. \tag{6}$$

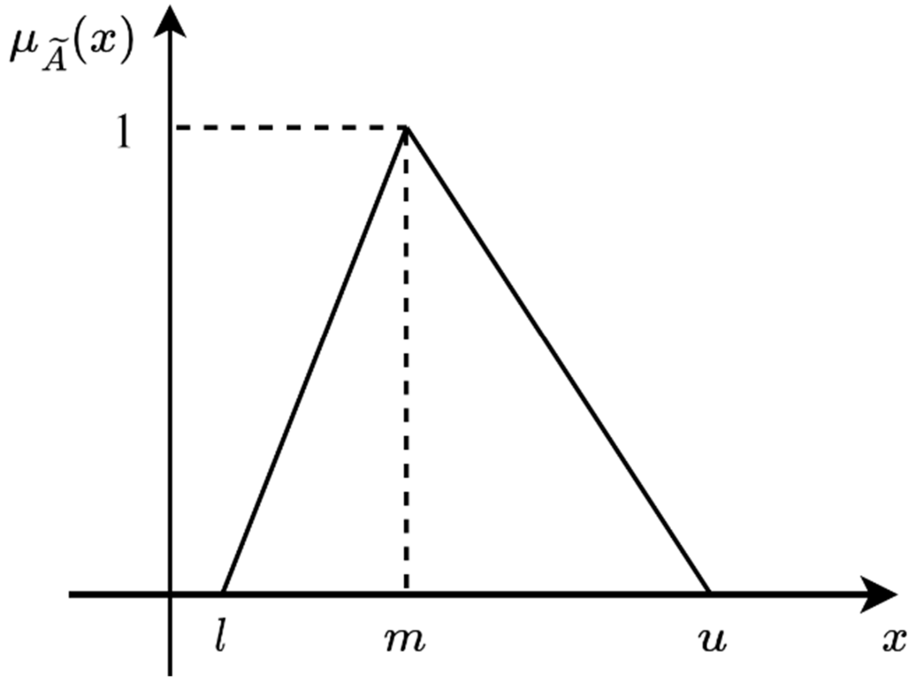

Figure 1. Diagram of TPN.

3. Failure Patterns of Drainage Pipes

Drainage pipes are usually buried in soil or hidden beneath the building infrastructure, and their failure patterns are affected by the physical properties of the pipes, the nature of the surrounding soil, hydraulic conditions, and the surrounding environment making the analysis of failure patterns challenging [25–27]. In the operation and maintenance of pipelines and inspection activity, due to the characteristics of deep burial, complex branching structure, different shapes of the pipe mouth, and complex internal conditions of the pipeline, manual detection methods are rarely adopted. Thus, representative pipeline inspection instruments and methods have been developed, such as closed-circuit television (CCTV), periscope, and sonar detection [28–30].

Mohammadi et al. analyzed the data presented in the literature, such as ProQuest for meta-indexed data on drainage pipe deterioration prediction models, to compile a list of regulatory criteria and evaluation methods commonly adopted between 2001 and 2019; the data shown in Figure 2 [27]. Based on the above results, we compiled the data from the Manual of Sewer Condition Classification (MSCC) [31], the National Association of Sewer Service Companies' Pipeline Assessment and Certification Program (PACP) [32], the Water Service Association of Australia's Conduit Inspection Reporting Code of Australia (CIRCA) [33], the European Standard EN 13508–2, and China's "Technical Specification for Inspection and Evaluation of Urban Sewer" (CJJ181–2012) to obtain a relatively complete set of drainage pipe damage patterns, which are divided into structural failures and operational failures according to the different modes of action required. Structural failures refer to the failures that affect the strength, stiffness, and service life of the pipeline structure, whereas operational failures refer to the failures that affect the normal operation of the pipeline under the action of external objects during the operation and maintenance of the pipeline. The grouping and description are presented in Table 1.

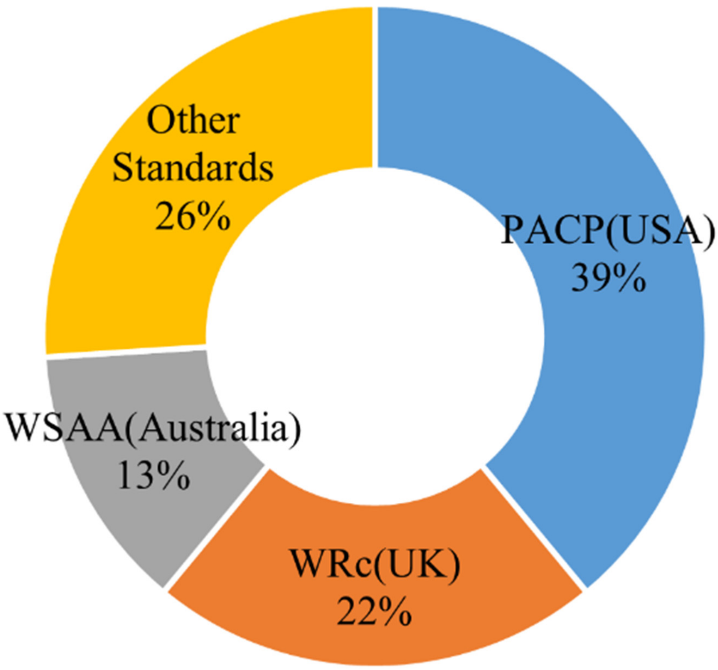

Figure 2. Common rating standards adopted during 2001–2019.

Table 1. Classification and description of sewer pipe failure patterns.

	Failure Name	Description
Structural Failures	Crack (CR)	The outer wall of the pipe produces obvious crack lines, but no obvious breakage of the pipe wall occurs
	Fracture (FR)	Cracks in the outer wall of the pipe are clearly cracked, but the broken pieces of pipe are still in place
	Broken (BR)	Some parts of the pipe are clearly separated, and the lost parts are no longer in place
	Collapse (COL)	The whole cross-section of the pipe is disconnected and cannot form an effective water interception section
	Deformation (DE)	There is a significant cross-sectional change in one part of the pipe compared to the nearby area
	Mismatch (MI)	The two orifices of the same interface produce lateral deviation and are not in the correct position of the pipe
	Disconnect (DI)	The ends of the two pipes are not sufficiently joined, or the interfaces are detached
	Interface Material Shedding (IMS)	Rubber ring, asphalt, cement, and other similar interface materials into the pipe
	Spalling (SP)	Pipe surface material breaks into small pieces due to corrosion of reinforcement or expansion of poor-quality material
	Corrosion (COR)	The inner wall of the pipe is eroded and lost or spalled, appearing pockmarked or exposed steel
	Weld Failure (WF)	Interface damage caused by improper human operation or material deformation at the pipeline interface during welding
	Branch Pipe Concealed Connection (BPCC)	The branch pipe is not directly connected to the main lateral through the inspection well
Operational Failures	Obstruction (OB)	There are obstructions inside the pipe that affect the overflow of the pipe
	Penetration (P)	Insertion of external objects other than the pipe itself or appurtenances into the pipe
	Root Intrusion (RI)	Individual roots or scaled roots grow naturally into the pipe
	Leakage (LE)	Water infiltration or seepage caused by structural damage to the pipe itself
	Impurity Deposits (ID)	Sedimentation and siltation of impurities at the bottom of the pipe
	Stump Walls and Roots (SWR)	Temporary brick wall blocking masonry when the pipe closed water test after the test is not removed or removed incomplete
	Scam and Floating Mud (SFM)	There is a collection of floating objects on the water surface in the pipe

For pipeline inspection, CCTV is generally used for in-pipe inspection to qualitatively evaluate the damage pattern of the pipeline by obtaining in-pipe images for manual identification and integrating the damage information for the whole pipeline to evaluate the condition of the pipeline as a whole. The images obtained by CCTV inspection are categorized into the typical pipeline failures summarized in Table 1, as shown in Figure 3.

