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Probabilistic Modeling of Occupational Health and Safety Culture Influence on Operational Safetyin Petrochemical and Oil and Gas Facilities Using Bayesian Networks

Supardi, Jerry, and Denny Hendrik Nainggolan

Politeknik Industri Petrokimia Banten,
Raya Anyer street KM 2, Ciwandan, Cilegon, Banten 42443, Indonesia.

Corresponding author: Supardi (supardi@poltek-petrokimia.ac.id)

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ABSTRACT - The oil and gas industry and petrochemicals are known for high-risk operations, characterized by complex processes, hazardous materials, and varied work conditions; therefore, there is a need for a strong OHS culture to promote operational safety. This paper examines the effect of OHS culture on operational safety by employing probabilistic analysis based on Bayesian Network modeling. In this study, a quantitative explanatory research design is used, in which data are obtained from 78 industrial placement students at Politeknik Industri Petrokimia Banten who worked in production and maintenance facilities at high-risk petrochemical and oil and gas companies in the industrial area of Cilegon-Banten, Indonesia. OHS culture is measured across four aspects: management commitment, safety communication, risk awareness, and safety participation. In contrast, operational safety is assessed using measures of safety behavior and near-miss reporting. OHS culture plays a major role in determining operational safety, with safety communication that has the greatest influence on safety performance. Probabilistic inference indicates that higher OHS culture levels lead to safer operating conditions, while a lack of communication is a significant factor in poor safety performance. Sensitivity analysis further supports communication as a key determinant of safety behavior and risk management.

Keywords: OHS culture, operational safety, bayesian network, oil and gas industry, safety communication

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INTRODUCTION

The occupational safety and health (OSH) problem remains relevant throughout the period 2021–2024. According to the ILO, nearly 2.3 million workers die yearly due to accidents and work-related illnesses, and more than 374 million non-fatal injuries are observed across the world. The overall fatality rate remains rather stable at 3.6 -4 deaths per 100,000 workers per year.

In Indonesia, the oil, gas, and petrochemical industries remain among the largest sources of occupational accidents. For instance, the Social Security Administering Body for Employment (BPJS Ketenagakerjaan) reports over 297,000 work accidents occurring in the country in 2023. These figures have been steadily growing for several years. What is more important, the above-mentioned industrial sectors have always been a focus of occupational accidents in Indonesia because of their high hazard levels. Additionally, as follows from government regulations, in particular Government Regulation No. 50 of 2012 (PP No. 50 Tahun 2012) on the Implementation of Occupational Safety and Health Management Systems (SMK3), all high-risk industries are required to use certain OHS management systems. In the oil, gas, and petrochemical industries, this means companies are obliged to implement OHS management system models. Compliance with this regulation, however, varies greatly among different firms, particularly between state-owned enterprises (BUMN) and private enterprises.

According to industry performance data, the oil and gas industries face higher risks than the global average. According to reports from the International Association of Oil and Gas Producers (IOGP), 20 deaths occurred in 2021, and the number rose slightly in subsequent years to 32 in 2024. The fatal accident rate was reduced to 0.77 deaths per million working hours due to the rising total number of working hours. Nevertheless, the accident rates in the industry remain significantly higher than those of other industries.

In addition to fatal accidents, the number of non -fatal accidents is crucial for analyzing the safety performance of oil and gas operations. Data show that non-fatal incidents still occur frequently in the field, with a considerable share attributed to equipment accidents and general operational risks. As for the causes of incidents in the industry, more than 60% are related to human factors, and less than 40% to technical and organizational factors.

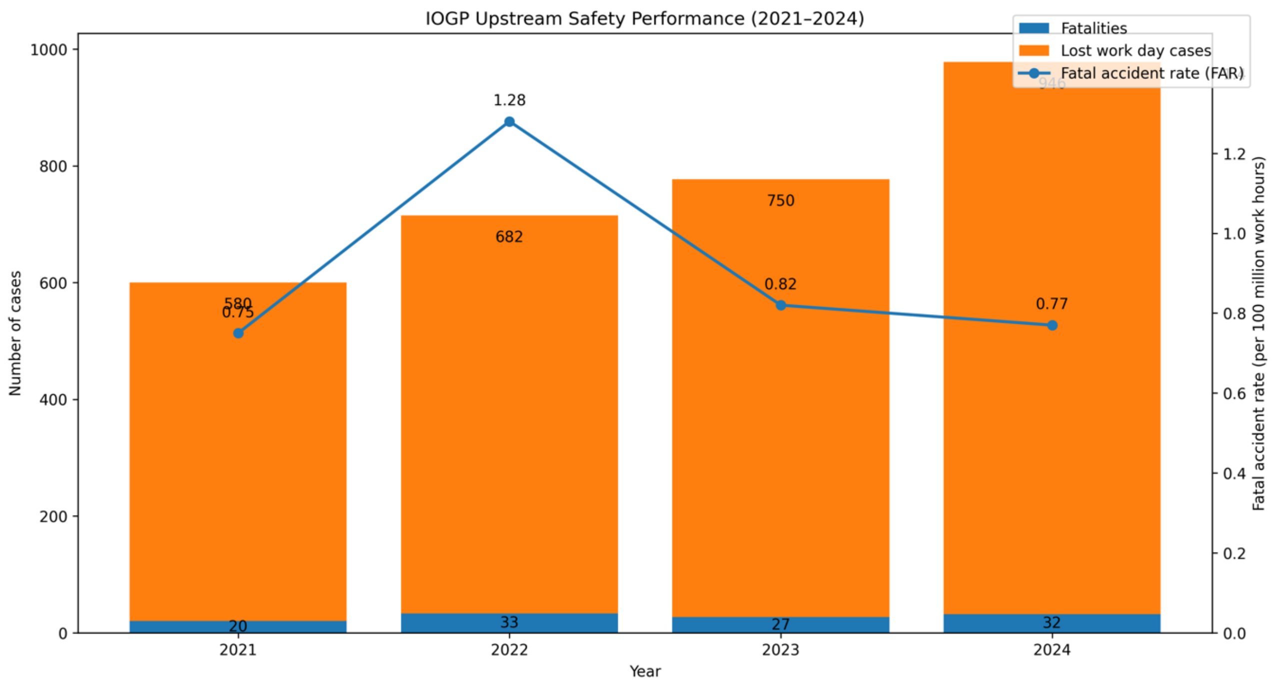

Figure 1. Safety performance trends in the oil and gas industry (2021–2024).
Based on IOGP safety performance indicators & ILO global occupational safety data.

