engineering proceedings

MDPI

Proceeding Paper

Operational Risk Analysis on Gas Distribution Process at PT—Perta Daya Gas Using FMECA Method †

Mirga Maulana Rachmadhani *, Mardhiah Gani, Jihan Muhrifa Faradillah, Asih Ahistasari and Irman Amri

Department of Industrial Engineering, Universitas Muhammadiyah Sorong, Sorong 98416, Indonesia; mardhiah@um-sorong.ac.id (M.G.); jihan.muhrifa@gmail.com (J.M.F.); asih@um-sorong.ac.id (A.A.); irmanamri@um-sorong.ac.id (I.A.)

* Correspondence: mirga@um-sorong.ac.id; Tel.: +62-81240591616

† Presented at the 9th Mechanical Engineering, Science and Technology International Conference (MEST 2025), Samarinda, Indonesia, 11–12 December 2025.

Abstract

This research identified and analyzed 30 valid operational risks out of 32 risks using the FMECA method. Four priority risks (R28, R1, R7, R9) were analyzed using a Fish-bone diagram to identify root causes. Mitigation strategies included technical aspects, operator competency enhancement, inspections, early warning systems, strengthened SOPs, and environmental controls. The evaluation results showed that there was a re-duction in RPN values of more than 75%, indicating the effectiveness of mitigation in reducing risks. The combination of FMECA and Fishbone has proven effective in da-ta-driven risk control mapping, analysis, and evaluation.

Keywords: fishbone; FMECA; operational risk; risk management; risk mitigation

1. Introduction

Natural gas distribution is a crucial component of the national energy system due to its role as a relatively clean and efficient transitional energy source [1–3]. Natural gas supports the operation of vital sectors such as power generation, manufacturing, and transportation, while contributing to the achievement of the government's decarbonization targets [4–6]. Risk management is an approach used to identify and manage uncertainty factors in an activity or process with the aim of achieving optimal levels of productivity, while minimizing the impact of undesirable factors [7–10].

Gas distribution through high-pressure pipelines cannot be separated from various potential technical and non-technical risks that can disrupt the continuity of supply [11–13]. These risks may stem from equipment failure, material degradation, external disturbances, or limitations of monitoring systems [14–18]. Therefore, the implementation of risk management based on international standards is essential to identify, assess, and control potential failures that can impact safety, system reliability, and operational efficiency [19–23]. The specific international standards are aligning with ISO 31000 about principal and guide-line risk management. Then, continue by mapping using FMECA as a method used for risk management, in line with ISO 31010:2019 on Risk Assessment. This standard was developed from ISO 31000:2018 on the principles and guidelines of risk management. The standard used is ISO 31000 regarding the principles and guidelines for risk management. Regarding FMECA parameters and the evaluation of risk mitigation measures, it refers to ISO 31010 regarding Risk Assessment. Therefore, the steps required in the risk assessment process using FMECA and the evaluation of risk mitigation are outlined in ISO 31010.

Check for updates

Academic Editors: Rusandi Noor, Sigiet Haryo Pranoto, Arbansyah, Sarjito, Waluyo Adi Siswanto, Agus Dwi Anggono and Taghfirul Azhima Yoga Siswa

Published: 22 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

PT Perta Daya Gas Sorong Gas Pipeline Unit manages the gas distribution process from PT Malamoi Olom Wobok (MOW) to the 50 MW Mobile Power Plant (MPP) in Sorong through a 3.7 km long underground pipeline with a depth of 1.5 m. The system delivers up to 8000 MSCM of gas per day, which in operation is exposed to a number of risks such as pipeline leakage due to corrosion, valve failure, and limited real-time monitoring of pressure and temperature parameters.

Based on the initial identification, there were 32 potential risks that could disrupt the smooth distribution of gas. However, after a more in-depth review, only 30 risks were taken as the focus of the analysis because the other 2 risks have similar meanings to the identified risks, so they are considered representative. It defines "similar risks" here based on subjective assessments by experts. Experts state that these two eliminated risks have the same significance and characteristics as the other two risks. Thus, this is an initiative to avoid duplicating the identification of the same risks, according to the experts. From the 30 risks, 62% were categorized as having a very high impact on work safety and operational stability. This condition shows the urgency of implementing a thorough and structured risk analysis, to obtain the right mitigation priorities and reduce the possibility of adverse incidents.

This research aims to analyze and mitigate risks in the gas distribution process at PT. Perta Daya Gas Sorong Gas Pipeline Unit by using the Failure Modes, Effects, and Criticality Analysis (FMECA) method and Fishbone diagram analysis. The main contribution of this research is the reassessment of risks after the implementation of mitigation, which is rarely discussed in previous studies. This is expected to provide a basis for more effective decision-making in the gas distribution risk management system.

2. Methods

This research uses a descriptive approach with the Failure Modes, Effects, and Criticality Analysis (FMECA) method to identify potential risks, evaluate, and prioritize risks in gas distribution at PT Perta Daya Gas Sorong Gas Pipeline Unit. The data used in this research consists of primary data and secondary data [24–27]. Primary data was obtained through field observations, structured interviews, and questionnaires from Operations Supervisors who understand gas distribution techniques [28–31]. The questionnaire assessed the three main FMECA parameters of severity (S), occurrence (O), and detection (D) [32,33]. Secondary data came from internal documents, technical reports, SOPs, and the gas industry risk management literature [22,24]. Furthermore, the number of experts involved was an expert for final validation and five operators who were interviewed, each representing their respective fields. The evaluation results were consistently assessed inter-rater agreement. This is objective because the assessments of Severity, Frequency, and Detection reflect the facts on the field. Each FMECA parameter is assessed based on specific criteria. Severity (S) measures the impact of the risk on safety and operational continuity. Occurrence (O) assesses the frequency of failure based on historical data. Detection (D) measures the ability of the system to detect the risk before the failure occurs [3,7,10]. The analysis technique in this research was carried out in several systematic stages:

a. Risk identification based on the results of observations, interviews, and questionnaires;
b. Initial risk assessment based on 3 FMECA parameters and calculating the Risk Priority Number (RPN);
c. Criticality level analysis to determine high-priority risks;
d. Risk mapping based on severity and occurrence values;
e. Root cause analysis using a Fishbone diagram to prioritize risks;
f. Recommendations for mitigation actions based on the results of the Fishbone diagram Analysis;

https://doi.org/10.3390/engproc2026137025

g. Reassessment after mitigation is carried out by recalculating the RPN value to determine the percentage of risk reduction and evaluate the effectiveness of mitigation actions that have been implemented. Reassessment is conducted after mitigation measures have been implemented to determine whether the RPN value for the identified risk remains high in terms of severity. This is done because the FMECA method uses the RPN value as the primary factor in assessing risk. The KPIs in question are already included in the FMECA matrix, which is divided into the categories of severity (S), occurrence (O), and detection (D).

