Analysis and Control of Occupational Health and Safety (OHS) Risk Using an Integrated HIRADC–AHP–Bowtie Analysis Approach on the Building X Construction Project

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***Abstract*—High-rise building projects face complex occupational health and safety (OHS) risks from work at height, heavy-equipment use, mechanical-electrical-plumbing (MEP) installation, and simultaneous multidisciplinary interaction. Previous studies generally apply HIRADC, AHP, and Bowtie Analysis separately, so hazard identification, risk prioritization, and barrier identification are not connected within one framework. This study proposes a sequential HIRADC–AHP–Bowtie framework in which HIRADC likelihood and severity ratings are weighted by AHP-derived expert judgment to produce a Weighted Risk Rating (WRR), and the risks classified as Very High on the risk map (ranked by WRR) are then carried into Bowtie Analysis to identify and structure their preventive and mitigative barriers. The framework was applied across all phases of the Building X Project in South Jakarta. Fifty respondents were selected from a population of 100 workers by disproportional stratified random sampling (Slovin formula, 10% margin of error). Hazards were identified through observation, interviews, and literature review and assessed on likelihood and severity, while three experts provided the AHP pairwise judgments. Identification yielded 103 OHS risk statements across six phases, predominantly at the high-risk level. The three Very High risks were fall from height due to scaffolding collapse (WRR 4.657), fire from electrical short circuit (WRR 4.313), and vertical fall into an unprotected shaft (WRR 3.970); 81 of the 103 risks were High. AHP pairwise judgments of three experts gave Severity a higher priority weight (0.657) than Likelihood (0.343). The novelty of this study lies in using risk-map level and WRR as an explicit link between quantitative risk prioritization and barrier-level analysis across a whole high-rise project, which yields a systematic, field-data-based control strategy and a replicable risk-analysis model for other high-rise projects.**

Keywords*—Analytical Hierarchy Process, Bowtie Analysis, Hierarchy of Control, High-Rise Building, HIRADC, OHS Risk Management.

I. INTRODUCTION

The construction sector is one of the strategic sectors in national infrastructure development and plays an important role in driving economic growth, yet it is equally synonymous with high occupational health and safety (OHS) risks. Although it employs only about 7% of the global workforce, the construction sector accounts for roughly 30% of all fatal occupational accidents worldwide, with the International Labour Organization (ILO) recording at least 108,000 worker deaths each year on construction sites [1]. In Indonesia, BPJS Ketenagakerjaan recorded 462,241 work-accident cases in 2024 [2], indicating that OHS implementation particularly proactive risk control has not yet run optimally, while accident-causation studies show that unsafe behavior and management factors continue to shape accident outcomes [3], [4].

These conditions are aggravated on high-rise projects, which exhibit more complex risk characteristics owing to activities at elevation, the use of heavy equipment, and simultaneous multidisciplinary interaction. A study [5] on unsafe-behavior chains in building construction confirms that falls, structural collapse, being struck by objects, and material lifting are the four dominant accident types in multi-storey buildings, while [6] found that scaffolders' compliance with fall-protection equipment remains low even though the risk is widely known. Fire risk from electrical installation in high-rise buildings under construction is also high, as shown by [7] through a fire-risk assessment model based on unascertained measure theory.

The Indonesian government has issued comprehensive regulations such as [8] on occupational safety, [9] on the Occupational Safety and Health Management System (SMK3), and [10], which mandates hierarchy-of-control-based risk management on every construction project, consistent with [11] and with the construction-specific OSH management guidelines in [31]. Nevertheless, various studies find a gap between regulation and field practice, in which contractors tend to satisfy administrative requirements without adequate data-based risk analysis [4]. Construction-accident causation models affirm that the combination of human, technical, and management factors interacts to form the unsafe conditions that culminate in workplace accidents [3], [5].

To identify and assess risks systematically, the Hazard Identification, Risk Assessment, and Determining Control (HIRADC) method has been widely applied and proven effective in mapping hazard sources across various construction projects [12], [13], [14]. However, HIRADC remains descriptive and does not include quantitative control prioritization. To address this weakness, integration with the Analytical Hierarchy Process (AHP) has been developed to derive quantitative risk-priority weights from structured, expert-based multi-criteria judgment [15], [16], [17], [18]. Because these weights rest on the judgment of a limited number of experts, they remain subjective and project-

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specific; with only two criteria the Consistency Ratio is zero by construction and therefore cannot serve as a check on that subjectivity (Section II-D). Even so, AHP only determines the order of risk priority without showing how the causes, consequences, and existing controls of the prioritized risks are structured [19].

On the other hand, Bowtie Analysis can map the structure of causes (threats), the top event, and risk consequences while simultaneously identifying preventive and mitigative barriers in a visual and structured manner [20], [21], but it lacks a quantitative mechanism to prioritize risks among the many identified hazards. To substantiate the research gap, a structured literature search was conducted in Scopus, Web of Science, and Google Scholar for the period January 2015 to June 2026. The search string combined the terms ("HIRADC" OR "hazard identification, risk assessment and determining control") AND ("AHP" OR "analytic hierarchy process") AND ("bowtie" OR "bow-tie") AND ("construction" OR "high-rise building"), with a broader search on pairs of methods (HIRADC–AHP, AHP–Bowtie, HIRADC–Bowtie). Only peer-reviewed journal articles and conference papers in English or Indonesian addressing construction OHS risk were included. The literature was screened based on relevance to construction OHS risk, risk identification and assessment methods, and applicability to the construction phases considered in this study. The selected studies were subsequently reviewed in full text. The search identified 103 records. After removing12 duplicates and excluding 68 Records, 23 articles were assessed in full text. A total of 15 Studies were retained, with eight representative studies.

Eight representative studies are compared in Table A. As summarized there, the retained studies applied one or two of the three methods, addressed a single phase or hazard type, or were conducted outside high-rise construction. To the best of our knowledge, and within the scope of this search, no study has combined HIRADC, AHP, and Bowtie Analysis in one sequential framework covering all construction phases of a high-rise building project in Indonesia [16], [18], [20], [42], [44], [46], [47].

