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Risk-Based Evaluation of Fire Hazard Prevention and Handling Systems in a High-Rise Building

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ABSTRACT (9 PT)

Fire incidents in high-rise office buildings continue to occur despite formal compliance with fire safety regulations, indicating a gap between regulatory requirements and effective fire risk control in practice. High-rise buildings concentrate occupants, assets, and operational activities within vertically complex environments, making fire events a significant managerial and organizational risk. This study aims to evaluate fire hazard prevention and handling systems in a high-rise office building using a risk-based management approach to identify priority fire risks and underlying systemic causes. A mixed qualitative–quantitative case study design was applied, with emphasis on quantitative fire risk assessment. Fire hazards were identified through field observations, structured interviews, and document review. Risks were assessed using a Hazard Identification and Risk Assessment (HIRARC) framework, adapted from the UNSW Health and Safety risk matrix, with likelihood and consequence scoring. Risk distribution and a fire risk pyramid were used to visualize the overall risk profile, while root cause analysis was conducted using a fishbone diagram. The results identified 15 fire-related hazards, with 66.7% classified as medium risk, 26.6% as high risk, 6.7% as extreme risk, and none as low risk. These findings indicate systemic operational and managerial vulnerabilities. The study concludes that effective fire safety requires an integrated, risk-based management approach that prioritizes risk reduction over regulatory compliance alone.

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1. INTRODUCTION

The rapid growth of high-rise office buildings in urban areas has intensified organizational exposure to fire-related risks. As strategic assets supporting business continuity and administrative operations, high-rise buildings concentrate large numbers of occupants, valuable resources, and complex operational systems within vertically constrained environments. Fire incidents in such buildings therefore pose not only safety hazards but also significant risks to organizational performance, financial stability, and operational resilience due to the potential for casualties, asset loss, and prolonged business disruption (Shi et al., 2021; Liu et al., 2024; Wardhani et al., 2024).

High-rise buildings present unique fire safety challenges due to their vertical configuration, high occupant density, complex evacuation processes, and dependence on active fire protection systems. Consequently, risk assessment approaches specifically designed for high-rise environments are required to identify critical vulnerabilities and prioritize mitigation strategies (Shi et al., 2021; Liu et al., 2024). Fire risk assessment has evolved from a compliance-oriented approach toward a risk-based methodology that systematically evaluates the probability and consequences of fire incidents to support informed decision-making and resource allocation (Hadjisophocleous et al., 2022). Furthermore, modern fire protection engineering emphasizes integrating technical systems, human behavior, and organizational preparedness as essential components of comprehensive fire safety management (Hurley et al., 2023).

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Despite the widespread provision of active and passive fire protection systems and formal compliance with regulatory requirements, fire incidents in high-rise buildings continue to occur both globally and nationally. Empirical evidence suggests that deficiencies in system readiness, maintenance effectiveness, evacuation preparedness, and emergency coordination frequently undermine fire safety performance, even in buildings that are compliant on paper. This condition indicates that regulatory compliance alone is insufficient to ensure effective fire risk control and that fire safety must be evaluated in terms of operational effectiveness rather than mere system availability (Liu et al., 2024; Shi et al., 2021).

Fire is a complex physical and chemical phenomenon that generates multidimensional risks when it occurs in building environments, including threats to human life, structural integrity, property, business continuity, and the surrounding environment. In high-rise buildings, these risks are amplified by vertical fire spread, smoke accumulation, and time constraints on evacuation. Consequently, fire safety should not be treated solely as a technical or engineering problem but rather as an integrated risk management issue involving technical systems, human behavior, organizational procedures, and managerial oversight (Badri et al., 2021; Pradita & Sentoso, 2022).

In Indonesia, fire prevention and protection in buildings are regulated by national and regional frameworks that mandate the provision of fire protection systems, life-safety facilities, and fire-safety management practices. While these regulations establish a comprehensive legal foundation, numerous studies reveal persistent gaps between documented compliance and actual implementation in operational settings. Common deficiencies include inadequate maintenance, limited inspection routines, insufficient emergency preparedness, and weak enforcement of safety procedures, particularly in high-rise office buildings with complex operational demands (PERDA DKI Jakarta No. 8 Tahun 2008; Liu et al., 2024).

Previous studies on fire safety in high-rise buildings have largely focused on evaluating individual fire protection components or conducting compliance-based audits. Although such studies provide useful technical information, they often assess fire safety elements in isolation and do not quantitatively prioritize hazards by likelihood and potential consequences. As a result, these approaches offer limited support for managerial decision-making, particularly in determining which deficiencies pose the greatest risk and require immediate corrective action (Shi et al., 2021; Liu et al., 2024; Anwar, 2023).

