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Original Research Article

FRAM Integrated Fuzzy FMEA Risk Analysis For Natural Gas Systems

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ABSTRACT: *Natural gas installation systems involve complex technical, organizational, and human interactions where failures can lead to catastrophic safety consequences. Conventional Failure Mode and Effects Analysis (FMEA) is constrained by subjective scoring and the limited capture of systemic variability. This paper proposes an integrated framework combining the Functional Resonance Analysis Method (FRAM), fuzzy logic-based FMEA, and Pareto analysis to address these limitations. FRAM was applied to model system functions and identify variability sources across installation stages, which were translated into candidate failure modes. A multidisciplinary expert panel evaluated the occurrence, severity, and detection scores for each failure mode. A Mamdani-type fuzzy inference system was then used to calculate the fuzzy Risk Priority Numbers (RPNs), and Pareto analysis was applied to prioritize critical failure modes. The framework was validated in a real building natural gas installation project, identifying 81 failure modes. Fuzzy-FMEA produced substantially different risk rankings than classical FMEA. Specifically, improper tightening of valve connection points emerged as the highest-risk failure mode. Pareto analysis showed that 52 failure modes (64.2%) account for 80% of the cumulative system risk. The proposed framework enhances the completeness of failure identification and the reliability of risk prioritization, providing a systematic decision-support tool for natural gas installation safety management.*

1. Introduction

Natural gas has become one of the most widely used energy resources worldwide owing to its relatively lower environmental impact, high calorific value, and operational efficiency compared with other fossil fuels. The increasing global demand for natural gas has led to a rapid expansion of natural gas infrastructures, including transmission pipelines, distribution networks, and building-level installation systems (Economides & Wood, 2009). While natural gas offers important economic and environmental advantages, the safe operation of this infrastructure is a critical engineering challenge.

Failures occurring within natural gas systems can lead to severe safety consequences, including explosions, fires, and environmental damage. These risks are particularly critical in urban areas where dense populations and complex infrastructures increase the potential impact of gas-related incidents (Guo et al., 2016). Previous studies have shown that failures in gas systems may originate from multiple sources, including design miscalculations, material defects, inadequate installation practices, and human or organizational errors (Ostfeld et al., 2013; Scott & Scott, 2019). Consequently, ensuring system reliability and implementing effective risk management strategies are essential for maintaining operational safety in natural gas installations (Chang et al., 2008; Der Kiureghian et al., 2007).

Risk assessment methods have been widely applied to identify and mitigate hazards in natural gas infrastructures. Various analytical techniques, including probabilistic risk assessment, scenario modeling, and reliability analysis, have been used to evaluate potential accident scenarios in gas installations (Wen et al., 2015; Vairo et al., 2020). For example, physical modeling has been used to analyze the consequences of potential gas explosions at metering and regulation stations (Bajcar et al., 2014). Other studies have focused on pipeline reliability and risk analysis in oil and gas infrastructures (Shahriar et al., 2012; Uddin et al., 2008).

Among the various risk assessment methods, Failure Mode and Effects Analysis (FMEA) is among the most widely used techniques for identifying potential failures in engineering systems. FMEA enables a systematic evaluation of possible failure modes and their impacts on system performance, allowing organizations to identify critical risks before they occur (Sharma et al., 2005). The method evaluates the risks using the Risk Priority Number (RPN), which is

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calculated by multiplying the occurrence, severity, and detection factors (Stamatis, 2003). FMEA has been widely applied in safety-critical industries, including aerospace, manufacturing, healthcare, and energy systems, owing to its simplicity and practicality (Chang, 2009).

Despite its widespread adoption, the classical FMEA approach has several limitations. One of the major criticisms concerns the subjectivity inherent in expert scoring and the limitations of the RPN calculation method. Different combinations of these parameters may yield identical RPN values because occurrence, severity, and detection factors are evaluated using discrete scales, potentially leading to inconsistent risk rankings (Can et al., 2025). Furthermore, classical FMEA does not adequately capture uncertainty in expert evaluations, potentially reducing the reliability of the prioritization process.

Hence, researchers have increasingly integrated fuzzy logic into FMEA models. Fuzzy set theory, originally introduced by Zadeh (1965), provides a mathematical framework for representing linguistic uncertainty and imprecise knowledge. Fuzzy-FMEA enables a more flexible and realistic representation of risk factors by transforming qualitative expert judgments into fuzzy numbers (Zadeh, 1973; Zadeh, 1975). Previous studies have applied fuzzy logic to reliability analysis and risk prioritization in complex engineering systems (Cheng & Mon, 1993; Keller & Kara-Zaitri, 1989). Applications of fuzzy-FMEA have been reported in several industrial contexts, including pipeline risk analysis (Brito et al., 2010), manufacturing systems (Maji et al., 2008), and safety management frameworks (Thurnes et al., 2015).

Although fuzzy-FMEA improves the robustness of risk prioritization, another important limitation remains in the early stage of the FMEA process: the identification of potential failure modes. In many practical applications, failure modes are generated primarily through expert brainstorming sessions or literature reviews. Such approaches may overlook important sources of variability that arise from interactions among technical, organizational, and human processes.

In complex socio-technical systems such as natural gas installations, system behavior emerges from interactions between multiple functional activities rather than from isolated component failures. Therefore, analyzing how variability in system functions can propagate across operational processes is essential for improving risk identification. The Functional Resonance Analysis Method (FRAM), developed by Hollnagel (2014), offers a systematic framework for modeling complex systems by analyzing functional interactions and performance variability. FRAM has been applied in several safety-critical domains, including aviation, healthcare systems, and industrial operations, to understand how normal operational variability can combine to produce unexpected outcomes.

Despite its growing use in safety science, the integration of FRAM with quantitative risk assessment methods remains relatively limited in natural gas engineering research. In particular, few studies have assessed the potential of combining FRAM with fuzzy-FMEA to enhance failure identification and risk prioritization processes.

Accordingly, the present study proposes an integrated risk assessment framework combining FRAM, fuzzy-FMEA, and Pareto analysis for the design and construction of natural gas installation systems. The proposed approach aims to improve the reliability of failure identification, reduce uncertainty in risk prioritization, and support more effective safety decision-making in natural gas installation projects.

The main contributions of this study can be summarized as follows:

(1) A FRAM-based framework for systematically identifying failure modes in natural gas installation processes.

(2) An uncertainty-aware risk prioritization approach using fuzzy-FMEA.

(3) A Pareto-based prioritization strategy for identifying the most critical failure modes requiring mitigation.

(4) A real-world application showing the effectiveness of the proposed methodology in building natural gas installation systems.

This study contributes a comprehensive methodological framework for improving safety management in natural gas infrastructures and other complex engineering systems by integrating functional system modeling with fuzzy risk assessment techniques.

2. Literature Review

2.1 Risk Assessment in Natural Gas Systems

Natural gas infrastructure is considered a safety-critical engineering system because of the potentially catastrophic consequences of gas leaks, explosions, and fire incidents. The increasing complexity of natural gas distribution networks and building installation systems has intensified the need for systematic risk assessment approaches that can identify potential hazards before they lead to operational failures.

Several studies have examined the reliability and safety of gas infrastructure systems. For example, Guo et al. (2016) analyzed pipeline failure risks in urban natural gas systems and emphasized that pipeline accidents in densely populated areas can cause significant human and economic losses. Similarly, Ostfeld et al. (2013) reported that multiple interacting factors, including infrastructure age, material degradation, and human operational errors, influence operational risks in gas distribution networks.

Other studies have focused on probabilistic modeling and simulation approaches to assess accident scenarios in gas infrastructure. Wen et al. (2015) proposed a probabilistic framework for evaluating the safety risks in gas transmission systems, while Vairo et al. (2020) investigated the safety performance of pipeline systems using reliability-based risk models. In addition, scenario-based explosion modeling has been used to analyze potential accident consequences in gas pressure regulation stations and storage facilities (Bajcar et al., 2014).

Despite these advances, risk identification at the building installation level is challenging because failures can occur across multiple project phases, including system design, material selection, installation practices, and commissioning procedures. These failures often arise from interactions among technical, organizational, and human factors rather than from isolated technical defects.

2.2 FMEA in Engineering Systems

FMEA is one of the most widely used techniques for proactive risk assessments in engineering systems. Originally developed in the aerospace industry, FMEA aims to identify potential failure modes, evaluate their effects on the system performance, and prioritize corrective actions to prevent system failures (Stamatis, 2003).

The core of the FMEA method lies in calculating the Risk Priority Number (RPN), which is obtained by multiplying three risk parameters: occurrence (O), severity (S), and detection (D). This structured approach enables analysts to evaluate potential risks systematically and determine which failure modes require immediate attention (Sharma et al., 2005).

FMEA has been applied widely in various sectors, including manufacturing, healthcare, energy systems, and process industries, owing to its simplicity and flexibility (Chang, 2009). In natural gas engineering, FMEA has been used to analyze the risks associated with pipeline operations, gas distribution networks, and installation processes. Specifically, Oztürk et al. (2023) compared FMEA with Fault Tree Analysis and Causal Analysis based on System Theory for accident investigation. They reported the strengths and inherent limitations of FMEA when applied in isolation to complex socio-technical events.

Nevertheless, the classical FMEA approach has several limitations that may affect the reliability of its risk prioritization results. One of the main issues concerns the use of crisp numerical scales to evaluate the risk factors, which may not adequately represent uncertainty in expert judgments (Can et al., 2025). In addition, the multiplicative structure of the RPN may lead to inconsistent rankings because different combinations of severity, occurrence, and detection values can yield identical RPN scores. These limitations have motivated researchers to develop improved FMEA-based risk assessment models.

2.3 Fuzzy Logic-Based FMEA Approaches

Fuzzy set theory provides a powerful mathematical framework for modeling uncertainty and vagueness in decision-making processes. Introduced by Zadeh (1965), fuzzy logic allows qualitative linguistic assessments such as “low”, “medium”, and “high” to be expressed using fuzzy numbers rather than fixed numerical values.

The integration of fuzzy logic into FMEA has been proposed as an effective way to overcome the limitations of the classical RPN method. In fuzzy-FMEA, expert evaluations are represented using fuzzy membership functions, and fuzzy inference systems are used to calculate the fuzzy risk priority numbers.

Several studies have shown that fuzzy-FMEA improves the accuracy of risk prioritization. For example, Cheng and Mon (1993) applied fuzzy logic to reliability analysis in engineering systems, showing that fuzzy models provide more flexible representations of uncertain system behavior. Similarly, Keller and Kara-Zaitri (1989) developed fuzzy reliability approaches for complex industrial systems.

Applications of fuzzy-FMEA have been reported in multiple industrial contexts. Brito et al. (2010) applied fuzzy-FMEA for risk analysis in gas pipeline systems, whereas Maji et al. (2008) reported the effectiveness of fuzzy models in evaluating safety risks in engineering processes. Recent studies have also highlighted the advantages of fuzzy logic in improving the robustness of decision-making processes in risk management frameworks (Thurnes et al., 2015). In an occupational health and safety context, Tak and Öztürk (2025) applied fuzzy-FMEA to assess OHS risks in a valve manufacturing process, confirming that the method provides more reliable risk prioritization than classical FMEA when expert judgments involve significant uncertainty.

Although fuzzy-FMEA improves the reliability of risk prioritization, its effectiveness still depends heavily on the completeness of the failure mode identification process.

2.4 Functional Resonance Analysis Method (FRAM)

Traditional safety analysis methods often focus on component failures and linear cause-and-effect relationships. On the other hand, modern engineering systems are increasingly recognized as complex socio-technical systems where accidents emerge from interactions among multiple system functions.

