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9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Major Accident Hazard Analysis and Determination of Safety Critical Elements at Gresik Gas Distribution Station Using the HAZOP Method

Jasillatul Hikmiyah[1*], **Dyah Santhi Dewi**[1], **Nurhadi Siswanto**[1]

[1] Department of Industrial and Systems Engineering, Faculty of Industrial Technology and Systems Engineering, Institut Teknologi Sepuluh Nopember, Surabaya 60111, **Indonesia**

* jasillatulhikmiyah@gmail.com

Abstract

The Gresik Gas Distribution Station (GDS) is a critical natural gas facility operating under high-pressure conditions, where process failures may lead to Major Accident Hazards (MAHs). Therefore, systematic hazard identification is essential to ensure process safety and operational reliability. This study aims to identify potential MAHs and determine the Safety Critical Elements (SCEs) required to prevent and manage these hazards. The study employed the Hazard and Operability Study (HAZOP) method to evaluate three key process nodes: the metering and regulating system, odorant injection system, and instrument air system. Process deviations were analyzed using guide words, followed by risk assessment to identify MAHs. Safety Critical Elements were subsequently identified based on their safety functions, including the prevention, detection, control, mitigation, and recovery of MAH events. The analysis identified 17 potential causes classified as Major Accident Hazards and 76 Safety Critical Elements, grouped into 26 SCE types. Based on the criticality assessment, 4 SCEs were classified as high criticality, 9 as medium criticality, and 13 as low criticality. The most critical SCEs were HC Pipework, Level Indicator, Fixed Point Flammable Gas Detectors, and Flame Detectors. These findings demonstrate that the HAZOP-based approach effectively identifies Major Accident Hazards and establishes priorities for Safety Critical Element management, providing a practical basis for improving process safety and operational reliability in natural gas distribution facilities.

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1. Introduction

The Gresik Gas Distribution Station (GDS) is a critical natural gas facility operating under high-pressure conditions, where equipment or process failures may indicate degradation of safety barriers and initiate Major Accident Hazards (MAHs) if preventive and protective functions are compromised. Therefore, systematic hazard identification is essential to evaluate the effectiveness of safety barriers and ensure process safety and operational reliability. This study aims to identify potential MAHs and determine the Safety Critical Elements (SCEs) required to prevent and manage these hazards [1].

The study employed the Hazard and Operability Study (HAZOP) method to evaluate three key process nodes: the metering and regulating system, odorant injection system, and instrument air system. Process deviations were analyzed using guide words and risk assessment to identify potential MAHs arising from degraded safety barriers [2]. Safety Critical Elements were subsequently identified according to their safety functions, including the prevention, detection, control, mitigation, and recovery of MAH events.

The analysis identified 17 potential causes classified as Major Accident Hazards and 76 Safety Critical Elements, grouped into 26 SCE types. Based on the criticality assessment, 4 SCEs were classified as high criticality, 9 as medium criticality, and 13 as low criticality. The most critical SCEs were HC Pipework, Level Indicator, Fixed Point Flammable Gas Detectors, and Flame Detectors [3]. These findings demonstrate that the HAZOP–SCE approach effectively links process deviations with safety barrier degradation, enabling the identification of critical protection layers and the prioritization of Safety Critical Element management to strengthen process safety and reduce the likelihood of Major Accident Hazards.

The Gresik Gas Distribution Station (GDS) plays a strategic role in ensuring the continuity of natural gas supply to industrial, commercial, and residential customers. The facility operates under high-pressure conditions and comprises several critical systems, including the metering and regulating system, odorant injection system, instrument air system, fire and gas protection system, and supporting electrical infrastructure[4]. The reliability of these systems directly affects both operational performance and process safety. Failure of a critical component may indicate the degradation of one or more safety barriers, reducing their ability to prevent, detect, control, or mitigate hazardous events [5]. As safety barrier effectiveness deteriorates, the likelihood of loss of containment, gas release, fire, or explosion increases, potentially initiating a Major Accident Hazard (MAH).

Therefore, maintaining the integrity and performance of Safety Critical Elements (SCEs) is essential to preserve safety barrier effectiveness and ensure safe operation of the facility.

