

OPERATIONAL RISK ASSESSMENT USING ANP: EVIDENCE FROM INDUSTRIAL ENTERPRISES IN DUNG QUAT ECONOMIC ZONE, VIETNAM

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ABSTRACT

This study investigates the operational risk assessment of industrial enterprises in the Dung Quat Economic Zone, Vietnam, applying the Analytic Network Process (ANP) to prioritize critical risk factors affecting production and sustainability. We analyzed the influence of process, human-related, environmental, management, and supply chain risks on the overall operational stability of the enterprises. Expert judgments from 25 industry specialists were collected to construct pairwise comparison matrices, forming a comprehensive network of risk interdependencies. The results reveal that equipment failures, production interruptions, and poor quality control are the most significant risks impacting operational continuity. Additionally, managerial and human factors such as safety violations and ineffective maintenance planning were identified as crucial contributors. The study highlights the need for integrated risk management approaches addressing technical, organizational, and environmental dimensions to enhance industrial resilience. This research contributes to the understanding of risk prioritization in emerging industrial zones and offers practical insights for risk mitigation strategies to promote sustainable industrial development in Vietnam.



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1. INTRODUCTION

Industrial enterprises operating in heavy-industry zones frequently encounter complex operational risks resulting (Dudin et al., 2016) from the interactions of machinery, human factors, environmental conditions, management systems, and supply chain dynamics. These risks are particularly pronounced in large-scale industrial clusters, where high-risk operations such as oil refining, petrochemical production, steel manufacturing, shipbuilding, chemical processing, and logistics are concentrated. In such environments, even minor failures can cascade through multiple operational domains, highlighting the need for robust risk assessment

frameworks that account for interdependencies among risk factors.

The Dung Quat Economic Zone (DQEZ) in Quang Ngai Province, Vietnam, represents a prominent example of a high-intensity industrial cluster (Le & Vu, 2022). As Vietnam's first national oil refinery hub, DQEZ hosts major industrial facilities, including the Binh Son Refining and Petrochemical Company (BSR), steel plants, shipbuilding and mechanical enterprises, chemical production units, port logistics operators, and numerous supporting industries.

The operational environment in DQEZ is characterized by frequent and interdependent risks. For instance, equipment malfunctions can trigger safety incidents; human errors may escalate into environmental accidents;

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management inefficiencies can propagate issues across departments; supply chain disruptions may halt production lines; and environmental hazards, including storms and floods common in Central Vietnam, can further amplify operational uncertainties. Collectively, these factors underscore the necessity for systematic and comprehensive approaches to evaluate and prioritize operational risks within the zone.

Despite several studies addressing industrial operational risks in Vietnam, very few have specifically examined large-scale industrial zones such as DQEZ, where the interactions among risk factors are complex and dynamic. In reality, operational risk factors are highly interdependent: human errors are influenced by management practices; equipment failures can exacerbate environmental and safety risks; supply chain interruptions affect production processes; and process deviations amplify both management and safety-related risks. These interdependencies indicate the need for a more advanced multi-criteria decision-making (MCDM) approach capable of capturing complex feedback mechanisms.

The Analytic Hierarchy Process (AHP) is a widely used multi-criteria decision-making (MCDM) technique that simplifies complex decisions by structuring them into hierarchical levels of criteria and alternatives. However, AHP assumes independence among criteria, which limits its effectiveness in situations where interdependencies and feedback exist (Nguyen & Tuyen, 2024; Nguyen & Tuyen, 2025). The Analytic Network Process (ANP) offers a suitable methodological framework for this context. ANP is a multi-criteria decision-making method. The Analytic Network Process (ANP) was developed as a generalization of AHP, allowing the modeling of complex interrelationships and feedback among criteria and alternatives (Tuyen, 2024a). As a powerful MCDM technique, ANP accommodates nonlinear relationships, feedback loops, and dependency structures among criteria and sub-criteria (Daimi & Rebai, 2023), providing a more realistic and comprehensive evaluation of operational risks compared to hierarchical models such as AHP. By capturing interdependencies among diverse risk factors, ANP enables more accurate prioritization and supports decision-making in complex industrial settings.