The Functional Resonance Analysis Method (FRAM), developed by Hollnagel (2014), was proposed as a systemic approach for analyzing complex systems and understanding how variability in normal operations may lead to unexpected outcomes. Instead of analyzing isolated component failures, FRAM models system behavior by examining the relationships among functional activities.

Each function within the FRAM model is described using six aspects:

- Input
- Output
- Preconditions
- Resources
- Control
- Time

Through this functional representation, FRAM allows analysts to identify variability sources within system processes and examine how these variations may propagate through the system.

FRAM has been widely applied in several safety-critical domains, including aviation safety, healthcare systems, railway operations, and industrial processes. For example, Kaya et al. (2019) applied FRAM to assess the performance variability in a hospital drug administration process, showing how functional interactions contribute to patient safety risks. Similarly, Kaya et al. (2021) integrated FRAM with a Monte Carlo simulation to conduct system-based risk analysis in a tram operating system, showing that combining FRAM with quantitative methods significantly enhances the depth of safety analysis. Previous studies have shown that FRAM provides valuable insights into complex system behavior and supports proactive safety management.

Nevertheless, applications of FRAM in natural gas installation processes remain limited. Furthermore, few studies have explored integrating FRAM with quantitative risk assessment techniques such as fuzzy-FMEA.

2.5 Research Gap and Study Contribution

Although significant progress has been made in risk analysis methods for natural gas systems, several research gaps remain. First, many studies focus primarily on pipeline infrastructure or industrial gas facilities, while relatively limited attention has been given to building-level natural gas installation processes. Second, traditional risk analysis approaches often treat failure identification and risk prioritization as separate processes without systematically linking system functionality to potential failure mechanisms.

Third, although fuzzy-FMEA has been widely used to improve risk prioritization under uncertainty, the method often relies on failure modes identified through conventional brainstorming techniques, which may overlook important sources of operational variability.

Accordingly, this paper proposes an integrated methodological framework that combines FRAM, fuzzy-FMEA, and Pareto analysis. In this framework, FRAM is used to model the functional structure of natural gas installation processes and systematically identify variability sources. These variability sources are then translated into failure modes and causes for FMEA analysis. Subsequently, fuzzy-FMEA is applied to prioritize risks under uncertainty, and Pareto analysis is used to identify the most critical failure modes requiring mitigation. The proposed approach contributes a more comprehensive and systematic methodology for risk governance in natural gas installation systems by integrating functional system modeling with fuzzy risk assessment techniques.

3. Methodology

3.1 Overall Research Framework

The methodology adopted in this study integrates three complementary analytical approaches: the Functional Resonance Analysis Method (FRAM), fuzzy logic-based FMEA (fuzzy-FMEA), and Pareto analysis. This integrated framework aims to improve the identification and prioritization of risks in building natural gas installation systems.

The research framework consists of four main stages:

(1) Functional modeling of the natural gas installation process using FRAM

(2) Identification of failure modes and causes based on FRAM variability analysis

(3) Risk evaluation using classical FMEA and fuzzy-FMEA

(4) Prioritization of critical risks using Pareto analysis

Fig. 1 presents the overall methodological framework adopted in the study.

In the first stage, the natural gas installation process was modeled using FRAM to identify the key system functions and their interactions. The analysis focused on the major stages of the installation process, including system design, material procurement, pipe installation, welding operations, ventilation arrangements, and commissioning procedures.

In the second stage, potential variability sources associated with each function were identified based on the six FRAM aspects: input, output, preconditions, resources, control, and time. These variability sources were then translated into a structured pool of potential failure modes and causes.

In the third stage, classical FMEA was conducted to evaluate the risks associated with each identified failure mode. A multidisciplinary expert panel evaluated occurrence, severity, and detection scores for each failure mode. Fuzzy logic was applied to transform linguistic risk assessments into fuzzy numerical values, thereby reducing subjectivity in the evaluation process. A Mamdani-type fuzzy inference system was used to calculate fuzzy risk priority numbers.

Pareto analysis was performed on the fuzzy risk priority numbers to identify the most critical failure modes that contribute to the majority of system risk.

The integration of the three methods in this study should be understood as a sequential yet interdependent analytical chain rather than a parallel combination of independent tools. FRAM provides the structural foundation for failure identification by systematically exploring how variability in each of the six functional aspects can propagate across installation activities. This variability-driven input directly shapes the scope and content of the FMEA failure mode dataset, ensuring that socio-technical sources of failure, including organizational preconditions, time pressures, and resource constraints, are captured alongside purely technical failure mechanisms.

Fuzzy-FMEA then leverages this richer failure mode dataset by applying linguistic uncertainty modeling to the expert evaluation stage, which is epistemically consistent with the inherently uncertain nature of variability-driven failure scenarios identified through FRAM. Classical FMEA would force evaluators to assign crisp numerical scores to risks whose very origin lies in variability and ambiguity. Fuzzy logic provides the appropriate representational framework for these evaluations.

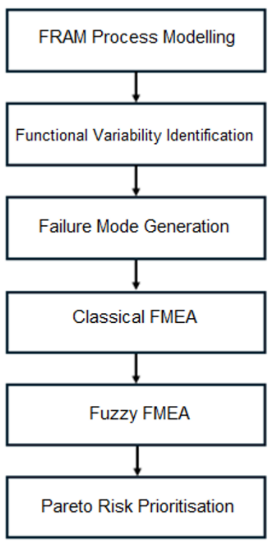

Fig. 1 Proposed research framework

Finally, Pareto analysis translates the fuzzy risk rankings into a manageable set of priority interventions that can be traced directly back to the originating FRAM variability sources, thereby establishing end-to-end traceability from process variability to safety action. This integrated traceability—from the FRAM variability scenario, through failure mode identification, fuzzy risk scoring, and Pareto-ranked intervention priority—represents the core methodological contribution of the proposed framework and distinguishes it from prior studies that apply these methods in isolation. Accordingly, the added value of the integration lies not merely in combining four methods, but in establishing analytical continuity from variability source to intervention priority. FRAM explains how risk emerges, PFMEA structures where it appears in the process, fuzzy inference refines how it should be prioritized under uncertainty, and Pareto analysis determines what should be addressed first in practice.

3.2 Expert Panel and Data Collection

FMEA analysis was conducted by a multidisciplinary expert team consisting of seven members with practical experience in natural gas installation projects. The expert panel included professionals responsible for project management, system design, site supervision, and installation operations. The diversity of expertise ensured that technical, operational, and safety perspectives were incorporated into the risk assessment process.

The panel met regularly over two months to review the natural gas installation process, identify potential failure modes, and evaluate risk parameters. Table 1 lists the composition of the expert panel.

Beyond functional decomposition, the FRAM model was further analyzed to identify the coupling relationships between functions, i.e., cases in which the output of one function serves as an input, precondition, or resource for one or more downstream functions. These coupling pathways constitute potential variability in propagation routes through which performance variability at an upstream function can amplify or trigger failure conditions at a downstream function. The identification of such propagation pathways is central to the FRAM concept of functional resonance, in which the coincidence of variability across coupled functions produces unexpected and potentially unsafe system outcomes. Two key variability propagation scenarios were identified in the analysis of the natural gas installation process:

Table 1 Composition of the expert panel

Code	Position	Educational background	Experience (years)
PR1	Project manager	Mechanical engineering	5
PR2	Business owner	Mechanical engineering	6
PR3	Site supervisor	Mechanical engineering	6
PR4	Technical craftsman	Mechanical engineering	6
PR5	Welder	Certified technical staff	11
PR6	Welder	Certified technical staff	11
PR7	Assembly technician	Certified technical staff	11

3.2.1 Scenario 1: Design-to-installation coupling (S1 → FM3–FM7)

Variability in the 'System Design' function— specifically, insufficient pipe diameter calculations (S1) and incorrect pressure drop estimations—is coupled with downstream variability in 'Material Procurement' and 'Pipe Installation' when upstream design errors are not detected before installation begins. The output of the 'System Design' function (approved pipe specifications) serves as a direct input to the 'Material Procurement' function (pipe size selection). This variability propagates unchecked in the absence of a mandatory design verification checkpoint, which was identified as a gap in the Control aspect of the 'Material Procurement' function, producing conditions for high-severity failure modes FM3 through FM7 (incorrect pipe sizing, pressure losses, flow velocity exceedances). This coupling pattern could not be identified from FMEA alone because FMEA does not model inter-function dependencies.

3.2.2 Scenario 2 — Welding-to-testing temporal coupling (FM41 → FM49)

Variability in 'Welding Operations' (incomplete slag removal and micro-porosity defects, FM41) interacts with downstream 'Pressure Testing' limitations (FM49: joints concealed inside floor and wall transitions) because defective welds that pass visual inspection are then sealed within structural elements before comprehensive leak testing is performed. This temporal coupling arising from the Time and Preconditions aspects of both functions significantly elevates the detection difficulty score for FM49 and contributes to its elevated risk ranking under fuzzy-FMEA. The identification of this scenario required an explicit analysis of the Output-of-Welding to Preconditions-of-Pressure-Testing coupling pathway in the FRAM model, showing that the risk is not inherent in either function alone but emerges from their functional interaction.

These propagation analyses show that the risk of certain failure modes is not solely attributable to individual technical errors but arises from the interaction of variability across multiple functions, which is precisely the phenomenon that the FRAM concept of functional resonance is intended to reveal. The identification of these coupling scenarios informed the structuring of the FMEA failure mode taxonomy and contributed to the elevated detection difficulty scores assigned to several failure modes by the expert panel.

3.3 FRAM-Based Failure Identification

FRAM was used as a systematic tool to identify potential failure modes and their underlying causes within the natural gas installation process. The installation process was first decomposed into its major operational functions. These functions were then analyzed using the six FRAM aspects:

- Input
- Output
- Preconditions
- Resources
- Control
- Time

Table 2 FRAM functions in natural gas installation

Function	Input (I)	Output (O)	Preconditions (P)	Resources (R)	Control (C)	Time (T)
F1. Project initiation & scope definition	—	Project scope, building type, preliminary requirements	Client request exists; legal responsibility defined	Client brief; contracting docs	Project governance/ scope approval	Project start window
F2. Establish design basis & applicable standards	Project scope, building type, preliminary requirements	Design basis & compliance criteria	Access to current standards/specs	Standard library; competent designer	Compliance checklist; independent review rule	Deadline pressure
F3. Site survey & as-built data acquisition	Project scope, preliminary requirements	Verified measurements & constraints	Site access permission; safety access	Survey tools; site team	Survey protocol; cross-check measurements	Limited site access time
F4. Device/load identification & operating conditions	Project scope, preliminary requirements	Device list, Capacities, Operating pressure assumptions	Equipment info available	Vendor datasheets; expert judgment	Assumption log; validation with stakeholders	Late device changes
F5. Hydraulic design (diameter–velocity–ΔP calculations)	Design basis, Device list, Capacities, Operating pressure assumptions	Pipe sizing, Velocity compliance results, Pressure-loss results	Correct boundary conditions	Calculation tools/templates	Design verification; peer review	Design iteration cycles
F6. Layout/routing & constructability design (incl. separation & penetrations)	Verified measurements, Pipe sizing, Velocity compliance results, Pressure-loss results, Design basis	Routing drawings, Placement rules, Penetration details	Inter-discipline coordination possible	Tools; coordination support	Constructability review; clash check	Field-change risk
F7. Ventilation & chimney/flue system design	Design basis, Verified measurements, Device list, Capacities, Operating pressure assumptions	Ventilation grille specs, chimney/ flue specs & criteria	Room classification known	Ventilation/draft calculation methods	Code compliance check; label/spec consistency rules	Late architectural constraints
F8. Material & component specification + procurement readiness	Pipe sizing, Routing drawings, Placement rules, Penetration details, Ventilation grille specs, Chimney/flue specs & criteria, Design basis & compliance criteria	Approved materials/components, Traceability docs	Approved supplier list	Procurement + incoming inspection	Acceptance criteria: TS/standard conformity checks	Supply lead times
F9. Mechanical installation & supports (routing execution)	Routing plan, Placement rules, Penetration details, Approved materials	Installed pipe routes/supports, Prepared penetrations	Site readiness; work permits	Skilled crew; tools; supports/clamps	Installation checklist; supervision	Parallel trades/ schedule pressure
F10. Joining/welding/ sealing + valve/meter assembly	Installed pipe routes/ supports, Prepared penetrations, Approved materials/components delivered, and design basis	Assembled system ready for testing	Qualified welders; correct joint methods	WPS/procedures; torque tools; PPE	Intermediate inspection; "no patch weld" rule	Night shifts/ fatigue risk
F11. Testing, commissioning & NDT/inspection	Assembled system	Leak test/NDT results, Acceptance decision	Isolation possible; calibrated gauges	Manometer; NDT service	Hold points before gas opening; acceptance sign-off	Commissioning deadline
F12. Documentation, labeling, and handover/user information	Acceptance decision, Leak test/NDT results, Installed pipe routes/supports, Assembled system ready for testing, Traceability docs	Handover package, Labels, User instructions	Document templates exist	Doc control system; responsible owner	Version control; handover checklist	Fast closure pressure

The variability sources identified within each function were then translated into candidate failure modes. This approach enabled failure identification based on technical design errors, organizational conditions, operational constraints, and human factors. Table 2 lists the identified natural gas installation functions.