TABLE I. COMPARISON OF REPRESENTATIVE PREVIOUS STUDIES ON HIRADC, AHP, AND BOWTIE ANALYSIS IN CONSTRUCTION OHS RISK MANAGEMENT

Study	Setting	Methods	Scope relative to this study
Aminbakhsh et al. [16]	Construction projects (planning and budgeting stage)	AHP	Prioritizes safety risks; no structured HIRADC register and no barrier analysis.
Unver and Ergenc [18]	Forest logging activities	AHP	Outside building construction; prioritization only.
Wang et al. [44]	Fire hazards in a commercial complex	Fault tree analysis + AHP	Single hazard type (fire); not organized by construction phase; no Bowtie barrier structure.
Li et al. [7]	Fire risk in high-rise buildings under construction	Uncertainty measure theory	Single hazard type (fire); does not combine HIRADC, AHP, and Bowtie.
Silvianita et al. [20]	Mooring replacement on a production barge	Bowtie	Marine/offshore project; no AHP-based prioritization linked to Bowtie.
Qie and Yan [42]	Subway construction accidents	Fault tree analysis + Bayesian network	Causation analysis only; different method set and structure type.
Logrosa et al. [46]	COVID-19 epidemic risk analysis, Davao City, Philippines (public health)	Bowtie + AHP	Uses AHP to rank control barriers from expert opinion; public-health rather than construction setting; no HIRADC register and no phase-by-phase coverage of a building project.
Sulistiarini et al. [47]	High-rise building maintenance (case study of a three-storey laboratory building)	HIRARC + AHP	Combines HIRARC with AHP-weighted sustainability criteria; operational phase, no Bowtie barrier analysis.
This study	High-rise Building X, six construction phases, South Jakarta	HIRADC → AHP (WRR) → Bowtie	Sequential integration in which risk-map level and WRR select the risks carried into barrier-level Bowtie analysis across all phases.

Integrating these three methods produces a more robust risk-management model: HIRADC for initial hazard identification and risk assessment, AHP for structured, expert-based weighted risk prioritization, and Bowtie Analysis for cause–effect mapping together with identification of preventive and mitigative barriers. This study focuses on a case study of the Building X Construction Project in South Jakarta, covering all major construction phases in an integrated manner—preparation and excavation, foundation and substructure, superstructure, architecture/envelope, MEP installation, and finishing and commissioning. It aims to identify hazards in each construction phase, prioritize risks through systematically weighted expert judgment, and identify the preventive and mitigative barriers of the highest-priority risks, thereby producing a proactive and structured OHS risk-control strategy toward acceptable risk. Academically, it contributes to developing an integrated OHS risk-analysis model applied comprehensively across all high-rise construction phases in Indonesia. Practically, the model is expected to serve as a reference for contractors in implementing a substantive, field-data-based SMK3 to reduce accident rates on similar high-rise projects.

II. RESEARCH METHOD

A. Data Collection

The sample size was determined using Slovin's formula, $n = N / (1 + N \cdot eZ)$, with a population of $N = 100$ workers and a margin of error of $e = 0.10$ (10%, corresponding to a 90% confidence level), giving $n = 100 / (1 + 100 \times 0.10Z) = 50$ respondents. Respondents were selected by disproportional stratified random sampling, with strata defined by job position (14 positions, from project manager to helper, grouped into four broader strata for reporting: management, engineers and experts, supervisors and foremen, and workers; Table B). Disproportional allocation was adopted because the workforce is dominated by field workers, whereas supervisory, technical, and managerial positions have very few members;

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proportional allocation would have left these strata with one or no respondents and their perspective unrepresented. Sampling fractions therefore differ among strata, from 0.25 to 1.00 across the 14 positions, with the single-member and two-member positions sampled at fractions of 0.50 to 1.00. Within each stratum, respondents were selected randomly using random numbers assigned to the project workforce list. The population, sample size, and sampling fraction of each stratum are given in Table B, and Table C groups them into the four reporting strata.

TABLE II. ALLOCATION OF RESPONDENTS BY STRATUM (DISPROPORTIONATE STRATIFIED RANDOM SAMPLING)

Stratum (job position)	Population (Nh)	Sample (nh)	Sampling fraction (nh/Nh)
Project manager	1	1	1.00
Technical manager	2	1	0.50
OHS expert	2	1	0.50
Structural civil expert	2	1	0.50
Architecture expert	2	1	0.50
Site engineer	3	1	0.33
Field supervisor	5	2	0.40
OHS officer	6	2	0.33
Field executor (pelaksana)	9	3	0.33
Foreman (mandor)	8	2	0.25
Head of craftsmen (kepala tukang)	12	3	0.25
ACP workers	18	7	0.39
Masons	17	13	0.76
Helpers	13	12	0.92
Total	100	50	0.50

The study was conducted on the Building X Construction Project in South Jakarta, a 12-storey building with a floor area of ±14,127 mZ and an investment value of about US$150 million. The project was selected for three main reasons. First, it was running all major construction phases simultaneously preparation and excavation, foundation and substructure, superstructure, architecture, and MEP allowing comprehensive and representative observation of OHS risks characteristic of high-rise buildings. Second, the complexity of activities, such as work at height, heavy-equipment use, MEP installation, and simultaneous multidisciplinary interaction, matches the study's focus on high-rise risk. Third, project management granted full access to OHS documents, the Health and Safety Plan (RKK), and field workers and supervisors as respondents, so that primary and secondary data could be obtained adequately.



Fig. 1. Site imagery of the Building X project.

B. Integrated Risk Analysis Framework

As a general overview before detailed hazard identification, this study develops a conceptual framework that follows the chronological sequence of building construction activities, comprising six phases: site preparation and excavation, foundation and substructure works, superstructure works, architectural/envelope works, MEP installation works, and finishing and commissioning. As illustrated in Fig. 2, each phase is described by its typical activities and the categories of potential hazards associated with them, such as heavy-equipment movement, excavation and slope failure, work at height and falling objects, manual material handling, electrical and fire hazards, and residual risk and human error. The framework does not rank the phases; the relative level of risk of each phase is determined empirically from the HIRADC and WRR results reported in Section III. The phases are linked to a continuous risk-management process comprising risk identification, assessment, prioritization, control implementation, and monitoring and improvement.



Fig. 2. Conceptual framework of construction phases, typical activities, and potential hazard categories.

C. HIRADC Analysis

Each risk was assessed on two main parameters, likelihood (the probability of occurrence) and severity (the severity of impact). Both were measured using a five-level ordinal scale, as presented in Tables I and II. The average likelihood and severity obtained from 50 respondents were then combined to compute the risk rating (Likelihood × Severity). The risk rating was subsequently used as the basis for risk-level classification following the risk matrix of the Ministry of Public Works and Housing (PUPR) [10].