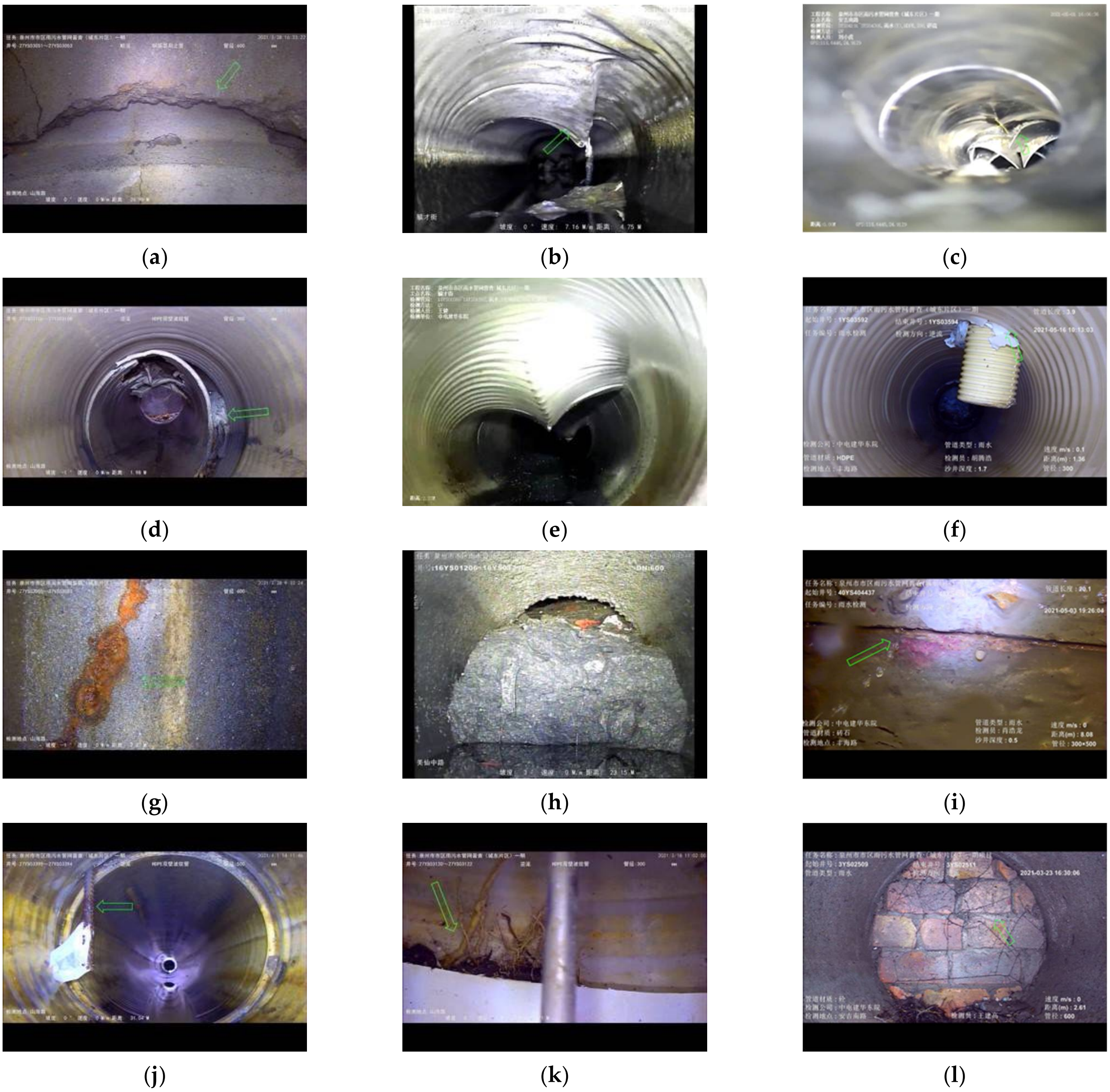

Figure 3. Typical failure patterns in sewer pipes. (**a**) Crack, (**b**) Fracture, (**c**) Broken, (**d**) Mismatch, (**e**) Deformation, (**f**) Branch Pipe Concealed Connection, (**g**) Corrosion, (**h**) Obstruction, (**i**) Leakage, (**j**) Penetration, (**k**) Root Intrusion and (**l**) Stump Walls and Roots.

4. FMEA Approach by Using ER and FST

The TFMEA method includes the following steps: identify potential risk issues, evaluate S, O, and D values of corresponding issues, convert to RPN values, and rank potential risks and focus on risks [16]. We incorporated the FST and ER and related algorithms into the traditional FMEA approach to overcome the shortcomings of TFMEA. The flowchart of the proposed approach is shown in Figure 4.

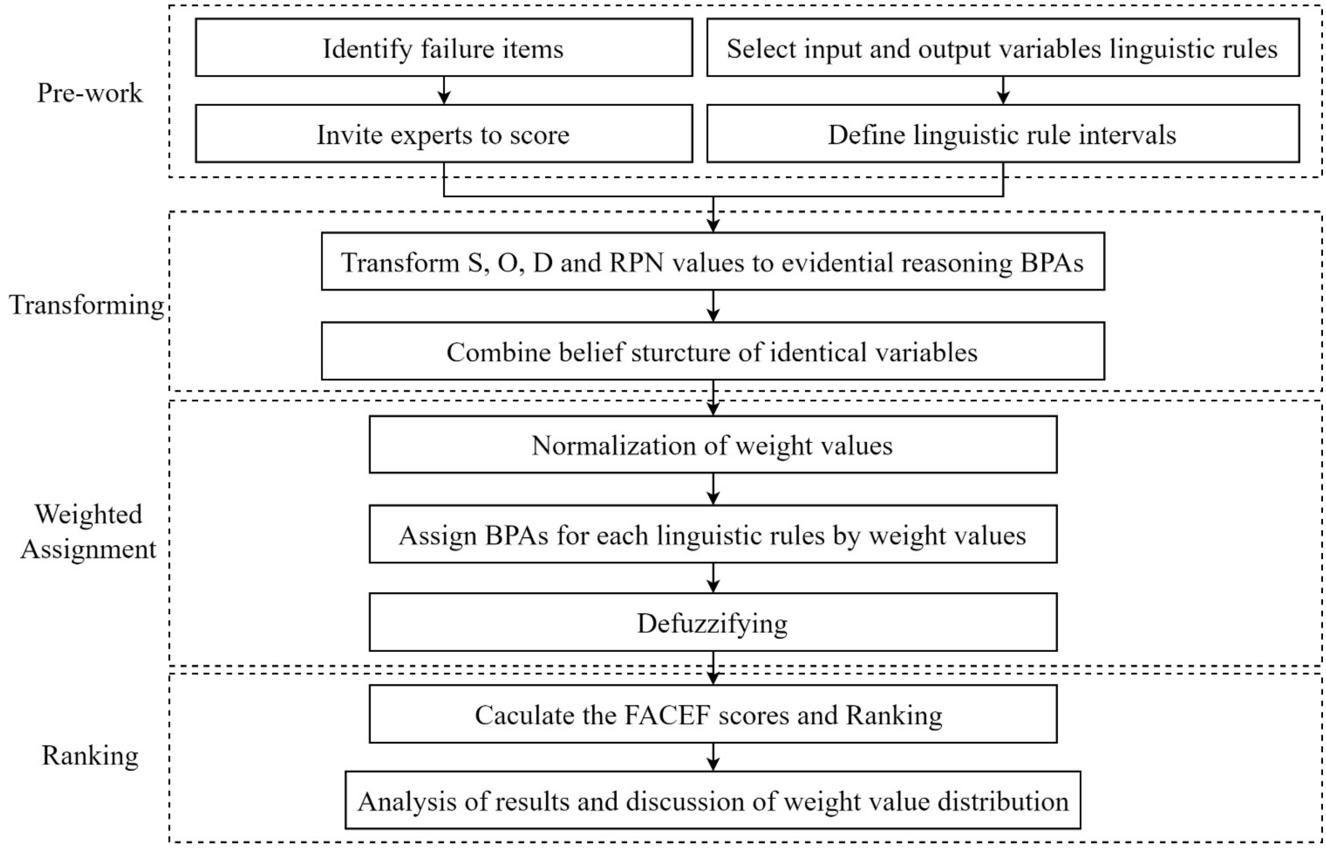

Figure 4. Flowchart of FACEF.