Historical operational records from 2023–2024 indicate several equipment failures and operational deviations within the facility. These include regulator seal leakage, unreadable level indicators, malfunctioning fire and gas detection systems, failure of HLR and SSOV components, hydrant system deficiencies, degraded UPS battery performance, electrical panel disturbances, and flame detector failures [6]. Although none of these incidents resulted in a major accident, they indicate degradation of safety barriers that may reduce the effectiveness of preventive and protective functions. Similar failures have been reported as precursors to loss of containment, overpressure, gas release, fire, and explosion events in natural gas facilities [1].

Previous studies have primarily focused on hazard identification using HAZOP or on the assessment of individual safety systems. However, limited research has systematically linked Major Accident Hazards with the identification and prioritization of Safety Critical Elements (SCEs) based on their safety functions and criticality [7]. This study addresses this gap by integrating HAZOP with SCE identification and criticality assessment, providing a structured framework for prioritizing safety barriers that prevent, detect, control, mitigate, and recover from Major Accident Hazards at the Gresik Gas Distribution Station [1].

The failure records from 2023–2024 indicate recurring issues across mechanical, instrumentation, electrical, and fire protection systems at the Gresik Gas Distribution Station. In 2023, the reported failures included regulator seal leakage, reduced readability of level indicators, sliding gate meter misalignment, fire safety panel fault indications, and HLR/SSOV solenoid malfunction [8]. In 2024, failures were predominantly associated with supporting and safety systems, including the need for a Fire and Gas (F&G) system upgrade, hydrant hose leakage, degraded UPS battery performance, disturbances in the hydrant power supply panel and jockey pump system, and flame detector malfunction [2], [9]. These recurring failures highlight the importance of implementing a reliability-based maintenance strategy to enhance equipment availability, operational safety, and overall system reliability[10], [11].

Research conducted by Ghasemi Pirbalouti et al. [3] emphasized that process industries require systematic hazard identification techniques capable of evaluating interactions between process parameters, equipment failures, and operational deviations. Among the available Process Hazard Analysis (PHA) methods, Hazard and Operability Study (HAZOP) is widely recognized as one of the most effective approaches for identifying deviations from design intent and evaluating their potential causes and consequences. HAZOP systematically combines process parameters and guide words to identify abnormal operating conditions that may compromise process safety [2], [12]. Furthermore, Swann and Preston (1995) [13] highlighted that HAZOP is particularly suitable for complex process facilities because it facilitates the identification of both technical and operational failures before they develop into hazardous events.

Considering the operational characteristics of the Gresik Gas Distribution Station and the occurrence of historical equipment failures, a comprehensive HAZOP study is required to identify potential process deviations, evaluate their causes and consequences, and determine existing safeguards. The results of this analysis provide the basis for subsequent risk assessment, identification of Major Accident Hazards (MAHs), and determination of Safety Critical Elements (SCEs) that are essential for maintaining the integrity and safety of the facility.

2. Methods

Hazard and Operability Study (HAZOP) is one of the most widely adopted hazard identification techniques in process industries due to its ability to systematically identify operational deviations based on process parameters and predefined guide words. The method has been extensively applied in the oil and gas, petrochemical, energy, and hydrocarbon storage and distribution sectors to identify potential hazards that may lead to loss of containment, fires, explosions, and operational disruptions. By systematically examining deviations from the intended design and operating conditions, HAZOP provides a structured framework for identifying potential causes, consequences, and existing safeguards associated with hazardous events [14].

In recent years, research on HAZOP has evolved significantly. Ghasemi Pirbalouti et al. [3] applied HAZOP in oil and gas processing facilities to identify process deviations that could potentially lead to major accidents. Their findings demonstrated that HAZOP is capable of systematically identifying hazard scenarios and providing a foundation for the development of effective risk mitigation strategies. Similarly, Kharat et al [5] conducted a HAZOP study in a petrochemical facility and concluded that the method is effective in identifying the relationships between equipment failures, operational errors, and process safety consequences.

More recent studies have expanded the application of HAZOP beyond conventional hazard identification. Priyanta et al. [11] demonstrated that HAZOP results can be utilized as a basis for identifying Safety Critical Elements (SCEs) through the evaluation of safety functions performed by critical equipment. Meanwhile, Zhang et al. [15] proposed a digital HAZOP approach to improve the accuracy and efficiency of process deviation identification in high-risk energy facilities. Furthermore, Liu et al. [7] reported that integrating HAZOP with quantitative risk assessment techniques enhances decision-making effectiveness in process safety management by providing a more comprehensive understanding of risk levels and mitigation priorities.