More precisely, human factors play the key role in accidents in oil and gas operations according to accident analyses. As shown in the HFACS-OGI model analysis, over 60% of accidents in the oil and gas industry stem from human factors, including individual errors, loss of situational awareness, and poor communication (Nwankwo et al., 2022). Technical factors account for only 10-20%, while organizational and environmental factors account for 10-15%.

To start with, the concept of OHS culture needs to be explained. OHS culture refers to people's perceptions of safety issues. In high-risk industries, OHS culture is an informal structure that influences workers' actions in high-risk situations. Studies have shown that organizations with a strong OHS culture have a good safety record, as they demonstrate higher compliance with safety standards and fewer accidents. In terms of numbers, a strong OHS culture can improve safety performance by 30-35% compared with organizations with a weak OHS culture (Ehiaguina et al., 2024; Jasmadi et al., 2025).

Moreover, modern concepts in industrial safety management include the vision of zero accidents, meaning that all industrial accidents can be prevented with a strong OHS culture in the company. Data show that implementing culture-based strategies can decrease accidents by 40-60% over time when combined with a leader's role in promoting effective communication and cooperation among employees (Blanco-Juárez & Buele 2025).

Examples of risky activities in the oil and gas industry reveal how a safety culture can be important in preventing accidents in high-risk situations. For example, working in confined spaces poses risks such as accidental inhalation of toxic gases or suffocation from lack of oxygen. According to research findings, about 70% of risks stem from improper execution of work procedures and employees' risky behavior, including inadequate atmospheric testing and the use of personal protective equipment (Silva & Amaral 2025). Thus, the effective functioning of safety systems relies heavily on employees' safety behavior.

Similarly, risk identification and evaluation methods (such as HIRARC) suggest that the success of risk control measures greatly depends on human factors. Although risks can be effectively identified and managed, their implementation is highly contingent on employees' awareness and willingness to comply. In particular, increased risk awareness has been shown to increase the effectiveness of risk controls by up to 25%; therefore, an OSH culture should be promoted to facilitate the work of the safety management system (Ihsan et al., 2025).

However, beyond purely technical considerations, psychosocial factors also contribute to workplace safety issues in the oil and gas industry. Offshore employees experience heavy workload, tough weather conditions, and isolation from their social environment; such stressful factors may significantly contribute to mental disorders and, therefore, increase accident risk. Research results indicate that under such conditions, psychosocial factors increase the possibility of accidents by 20–30% (D'Antoine et al., 2023). Workplace safety in the oil and gas industry thus requires a comprehensive approach that accounts for both psychological and technical considerations.

Safety performance management methods have expanded from lagging to leading indicators. Leading indicators such as safety culture, procedural compliance, and safety training were found to be much more indicative of safety performance than traditional lagging indicators, such as accident count. In other words, using leading indicators can improve the effectiveness of safety management practices by up to 50%; as such, leading indicators, especially safety culture, need to be included in safety systems (Niu et al., 2023).

Based on a thorough literature review, it was found that although many studies have explored various applications of Bayesian Networks (BN) for technical safety, very few have applied BN to behavioral and psychosocial safety problems. Within the oil and gas industry in particular, most research papers analyzing OSH culture issues relied on traditional statistical methods, such as regression analysis or SEM. Given the limitations of conventional analysis methods, the current study employs BN as an appropriate tool to analyze the impact of OSH culture on workplace safety.

Although numerous research studies explore OSH culture and its influence on workplace safety, the vast majority rely on classical statistical techniques that cannot effectively handle complex interactions among variables and the uncertainty inherent in real-world data. In practice, the relationship among safety culture, human factors, and workplace safety is uncertain and nonlinear. Therefore, this study aims to develop a BN-based probabilistic model for analyzing the impact of OSH culture on operational safety in the petrochemical and oil and gas industries. Expected contribution includes scientific development in the area of probabilistic safety analysis, as well as some recommendations to increase OSH effectiveness in the industry.

METHODOLOGY

Research design

An explanatory quantitative design will be used in the present study to investigate the influence of occupational safety and health (OSH) culture on operational safety in high-risk industries. An explanatory approach was chosen to detect relationships among the variables analyzed and to measure the magnitude of their influence on one another. To capture the complexity and uncertainty of interactions among variables, the Bayesian Network (BN) methodology was adopted; this method allows for estimating probabilistic dependencies among variables and predicting the probability of accidents under certain conditions.

Population and sample

The population consists of all third-year, sixth-semester students at the Banten Petrochemical Industry Polytechnic undergoing industrial placement; the total number of subjects is 112. The survey was conducted at sites where students undergo industrial placement at several petrochemical and oil and gas companies operating in the Cilegon-Banten industrial complex, one of the largest petrochemical hubs in Indonesia. Participating companies include state-owned enterprises, such as PT Chandra Asri Petrochemical and PT Krakatau Steel, as well as related companies that adhere to SMK3 safety standards established by Government Regulation No. 50 of 2012 (PP No. 50/2012). None of the multinational companies was surveyed.

Sampling will be conducted on purposive grounds; specifically, only students who spent at least 3 months in industrial practice and worked in hazardous departments (production, process, and maintenance divisions) will be included in the survey; as a result, 78 samples will be selected.