In addition to technical deficiencies, human and organizational factors have been widely identified as dominant contributors to fire safety failures. Limited fire safety awareness, insufficient training, unclear standard operating procedures, and weak management commitment frequently lead to unsafe behavior, delayed emergency response, and ineffective use of fire protection equipment. These factors often interact with technical shortcomings, significantly increasing both the likelihood and severity of fire incidents, thereby reinforcing the systemic nature of fire risk in high-rise buildings (Pradita & Sentoso, 2022; Kuligowski, 2021).

Despite growing recognition of the need for integrated fire safety management, empirical studies that systematically integrate hazard identification, quantitative fire risk assessment, conformity analysis, and root cause analysis within a single research framework remain limited, particularly for high-rise office buildings in Indonesia. Many existing studies rely on qualitative descriptions or compliance checklists without translating findings into prioritized risk categories and actionable management insights, thereby limiting their practical applicability for building managers and policymakers (Shi et al., 2021; Anwar, 2023).

A structured risk-based approach is therefore required to address these limitations. Hazard Identification and Risk Assessment (HIRA) provides a systematic method for identifying fire hazards, evaluating their likelihood and consequences, and classifying risks into priority levels. When complemented by conformity evaluation and root cause analysis techniques, such as fishbone diagrams, HIRA enables the identification of systemic weaknesses underlying elevated fire risks. Risk visualization tools, including risk distribution analysis and risk pyramids, further support managerial decision-making by illustrating patterns of vulnerability and clarifying risk control priorities (Badri et al., 2021; Kuswardana et al., 2017).

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Accordingly, this study aims to: (1) identify fire hazards in a high-rise office building through systematic observation, interviews, and document review; (2) assess fire risks using a quantitative likelihood–consequence framework to determine risk levels; (3) evaluate the conformity and effectiveness of active fire protection systems, life safety facilities, and fire safety management practices based on their associated risk severity; and (4) analyze dominant inhibiting factors contributing to elevated fire risks using a cause-and-effect (fishbone) approach. By integrating quantitative risk assessment with root cause analysis, this study seeks to bridge the gap between regulatory compliance and practical fire safety effectiveness and to provide prioritized, evidence-based recommendations for improving fire hazard prevention and handling systems in high-rise buildings (Anwar, 2023; Shi et al., 2021; Liu et al., 2024).

2. RESEARCH METHOD

This methodological design was specifically developed to move beyond compliance-based fire safety evaluation by quantitatively linking system conformity with risk severity. This study employed a mixed qualitative–quantitative case study design with a strong emphasis on quantitative fire risk assessment to support risk-based managerial decision-making. The quantitative approach was used to overcome the limitations of compliance-based fire safety evaluations by enabling systematic risk prioritization based on likelihood and severity of consequences. The qualitative component complemented the analysis by providing contextual understanding of organizational and operational factors influencing fire safety performance in a high-rise office building (Shi et al., 2021; Liu et al., 2024; Anwar, 2023).

The research was conducted in a twelve-story high-rise office building in Jakarta, Indonesia, selected for its high occupancy, functional complexity, and availability of fire safety documentation. High-rise office buildings represent a critical risk environment because they combine dense human activity with complex technical systems and managerial structures. The study's scope covered all floors and major fire safety components to ensure a comprehensive assessment of systemic fire-risk conditions rather than isolated technical deficiencies (Wardhani et al., 2024; Liu et al., 2024).

The unit of analysis in this study was the building fire safety system, encompassing active fire protection systems, life safety facilities, fire prevention practices, and fire safety management procedures. To maintain consistency with the research objectives and results structure, the analysis was conducted through four sequential stages: hazard identification, quantitative fire risk assessment, conformity evaluation, and root cause analysis. This staged framework ensures that identified hazards are systematically prioritized and linked to their underlying organizational and technical causes (Anwar, 2023; Shi et al., 2021).

Hazard identification was conducted through structured field observations, semi-structured interviews with building management and occupants, and document review of fire safety records and inspection reports. Standardized inspection checklists were used to identify deficiencies related to fire detection, suppression, evacuation facilities, and management practices. This systematic identification process aimed to capture both technical and non-technical hazards that contribute to fire risk under normal operational conditions (Shi et al., 2021; Liu et al., 2024; Badri et al., 2021).

Fire risk values were calculated using the formula (UNSW / HIRARC):

Risk Score (R) = Likelihood (L) × Consequence (C)

Table 1. Risk Assessment Matrix Based on UNSW Health & Safety (HIRARC / HIRADC)

A. Likelihood Criteria (UNSW Standard)

Level	Likelihood	Qualitative Description	Indicative Frequency
1	Rare	May occur only in exceptional circumstances	< 1 time in 10 years
2	Unlikely	Could occur at some time, but not expected	1 time in 5–10 years
3	Possible	Might occur at some time	1 time per year
4	Likely	Will probably occur in most circumstances	Several times per year
5	Almost Certain	Expected to occur in most circumstances	Monthly or more

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B. Consequence / Severity Criteria (UNSW Standard)

