

A Sustainability-Based Occupational Safety Risk Prioritization Model for High-Rise Building Maintenance Using HIRARC and AHP

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ABSTRACT

High-rise building maintenance involving work at height presents significant occupational safety risks, particularly fall-related incidents that may result in severe injuries, operational disruptions, and financial losses. Conventional risk assessment approaches such as Hazard Identification, Risk Assessment, and Risk Control (HIRARC) primarily rely on technical likelihood–severity scoring and do not explicitly incorporate sustainability consequences into risk prioritization. This study develops a sustainability-based occupational safety risk prioritization model for high-rise building maintenance by introducing a Sustainability Risk Priority Index (SRPI) that integrates HIRARC-based technical risk scores, Triple Bottom Line (TBL) weighting derived from the Analytic Hierarchy Process (AHP), and hazard-level sustainability impact assessment. Unlike conventional approaches that prioritize hazards primarily based on technical risk magnitude, the proposed SRPI provides a composite prioritization framework that also captures People, Planet, and Profit consequences in measurable terms. The model was demonstrated through a case study of a three-story laboratory building that identified six hazards. The results show that falls from the rooftop edge and falls from a narrow canopy platform remain the highest technical risks ($R = 20$). The AHP weighting yielded People = 0.60, Profit = 0.25, and Planet = 0.15, with a Consistency Ratio (CR) of 0.07. The proposed model differentiates medium-level hazards more clearly by incorporating sustainability consequences while preserving the dominance of hazards with potentially fatal outcomes. Sensitivity analysis with $\pm 10\%$ variation in the People weight indicates that the highest-priority hazards remain stable across scenarios.

Keywords: Occupational safety; Sustainability risk prioritization; HIRARC; AHP; High-rise building maintenance

Introduction

High-rise building maintenance involving work at height is widely recognized as a high-risk activity in the construction and facilities management sectors. Falls from height (FFH) remain one of the leading causes of severe injuries and fatalities in construction and other elevation-based activities, including rooftop work, edge work, and temporary platform operations [1]–[5]. Recent technological developments, including sensor-based recognition and drone-assisted monitoring, have also been explored to improve the detection and control of fall-related hazards in construction environments [6], [7]. In high-rise building settings, maintenance work is carried out repeatedly because building components and service systems deteriorate over time. This condition makes maintenance decision-making inseparable from occupational safety and operational continuity.

Occupational Health and Safety Risk Assessment (OHSRA) methods are widely used because they provide systematic procedures for hazard identification, risk evaluation, and risk control. One of the most commonly applied approaches is HIRARC, which structures the process through hazard identification, risk assessment, and risk control stages [8]. Conventional HIRARC-based prioritization, however, is generally centred on technical likelihood x severity scores. This approach is effective at identifying hazards with potentially fatal consequences, but it does not explicitly account for broader consequences, such as impacts on people, the environment, and operational and economic performance. As a result, hazards with similar technical scores may receive similar priorities even when their wider sustainability implications differ substantially. In the Indonesian context, HIRARC/HIRADC studies have also predominantly focused on hazard identification, risk assessment, and control formulation, without developing a sustainability-based risk prioritization index [9]–[11].

Multi-Criteria Decision Making (MCDM) methods, particularly the Analytic Hierarchy Process (AHP), have been widely adopted in decision-support systems for risk evaluation and maintenance management. AHP is useful for structuring criteria weighting, testing judgment consistency, and improving transparency in decision-making [12]–[15]. Its application has also appeared in maintenance-related decision-making in Indonesia, for example, in vendor selection based on measurable criteria [16]. Even so, most MCDM/AHP studies focus on weighting decision criteria or ranking alternatives rather than developing an occupational hazard prioritization index that combines technical risk magnitude and sustainability consequences at the hazard level.

The Triple Bottom Line (TBL) concept has become increasingly prominent in risk management and decision-making literature because it expands evaluation beyond short-term technical targets by incorporating social, environmental, and economic consequences simultaneously [17]. Recent studies show that sustainability-driven, multidimensional risk management can alter priority structures by explicitly considering sustainability dimensions, transparency, decision resilience, and multi-criteria sustainability performance [18]–[21].