All participating companies operate in accordance with SMK3 safety standards established by Government Regulation No. 50 of 2012 (PP No. 50/2012); some also adhere to internationally recognized OHS standards, such as ISO 45001:2018 and IOGP safety guidelines. These safety systems formed the basis for assessing students' perceptions of safety culture and safety behavior.

Research variables

Variables are considered either independent or dependent in this research within a Bayesian Network framework. The independent variable in the analysis is Occupational Health and Safety (OHS) Culture, while the dependent variable is Operational Safety. The indicators of each variable are outlined in Table 1. The two research variables are modeled as nodes in the Bayesian Network that show their relationship.

Data collection techniques

Data collection was conducted using a structured questionnaire with a five-point Likert-scale response format. These include response choices of 1 (Strongly disagree), 2 (Disagree), 3 (Neither agree nor disagree), 4 (Agree), and 5 (Strongly Agree). The research tools were developed by drawing on reliable indicators of OSH culture and operational safety identified in previous research. Field observation was also conducted alongside the questionnaires to validate the responses.

Table 1. Research variables and indicators

Variable	Dimension	Indicator
OHS culture	Management Commitment	Leadership support for OSH
	Safety Communication	Risk Information Communication
	Risk Awareness	Ability to identify hazards
	OSH participation	Involvement in OSH programs
Operational safety	Procedural compliance	Adherence to SOPs
	Use of PPE	Consistent use of PPE
	Near-miss reporting	Willingness to report incidents
	Safe behavior	Safe work practices

Data processing and analysis

A Bayesian Network model was used to analyze the data through three main processes: structure learning, parameter estimation, and probabilistic inference. From a mathematical perspective, Bayesian Networks depend on Bayes' theorem as follows Equation 1,

$$P(A \mid B) = \frac{P(B \mid A) P(A)}{P(B)} \tag{1}$$

where *P(A|B)* is the posterior probability, *P(B|A)* is the likelihood, *P(A)* is the prior probability, and P (B) is the evidence probability. For models with multiple variables, the joint probability is expressed as Equation 2,

$$P(X_1, X_2, \dots, X_n) = \prod_{i=1}^{n} P\big(X_i \mid \mathrm{Pa}(X_i) \big) \tag{2}$$

where Pa(Xi) is the parent node of variable Xi.

Survey data, in the form of Likert-scale responses, are then converted into probabilities to construct a Conditional Probability Table (CPT) for each node. An example of a CPT structure is shown in Table 2.

The second phase entails inferential analysis to determine the probability of operational safety at different values of the OSH culture variable. Sensitivity analysis was conducted to identify the variables with the greatest impact on operational safety.

Validity and reliability

Pearson correlation with a criterion coefficient of over 0.3 was used to test the validity. On the other hand, Cronbach's Alpha of 0.7 was the cutoff for assessing reliability. Results show that all research instruments met the validity and reliability requirements for Bayesian Network analysis.

RESULT AND DISCUSSION

Respondent characteristics and data description

A total of 78 respondents were analyzed. All the respondents were industry trainees with a three-month placement period in high-risk environments. As for placement area, 50 respondents (64.1%) were placed in the Production/Operation unit, while 28 respondents (35.9%) were in the Maintenance Unit. About placement duration, 31 respondents (39.7%) completed 3–4 months of placement; 29 respondents (37.2%) completed 5–6

Table 2. Example of a conditional probability table (CPT)

OHS culture	Operational safety (safe)	Operational safety (unsafe)
High	0.85	0.15
Medium	0.65	0.35
Low	0.40	0.60

months of placement; and 18 respondents (23.1%) exceeded 6 months of placement When asked about safety orientation, 56 respondents (71.8%) received safety induction before going into work area; and 35 respondents (44.9%) received intensive training of hazards in the unit. This means that although all respondents have worked in operational environments, they have not been equally reinforced in OSH at the hazard -specific level.

From the above characteristics of the respondents, it is apparent that most respondents have worked in hazardous environments. However, some discrepancies have arisen regarding the transfer of safety competence from general safety induction to hazard-specific training. This implies a lack of safety knowledge transfer, especially on operational hazards such as chemical handling, hot work, confined space, and high-energy mechanical operations.

Descriptive analysis of OSH culture and operational safety

Based on the descriptive statistics, OSH Culture is in the 'Good' category, with a mean score of 68.5%. As for dimensions, risk awareness achieved the highest score of 74.3%, followed by management commitment (71.0%) and safety participation (67.0%), while safety communication had the lowest score of 61.2%. This means that trainees have adequate knowledge of risks but face challenges in communicating those safety-related risks.Before providing descriptive statistics, it is worth noting the criterion used to classify scores on the five-point Likert scale. Scores between 81%–100% fall under Very Good; scores between 61%–80% fall under Good; scores between 41%–60% fall under Fair; scores between 21%–40% fall under Poor, while scores between 0%–20% fall under Very Poor. These criteria, which are adopted from Riduwan (2013), have been used throughout the analysis.

The highest score of the risk awareness dimension depicts a good perception of hazards in the work environment. On the other hand, the lowest score for the safety communication variable indicates a poor willingness to communicate hazards and to report near misses. It is worth noting that safety communication is a key element in enhancing safety operations. Therefore, to achieve operational safety, the first step is to identify risks through safety communication.

Table 3. Respondent characteristics

Characteristics	Category	n	%
Assignment area	Production/operations	50	64.1
	Maintenance	28	35.9
Duration of placement	3–4 months	31	39.7
	5–6 months	29	37.2
	> 6 months	18	23.1
Safety orientation	Yes	56	71.8
	No	22	28.2
Specific hazard training	Yes	35	44.9
	No	43	55.1

Table 4. Descriptive scores of OSH culture dimensions

Operational safety indicators	Average score	Percentage (%)	Category
Compliance with SOP	3.48	69.6	Good
Use of PPE	3.32	66.4	Good
Near-miss reporting	2.89	57.8	Fair
Safe work behavior	3.41	68.2	Good
Total average	3.28	65.5	Good

Table 5. Operational safety indicators

Operational safety indicators	Average score	Percentage (%)	Category
Compliance with SOP	3.48	69.6	Good
Use of PPE	3.32	66.4	Good
Near-miss reporting	2.89	57.8	Fair
Safe work behavior	3.41	68.2	Good
Total average	3.28	65.5	Good

One of the major differences here is in safety communication, where the gap between risk awareness and safety communication has widened. This suggests that trainees have been unable to translate knowledge of risks into effective safety communication. That is why they have shown good awareness of risks but poor safety communication skills.