Level	Severity	Description	Impact Indicator
1	Insignificant	No injury, no damage, no operational impact	No lost time
2	Minor	Minor injury, minor damage	First aid only
3	Moderate	Serious injury requiring medical treatment	Lost time < 3 days
4	Major	Severe injury or permanent disability	Lost time ≥ 3 days
5	Catastrophic	Fatality or multiple fatalities	Permanent loss

C. Risk Matrix and Risk Level Classification

Likelihood ↓ / Consequence →	1	2	3	4	5
5 – Almost Certain	5 (M)	10 (H)	15 (H)	20 (E)	25 (E)
4 – Likely	4 (M)	8 (M)	12 (H)	16 (E)	20 (E)
3 – Possible	3 (L)	6 (M)	9 (M)	12 (H)	15 (H)
2 – Unlikely	2 (L)	4 (M)	6 (M)	8 (M)	10 (H)
1 – Rare	1 (L)	2 (L)	3 (L)	4 (M)	5 (M)

D. Risk Level Interpretation (UNSW Alignment)

Risk Score	Risk Level	Required Action (UNSW Principle)
1–3	Low (L)	Acceptable; managed by routine procedures
4–9	Medium (M)	Requires control and monitoring
10–15	High (H)	Requires immediate risk reduction
16–25	Extreme (E)	Unacceptable; stop the activity until it is controlled

Each identified hazard was assessed using a Hazard Identification and Risk Assessment (HIRARC) framework adapted from the UNSW Health and Safety risk matrix. Fire risk levels were determined by multiplying the likelihood and consequence scores, where likelihood reflects the probability of a hazard occurring, and consequence represents the potential impacts on life safety, property, and operational continuity. This quantitative approach enables objective comparison and prioritization of fire risks across different building areas and system components (Badri et al., 2021; Wardhani et al., 2024). The selection of the HIRARC approach is supported by prior studies demonstrating its effectiveness in systematically identifying hazards, assessing risk severity, and prioritizing corrective actions across diverse occupational and operational contexts (Badri et al., 2021; Tchiehe & Gauthier, 2022).

The resulting risk scores were classified into low, medium, high, and extreme categories to support managerial prioritization of corrective actions. Risk distribution analysis was used to examine the proportion of hazards across risk levels, while a fire risk pyramid was developed to visualize the hierarchical structure of systemic fire risks within the building. These visualization tools support strategic decision-making by distinguishing between tolerable risks and unacceptable conditions requiring immediate intervention (Shi et al., 2021; Liu et al., 2024; Anwar, 2023).

Following risk scoring, a conformity analysis was conducted by comparing observed fire safety conditions with applicable regulatory requirements and technical standards. Unlike conventional compliance audits, this analysis linked each non-conformity to its corresponding risk level, allowing regulatory deviations to be evaluated based on their potential impact rather than treated as equal deficiencies. This approach aligns conformity assessment with risk-based fire safety management principles (Liu et al., 2024; Shi et al., 2021).

To explain the underlying causes of high and extreme fire risks, root cause analysis was performed using a fishbone (cause-and-effect) diagram based on the 4M+1E framework, encompassing human, machine, method, material, and environmental factors. Although qualitative in nature, the analysis was guided by quantitative risk results, with analytical emphasis placed on hazards with the highest risk scores. This integration ensures that managerial recommendations address systemic weaknesses rather than isolated symptoms (Kuswardana et al., 2017; Anwar, 2023).

3. RESULTS AND DISCUSSION

3.1 Results

The results presented in this section are structured according to the sequential analytical framework described in the Research Method, comprising hazard identification, quantitative fire risk assessment, risk distribution analysis, and root cause analysis. This structured presentation ensures that the findings directly reflect the application of the UNSW-adapted Hazard Identification and Risk Assessment (HIRARC) method and support risk-based prioritization of fire safety issues. By systematically linking identified hazards to quantified risk levels and underlying contributing factors, the results provide an integrated representation of fire risk conditions within the high-rise office building, moving beyond compliance-based descriptions toward evidence-based risk evaluation (Shi et al., 2021; Liu et al., 2024; Anwar, 2023).

Risk Identification. Risk identification was conducted using the HIRARC framework through direct field observations, structured interviews, and document review, focusing on fire safety conditions in the high-rise building. This process identified 15 fire-related hazards and 15 corresponding risks across multiple operational and environmental aspects of the building. The identified hazards encompass deficiencies in active fire protection systems, life safety facilities, fire prevention practices, and human behavior. Common hazards include malfunctioning or poorly maintained fire detection and suppression equipment, obstructed evacuation routes, inadequate emergency signage, unsafe occupant behavior, and insufficient fire safety management procedures. These hazards reflect both technical and non-technical dimensions of fire safety, indicating that fire risk is not confined to isolated system failures but is embedded within everyday building operations.