3.4 Classical Process-FMEA (PFMEA) Analysis

Following the FRAM-based failure identification stage, the identified failure modes were analyzed using a process-oriented FMEA (PFMEA) framework. This choice is appropriate because the risks examined in this study arise mainly from process activities performed during design verification, procurement, installation, welding, ventilation arrangement, testing, and commissioning, rather than from a single product design deficiency.

For each failure mode, three standard risk factors were evaluated by the expert panel: occurrence (O), severity (S), and detection (D), using a ten-point scale. The classical risk priority number (RPN) was calculated as follows:

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

The effects of each failure mode were interpreted at three levels to make the analytical structure more explicit:

(1) local process effect (immediate process deviation or workmanship

error),

(2) installation/subsystem effect (impact on a pipeline segment, equipment connection, ventilation path, or inspection/testability), and

(3) end-use/system safety effect (e.g., gas leakage, loss of containment, ignition, explosion, or unsafe operation).

This clarification aligns the study more consistently with a PFMEA perspective. The AIAG and VDA FMEA Handbook (AIAG & VDA, 2019) is identified by AIAG as the reference manual for Process FMEA.

3.5 Fuzzy-FMEA Model

The crisp-score limitations of classical RPN calculations were reduced using a Mamdani-type fuzzy inference system to transform expert evaluations of occurrence, severity, and detectability into fuzzy risk priority numbers (fuzzy RPNs). The fuzzy model was implemented in MATLAB using triangular membership functions for the input variables and a centroid-based defuzzification procedure. Mamdani systems commonly convert the aggregated output fuzzy set to a crisp value using centroid defuzzification.

Let x_O, x_S, and x_D denote the crisp occurrence, severity, and detectability scores provided by the expert panel. Each input was fuzzified into five linguistic classes: Very low (VL), Low (L), Medium (M), High (H), and Very high (VH). For a triangular membership function, the degree of membership can be represented as Eq. (2):

$$\mu_A(x) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a < x \le b \\ \dfrac{c-x}{c-b}, & b < x < c \\ 0, & x \ge c \end{cases} \tag{2}$$

where a, b, and c define the triangular support and peak of the linguistic term.

The fuzzy rule base consists of 125 rules corresponding to all possible combinations of the five linguistic levels of occurrence, severity, and detectability:

$$5 \times 5 \times 5 = 125$$

A generic rule takes the form given in Eq. (3):

$$\text{IF } O \text{ is } A_i \text{ AND } S \text{ is } B_j \text{ AND } D \text{ is } C_k \text{ THEN } RPN \text{ is } R_{ijk} \tag{3}$$

where A_i, B_j, and C_k are linguistic input terms and R_{ijk} is the corresponding linguistic output class. The rule firing strengths were obtained using the Mamdani minimum operator, as expressed in Eq. (4):

$$\alpha_{ijk} = \min \left[\mu_{A_i}(x_O), \mu_{B_j}(x_S), \mu_{C_k}(x_D)\right] \tag{4}$$

The clipped outputs of all activated rules were then aggregated through the maximum operator to form the final output fuzzy set, as expressed in Eq. (5):

$$\mu_R(y) = \max_{ijk} \left[\alpha_{ijk} \wedge \mu_{R_{ijk}}(y)\right] \tag{5}$$

Finally, the fuzzy output was transformed into a crisp fuzzy RPN using centroid defuzzification, as expressed in Eq. (6):

$$RPN_f = \frac{\int y \ \mu_R(y) \ dy}{\int \mu_R(y) \ dy} \tag{6}$$

For the output variable, a 0–100 scale was used with seven linguistic classes: Very very low (VVL), Very low (VL), Low (L), Medium (M), High (H), Very high (VH), and Very very high (VVH).

As an illustrative example of the discriminative value of the fuzzy approach, consider Failure Mode 14 (FM14: insufficient cathodic protection in underground piping lines) with scores $O = 4$, $S = 9$, $D = 1$, yielding a classical $RPN = 4 \times 9 \times 1 = 36$. In the fuzzy model, the very high severity score ($S = 9$) strongly activates the "Very High" severity membership function (μ_VH(9) ≈ 0.67), and the very low detectability score ($D = 1$) activates the "Very Low" detection membership function at full strength (μ_VL(1) = 1.0). These two dominant activations trigger high-output Mamdani rule clusters, yielding a fuzzy RPN of 35.4 after centroid defuzzification. Failure Mode 22 (FM22: flexible pipe omissions in building dilatation lines) also yields a classical RPN of 36, calculated as $O = 6 \times S = 3 \times D = 2$. On the other hand, $S = 6$ and $S = 3$ activate only the "Medium" membership region, and $D = 2$ provides moderate detectability, resulting in weaker rule activations and a fuzzy RPN of 27.8. Under classical FMEA, FM14 and FM22 receive identical risk rankings because 4 × 9 × 1 = 6 × 3 × 2 = 36. The fuzzy model differentiates them, assigning FM14 a Fuzzy RPN of 35.4 (Rank 14) and FM22 a Fuzzy RPN of 27.8 (Rank 21). This captures a meaningful real-world distinction: a very-high-severity failure that is highly difficult to detect (FM14, $S = 9$, $D = 1$) represents a qualitatively more dangerous risk profile than a moderate-severity failure with medium detectability (FM22, $S = 6$, $D = 2$), even when their classical RPN products are equal. The fuzzy inference system encodes this qualitative difference through non-linear membership function interactions, whereas the classical multiplicative RPN formula is blind to it. In addition, Failure Mode 19 (FM19: incorrect pipeline routing during the design phase) shares the same *O, S, D* input scores as FM22 ($O = 3$, $S = 6$, $D = 2$). Therefore, the Mamdani fuzzy inference system, being a deterministic function of its inputs, produces an identical fuzzy RPN of 27.8 for FM19. This is the mathematically correct and expected behavior of the model: identical inputs must yield identical outputs in a deterministic fuzzy system. The apparent discrepancy in the previous version of Table 5, where FM19 was listed with a fuzzy RPN of 16.2, was a typographical error that has been corrected in the current version. Both FM19 and FM22 now correctly appear with Fuzzy $RPN = 27.8$ and share Rank 21 in Table 5.

In this study, fuzzy RPNs were calculated using a triangular-fuzzy representation, with inference performed via the Mamdani method in MATLAB. Fig. 2 presents the overall fuzzy model, including input and output membership functions and the rule base.

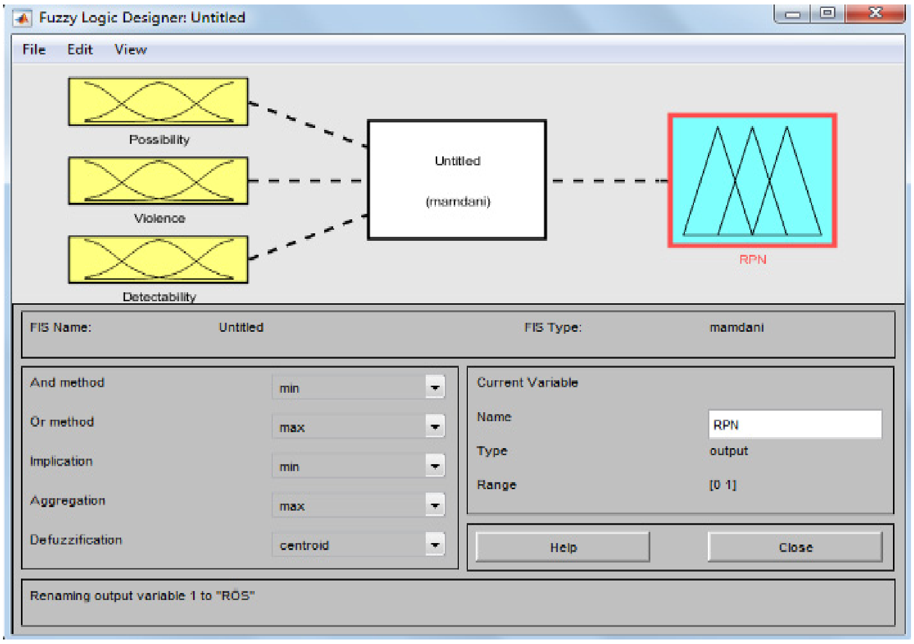

Fig. 2 Fuzzy model

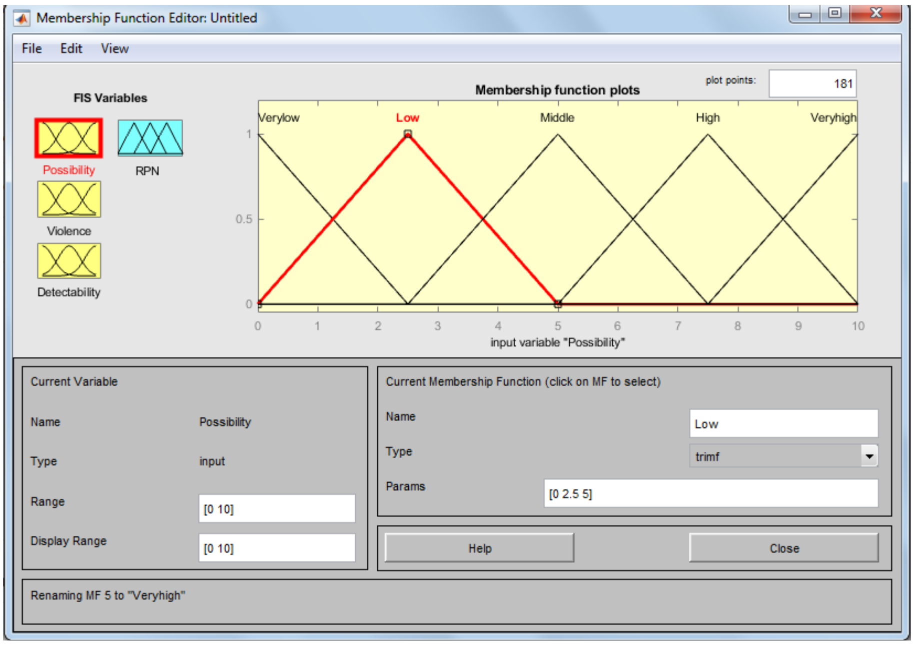

Fig. 3 Membership functions for the input variables (occurrence, severity, detectability).