To strengthen the description of operational safety, measurements were also taken for four outcome indicators: SOP compliance, PPE use, near-miss reporting, and safe work behavior.

Safety operations are classified as good, while the near-miss reporting indicator remains rated as average. This combination of ratings indicates that the level of safety communication identified in the survey data is low. It is important to acknowledge that there is a direct connection between the lack of safety communication and the low incidence of near-miss reports, which is one of the most important indicators for preventing more serious accidents.

Development of a Bayesian network structure

Bayesian network structure development aims to model the causal structure between the components of OSH culture dimensions and operational safety in the complex context of the petrochemical industry and oil-and-gas sector. Therefore, the structure of the Bayesian Network (BN) includes three basic layers: 1). The organizational layer; 2). The behavioral layer; and 3). The operational outcome layer.

Organizational Layer – OSH cultural components at the organizational level are root causes. Such variables characterize this layer as management commitment, safety communication, risk awareness, and safety participation. These variables can be viewed as major determinants of individual worker behavior.

Behavioral Layer – worker behavior resulting from the effects of various OSH cultural components. Variables such as safe behavior, tendency toward unsafe behavior, and near-miss reporting behavior are included in this layer. Herein, safe behavior refers to compliance with safe procedures. Unsafe behavior is characterized by violations and actions that pose potential risks. Near-miss reporting is a proactive indicator of OSH performance.

Operational Outcome Layer – operational safety conditions as major outcomes of OSH performance. The operational safety state variable is used here. This is the main output of the BN model. Worker behavior (the previous layer) directly affects the operational safety state variable.

It should be emphasized that the relationship structure is built on a cause-and-effect basis, a widely recognized approach in the industrial safety literature. Organizational causes affect behavior, which, in turn, leads to safety consequences. First, safety communication and management commitment affect such components as near-miss reporting and safe behavior. Secondly, increased risk awareness leads to better hazard identification and safe behavior. Thirdly, both safe behavior and near-miss reporting behavior are directly linked to the probability of safe operational conditions.

Table 6. Node and state structure in a Bayesian network

Layer	Node	Description	State
Organizational	Management commitment	Level of management commitment to OSH implementation	Low, Medium, High
Organizational	Safety communication	Effectiveness of risk and safety communication	Low, Medium, High
Organizational	Risk awareness	Individual ability to recognize and understand hazards	Low, Medium, High
Organizational	Safety participation	Level of involvement in occupational safety and health programs	Low, Medium, High
Behavioral	Safe behavior	Level of compliance with safety procedures	Low, Moderate, High
Behavioral	Tendency toward unsafe behavior	Tendency to engage in unsafe behavior	Low, Moderate, High
Behavioral	Near-miss reporting	Level of near-miss reporting	Low, Moderate, High
Intermediate	Hazard exposure level	Hazard exposure level	Low, Medium, High
Intermediate	Control effectiveness	Effectiveness of risk control in the field	Low, Moderate, High
Outcome	Operational safety status	Operational safety status	Safe, Unsafe

Note: The 'Intermediate' layer nodes (Hazard Exposure Level and Control Effectiveness) serve as bridging variables between the behavioral layer and the operational outcome layer. These nodes are not directly observed through the questionnaire but are inferred through probabilistic relationships derived from the parent nodes in the organizational and behavioral layers. This distinction prevents conceptual overlap between the node categories and ensures structural clarity in the Bayesian Network topology.

To increase the model's complexity and make it more realistic, the inter-variable relationship structure includes intermediary variables (nodes). The major relationships are described below:

- Management commitment, safety communication and safety participation. Improved management commitment leads to better safety communication and worker participation in OSH activities.
- Safety communication, near-miss reporting and safe behavior. Efficient safety communication increases risk information transparency and promotes near-miss reporting and safe behavior.
- Risk awareness, safe behavior and tendency toward unsafe behavior. Higher risk awareness encourages safe behavior and reduces tendency toward unsafe behavior.
- Safety participation, control effectiveness. Increased participation in OSH programs enhances control effectiveness in the field.
- Tendency toward unsafe behavior, level of hazard exposure. Increased tendency to unsafe behavior means higher hazard exposure.
- Safe behavior + control effectiveness, operational safety state. Both safe behavior and control effectiveness affect the probability of operating conditions being safe. Both safe behavior and control effectiveness affect the probability of operating conditions being safe.

According to the Bayesian network structure developed in this study, operational safety depends on the interactions between organizational causes, human behavior, and operational conditions. The network model demonstrates that changes in OSH culture will lead to improved operational safety conditions, not only through direct effects but also through behavioral change.

The use of intermediary variables, such as hazard exposure level and control effectiveness, creates another aspect of real-life operations. Overall, the BN model enables the explanation of the link between OSH culture and operational safety, as well as the development of decision-making scenarios.

Probability estimation and conditional probability table (CPT)

After constructing the BN network structure, the next step concerns probability estimates and the Conditional Probability Table (CPT). According to the results, the initial probabilities of OSH culture components performing are moderate to high. Risk awareness shows the highest probability distribution. Thus, the probability of belonging to the high-risk awareness group is 0.46, while the probability of high safety communication is only 0.28.