Importantly, hazard identification revealed that several fire risks are systemic, meaning similar deficiencies recur across different locations or safety components. This finding suggests that fire safety challenges are influenced by organizational and management practices rather than isolated incidents. The identification stage, therefore, establishes a comprehensive baseline for subsequent quantitative risk assessment and prioritization. The results begin with the identification of fire-related hazards observed across building systems and operational practices, followed by quantitative risk scoring based on likelihood and consequence criteria. This approach allows each identified hazard to be objectively evaluated for its potential impact on life safety, property, and operational continuity. The subsequent risk classification and visualization stages translate numerical risk values into managerial insights, enabling clear differentiation between tolerable and unacceptable fire risk conditions that require prioritized control measures (Badri et al., 2021; Wardhani et al., 2024).

Risk Scoring (UNSW–HIRARC). Following hazard identification, each risk was quantitatively assessed using the UNSW-adapted HIRARC risk scoring method, which combines likelihood and consequence parameters. Likelihood scores represent the probability of fire occurrence based on exposure frequency, historical conditions, and system reliability, while consequence scores reflect potential impacts on life safety, property damage, and operational continuity. The risk scoring process resulted in a risk profile dominated by medium- to high-severity levels, with one risk classified as extreme. Specifically, the assessment identified one extreme risk, four high risks, and ten medium risks, with no risks categorized as low. This distribution indicates that all identified fire risks exceed acceptable thresholds and require active management.

The extreme risk category is associated with life-threatening scenarios, such as unsafe occupant behavior during fire emergencies or failure of critical fire protection systems. High-risk conditions typically relate to delayed detection, limited suppression capability, or compromised evacuation effectiveness. Medium risks, although less severe individually, represent persistent vulnerabilities that can escalate under adverse conditions. The absence of low-risk findings reinforces the inherently hazardous nature of fire risk in high-rise buildings and underscores the need for comprehensive control measures.

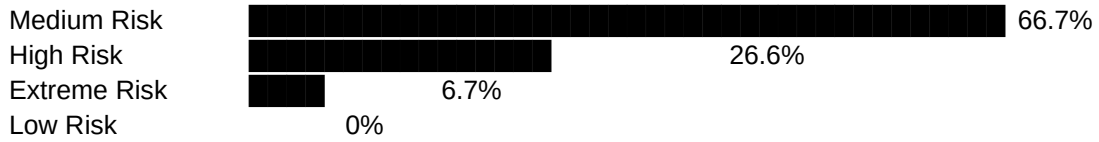


Fig 2. Distribution of Fire Risk Levels Identified in the Study

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Figure 2. Distribution of fire risk levels identified through the UNSW-based HIRARC assessment. The results show that 66.7% of hazards are classified as medium risk, 26.6% as high risk, and 6.7% as extreme risk, while no hazards fall within the low-risk category. This distribution highlights the absence of acceptable risk conditions and emphasizes the need for systematic fire risk control measures.

Risk Distribution. Risk distribution analysis was performed to examine how fire risks are spread across different stages of building operation and safety components. The results show that medium risks constitute the largest proportion of identified hazards, indicating widespread moderate deficiencies rather than isolated critical failures. These risks are mainly associated with routine operational conditions, maintenance practices, and occupant behavior.

High and extreme risks, while fewer in number, are concentrated in areas directly related to life safety and emergency response, such as evacuation preparedness, fire detection reliability, and human interaction with hazardous conditions. This concentration suggests that the most severe fire risks emerge not from single technical failures, but from the interaction between technical limitations and human or procedural shortcomings.

The distribution pattern highlights a layered risk structure, where moderate risks form a broad base of vulnerability, while high and extreme risks represent critical escalation points. This pattern provides important insight for prioritizing control strategies by distinguishing between risks that require immediate intervention and those that demand long-term systemic improvement. The quantitative distribution confirms that 93.3% of identified fire hazards fall within the medium-to-extreme risk categories, indicating a high overall fire risk profile and the absence of acceptable (low-risk) conditions.

Table 2. Distribution of Fire Risk Levels

Risk Level	Risk Score Range	Number of Hazards	Percentage (%)
Extreme (E)	16–25	1	6.7
High (H)	10–15	4	26.6
Medium (M)	4–9	10	66.7
Low (L)	1–3	0	0
Total	—	**15**	**100**

Risk Pyramid. To visualize the overall fire risk profile, a risk pyramid model was developed based on the results of the UNSW–HIRARC scoring. The pyramid illustrates the hierarchical structure of fire risks, with medium risks forming the base, high risks occupying the middle layer, and extreme risks at the apex. The dominance of medium risks at the base of the pyramid indicates that fire safety weaknesses are widespread and embedded within daily building operations. Although these risks may not lead to immediate catastrophic outcomes, their accumulation significantly increases the likelihood of escalation in emergency situations. The presence of high risks in the middle layer reflects conditions with serious potential consequences that require prioritized control. The extreme risk at the top of the pyramid represents an unacceptable condition that demands immediate corrective action.