4.1. *Defining Fuzzy Linguistic Rules*

According to the norms such as MSCC, PACP, and CIRCA, the three input variables (i.e., S, O, D) can be classified into five classes, namely very low (VL), low (L), middle (M), high (H), and very high (VH), and the output RPN can be classified into eight classes, namely very good (VG), good (G), moderately good (MG), fair (F), middle bad (MB), bad (B), very bad (VB), and completely bad (CB):

$$\Theta_S = \Theta_O = \Theta_D = \{VL, L, M, H, VH\},$$
$$\Theta_V = \{VG, G, MG, F, MB, B, VB, CB\}.$$

To ensure engineering applicability, the appropriate TPN values of input variables are selected, as shown in Table 2. The TPN values of output variables are presented in Table 3, and the membership functions of the input and output variables are shown in Figures 5 and 6.

Table 2. TPN values of input variables.

Linguistic Level	TPN	*S*	*O*	*D*
VL	(0, 0, 2.5)	Minimal impact on pipeline management	Very low probability of occurrence	Very easy to detect
L	(0, 2.5, 5)	Low impact on pipeline management	Low probability of occurrence	Easy to detect
M	(2.5, 5, 7.5)	Insignificant impact on pipeline management	Moderate probability of occurrence	Moderate probability of detection
H	(5, 7.5, 10)	High impact on pipeline management	High probability of occurrence	Hard to detect
VH	(7.5, 10, 10)	Great impact on pipeline management	Very high probability of occurrence	Almost undetectable

Table 3. TPN values of output variables.

Linguistic Level	VG	G	MG	F	MB	B	VB	CB
Range	(0, 0, 20)	(0, 20, 60)	(20, 60, 90)	(60, 90, 120)	(90, 120, 240)	(120, 240, 500)	(400, 600, 800)	(700, 1000, 1000)

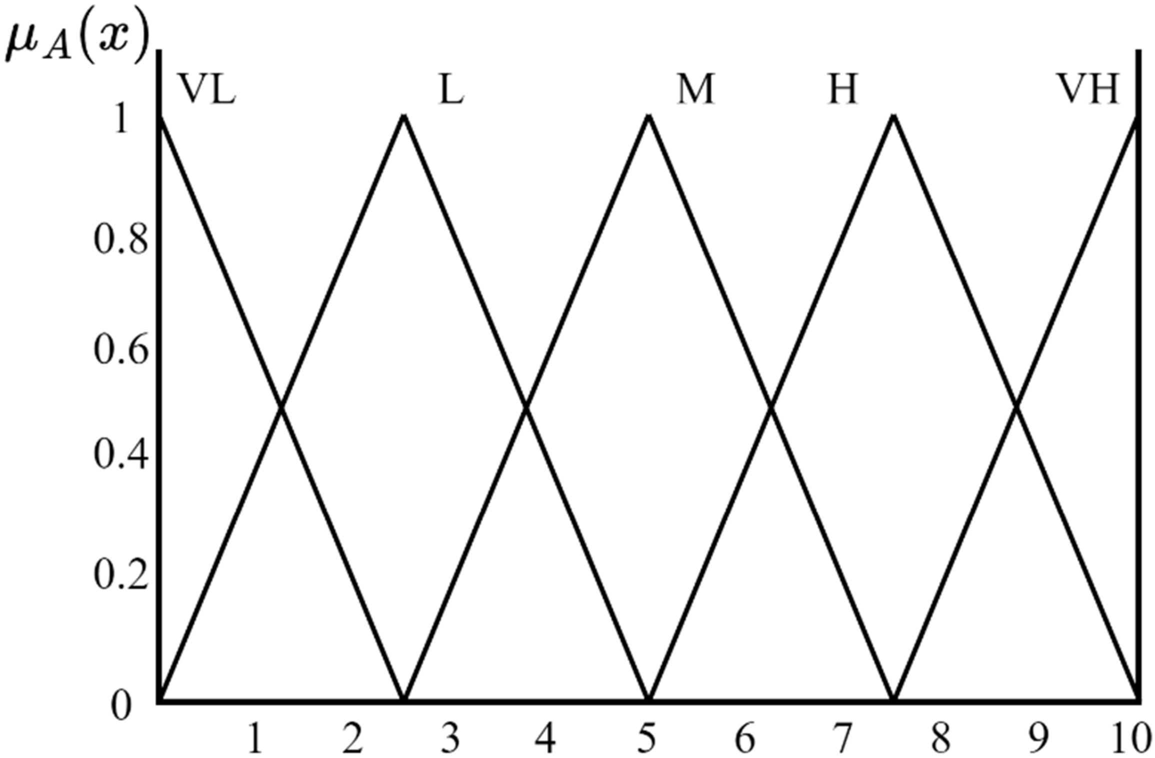

Figure 5. Membership functions of input variables.

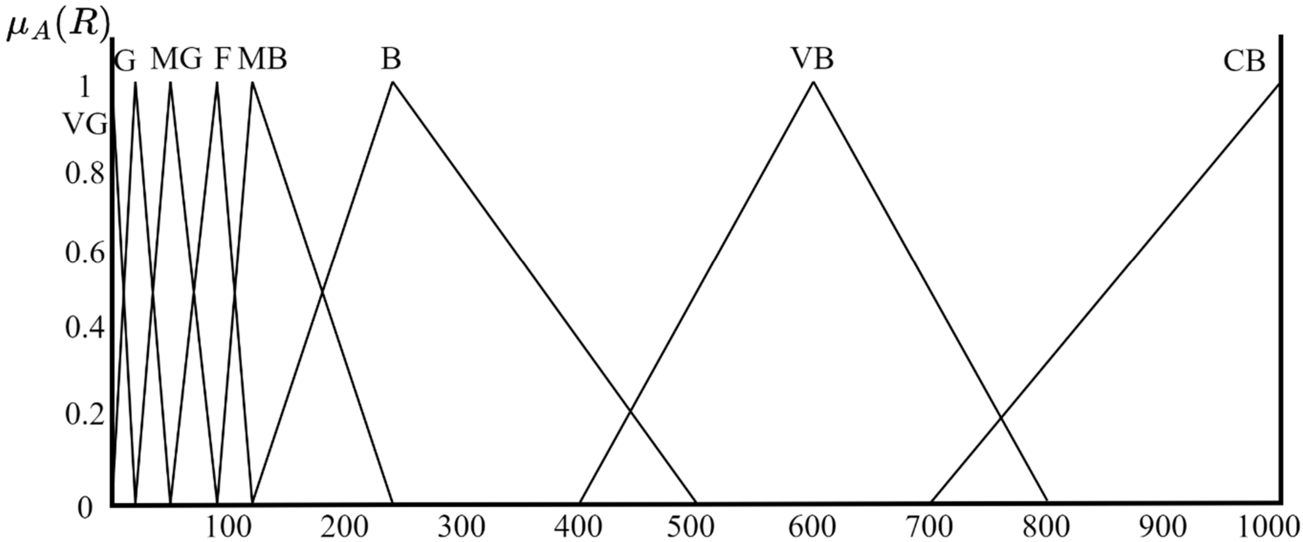

Figure 6. Membership functions of output variables.