Accordingly, this study aims to (i) identify the major operational risks faced by industrial enterprises in DQEZ, (ii) develop an ANP-based model to evaluate the dependencies among risk factors, (iii) determine the relative importance of each operational risk category, and (iv) provide management recommendations for risk prevention and mitigation. The contributions of this research are fourfold: it introduces the first ANP-based operational risk model specifically applied to DQEZ; captures interdependent relationships among risk factors that have been overlooked in previous studies; offers a decision-support tool for managers to prioritize and mitigate critical risks; and enriches the literature on quality management, industrial risk assessment, and MCDM applications in developing industrial contexts.

2. LITERATURE REVIEW

2.1 Operational Risk in Industrial Enterprises

Operational risk is widely recognized as one of the most critical challenges in industrial enterprises, particularly in high-risk sectors such as oil refining, petrochemicals, metallurgy, chemical production, shipbuilding, and logistics. Operational risks are defined as the potential for losses arising from inadequate or failed internal processes, human errors, equipment failures, or external events (Pangestuti et al., 2021). In industrial contexts, these risks are not only frequent but also often interdependent, leading to cascading failures that can significantly impact production continuity, safety, and financial performance.

Several studies have investigated operational risks in industrial settings. For example, Soltanzadeh et al. (2024) assessed safety and security risks in the chemical process industries, while Vital-Soto & Olivares-Aguila (2023) reviewed and assessed the exploration of operational risks and disruptions in production operations. Most of these studies emphasize the importance of systematically identifying, prioritizing, and mitigating operational risks, particularly in environments with high interconnectivity among risk factors.

2.2 Risk Assessment Methods in Industry

Various approaches have been developed to assess operational risks, including qualitative, quantitative, and hybrid methods. Traditional techniques often rely on checklists, failure mode and effect analysis (FMEA), and risk matrices. For example, the study by Immawan et al. (2018) analyzed operational risks with the FMEA method. While these approaches provide basic insights, they are limited in addressing interdependencies among multiple risk factors.

Multi-criteria decision-making (MCDM) methods, such as the Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP), have been increasingly applied to industrial risk assessment due to their ability to structure complex problems and quantify the relative importance of risk factors. AHP has been widely used for prioritizing risks; for example, Tuyen (2024b) applied AHP in prioritizing risks in island tourism activities, Nguyen et al. (2025) applied AHP to prioritize supply chain risks, and Van et al. (2025) used AHP in prioritizing risks in production, but its hierarchical structure assumes independence among criteria, which is often unrealistic in industrial contexts.

2.3 Analytic Network Process for Risk Assessment

The Analytic Network Process (ANP) extends AHP by incorporating dependencies and feedback among elements (Saaty, 2016), making it highly suitable for evaluating operational risks in industrial environments. ANP has been applied in diverse sectors, including manufacturing, energy, logistics, and chemical industries.

For example, Yu et al. (2019) applied ANP to analyze the factors affecting occupational safety and health in coal

chemical enterprises. Similarly, Patradhiani (2021) used ANP to evaluate the human factor causes of occupational risks in the chemical industry. These studies demonstrate the effectiveness of ANP in providing a comprehensive and realistic assessment of operational risks, especially in settings where multiple risk factors influence each other.

2.4 Key Risk Criteria in Industrial Enterprises

Based on the literature, operational risks in industrial enterprises can be broadly categorized into five main clusters. Process risks encompass equipment failure, process deviations, production interruptions, and poor quality control (Alsaidalani & Elmadhoun, 2022). Human-related risks include lack of training, safety violations, workforce shortage, and fatigue (Diao & Ghorbani, 2018). Environmental and safety risks cover fires, explosions, environmental pollution, workplace accidents, and natural hazards (Manawil, 2020). Management risks involve inadequate supervision, poor communication, insufficient risk assessment, and ineffective maintenance planning (Zhao et al., 2023). Finally, supply chain risks include material shortages, supplier unreliability, transportation delays, and price volatility (Kanike, 2023). These five clusters closely reflect the characteristics of industrial enterprises in the Dung Quat Economic Zone, providing a suitable framework for developing an ANP-based risk assessment model.

2.5 Research Gap and Justification for Current Study

Despite extensive research on operational risk, several important gaps remain in the literature. First, few studies have examined interdependent risks in industrial zones, particularly using the Analytic Network Process (ANP), which is capable of capturing complex feedback and dependency structures among risk factors. Second, limited research has focused on emerging industrial contexts in developing countries, including Vietnam, where operational environments are characterized by unique challenges such as workforce skill gaps, limited safety culture, and exposure to environmental hazards. Third, existing studies often fail to provide actionable decision-support tools for managers operating in complex industrial settings, reducing the practical relevance of their findings. To address these gaps, the present study develops an ANP-based operational risk model specifically for industrial enterprises in the Dung Quat Economic Zone, Vietnam. By capturing the

interdependencies among five major risk clusters—process, human, environmental and safety, management, and supply chain risks—the model provides a structured and practical framework for prioritizing operational risks and supporting managerial decision-making.