Table 7. Initial probabilities of several main nodes

Node	Low	Medium	High
Management commitment	0.18	0.44	0.38
Safety communication	0.24	0.48	0.28
Risk awareness	0.14	0.40	0.46
Safety participation	0.20	0.47	0.33

Moreover, the first probability distribution is consistent with the earlier descriptive analysis, where risk awareness is more prevalent than any other element. The dimension of safety communication has the smallest portion of high categories among all others. It implies that communication barriers not only emerge within the medium category but also persist in the probability distribution. As an example of the CPT, Table 8 illustrates how the probability of the system being safe depends on safe behavior and near-miss reporting.

According to the table, the highest probability of the system operating safely occurs when both the level of safe behavior and the rate of near-miss reporting are high. However, when safe behavior and near-miss reporting are low, the system is likely unsafe to operate. Hence, the CPT confirms that safe behavior and near-miss reporting are the two main mediators between OSH culture and operational safety.

In terms of organizational behavior, these CPT values mean that if organizations do not motivate employees to engage in proactive reporting and adhere to certain procedures, they expose themselves to a high risk of failure. It implies that organizations should ensure a specific behavioral outcome by implementing policies. Specifically, regular safety briefings, leadership presence in operational areas, and non-punitive incident-reporting systems can improve overall safety.

Probabilistic inference analysis

To estimate the influence of OSH culture on operational safety, an inferential analysis was conducted. In the baseline scenario, the probability of safety is 0.68. On the contrary, the probability that the system is in an unsafe state is 0.32. If all OSH culture dimensions are high, then the probability of safety increases to 0.86. On the other hand, low probability occurs when all dimensions are in low categories; it amounts to 0.41.

The comparison of probability values obtained for different scenarios demonstrates that OSH culture influences operational safety. For instance, increasing all dimensions results in a high safety probability (0.86). On the contrary, the probability of safety in the low-communication scenario is 0.57. This result indicates that safety communication is an important control point in the operational safety system.

Table 8. Example of a conditional probability table (CPT) for operational safety

Safe behavior	Near-miss reporting	P(Safe)	P(Unsafe)
Safe	High	0.92	0.08
Safe	Moderate	0.84	0.16
Safe	Low	0.73	0.27
Medium	High	0.78	0.22
Medium	Moderate	0.65	0.35
Moderate	Low	0.51	0.49
Unsafe	High	0.42	0.58
Unsafe	Moderate	0.31	0.69
Unsafe	Low	0.18	0.82

Table 9. Results of probabilistic inference for several scenarios

Scenario	P(safe)	P(unsafe)
Baseline	0.68	0.32
High OHS culture	0.86	0.14
Moderate OHS culture	0.68	0.32
Low OHS culture	0.41	0.59
High communication, others moderate	0.76	0.24
Low communication, others moderate	0.57	0.43

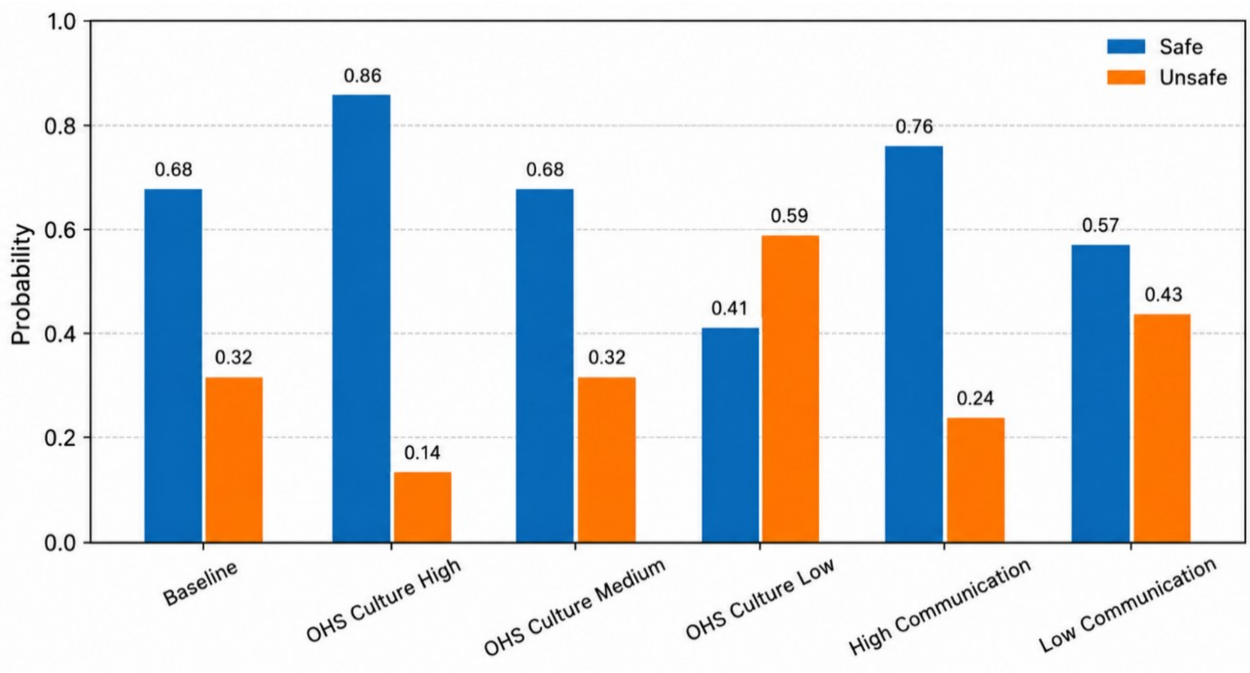

Figure 2. Bayesian inference results for several scenarios

Figure 2 shows the results of Bayesian inference across different safety culture scenarios. From the figure, it can be seen that when all OHS culture dimensions are high simultaneously, the probability of safety is 0.86, whereas under low conditions, it drops to 0.41. In turn, reducing the dimension of safety communication lowers the probability of operational safety. More specifically, it decreases from 0.68 to 0.57. As a result, the dimension of safety communication serves as a pivotal control point for operational safety. This conclusion is consistent with the study by Naji et al. (2022). The researchers have proven that safety communication mediates the relationship between safety culture and performance.