4.2. Transforming the Values of S, O, and D and RPNs to Evidential Reasoning BPAs

As can be seen from Figure 5, because of the incorporation of FST in the proposed algorithm, in most cases, a given value of x yields two values of $\mu_A(x)$ (e.g., $\mu_{A_1}(x=2)=0.2$ and $\mu_{A_2}(x=2)=0.8$ for $x=2$). Let these two simultaneous cases be $\widetilde{A_1}$ and $\widetilde{A_2}$, $\mu_{\widetilde{A_1}}(x)=h_1$ and $\mu_{\widetilde{A_2}}(x)=h_2$, and h_1 and h_2 satisfy $h_1+h_2=1$. Then, the mass function can be obtained as follows [34]:

$$\begin{cases} m\left(\widetilde{A_1}\right)=h_1,\ m\left(\widetilde{A_1},\ \widetilde{A_2}\right)=h_2,\ if\ h_1>h_2 \\ m\left(\widetilde{A_2}\right)=h_2,\ m\left(\widetilde{A_1},\ \widetilde{A_2}\right)=h_1,\ if\ h_1<h_2 \end{cases}. \tag{7}$$

Taking $x=2$ as an example, we obtain $m\left(\widetilde{A_2}\right)=\mu_{A_2}(x=2)=0.80$ and $m\left(\widetilde{A_1},\ \widetilde{A_2}\right)=\mu_{A_1}(x=2)=0.20$ according to Equation (7). We take "IF ... THEN ... " as a conversion statement and use "$S=2,\ O=5,\ D=10$" as an example:

Before transformation:

IF $S=2,\ O=5,\ D=10$, THEN $RPN=2\times5\times10=100$

After transformation:

$$S=2: m(L)=0.80,\ m(VL,\ L)=0.20$$
$$O=5: m(M)=1$$
$$D=10: m(VH)=1$$

IF $m_S(\{L\})=0.80,\ m_S(\{VL,\ L\})=0.20\ \wedge\ m_O(\{M\})=1\ \wedge m_D(\{VH\})=1$

THEN $m_{RPN}(F)=0.67,\ m_{RPN}(F,\ MB)=0.33$

4.3. Constructing a Fuzzy Weighted ER Rule

A set of BPAs corresponding to $S,\ O,\ D,$ and RPN are obtained by performing the "IF ... THEN ... " conversion; however, different input variables may yield the same output variable. Thus, weight processing and ER rule establishment are required. We selected $S=2,\ O=5,\ D=10$ and $S=2,\ O=5,\ D=9$ to demonstrate the establishment of the rule.

4.3.1. Combining Same Rule Items

After the "IF ... THEN ... " conversion statement for $S=2,\ O=5,\ D=10$ has been obtained (Section 4.2), it can be observed that there are two BPAs for S, one BPA each for O and D, and two BPAs for the output parameter RPN in this set of input items. The same BPAs are obtained for the combination of $S=2,\ O=5,\ D=9$, as can be seen in Table 4.

Table 4. Fuzzy ER rules for $S=2,\ O=5,$ and $D=9$.

Rule	S	O	D	RPN
Rule 5	$m(L)=0.80$	$m(M)=1$	$m(VH)=0.60$	$m(F)=1$
Rule 6	$m(L)=0.80$	$m(M)=1$	$m(H,\ VH)=0.30$	$m(F)=1$
Rule 7	$m(VL,\ L)=0.20$	$m(M)=1$	$m(VH)=0.60$	$m(F)=1$
Rule 8	$m(VL,\ L)=0.20$	$m(M)=1$	$m(H,\ VH)=0.30$	$m(F)=1$

As can be seen from Tables 4 and 5, Rules 1 and 5, Rules 3 and 7 are consistent in the combination of rules. The combined ER rule can be obtained from the four groups of rules as follows (Table 6):

$$\overline{m_v}(U)=\frac{\sum_{i=1}^{N} m_{v_i}(U)}{n},\ U\in 2^{\Theta_V} \tag{8}$$

where n is the number of rules satisfying $(S=i)\wedge(O=j)\wedge(D=k)\rightarrow(RPN=l)$ for a given failure.

Table 5. Fuzzy ER rules for $S = 2,\ O = 5,$ and $D = 10$.

Rule	S	O	D	RPN
Rule 1	$m(L) = 0.80$	$m(M) = 1$	$m(VH) = 1$	$m(F) = 0.67$
Rule 2	$m(L) = 0.80$	$m(M) = 1$	$m(VH) = 1$	$m(F,\ MB) = 0.33$
Rule 3	$m(VL,\ L) = 0.20$	$m(M) = 1$	$m(VH) = 1$	$m(F) = 0.67$
Rule 4	$m(VL,\ L) = 0.20$	$m(M) = 1$	$m(VH) = 1$	$m(F,\ MB) = 0.33$

Table 6. Combined ER rules for $S = 2,\ O = 5,\ D = 10$ and $S = 2,\ O = 5,\ D = 9$.

Rules	S	O	D	Before Combined BPAs	Combined BPAs
Rule 1, Rule 5	$m(L)$	$m(M)$	$m(VH)$	$m_1(F) = 0.67$ $m_5(F) = 1$	$\overline{m}_1(F) = 0.835$
Rule 3, Rule 7	$m(VL,\ L)$	$m(M)$	$m(VH)$	$m_3(F) = 0.67$ $m_7(F) = 1$	$\overline{m}_3(F) = 0.835$

Combining the contents of Tables 4–6, the use of the "IF ... THEN ... " statement yields six sets of rules:

Rule 1: IF $(S = L) \wedge (O = M) \wedge (D = VH)$, THEN $\overline{m}_1(F) = 0.835$
Rule 2: IF $(S = L) \wedge (O = M) \wedge (D = VH)$, THEN $\overline{m}_2(F,\ MB) = 0.33$
Rule 3: IF $(S = \{VL,\ L\}) \wedge (O = M) \wedge (D = VH)$, THEN $\overline{m}_3(F) = 0.835$
Rule 4: IF $(S = \{VL,\ L\}) \wedge (O = M) \wedge (D = VH)$, THEN $\overline{m}_4(F,\ MB) = 0.33$
Rule 5: IF $(S = L) \wedge (O = M) \wedge (D = \{H,\ VH\})$, THEN $\overline{m}_5(F) = 1$
Rule 6: IF $(S = \{VL,\ L\}) \wedge (O = M) \wedge (D = \{H,\ VH\})$, THEN $\overline{m}_6(F) = 1$

For the output variables used in this study (Figure 6), a single set of rules occurred in the intervals (240, 400), (500, 700), and (800, 1000) (e.g., if $R = 300$ there is and only $B : \mu_A(R) = 0.7692$), which is complementary to the full set of confidence levels (e.g., $m(B) = 0.7692$ for $R = 300$ with $m(\Phi) = 0.2308$).

4.3.2. Belief Degree Assignment by Using Weight Values

In the expert scoring system, the weights of the experts' scores can be expressed in terms of $S,\ O,$ and D for a failure, e.g., if 75% of the experts' scores are in the interval of L and 25% of the experts' scores are in the interval M for the severity (S) of a certain failure, then S for this failure has $m(L) = 0.75,\ m(M) = 0.25$.

As described in Section 4.3.1, in the use of the "IF ... THEN ... " statement, each $S,\ O,\ D$ is assigned a weight value, and the product of the $S,\ O,\ D$ weights is the corresponding output variable. The weight values of different rules for one type of failure are summed up and normalized and then multiplied with each group of combined ER rules to obtain a set of fuzzy weighted ER rules:

$$\begin{cases} w_{i,\ j,\ k} = m_S(i) \times m_O(j) \times m_D(k) \\ \overline{w}_{i,\ j,\ k} = \frac{w_{i,\ j,\ k}}{\sum_i \sum_j \sum_k w_{i,\ j,\ k}} \\ \overline{m}_v(U) = \sum\limits_i \sum\limits_j \sum\limits_k m_{v_{i,\ j,\ k}}(U) \times \overline{w}_{i,\ j,\ k} \end{cases}, \tag{9}$$

where $(S = i) \wedge (O = j) \wedge (D = k)$, and $\left\{m_{i,\ j,\ k}(U) = e_l,\ U \in 2^{\Theta_V}\right\}$.