The assessment criteria for each FMECA parameter are organized systematically and presented in Tables 1–5 and Figures 1 and 2:

Table 1. Severity score.

Category	Description	Rating
Very Fatal	Causing major losses, serious accidents, or halting all operations.	10
Fatal	Resulting in major damage, serious injury, or disruption of key operations.	9
Very Serious	Causing significant damage or having a major impact on safety and the environment.	8
Serious	Causing moderate damage or disruption to critical systems, but still controllable.	7
Quite Serious	Disrupting some operations, but recoverable without long-term impact.	6
Moderate	Limited impact, affecting only a small part of the process or system.	5
Mild	Causing minor disruptions, without damaging the system or posing a hazard.	4
Very Mild	Very minor impact, not affecting operational smoothness.	3
Almost None	Impact is barely noticeable, causing no disruptions.	2
None	No impact at all, not affecting the system or safety.	1

Source: Ref. [34].

Table 2. Occurrence score.

Category	Description	Rating
Almost Certain	Very likely to occur in the near future based on current conditions.	10
Very High	Highly likely to occur if repairs or controls are not carried out immediately.	9
High	Quite likely to occur in the near future if conditions are left unaddressed.	8
Somewhat High	Possible to occur in the next 1–2 years if surveillance or maintenance is not improved.	7
Moderate	Possible, but only under certain conditions or in less controlled situations.	6
Low	It is unlikely to occur, but still possible if no additional preventive measures are taken.	5
Very Low	It is very rare, only possible if several abnormal conditions occur simultaneously.	4
Almost Never	It is highly unlikely to occur, only possible if there is a major failure or an extremely unusual situation.	3
Never	It is almost impossible to occur under current working and operational conditions.	2
Did Not Occur	It is impossible to occur because it has been prevented or completely eliminated from the system.	1

Source: Ref. [34].

Table 3. Detection score.

Category	Description	Rating
Very Difficult to Detect	Almost impossible to detect before failure occurs.	10
Difficult to Detect	Very unlikely to be detected before it occurs.	9
Low Probability of Detection	Usually not detected until failure occurs.	8
Low Detection	Tends not to be detected by normal systems.	7
Slightly Monitored	May be detected by manual inspection or indirect signs.	6
Fairly Detectable	May be detected before it occurs, if routine monitoring is performed.	5
Frequently Detected	Often detected by control systems or field indicators.	4
Easy to Detect	Generally detected immediately by monitoring devices or standard procedures.	3
Very Easy to Detect	Very easy to recognize and prevent before it has an impact.	2
Certainly Detected	Certainly detected before it occurs because it is protected by automatic systems or alarms.	1

Source: Ref. [34].

$$RPN = Severity \times Occurrence \times Detection \quad (1)$$

$$\text{Percentage Decrease in } RPN = \frac{RPN\ Before - RPN\ After}{RPN\ Before} \times 100\% \quad (2)$$

Table 4. Criticality level.

Critically		Risk Acceptance
Criticallity Level	**Range Score RPN**	
Very Low	0–30	The risk is acceptable without corrective action.
Low	31–60	The risk is sufficiently controlled, but further monitoring and evaluation are needed.
Moderate	61–180	The risk is still within reasonable limits without the need for special mitigation measures.
High	181–252	The risk is serious and requires immediate corrective action to prevent greater impact.
Critical	253–324	The risk is extremely dangerous and must be addressed immediately to avoid adverse consequences.
Very Critical	>324	The risk is extreme and unacceptable, requiring immediate corrective action to avoid major failure or disaster.

Source: Ref. [34].

Table 5. Risk Map Scale.

Risk Category	Risk Scale	Description	Color
Unacceptable Risk	45–100	The risk is very high and unacceptable. It must be controlled immediately.	
Tolerable Risk	7–48	The risk is still acceptable, but additional evaluation and control are needed.	
Acceptable Risk	1–20	The risk is low and acceptable. Periodic monitoring is sufficient.	

Source: Ref. [17].

Risk Matrix		Severity									
		1	2	3	4	5	6	7	8	9	10
Occurrence	10	10	20	30	40	50	60	70	80	90	100
	9	9	18	27	36	45	54	63	72	81	90
	8	8	16	24	32	40	48	56	64	72	80
	7	7	14	21	28	35	42	49	56	63	70
	6	6	12	18	24	30	36	42	48	54	60
	5	5	10	15	20	25	30	35	40	45	50
	4	4	8	12	16	20	24	28	32	36	40
	3	3	6	9	12	15	18	21	24	27	30
	2	2	4	6	8	10	12	14	16	18	20
	1	1	2	3	4	5	6	7	8	9	10

Figure 1. Risk matrix 10 × 10 (source: Ref. [17]).