Table 1. Research Gap HAZOP Research (2021–2025)

No.	Author(s)	Year	Research Object	Method	Key Findings	Research Gap
1	Liu et al.	2021	Natural Gas Processing Plant	HAZOP and Quantitative Risk Assessment	Identified process deviations and quantified associated risks in natural gas processing operations.	The study focused on risk quantification and did not specifically identify Major Accident Hazards (MAHs).
2	Kharat et al.	2022	Petrochemical Plant	HAZOP	Identified operational deviations, equipment failures, and their potential process safety consequences.	The research was limited to petrochemical production facilities and did not address gas distribution systems.
3	Ghasemi Pirbalouti et al.	2023	Oil and Gas Processing Facility	HAZOP	Systematically identified hazard scenarios resulting from process deviations and equipment malfunctions.	The study did not evaluate Safety Critical Elements (SCEs) associated with identified hazards.
4	Zhang et al.	2023	High-Risk Energy Facility	Digital HAZOP	Improved the efficiency and accuracy of hazard identification through a digitalized HAZOP framework.	The study focused on digital implementation and did not investigate MAHs or SCEs.
5	Priyanta et al.	2024	Process Industry Facility	HAZOP	Demonstrated the applicability of HAZOP results for supporting the identification of Safety Critical Elements.	The research was not conducted in natural gas distribution facilities and did not specifically address MAHs.
6	Sharma et al.	2025	Gas Compression Station	HAZOP	Identified operational and safety risks associated with high-pressure gas systems.	The study focused on operational risk assessment without explicitly classifying Major Accident Hazards.
7	**This Research**	**2026**	**Gresik Gas Distribution Station**	**HAZOP**	**Identifies process deviations, possible causes, consequences, and Major Accident Hazards (MAHs) within the Metering and Regulating System, Odorant Injection System, and Instrument Air System.**	**Addresses the research gap by applying HAZOP to a natural gas distribution facility and utilizing the identified MAHs as the basis for determining Safety Critical Elements (SCEs).**

Despite the widespread application of HAZOP in the oil and gas and petrochemical industries, most previous studies have primarily focused on process deviation identification and general risk control recommendations. Research specifically addressing the identification of Major Accident Hazards (MAHs) in natural gas distribution facilities remains relatively limited. Moreover, only a few studies have linked HAZOP findings to the determination of Safety Critical Elements (SCEs), which play a crucial role in preventing, controlling, and mitigating major accident scenarios. Therefore, this study aims to address these research gaps by applying HAZOP at the Gresik Gas Distribution Station to identify Major Accident Hazards (MAHs) and provide a systematic basis for determining Safety Critical Elements (SCEs) that are critical to process safety performance.

The HAZOP study was conducted by a multidisciplinary team consisting of process engineers, operation supervisors, maintenance engineers, instrumentation and control engineers, HSE personnel, and facility operators who were directly involved in the operation of the Gresik Gas Distribution Station. All participants had practical experience in natural gas distribution and process safety management. Process deviations were evaluated using the guide words specified in IEC 61882:2016. Risk levels were determined using a 5 × 5 Risk Matrix based on the company's Process Safety Management procedure, where likelihood was estimated from historical operational records and engineering judgment, while severity was assessed according to the potential consequences for personnel, assets, the environment, and business continuity. A hazard scenario was classified as a Major Accident Hazard (MAH) when it had the potential to cause loss of containment of flammable gas leading to fire, explosion, multiple fatalities, major environmental damage, or significant asset loss requiring emergency response. Safety Critical Elements (SCEs) were identified from each MAH scenario based on their safety functions. Equipment performing one or more of the functions of prevention, detection, control, mitigation, or recovery was classified as an SCE. The identified SCEs were then ranked according to their contribution to maintaining safety barrier effectiveness.