Fig 1. Fire Risk Pyramid Based on UNSW–HIRARC Risk Classification

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The risk pyramid effectively demonstrates that reducing extreme and high fire risks requires not only targeted interventions at the top levels but also systematic reduction of medium risks at the base. This visualization reinforces the importance of adopting an integrated, preventive approach to fire risk management in high-rise buildings. Figure 1. Fire risk pyramid illustrating the hierarchical distribution of fire hazards based on the UNSW HIRARC risk classification. The pyramid shows that most identified hazards are at the medium-risk level, indicating widespread operational and procedural vulnerabilities. High and extreme risks occur at the upper levels, representing critical life-safety threats that require immediate corrective action and management intervention.

The fire risk pyramid shows a concentration of hazards in the medium-risk category, indicating widespread operational vulnerabilities, while the presence of high and extreme risks at the apex highlights critical life-safety threats requiring immediate corrective action. Figure 1 presents the fire risk pyramid, showing that the majority of hazards are concentrated at the medium-risk level, while a smaller proportion of high- and extreme-risk hazards represent critical safety threats. This distribution indicates that although most hazards do not pose immediate catastrophic consequences, their cumulative effect significantly elevates the building's overall fire risk profile.

The risk pyramid shows that the medium risk in the base layer reflects widespread systemic risks in building operations, so it needs to be controlled by strengthening work procedures, conducting routine inspections, and maintaining continuous monitoring. The high-risk layer at the intermediate level denotes priority risks requiring immediate technical and managerial action, such as improving fire protection systems and strengthening supervision. Extreme risk at the top of the pyramid is an intolerable condition and must be handled using the stop-fix–verify principle: stop risky activities, make improvements, and verify the effectiveness of controls before resuming operations.

3.2 Discussion

Interpretation of Fire Risk Profile. The fire risk profile identified in this study shows a clear predominance of medium-to-extreme risk categories, with no hazards classified as low risk. Based on the UNSW-adapted HIRARC assessment, 66.7% of identified hazards fall within the medium-risk category, while 26.6% and 6.7% are classified as high and extreme risks, respectively. This distribution indicates that fire risk in the assessed high-rise office building is not characterized by isolated critical failures, but rather by widespread systemic vulnerabilities embedded in routine operations and management practices. The absence of low-risk findings further suggests that existing fire safety measures have not yet achieved an acceptable level of risk control, reinforcing the need to interpret fire safety performance through a risk-based lens rather than regulatory compliance alone (Shi et al., 2021; Liu et al., 2024; Anwar, 2023).

The predominance of medium-risk hazards represents a critical managerial insight rather than a benign condition. Although medium risks may not immediately result in catastrophic consequences, their widespread presence creates a structural vulnerability that can escalate rapidly under adverse conditions, such as delayed detection, human error, or system malfunction. In high-rise buildings, the accumulation of multiple medium-risk deficiencies significantly increases exposure during emergency situations, thereby amplifying the potential severity of fire incidents. This pattern supports previous findings that systemic operational weaknesses, when left unmanaged, often serve as precursors to high-impact fire events (Badri et al., 2021; Wardhani et al., 2024). Similar findings have been reported in high-rise building fire safety studies, where the accumulation of moderate operational deficiencies significantly increased overall fire vulnerability despite the absence of major system failures (Shi et al., 2021; Liu et al., 2024).

High and extreme fire risks, although fewer in number, pose critical life-safety threats that require immediate managerial attention. These risks are primarily associated with failures in fire detection reliability, evacuation preparedness, and occupant behavior, all of which directly influence the consequence dimension of fire risk. Within the HIRARC framework, such risk levels are classified as unacceptable or as requiring urgent risk reduction, indicating that continued operation without corrective action would expose occupants and organizations to severe harm. The concentration of high and extreme risks at the upper levels of the risk

pyramid underscores the need to prioritize these hazards in a structured fire risk management strategy (Shi et al., 2021; Liu et al., 2024).

The identified risk profile provides a foundation for deeper analysis of how different fire safety components and organizational factors contribute to elevated risk levels. By linking quantitative risk scores to specific system deficiencies and management practices, the discussion moves beyond descriptive assessment toward explanatory analysis. This approach enables the identification of dominant contributing factors through root cause analysis, facilitating the development of targeted and prioritized risk control measures aligned with the hierarchy of controls and organizational risk management principles (Anwar, 2023; Kuswardana et al., 2017).