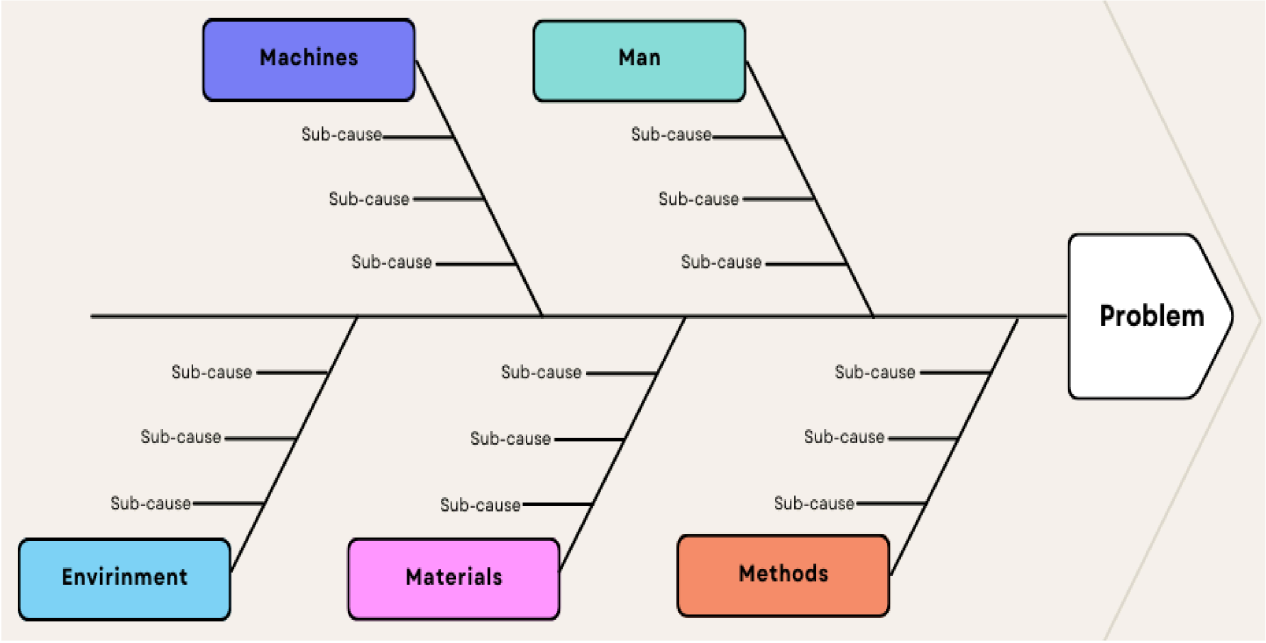


Figure 2. Fishbone diagram (Ishikawa) (source: Ref. [17]).

3. Results and Discussion

In accordance with the stages described in the research Section 2, the results of the research conducted are presented below.

3.1. Risk Identification

Based 32. potential operational risks were identified through observation and interviews, which were then validated to ensure their relevance to the conditions in the field. Interviews were conducted with five operators from different fields to compile a list of potential risks. The identified risks were then validated in consultation with experts in this case, operational supervisors in the gas distribution sector, to ensure the validity of the risk list. The list of identified risks can be seen in Table 6.

Table 6. Risk Identification and Validation.

Risk Category	Risk Code	Possible Risks	Already Compliant (✓/×)
Operational	R1	Gas leaks due to corrosion or degradation of pipe materials	✓
	R2	Failure of gas leak detection systems (sensors not functioning or inaccurate)	✓
	R3	Failure of gas pressure control systems (valves and regulators)	✓
	R4	Human error in operating equipment	✓
	R5	Extreme environmental or natural factors (earthquakes, weather, floods, erosion, plant infestation)	✓
	R6	Damage caused by external activities (construction or industrial activities in the vicinity)	✓
	R7	Risk of fire or explosion due to gas leaks near electrical equipment	✓
	R8	Non-compliance with industrial gas safety regulations	✓
	R9	Damage to portable fire extinguishers (APAR)	✓
	R10	Power outage due to external disruptions	✓
	R11	Use of substandard pipe materials	✓
	R12	Workplace accidents due to procedural errors or negligence	×
	R13	Security breaches or sabotage of gas infrastructure	✓
	R14	Improper handling of hazardous materials	✓
	R15	Logistics and transportation issues	✓
	R16	Obsolete technology impacting operational efficiency and safety	✓
	R17	Failure in emergency response planning	✓
	R18	Health and safety risks to workers due to exposure to hazardous materials or the work environment	✓
	R19	Non-compliance with standard operating procedures	✓
	R20	Unstable gas pressure fluctuations	✓
	R21	Dependence on a single gas supplier	✓
	R22	Gas supply shortages from the main source	✓
	R23	Gas contamination due to foreign substances entering the distribution process	✓
	R24	Communication disruptions in gas distribution operations	✓
	R25	Gas pressure monitoring system failure (inaccurate pressure sensors or unresponsive systems)	✓
	R26	Disruption to the cathodic protection system of gas pipes	✓
	R27	Risk of leakage due to excessive pressure in pipes	✓
	R28	Risk of disruption due to backpressure in the distribution system	✓
	R29	Mechanical damage to valves due to high operational pressure	✓
	R30	Decline in gas quality due to excessive condensation in pipes	✓
	R31	Risk of hazardous substance spills during facility maintenance	✓
	R32	Disruption due to vibration and ground shifting along the pipeline route	×

Source: Data collection results.

Some risks were deemed unacceptable because they overlapped with other more representative risks. Risk R12 was considered similar to R4 because both were related to human error, while R32 was covered by R5 and R6, which addressed environmental impacts and external activities. Experts state that these two eliminated risks have the same significance and characteristics as the other two risks. Thus, this is an initiative to avoid duplicating the identification of the same risks, according to the experts. From the 30 risks, 62% were categorized as having a very high impact on work safety and operational stability.

3.2. Risk Assessment

After identifying and validating the 32 existing risks, only 30 risks were accepted to proceed to the assessment stage using a questionnaire taken by experts from PT. Perta Daya Gas Unit Gas Pipeline Sorong, considering three main parameters: severity (S), occurrence (O), and detection (D). Each parameter was assessed on a scale of 1 to 10, and these values were used to calculate the Risk Priority Number (RPN) using the following formula: RPN = S × O × D. The use of these multiplicate models is based on the FMECA method in finding out RPN. The assessment results are presented in Table 7.

Table 7. Risk assessment and RPN calculation.

Code	Risk	(S)	(O)	(D)	RPN
R1	Gas leaks due to corrosion or degradation of pipe materials	10	5	5	250
R2	Failure of gas leak detection systems (sensors not functioning or inaccurate)	8	5	4	160
R3	Failure of gas pressure control systems (valves and regulators)	8	5	3	120
R4	Human error in operating equipment	6	4	2	48
R5	Extreme environmental or natural factors (earthquakes, weather, floods, erosion, plant infestation)	8	4	3	96
R6	Damage due to external activities (construction or industrial activities in the vicinity)	7	4	4	112
R7	Risk of fire or explosion due to gas leaks	9	5	5	225
R8	Non-compliance with industrial gas safety regulations	6	4	3	72
R9	Damage to fire extinguishers (APAR)	9	6	4	216
R10	Power outages due to external disturbances	4	4	3	48
R11	Use of pipes that do not meet standards	8	5	3	120
R13	Security breaches or sabotage of gas infrastructure	7	5	2	70
R14	Improper handling of hazardous materials	6	4	2	48
R15	Logistics and transportation issues	6	3	2	36
R16	Obsolete technology affecting operational efficiency and safety	3	3	2	18
R17	Failure in emergency response planning	8	3	3	72
R18	Health and safety risks for workers due to exposure to hazardous materials or the work environment	6	4	3	72
R19	Non-compliance with standard operating procedures	6	4	3	72
R20	Unstable gas pressure fluctuations	5	5	3	75
R21	Reliance on a single gas supplier	7	4	3	84
R22	Shortage of gas supply from the main source	6	3	3	54
R23	Gas contamination due to foreign substances entering the distribution process	6	5	3	90
R24	Communication disruptions in gas distribution operations	4	3	2	24
R25	Failure of the gas pressure monitoring system (inaccurate pressure sensors or unresponsive systems)	5	3	3	45
R26	Disruptions in the cathodic protection system of gas pipelines	5	4	3	60
R27	Risk of leaks due to excessive pressure in pipelines	9	4	3	108
R28	Risk of disruptions due to backpressure in the distribution system	8	7	5	280
R29	Mechanical damage to valves due to high operational pressure	8	3	4	96
R30	Decreased gas quality due to excessive condensation in the pipeline	5	5	3	75
R31	Risk of hazardous substance spills during facility maintenance	5	4	3	60

3.3. Criticality Analysis

Based on the results of the Risk Priority Number (RPN) calculations in Table 7, Table 8 was compiled, presenting the RPN in descending order from highest to lowest. This table serves as the basis for conducting a criticality analysis, which aims to facilitate the identification of risks with the highest priority for handling, in accordance with the established criticality level. The results of the criticality analysis are presented in Table 8.