The input and output variables in this model are represented by membership functions and connected via a rule base. Membership functions are defined for the three input factors—occurrence (probability), severity, and detectability. A decimal scale was adopted for the membership definitions, and triangular membership functions (trimf) were used as the inputs. Five linguistic terms were specified for each risk factor, with interval bounds set on the decimal scale based on expert judgment and experience. Fig. 3 presents the representative sub-regions of the triangular membership functions, labeled VL (Very low), L (Low), M (Medium), H (High), and VH (Very high).

For the output variable (RPN), a 0–100 scale is partitioned into seven categories: VVL (Very very low), VL (Very low), L (Low), M (Medium), H (High), VH (Very high), and VVH (Very very high), as shown in Fig. 4.

A rule base was constructed to enable inference under fuzzy logic. In this model, the rule base comprises 125 rules (i.e., 5 × 5 × 5 combinations of occurrence, severity, and detectability). Each rule was formulated and reviewed individually to cover the full cross-product of input linguistic terms (see Fig. 5). The resulting fuzzy inferences yielded output RPN memberships, which, when aggregated and defuzzified, produced scalar RPN values. Fig. 6 presents the variation of the RPN across different input combinations.

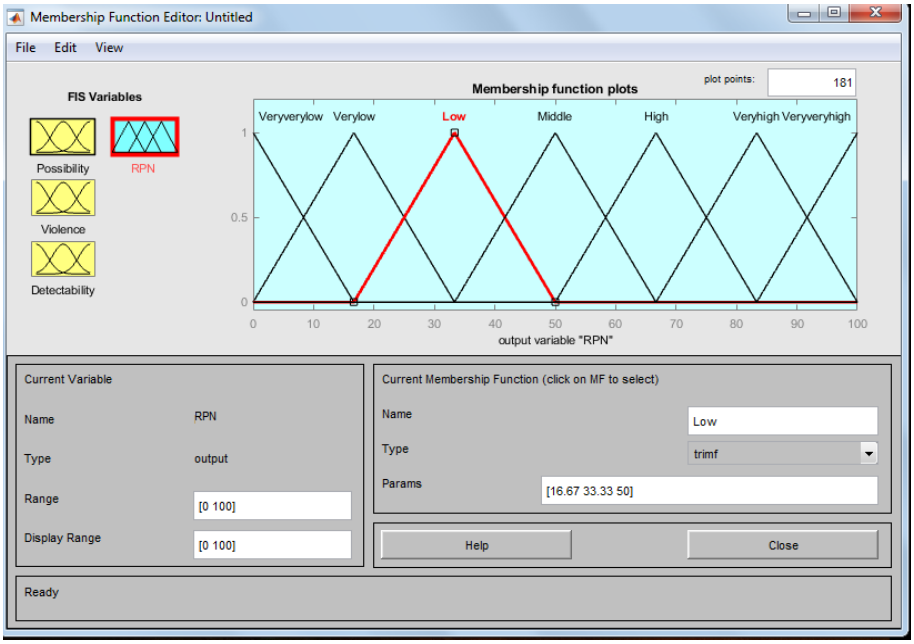

Fig. 4 RPN output-variable membership functions

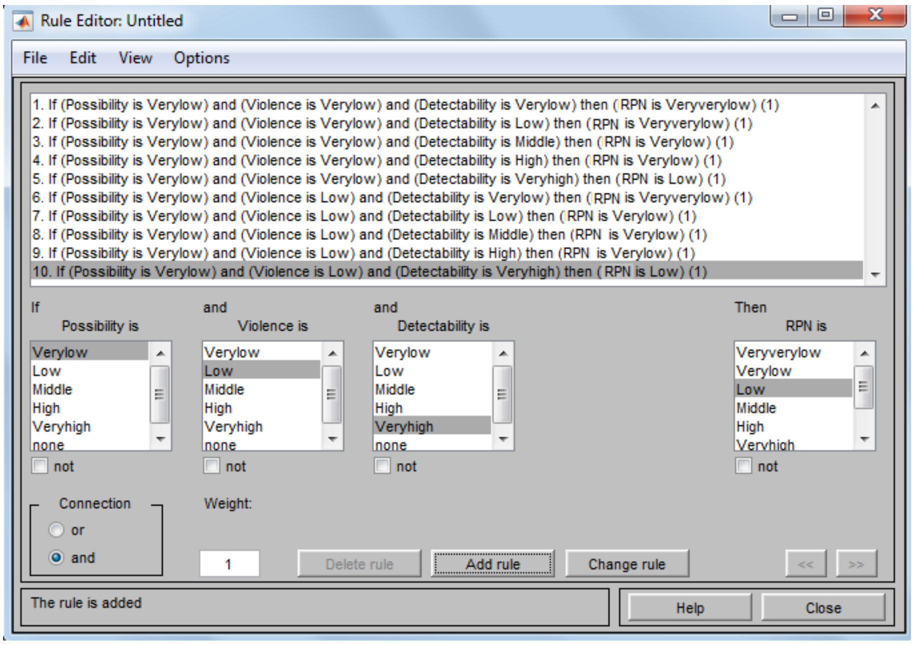

Fig. 5 Rule base

3.5.1 Sensitivity analysis

The robustness of the fuzzy-FMEA results was evaluated through sensitivity analysis that systematically varied the triangular membership function breakpoints for the three input variables (*O, S, D*) by ±10% and ±20% around their central values. The rank stability of the top 20 failure modes was assessed across all four perturbation scenarios. The results suggested that the relative ordering of the top 10 ranked failure modes remained unchanged across all tested parameter configurations, showing that the principal risk prioritization conclusions are insensitive to moderate uncertainty in membership function specification.

A consistency assessment between classical and fuzzy RPN rankings was further performed using Kendall's rank correlation coefficient. The computed value of τ = 0.61 (p <0.01) confirms moderate but significant correspondence between the two ranking methods. The divergences were concentrated among failure modes with intermediate *O, S, D* score combinations, specifically those in which identical classical RPN values mask meaningfully different risk profiles when evaluated under fuzzy logic. This confirms that fuzzy-FMEA provides substantive additional discriminative value in precisely those cases where classical FMEA is most prone to rank ambiguity.

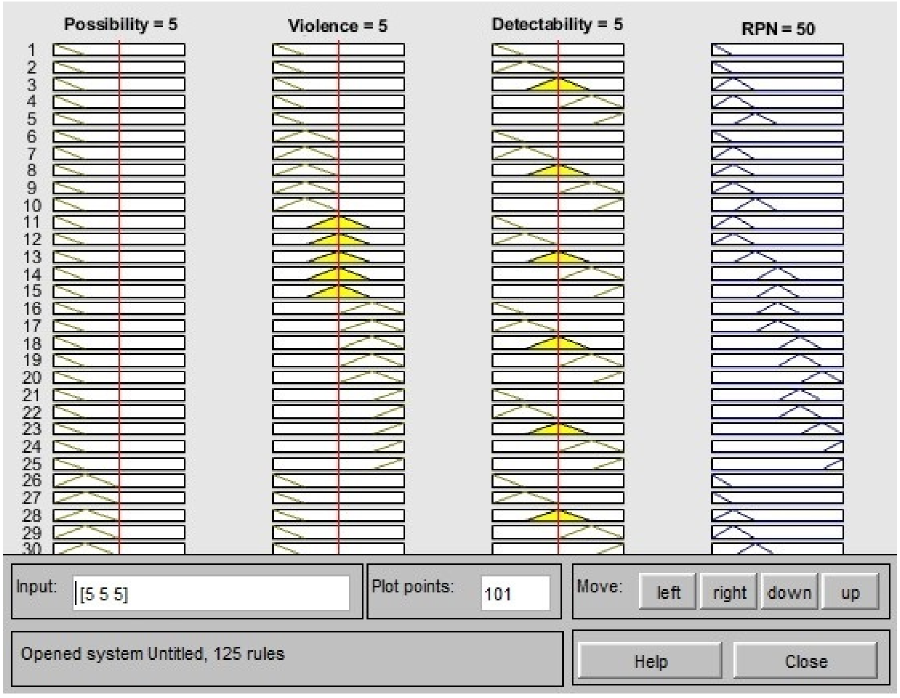

Fig. 6 RPN numbers for probability, severity, and detectability status

3.6 Pareto Risk Prioritization

After calculating the fuzzy risk priority numbers, Pareto analysis was performed to identify the failure modes that contribute most significantly to the overall system risk. The Pareto principle is commonly applied to risk prioritization under the premise that a minority of failure modes accounts for the majority of system risk. In this study, the analysis showed that 52 of the 81 failure modes (64.2%) collectively accounted for 80% of the cumulative fuzzy risk, confirming a dispersed but actionable risk concentration pattern. Therefore, focusing safety improvement efforts on the most critical failure modes allows organizations to allocate resources more effectively.

4. Results

4.1 FRAM Modeling of the Natural Gas Installation Process

The first stage of the analysis involved modeling the natural gas indoor installation process using the Functional Resonance Analysis Method (FRAM). The purpose of this step was to identify the functional structure of the installation system and analyze the sources of variability that may lead to operational failures.

Unlike traditional risk analysis techniques that focus primarily on component failures, FRAM models the system as a set of interacting functions whose performance may vary under different operational conditions (Hollnagel, 2014). Variability in these functions may

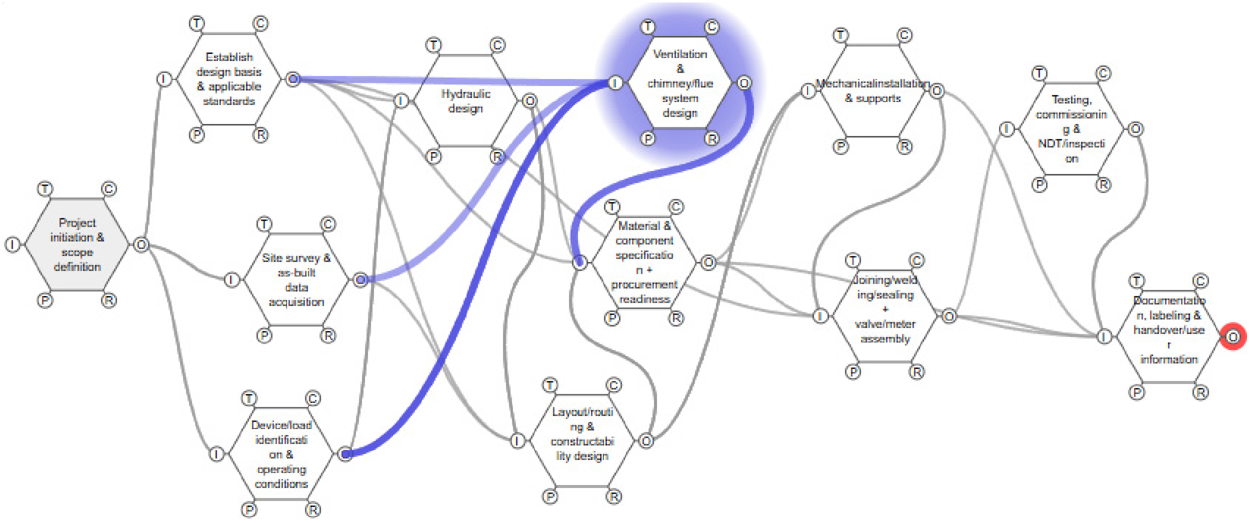

Fig. 7 FRAM modeling of the building natural gas installation process

propagate through the system, leading to unsafe states or failures.