Despite this development, sustainability-oriented risk assessment has rarely been quantitatively integrated into the prioritization of occupational hazards for high-rise building maintenance activities. Most existing studies still position such assessment at the project or broader managerial level rather than at the hazard level [22].

These three streams of literature reveal a clear gap. Conventional HIRARC/OHSRA studies are strong in technical risk assessment, MCDM/AHP studies are strong in structured weighting and decision ranking, and sustainability risk assessment studies are strong in incorporating broader sustainability dimensions [8], [12]–[14], [17], [18], [22]. What remains limited is an integrated framework that explicitly combines: (1) HIRARC-based technical risk magnitude, (2) AHP-based weighting of sustainability criteria, and (3) hazard-level impact assessment across People–Planet–Profit within a single risk prioritization model. This gap is particularly important in high-rise building maintenance, where control decisions often focus on the most visibly fatal hazards, while medium-level hazards with operational and environmental implications may remain under-prioritized. From an Industrial Engineering perspective, this condition highlights the need for a decision-support framework that is not only technically sound but also transparent, auditable, and aligned with sustainability-oriented maintenance management.

This study develops a Sustainability Risk Priority Index (SRPI) for prioritizing occupational safety risks in high-rise building maintenance. The proposed SRPI integrates HIRARC-based technical risk scores with AHP-based TBL weighting and hazard-level sustainability impact assessment. The novelty of this study does not lie merely in combining HIRARC and AHP, but in developing a composite prioritization index that links technical risk magnitude with People–Planet–Profit consequences within a single measurable framework. The study therefore contributes, theoretically and methodologically, to the Industrial Engineering literature by extending occupational safety risk prioritization from predominantly technical models to a framework that explicitly incorporates sustainability considerations. In practice, the proposed model provides a more systematic basis for facility managers, maintenance supervisors, and occupational safety practitioners to establish more comprehensive control priorities for high-rise building maintenance activities.

Research Methods

This study develops a sustainability-based occupational safety risk prioritization model for high-rise building maintenance by integrating Hazard Identification, Risk Assessment, and Risk Control (HIRARC), Triple Bottom Line (TBL) weighting using the Analytic Hierarchy Process (AHP), and the

computation of a Sustainability Risk Priority Index (SRPI). Methodologically, the model was designed to capture two components simultaneously, namely technical risk magnitude and sustainability-related consequences at the hazard level. Accordingly, risk priority is not determined solely by likelihood \times severity, but also by the impact of each hazard on People, Planet, and Profit.

Research Framework

The research framework was simplified into six main stages:

- (1) Work activity and hazard identification,
- (2) Technical risk assessment using HIRARC,
- (3) Definition of the People–Planet–Profit dimensions,
- (4) Relative weighting of the TBL dimensions using AHP,
- (5) Computation of the Sustainability Risk Priority Index (SRPI), and
- (6) Comparison of ranking results between conventional HIRARC and SRPI.

This simplified structure was intended to highlight the study's core contribution: integrating technical risk magnitude and sustainability consequences into a single, transparent, and measurable risk-prioritization model.

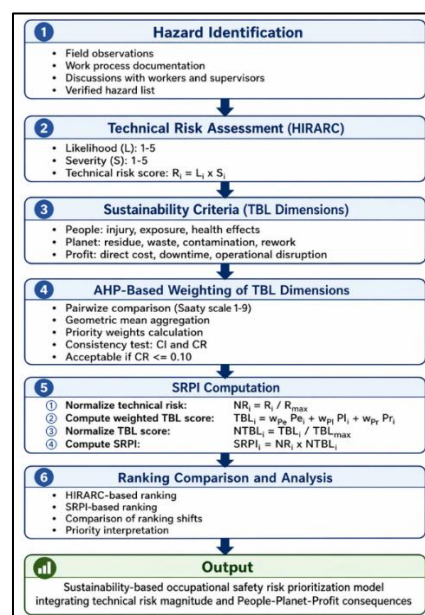


Figure 1. Conceptual research framework of the proposed Sustainability Risk Priority Index (SRPI) model

Data Collection and Expert Panel

The study was conducted on maintenance activities in a three-story laboratory building that involved work at height, including roof-leak repair, patching of damaged upper-edge areas, and reapplication of waterproofing material in seepage locations. Data were collected through field observations, documentation of work processes and workplace conditions, and structured discussions with workers and supervisors to verify work stages, hazard exposures, and the identified hazard list.