3. METHODOLOGY

3.1 Identification of Risk Criteria

To comprehensively assess operational risks in industrial enterprises within the Dung Quat Economic Zone (DQEZ), this study developed a structured set of risk criteria through a multi-step approach combining literature synthesis, field observations, and expert consultation. Although no single study provides an exhaustive list of operational risks applicable to the specific context of heavy industrial zones in Vietnam, the five primary risk clusters—Process Risks, Human-Related Risks, Environmental & Safety Risks, Management Risks, and Supply Chain Risks—along with their representative sub-criteria, were derived from an extensive review of international studies on industrial, operational, and supply chain risks (Alsaidalani & Elmadhoun, 2022; Diao & Ghorbani, 2018; Manawil, 2020; Zhao et al., 2023; Kanike, 2023) and adapted to reflect the particular operational environment of DQEZ. To ensure the relevance, completeness, and contextual applicability of these criteria, they were validated through consultations with five industrial experts and safety managers operating in DQEZ. This process confirmed that the selected sub-criteria capture the most significant operational risks that industrial enterprises encounter locally, including high-impact equipment failures, safety violations, process deviations, supply chain disruptions, and environmental hazards. Furthermore, the subsequent Analytic Network Process (ANP) analysis allows for the quantitative prioritization of risks by capturing the interdependencies among these criteria, ensuring that the resulting risk model is both contextually grounded and methodologically rigorous. In summary, the proposed set of operational risk criteria represents a synthesis of theoretical insights and practical realities, providing a scientifically defensible foundation for the assessment and prioritization of risks in industrial operations at DQEZ. Table 1 shows a list of risks.

Table 1. Operational risk criteria and sub-criteria

Criteria	Sub-Criteria	Definition / Description
Process Risks (PR)	Equipment Failures (R1)	Unexpected malfunctions or breakdowns of production machinery and equipment that disrupt operational continuity and reduce efficiency.
	Process Deviations (R2)	Variations or departures from established standard operating procedures or process parameters, potentially compromising product quality or production performance.
	Production Interruptions (R3)	Unplanned halts or delays in production processes that negatively affect output, timelines, or operational efficiency.
	Poor Quality Control (R4)	Ineffective monitoring, inspection, or enforcement of quality standards, resulting in defective or substandard products.

Human-Related Risks (HR)	Lack of Training (R5)	Insufficient employee knowledge, technical skills, or competence to perform tasks safely and efficiently, increasing the likelihood of errors.
	Safety Violations (R6)	Non-compliance with workplace safety policies, procedures, or regulations, potentially leading to accidents or hazardous incidents.
	Workforce Shortage (R7)	Inadequate staffing or insufficient human resources to maintain normal operational levels, causing production delays or overload on existing staff.
	Fatigue / Overwork (R8)	Physical or mental exhaustion of employees due to prolonged working hours or high workloads, increasing the probability of mistakes and accidents.
Environmental & Safety Risks (ES)	Fires & Explosions (R9)	Incidents involving combustion, chemical reactions, or ignition events that pose threats to life, property, and operational continuity.
	Environmental Pollution (R10)	Release of pollutants, hazardous substances, or contaminants into the environment (air, water, or soil) with potential regulatory, health, or operational consequences.
	Workplace Accidents (R11)	Occurrences of injury, illness, or health hazards within the workplace due to unsafe practices, conditions, or human errors.
	Natural Hazards (R12)	External environmental events such as storms, floods, or earthquakes that disrupt operations and increase operational uncertainty.
Management Risks (MG)	Inadequate Supervision (R13)	Insufficient oversight, monitoring, or guidance of operational activities, leading to errors or inefficiencies.
	Poor Communication (R14)	Lack of effective information flow, coordination, or clarity among teams and departments, resulting in misunderstandings or operational delays.
	Insufficient Risk Assessment (R15)	Failure to systematically identify, evaluate, and prioritize operational risks, reducing preparedness for potential incidents.
	Ineffective Maintenance Planning (R16)	Inadequate scheduling, execution, or monitoring of maintenance activities, increasing the likelihood of equipment failure or downtime.
Supply Chain Risks (SC)	Material Shortages (R17)	Insufficient availability of essential raw materials or components, leading to disruptions in production schedules.
	Supplier Unreliability (R18)	Inconsistent performance of suppliers in delivering materials or services on time, with required quality, or in sufficient quantity.
	Transportation Delays (R19)	Disruptions or delays in the logistics and delivery processes, impacting production continuity or supply chain efficiency.
	Price Volatility (R20)	Sudden fluctuations in the cost of raw materials, components, or inputs that affect budgeting, procurement, and production planning.