Therefore, the natural gas installation process was decomposed into its principal operational functions, including system design verification, material procurement, pipeline installation, welding operations, ventilation configuration, leak testing, and commissioning procedures.

Each function was analyzed according to the six FRAM aspects: input, output, preconditions, resources, control, and time; Fig. 7 presents the installation model. The model illustrates the interactions between the main operational functions involved in the installation process.

4.2 Identification of the Functional Variability

Following the FRAM modeling stage, potential variability sources were analyzed for each function. Functional variability may originate from technical deviations, human factors, organizational constraints, or deviations from established procedures.

The variability analysis showed that installation risks may arise from several sources, including design calculation errors, improper material selection, installation deviations, and insufficient inspection procedures.

4.3 Mapping Functional Variability to FMEA Failure Modes

The variability sources identified through the FRAM analysis were translated into candidate failure modes and causes. This step established a direct relationship between the functional variability sources and the failure modes used in the FMEA dataset. The mapping process ensured that failure identification was based on a systematic functional analysis rather than on expert intuition alone. Table 3 lists the mapping between FRAM variability scenarios and the corresponding FMEA failure modes.

Table 3 Mapping of FRAM variability sources to FMEA failure modes

Scenario	Variability source	Effect of variability
S1. Pipeline sizing in the design phase	Demand/capacity inputs uncertain; wrong assumptions; missing independent review	Wrong diameters, excessive velocity, high pressure loss → noncompliant hydraulic performance (FM 1, 3–7, 62)
S2. Building survey and routing decisions	Incomplete measurements; late architectural constraints; poor interdisciplinary coordination	Wrong routing/direction; inaccessible/damp/no-airflow placement; increased damage risk (FM 19–20, 27)
S3. Proximity to electrical/weak-current systems	Site changes not reflected; marking errors; checklist not enforced	Separation distance violation → increased interference/safety hazard (FM 8)
S4. Material substitution under supply pressure	Supply delays; substitution requests; weak incoming inspection/traceability	Nonconforming pipes/valves/chimneys → hidden defects and standard noncompliance (FM 18, 28, 72)
S5. Underground joint protection	Hot wrap procedure not followed (no heating/overlap); inspection hold-points skipped	Coating failure at joints → corrosion risk and long-term leakage (FM 11–12)
S6. Cathodic protection execution	CP design unclear; resource shortage; wrong Mg anode placement	Insufficient CP performance → accelerated corrosion/failure (FM 14–15)
S7. Underground–aboveground transition	Insulation joint not installed due to missing detail/part	Electrical/corrosion continuity issues → increased failure likelihood (FM 16)
S8. Underground geometry compliance	DN < 25 used due to design/procurement mismatch	Capacity/pressure problems + noncompliance (FM 13)
S9. Device connections and dilation	Flexible connections omitted due to habit/training gap	Stress transfer and joint failure risk; device connection noncompliance (FM 21–22)
S10. Cold bending practice	Lack of elbows; installer convenience; rushed work	Over-bending / bending DN50+ → deformation, stress concentration, leakage risk (FM 24–25, 10, 75)
S11. Valve selection mismatch	Wrong valve spec; poor incoming inspection	Valve diameter mismatch → flow restriction, installation issues (FM 26)
S12. AKV/KKV installation method	Unclear method; nonstandard "external record connection" practice	Improper mounting → leakage/integrity issues (FM 30, 17)
S13. Tightening without torque discipline	No torque tool/standard; fatigue	Over/under-tightening → leaks or mechanical damage (FM 31)
S14. Service box regulator selection (300 mbar)	Wrong component selection; shut-off requirement missed	Unsafe regulator configuration → reduced safety margin (FM 32)
S15. Patch welding culture	Time pressure; lack of repair policy enforcement	Patch weld on holed fittings → latent defect, future rupture (FM 33)

Table 3 Mapping of FRAM variability sources to FMEA failure modes (Continuation)

Scenario	Variability source	Effect of variability
S16. Meter connection orientation errors	Misread direction; poor marking	Wrong inlet/outlet orientation → functional/operational issues (FM 34)
S17. Meter placement decision	Maintainability constraints ignored; site pressure	Meter placed incorrectly → access/operation risks (FM 35)
S18. Pipes hidden under plaster	Aesthetics/finishing pressure; weak enforcement	Buried pipes → inspection/maintenance impossible, increased hazard (FM 36)
S19. Ventilation grille removed/ closed after installation	User intervention; lack of "no-closure" control	Loss of ventilation → accumulation risk (FM 37)
S20. Welding method selection	Wrong WPS; unqualified welder	Wrong welding method → defects and leakage (FM 38)
S21. Welding fit-up quality	Misalignment; poor contact; lack of fixtures	Adhesion/contact deficiencies → weak joint integrity (FM 39)
S22. Welding process parameter variability	Incorrect settings; fatigue	Burn-in/notch formation → crack initiation (FM 40)
S23. Welding defects (slag/pores/cracks)	Contamination; inadequate technique; missing NDT	Defects persist undetected → leakage/rupture risk (FM 41, 79)
S24. Noncompliant joint types in the column line	Habitual practices; unclear prohibition	Threaded/sleeve welding where prohibited → integrity hazard (FM 42)
S25. Floor transition without sheath	Missing materials; poor inspection	No steel sheath → mechanical damage risk (FM 43)
S26. Sheath gap not filled	Workmanship gaps; missing protective filler	Unsealed gap → wear/vibration, leakage risk (FM 44)
S27. Wall transitions without sheath/ insulation	Resource shortage; control skipped	Lack of protective insulation → abrasion/corrosion risk (FM 45)
S28. Cleaning branch omitted	Design detail missing; installer unaware	Maintenance/cleaning impossible → operational risk (FM 46)
S29. Meter entry shut-off valves omitted	Design/procurement oversight; checklist gap	Inability to isolate each meter → increased incident impact (FM 47)
S30. Test mouth/nipple omitted	Commissioning fittings not planned	Testing becomes difficult → leak test quality reduced (FM 48)
S31. Joints inside protective sheath	Poor planning; space constraints	Hidden joint defect cannot be inspected → latent leakage risk (FM 49)
S32. Boiler room space too small	Design ignores maintainability	Unsafe maintenance conditions; increased operational risk (FM 50)
S33. Burner capacity/characteristics wrong	Device data unclear; wrong selection	Inefficient/unsafe combustion and system mismatch (FM 51, 62)
S34. Gas alarm placement missing	Design omission; procurement delay	Late detection of gas accumulation → higher consequence (FM 52)
S35. No solenoid valve linked to alarm	Integration not specified	Alarm cannot trigger isolation → reduced protection (FM 53)
S36. No main cut-off switch	Safety design incomplete	Delayed emergency isolation → increased harm (FM 54)
S37. Non-ex-proof electrical equipment	Wrong spec/procurement	Ignition risk in hazardous environment (FM 55)
S38. Vent grille sizing inconsistency	Calculation not followed; install deviation	Poor airflow balance → ventilation inefficiency (FM 56)
S39. Damaged/perforated pipe handling	Emergency procedure unknown; poor training	Improper intervention → escalation of leakage/incident (FM 57–59)
S40. Burner gas control line missing equipment	Specification unclear; procurement gaps	Control line incomplete → unsafe operation (FM 60)
S41. Meter undersized vs Qmin	Wrong selection; unclear demand data	Flow cannot be measured accurately → operational/control failure (FM 61)
S42. Industrial installation lines not per spec	Spec not translated into design/execution	System built contrary to requirements → systemic noncompliance (FM 63)

Table 3 Mapping of FRAM variability sources to FMEA failure modes (Continuation)

Scenario	Variability source	Effect of variability
S43. Collector symmetry issue (two service boxes)	Design oversight	Flow imbalance/operational instability (FM 64)
S44. Unsafe actions during work	Weak HSE governance; supervision absence	Increased accident probability (FM 65, 58)
S45. Prohibited items in the boiler room	Poor housekeeping/enforcement	Increased fire/explosion load (FM 66)
S46. Boiler room door wrong	Fire safety rules ignored	Evacuation/fire spread risk increases (FM 67)
S47. Common/shunt flue misuse	Legacy practice; noncompliant design	Backdraft/CO risk increases (FM 68)
S48. Chimney termination location wrong	Roof geometry not considered	Exhaust impacts neighbor/breathing zone; safety risk (FM 69)
S49. Chimney absent / no draft calculation	Design incomplete; time pressure	Poor draft → unsafe combustion/exhaust (FM 70)
S50. Chimney label vs project mismatch	Document control weak; supplier mismatch	Incorrect installation/configuration risk (FM 71)
S51. Chimney supplier not certified / no labels	Supplier qualification failure	Noncompliant product used → increased defect probability (FM 72)
S52. No chimney cap	Missing component; checklist gap	Rain/wind effects; draft issues (FM 73)
S53. Chimney grounding missing	Bonding requirement missed	Electrical safety and ignition risk (FM 74)
S54. Excavation vehicle precautions missing	Barriers/signage absent	Pipe damage during excavation → leakage risk (FM 76)
S55. Cutting/grinding unsafe in groove prep	Wrong tools; missing protection	Damage to pipe/coating; injury risk (FM 77)
S56. Molten metal spatter; no welding glasses	PPE noncompliance	Injury risk; work quality degradation (FM 78)
S57. No NDT (X-ray/UT) inspection	Quality plan missing; cost/time pressure	Weld defects remain undetected → failure during operation (FM 79, 41)
S58. Pipelines close to flammable materials	Routing constraints; inspection weak	Increased ignition/fire consequence if leak occurs (FM 80)
S59. No electrical bridging at meter	Bonding control missing from checklist	Static/stray current risk increases (FM 81, 23)
S60. Paint before leak check	Wrong sequence; commissioning rush	Leak presence masked; delayed detection (FM 29)

4.4 Construction of the FMEA Dataset

A comprehensive FMEA dataset was constructed according to the FRAM-based failure identification process. Eighty-one failure modes were identified within the natural gas installation process, as listed in Table 4. These failure modes cover the entire lifecycle of the installation system, including design errors, installation deviations, material non-compliance, welding defects, ventilation problems, and operational safety violations.