Contribution of Fire Safety Components. The analysis of fire safety components indicates that active fire protection systems contribute the most to elevated fire risk levels within the assessed high-rise building. Deficiencies in fire detectors, alarm systems, portable fire extinguishers, and hydrant systems significantly affect both likelihood and consequence scores in the HIRARC assessment. Inadequate detector distribution and obstructed manual call points increase the probability of delayed fire detection, while poorly maintained suppression equipment reduces the effectiveness of early fire control. These findings confirm that technical systems are a primary determinant of fire risk when their functionality, reliability, and accessibility are compromised, even in buildings that are formally compliant with fire safety regulations (Shi et al., 2021; Liu et al., 2024; Wardhani et al., 2024).

Life safety facilities, including evacuation routes, emergency exits, signage, and assembly points, play a critical role in shaping the consequence dimension of fire risk. Although structural elements such as stairwells may satisfy design requirements, their effectiveness is substantially reduced when evacuation routes are obstructed, emergency lighting is inadequate, or signage is unclear and inconsistent. Furthermore, the absence or poor visibility of assembly points contributes to high-risk conditions by hindering post-evacuation accountability and coordination during emergency response. This finding indicates that life safety performance is strongly influenced by clarity, usability, and occupant familiarity rather than structural compliance alone (Liu et al., 2024; Kobes et al., 2022).

Fire prevention and handling management practices also contribute significantly to systemic fire risk. The lack of formal emergency response procedures, the limited frequency of fire drills, and the absence of routine internal audits weaken the organization’s capacity to manage fire emergencies effectively. Although management-related deficiencies do not directly cause fire ignition, they substantially exacerbate fire consequences by delaying response, reducing coordination, and increasing occupant exposure. Consequently, weaknesses in the fire safety management function act as risk multipliers, amplifying the impact of technical failures and unsafe human behavior in high-rise buildings (Pradita & Sentoso, 2022; Kuligowski, 2021). The interaction among technical systems, life safety facilities, and management practices illustrates that fire risk is inherently multidimensional and interdependent. Failures in one component can undermine the effectiveness of others, explaining why medium-risk hazards dominate the overall risk profile identified in this study. This interdependence further clarifies why isolated technical improvements are insufficient to achieve meaningful risk reduction without parallel enhancements in management systems, procedural enforcement, and occupant preparedness within a risk-based fire safety framework (Anwar, 2023; Badri et al., 2021).

Root Cause Analysis of Fire Risk Using Fishbone Diagram. Fishbone (cause–and–effect) analysis was applied to explain the underlying factors contributing to the dominance of medium-to-extreme fire risks identified through the quantitative UNSW-based HIRARC assessment. While risk scoring defines the priority and severity of hazards, the fishbone analysis provides explanatory depth by identifying systemic drivers of elevated fire risk. Contributing factors were grouped into six dimensions—Human, Machine, Method, Material, Measurement, and Environment—to reflect the multidimensional nature of fire risk in high-rise buildings and to support structured managerial interpretation of root causes (Anwar, 2023; Badri et al., 2021).

The Human factor plays a significant role in increasing the likelihood of fire risk through behavioral and competency-related deficiencies. Limited fire safety awareness, insufficient training, and unsafe behaviors—

such as improper use of electrical appliances, unsafe cooking practices, and smoking in restricted areas—substantially increase the likelihood of a fire. Inadequate familiarity with evacuation routes and emergency procedures further weakens the effectiveness of emergency response, thereby increasing overall risk, particularly during the early stages of fire development (Shi et al., 2021; Liu et al., 2024; Pradita & Sentoso, 2022). The Machine factor is closely associated with equipment reliability and maintenance performance. Electrical system malfunctions, damaged portable fire extinguishers, and poorly maintained sprinkler and alarm systems increase both the likelihood of fire occurrence and the severity of potential consequences. These findings demonstrate that the mere presence of fire protection systems does not guarantee risk reduction unless supported by consistent functional testing, preventive maintenance, and assurance of accessibility (Wardhani et al., 2024; Liu et al., 2024).

The Method factor reflects deficiencies in fire safety management procedures, including unclear evacuation plans, ineffective alarm-testing routines, and a lack of systematic inspections. Procedural weaknesses primarily affect the consequence dimension of fire risk by delaying evacuation, disrupting coordination, and reducing the efficiency of emergency response. This condition explains the persistence of high- and extreme-risk categories in life safety preparedness despite partial compliance with technical standards (Anwar, 2023; Shi et al., 2021; Liu et al., 2024). The Material factor contributes to increased fire severity through the use of flammable interior finishes and improper storage of combustible materials and waste. Accumulated combustible loads increase fire intensity and accelerate fire spread, thereby elevating potential damage and injury severity. Although material-related hazards may have a moderate likelihood, their impact on fire development significantly increases overall risk scores within the HIRARC framework (Badri et al., 2021; Wardhani et al., 2024).