D. Criteria Weighting with AHP and Weighted Risk Rating (WRR)

Rating (WRR) 274 PUPR SMKK Guidelines [10], as presented in Table V and Criteria weighting was performed using the Analytical Hierarchy Process (AHP) to obtain the relative weights of the likelihood and severity parameters

based on expert judgment. Assessment was carried out through pairwise comparison using Saaty's 1–9 fundamental scale, as presented in Table III. Values from three experts (pairwise judgments of 1/9, 1/7, and 9 for Likelihood relative to Severity) were aggregated using the geometric mean, giving a Severity-to-Likelihood ratio of 1.913, then normalized to obtain each criterion's priority weight (wL = 0.343, wS = 0.657). Because the comparison matrix has only two criteria, it is consistent by construction (Consistency Ratio = 0) [15], [17]; the wide spread of the individual expert judgments is nonetheless a limitation on how far the weights can be generalized beyond this project. likelihood and severity to produce the Weighted Risk Rating (WRR = wL·LY + wS·SY). WRR aims to yield a more representative risk priority than the conventional Risk Priority Number (RPN), because RPN treats all parameters with equal importance and therefore cannot represent each parameter's relative contribution to the risk level. Through AHP weighting, likelihood and severity are weighted according to their importance, making risk prioritization a structured, expert-weighted process rather than treating both criteria as equally important. WRR is used to rank risks from highest to lowest priority, while each risk's position on the risk map is determined by the likelihood–severity combination referring to the risk matrix in the Fig. 4 in the Results.

E. Risk Map

Besides producing the WRR, the likelihood and severity results from HIRADC were also visualized as a risk map— a matrix referring to the PUPR SMKK risk matrix [10]. Each risk statement is positioned on the matrix based on its combination of average likelihood and severity scores, then grouped into five risk levels following the PUPR SMKK risk matrix: Very Low (1–5), Low (6–10), Medium (11–15), High (16–19), and Very High (20–25). The risk map complements the WRR weighting by providing a visual picture of the overall distribution of risk statements, so that concentration patterns at particular likelihood–severity combinations can be quickly identified as a basis for control prioritization, as presented in Fig. 4.

F. Top Event and Bowtie Analysis

Bowtie Analysis was applied to the three risks in the Very High category (matrix score 20–25; Section II-E), ranked by WRR. They were selected because they combine potentially fatal consequences with the highest urgency for control and therefore require deeper analysis, and because they represent three different top events. This approach enables identification of the relationships among basic causes (threats), the top event, consequences, and the preventive and mitigative barriers that can interrupt the causal pathway. Preventive barriers reduce the likelihood of the top event through engineering, administrative, or PPE controls, while mitigative barriers reduce the severity of impact if the top event still occurs. Thus, Bowtie Analysis provides more comprehensive information than conventional risk-assessment methods that generally only rank risks without mapping their causal structure and barriers.

G. Risk-Control Strategy and Discussion

Risk-control strategies were formulated from the preventive and mitigative barriers identified in the Bowtie stage, then mapped onto the hierarchy of control— elimination, substitution, engineering controls, administrative controls, and PPE [10]. Barriers that directly eliminate or reduce the hazard source are classified as engineering controls; barriers related to procedures, inspection, and work-permit systems as administrative controls; while barriers that depend on individual worker compliance, such as PPE use, are placed lower in the hierarchy because their reliability is more vulnerable to human factors. The strategy also considers the cost-of-safety principle [16] efficient allocation of safety resources by prioritizing control of the highest-WRR risks, so that prevention efforts focus on the critical points that yield the greatest risk reduction per unit cost. This study identifies and classifies barriers; it does not measure their field performance (e.g., percentage effectiveness or an adequacy rating), which is left for further research.

III. Results and Discussion

A. Data Collection

Results and Discussion analyzed to describe the distribution of roles involved in the study, covering field workers, technical personnel, and managerial personnel directly involved in project execution. Respondents were drawn from four strata— management, engineers and experts, supervisors and foremen, and workers (Table C). The sampling fraction differs among strata (0.30 for supervisors and foremen, 0.44 for engineers and experts, and 0.67 for both management and workers), so the design is disproportionate: the smaller managerial and technical strata were sampled at a higher fraction than the supervisory stratum to ensure that managerial and technical perspectives were represented. The overall sample is 50 of 100 workers (Section II-A). The job position distribution is presented in Fig. 3.

TABLE III. Strata, Population, Sample, and Sampling Fraction

Stratum	Population (Nh)	Sample (nh)	Sampling fraction (nh/Nh)
Management (project manager, technical manager)	3	2	0.67
Engineers and experts (OHS, structural civil, architecture, site engineer)	9	4	0.44
Supervisors and foremen (field supervisor, OHS officer, field executor, foreman, head of craftsmen)	40	12	0.30
Workers (masons, helpers, ACP workers)	48	32	0.67
Total	100	50	0.50

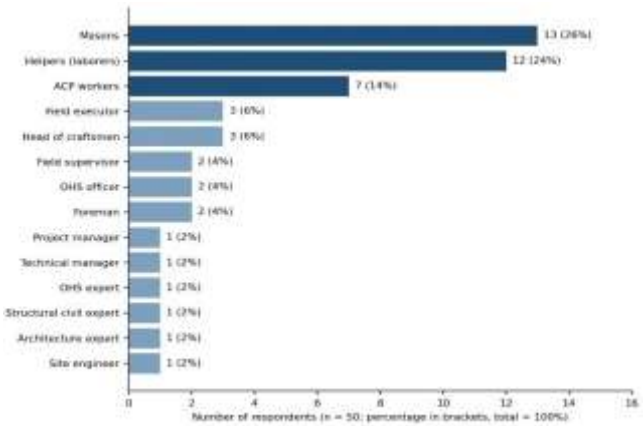

Fig. 3. Distribution of respondents by job position (n = 50).

Respondent characteristics show that the study was dominated by field workers, with the largest proportions being

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masons (26%), helpers (24%), and aluminium composite panel (ACP) workers (14%), reflecting the workforce composition of high-rise construction projects (Fig. 3). The largest age group was over 40 years (26%), and the most common education level was senior-high/vocational school (32%); 44% of respondents had 6–10 years of experience, so risk assessments were obtained from workers with field experience and competence representative of project conditions. Before use in the risk-analysis stage, the quality of the instrument was examined in two separate ways. First, the content validity of the hazard statements rests on their derivation from observation, interviews, literature, and technical and regulatory standards (Section III-C), and on expert review of each statement for relevance, clarity, and representativeness by OHS experts with at least five years of experience. Second, the reliability of the respondents' likelihood and severity ratings was tested with corrected item–total correlation and Cronbach's alpha. These statistics show whether respondents rated the statements consistently; they do not show that the hazard list is complete. Cronbach's alpha was 0.973 for Likelihood and 0.953 for Severity, above the 0.70 minimum. For $n = 50$ ($\alpha = 0.05$) the critical r is 0.279; 7 Likelihood items and 6 Severity items had item–total correlations below this threshold. Because each statement describes a distinct hazard rather than an indicator of one latent construct, and the statements had been judged relevant by the experts, these items were retained; the complete item statistics are given in the Supplementary Material.