3.2 Data Collection and Expert Selection

Primary data were collected through structured questionnaires and interviews with industry professionals and managers in DQEZ. A total of 25 experts were selected based on their experience in operational management, safety, quality control, and supply chain coordination. The inclusion criteria ensured that respondents had at least five years of relevant industrial experience and direct involvement in operational decision-making.

Table 2. Impact of New Technology on Yield and Profitability

Definition	Level of importance	Description
Equal importance	1	Criteria i and j are equally important.
Moderate importance	3	Criteria i is less important than Criteria j.
Important	5	Criteria i is more important than Criteria j.
Very important	7	Criteria i is very important than Criteria j
Extremely important	9	Criteria i is definitely more important than Criteria j
Intermediate value	2;4;6;8	

Experts were asked to make pairwise comparisons of risk factors within and between clusters using a 9-point scale (Saaty, 2008), which is standard in ANP methodology.

The data collection process ensured consistency and reliability, and respondents were guided to consider interdependencies among risk criteria during the evaluation (Table 2).

3.3 ANP Model Development

The Analytic Network Process (ANP) was employed to assess the relative importance of operational risks and capture interdependencies among risk clusters. According to Alinezhad & Khalili (2019), the modeling process includes the following steps:

Structuring the Network: The five risk clusters and their sub-criteria were arranged into a network, with interdependencies explicitly mapped based on expert input. Feedback loops between clusters and within clusters were considered to represent real-world operational risk dynamics.

Pairwise Comparisons: Experts conducted pairwise comparisons to evaluate the relative influence of each element. The comparisons were performed both within clusters and across clusters that influence each other.

Supermatrix Formation: The pairwise comparison results were compiled into an unweighted supermatrix, representing the influence of each element on every other element in the network. The Hyperlink Matrix is formed by defining the priority vectors as the matrix of Equation (1).

$$W = \begin{matrix} & \begin{matrix} Goal & Criteria & Sub - criteria \end{matrix} \\ \begin{matrix} Goal \\ Criteria \\ Sub - criteria \end{matrix} & \begin{bmatrix} 0 & 0 & 0 \\ W_{21} & W_{22} & 0 \\ 0 & W_{32} & W_{33} \end{bmatrix} \end{matrix} \quad (1)$$

In which: W21: Pairwise comparison matrix of criteria; W22: Internal relationship comparison matrix of criteria; W32: Pairwise comparison matrix of sub-criteria; W33: Internal relationship comparison matrix of sub-criteria.

Weighted Supermatrix: The unweighted supermatrix was normalized to obtain a weighted supermatrix, ensuring that the column sums equal one.

Limit Supermatrix Calculation: The weighted supermatrix was raised to powers until convergence to obtain the limit supermatrix, which provides the final global priority weights of all risks. The hyperlink matrix converges, that is, it reaches a steady state, also known as the limit matrix. Then $\lim_{k \rightarrow \infty} (W)^k = W_{limit}$ or $W^k = W^{k+1}$, where W_{limit} is the limit matrix, and k is the number of iterations, also known as the exponent.

3.4 Reliability and Validity

The consistency of expert judgments was verified using the Consistency Ratio (CR). Comparisons with CR values exceeding 0.1 were revised until acceptable consistency was achieved. To ensure reliability and consistency in data processing and calculation, the research team used Microsoft Excel software as a calculation support tool. The calculated value is only accepted when the consistency ratio $CR \leq 10\%$ (0.1), with CI, CR is calculated by the following formula: CR consistency ratio: $CR = CI/RI$.

In which RI is the random consistency index (presented in Table 3), and CI is the consistency index, $CI = (\lambda_{max} - n)/(n-1)$; λ_{max} is the eigenvalue of the matrix, $\lambda_{max} = \sum_{i=1}^n w_i \times \sum_{j=1}^n a_{ij}$.