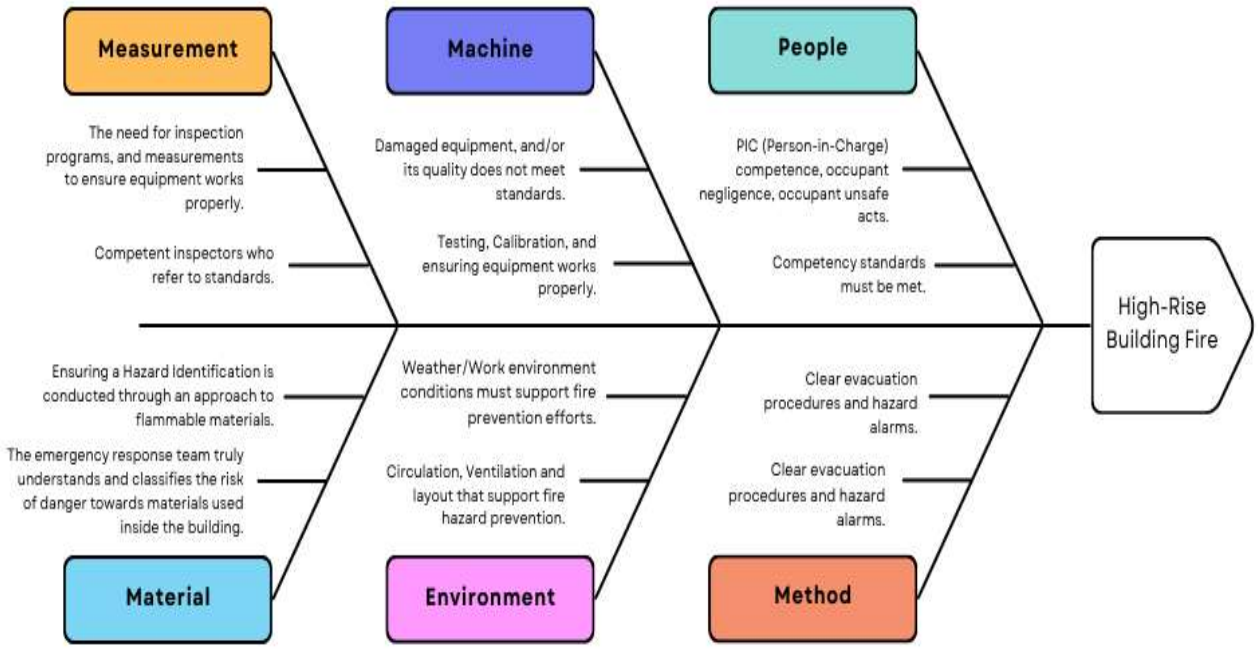


Fig 2. Analysis of Ishikawa (Fishbone)

The Measurement factor acts as a systemic enabler of fire risk by limiting the early detection of deficiencies across other categories. Inadequate monitoring systems, incomplete inspection records, and the absence of performance indicators allow hazards to persist and deteriorate over time without corrective action. In addition, Environmental factors—such as adverse weather conditions, building layout constraints, and limited external firefighting access—can further amplify the impact of fire once ignition occurs, particularly in dense urban high-rise settings (Shi et al., 2021; Liu et al., 2024; Anwar, 2023). Overall, the fishbone analysis indicates that elevated fire risks stem from interconnected technical, behavioral, and managerial weaknesses rather than isolated failures. Addressing these root causes through integrated and risk-based control strategies is essential to reducing both the likelihood and consequences of fire incidents, thereby strengthening fire safety performance and organizational resilience in high-rise buildings (Anwar, 2023; Badri et al., 2021). These

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findings are consistent with contemporary research emphasizing that human behavior remains one of the most significant determinants of fire outcomes, particularly regarding risk perception, emergency decision-making, and evacuation performance (Kuligowski, 2021; Kobes et al., 2022). Effective fire risk management requires not only technical compliance but also systematic organizational processes that support preparedness, communication, and emergency response coordination (Tchiehe & Gauthier, 2022; Badri et al., 2021).

Implications for Fire Risk Control. The findings of this study have important implications for fire risk control in high-rise buildings. The dominance of medium- to extreme-risk categories indicates that fire safety improvement efforts should prioritize risk-reduction strategies rather than compliance-driven approaches alone. This recommendation aligns with contemporary fire risk management principles, which advocate proactive identification and mitigation of vulnerabilities before incidents occur rather than relying solely on post-event corrective actions (Hadjisophocleous et al., 2022; Liu et al., 2024). Hazards classified as extreme and high risk require immediate corrective actions, including repair or replacement of defective equipment, revision of emergency procedures, and strict enforcement of safety rules. Medium-risk hazards, although less critical individually, should be addressed through systematic monitoring, preventive maintenance, and continuous improvement programs to prevent escalation to higher-risk levels (Shi et al., 2021; Liu et al., 2024; Anwar, 2023).