Table 8. Criticality analysis.

Code	Risk	(S)	(O)	(D)	RPN	Criticallity Level
R28	Risk of disruption due to backpressure in the distribution system	8	7	5	280	Critical
R1	Gas leaks due to corrosion or degradation of pipe materials	10	5	5	250	High
R7	Risk of fire or explosion due to gas leaks	9	5	5	225	High
R9	Damage to fire extinguishers (APAR)	9	6	4	216	High

Table 8. *Cont.*

Code	Risk	(S)	(O)	(D)	RPN	Criticallity Level
R2	Failure of gas leak detection systems (sensors not functioning or inaccurate)	8	5	4	160	Moderate
R3	Failure of gas pressure control systems (valves and regulators)	8	5	3	120	Moderate
R11	Use of non-standard pipe materials	8	5	3	120	Moderate
R6	Damage due to external activities (construction or industrial activities in the vicinity)	7	4	4	112	Moderate
R27	Risk of leaks due to excessive pressure in pipes	9	4	3	108	Moderate
R5	Extreme environmental or natural factors (earthquakes, weather, floods, erosion, plant infestation)	8	4	3	96	Moderate
R29	Mechanical damage to valves due to high operating pressure	8	3	4	96	Moderate
R23	Gas contamination due to the entry of foreign substances from the distribution process	6	5	3	90	Moderate
R21	Dependence on a single gas supplier	7	4	3	84	Moderate
R20	Unstable gas pressure fluctuations	5	5	3	75	Moderate
R30	Decline in gas quality due to excessive condensation in the pipeline	5	5	3	75	Moderate
R8	Non-compliance with gas industry safety regulations	6	4	3	72	Moderate
R17	Failure in emergency response planning	8	3	3	72	Moderate
R18	Health and safety risks for workers due to exposure to hazardous materials or working environments	6	4	3	72	Moderate
R19	Non-compliance with standard operating procedures	6	4	3	72	Moderate
R13	Security breaches or sabotage of gas infrastructure	7	5	2	70	Moderate
R26	Disruption to the cathodic protection system of gas pipelines	5	4	3	60	Low
R31	Risk of hazardous substance spills during facility maintenance	5	4	3	60	Low
R22	Shortage of gas supply from the main source	6	3	3	54	Low
R4	Human error in equipment operation	6	4	2	48	Low
R10	Power outage due to external disruption	4	4	3	48	Low
R14	Improper handling of hazardous materials	6	4	2	48	Low
R25	Failure of the gas pressure monitoring system (inaccurate pressure sensors or unresponsive system)	5	3	3	45	Low
R15	Logistics and transportation issues	6	3	2	36	Low
R24	Communication disruptions in gas distribution operations	4	3	2	24	Very Low
R16	Obsolete technology that impacts operational efficiency and safety	3	3	2	18	Very Low

3.4. Risk Map

Based on the results of the criticality analysis table, the risks with the highest Risk Priority Number (RPN) values are R28, R1, R7, and R9, which are classified as high priority and require immediate attention. To confirm the priority level based on severity and occurrence, risk mapping was carried out as shown in Figure 3.

Risk Matrix	Severity										
		1	2	3	4	5	6	7	8	9	10
Occurrence	10										
	9										
	8										
	7								R28		
	6									R9	
	5					R19,R29	R22	R12	R2,R3,R11	R7	R1
	4				R10	R25,R30	R4,R8,R13,R17,R18	R6,R20	R5	R26	
	3			R15	R23	R24	R14,R21		R16,R27		
	2										
	1										

Figure 3. Risk matrix results 10 × 10.

Furthermore, of the 30 identified risks, 4 are classified as high risk and require priority in risk mitigation. Meanwhile, the other risks are considered reasonable. The classification of risks is summarized in Table 4 in the Methods discussion.

3.5. Risk Evaluation with Root Cause Analysis (Fishbone)

To assess the four priority risks that have been identified, the Fishbone diagram method is used. This method aims to identify and analyze the main factors that cause each of these risks. The following is a Fishbone diagram in Figures 4–7 that illustrates the main causes of each priority risk:

1. Fishbone Diagram of Risk Number 28

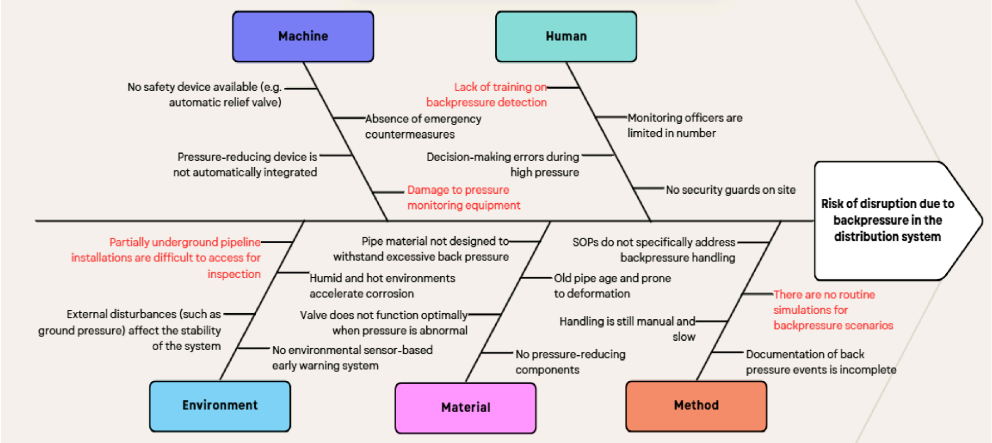


Figure 4. Fishbone diagram of risk number 28.