Table 3. RI index (Ibrahim et al., 2025)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.5 8	0.9	1.1 2	1.2 4	1.3 2	1.4 1	1.4 5	1.4 9
n	11	12	13	14	15	16	17	18	19	20
RI	1.5 3	1.5 4	1.5 6	1.5 7	1.5 9	1.6 0	1.6 1	1.6 1	1.6 2	1.6 3
n	21	22	23	24	25	26	27	28	29	30
RI	1.6 3	1.6 4	1.6 5	1.6 5	1.6 6	1.6 6	1.6 6	1.6 6	1.6 7	1.6 7

In addition, a sensitivity analysis was conducted to test the robustness of the priority rankings, ensuring that small changes in input judgments would not significantly alter the results.

4. RESULTS

To develop the pairwise comparison matrices required in the ANP model, judgments were obtained from 25 experts who possess extensive experience in operational management, safety, engineering, and supply chain

activities within industrial enterprises in the Dung Quat Economic Zone. Each expert independently evaluated all required pairwise comparisons. Because the ANP framework involves multiple hierarchical levels and numerous interdependent relationships, this process generated 25 individual comparison matrices for each decision context.

To synthesize these assessments into a single representative matrix, the study applied a mode-based aggregation approach. For every element in each matrix, the value most frequently selected by the experts was adopted as the final judgment. This aggregation rule ensures that the resulting matrix reflects the dominant expert perspective while minimizing the influence of extreme or inconsistent responses. The consolidated matrices thus provide a coherent and collectively informed foundation for the subsequent stages of the ANP analysis.

After completing the pairwise comparisons among criteria, among sub-criteria, between criteria and sub-criteria, and among all internal dependencies within and across clusters, the study constructed the hyperlink matrix (W), presented in Appendix A1. This matrix fully represents the feedback structure and interdependence among the identified operational risk factors, serving as a critical input for determining the global weights of risks.

Table 4. The overall weighting results of the risks.

Code	Risk Description	OW	Rank
R1	Equipment Failures	0.098	1
R3	Production Interruptions	0.090	2
R4	Poor Quality Control	0.080	3
R6	Safety Violations	0.071	4
R16	Ineffective Maintenance Planning	0.064	5
R15	Insufficient Risk Assessment	0.063	6
R9	Fires & Explosions	0.061	7
R11	Workplace Accidents	0.059	8
R5	Lack of Training	0.058	9
R2	Process Deviations	0.053	10
R8	Fatigue / Overwork	0.044	11
R17	Material Shortages	0.038	12
R13	Inadequate Supervision	0.036	13
R18	Supplier Unreliability	0.036	13
R10	Environmental Pollution	0.029	14
R14	Poor Communication	0.027	15
R19	Transportation Delays	0.026	16
R7	Workforce Shortage	0.024	17
R12	Natural Hazards	0.024	17
R20	Price Volatility	0.018	18

From the initial hyperlink matrix W, the research proceeded to derive a convergence matrix. By repeatedly multiplying matrix W (12 iterations, with a convergence threshold of 10^{-3}), a stable matrix—referred to as the limit hyperlink matrix (W_{limit})—was obtained. This matrix represents the steady-state weights of all criteria

and sub-criteria, indicating their long-term relative influence within the operational risk system of industrial enterprises in the Dung Quat Economic Zone. The final results are reported in Appendix A2.

Based on the limit supermatrix obtained after the convergence process, the final overall weights of all risk factors were derived. These weights reflect the long-term relative influence of each sub-risk within the integrated operational risk structure. The ranking of the twenty sub-criteria is presented in Table 4.

To assess the stability of the operational risk prioritization results, a sensitivity analysis was conducted under three scenarios: (1) baseline, using the original ANP global weights; (2) +10%, reflecting a slight increase in the weight of the most influential cluster (Process Risks) to simulate potential variations in expert evaluations; and (3) -10%, examining the effect of a reduced weight in the same cluster. This analysis measures the variation in risk rankings when cluster weights change, which is crucial in MCDM studies like ANP, where final decisions rely on multiple interdependent criteria and expert judgments. Weight variations within $\pm 10\%$ were assumed to reflect natural fluctuations in expert assessments.

Figure 1 illustrates the changes in global weights and rankings of all 20 prioritized risks across these scenarios. The y-axis is inverted to emphasize that a lower numerical rank corresponds to a higher risk priority.