Based on previous studies, HAZOP has been widely applied in the oil and gas, petrochemical, and energy sectors for identifying process deviations, equipment failures, and operational hazards. However, three major research gaps can be identified. First, the application of HAZOP in natural gas distribution facilities, particularly Gas Distribution Stations (GDS), remains limited compared to its application in processing and production facilities. Second, most studies focus primarily on hazard identification and risk assessment without explicitly classifying Major Accident Hazards (MAHs). Third, only a limited number of studies have linked HAZOP findings to the identification of Safety Critical Elements (SCEs), which are essential for preventing, controlling, and mitigating major accident scenarios. Therefore, this study contributes to the existing body of knowledge by applying HAZOP to the Gresik Gas Distribution Station to identify MAHs and provide a systematic basis for determining Safety Critical Elements that are critical to process safety performance.

The research employed the Hazard and Operability Study (HAZOP) as the primary method for hazard identification and risk analysis at the Gresik Gas Distribution Station. The study began with the selection of process nodes based on the Process Flow Diagram (PFD) and Piping and Instrumentation Diagram (P&ID) of the facility. Subsequently, process parameters such as flow, pressure, temperature, and level were analyzed using HAZOP guide words to identify potential deviations from the intended operating conditions. For each identified deviation, possible causes, consequences, and existing safeguards were systematically evaluated.

Following the hazard identification stage, a risk analysis was conducted by assessing the likelihood and severity of each identified scenario using a Risk Matrix. The combination of likelihood and consequence ratings was used to determine the overall risk level and prioritize hazardous scenarios. Finally, scenarios classified as high-risk and possessing the potential to cause significant consequences to personnel, assets, the environment, or business continuity were screened and categorized as Major Accident Hazards (MAHs). The identified MAHs served as the primary output of the HAZOP study and provided a basis for subsequent process safety improvement initiatives.

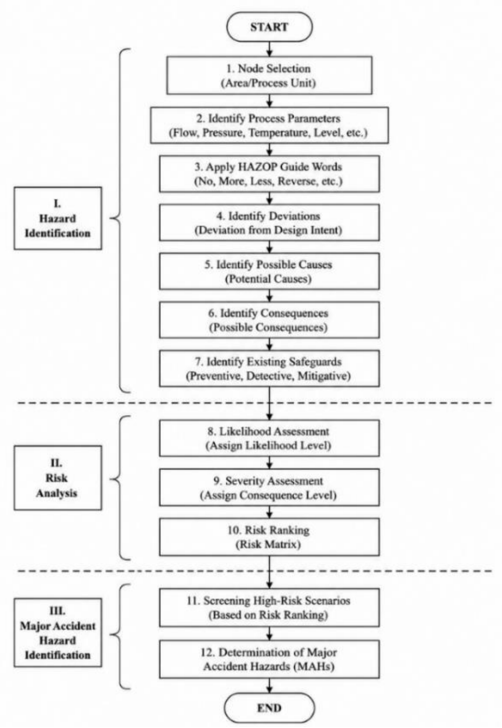

Figure 1. Research flowchart

3.Results and Discussion

3.1 Result

The HAZOP analysis at the Gresik Gas Distribution Station evaluated three main process nodes: the Metering and Regulating System (Node 1), Odorant Injection System (Node 2), and Instrument Air System (Node 3). The node selection was based on the Process Flow Diagram (PFD) and Piping and Instrumentation Diagram (P&ID). Process deviations were identified using HAZOP guide words for key parameters, including flow, pressure, temperature, and level, and each deviation was assessed in terms of its causes, consequences, and existing safeguards.

The results indicate that Node 1 is the most critical process area, with the highest number of hazardous scenarios. The identified deviations were mainly associated with regulator failures, pipeline leakage, valve malfunction, instrumentation failure, and gas flow interruption. In contrast, Node 2 was dominated by odorant injection failures that could reduce gas leak detectability, while Node 3 primarily involved failures of the instrument air system that could affect pneumatic equipment performance.

Risk assessment using the Risk Matrix showed that most scenarios in Node 1 were classified as moderate to high risk, whereas the majority of scenarios in Nodes 2 and 3 fell within the ALARP (As Low As Reasonably Practicable) region. Although no scenarios were categorized as high risk, the concentration of moderate to high-risk scenarios in Node 1 indicates that this system requires the highest priority for risk reduction.