The results of the Fishbone diagram analysis related to the risk of disruption due to backpressure in the distribution system identified four main causes marked in red, namely: damage to pressure monitoring equipment (machinery), lack of training in backpressure detection (people), lack of routine simulations for backpressure (method), and underground pipes that are difficult to access for inspection (environment). These four main causes are prioritized in the development of risk mitigation strategies to ensure the reliability and safety of the gas distribution system.

2. Fishbone Diagram of Risk Number 1

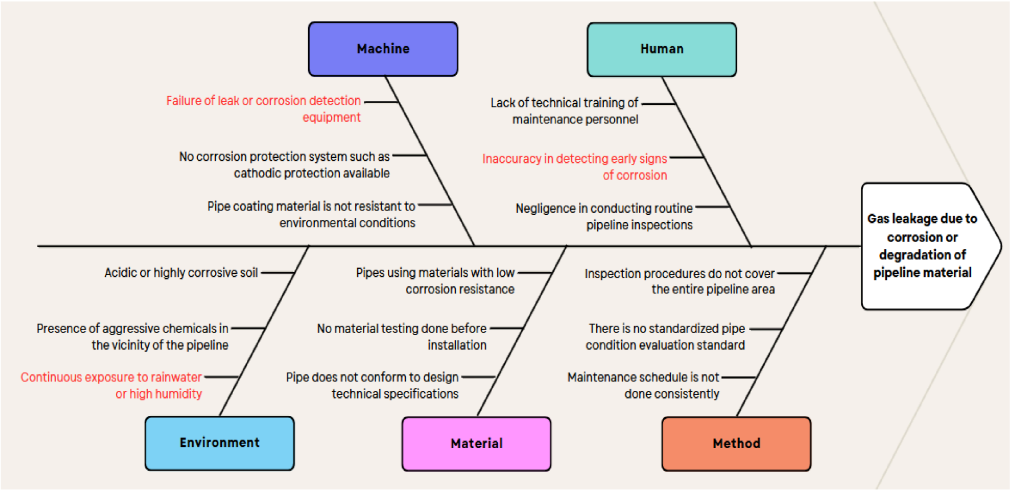


Figure 5. Fishbone diagram of risk number 1.

The results of the Fishbone diagram analysis related to the risk of gas leaks due to corrosion in distribution pipes show that there are three main causes that are the priority focus, namely: failure of leak or corrosion detection equipment (machinery), inaccuracy in detecting early signs of corrosion (human), and continuous exposure to rainwater or high humidity (environment). These three primary causes are prioritized in the development of risk mitigation strategies to prevent further damage and ensure the safety and reliability of the gas distribution system.

2. Fishbone Diagram of Risk Number 7

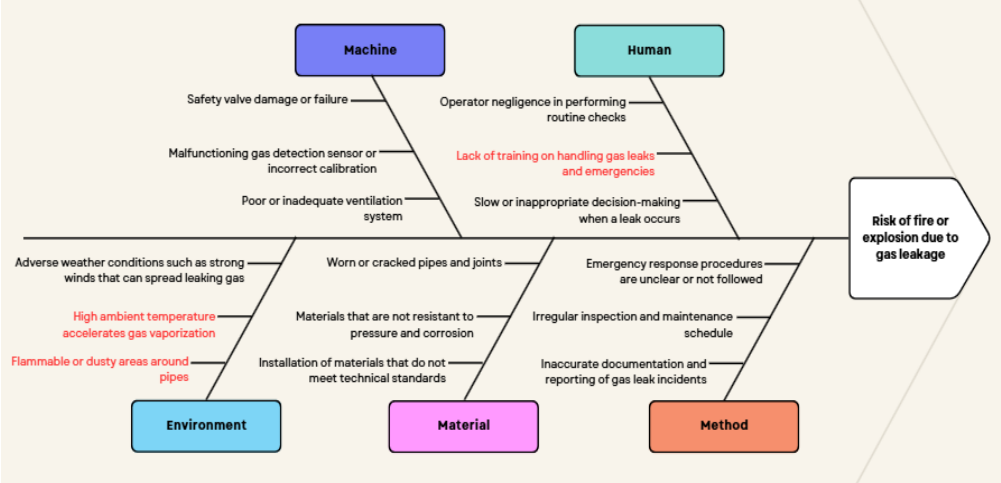


Figure 6. Fishbone diagram of risk number 7.

The analysis results show that the risk of fire or explosion due to gas leaks is mainly triggered by a lack of training in handling gas leaks and emergencies (human), high ambient temperatures that accelerate gas evaporation (environment), and areas around pipes that are flammable or dusty (environment). These three factors are the top priorities in developing mitigation strategies to prevent incidents and ensure the safety of the gas distribution system.

2. Fishbone Diagram of Risk Number 9

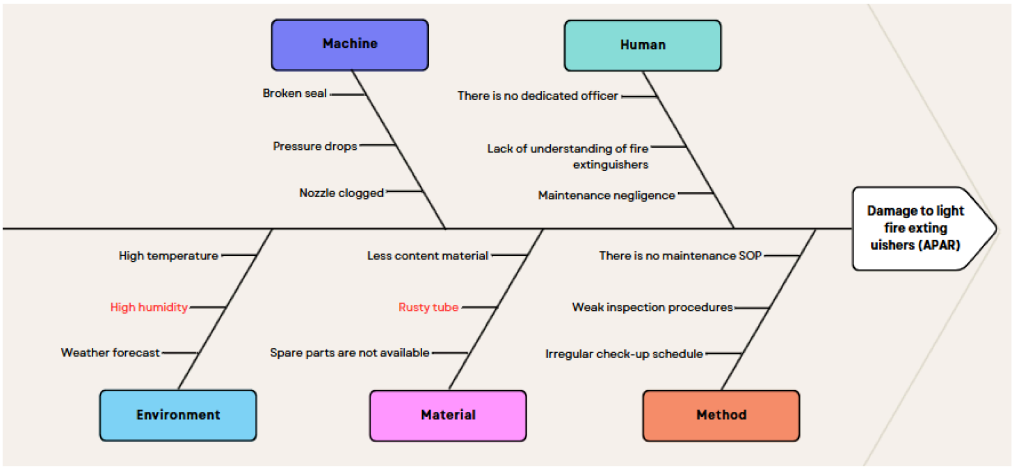


Figure 7. Fishbone diagram of risk number 9.

The results of the Fishbone diagram analysis related to the risk of damage to portable fire extinguishers (APAR) show two main causes divided into two factors. The first factor is the material aspect, namely the presence of rust on the APAR cylinder. The second factor

is the environmental aspect, which includes high humidity levels. Based on these two main causes, mitigation measures will be designed in the next stage.

3.6. Risk Mitigation

Based on the results of the Fishbone diagram analysis, each identified risk has causes and effects that can be addressed with appropriate mitigation strategies. Recommendations for mitigation strategies for each priority risk are presented in Tables 9 and 10.