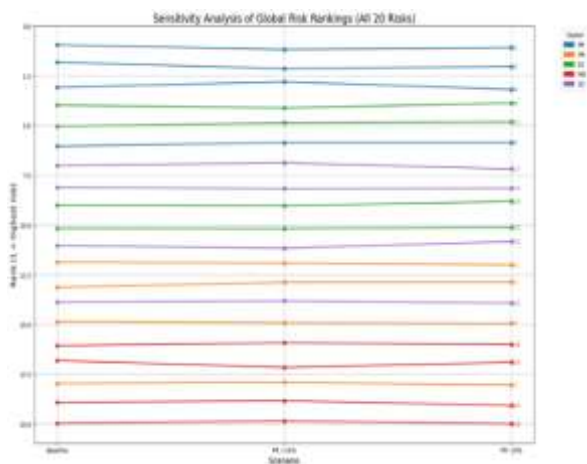


Figure 1. Sensitivity analysis results

The results reveal minor fluctuations in rankings across scenarios, with most risks experiencing changes within one or two positions. Specifically:

Process Risks (R1–R4) consistently retained the highest priority. R1 (Equipment Failures), R3 (Production Interruptions), and R4 (Poor Quality Control) maintained their leading positions across all scenarios, confirming the dominant influence of the Process Risks cluster. R2 (Process Deviations) showed a small shift but remained among the top-ranked risks.

Environmental & Safety Risks (R9–R12), particularly R9 (Fires & Explosions) and R11 (Workplace Accidents), slightly increased in ranking when the Process Risks

cluster was augmented by +10%, but none surpassed the top PR risks.

Human-Related Risks (R5–R8) showed stable rankings with minor fluctuations. R6 (Safety Violations) and R5 (Lack of Training) remained moderately high, whereas R7 (Workforce Shortage) and R8 (Fatigue / Overwork) stayed in lower-middle positions.

Management Risks (R13–R16) and Supply Chain Risks (R17–R20) demonstrated stable rankings with only slight variations, indicating their consistent but relatively lower influence on the overall risk prioritization. For example, R16 (Ineffective Maintenance Planning) and R15 (Insufficient Risk Assessment) remained moderately ranked, while R20 (Price Volatility) stayed as the lowest-ranked risk.

These controlled fluctuations confirm the robustness of the ANP-based operational risk prioritization model. The top-ranked risks remain consistently identified regardless of reasonable changes in cluster weights, ensuring that the prioritization is both reliable and defensible. Decision-makers can confidently focus mitigation efforts on the high-priority operational risks while maintaining awareness of moderate and lower-priority risks within industrial enterprises in Dung Quat Economic Zone.

The overall weights derived from the ANP analysis present a prioritized hierarchy of operational risks confronting industrial enterprises within the Dung Quat Economic Zone. The predominance of Equipment Failures as the highest weighted risk factor (0.098) reflects the intrinsic dependency of production continuity on machinery reliability. This finding highlights the critical importance of advanced maintenance regimes and technology modernization to mitigate unexpected disruptions that can severely compromise operational efficiency.

Closely ranked are Production Interruptions (0.090) and Poor Quality Control (0.080), emphasizing the fragility of industrial workflows and the paramount significance of maintaining stringent quality assurance measures. The substantial weights of these risks elucidate the vulnerability of enterprises to both process deviations and quality inconsistencies, which, if unaddressed, can undermine product competitiveness and customer satisfaction.

Human and managerial factors also emerge as significant contributors, with Safety Violations (0.071), Ineffective Maintenance Planning (0.064), and Insufficient Risk Assessment (0.063) demonstrating considerable influence. This underscores that beyond technical vulnerabilities, governance, risk awareness, and workforce competence are pivotal in shaping an enterprise's operational resilience. The results suggest that many organizations may still be in nascent stages of embedding comprehensive risk management and safety cultures, necessitating targeted interventions.

Environmental and safety-related risks, such as Fires & Explosions (0.061) and Workplace Accidents (0.059), while slightly lower in ranking, nonetheless represent persistent hazards inherent to heavy industrial operations. Their presence reaffirms the need for sustained emphasis

on safety protocols and emergency preparedness to safeguard human life and assets.

Conversely, risks associated with external and market uncertainties, including Workforce Shortage (0.024), Natural Hazards (0.024), and Price Volatility (0.018), were assigned relatively minor weights. This distribution of priorities indicates a perception among experts that internal operational challenges pose more immediate and controllable threats compared to broader environmental or economic factors. Such an outlook may be attributed to the regulated and relatively stable industrial environment within Dung Quat.