B. Integrated Risk Analysis Framework

Referring to the risk characteristics framework previously described in the methodology section, risk identification was systematically conducted for all construction work packages in this project. The identification results are presented in Section III-C and Table IV.

C. HIRADC Analysis Results

Hazard identification produced 103 OHS risk statements distributed across six construction work phases: preparation and excavation, foundation and substructure, superstructure, architecture/building envelope, MEP, and finishing and commissioning. Hazard statements were compiled in four steps (Fig. A). (1) An initial pool of 136 hazards was compiled from site observation (26), interviews with site personnel (40), and literature and technical standards (70). (2) Statements outside the scope of the six construction phases were screened out (31 removed), giving 105 candidate statements that were placed in the questionnaire. (3) Two statements with the same meaning as other statements were not carried into the analysis, leaving 103. (4) Expert review of relevance, clarity, and representativeness confirmed the final 103 risk statements. Their distribution over the six phases is 15, 12, 21, 18, 21, and 16 (Table IV). The largest concentration of risk statements was found in superstructure and MEP work, which have the highest complexity and activity intensity. Table IV summarizes the identification by construction phase; the complete HIRADC register listing every risk statement with its likelihood, severity, and RPN value is provided as Supplementary Material.

TABLE IV. SUMMARY OF HIRADC OHS RISK IDENTIFICATION BY CONSTRUCTION PHASE, WITH THE NUMBER OF RISKS (N), THEIR SHARE OF THE TOTAL

Construction Phase	Work Scope	n	%	VH	H	M	L	RPN range	Highest-Rated Risk (RPN)
1. Preparation & Excavation	Site clearing, basement excavation, underground-utility relocation, dust control and soil disposal	15	14.6	0	9	4	2	6–12	Excavation collapse from inadequate shoring (12)
2. Foundation & Substructure	Bored pile and pile cap, confined-space basement work, foundation-component lifting, basement waterproofing	12	11.7	0	6	5	1	6–16	Falling or being struck due to poor lighting during lifting (16)
3. Superstructure	Formwork and scaffolding, reinforcement, concrete casting, floor-edge work, tower-crane operation, core/shaft work, parapet and roof	21	20.4	1	19	0	1	4–20	Fall from height due to scaffolding collapse (20)
4. Architecture / Envelope	Façade (curtain wall, glass, cladding), partitions/ doors/ windows, floor and ceiling, sealant and coating, roof installation	18	17.5	0	18	0	0	12–16	Fall from the building edge during façade work (16)
5. MEP	Panel and electrical, HVAC ducting, fire protection, plumbing and sanitary, MEP shafts/risers, mechanical-electrical testing	21	20.4	1	15	5	0	8–16	Electric shock from unidentified live cables (16)
6. Finishing & Commissioning	Plastering/tiling/gypsum, interior painting and coating, ceiling and lighting, final cleaning and waste removal, testing and commissioning, parallel multidisciplinary work	16	15.5	1	14	1	0	8–16	Slips, trips, and falls from scattered material or wet surfaces (16)
Total		103	100.0	3	81	15	4	4–20	Fall from height due to scaffolding collapse (20)

Note: VH = Very High; H = High; M = Medium; L = Low. No risk fell in the Very Low (VL) level in any phase. Levels follow the PUPR SMKK risk matrix [10]: Very Low 1–5, Low 6–10, Medium 11–15, High 16–19, Very High 20–25. RPN = Risk Priority Number (L × S). Percentages may not add exactly because of rounding.

Table IV shows that High is the dominant level in every phase, ranging from 50% of the risks in foundation and substructure to 100% in architecture/envelope, in line with [5], which found falls, structural collapse, being struck by objects, and material lifting as the four dominant accident patterns in building construction. The three Very High risks occur one each in the superstructure, MEP, and finishing phases, and all relate to potentially fatal falls from height, fire, and vertical falls, affirming the relevance of the ILO classification of major construction hazards [1]. The risk mapping shows the largest concentration at the likelihood-3–4 and severity-4 combination, indicating that most risks on the Building X Project have significant impact on worker safety even though their frequency varies. This is consistent with [6] on the high risk of work at height in scaffolding work and [7] on the significance of fire risk in high-rise buildings under construction. The average likelihood and severity alone are insufficient to determine which risk is most critical overall, since each criterion has different importance, so the analysis proceeds with AHP to produce expert-weighted importance weights for each risk criterion.

Identification of each risk statement in the complete HIRADC register (Supplementary Material) was further grounded in hazard-specific technical and regulatory standards. Electrical hazards were assessed against national electrical-installation and workplace electrical-safety standards [23]–[25], while fire and explosion hazards referred to fire-protection and electrical-code standards [26]–[28]. Chemical, dust, and general working-environment exposures were evaluated based on Ministerial Regulation No. 5 of 2018

on Occupational Safety and Health in the Working Environment [29], including hazardous-waste-related exposures during final cleanup and waste removal, which additionally referred to Government Regulation No. 101 of 2014 on the Management of Hazardous and Toxic Waste [41].

Material-specific chemical exposures, such as volatile organic compounds from painting and coating work, were further assessed using the relevant Safety Data Sheets [35]. Work-at-height hazards followed Ministerial Regulation No. 9 of 2016 on Occupational Safety and Health in Work at Height [30]. Lifting and crane-related hazards were assessed against Ministerial Regulation No. 8 of 2020 and applicable crane-safety standards [32], [33], whereas scaffolding and excavation hazards referred to established scaffold and excavation-safety standards [22], [34]. Façade and glazing-related hazards were evaluated against the edge-protection standard EN 13374 [36], while manual-handling, repetitive-motion, and airborne-contaminant risks were assessed using ergonomic and occupational-exposure standards [37]–[40]. This standard-based grounding ensured that each of the 103 risk statements was not only derived from field observation but also anchored in recognized technical and regulatory benchmarks.