These findings suggest that failures in the Metering and Regulating System may weaken safety barriers and increase the likelihood of loss of containment, gas release, fire, or explosion if preventive and protective measures fail. Therefore, the identified Major Accident Hazard (MAH) scenarios provide the basis for determining Safety Critical Elements (SCEs) that perform preventive, detection, control, mitigation, and recovery functions. This integrated HAZOP–MAH–SCE approach strengthens risk-based process safety management by prioritizing the safety barriers that have the greatest contribution to preventing major accidents.

3.2 HAZOP Analysis and MAH Identification Results

This research focuses on the piping process area that plays a direct role in distributing gas to customers at the Gresik Gas Distribution Station. This process area consists of three systems: the metering system (measuring gas flow rate) and regulating system (regulating gas pressure), the odorant system (injecting odorants), and the instrument air system (providing compressed air for control equipment). The overall process flow diagram is shown in **Figure 2**.

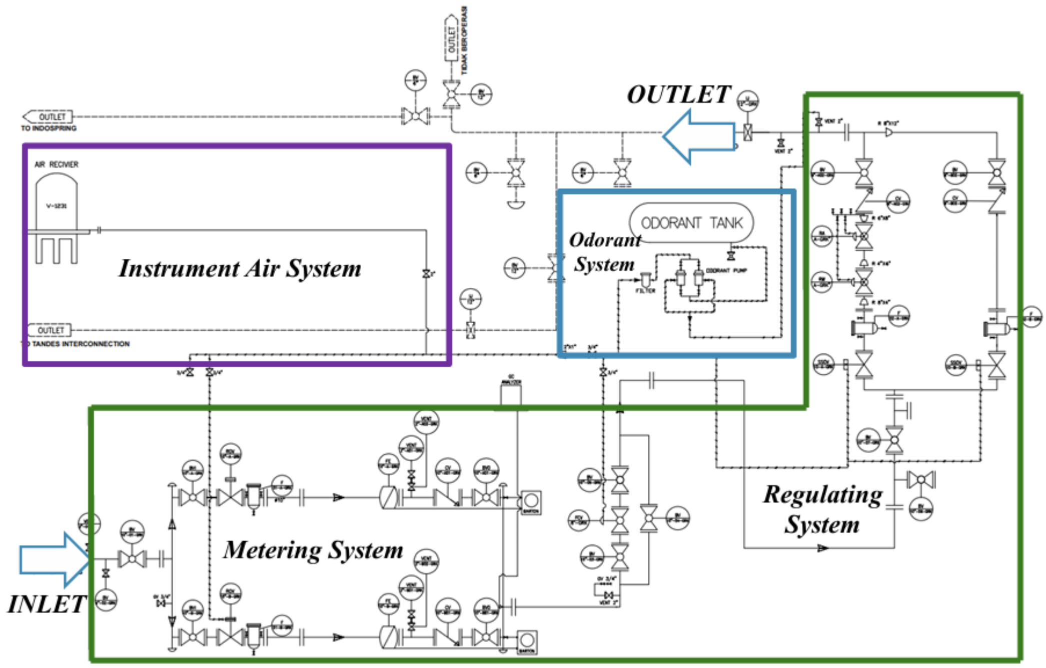

Figure 2. Process Flow Diagram (PFD) of Gresik Gas Distribution Station

The HAZOP study evaluated three critical process nodes at the Gresik Gas Distribution Station: Node 1 (Metering and Regulating System), Node 2 (Odorant Injection System), and Node 3 (Instrument Air System). The nodes were selected based on the Process Flow Diagram (PFD) and Piping and Instrumentation Diagram (P&ID) to ensure that all safety-critical process sections were systematically assessed. Process deviations were identified using HAZOP guide words for key parameters, including flow, pressure, temperature, and level.

The analysis identified several process deviations, including No Flow, Less Flow, More Flow, High Pressure, Low Pressure, High Level, and Low Level. Node 1 exhibited the highest number of deviations, primarily associated with regulator failures, pipeline leakage, valve malfunction, instrumentation failure, and gas flow interruption. In comparison, Node 2 was mainly affected by odorant injection failures that could reduce gas leak detectability, while Node 3 was dominated by instrument air system failures that could disrupt pneumatic equipment operation.