Collectively, these findings highlight the imperative for integrated risk management frameworks that concurrently address technological reliability, process stability, human resource capability, and safety governance. By adopting such holistic strategies, enterprises in Dung Quat can better anticipate and mitigate multifaceted risks, fostering sustainable industrial development aligned with regional economic objectives.

5. DISCUSSION

This study employed the ANP approach to assess and prioritize operational risks faced by industrial enterprises in the Dung Quat Economic Zone, providing valuable insights into the interconnected nature of these risks within the local industrial ecosystem. The findings highlight the critical role of equipment reliability, production continuity, and quality control in shaping operational resilience.

The highest overall weight assigned to Equipment Failures (0.098) underscores the centrality of machinery performance in maintaining uninterrupted production processes. This reflects the region's heavy industrial focus, where machinery breakdowns can trigger cascading disruptions across the entire production chain (da Silva et al., 2025). Such a result aligns with broader industrial trends emphasizing the imperative for advanced maintenance strategies and technological upgrades to reduce unplanned downtime and enhance operational efficiency.

Production Interruptions (0.090) and Poor Quality Control (0.080) also emerged as major concerns, illustrating vulnerabilities in process stability and product standards. These factors not only directly impact productivity but also influence customer satisfaction and market competitiveness. The significant weights of these risks indicate a pressing need for enterprises to invest in process optimization, quality assurance systems, and robust monitoring mechanisms (Okuyelu & Adaji, 2024). Human-related and managerial risks, particularly Safety Violations (0.071), Ineffective Maintenance Planning (0.064), and Insufficient Risk Assessment (0.063), further highlight the importance of governance and human factors in operational risk management. Safety compliance remains a critical challenge that, if neglected, can lead to severe consequences including accidents and

regulatory penalties (Jahidi et al., 2024). Meanwhile, the relatively high importance of maintenance planning and risk assessment indicates that many enterprises might still be in the early stages of adopting systematic, proactive risk management frameworks, which are vital for sustainable operations.

Environmental and safety hazards such as Fires & Explosions (0.061) and Workplace Accidents (0.059) continue to pose substantial threats, reflecting the inherent hazards present in heavy industrial environments. Although these risks rank slightly lower than equipment and process-related factors, their potential impact on human life, assets, and operational continuity demands sustained attention.

In contrast, risks related to external factors like Workforce Shortage (0.024), Natural Hazards (0.024), and Price Volatility (0.018) received comparatively lower weights. This suggests that experts perceive internal operational challenges as more immediate and manageable than broader environmental and market uncertainties. It also implies that external risks may be mitigated through strategic planning and are less frequently encountered or less disruptive in the day-to-day operations within the Dung Quat industrial context.

The results underscore the necessity of integrated risk management approaches that simultaneously address technical equipment reliability, process optimization, human resource development, and safety governance. Enhancing these areas will enable enterprises to build resilience against both predictable and emergent operational risks, contributing to sustainable industrial development in the region.

6. CONCLUSION

This study employed the Analytic Network Process (ANP) to systematically assess and prioritize operational risks faced by industrial enterprises in the Dung Quat Economic Zone. The results reveal that equipment failures, production interruptions, and poor quality control represent the most critical risk factors undermining operational continuity and efficiency in this industrial context.

Moreover, human and managerial risks, including safety violations, ineffective maintenance planning, and insufficient risk assessment, also play a significant role in shaping the overall risk profile. These findings emphasize that beyond technological vulnerabilities, the governance structure and workforce competence are essential components for fostering resilience.

While environmental hazards and external uncertainties, such as natural disasters and price volatility, were assigned comparatively lower importance, their potential impact cannot be overlooked given the inherent complexity of industrial operations.

The study highlights the necessity for comprehensive, integrated risk management approaches that combine technical, human, and organizational dimensions. Emphasizing advanced maintenance regimes, rigorous

quality control, and safety compliance will be indispensable for reducing vulnerabilities.

Ultimately, these prioritized insights offer valuable guidance for policymakers and industrial managers to design targeted mitigation strategies, improve resource allocation, and enhance sustainable industrial development in the Dung Quat Economic Zone. Future research should explore dynamic risk interactions and the effectiveness of implemented control measures to further strengthen operational resilience.

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