The TBL assessment and AHP pairwise comparison were conducted by a purposively selected panel of seven experts, comprising one occupational safety academic, one maintenance supervisor, one facility manager, and four senior workers with relevant experience in maintenance activities and work-at-height operations. This panel was selected to represent complementary academic, managerial, and operational perspectives relevant to the case context. The minimum criterion for inclusion was adequate professional or practical experience in occupational safety, facility maintenance, or work-at-height activities, enabling the panel members to provide context-sensitive judgments regarding People, Planet, and Profit impacts.

The role of this panel was to provide contextual expert judgment for the case study rather than to support statistical generalization to a broader population. Accordingly, expert assessment was treated as a decision-support input within the case context rather than as population-based inference.

Hazard Identification and HIRARC Risk Assessment

Hazard identification was carried out as the initial stage to ensure that the hazard list accurately reflected the actual working conditions of high-rise building maintenance activities. The hazard list was

established based on field observations, documentation of work activities, and structured discussions with workers and supervisors. The identified hazards were subsequently assessed using a 5 × 5 HIRARC risk matrix.

Technical risk assessment employed two parameters, namely Likelihood (L) and Severity (S), each rated on a 1–5 scale. Likelihood represents the frequency or probability of a hazard occurring under actual work conditions, whereas Severity represents the most realistic consequence level if the hazard occurs.

The technical risk score for hazard *i* was calculated as:

$$R_i = L_i \times S_i \quad (1)$$

Where:

R_i = technical risk score of hazards *i*

L_i = likelihood value of hazard *i*

S_i = severity value of hazard *i*

Operationally, the 1–5 Likelihood scale ranges from very rare to very frequent, while the 1–5 Severity scale ranges from minor consequences to fatal/catastrophic consequences. This approach was used because HIRARC is a widely adopted method for occupational hazard identification and technical risk prioritization [8].

TBL Criteria and AHP-Based Weighting

To incorporate a sustainability perspective into risk prioritization, this study adopted the three Triple Bottom Line (TBL) dimensions of People, Planet, and Profit [17], [22]. In this study, the dimensions were operationally defined as follows:

People: potential injury, exposure level, and possible short- to medium-term health effects on workers.

Planet: potential material residue, waste generation, local contamination, and rework that increases material consumption and additional waste.

Profit: direct costs, downtime, work delays, operational disruption, and rework-related costs.

AHP was selected because it enables structured multi-criteria weighting through pairwise comparison while also providing a consistency check for expert judgments [14], [23]. The experts compared the relative importance of People, Planet, and Profit using the Saaty 1–9 scale [23]. Since the assessment was conducted in a group setting, each element of the pairwise comparison matrix was aggregated using the geometric mean before the priority weights were calculated.

The criterion weights were obtained through eigenvector calculation. Judgment consistency was evaluated using the Consistency Index (CI) and the Consistency Ratio (CR):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

Where λ_{\max} is the maximum eigenvalue of the comparison matrix, *n* is the number of criteria, and RI is the Random Index. In this study, the resulting weights were People = 0.60, Profit = 0.25, and Planet = 0.15, with CR = 0.07. Because CR ≤ 0.10, the degree of inconsistency was considered acceptable, and the derived weights were deemed methodologically suitable for further analysis [23].

TBL Impact Scoring

The sustainability impact of each hazard was then assessed on a 1–5 scale for each TBL dimension. A score of 1 indicates very low/minor impact, while a score of 5 indicates very high/catastrophic impact. Scores were assigned by the expert panel based on the hazard context, actual work conditions, and the most plausible consequences if the hazard occurs.

With this approach, the assessment was intended not only to capture direct injury-related consequences but also to extend the analysis to environmental and operational-economic implications relevant to maintenance management [17], [22].

Sensitivity Analysis

A sensitivity analysis was conducted to assess the relative stability of the SRPI ranking under moderate changes in the expert-derived TBL weights. In this study, the People dimension was selected as the focus of the sensitivity analysis because it received the highest weight in the initial AHP results (0.60), indicating that it was the most dominant criterion in the weighting structure. The People weight was then varied by ±10% from its baseline value, while the Profit and Planet weights were adjusted

proportionally to maintain a total weight of 1.00. The proportional adjustment was performed by maintaining the initial Profit:Planet ratio of 5:3.