Overall, Node 1 was identified as the most critical process area because failures within the metering and regulating system may lead to loss of pressure control, loss of containment, and the escalation of Major Accident Hazards (MAHs) if safety barriers are degraded. Therefore, the HAZOP results provide the basis for subsequent risk assessment and the identification of Safety Critical Elements (SCEs) required to prevent, detect, control, and mitigate major accident scenarios.

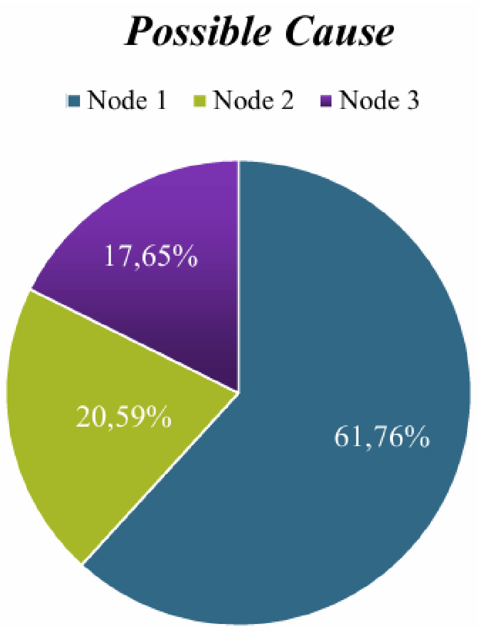

Figure 3. Possible Cause Diagram at each Node

Following the HAZOP analysis, all identified hazard scenarios were subjected to risk assessment using the Risk Matrix approach. The assessment was performed by evaluating each hazard scenario based on two key dimensions, namely the likelihood of occurrence and the severity of potential consequences. The likelihood rating reflected the probability of a hazardous event occurring, while the severity rating represented the magnitude of its impact on personnel, assets, the environment, and business continuity. The combination of these two parameters produced a risk ranking that was used to prioritize hazard scenarios requiring further attention.

Table 2. Risk Assessment Mapping in the Risk Matrix

Severity Level	Severity Description	Likelihood 1 (0% < X < 20%)	Likelihood 2 (20% < X < 40%)	Likelihood 3 (40% < X < 60%)	Likelihood 4 (60% < X < 80%)	Likelihood 5 (80% < X < 100%)
5	Catastrophic	–	1.1.1; 1.1.2; 1.1.3; 1.1.4; 1.1.5; 1.1.6; 1.1.7; 1.1.8; 1.1.9; 1.1.10; 1.1.11; 1.1.12; 1.3.4; 1.5.1; 1.12.1; 2.10.1; 2.11.1	MAH	MAH	MAH
4	Major	–	–	–	–	–
3	Moderate	1.2.1; 1.2.2	–	1.3.2; 1.3.3; 2.1.3; 3.1.1; 3.1.2; 3.1.3; 3.1.13	1.3.1	–
2	Minor	–	–	2.1.1; 2.1.2; 2.2.1	–	–
1	Insignificant	–	1.15.1; 2.15.1; 3.7.1; 3.15.1	–	–	–

The risk assessment results revealed variations in risk levels across the three analyzed nodes. Node 1 (Metering and Regulating System) exhibited the highest number of risk scenarios and the greatest concentration of moderate-to-high risk events compared with Nodes 2 and 3. This finding indicates that the Metering and Regulating System represents the most critical subsystem within the Gresik Gas Distribution Station due to its direct involvement in gas pressure regulation and flow control. Failures occurring within this system may result in gas release, pressure instability, and loss of containment, potentially leading to significant safety consequences. In contrast, the identified risks in the Odorant Injection System and Instrument Air System were generally associated with supporting functions and exhibited lower overall risk levels.

Based on the Risk Matrix evaluation, hazard scenarios with catastrophic consequences were further screened to determine whether they qualified as Major Accident Hazards (MAHs). The identification process focused on scenarios capable of causing severe impacts, including fatalities, major asset damage, environmental harm, and prolonged operational disruption. As a result, seventeen possible causes were identified as MAHs. These MAHs originated primarily from failures related to gas containment systems, pressure control equipment, instrumentation systems, and safety-related components within the facility.

The results demonstrate that not all hazard scenarios identified through HAZOP have the potential to develop into major accidents. However, a subset of scenarios possesses the characteristics of MAHs due to their catastrophic consequences despite relatively low frequencies of occurrence. This finding highlights the importance of considering consequence severity in addition to likelihood when evaluating process safety risks. The identified MAHs subsequently became the basis for the next stage of the research, namely the development of Bow Tie diagrams and the determination of Safety Critical Elements (SCEs) required to prevent, control, and mitigate major accident scenarios.