Table 9. Mitigation strategies.

Code	Risk	Cause	Impact	Mitigation
R28	Disturbances caused by backpressure	Damage to pressure monitoring devices (Machinery)	Overpressure, pipe damage, gas flow stoppage	1. Calibration (comparison process) of pressure measuring instruments with SNI/ISO standards 2. Replacement of instruments if the results differ by more than 5% from the expected value 3. Procurement of instruments with automatic alarm and auto-shutdown features 4. Monthly performance audits of instruments based on inspection reports
		Lack of training in backpressure detection (People)	Operators failed to recognize backpressure symptoms early on	1. Intensive training based on real cases (case-based training) 2. Competency test for detecting abnormal pressure every 6 months 3. Direct supervision during critical shifts (peak hours) 4. Evaluation of training effectiveness through feedback and live simulations
		No routine simulation of backpressure scenarios (Methods)	Unprepared for sudden pressure surges	1. Backpressure scenario simulation with actual parameters (not just theory) 2. Review and revision of SOPs based on simulation results 3. HSE-Operator collaboration in simulation (not just a formality) 4. Documentation of simulation results as a reference for improvement
		Underground pipe installations are difficult to access for inspection (Environment)	Slow detection of abnormal pressure symptoms	1. Re-mapping of underground pipelines and addition of inspection access points 2. Utilization of smart pigging for internal pipeline detection 3. Installation of automatic pressure sensors at critical points 4. Physical and digital audit of underground pipeline conditions
R1	Gas leaks due to corrosion or degradation of pipe materials	Failure of leak or corrosion detection equipment (Machinery)	causing pipe damage and potential serious accidents	1. Perform routine calibration of Pressure Gauge (PG) and Pressure Transmitter (PT) 2. Conduct periodic inspections using portable Non-Destructive Testing (NDT) tools 3. Add simple pressure and flow monitoring as an early warning system 4. Perform routine visual checks at critical points
		Inaccuracy in detecting early signs of corrosion (Human)	Corrosion is not identified early, increasing the risk of gas leaks	1. Provide technical training related to corrosion identification for operators 2. Develop inspection guidelines in the form of checklists to facilitate field inspections 3. Implement a system of verification of logsheet completion by two officers 4. Conduct periodic evaluation and revision of inspection SOPs
		Continuous exposure to rainwater or high humidity (Environment)	Accelerating the corrosion process and damaging the pipe coating, thereby increasing the risk of leaks	1. Strengthening the coating of underground pipes with corrosion-resistant materials 2. Repairing and optimizing the drainage system around the pipeline 3. Conducting regular moisture monitoring in vulnerable areas 4. Carrying out the re-closure of excavated soil in accordance with standards to prevent water accumulation

Table 9. *Cont.*

Code	Risk	Cause	Impact	Mitigation
R7	Risk of fire or explosion due to gas leaks	Lack of training in leak and emergency response (Human)	Delayed or incorrect response, causing gas leaks to develop into fires or explosions.	1. Conduct regular training for all staff in handling gas leaks and emergencies. 2. Conduct emergency response simulations at least twice a year to improve preparedness. 3. Provide emergency response SOPs that are easily understood and accessed in every work area.
		High ambient temperatures accelerate gas evaporation (Environment)	Increased concentrations of flammable gases, increasing the risk of fire and explosion.	1. Install automatic temperature and gas sensors in vulnerable locations for early detection. 2. Conduct routine monitoring of environmental temperature, especially during summer. 3. Plant trees or shade plants around the pipeline area to lower surface temperatures and reduce gas evaporation.
		The area around the pipe is flammable or dusty (Environment)	Sparks caused by dust or flammable materials, triggering fires or explosions.	1. Routinely cleaning the area around the pipeline from dry vegetation and combustible dust. 2. Creating and maintaining a flammable material free zone of at least 3 m on both sides of the pipeline. 3. Placing fire extinguishers (APAR) at strategic points and conducting periodic checks
R9	Damage to light fire extinguishers (APAR)	Rust on the fire extinguisher tube (Material)	Pressure decreased, contents leaked, extinguisher failed to be used in an emergency	1. Visual inspection and physical checking of tubes every month 2. Repainting of scratched or corroded tubes 3. Replacement of fire extinguishers that are more than 5 years old 4. Store fire extinguishers in moisture-proof brackets / supports 5. Use the services of an experienced third party for APAR maintenance so that all tools remain in good condition and avoid rust.
		Environmental humidity is too high (Environment)	Rapid corrosion, mechanical parts damaged, label damaged	1. Installation of silica gel in the extinguisher storage room 2. Placement of fire extinguishers in locations with good air circulation 3. Avoid placement near outside walls or leaking areas 4. Monitoring room temperature and humidity every week

3.7. Control Analysis

After the mitigation strategies are designed on a limited basis or through simulation, a reassessment of the four prioritized risks is conducted using the same S, O, and D parameters as in the initial FMECA. The assessment involved PT Perta Daya Gas Sorong Gas Pipeline Unit experts to ensure the results reflect the effectiveness of the mitigation actions.

Table 10 presents a comparison of RPN values before and after mitigation, as an indicator of the success of mitigation in reducing risk levels.

Table 10. Comparison of RPN values before and after mitigation.

Code	Risk	Before Mitigation					After Mitigation					Percentage Decrease (%)
		(S)	(O)	(D)	RPN	Criticality Level	(S)	(O)	(D)	RPN	Criticality Level	
R28	Risk of disruption due to backpressure in the distribution system	8	7	5	280	Critical	4	5	3	60	Low	79%
R1	Gas leakage due to corrosion or degradation of pipe material	10	5	5	250	High	5	3	4	60	Low	76%
R7	Risk of fire or explosion due to gas leakage	9	5	5	225	High	3	3	3	27	Low	88%
R9	Malfunction of light fire extinguisher (APAR)	9	6	4	216	High	5	3	3	45	Low	79%

The mitigation strategy proved effective on priority risks R28, R1, R7, and R9, which showed a decrease in RPN of more than 75%. This reflects the success of the controls in lowering likelihood, increasing detection, and reducing impact. The results of this reassessment are presented in a risk map to make it easier to visualize the reduction, which is presented in Figure 8.

Risk Matrix		Severity									
		1	2	3	4	5	6	7	8	9	10
Occurrence	10										
	9										
	8										
	7										
	6										
	5				R28						
	4										
	3			R7		R1,R9					
	2										
	1										

Figure 8. Risk matrix results 10 × 10 after mitigation.