Adopting the allocation principle of Equation (4), the belief degree is divided using the output variable evaluation interval. If $m_1(B) = 0.051,\ m_2(B,\ VB) = 0.012,$ and $m_3(MB,\ B)$ = 0.024 , then according to the allocation principle, $m(MB) = m_3(MB,\ B) \times 0.5 = 0.024 \times 0.5 = 0.012,\ m(B) = m_1(B) \times 1 + m_2(B,\ VB) \times 0.5 + m_3(MB,\ B) \times 0.5 = 0.051 \times 1 + 0.012 \times 0.5 + 0.024 \times 0.5 = 0.069, m(VB) = m_2(B,\ VB) \times 0.5 = 0.012 \times 0.5 = 0.006$. Next, the belief degrees of eight sets for the output variable intervals are sequentially obtained: $\Theta = \{VG,\ G,\ MG,\ F,\ MB,\ B, VB, CB\}$.

4.4. Defuzzifying BPAs and Ranking

Defuzzifying is an important part of FMEA, and extensive research has been conducted on defuzzifying methods. Current mainstream methods include the mean of maxima, last of maximum, and center of gravity (CoG) [35,36]. In this study, CoG was employed as the defuzzifying method and calculated as follows:

$$x^* = \frac{\int x \cdot \mu_{\widetilde{A}}(x)dx}{\int \mu_{\widetilde{A}}(x)dx}, \tag{10}$$

where $\mu_{\widetilde{A}}(x)$ is obtained from Equation (5), and the CoG values (Table 7) for the eight classes in Figure 6 are obtained using Equation (10).

Table 7. CoG values of output variables.

Linguistic Item	VG	G	MG	F	MB	B	VB	CB
CoG	6.6667	26.6667	56.6667	90	150	286.6667	600	900

The new RPN Y can be obtained using Equations (9) and (10) as follows:

$$Y = \sum_{A \in \Theta} \overline{m}_v(A) \times x^*_A, \tag{11}$$

where A is the part belonging to the set of evaluation terms Θ = {*VG, G, MG, F, MB, B, VB, CB*}. The ranking value is obtained using the rules for rating and ranking, and the final evaluation results are obtained.

4.5. Chapter Discussion

In this chapter, an FMEA-based algorithm is developed that employs FST to fuzzify the input information and statistically process the data information into a belief weight distribution through the structured adjustment of ER. The data source and driving force of the algorithm come from expert evaluation scoring, and the core value of its operation is to divide the expert scores into corresponding interval weights and weighting processes. The purpose of this algorithm is to rank selected research objects according to the final score of the algorithm and to perform targeted analysis to rationalize the allocation of resources to achieve efficient scientific management.

5. Failure Risk Analysis by Using the Proposed Method

We performed the risk analysis of drainage pipeline failures during O&M.

5.1. Pre-Work

Drainage pipeline O&M and inspection tasks have high technical barriers. To ensure that the evaluation results meet the needs of engineering practice and scientific research, ten experts with diverse experience and research backgrounds were invited to participate in the evaluation process: two project managers who have been engaged in pipeline operation and maintenance for many years, four experienced pipeline inspection engineers, and four researchers with a certain research background. The experts with engineering backgrounds were sourced from drainage pipe inspection and evaluation projects in the southern coastal region of China. Meanwhile, the experts with research backgrounds were selected from researchers in the southern region of China who specialize in underground space engineering and pipeline research.

Because the developed approach chosen for this study is based on FMEA, this provides us with three different perspectives for analyzing failures: severity of the failure, occurrence of the failure, and the probability of not detecting the failure. Before inviting the experts to participate in the scoring, they were given a detailed description of the pipeline failure classification framework adopted in this study and were asked to rate each failure from three different perspectives (*S*, *O*, *D*) based on their own experience or research knowledge.

For each type of failure, they were asked questions such as "Do you feel that crack has a significant impact on the pipeline or the surrounding environment," "Do you feel that crack is easy to occur in pipeline operations and maintenance," and "Do you feel that crack is easy to detect if it occurs in the pipeline?" They were asked to rate 19 types of defects on a 10-point scale according to the above guided questions. The results of the experts' scoring are presented in Table 8.

Table 8. Sewer pipeline failure pattern evaluation by experts (The extreme values in the table (greater than or equal to 9 for part S, greater than or equal to 6 for part O, and greater than or equal to 8 for part D) are marked in bold font).

	CR	**FR**	**BR**	**COL**	**DE**	**MI**	**DI**	**IMS**	**SP**	**COR**	**WF**	**BPCC**	**OB**	**P**	**RI**	**LE**	**ID**	**SWR**	**SFM**
	5	7	**9**	**10**	6	7	8	3	2	2	5	7	8	7	8	8	5	**9**	2
	5	7	8	**9**	5	8	8	3	3	4	5	8	7	8	7	**9**	6	8	2
	6	8	**9**	**10**	6	8	**9**	2	2	3	4	7	7	6	7	8	5	**9**	3
	6	8	8	**9**	6	7	8	4	3	3	6	8	8	7	8	8	5	8	2
S	5	7	**9**	**10**	5	8	**9**	3	3	3	5	7	7	8	8	**10**	4	8	2
	4	7	**10**	**9**	7	7	7	3	4	5	5	8	8	7	7	8	5	8	2
	5	7	8	**10**	6	7	8	3	3	4	6	**9**	8	7	8	8	5	**9**	1
	6	6	**9**	**10**	6	8	8	2	3	4	5	7	7	7	7	8	4	8	2
	4	8	8	**10**	5	7	7	3	3	2	5	**9**	7	8	7	**9**	6	7	3
	5	7	8	**10**	7	7	8	3	3	3	5	8	8	7	8	**9**	5	8	2
	7	**6**	3	3	5	4	4	1	5	**7**	4	2	4	5	5	4	**6**	1	2
	7	5	5	2	5	4	2	2	**6**	5	4	3	4	4	4	3	**6**	1	3
	8	**7**	4	3	**6**	3	2	2	5	**6**	3	3	5	4	4	4	**7**	2	4
	7	**6**	3	1	4	5	3	3	4	**7**	5	4	**6**	**6**	3	2	**7**	2	3
O	**8**	5	4	4	**6**	4	1	3	5	**6**	4	3	4	5	4	2	5	1	3
	9	**7**	4	2	5	5	2	3	5	**7**	3	3	5	5	4	3	**7**	3	2
	8	4	5	1	5	3	2	2	**6**	5	4	3	5	5	3	3	**6**	2	3
	8	5	3	3	**6**	4	2	1	4	5	4	3	4	5	2	3	5	2	5
	9	**6**	4	2	**6**	3	3	3	5	**6**	4	4	4	**6**	3	3	**6**	1	2
	7	4	4	3	5	4	1	2	5	5	4	3	5	4	3	2	**7**	3	3
	9	5	3	3	**8**	6	**8**	6	4	6	3	6	7	**9**	5	7	5	2	6
	9	6	2	1	7	7	7	7	5	6	3	7	6	**9**	6	**8**	6	3	5
	6	4	4	2	5	7	7	7	4	7	4	7	5	**8**	4	7	5	1	4
	8	5	2	3	**8**	**8**	7	6	5	**8**	3	6	6	**8**	5	6	5	2	4
D	**9**	4	3	2	6	7	7	7	6	6	3	**8**	5	**9**	4	7	4	2	6
	8	5	3	2	5	6	**8**	6	5	6	2	6	5	**9**	5	**8**	5	3	5
	6	5	1	3	6	7	**8**	5	5	7	3	7	6	**10**	4	**8**	6	2	5
	7	4	2	4	7	6	7	7	7	6	3	**9**	4	**9**	5	7	5	1	3
	8	3	3	2	6	7	7	6	6	6	2	6	6	**9**	4	8	5	2	5
	8	3	3	2	5	7	**8**	7	6	7	3	**8**	5	**9**	3	**8**	6	2	6