Superstructure works and MEP installation each contain 21 of the 103 risk statements (20.4% each), the most of any phase. These two phases combine the largest number of distinct activities executed simultaneously on the same floor plates—formwork, scaffolding, reinforcement, concrete pumping, and tower-crane lifting in the superstructure; live electrical panels, ducting, fire protection, plumbing, and shaft work in MEP—so that hazards arise not only from each activity but also from their interaction. This interpretation is consistent with the simultaneous execution of all major phases on the Building X Project (Section II-A) and with the dominance of falls, collapse, and being struck by objects reported in [5].

Severity dominated the expert judgment (weight 0.657 against 0.343 for Likelihood, about 1.9 times higher). Conventional RPN or risk matrices treat the two dimensions as equal. Our result suggests that, for a high-rise project where the leading hazards (falls from height, fire, electrical contact) are usually fatal or permanently disabling even when infrequent, practitioners implicitly rank consequence above frequency. Weighting changed the ranking: fire from an electrical short circuit (L = 3, S = 5, RPN = 15) is ranked below 35 risks with RPN = 16 under RPN, but above all of them under WRR (4.313 against 4.000), and WRR separates combinations that RPN treats as equal (L2×S4 = 3.313 against L4×S2 = 2.687). The weights come from three experts whose judgments differed, so they are specific to this project and should be re-elicited elsewhere; the ranking of the fire risk depends on Severity being weighted above Likelihood, and the shaft-fall risk would outrank the 35 tied risks only if Severity were weighted more than twice Likelihood (the observed ratio is 1.9). The shaft-fall risk (L = 2, S = 5) is Very High on the risk map (score 21) but has a lower WRR (3.970) than the 35 risks at L = 4 and S = 4 (4.000). The two instruments therefore complement rather than duplicate each other: the risk map flags severe but infrequent events, whereas WRR orders risks by the expert-weighted balance of frequency and consequence. For SMKK, this supports treating all Very High (20–25) risks as mandatory targets for barrier analysis, irrespective of WRR rank, and using WRR to sequence the 81 High-level risks. The novel findings are (i) the empirical demonstration, across all six phases of one high-rise project, that expert-weighted WRR reorders risks relative to RPN, and (ii) the sequential use of risk-map level and WRR to select the risks carried into Bowtie analysis.

D. AHP Weighting and WRR Results

AHP weighting produced a Severity weight of 0.657 and a Likelihood weight of 0.343 (wL + wS = 1), with WRR = 0.343·LY + 0.657·SY . Because the comparison matrix has only two criteria, it is consistent by construction (Consistency Ratio = 0). The expert judgments were not unanimous (one of the three experts judged Likelihood as absolutely more important than Severity), so the weights reflect the group aggregate and should be interpreted as project-specific. The WRR results were then used to rank risks across all construction activities. The highest-ranked risks and the third Very High risk are presented in Table V.

TABLE V. HIGHEST-RANKED RISKS BY WRR

Rank	Risk	L	S	RPN	WRR	Matrix score	Level
1	Fall from height due to scaffolding collapse (overload, incomplete connections)	4	5	20	**4.657**	24	Very High
2	Fire from electrical short circuit	3	5	15	**4.313**	22	Very High
3–37 (tie)	Fall/impact due to poor lighting	4	4	16	**4.000**	19	High
3–37 (tie)	Slipping while climbing scaffolding (slippery surface, incomplete PPE)	4	4	16	**4.000**	19	High
3–37 (tie)	Injury during column/beam/slab reinforcement installation	4	4	16	**4.000**	19	High
3–37 (tie)	Slipping during concrete pumping (wet/muddy surface)	4	4	16	**4.000**	19	High
3–37 (tie)	Tripping over projecting formwork/rebar at edge areas	4	4	16	**4.000**	19	High
3–37 (tie)	Struck by a falling load from a broken sling (tower crane)	4	4	16	**4.000**	19	High
3–37 (tie)	Grazed by crane swing in the work area	4	4	16	**4.000**	19	High
38	Vertical fall into an unprotected shaft	2	5	10	**3.970**	21	Very High

Note: RPN = L × S; matrix score = number of the L–S cell in the PUPR 5×5 matrix (cells numbered 1–25 in increasing order of risk); for example, L4 × S4 gives RPN 16 and cell number 19. Levels follow the PUPR SMKK risk matrix [10]: Very Low 1–5, Low 6–10, Medium 11–15, High 16–19, Very High 20–25. Ranks 3–37 are 35 risks with L = 4 and S = 4 and identical WRR; seven are shown. The shaft-fall risk is Very High on the risk map but ranks 38th by WRR.

The top two risks by WRR are the fall-from-height risk due to scaffolding collapse (WRR = 4.657) and the fire risk 543 as Very High on the risk map. The 35 risks with likelihood from electrical short circuit (WRR = 4.313), both classified = 4 and severity = 4 all share the identical RPN (16) and WRR (4.000), so they occupy a tied rank (3–37) rather than a sequence of distinct ranks; seven representative risks are shown in Table V. This equality is a direct consequence of the identical likelihood–severity combination and confirms that risks with the same likelihood–severity profile always receive the same WRR regardless of hazard type. The vertical-fall-into-shaft risk is Very High on the risk map (matrix score 21; likelihood = 2, severity = 5) but has a lower WRR (3.970) than the tied group because its likelihood is low; it ranks 38th by WRR

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while remaining a mandatory Bowtie target under the risk-map criterion.

Weighting also reorders risks relative to the conventional RPN: the electrical-fire risk (RPN = 15) ranks below the 35 risks with RPN = 16 under plain RPN, but above all of them under WRR, because Severity is weighted about 1.9 times higher than Likelihood. This finding should be read with the limitation that the weights rest on three experts whose individual judgments differed substantially, so the ordering of tied and near-tied risks is sensitive to the weighting and may not generalize beyond this project. On closer inspection, the 35 tied high-category risks are dominated by superstructure work and tower-crane lifting activities, such as risks from poor lighting during lifting, slipping while climbing scaffolding, injury during reinforcement installation, slipping during concrete pumping, tripping over formwork at floor edges, being struck by a load from a broken sling, and being grazed by crane swing.