The failure modes were categorized according to their installation segments:

- building connection pipelines
- vertical riser lines
- indoor installation systems

4.5 Comparison of Classical FMEA and Fuzzy-FMEA

Fuzzy logic was applied to calculate fuzzy risk priority numbers and

Table 4 FMEA dataset for natural gas installation processes

Failure No.	Failures	Failure effects that may occur	Possible causes of failure	Current controls	Severity (S)	Occurrence (O)	Detection (D)	RPN
1	Giving wrong diameters of pipelines to be made in the project	Obstacle in giving proper flow rate in use	Pipe diameter calculation error	Checking the prepared project, determining its compliance with the specification	7	3	1	21
2	Failure to use clamps at appropriate distances for natural gas pipelines and valves.	Movement of pipes due to excessive load and leakage from joints	Carelessness and lack of work experience	Determination of conformity during construction	3	2	1	6
3	When the pressure is P50 mbar, the flow velocity exceeds v ≤ 6 m / s	Flow rate problematic in use	Wrong account error	Checking the prepared project, determining its compliance with the specification	5	3	2	30
4	In case of pressure P 50 mbar, flow velocity exceeding v ≤ 15 m / s in DN65 and small diameters	Problematic situation of flow rate in use	Incorrect calculation error	Checking the prepared project, determining its compliance with the specification	5	3	2	30
5	Exceeding v ≤ 25 m / s in DN80 and large diameters in facilities with large consumption	Problematic situation of flow rate in use	Incorrect calculation error	Checking the prepared project, determining its compliance with the specification	5	3	2	30

Table 4 FMEA dataset for natural gas installation processes (Continuation)

Failure No.	Failures	Failure effects that may occur	Possible causes of failure	Current controls	Severity (S)	Occurrence (O)	Detection (D)	RPN
6	Total pressure loss between the delivery point of the gas and the device used is more than ⊿P∑ 1.8 mbar	The situation that using the device will not be efficient without proper pressure	Using more equipment than in the design building instruction	Checking the prepared project, determining its compliance with the specification	4	2	3	24
7	If the gas pressure of the meter is 300 mbar, the total pressure loss between it and the service box is more than ∑P 21 mbar	The situation that using the device will not be efficient without proper pressure	Using more equipment than in the design building instruction	Checking the prepared project, determining its compliance with the specification	4	2	3	24
8	Natural gas pipelines and all weak current telephones, bells, door automats, cable TV. antenna, etc., cables and making them closer than 15 cm from the junction boxes	The situation of creating fire or explosion by spark in case of leakage in case of close proximity	Inadequate measurements during installation	Determining the suitability of the installation to the project	10	4	7	280
9	Making screw connections with the wrong screw type	Gas leak in pipe connections	Wrong screw joint selection	Determining the suitability of the tooth type for the standard material	4	2	2	16
10	For places where elbows are required in underground pipelines, bending the existing pipes instead of using elbows	More corrosion effect on the material	Carelessness, lack of experience and work experience	Checking the prepared project, determining its compliance with the specification	3	4	1	12
11	Underground pipelines are covered with polyethylene, but cold wraps are used instead of hot wraps on the joints	More corrosion effect due to lack of protection in the material	Choosing the faulty manufacturing application method	Control of production and determination of suitability during application	3	5	2	30
12	Underground pipelines are covered with polyethylene, but they have not been built without heating the hot polyethylene wrap to the joints and using 50% coil overlap method	More corrosion effect due to lack of protection in the material	Carelessness, lack of experience and work experience	Determination of suitability during construction	4	5	2	40
13	Using pipes with a diameter smaller than DN 25 in underground piping	The case of insufficient gas flow rate	Use of material that is not in accordance with the specification	Determining the suitability of the installation to the project	3	1	2	6
14	Failure or insufficient cathodic protection in underground piping lines	Inability to transfer the static load to the soil, damage to the device and corrosion of the pipe.	Lack of training, experience and work experience	Determining the suitability of the installation to the project	9	4	1	36
15	Misapplication of Mg anode application place	Cathodic protection is not done and static charge is not transferred	Lack of training, experience and work experience	Determination of suitability during construction	9	4	1	36
16	Not separating the underground and above ground lines with insulation joint	Grounding and cathodic protection inadequate	Lack of training, experience and work experience	Determining the suitability of the installation to the project	5	3	2	30
17	If the line after the service box passes underground and goes to a closed area in the piping lines, AKV should not be installed after the service cabinet (S.K: Service Cabinet)	Installation is not accepted, it is requested to be installed	Overlooked	Determining the suitability of the installation to the project	5	1	2	10
18	Using pipes other than natural gas pipes	Different effects depending on the material used	Wrong choice of material	Detection of material property and standard control	5	1	1	5
19	Giving the wrong direction of pipelines to be constructed during the design phase	Incorrect manufacturing situation as application and project may be different	Not controlling the project	Checking the prepared project, determining its compliance with the specification	6	3	2	36
20	Incorrect measurements of the pipelines for the building to be applied, making the project with the wrong measurements	Since the calculations will be wrong, an inappropriate line is laid, and then it cannot be inspected, so the gas is not opened	Wrong size given error	Checking the pipe dimensions to be made on site and the dimensions of the drawn project	7	4	3	84
21	Not connecting with natural gas consumption devices with flexible pipes	Leakage in connection points in device movements	Lack of controls	Determination of conformity control to standards during gas opening	4	2	1	8
22	Interconnections in the dilatation lines of buildings are not made with flexible pipes	Bending and fracture situation in pipelines in building movement	Carelessness, lack of experience and work experience	Determining the suitability of the installation to the project	6	3	2	36

Table 4 FMEA dataset for natural gas installation processes (Continuation)

Failure No.	Failures	Failure effects that may occur	Possible causes of failure	Current controls	Severity (S)	Occurrence (O)	Detection (D)	RPN
23	Natural gas pipes have been used out of purpose and cannot protect against static electricity charges	If the line is used as a grounding line	Lack of training, experience and work experience	Determining the suitability of the installation to the project	5	6	8	240
24	More than normal bending of the pipe in cold bending in aboveground installations	The thickness of the bent pipe gets thinner and its strength decreases	Inattention and carelessness of the person doing the job	Determining the suitability of the installation to the project	5	4	1	20
25	Bending in aboveground pipelines in diameters of DN 50 and above	The thinning of the thickness of the bent pipe and the decrease of its strength.	Inattention and carelessness of the person doing the job	Inspected at the end of the job	6	3	2	36
26	The valve used in the pipelines has a different diameter than the pipe diameter where it is used	Pressure loss on the line	Inattention and carelessness of the person doing the job	At the end of the job, the line is checked with the necessary measurement processes	5	3	1	15
27	Passing the main pipe connection lines in unsuitable places where there is no airflow, damp, difficult to reach, not considered as a common area of the building and where the pipes will be damaged.	Corrosion of pipes and non-intervention	Failure to comply with standards and carelessness	Checked during gas opening	4	3	1	12
28	Using valves and materials that are not suitable for TS and standards	If the line is not working efficiently and is easily damaged	Desire to avoid costs	Checking the prepared project, determining its compliance with the specification	6	7	2	84
29	Painting the pipelines in the natural gas installation with yellow paint over antirust before opening the gas and not checking the leakage.	Leak gases not being detected	Failure to follow work instructions	Insufficient control in process steps	3	1	1	3
30	Mounting of AKV and KKV to the installation by an external method of record connection	A connection that cannot be disassembled and no intervention	Failure to follow work instructions	Inspected at the end of the job	6	2	1	12
31	Over or under-tightening of the connection points of the valve during the installation of natural gas valves to the installation.	Excessive tightening will damage the material, less tightening has created gas leakage.	Inattention and carelessness of the person doing the job	Regular control of work steps	9	5	3	135
32	Having a domestic regulator without shut off in service boxes with 300 mbar output	An explosion that may occur in the event of sudden failure to close the gas flow	Lack of education, experience and work experience	Checking according to work instruction	9	1	1	9
33	Patch welding when fittings have holes	Leakage situation in the installation	Material strength insufficiency	Inspected at the end of the job	8	2	1	16
34	Connections to the meter entering from the right and leaving from the left	Inability to measure the amount of gas passing through the natural gas meter	Improper installation	Inspected at the end of the job	3	2	1	6
35	Incorrect determination of the place where the meter is placed	Negative effect on the materials on the line	Failure to comply with the job instruction to the project	Controlling the project and determining its suitability	3	3	3	27
36	Burying natural gas pipes under plaster	Failure to intervene	Non-standard manufacturing	Controlling the project and determining its suitability	6	1	1	6
37	No ventilation grille or cancellation (closing) of the existing grille afterward	The situation of drowning in the environment, causing a fire	The doer and the user are uneducated and uninformed.	Controlling the project and determining its suitability	9	5	6	270
38	Application of wrong welding method for natural gas pipelines	Gas leakage due to manufacturing errors in line use	Lack of training, experience and work experience	Controlling the project and determining its suitability	5	2	1	10
39	Misalignment, insufficient contact and adhesion deficiency in pipes to be welded	The line is not working efficiently and is easily damaged	Mistake and carelessness of the doer	It is controlled visually during construction	6	5	5	150
40	Burn-in error and burning notch formation while welding	Requirement of renovation again after a certain period of time	Mistake and carelessness of the doer	It is controlled visually during construction	6	4	1	24
41	Slag error, pores and crack errors while welding	If the line is not working efficiently and is easily damaged	Mistake and carelessness of the doer	It is controlled visually over the line	5	4	6	120

Table 4 FMEA dataset for natural gas installation processes (Continuation)

Failure No.	Failures	Failure effects that may occur	Possible causes of failure	Current controls	Severity (S)	Occurrence (O)	Detection (D)	RPN
42	A threaded connection or sleeve welding in the column line up to the meter valve	Gas leakage in the following times	Not following the standard to the project	Project control is done	6	2	1	12
43	No steel sheaths are used in floor transitions on the column line	Condition of destruction on the line in building motion and shaking	Use of wrong materials	It is visually checked at the end of the job	4	3	1	12
44	The gap between the pipe and the sheath is not filled in the floor transitions in the column line	Condition of destruction on the line in building motion and shaking	Inattention and carelessness of the person doing the job	It is visually checked at the end of the job	3	2	1	6
45	Not using sheaths in-wall transitions in indoor installation, lack of insulation with protective material between the sheath and the pipe	Corrosion situation as the pipeline can be damaged and not protected	Inattention and carelessness of the person doing the job	It is visually checked at the end of the job	3	2	1	6
46	Leaving a branch for cleaning at the lowest or highest point of the column line	State of danger when used for different purposes	Unconscious user and worker working without a project	It is visually checked at the end of the job	4	2	1	8
47	No shut-off valves are installed in each meter entry	The situation of not cutting gas in leakages and errors	Inattention and carelessness of the person doing the job	It is visually checked at the end of the job	10	1	1	10
48	Test mouth and test nipple not left after the meter	Failure to test the line for leakage	Mistake and carelessness of the doer	Controlling the project and determining its suitability	7	1	2	14
49	Having joints in natural gas pipes inside the protective sheath in floor and wall transitions	Inability to intervene in case of a gas leak	Application error	Controlling the project and determining its suitability	6	2	8	96
50	The dimensions of the place where the boiler is placed are too small to allow maintenance and repair.	The situation that maintenance and possible malfunctions cannot be solved	The user does not allow the boiler to be in another location	Standard boiler room size control	9	1	1	9
51	Choosing the wrong capacity and characteristics of the burner	Inadequacy for the boiler	Making a selection without taking into account the calculations	Detection of material property and standard control	6	4	1	24
52	Not placing a gas alarm device at the top of the place where pipelines are located in the boiler room.	The situation that gas leaks are not noticed	Application error and carelessness	Controlling the project and determining its suitability	9	1	2	18
53	There is no solenoid valve in the boiler room connected with the gas alarm device.	Inability to shut off the gas flow in case of a gas leak	Application error and carelessness	Controlling the project and determining its suitability	8	1	2	16
54	Failure to put a main cut-off switch for possible gas leaks.	Case of greater damages in power failure	Desire to avoid costs	Checking the prepared project, determining its compliance with the specification	9	5	2	90
55	Electricity control panels and lighting in the boiler room are not etange type ex-proof	Prevention of protection from explosion or fire and the situation of destruction	Avoiding cost and lack of care	Checking the prepared project, determining its compliance with the specification	9	2	2	36
56	Making the dimensions of the lower ventilation and upper ventilation grilles in the boiler room in different sizes	Inability to get enough air at a standard level, the condition of the airlessness of the environment	Failure to manufacture in accordance with the dimensions in the project	Project control is done at the end of the job	8	3	1	24
57	Improper intervention to perforated pipelines encountered during manufacturing or pipes that come into rupture	Leak formation and explosion on lines	Lack of training, experience and work experience	Standard intervention technique is checked during construction	6	2	1	12
58	Life safety, property safety, environmental safety and not doing the work in accordance with the procedures and rules in the mistakes encountered	The situation of causing various accidents	Failure to comply with the work instructions	Occupational health and safety control is made	9	3	3	81
59	Application of incorrect intervention technique in uncontrolled gas exits	Different explosion situations may occur	Lack of education, experience and work experience	Standard intervention technique is checked during construction.	8	3	1	24
60	Application of missing equipment in the burner gas control line to be made	System inefficient or not working at all	Desire to avoid costs	Checking the prepared project, determining its compliance with the specification	5	7	1	35