The integration of quantitative risk scoring with fishbone analysis underscores the need to implement a balanced fire risk control strategy that combines technical, organizational, and behavioral interventions. Technical controls should focus on ensuring the functionality, accessibility, and reliability of fire detection, suppression, and evacuation systems. Organizational controls must include the development and enforcement of clear fire emergency procedures, routine inspections, and documented internal audits. Behavioral controls should emphasize regular fire safety training, drills, and awareness programs to reduce unsafe acts and improve emergency response performance among occupants and staff (Badri et al., 2021; Pradita & Sentoso, 2022).

Furthermore, the results suggest that effective fire risk control should adopt a preventive, proactive orientation rather than a reactive approach to incidents. Emphasis should be placed on early detection of system degradation, periodic performance testing, and continuous evaluation of fire safety practices. Strengthening measurement and monitoring mechanisms is essential for identifying emerging risks at an early stage and preventing medium-risk conditions from escalating into high or extreme categories, particularly in complex high-rise building environments (Wardhani et al., 2024; Liu et al., 2024). In conclusion, effective fire risk control in high-rise buildings requires an integrated risk-based management framework that addresses both immediate hazards and underlying systemic weaknesses. By aligning fire safety controls with the identified risk profile and root causes, building management can significantly reduce the likelihood and consequences of fire incidents, enhance occupant safety, and improve organizational resilience and operational continuity. This approach reinforces the importance of moving beyond formal compliance toward sustained risk-informed fire safety management practices (Anwar, 2023; Shi et al., 2021; Liu et al., 2024).

Recommendations. Based on the identified fire risk profile and dominant root causes, the following recommendations are proposed to support risk reduction using a hierarchy of controls approach (Table 3).

Based on the identified fire risk profile, fire risk control measures should be prioritized according to risk level and implemented using a hierarchy of controls approach. Extreme and high-risk hazards require immediate and corrective interventions, while medium-risk conditions should be managed through systematic improvement programs to prevent escalation. This risk-based prioritization ensures that control efforts are proportional to potential consequences and resource allocation is optimized.

Fire risk control should emphasize higher-level controls, particularly elimination, substitution, and engineering measures, as primary strategies to reduce the likelihood and consequences of fire. The effectiveness of technical fire protection systems depends not only on their presence but also on their functionality, accessibility, and integration with building evacuation design. Lower-level controls, including administrative

measures and personal protective equipment, should be applied to support and reinforce technical interventions rather than replace them. To ensure sustainability, fire risk control programs should be embedded within routine management processes, including scheduled inspections, preventive maintenance, structured training, and performance monitoring. Aligning control measures with the assessed risk levels and underlying root causes will support continuous improvement in fire safety performance and enhance the resilience of high-rise building operations.

Table 3. Risk Level–Based Fire Risk Control Recommendations

Risk Level	Priority	Dominant Risk Characteristics	Recommended Control Measures (Hierarchy of Controls)
Extreme	Immediate	High likelihood and severe consequences; failure of critical fire protection and life safety systems	Eliminate unauthorized ignition sources; substitute non-compliant electrical components; immediately repair or replace defective detectors, alarms, hydrants, and extinguishers; enforce strict access control and emergency procedures
High	High	Significant deficiencies in active protection and evacuation readiness	Engineering upgrades to detection and suppression systems; improve visibility and accessibility of exits and manual call points; conduct intensive inspections and corrective maintenance; strengthen emergency response procedures and drills
Medium	Moderate	Partial non-conformity and reduced system reliability; potential for escalation	Scheduled preventive maintenance; routine system testing; refresher fire safety training; housekeeping improvements to reduce fire load; continuous monitoring and internal audits
Low	Routine	Minor deviations with limited impact on fire likelihood or consequences	Periodic review of fire safety systems; documentation updates; awareness programs; standard operational controls

4. CONCLUSION

This study confirms that evaluating fire safety in high-rise office buildings requires more than compliance-based inspection. The application of a risk-based HIRARC approach enables clearer prioritization of fire hazards and reveals systemic vulnerabilities that may not be apparent through conventional assessments. The identified risk profile indicates that medium-risk conditions form a critical base for potential escalation, while high and extreme risks represent immediate threats that demand focused managerial attention. The integration of quantitative risk assessment with component-level and root cause analysis demonstrates that fire risk arises from the interaction of technical reliability, human behavior, and management practices. Therefore, effective fire risk control depends not only on the availability of fire protection systems but also on their functionality, accessibility, and alignment with organizational procedures and preparedness. The findings support previous research emphasizing that effective fire safety management in high-rise buildings requires an integrated approach combining risk assessment methodologies, reliable fire protection systems, organizational preparedness, and human-centered emergency response strategies (Hadjisophocleous et al., 2022; Hurley et al., 2023; Kuligowski, 2021). Overall, this study highlights the importance of adopting an integrated, proactive fire risk management framework that aligns control measures with risk severity and systemic causes, thereby enhancing occupant safety and operational resilience in high-rise buildings.

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