Some information can be analyzed from Table 8:

a) From the distribution of extreme values in the S section, it can be seen that all experts consider collapse as a disaster with a great degree of damage, and half of the experts for broken also consider its damage impact to be great. Meanwhile, disconnect, branch pipe concealed connection, leakage, and stump walls and roots are considered by some experts to cause serious damage.

b) In the O section, we have narrowed the range of extreme values selected, analyzing the reason may be that O in this study represents the probability of defect generation in the view of experts with an engineering background and scientific research background, resulting in a certain degree of quantitative loss (not generating a certain number of values greater than or equal to 9). In this extreme value interval, all the experts believe that the occurrence of cracks is very high, and the analysis may be due to the very high frequency of such failure in engineering practice. In addition, fracture, deformation, spalling, obstruction, penetration, and impurity deposits are considered high-frequency defects by experts in different degrees.

c) As can be seen from the extreme value distribution of D in Table 8, penetration is considered to be the most difficult failure to be detected, probably due to the fact that the detection process mostly uses CCTV inspection, which requires pre-detection cleaning work, a process that greatly increases the difficulty of detecting penetration.

Similarly, crack is also considered by experts to be the most difficult fault to be detected, presumably because the dim working environment inside the pipeline and the uncertainty of noise variables increase the difficulty of detection. In addition, deformation, mismatch, disconnect, corrosion, branch pipe concealed connection, and leakage have been identified by experts to varying degrees as difficult to detect failures.

5.2. Establishing a Fuzzy ER Rule on Sewer Pipeline Failures

Processing Table 8 according to Equation (7), and the data in Tables 8 and 9 were converted into belief degrees for eight output variable intervals (i.e., $\Theta = \{VG, G, MG, F, MB, B, VB, CB\}$) by using automated data processing techniques in Python and Excel, as shown in Table 9.

Table 9. Fuzzy weighted ER rule belief degrees for sewer pipeline failures.

	VG	G	MG	F	MB	B	VB	CB
CR	0	0	0	0	0	1	0	0
FR	0	0	0.02004	0.18036	0.38231	0.41728	0	0
BR	0	0.38102	0.27704	0.33162	0.34573	0.00752	0	0
COL	0.00718	0.35239	0.23920	0.32226	0.07889	0	0	0
DE	0	0	0	0	0.34259	0.65741	0	0
MI	0	0	0	0	0.49678	0.50322	0	0
DI	0	0	0.24661	0.07233	0.56447	0.11659	0	0
IMS	0.05725	0.39471	0.46742	0.08063	0	0	0	0
SP	0	0.05908	0.32831	0.59737	0.01524	0	0	0
COR	0	0	0.17902	0.25993	0.47840	0.08266	0	0
WF	0	0.21036	0.37947	0.41017	0	0	0	0
BPCC	0	0	0.01188	0.10690	0.47568	0.40554	0	0
OB	0	0	0	0.04816	0.49211	0.45973	0	0
P	0	0	0	0	0.02269	0.96395	0.01337	0
RI	0	0	0.14304	0.32324	0.47456	0.05916	0	0
LE	0	0	0	0.06966	0.41288	0.51747	0	0
ID	0	0	0.02799	0.16284	0.36584	0.44334	0	0
SWR	0.03989	0.58861	0.33426	0.03724	0	0	0	0
SFM	0.02764	0.74026	0.23211	0	0	0	0	0

The defuzzification results of drainage pipe failures were obtained for the values presented in Table 7 by using Equation (11) and compared with the calculation results obtained using TFMEA for the same dataset. The defuzzification results are presented in Table 10.

Table 10. Ranking of sewer pipe failures by using FACEF and TFMEA.

Failure	FACEF	Ranking of FACEF	Traditional FMEA	Ranking of TFMEA
Penetration	287.7597	1	315.5	1
Crack	286.6667	2	304.6	2
Deformation	239.8461	3	192.9	4
Mismatch	218.7734	4	195.6	3
Leakage	216.5428	5	181.2	6
Obstruction	209.9402	6	191.5	5
Impurity Deposits	198.2085	7	164.4	9
Branch Pipe Concealed Connection	197.901	8	168.9	8

Table 10. *Cont.*

Failure	FACEF	Ranking of FACEF	Traditional FMEA	Ranking of TFMEA
Fracture	194.3348	9	175.7	7
Disconnect	138.5772	10	128.8	10
Corrosion	128.994	11	125.3	11
Root Intrusion	125.3404	12	119	12
Broken	109.7205	13	86.7	13
Spalling	76.22901	14	77.4	14
Weld Failure	64.02822	15	58	15
Collapse	63.8365	16	56.1	16
Interface Material Shedding	44.65113	17	41.7	17
Stump Walls and Roots	38.25523	18	29.4	18
Scam and Floating Mud	33.07747	19	29.3	19

6. Discussion

6.1. Result Analysis and Maintenance Measures

Analysis of the FACEF scoring results presented in Table 10 provides a novel approach. In engineering practice and scientific research, crack, fracture, broken, and corrosion are considered the main failures that affect the normal operation of pipelines. In pipeline O&M and inspection, the detection of these failures is the primary objective; however, FACEF results revealed that penetration, crack, deformation, mismatch, leakage, and obstruction are the six pipeline failure patterns that should be paid the most attention. The scientific scoring enabled by the proposed method provides a relatively objective cognition of pipeline failures for engineering applications and scientific research. The mean values of S, O, and D for each of the 19 failures are plotted as histograms in Figures 7–9, focusing on typical pipeline failures according to the FACEF scoring intervals.

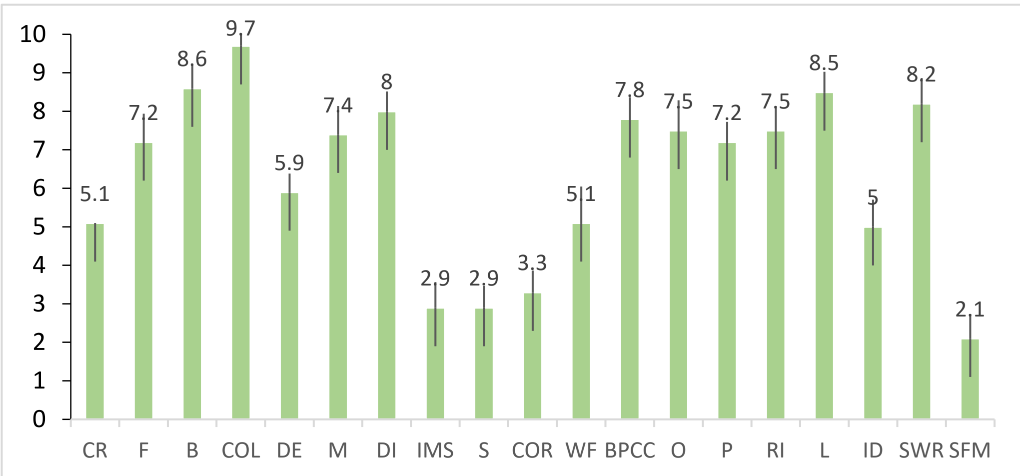

Figure 7. Mean values of S.