3.3 Discussion

The HAZOP results indicate that Node 1 (Metering and Regulating System) represents the most critical process area within the Gresik Gas Distribution Station. As shown in **Table 3**, most identified scenarios in this node were classified as Category IV (Moderate to High Risk), while no scenarios were categorized as Category V (High Risk). This finding reflects the critical function of the metering and regulating system in controlling gas pressure and maintaining containment integrity. Similar observations have been reported by Penelas and Pires [10], who identified hydrocarbon handling systems as the most critical units because failures can directly compromise process safety.

Table 3. Summary of Risk Analysis Results

Risk Level	Node 1 Total	Node 1 Percentage	Node 2 Total	Node 2 Percentage	Node 3 Total	Node 3 Percentage
Category V – High (High)	0	0%	0	0%	0	0%
Category IV – Moderate to High (Moderate to High)	16	76%	2	29%	0	0%
Category III – Moderate (Moderate)	2	10%	4	57%	4	67%
Category II – Low to Moderate (Low to Moderate)	0	0%	0	0%	0	0%
Category I – Low (Low)	3	14%	1	14%	2	33%
TOTAL	21	100%	7	100%	6	100%

The dominant risk scenarios were associated with pressure and flow deviations caused by failures of regulators, valves, pipelines, and instrumentation. These failures may weaken safety barriers, leading to loss of pressure control, gas leakage, and ultimately loss of containment. This finding is consistent with Ghasemi Pirbalouti et al. (2023) and Kharat et al. [5], who reported that equipment degradation and instrumentation failures are among the primary initiating events of major process safety incidents.

Although no scenarios were classified as High Risk, several were associated with catastrophic consequences, emphasizing that consequence severity should be considered alongside likelihood during risk evaluation. Based on the defined MAH criteria, 17 scenarios were identified as Major Accident Hazards, most of which were related to failures in gas containment, pressure regulation, and safety-critical instrumentation. These results support previous studies showing that failures of containment and safety-critical equipment frequently initiate major accident scenarios in oil and gas facilities [4], [10].

Overall, this study confirms that HAZOP provides an effective framework for identifying process deviations and prioritizing Major Accident Hazards in natural gas distribution facilities. Unlike most previous studies, which focused primarily on hazard identification or general risk assessment, this research integrates HAZOP, MAH identification, and safety barrier evaluation to establish a risk-based foundation for determining Safety Critical Elements (SCEs) [11], [12], [13]. This integrated approach provides practical guidance for strengthening process safety, improving operational reliability, and prioritizing safety barrier management at the Gresik Gas Distribution Station [14], [15].

4. Conclusion

This study applied the Hazard and Operability Study (HAZOP) methodology to identify process hazards and Major Accident Hazards (MAHs) at the Gresik Gas Distribution Station. The analysis of the Metering and Regulating System, Odorant Injection System, and Instrument Air System identified the Metering and Regulating System (Node 1) as the most critical process area, exhibiting the highest number of process deviations and hazardous scenarios. Risk assessment showed that most scenarios in Node 1 were classified as Category IV (Moderate to High Risk). Although no scenarios were categorized as Category V (High Risk), 17 scenarios were identified as Major Accident Hazards (MAHs) because of their potential to result in catastrophic consequences, primarily involving failures of pressure regulation systems, gas containment equipment, pipelines, valves, and critical instrumentation.

The study further demonstrated that integrating HAZOP with Safety Critical Element (SCE) identification provides a systematic basis for strengthening process safety management. The identified SCEs support the prioritization of maintenance activities by focusing resources on equipment that performs essential safety functions, improve risk-based inspection programs through targeted monitoring of safety-critical equipment, and enable the evaluation of safety barrier performance by assessing the effectiveness of preventive, detection, control, mitigation, and recovery functions against Major Accident Hazards. Therefore, the proposed HAZOP–MAH–SCE framework offers a practical decision-support approach for improving operational reliability, enhancing safety barrier integrity, and reducing the likelihood of major accidents in natural gas distribution facilities.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

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