Table 4 FMEA dataset for natural gas installation processes (Continuation)

Failure No.	Failures	Failure effects that may occur	Possible causes of failure	Current controls	Severity (S)	Occurrence (O)	Detection (D)	RPN
61	For the installation to be applied, the meter is smaller than the Qmin value and the gas flow cannot be measured	Failure to measure gas passage from the meter, the inability of gas at the appropriate pressure	Gas pressure operations determined as a result of incorrect calculations	Checking the prepared project, determining its compliance with the specification	9	1	1	9
62	Selection of inappropriate flow rate values for devices in case the capacities of the products are not known clearly	The situation that prevents use due to incorrect capacity determination	The mistake of making the wrong choice	Checking flow rates from device brochures	4	2	1	8
63	Lack of project preparation according to the specification and failure to do the installation in this direction when the line for the kitchen, heating installation line, steam installation line will be built for the gas-infused Industrial Installation	Failure to manufacture in accordance with the specification	Doing work without a project and drawing error of the design project	Checking the new project to be prepared, determining its compliance with the specification	5	4	6	120
64	The box outlet collector of the lines fed by two service boxes is not made symmetrical.	The situation affecting the gas passages for the downstream line	Failure of the person who does the job to comply with the project	Project control is done at the end of the job	6	2	2	24
65	Unsafe actions during work, manufacturing	The situation of self-mutilation and poor quality of the work done	Inattention and carelessness of the person doing the job	Occupational health and safety control is made	10	4	2	80
66	Keeping electric generators and solid, liquid and gas fuel tanks in boiler rooms	Problems in natural gas lines and general own lines	Failure to comply with standards and carelessness	Boiler room control before gas opening at the end of the work	9	2	1	18
67	Making the doors of the boiler room from burning material and opening to the inside	Door burning and intervention difficulty	Use of non-standard materials	Appropriate material control is made	8	2	1	16
68	Using common (shunt) flue or ordinary flue for natural gas devices	Chimney flushing and depressions	Lack of effective control	It should be checked that it is a self-contained chimney	9	3	1	27
69	The mouth of the natural gas chimney is under the roof ridge or its direction is connected to the neighborhood where breathing can be made	Poisoning by inefficient traction and breathing	Sloppy work, non-compliance with standards	Project control is done at the end of the job	10	3	2	60
70	No chimney is placed in the project/installation and no chimney draft calculation is made	Not accepted due to missing project	Incomplete work and carelessness error	Checking the prepared project, determining its compliance with the specification	1	2	2	4
71	The cross-section, height and location values on the chimney label and the chimney values in the project do not match	Inefficient working	Misconduct and carelessness	Project control is done at the end of the job.	6	3	2	36
72	The chimney manufacturer does not have TS 11383 certificate and no labels are attached to the chimney	It is not suitable for standards and does not have the desired features	Employing unauthorized companies for low cost	Determination of conformity to the specification	5	4	1	20
73	Not using a chimney cap	Rainwater and different objects entering the chimney	The carelessness of the chimney manufacturer	A chimney firm that is suitable for standards will check.	6	2	1	12
74	Chimney grounding is not done	Impact from lightning disaster	The carelessness of the chimney manufacturer	A chimney firm that is suitable for standards will check.	8	1	2	16
75	Having more elbows than shown in the project	Pressure loss low efficiency	Existing non-project manufacturing practices	Project control is done.	5	2	2	20
76	Failure to take precautions for construction equipment, trucks and other motor vehicles operating in the excavated area	The situation that poses a problem for both the employee and the workplace	Not taking action	Occupational health and safety control is made	9	2	2	36
77	Cutting the pipe with grinding, cleaning the insulation on the pipe and the absence of the spiral stone protector during the welding groove	Problems for the employee himself	Equipment shortage	Occupational health and safety control is made	8	2	2	32
78	Spatter of molten metal during the welding process and not using welding glasses	Problems for the employee himself	Inattention and carelessness of the person doing the job	Occupational health and safety control is made	10	5	2	100

Table 4 FMEA dataset for natural gas installation processes (Continuation)

Failure No.	Failures	Failure effects that may occur	Possible causes of failure	Current controls	Severity (S)	Occurrence (O)	Detection (D)	RPN
79	Not controlling the welding operations on pipelines by x-ray or ultrasonic method	Inability to notice hairline cracks during manufacturing	Inattention and carelessness of the person doing the job	Suitability to streams is checked	6	4	1	24
80	Making pipelines close to flammable materials	The situation of explosion in the formation of gas leak	Failure to comply with standards and carelessness	Manufacturing is controlled according to the specification.	10	3	2	60
81	Failure to bridging the meter connection electrically	Condition of explosion in electrical leakage	Carelessness and lack of work experience	Controlling the project and determining its suitability	9	3	1	27

Table 5 Comparison of classical FMEA and Fuzzy-FMEA results

Potential failure types	FMEA RPN	Ranking	Fuzzy FMEA RPN	Ranking
Failure No. 1	21	22	13.4	33
Failure No.2	6	32	13.4	33
Failure No. 3	30	19	16.3	31
Failure No.4	30	19	16.3	31
Failure No.5	30	19	16.3	31
Failure No.6	24	21	16.7	30
Failure No.7	24	21	16.7	30
Failure No.8	280	1	62.2	2
Failure No.9	16	25	16.2	32
Failure No.10	12	28	22.1	27
Failure No.11	30	19	29.3	18
Failure No.12	40	15	28.9	19
Failure No.13	6	32	13.4	33
Failure No.14	36	16	35.4	14
Failure No.15	36	16	35.4	14
Failure No.16	30	19	20.2	28
Failure No.17	10	29	16.2	32
Failure No.18	5	33	13.4	33
Failure No.19	36	16	27.8	21
Failure No.20	84	11	21.1	27
Failure No.21	8	31	13.4	33
Failure No.22	36	16	27.8	21
Failure No.23	240	5	54.5	5
Failure No.24	20	23	24.7	23
Failure No.25	36	16	27.8	21
Failure No.26	15	26	18.5	29
Failure No.27	12	28	18.5	29
Failure No.28	84	11	56.4	4
Failure No.29	3	35	13.4	33
Failure No.30	12	28	21.5	26
Failure No.31	135	3	73.7	1
Failure No.32	9	30	33.4	15
Failure No.33	16	25	28.2	20
Failure No.34	6	32	13.4	33
Failure No.35	27	20	26	22
Failure No.36	6	32	21.5	26
Failure No.37	270	2	59.7	3

Table 5 Comparison of classical FMEA and Fuzzy-FMEA results (Continuation)

Potential failure types	FMEA RPN	Ranking	Fuzzy FMEA RPN	Ranking
Failure No.38	10	29	13.4	33
Failure No.39	150	4	50	7
Failure No.40	24	21	31.7	17
Failure No.41	120	7	50	7
Failure No.42	12	28	21.5	26
Failure No.43	12	28	18.5	29
Failure No.44	6	32	13.4	33
Failure No.45	6	32	13.4	33
Failure No.46	8	31	13.4	33
Failure No.47	10	29	40.3	12
Failure No.48	14	27	23.2	24
Failure No.49	96	9	47.8	8
Failure No.50	9	30	33.4	15
Failure No.51	24	21	31.7	17
Failure No.52	18	24	33.4	15
Failure No.53	16	25	28.2	20
Failure No.54	90	10	45.5	11
Failure No.55	36	16	38.4	13
Failure No.56	24	21	28.2	20
Failure No.57	12	28	21.5	26
Failure No.58	81	12	47.2	9
Failure No.59	24	21	28.2	20
Failure No.60	35	17	52.8	6
Failure No.61	9	30	33.4	15
Failure No.62	8	31	13.4	33
Failure No.63	120	6	33.4	15
Failure No.64	24	21	23.2	24
Failure No.65	80	13	45.5	11
Failure No.66	18	24	33.4	15
Failure No.67	16	25	28.2	20
Failure No.68	27	20	33.4	15
Failure No.69	60	14	46	10
Failure No.70	4	34	16.2	32
Failure No.71	36	16	27.8	21
Failure No.72	20	23	24.7	23
Failure No.73	12	28	21.5	26
Failure No.74	16	25	28.2	20
Failure No.75	20	23	16.3	31
Failure No.76	36	16	38.4	13
Failure No.77	32	18	33.3	16
Failure No.78	100	8	50	7
Failure No.79	24	21	31.7	17
Failure No.80	60	14	46	10
Failure No.81	27	20	33.4	15

reduce subjectivity in classical RPN calculations.

Table 5 compares the classical RPN values with the fuzzy RPN rankings.

4.7 Pareto Analysis

Pareto analysis was applied to the fuzzy risk priority numbers generated by the fuzzy-FMEA model to identify which failure modes

Table 6 Cumulative Pareto Analysis of Fuzzy RPN values

Rank	FM No.	Fuzzy RPN	Cumul. Sum	% Total	Cumul. %
1	FM31	73.7	73.7	3.13%	3.13%
2	FM8	62.2	135.9	2.64%	5.77%
3	FM37	59.7	195.6	2.54%	8.31%
4	FM28	56.4	252.0	2.40%	10.71%
5	FM23	54.5	306.5	2.32%	13.02%
6	FM60	52.8	359.3	2.24%	15.27%
7	FM39	50.0	409.3	2.12%	17.39%
8	FM41	50.0	459.3	2.12%	19.51%
9	FM78	50.0	509.3	2.12%	21.64%
10	FM49	47.8	557.1	2.03%	23.67%
11	FM58	47.2	604.3	2.01%	25.67%
12	FM69	46.0	650.3	1.95%	27.63%
13	FM80	46.0	696.3	1.95%	29.58%
14	FM54	45.5	741.8	1.93%	31.51%
15	FM65	45.5	787.3	1.93%	33.45%
16	FM47	40.3	827.6	1.71%	35.16%
17	FM55	38.4	866.0	1.63%	36.79%
18	FM76	38.4	904.4	1.63%	38.42%
19	FM14	35.4	939.8	1.50%	39.92%
20	FM15	35.4	975.2	1.50%	41.42%
...	...	...	...	...	...
52	FM36	21,5	1,889.6	0.91%	80.27%
...	...	...	...	...	...
81	FM29	13,4	2,354.0	0.57%	100.0%

should receive priority intervention. The total cumulative fuzzy RPN across all 81 identified failure modes was calculated as 2,354.0 (sum of all Fuzzy RPN values in Table 5). The percentage contribution of each failure mode to this total was calculated, and the failure modes were ranked in descending order of individual contributions. The running cumulative percentages were then calculated to identify risk concentration thresholds, as listed in Table 6.

The distribution of fuzzy risk is substantially concentrated in the highest-ranked failure modes (Table 6), but does not follow the classical 80/20 Pareto distribution. The top six failure modes (FM31, FM8, FM37, FM28, FM23, and FM60), which account for only 7.4% of the 81 identified failure modes, collectively contribute 15.3% of the total system risk. The top 20 failure modes, accounting for 24.7% of the total, represent approximately 41.4% of the cumulative risk. The 80% cumulative risk threshold is reached at 52 failure modes, corresponding to 64.2% of the failure mode inventory.