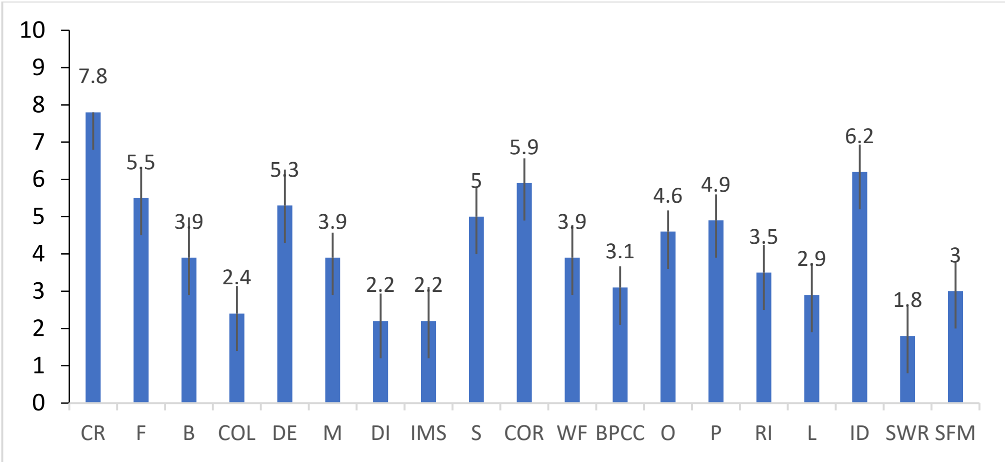

Figure 8. Mean values of *O*.

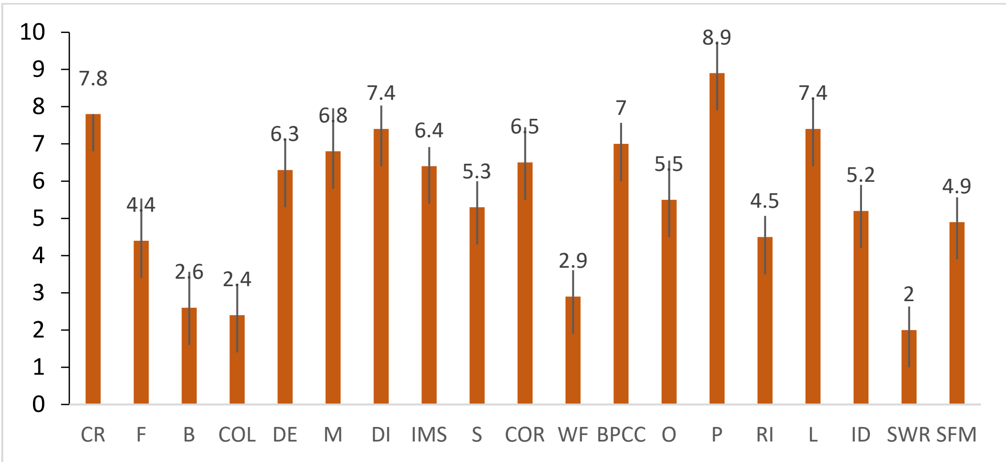

Figure 9. Mean values of *D*.

a) Failures with FACEF scores ≥250: Penetration and crack are important failures that affect the condition of the pipeline, and as can be seen in Figures 7–9, the S, O, and D scores for these two failures are at the high end of the scale, indicating that the severity of these failures is high, the probability of occurrence of these failures is relatively high, and that they are difficult to be detected. The clustered occurrence of penetration failure is attributed to inadequate planning of the surrounding environment during the pipeline design and construction phase, with a large number of complex foundation sections appearing in the vicinity of the pipeline, increasing the risk of pipeline penetration. Frequent changes in dynamic loads overlying the pipeline cause uneven stresses in the soil layer; this, in turn, accelerates the migration of foreign objects in the soil layer, posing a penetration risk to the outer wall of the pipeline. Some pipelines are made of soft materials that are easily penetrable (e.g., PVC) and have low internal resistance to penetration, making them more susceptible to penetration [25].

Crack is one of the most common pipeline failures and occurs mainly when the external pressure on the pipeline exceeds the bearing capacity of the pipeline. Cracks are often found at vulnerable locations such as joints and interfaces and are often accompanied by failures such as mismatch. Yahaya [37] and Pritchard [38] demonstrated that the loading and movement of ground load could lead to the migration of water in the soil around the pipeline; this affects soil porosity and structural properties, resulting in failures such as cracks. Liao et al. stated that pipe failures such as crack are likely to occur on main traffic roads and in areas with high traffic volumes because the high vertical load in such areas exert immense pressure on the ground surface for long periods and are transferred to the upper and lateral parts of the pipe through the soil layer, squeezing the pipe and resulting in failures [39].

Reinforced concrete pipes are highly resistant to compression [40] and external pressures. While Folkman argued that corrosion is the main reason for the emergence of cracks, data have shown that circumferential damage is more likely to cause damage to pipes [41]. The probability of crack occurrence in pipelines can be greatly reduced by paying attention to the proportion of concrete pipes in the pipeline design and construction process, as well as by optimizing the corrosion resistance of pipelines.

b) Failures with FACEF scores $\geq$200: Deformation is a type of failure in which cross-sectional changes occur in the pipe structure under external extrusion. Due to aging, small-diameter flexural pipes become increasingly prone to deformation at the interfaces, and local soil builds up in the direction of the deformation, producing deformation over time. In flexural pipes such as HDPE, due to the lack of rigidity, existing unevenly stressed pipe wall local deformations get enlarged and gradually develop into cracks, severely affecting the structure of the pipe [42,43]. When uneven settlement of the overlying geotechnical body causes uneven external forces on the pipeline or when man-made construction causes damage to the pipeline, the pipeline structure changes, and deformation occurs [26]. Therefore, in the case of uneven soil cover around the pipeline or the presence of special soil, rigid pipelines with large diameter should be adopted to reduce the probability of deformation generation.

A mismatch is an accompanying pipeline failure that often occurs in pipelines with cracks or in pipe sections with deformations. The value for mismatch obtained using FACEF revealed that the severity of mismatch failure is high, and it cannot be easily detected due to the physical restrictions encountered during the inspection process. The probability of mismatch failure occurrence is greatly affected by failures such as cracks. As such, the occurrence of mismatch failure can be decreased by preventing failures such as cracks and enhancing the strength of pipeline joints. Some researchers have explored this subject in detail. For example, Lu used cement mortar at pipe interfaces to increase the tightness of pipe joints while ensuring increased strength [44]. Meijering et al. conducted research on double-socket joints for over 30 years through sealing tests of pipe joint deflection and compression permanent deformation estimation and determined the basic mechanical properties to assess the condition of the joints. Leakage was observed only when the pipe deflection exceeded 36%, whereas in one case, critical deflection reached the level of 81% [45].

Leakage is a very destructive failure and not only causes soil contamination due to the outflow of liquid inside the pipe but also causes erosion of the soil around the pipe and affects the surrounding soil and water. At the same time, in the CCTV inspection process, because the drainage dredging work before the inspection led to the leakage characteristics were not obvious (Figure 3i); thus, small-scale drip leakages in the pipe get ignored and gradually transformed into major leakages. However, the probability of leakage occurrence can be controlled by considering the structural breakage and external hydraulic conditions of the pipeline. The mechanism related to this failure has been studied. For example, Zamanian et al. concluded that the properties of concrete pipes, backfill overlying the pipes, and variables associated with truckloads have the most significant effect on pipeline leakage [46]. The use of detection techniques that do not require drainage dredging, such as electromagnetic detection [47] and acoustic detection [48], allows more accurate pipeline leakage detection and thus reduces the occurrence of leakage detection [49–51].