This pattern is consistent with the characteristics of the superstructure phase, which combines work at height, heavy-material lifting, and simultaneous interaction of many workers. Nevertheless, only the three risks classified as Very High on the risk map were selected for further Bowtie Analysis. This selection rests on two considerations: first, they are the only risks in the Very High category and thus combine potentially fatal consequences with the highest urgency for control, an urgency the risk-map level identifies more directly than WRR alone; second, they represent three top events with different causal characteristics temporary-structure failure (scaffolding), electrical-system failure (fire), and vertical-opening protection failure (shaft) so Bowtie Analysis on these three can represent a broader range of accident mechanisms than analyzing the much larger tied group of High-category risks.

E. Risk Map

Based on the likelihood and severity results, all risks were mapped onto the risk matrix to depict the distribution of risk levels across construction activities. This mapping aims to visualize the risk distribution by the combination of probability and severity, easing identification of the risk categories requiring control priority. The mapping result is presented in Fig. 4.

The matrix in Fig. 4 shows the distribution of the 103 risk statements by likelihood–severity combination. The largest concentration is in cell L3/S4 (matrix score 17, 45 risks) and cell L4/S4 (matrix score 19, 35 risks), together covering more than two-thirds of all identified risks.

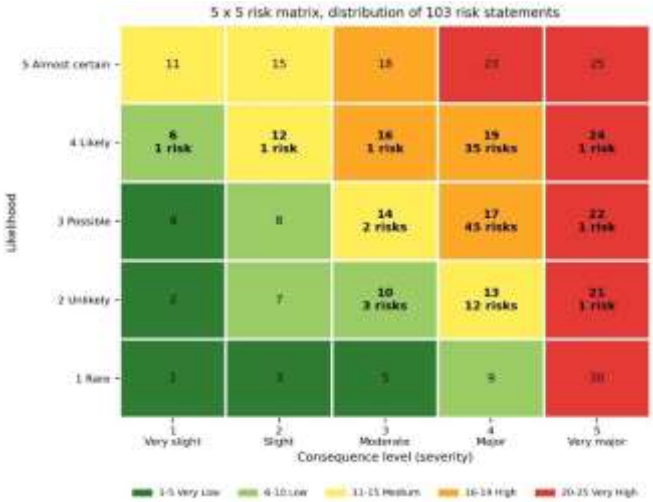

Fig. 4. Risk-level matrix: each cell shows the PUPR matrix-score number (not the RPN) and, where occupied, the number of risk statements. Levels and colors match Table IV and Table V (Very Low 1–5, Low 6–10, Medium 11–15, High 16–19, Very High 20–25).

Only three risks occupy Very High cells (matrix score 20–25): the scaffolding-collapse and electrical-fire risks, which also rank first and second by WRR, and the shaft-fall risk, whose low likelihood (2) gives it a lower WRR (3.970) than the 35 tied High-category risks even though its risk-map level is Very High. The risk map and WRR therefore complement rather than duplicate each other: the map flags severe but sometimes infrequent events, while WRR orders risks by the expert-weighted balance of frequency and consequence. The risk map yields levels and counts without explaining failure mechanisms or the barriers available to control them, so the three Very High risks are further examined through Bowtie Analysis in Section III-F.

F. Top Event and Bowtie Analysis

Based on the risk-map level (Section III-E), three top events were established for Bowtie Analysis: (1) fall from height due to scaffolding collapse, (2) fire from electrical short circuit in MEP work, and (3) vertical fall into an unprotected shaft. The summary of threats, consequences, and preventive and mitigative barriers for the three top events is presented in Table VI.

TABLE VI. HIGHEST-PRIORITY TOP EVENTS

Top Event	Main Threats	Consequences	Preventive Barrier	Mitigative Barrier
Fall from height (scaffolding collapse)	Overload; incomplete connections; irregular inspection; low assembler competence	Serious injury–death; material damage; project delay	Periodic inspection, permit to work, load limitation, toolbox meeting	Full body harness, safety net, emergency-response procedure
Fire (electrical short circuit)	Substandard cable installation; damaged insulation; inadequate current protection; electrical overload	Burns; asset damage; operational disruption	Standard cable/equipment inspection, circuit breaker/ELCB	Fire extinguisher (APAR), fire emergency-response system, evacuation route
Vertical fall into shaft	No guardrail/cover; poor lighting; no barricade; suboptimal PPE	Serious injury–death; evacuation obstruction	Shaft guardrail/cover, signage, additional lighting, permit to work	Emergency rescue procedure, first-aid team, evacuation system

Bowtie Analysis shows that the threats leading to each top event stem from a combination of technical, human, and management factors. This indicates that workplace accidents on construction projects are not caused by a single cause but result from the interaction of various factors developing progressively into a top event. These are contributing factors along the causal pathway rather than organizational root causes; tracing them to an underlying root cause would require a dedicated method such as the 5 Whys, Fault Tree Analysis, or Root Cause Analysis, which is outside the scope of this study. Barrier mapping shows that preventive barriers are positioned to reduce the likelihood of the top event because they can halt the risk-escalation path early, while mitigative barriers are positioned to limit impact severity if the top event still occurs; their actual field performance was not measured

in this study. The complete Bowtie diagrams for the three top events are presented in Figs. 5, 6, and 7.