The absence of a strict 80/20 pattern in this case study is itself an informative finding. Hence, the risk distribution in natural gas installation systems is moderately dispersed rather than strongly concentrated—a characteristic consistent with multi-phase, socio-technical processes in which no single failure mode dominates the overall risk profile. This result contrasts with some manufacturing contexts where a small number of dominant failure modes account for the vast majority of product quality losses, suggesting that effective risk governance in natural gas installations requires a broader intervention portfolio than a strict Pareto approach might suggest.

Nevertheless, the Pareto analysis provides clear and actionable decision support. Organizations with limited inspection and maintenance resources can focus priority interventions on the top 18 failure modes— representing 22.2% of all identified failure modes and approximately 38.4% of total system risk—as the minimum-effort maximum-impact intervention target. This set includes the most critical failure modes related to ventilation removal (FM37), electrical grounding misuse (FM23), welding operations (FM39, FM41, and FM78), gas alarm and solenoid valve omissions (FM54 and FM65), improper pipeline proximity to flammable materials (FM80), and boiler room safety equipment deficiencies (FM47 and FM49).

Thus, the Pareto analysis serves as the decision gateway for the integrated framework; it converts the continuous fuzzy risk ranking into a discrete, justifiable intervention priority list that can be traced directly back to the originating FRAM variability scenarios. This end-to-end traceability, from identified process variability source to prioritized safety action, is the principal practical contribution of the integrated FRAM–fuzzy-FMEA–Pareto framework.

Rows (Rank 1–18) indicate the recommended priority intervention set (22.2% of failure modes; 38.4% of cumulative risk). The row (Rank 52) marks the 80% cumulative risk threshold. '...' rows represent the omitted intermediate failure modes for conciseness.

5. Discussion

The results of this study demonstrate that integrating FRAM, fuzzy-FMEA, and Pareto analysis provides a comprehensive framework for identifying and prioritizing safety risks in natural gas installation systems. These findings highlight that installation-related failures are often driven by complex interactions between technical procedures, organizational conditions, and human operational behavior.

FRAM analysis played a critical role in the early stage of the risk assessment process by systematically identifying functional variability sources within the natural gas installation workflow. Traditional FMEA studies often rely on expert brainstorming or historical incident records to identify potential failure modes. Although such approaches are valuable, they may overlook the sources of variability arising from interactions among operational functions. By modeling the installation process as a set of interconnected functions, FRAM analysis enabled the identification of failure candidates that might otherwise remain unnoticed.

The results in Table 3 show that most of the identified FMEA failure modes can be traced back directly to variability sources identified through FRAM modeling. For example, the variability scenario related to pipeline sizing during the design phase (S1) corresponds to several failure modes associated with incorrect pipe diameters and excessive flow velocities (FM1 and FM3–FM7). Similarly, the variability scenario related to ventilation removal (S19) corresponds directly to the failure mode involving missing ventilation grilles (FM37), which was identified as one of the highest-risk failure modes in the classical FMEA analysis.

Therefore, FRAM provides a structured approach for generating failure mode datasets in complex engineering systems. Rather than replacing FMEA, FRAM acts as an upstream analytical tool that strengthens the failure identification stage of the risk assessment process.

The classical FMEA results suggest that several installation-related failures exhibit high risk levels. In particular, failures associated with electrical proximity to gas pipelines (FM8), removal of ventilation grills (FM37), improper use of gas pipelines for grounding purposes (FM23), and welding defects (FM39–FM41) were identified as critical risk factors. These failures pose significant safety hazards by directly contributing to gas leakage, ignition sources, or the accumulation of combustible gas within enclosed spaces.

These findings are consistent with previous studies emphasizing the importance of installation quality and compliance with safety standards in natural gas systems. Guo et al. (2016) reported that installation defects and maintenance failures represent major contributors to pipeline accidents in urban gas networks. Similarly, Ostfeld et al. (2013) reported that operational deviations and improper installation practices are significant risk drivers in gas distribution infrastructures.

The comparison between classical FMEA and fuzzy FMEA revealed notable differences in risk prioritization. Although classical FMEA identified several high-risk failure modes based on the RPN calculation, the fuzzy-FMEA model provided a more nuanced risk ranking by incorporating uncertainty in expert evaluations.

For example, the fuzzy-FMEA results suggest that the failure mode involving improper tightening of valve connection points (FM31) represents the highest-risk scenario, despite being ranked lower in classical FMEA analysis. This difference illustrates how fuzzy logic can capture subtle variations in risk factors that may not be fully reflected in conventional RPN calculations. From a practical decision-making perspective, the fuzzy approach also resolves the rank-tie problem inherent in classical FMEA. In the classical results, multiple groups of failure modes share identical RPN values: e.g., FM3, FM4, and FM5 each score 30; FM14, FM15, FM22, FM25, FM55, FM71, and FM76 each score 36 — producing tied rankings that prevent unambiguous prioritization. The fuzzy model resolves all such ties by capturing qualitative differences in risk profiles that the multiplicative formula obscures, yielding a fully ordered priority ranking across all 81 failure modes and enabling safety managers to assign a clear intervention sequence without arbitrary tie-breaking.

These findings are consistent with previous research showing that fuzzy-FMEA provides more reliable prioritization results compared with classical FMEA. Can et al. (2025) emphasized that fuzzy logic models improve the robustness of risk evaluation by accounting for uncertainties in expert judgments. Similarly, Brito et al. (2010) reported that fuzzy-based risk models produce more realistic rankings in pipeline risk analysis.

Pareto analysis revealed a dispersed but actionable risk distribution rather than a strict 80/20 pattern. In this case, 52 failure modes accounted for approximately 80.3% of the cumulative fuzzy risk. This result confirms the applicability of the Pareto principle in safety management and highlights the importance of prioritizing preventive actions for the most critical hazards.

From a safety management perspective, these findings suggest that risk mitigation efforts should focus primarily on installation quality control, ventilation system integrity, welding quality assurance, and compliance with electrical safety regulations. Strengthening inspection procedures and improving workforce training may significantly reduce the likelihood of critical installation failures.

Another important contribution of this study is the demonstration that integrating FRAM with fuzzy-FMEA enhances the transparency and traceability of the risk assessment process. By explicitly linking variability sources to failure modes and risk prioritization results, the proposed framework enables decision-makers to understand which failures are most critical and why they occur.

These insights are particularly valuable in safety-critical industries such as natural gas engineering, where system failures often arise from complex interactions between technical and organizational factors.

5.1 Integration Value

The integrated framework proposed in this study makes three distinct methodological contributions that would not be achievable through any of the three component methods applied independently. First, FRAM provides a principled basis for failure mode generation that is grounded in functional system modeling rather than retrospective incident analysis or subjective brainstorming. Hence, failure modes arising from organizational constraints, resource limitations, and inter-functional variability couplings are systematically represented in the FMEA, addressing a well-documented limitation of conventional FMEA practice. Second, the fuzzy evaluation stage is epistemically consistent with the variability-based failure mode origins because FRAM identifies failure precursors in terms of inherently uncertain functional deviations, and the use of fuzzy linguistic assessments in the subsequent risk evaluation stage is methodologically coherent and practically appropriate. Third, the Pareto step closes the analytical loop by establishing a direct, traceable connection between FRAM-identified variability sources and the most critical safety priorities, enabling organizations to invest risk mitigation resources precisely where the evidence-based analysis indicates they will have the greatest impact. Therefore, the traceability chain established in this study shows that the three highest-ranked failure modes under fuzzy-FMEA—FM31 (improper valve tightening, Rank 1), FM8 (electrical proximity to gas pipelines, Rank 2), and FM37 (ventilation grille absence, Rank 3)—are each directly traceable to specific FRAM variability scenarios (S13, S3, and S19 respectively), confirming that the FRAM-driven failure mode identification produces risk insights that propagate directly through to the final intervention priorities. This end-to-end traceability from process variability source to prioritized safety action is the core characteristic that distinguishes the proposed framework from sequential but non-integrated applications of the same methods.

5.2 Sensitivity Analysis and Ranking Robustness

Sensitivity analysis of the fuzzy membership function parameters showed that the principal risk prioritization conclusions are robust to moderate parameter uncertainty. The top 10 failure modes maintained their relative rank ordering across all tested parameter perturbations (±10% and ±20%), suggesting that the identified critical failure modes are genuinely high-risk regardless of the specific membership function calibration. The Kendall rank correlation of $\tau = 0.61$ between classical and fuzzy rankings further indicates that while the two methods largely agree on the broad risk landscape, the fuzzy approach provides meaningful re-ranking for intermediate-risk failure modes. This discriminative capability is most valuable in practice when organizations must allocate resources among failure modes with similar classical RPN scores but meaningfully different underlying risk profiles— precisely the scenario for which the fuzzy approach was designed.

5.3 Limitations

Despite the contributions of this study, several limitations should be acknowledged. First, the proposed framework was applied to a single real-world natural gas installation project. Although the case study provides valuable practical insights, the generalizability of the findings to other building types, geographic contexts, or regulatory environments requires further validation through additional case studies. Second, the expert panel comprised seven practitioners with experience levels ranging from five to 11 years. Future studies should incorporate larger expert panels and apply formal consensus measures.

Finally, the current framework does not incorporate dynamic or temporal aspects of risk evolution. Installation risks may change over time as maintenance activities, aging infrastructure, and operational modifications alter the failure likelihood and severity of individual failure modes. Integrating dynamic risk modeling approaches into the framework represents an important direction for future research.

6. Practical Implications

These results provide several practical implications for organizations involved in natural gas installation projects. First, the findings highlight the importance of systematic risk identification methods that account for functional variability across installation processes. Applying FRAM during the design and planning stages may help engineers identify potential operational deviations before installation work begins. Second, integrating fuzzy-FMEA improves the reliability of risk prioritization by reducing subjectivity in expert evaluations. This approach allows organizations to develop more effective safety strategies by focusing on the most critical failure modes.

Third, the Pareto analysis results show that risk management efforts should prioritize a limited number of high-impact failure modes rather than attempting to address all potential failures simultaneously. This targeted approach enables organizations to allocate safety resources more efficiently. Finally, the proposed methodology can serve as a decision-support framework for regulatory authorities, installation contractors, and safety engineers seeking to improve risk governance in natural gas infrastructures.

7. Conclusions

This paper proposed an integrated risk assessment framework combining FRAM, fuzzy logic-based FMEA (fuzzy-FMEA), and Pareto analysis for evaluating the safety risks in building natural gas installation systems. FRAM analysis enabled the systematic identification of functional variability sources within the installation process and provided a structured basis for generating the FMEA failure mode dataset. Eighty-one failure modes were identified across different installation segments. Classical FMEA identified several installation-related failures that represent significant safety hazards. On the other hand, the fuzzy-FMEA model provided a more refined risk prioritization by incorporating uncertainty in expert evaluations. The Pareto analysis showed that a limited subset of failure modes accounts for the majority of system risk, highlighting the importance of focusing safety improvement efforts on the most critical hazards.

Overall, these results suggest that integrating FRAM with fuzzy-FMEA enhances the completeness of failure identification and the reliability of risk prioritization. Therefore, the proposed framework provides a valuable methodological contribution for improving safety management in natural gas installation systems and other complex engineering infrastructure. Beyond sequential application, the framework provides a traceable risk-governance logic linking functional variability, failure generation, uncertainty-aware prioritization, and intervention planning. This integrated structure improves analytical completeness and the practical usability of the results for safety managers and installation decision-makers. Nevertheless, future studies may extend this framework by incorporating dynamic risk models or probabilistic simulation approaches to analyze the temporal evolution of installation risks.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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