Obstruction is a failure with high severity and probability of occurrence and often leads to the obstruction of the function of the entire pipeline. Obstruction is usually caused due to the following reasons: (i) Because of pipe outlet anomaly, the flow gets blocked and cannot be discharged downstream. The water and debris in the pipe accumulate in the inspection well, resulting in obstruction blockage between the inspection well and the end of the adjacent pipe. (ii) The design slope changes during the operation life of the pipe, resulting in the backward slope phenomenon. As such, the flow gets blocked and cannot flow downstream, and various types of debris accumulate in part with a relatively low elevation, resulting in obstruction. (iii) An abrupt reduction in the diameter of the pipeline is caused when a large-diameter pipe is directly connected to a small-diameter pipe, resulting in a high amount of debris in the small pipe; this leads to blockage. Obstruction is a typical functional failure and can be prevented and controlled through regular maintenance and cleaning of the pipeline and good pipeline path planning.

c) Failures with FACEF scores ≥100: Common failures in this score range are corrosion and root intrusion. Corrosion is one of the most widely studied pipeline failures and is the main causative factor for most pipeline failures [41]. Corrosion is greatly affected by the pipe material; for example, concrete pipes [27] and galvanized copper pipes [52] are highly susceptible to corrosion. Seasonal changes also induce corrosion in pipes. Barton et al. concluded that the probability of corrosion in AC and PVC pipes is considerably higher in summer than in the other three seasons. Iron, ductile iron, and steel pipes are more prone to corrosion deterioration in the cold winter months than in the humid summer and mild autumn months [25]. The application of the pipeline is also an important factor contributing to corrosion. Ariaratnam et al. concluded that sewer pipes are the most prone to corrosion compared to stormwater pipes and combined sewage pipes [53]. Hahn et al. stated that biochemical, electrochemical, and physical reactions caused by the water inside the pipeline affect the long-term use of pipeline materials and highlighted that internal corrosion of the pipeline mainly depends on the nature of the liquid inside the pipeline [54]. To sum up, good protection of pipelines against corrosion and reasonable planning of pipeline route distribution can reduce the occurrence probability of corrosion in pipelines.

Root intrusion is a phenomenon in which naturally growing tree roots enter the pipe and form a blockage inside the pipe, often at pipe joints, cracks, pipe ends, and pipe bodies. According to Orvesten and Stål, drainage pipes are rich in resources for tree growth (e.g., air, water, and compounds containing nitrogen and phosphorus); thus, roots implanted in the pipe grow faster due to the favorable environment inside the pipe. This adds to the risk of breakage inside the pipe. In addition, roots seek out more favorable environments, making them more likely to find vulnerable areas of the pipe [55]. Ridgers et al. concluded that selecting an appropriate location for pipeline construction can reduce the risk of root intrusion. The frequency of root intrusion can be greatly reduced by protecting the vulnerable parts of the pipeline (e.g., manholes, pipe junctions, and transitions between pipe materials and service pipes) during pipeline construction [56]. In addition, irregular construction, aging of the pipe structure, and disturbance by external factors make the interface more prone to root intrusion [57]. In summary, the pipeline construction area must be selected beyond the growth range of large trees during the pre-planning and construction of the pipeline to reduce the risk of root intrusion.

6.2. Algorithm Improvement and Discussion

Analysis of the results obtained using FACEF and TFMEA methods revealed differences in terms of two aspects: scoring and ranking. In terms of scoring, large differences were observed for penetration, crack, deformation, and mismatch failures. The TFMEA scores for these types of failures vary widely (315.5, 304.6, 192.9, and 195.6, respectively), whereas the FACEF scores narrow the gap to some extent for these failures. In terms of ranking, large differences were observed for deformation, mismatch, leakage, obstruction, impurity deposits, and fracture failures. From the data presented in Table 9, it can be observed that the large differences between the results obtained using the two methods in terms of the six aforementioned failures are due to the higher weight of the higher output variable intervals (e.g., B, VB, and CB), whereas the failures with fewer differences between FACEF and TFMEA ranking (e.g., corrosion, root intrusion, and breakage) have higher weight values for lower output variable intervals and are thus more stable. Comparing the two methods, the following conclusions can be drawn:

a) FACEF converts expert opinions into belief degrees for different output variable intervals, thus solving to some extent the problem that the approximate average values of RPNs obtained using TFMEA can cause ambiguity in experts' perception of extreme values of evaluation and the belief degree can relatively objectively reflect experts' perception, making the algorithm results more interpretative.
b) TFMEA scores cannot be categorized due to excessive variations, making the secondary analysis of failures impossible. In contrast, FACEF scores can be categorized, thus enabling analyses highly relevant to engineering perceptions.
c) FACEF results are greatly influenced by the belief degree and defuzzification values. Obtaining evaluation results from experts with different backgrounds is beneficial for obtaining information regarding different belief intervals and expanding the cognitive scope of the algorithm.
d) The linguistic rule interval setting of FACEF can be understood as the total set of all cases that may have occurred or may occur in the future. As can be seen from Table 9, the frequency of two extreme cases, VB and CB, was extremely low; in particular, CB did not appear in the application of the evaluation model in this study, but the analysis results revealed that the RPN values required to reach these two extreme cases are extremely high (requiring S, O, and D to be assigned high values). Thus, these two extreme cases should be given special consideration. In the FACEF evaluation method, attention should be paid to the belief degrees assigned to these two groups of intervals, and if a failure has a belief degree of extreme cases, the reasons should be analyzed, and timely secondary evaluation and information feedback should be conducted to solve the problem.

7. Conclusions and Recommendations

This study aims to address the scarcity of risk analysis at the level of drainage pipe failures in the field of pipeline evaluation and provides a novel algorithm that incorporates FMEA, ER, and FST to overcome the subjectivity inherent in traditional expert evaluation methods. The major findings of the study are as follows:

a) Five commonly used pipeline evaluation specification methods were analyzed, and 19 drainage pipeline failures were summarized by categorizing them into structural failures and operational failures.
b) Ten experts with engineering or research backgrounds were consulted to assess the 19 pipe failures using expert opinion. Each failure was evaluated in terms of its severity (S), occurrence (O), and probability of being undetected (D). The results indicate that collapse, crack, and penetration had the highest scores in the S, O, and D sections, respectively.
c) The newly developed algorithm was used to statistically process the expert scores, and the weight values for each failure were determined. The results reveal that penetration, crack, deformation, mismatch, leakage, and obstruction are the six pipeline failures that demand the most attention, and the S, O, and D weight distributions for typical failures in each scoring range are discussed in detail.

Although this study provides a new perspective on drainage pipe risk management in the application of the new algorithm, there are still some improvements that can be expected to be iterated in future studies.

a) The expert evaluation scoring revealed that only one score in the O section exceeded 8. This is primarily due to the fact that the score reflects the experts' perception of the probability of a pipe failure (e.g., a score of nine corresponds to nearly 90% occurrence). Such situations should be avoided in future studies to minimize the potential loss of scores and increase the accuracy of the final results.
b) Table 9 shows that the weights of the extreme intervals are minimal, making it difficult to perform further analysis on the weights. As a result, some of the advantages of the algorithm are lost. In future studies, the VB (Very High) and CB (Completely bad) intervals can be expanded to include a wider range of weights.

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Abbreviations

B	Bad
BPA	Basic probability assignment
BPCC	Branch Pipe Concealed Connection
BR	Broken
CB	Completely bad
CCTV	Closed-circuit television
CIRCA	Conduit Inspection Reporting Code of Australia
CoG	Center of gravity
COL	Collapse
COR	Corrosion
CR	Crack
D	The probability of not detecting the failure
DE	Deformation
DI	Disconnect
ER	Evidential reasoning
F	Fair
FACEF	FMEA approach combined with ER and FST
FMEA	Failure mode and effect analysis
FR	Fracture
FST	Fuzzy set theory
G	Good
H	High
ID	Impurity Deposits
IMS	Interface Material Shedding
L	Low
LE	Leakage
MI	Mismatch
M	Middle
MB	Middle bad
MSCC	The manual of Sewer Condition Classification
O	The occurrence of failure mode
O&M	Operation and maintenance
OB	Obstruction
P	Penetration
PACP	Pipeline Assessment and Certification Program
PPT	Pignistic probability transformation
RI	Root Intrusion
RPN	Risk priority number
S	Severity of the failure

SP	Spalling
SFM	Scam and Floating Mud
SWR	Stump Walls and Roots
TFMEA	Traditional failure mode and effect analysis
TPN	Triangular fuzzy number
VB	Very bad
VG	Very good
VH	Very high
VL	Very low
WF	Weld Failure

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