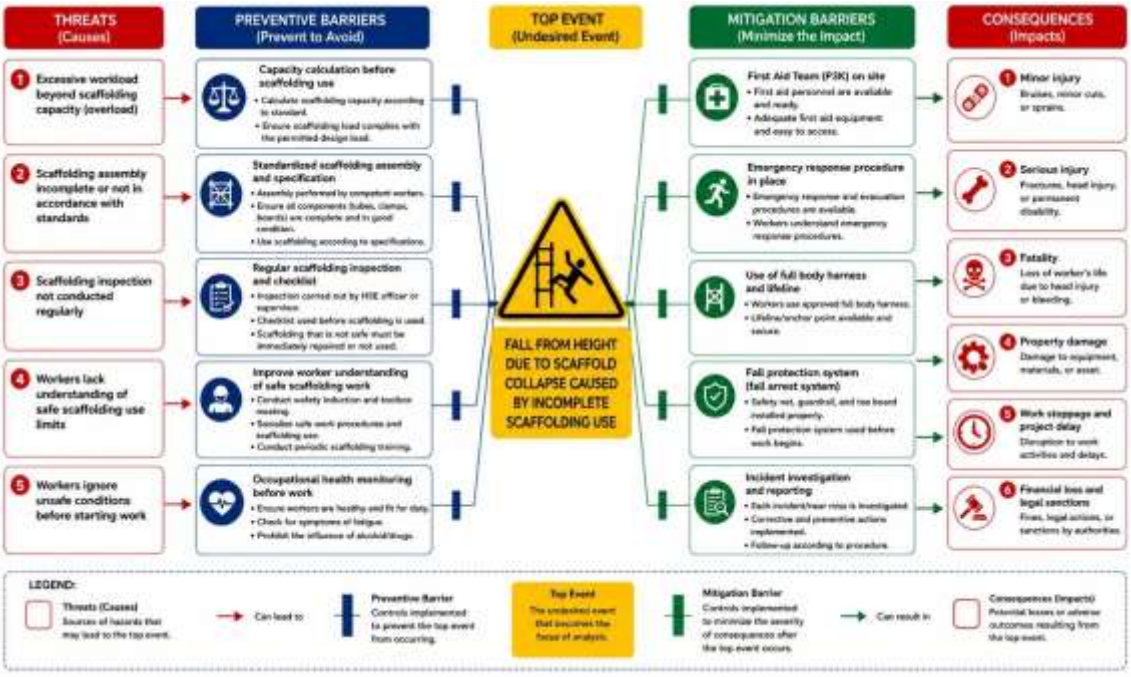

Fig. 5. Bowtie diagram for the fall-from-height risk.

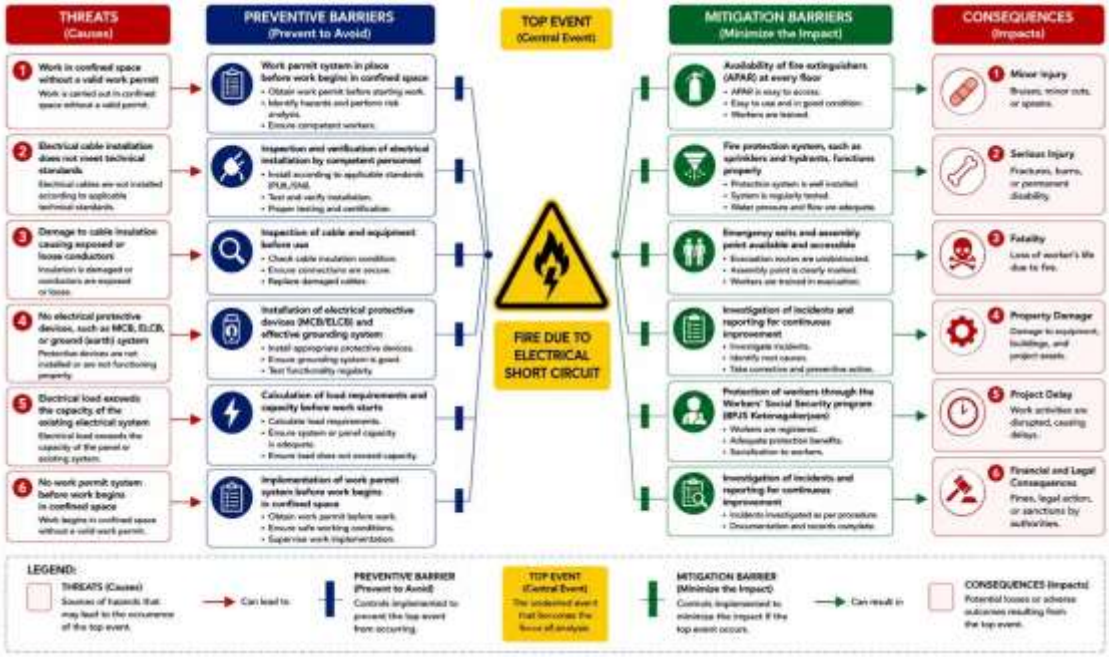

Fig. 6. Bowtie diagram for the fire risk from electrical short circuit.

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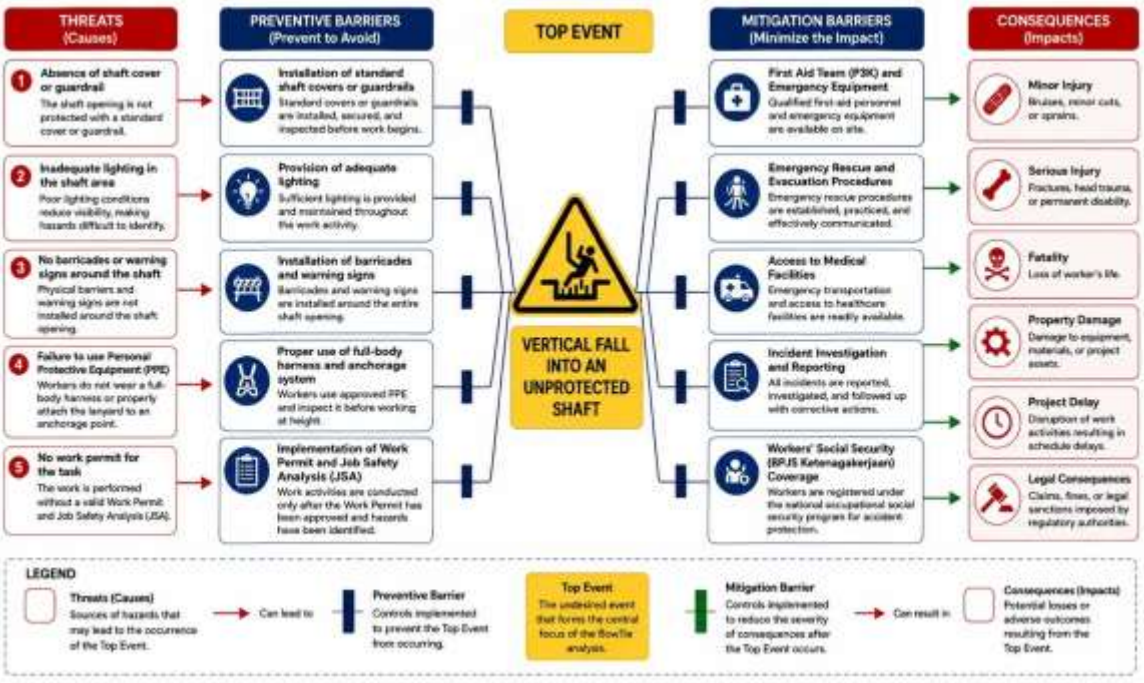

Fig. 7. Bowtie diagram for the vertical-fall-into-shaft risk.