After implementing mitigation measures and control analysis, the risk mapping results showed that risks R28, R1, and R9, which were originally classified as Unacceptable Risks, were successfully reduced to Tolerable Risks. Meanwhile, Risk R7 experienced a more significant reduction from Unacceptable Risk to Acceptable Risk. These results will be further reviewed by the company to ensure they are effectively implemented in its operational processes. This finding confirms that the Failure Modes, Effects, and Criticality Analysis (FMECA) method is not only effective in systematically mapping initial risks but also serves as an evaluative tool for assessing the effectiveness of implemented risk controls and mitigation measures.

4. Conclusions

This study successfully identified and analyzed operational risks in the gas distribution system from PT Malamoi Olom Wobok to the 50 MW Sorong MPP PLTMG using the FMECA method. Based on the results of 32 identified risks, 30 were accepted for further analysis following validation. Four main priority risks, namely R28 (disturbance due to back pressure), R1 (gas leakage due to corrosion), R7 (fire or explosion due to gas leakage), and R9 (damage to light fire extinguishers), were analyzed in more depth using a Fishbone diagram to identify the root causes. Based on this analysis, mitigation strategies were designed and implemented, covering technical aspects, operator competency improvement, periodic inspections, early warning systems, SOP reinforcement, and environmental control and equipment storage.

The evaluation results show that this mitigation strategy is effective in reducing risk with a decrease in Risk Priority Number (RPN) of more than 75% for the four priority risks. This decrease in RPN reflects the strategy's ability to reduce the likelihood of risk occurrence, improve early detection, and minimize the impact of losses. Thus, the application of a combination of FMECA and Fishbone analysis methods has proven effective for risk mapping, root cause identification, and data-based risk control evaluation in gas distribution systems. However, for risks with environmental factors, an additional sustainable approach is needed to ensure the long-term effectiveness of mitigation. In

addition, the research was conducted within a limited time, the implementation process could not be carried out. The research was limited to the simulation phase. It is hoped that this can serve as a basis for further research to examine the full results of implementing risk mitigation measures.

Author Contributions: M.M.R.: Conceptualization, methodology, and validation. J.M.F.: formal analysis, investigation, resources, data curation, writing—original draft preparation, and writing review and editing. M.G.: visualization and supervision. A.A.: project administration. I.A.: funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Institute of Research and Innovation of Universitas Muhammadiyah Sorong, grant number: 2.03.02.16.1.02.03.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: The data presented in this study is available on request from the corresponding author.

Acknowledgments: The authors thank the research team for their contributions, their assistance in every aspect of our research, and their support in writing this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sari, S.I. Perancangan Profil Risiko Pada Klaster Industri Olahan Hasil Laut Dengan Metode Fmea (Studi Kasus: Umkm Olahan Hasil Laut Kecamatan Bulak, Surabaya). Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, 2019. Available online: http://repository.its.ac.id/id/eprint/64367 (accessed on 14 June 2026).
2. Wibowo, Y.; Herlina; Soekarno, S.; Wiyono, A.E.; Prihani, S.T. Manajemen Risiko Pengembangan Industri Mocaf (Modified Cassava Flour) Di Kabupaten Jember. *J. Teknol. Ind. Pertan.* **2023**, *33*, 239–253. [CrossRef]
3. Bastian, M.T. Analisa Risiko Fmeca Pada Kamar Mesin Kmp Takabonerate 500 Gt. Bachelor's Thesis, Universitas Hasanuddin, Makassar, Indonesia, 2020. Available online: https://repository.unhas.ac.id/id/eprint/1684/ (accessed on 14 June 2026).
4. Nuraini, L. Analisis Keandalan Dengan Metode Fmeca Pada Sistem Distribusi Pt. Pln Ulp Daruba Maluku Utara. Bachelor's Thesis, Universitas Islam Sultan Agung, Semarang, Indonesia, 2024. Available online: https://repository.unissula.ac.id/37388/ (accessed on 14 June 2026).
5. Firmansyah, E.; Sulistiyowati, W. Analysis of Quality Control of Suitcases to Minimize Defects Using the Control Map Method and FMECA (Failure Mode Effect and Criticality Analysis) Pt. Mitra Mutu Abadi. *Perpus UMSIDA* **2024**, 1–15. [CrossRef]
6. Banin, M.M. Analisis Risiko Pada Ukm Omah Batik Ngesti Pandowo Di Kampung Batik Semarang. Bachelor's Thesis, Universitas Islam Indonesia, Yogyakarta, Indonesia, 2022. Available online: https://dspace.uii.ac.id/handle/123456789/39742 (accessed on 15 June 2026).
7. Rahman, A.; Fahma, F. Penggunaan Metode Fmeca (Failure Modes Effects Criticality Analysis) Dalam Identifikasi Titik Kritis Di Industri Kemasan. *J. Teknol. Ind. Pertan.* **2021**, *31*, 110–119. [CrossRef]
8. Alijoyo, A.; Wijaya, B.; Jacob, I. Failure Mode Effect Analysis Analisis Modus Kegagalan Dan Dampak Risk Evaluation Risk Analysis: Consequences Probability Level of Risk. In *31 Teknik Penilaian Risiko Berbasis ISO 31010*; LSP MKS: Bandung, Indonesia, 2020.
9. Novanandini, E.R.; Dewi, O.C.; Nugroho, Y.S. Evaluation of Fire Safety Maintenance of an Educational Laboratory Facility. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing Ltd.: Vancouver, BC, Canada, 2021; Volume 933, pp. 1–10. [CrossRef]
10. Khikmawati, E.; Anggraini, M.; Pratiwi, N.R. Analisis Penyebab Produk Rusak Dengan Metode Fmeca Dan Memberikan Usulan Perbaikan Dengan Konsep Kaizen 5w 1h Pada Produk Air Demineral Kemasan 200 ML (Study Kasus: Cv. Gowinda Jaya Tirta Buana). *J. Rekayasa Teknol. Dan Sains* **2025**, *9*, 22–28. [CrossRef]
11. Hooijberg, E.H.; Cook, J.R.; Freeman, K.P. Equipment Maintenance and Instrument Performance. *J. Am. Vet. Med. Assoc.* **2021**, *258*, 725–731. [CrossRef] [PubMed]
12. Nasser, A.H.A.; Ndalila, P.D.; Mawugbe, E.A.; Kouame, M.E.; Paterne, M.A.; Li, Y. Mitigation of Risks Associated with Gas Pipeline Failure by Using Quantitative Risk Management Approach: A Descriptive Study on Gas Industry. *J. Mar. Sci. Eng.* **2021**, *9*, 1. [CrossRef]