Sensitivity analysis

The purpose of the sensitivity analysis was to identify OHS culture nodes that most strongly influence the probability of operational safety. Based on the results obtained, the highest sensitivity is observed in the safety communication node, with a weight of 0.34. Management commitment node follows with a sensitivity weight of 0.27, whereas risk awareness equals 0.23. Lastly, safety participation has a sensitivity weight of 0.16. Therefore, it can be concluded that safety communication is the most important variable affecting changes in the probability of safety.

Based on these results, it is clear that improving the quality of safety communication, including hazard reporting, toolbox talks, and feedback, may significantly reduce the likelihood of risks occurring. Management commitment is also important because it serves as a policy guide, sets an example for other employees, and allocates safety resources.

As illustrated in Figure 3, the sensitivity weight at the safety communication node is 0.34. According to this parameter, any change at this node has the greatest influence on operational safety outcomes. The findings are similar to those reported by Mathisen et al. (2022), who found that safety voice has important predictive value for safety outcomes on offshore oil rigs. Such a voice represents a form of safety communication, guided by leadership presence and job control.

Based on the sensitivity chart, it is possible to outline the priority of intervention. Specifically, safety communication is the first intervention node. This is confirmed by the results of the descriptive analysis, in which safety communication received the lowest score.

Figure 3. Sensitivity analysis of operational safety

Discussion

Based on the findings of this study, it becomes evident that an OSH culture significantly impacts operational safety via systemic factors rather than linear ones. In particular, according to the constructed Bayesian Network, the dimensions of OSH culture – namely, management commitment, safety communication, risk awareness, and safety participation – affect safe behavior, near-miss reporting, and operational safety. Such a pattern is particularly important for oil and gas and petrochemical organizations, where hazardous environments predominate due to large hydrocarbon inventories, high pressure and temperature levels, explosive gases, and simultaneous operation under risky conditions (Skiba 2025). In other words, operational safety in such organizations stems from a combination of human, organizational, technological, and environmental interactions. It is in line with the modern approach to OSH issues, which views accidents as resulting from multiple layers of failure rather than a single factor (Jamil et al., 2025; McKinnon 2025).

Interpreting the descriptive findings, in which the highest dimension value corresponds to risk awareness and the lowest to safety communication, it is worth noting that this information is particularly important in oil and gas organizations (Tribuana et al., 2018). Indeed, the latter often have workers who recognize risks such as fire danger, explosions, H2S, flammable atmospheres, or hazards associated with confined spaces. However, they do not communicate their views on these matters either due to hierarchical barriers, pressure from production targets, or a lack of a communicative safety culture (Okon et al., 2025. These findings are consistent with those of Quaigrain et al., who argue that workers' knowledge and attitudes towards OSH issues affect compliance in Ghana's oil and gas industry, and with those reported by Mathisen et al. on the impact of the "safety voice" on offshore oil rigs. More precisely, the authors state that such a measure increases in cases when leadership support and job control are available, while high work demands reduce it. As such, there is no automatic transition from risk awareness to safe behaviors in the absence of a psychologically safe communication environment (Mathisen et al., 2022; Quaigrain et al., 2022).

As for the concepts that explain this study's findings, the most relevant are safety climate and safety culture. While the first refers to workers' perceptions of the importance of safety-related actions and measures at a given point in time, the second term describes the underlying values, beliefs, norms, and practices related to OSH in organizations (Houette & Mueller-Hirth 2022. For instance, oil and gas organizations may have OSH management programs described on paper. However, their implementation and effectiveness in practice may vary depending on employees' perceptions of the importance of OSH measures, management's actual commitment, and other factors. Djunaidi et al. reported the effects of a change in ownership from multinational corporations to state-run companies on workers' perceptions of safety climate in oil and gas organizations in Indonesia. Their findings are consistent with this research and demonstrate that the safety culture dimension is highly sensitive to organizational, leadership, and regulatory changes (Djunaidi et al., 2024).

Turning to the Indonesian regulatory system, the state-owned enterprises (BUMN) in the oil, gas, and petrochemical sectors are obliged to implement the OHS Management System (SMK3) pursuant to Government Regulation No. 50 of 2012 (PP No. 50/2012). Conducting a brief gap analysis of its application reveals the following strengths and weaknesses of the policy. Its main strength is that PP No. 50/2012 provides a set of elements for the OHS management system, comprising 12 parts, including policy development, planning, hazard identification, and performance evaluation. One of the main drawbacks is that the regulation is implemented in a rather mechanistic way: organizations meet documentation requirements yet fail to achieve cultural internalization, as evidenced by a relatively low rate of safety communication (61.2%). In addition, PP No. 50/2012 does not include the use of probabilistic risk assessment or the quantitative measurement of OSH culture. All these gaps indicate that PP No. 50/2012 can serve as a foundation for developing a safety culture to improve safety performance in the study organization.

From a technical point of view, the Bayesian model's finding that a high level of safety culture significantly increases the likelihood of safe conditions seems quite understandable. First, management commitment affects specific decisions such as the allocation of the HSE budget, the quality of permits to work, process discipline, proper worker training, toolbox meetings, field audits, and readiness to stop operations when conditions are unsafe (Salleh et al., 2024. Second, implementing the Occupational Health and Safety Management System requires specific organizational and behavioral factors: leadership, worker participation, risk assessment, operational control, and improvement measures. The absence of at least one element increases barriers and corresponding safety performance (McKinnon 2025).