In Fig. 5, the top event "fall from height due to scaffolding collapse" arises from five threats spanning technical (overload, substandard connections), management (irregular inspection), and human (limited understanding of safe limits, unfit condition) factors. The most decisive preventive barriers are load-capacity calculation and standard-compliant assembly, which cut the escalation path before work begins; the full body harness and lifeline form the last mitigative layer, though their effectiveness still depends on worker compliance. In Fig. 6, the top event "fire from electrical short circuit in MEP work" develops progressively from substandard cable installation and damaged insulation, through the absence of current protection (circuit breaker/ELCB), to electrical overload and weak permit-to-work enforcement.

The most decisive preventive barriers are pre-work inspection of cable installation and protection devices (MCB, ELCB, panel fuses); on the mitigation side, fire extinguishers (APAR) on every floor plus automatic sprinklers and hydrants provide the dispersed coverage that simultaneous, multi-area MEP work requires [28]. In Fig. 7, the top event "vertical fall into an unprotected shaft" stems from missing covers/guardrails, poor lighting, absent barricades, unused PPE, and no permit system. Being cross-disciplinary—shaft openings form during structural work but are later accessed by MEP and elevator teams—its most decisive preventive barrier is installing standard covers and guardrails, backed by a permit-to-work and Job Safety Analysis (JSA) system; clear rescue and evacuation procedures with an on-site first-aid team mitigate the harder evacuation inherent to confined shaft access.

G. Risk-Control Strategy and Discussion

Referring to the hierarchy-of-control approach and the cost-of-safety principle described in Section II-G, the control strategies for the three priority risks from Bowtie Analysis are discussed below, emphasizing the barriers judged most decisive on the causal structure in Table VI and Figs. 5–7 (an expert-based prioritization of barriers, not a measured effectiveness score). The fall-from-height risk due to scaffolding collapse holds the top priority (WRR = 4.657), consistent with Nor Haslinda et al., who identified bracing failure, scaffold collapse, and assembler incompetence as dominant causes of scaffolding accidents [13], and with [6], which found low scaffolder compliance with fall protection despite known risks. The recommended controls emphasize administrative controls (permit to work, periodic inspection) and engineering controls (installation to specification), consistent with the cost-of-safety principle that stresses efficient allocation of safety resources through AHP prioritization [16].

The fire risk from electrical short circuit in MEP work (WRR = 4.313) confirms that temporary electrical installations on high-rise projects require strict engineering controls, consistent with multi-criteria fire-risk assessment models for high-rise buildings [7], [44]. The vertical-fall-into-shaft risk (WRR = 3.970) is cross-disciplinary because shaft openings form during the structural phase and are later accessed by MEP and elevator work, so its control requires inter-disciplinary coordination, consistent with the systemic view of construction-accident causation [4], [3]. Methodologically, these results reinforce the argument that conventional HIRADC relying solely on likelihood–severity scores is prone to producing risk rankings that poorly distinguish handling urgency, as critiqued in reviews of occupational-safety risk-analysis methodology [43], [14]. Integration with AHP provides a mathematically verifiable weighting mechanism [15], [17], [18], while Bowtie Analysis complements AHP's shortcoming in structuring causal paths and identifying preventive and mitigative barriers [19], [20], including mapping layered causal paths as shown in the fault-tree– Bayesian-network analysis of underground construction accidents [42].

The resulting control recommendations follow the hierarchy of control [11], from engineering and administrative controls to PPE as the last layer. Besides lowering accident probability, applying these controls is also economically relevant: under Government Regulation No. 82 of 2019, fatal workplace accidents create direct compensation obligations, beyond indirect costs such as project delay, investigation, and reputational decline, so prevention investment through SMK3/SMKK is far more economical than bearing the losses of a fatal accident, consistent with the cost-of-safety approach

in construction risk management [16], [45]. Overall, the proposed integrated HIRADC–AHP– Bowtie framework can be applied sequentially and complementarily. HIRADC successfully identified 103 risks across all construction phases, AHP produced expert-weighted prioritization yielding risk priorities based on WRR, while Bowtie Analysis complemented both by visually mapping causal paths and identifying the threats, consequences, and preventive and mitigative barriers of the three priority risks, so that the three complement one another and produce a more complete risk picture than applying each method separately. 812 parties who assisted this research, including the IV. CONCLUSION Conclusion through structured expert judgment, and identify preventive and mitigative barriers across all phases of the Building X Construction Project through an integrated HIRADC–AHP–Bowtie Analysis approach. Hazard identification using HIRADC produced 103 OHS risk statements across six work phases, comprising 3 Very High, 81 High, 15 Medium, and 4 Low-category risks, with 78.6% in the High category. AHP weighting showed that Severity received a higher expert-derived priority weight (0.657) than Likelihood (0.343), indicating that accident-impact magnitude was the main consideration in setting control priorities. The three risks classified as Very High on the risk map—fall from height due to scaffolding collapse (WRR = 4.657), fire from electrical short circuit (WRR = 4.313), and vertical fall into a shaft (WRR = 3.970)—were established as top events and analyzed using Bowtie Analysis, which mapped combinations of technical, human, and management threats and contributing factors along the causal pathway and produced layered control strategies comprising preventive barriers (periodic inspection, load limitation, electrical-installation improvement) and mitigative barriers (full body harness, safety net, emergency-response procedures) identified in line with the ISO 45001:2018 hierarchy of control. The relative priority given to specific barriers in the discussion (Section III-G) reflects expert-based judgment of their role in the causal pathway, not a measured performance score.

Integrating these three methods shows that HIRADC served the initial field-perception-based hazard identification and risk assessment, AHP added a structured, expert-based criteria-weighting mechanism to produce the Weighted Risk Rating, while Bowtie Analysis complemented both by visually mapping causal pathways and identifying preventive and mitigative barriers, so that the three complement one another and produce a more complete risk picture than applying each method separately. This study has limitations regarding the small number of AHP experts, the scope of AHP criteria, the perceptual nature of the risk data, the identification (rather than performance measurement) of barriers, the mapping of contributing factors rather than organizational root causes, and its single-case-study scope, so generalizing the findings to other high-rise projects should be done cautiously, and further research is advised to broaden the weighting criteria and the range of project types analyzed, to measure the field performance of the identified barriers, and to trace contributing factors to root causes using dedicated methods such as the 5 Whys, Fault Tree Analysis, or Root Cause Analysis. Academically, this study contributes to developing an integrated HIRADC– AHP–Bowtie OHS risk-analysis model applied comprehensively across all high-rise construction phases in Indonesia; practically, the model is expected to serve as a reference for contractors in implementing a substantive, field-data-based SMK3 to reduce accident rates on similar high-rise projects in the future.

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