13. Ariyon, M.; Rahman, B.; Sastraningsih, E.; Mayes, A. The Mitigation of Risk Management: Non-Productive Time Analysis on Drilling Operations in Zy Field. *J. Geosci. Eng. Environ. Technol.* **2024**, *9*, 174–179. [CrossRef]
14. Geofanny, G.K.; Tanaamah, A.R. Sistem Manajemen Risiko Berbasis Iso 31000:2018 Di Pt. Bawen Mediatama. *J. Tek. Inform. Dan Sist. Inf.* **2022**, *9*, 2870–2878.
15. Kassem, M.A. Risk Management Assessment in Oil and Gas Construction Projects Using Structural Equation Modeling (Pls-Sem). *Gases* **2022**, *2*, 33–60. [CrossRef]
16. Shanks, K.; Hamad, A.; Ameer, A. Failure Modes Effects and Criticality Analysis and Fault Tree Analysis Case Study of Waste Heat Recovery Plant in a Cement Factory, United Arab Emirates. *J. Fail. Anal. Prev.* **2020**, *20*, 40–50. [CrossRef]
17. Dudek, E.; Kozłowski, M. The Concept of Risk Tolerability Matrix Determination for Aeronautical Data and Information Chain. *J. KONBiN* **2017**, *43*, 69–94. [CrossRef]
18. Khalilzadeh, M.; Banihashemi, S.A.; Heidari, A.; Orazani, S.M.H.; Taebi, P. Risk Management in the Production Phase of Oil and Gas Projects: Evaluating Risk Responses and Their Impact on Safety and Damage Reduction. *Discov. Civ. Eng.* **2025**, *2*, 91. [CrossRef]
19. Nugroho, O.A.; Utama, A.A. Improving Regional Sulawesi Downstream Oil and Gas Construction Risk Management: A Literature Review. *Eur. J. Bus. Manag. Res.* **2025**, *10*, 28–32. [CrossRef]
20. Tanjung, W.N.; Atikah, S.A.; Hidayat, S.; Ripmiatin, E.; Asti, S.S.; Khodijah, R.S. Risk Management Analysis Using Fmeca and Anp Methods in the Supply Chain of Wooden Toy Industry. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *528*, 1–8. [CrossRef]
21. Jaya, R.; Ismail, M.; Yusriana; Mirza, I.; Mehran; Asis; Bakar, B.A. Analisis Dan Mitigasi Risiko Rantai Pasok Minyak Pala Kabupaten Aceh Selatan Menggunakan Fmeca. *J. Teknol. Ind. Pertan.* **2019**, *29*, 79–87. [CrossRef]
22. Baradari, F.; Nopiah, Z.M.; Ja'afar, S.; Dahalan, W.S.A.W. Critical Risk Factors of Joint Venture Projects in the Oil and Gas Industry between Malaysia and Thailand. *Int. J. Glob. Optim. Its Appl.* **2022**, *1*, 58–69. [CrossRef]
23. Putri, W.F. Penilaian Resiko Pipa Gas Distribusi Dengan Metode Pipeline Integrity Management System. *J. Ilm. Tek. Ind. Prima* **2022**, *6*, 15–19. [CrossRef]
24. Karimah; Muzakir. Analisa Manajemen Risiko Operasional Receiving & Storage Pada Pt. Pertamina Fuel Terminal Meulaboh Dengan Menggunakan Metode Fmea. *J. Akunt. Manaj. Dan Ilmu Ekon.* **2022**, *2*, 260–267. [CrossRef]
25. Pratama, M.R.; Alhilman, J.; Pamoso, A. Usulan Estimasi Optimal Inspection & Maintenance Pada Pipa Penyaluran Gas Dengan Menggunakan Metode Risk Based Inspection Dan Risk Based Maintenance Di Pt Xyz. *E-Proceeding Eng.* **2020**, *7*, 6439–6446.
26. Rustono; Triasrini, F.M.; Paniya. Failure Mode and Effect Analysis on Risk Management at an Oil and Gas Survey Company in Indonesia. *Int. J. Sci. Technol. Manag.* **2023**, *4*, 1725–1732. [CrossRef]
27. Faradillah, J.M.; Rachmadhani, M.M.; Kadang, D.R.; Mahmud, F.; Amri, I. Analisis Dan Evaluasi Manajemen Risiko Pada Usaha Laundry Rumahan Menggunakan Metode Likelihood Dan Consequence Risk Matriks. *Ind. Eng. J.-Syst.* **2024**, *02*, 54–66.
28. Rachmadhani, M.M.; Histiarini, A.R.; Kayatun, S.N.; Wahyudien, M.A.N.; Ahistasari, A. Analisis Manajemen Risiko Aset Pada Biro Administrasi Akademik Dan Kemahasiswaan Universitas Muhammadiyah Sorong. *JISI J. Integr. Sist. Ind.* **2024**, *11*, 171–182. [CrossRef]
29. Rachmadhani, M.M.; Immawan, T.; Mansur, A.; Choi, W. Risk Management Framework Design Based on Iso 31000 and Scor Model. *Spektrum Ind.* **2023**, *21*, 41–51. [CrossRef]
30. Subagja, I. Peranan Perusahaan Migas Nasional Terhadap Ketersediaan Energi Indonesia (Study Di Perusahaan Pt. Bahtera Abadi Gas Kabupaten Tuban). *JUSTITIABLE* **2019**, *1*, 117–130. [CrossRef]
31. Yaqin, R.I.; Zamri; Siahaan, J.P.; Priharanto, Y.E.; Alirejo, M.S.; Umar, M.L. Pendekatan Fmea Dalam Analisa Risiko Perawatan Sistem Bahan Bakar Mesin Induk: Studi Kasus Di Km. Sidomulyo. *J. Rekayasa Sist. Ind.* **2020**, *9*, 189–200. [CrossRef]
32. Maulana, F.C.; Wardana, S.P.; Aji, T.R.; Haryono, D.S. Analisis Pengendalian Risiko Kecelakaan Kerja Di Kilang Dan Unit Utilitas Ppsdm Migas Cepu. *Maj. Ilm. Swara Patra* **2024**, *14*, 13–20. [CrossRef]
33. Maharani, A.I.; Aziza, A.H.; Lubis, A.F.; Zaharani, Y.T. Manajemen Risiko Industri Minyak Bumi Dan Gas Pada Proses Industri Dan Manajemen Risiko. *Environ. Confl.* **2024**, *1*, 32–41. [CrossRef]
34. Solikha, N.R.; Marodiyah, I. Risk Management in Production Using Quality Risk Approach and Fmea. *Indones. J. Law Econ. Rev.* **2024**, *19*, 6–14. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.