First, it should be noted that the result that safety communication is the most influential factor in the model is very robust from both practical and theoretical viewpoints. According to research by Naji et al., safety communication acts as a mediator between safety culture and safety performance in the petrochemical industry, meaning that a good safety culture does not necessarily translate into safety performance unless there is effective communication. This is true in the present study as well, because when situations related to safety communication are limited, the likelihood of maintaining safe operations becomes much lower even with the same other variables (Miloševiæ et al., 2025. It is natural from an industrial viewpoint because almost any high-risk process performed in the oil and gas or petrochemical industries involves communication: shift handovers, coordination of energy isolation, checking equipment status, reporting process deviations, SIMOPS activities, reporting near misses, and making stop-work decisions. A lack of communication at any step can trigger a chain of events that culminates in loss of control over the process or employee injury (Naji et al., 2022).

As far as human factors are concerned, the study's findings align with the conclusions of Nwankwo et al., who found that accidents in the oil and gas industry were usually caused by human factors such as unsafe decisions, lack of supervision, and organizational issues. According to the HFACS-OGI framework, workers' mistakes are symptoms of organizational issues, not the causes themselves. Using Bayesian network analysis, the study concluded that unsafe behavior was not spontaneous but stemmed from limited communication and participation, and ineffective safety controls. Thus, improving the situation by focusing solely on workers' discipline is not an effective strategy (Manikumar et al., 2024; Nwankwo et al., 2022).

When discussing the relevance of the results to the petrochemical industry, it is necessary to consider the industry's sensitivity to process deviations. Indeed, compared to most traditional manufacturing industries, petrochemical companies rely on stable processes and quick reaction to deviations in them. Since petrochemical operations involve flammable materials, complex chemical reactions, high pressures, and interconnected utilities, small defects can easily become significant threats to employees or processes (Alahjil et al., 2025. Thus, reporting of near misses within this study is to be regarded as a leading indicator rather than a lagging one. If near-miss reporting is limited, it will be much harder for companies to discover weaknesses in safety barriers (Chukwuma 2023). This conclusion aligns with the literature that distinguishes between the two types of safety indicators (Pati 2023).

About the safety culture maturity theory, the study results indicate that the investigated system's current safety culture is at an intermediate maturity level. Workers have relatively high levels of risk awareness, but safety communication and active participation have not yet developed to a sufficient level. The characteristics of mature safety cultures include openness to reporting, collective learning, consistent leadership and decision-making, and the integration of safety into decision-making processes. As stated by Foussard et al., improvements in safety performance in multinational oil and gas companies are attributable to a higher level of maturity in their safety culture. Other studies also showed that maturity levels presented opportunities for further improvement in safety performance in the oil and gas industry. Thus, the sensitivity analysis highlighting the importance of safety communication can be interpreted as necessitating an organization's shift from a reactive or compliance-oriented approach to a proactive or generative one (Foussard et al., 2025; Rahim et al., 2025; Yudiawan et al., 2025).

Finally, safety behavior theory should also be discussed. In the oil and gas industry, employee safety behavior is usually determined by a variety of factors, including employees' knowledge and attitudes, the organizational environment, and system factors. According to the findings obtained by Quaigrain et al., compliance is determined by the first two factors mentioned. Guzman et al. also focused on the influence of occupational safety vulnerabilities and organizational environment on workers' safety. In addition, the study's findings revealed that this connection is unstable and depends on factors such as management commitment, safety communication, and participation. In other words, when all three factors improve simultaneously, the likelihood of safe behavior increases significantly (Haleem et al., 2025. In fact, it is why Bayesian Networks can be used to analyze the oil and gas industry and petrochemicals (Guzman et al., 2022; Quaigrain et al., 2022).

In addition, the interaction between safety culture and organizational performance warrants consideration. Bautista-Bernal et al. found that safety culture is related not only to safety performance but also to organizational performance. For the oil and gas industry, these findings mean that not only does poor safety culture increase injury risks, but it also poses threats of production losses, unplanned plant shutdowns, equipment damage, the cost of accident investigations, potential fines, and reputational damage. For petrochemical companies, even a small deviation can disrupt utilities, reactors, storage facilities, or loading/ unloading systems. Thus, the present study demonstrated that investing in safety culture is equivalent to investing in organizational success (Bautista-Bernal et al., 2024).

The topic of workplace fatigue deserves attention, especially in offshore operations, in long work schedules, and jobs requiring constant alertness. In their study, Wang et al. show a strong correlation between safety culture and the management of employee fatigue in the offshore oil and gas industry. In this research context, management commitment and safety communication could be seen as preconditions that enable fatigue, workload, and human resource capabilities to be perceived as elements of the safety culture rather than as individual issues for workers. Organizations lacking opportunities to discuss fatigue-related problems will be at risk of unsafe practices, even if employees' hazard awareness is quite high. This explains why the awareness of risks is not enough to ensure effective safety management (Wang et al., 2024).

On the governance and reporting side, the discussion is relevant to Pati's paper, which addresses sustainability reports and whether they reflect the level of organizational safety culture in the oil and gas and process sectors. In other words, formal safety indicators used in enterprise reporting cannot reveal the true quality of the safety culture implemented within the company. In the case under consideration, descriptive results and probabilities indicate a problem: deficiencies in safety communication go unnoticed in companies that focus solely on formal compliance and lagging statistics (Agustini et al., 2024. Hence, these results suggest that deeper indicators, such as near-miss reporting, safety voice, and control effectiveness, must be used to provide an accurate picture of organizational safety (Pati 2023).

From this perspective, it becomes clear that Indonesia's oil and gas industry needs a model for analyzing OSH culture that includes both the descriptive features of culture and the probability of relationships among its elements, while prioritizing interventions. Methodologically, the Bayesian Network used in the current research can serve as a tool for simulating scenarios to analyze what will happen if, for instance, organizations improve safety communication and increase the likelihood of successful operations (Asyik et al., 2026; Nurdiansyah & Lestari 2026).

Thus, the above discussion shows that OSH culture in the oil and gas and petrochemical industries constitutes a socio-technical system that affects operational reliability. Management commitment defines priorities; safety communication makes hazards audible; risk awareness helps workers identify deviations from established safety standards; and, finally, safety participation fosters learning processes. As a result, these four elements determine safe work behaviors, near-miss reports, effectiveness of controls, and operational safety conditions. Therefore, any strategy for improving OSH should focus on developing a culture of communication, a safety voice, cultural maturity, and the use of worker behavior data in operational systems.

CONCLUSION

Occupational safety and health (OSH) culture profoundly influences operational safety in the oil and gas and petrochemical sectors through systemic and probabilistic mechanisms. According to the analysis, the safety communication element is the most important variable influencing changes in the probability of creating and maintaining safe operating conditions in the industry, followed by management commitment, risk awareness, and safety participation. The identified factors shape safe work behavior and near-misses, which serve as mediators in the safety system under study. Thus, improvements in operational safety depend on much more than procedural measures; they require building a safety culture embedded in the safety management system and enabled by communication. For these reasons, it is recommended to focus on improving safety communication through transparent reporting systems, fostering a safety voice, and enhancing workers' participation in safety programs. Moreover, it is important to develop probabilistic methods for safety analysis (such as Bayesian Networks) as decision-support tools. Implications suggest that effective OSH management requires recognizing that it is part of a socio-technical system that influences business sustainability.

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DECLARATIONS

The authors declare that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. All authors have read and approved the final version of the manuscript and agree to its submission for publication.

Author contributions

Supardi contributed to the conceptualization, data collection, formal analysis, and preparation of the original manuscript draft. Samsudi, Arief Yulianto, and Suwito Eko Pramono contributed as supervisors through methodological guidance, validation, critical review, and manuscript editing throughout the research process.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of the use of AI and AI-assisted technologies

During the preparation of this manuscript, the authors used AI-assisted technology to support language editing, translation, and improvement of grammar and readability. The authors carefully reviewed and revised the content and take full responsibility for the accuracy, integrity, and originality of the final manuscript.

GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
OHS	Occupational Health and Safety — the interdisciplinary field concerned with the safety, health, and welfare of workers in occupational settings	
OSH	Occupational Safety and Health — used interchangeably with OHS in this study; refers to K3 (Keselamatan dan Kesehatan Kerja) in the Indonesian regulatory context	
K3	Keselamatan dan Kesehatan Kerja — the Indonesian term for Occupational Safety and Health, as mandated under PP No. 50/2012 (SMK3)	
BN	Bayesian Network — a probabilistic graphical model representing a set of variables and their conditional dependencies via a directed acyclic graph (DAG)	
CPT	Conditional Probability Table — a table that specifies the probability of each state of a node given all possible combinations of states of its parent nodes in the Bayesian Network	
DAG	Directed Acyclic Graph — a graph in which edges have a direction and no directed cycles exist; forms the structural backbone of a Bayesian Network	
SMK3	Sistem Manajemen Keselamatan dan Kesehatan Kerja — Indonesian OHS Management System as mandated by Government Regulation No. 50 of 2012 (PP No. 50/2012)	
PPE	Personal Protective Equipment — protective gear worn by workers to minimize exposure to occupational hazards (e.g., helmets, gloves, respirators, safety goggles)	
SOP	Standard Operating Procedure — documented step-by-step instructions designed to ensure consistent and safe execution of specific operational tasks	
HIRARC	Hazard Identification, Risk Assessment, and Risk Control — a systematic method for identifying workplace hazards, evaluating associated risks, and implementing appropriate control measures	

HFACS-OGI	Human Factors Analysis and Classification System — Oil and Gas Industry adaptation; a framework for classifying human factors that contribute to accidents in the oil and gas sector
IOGP	International Association of Oil and Gas Producers — global industry body that publishes safety performance indicators used as benchmarks in this study
ILO	International Labour Organization — a United Nations agency that sets international labour standards and collects global occupational safety data referenced in this study
BPJS Ketenagakerjaan	Badan Penyelenggara Jaminan Sosial Ketenagakerjaan — Indonesian Social Security Administering Body for Employment; the primary source of national occupational accident statistics in this study
P(A|B)	Posterior probability — the conditional probability of event A occurring given that event B has occurred; the primary output of Bayesian inference in this model
P(B|A)	Likelihood — the probability of observing evidence B given that hypothesis A is true; used in Bayes' theorem to update prior beliefs
P(A)	Prior probability — the initial probability of hypothesis A before observing any evidence; derived from survey data and literature in this study
P(B)	Evidence probability (marginal likelihood) — the total probability of observing evidence B across all possible hypotheses; acts as a normalizing constant in Bayes' theorem
Pa(X_i)	Parent node set of variable X_i — denotes the set of direct predecessor nodes of X_i in the Bayesian Network DAG; used in the joint probability factorization formula
P(Safe)	Probability of safe operational condition — the inferred probability that the operational safety node is in the "Safe" state given observed evidence in the Bayesian Network
P(Unsafe)	Probability of unsafe operational condition — the complement of P(Safe); represents the likelihood that operational safety conditions are hazardous given current evidence states
Near-miss	An unplanned event that did not result in injury, illness, or damage but had the potential to do so; used as a leading safety indicator and proactive reporting metric in this study
SIMOPS	Simultaneous Operations — concurrent execution of multiple activities in close proximity, presenting compounded safety risks that require heightened

	heightened communication and coordination
Likert scale	A five-point psychometric rating scale (1 = Strongly Disagree to 5 = Strongly Agree) used in this study to quantify respondents' perceptions of OHS culture and operational safety
Cronbach's Alpha (α)	A coefficient of internal consistency reliability; values ≥ 0.7 indicate acceptable reliability of the research instrument, as applied in this study's validity and reliability testing
SEM	Structural Equation Modeling — a conventional multivariate statistical method; contrasted with the Bayesian Network approach in this study due to its assumption of linear relationships
BUMN	Badan Usaha Milik Negara — Indonesian state-owned enterprise; refers to government-owned companies such as PT Chandra Asri Petrochemical and PT Krakatau Steel included in this study's sample context

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