Based on this procedure, three weighting scenarios were established: the baseline condition with People = 0.60, Profit = 0.25, and Planet = 0.15; Scenario A, in which the People weight was reduced by 10% to 0.54; and Scenario B, in which the People weight was increased by 10% to 0.66. For each scenario, the SRPI values were recalculated using the same technical risk scores and hazard-level TBL scores as in the baseline condition. The resulting SRPI values and hazard rankings were then compared to examine the extent to which the risk priorities remained stable under changes in the weighting scheme.

This analysis was intended to provide an indication of the limited robustness of the prioritization results, particularly for the highest-ranked hazards, rather than to claim universal validation of the model.

Results and Discussion

Case Description

The case study was conducted in a three-story educational laboratory building used for academic and practical activities. The observed maintenance tasks included repairing roof leaks, patching damaged areas near the upper-floor edge, and reapplying waterproofing materials at locations experiencing water seepage. These activities were performed at elevations of approximately 10–12 m above ground level, thereby classifying them as work-at-height activities with significant occupational safety implications.

Field observations showed that workers performed maintenance tasks near the building edge and on a narrow canopy that was not designed as a permanent working platform. No adequate fall protection systems were in place at the work location, and workers were not using personal fall protection equipment, such as full-body harnesses and lifelines. These conditions indicate that the existing hazard control measures had not yet aligned with the hierarchy of controls, which prioritizes engineering controls before administrative controls and personal protective equipment [24]. This observation is also consistent with previous studies showing that the absence of collective fall protection and low compliance with personal protective equipment are major contributors to fall-from-height incidents in construction and other elevation-based work activities [2]–[4].

In addition to fall-related hazards, the observed maintenance work involved the use of waterproofing and sealant materials, which may result in mild to moderate chemical exposure as well as material residues, such as leftover compounds, containers, and cleaning waste, when housekeeping and waste handling are not properly implemented. These consequences extend the evaluation beyond technical safety risk to include environmental implications (Planet) and operational-economic consequences (Profit). Therefore, this case provides a relevant setting for examining sustainability-oriented occupational safety risk prioritization from a Triple Bottom Line (People–Planet–Profit) perspective [17], [22].



Figure 2. Observed work-at-height maintenance activity at approximately 10–12 m elevation without adequate fall protection systems

Hazard Identification

Hazard identification was conducted to establish a hazard list that accurately reflected the actual working conditions observed during the high-rise building maintenance activities. Based on field observation, work activity documentation, and structured discussions with workers and supervisors, six main hazards were identified:

1. Fall from rooftop edge, due to work performed near the edge without collective fall protection.
2. Fall from a narrow canopy platform, because workers stood on a canopy that was not designed as a permanent working platform.

3. Slipping during waterproofing application, as surfaces may become slippery during or after material application.
4. Falling objects to the lower area, including tools or materials that may fall from the work edge.
5. Chemical exposure from sealant or waterproofing materials, particularly from vapors or splashes during application and cleaning activities.
6. Postural fatigue or instability, caused by limited workspace and unstable footing.

These identified hazards indicate that the observed maintenance activities involve not only direct worker safety risks (People), but also broader implications for Planet and Profit, particularly regarding material residue, rework potential, and operational disruption [17], [22]. The identified hazards served as the basis for the technical risk assessment and the sustainability-based prioritization analysis in the following subsections.

Technical Risk Assessment and Sustainability-Based Prioritization

The six identified hazards were subsequently assessed using HIRARC. The results in Table 1 show that the two hazards with the highest technical risk scores were fall from rooftop edge (H1) and fall from narrow canopy platform (H2), each with a value of R = 20 and classified as High. This finding confirms that fall-from-height hazards remain the primary priority in high-rise building maintenance.

The hazards slipping during waterproofing application (H3) and falling objects to the lower area (H4) both obtained a score of R = 12 and were classified as Medium, whereas chemical exposure (H5) and postural fatigue/instability (H6) showed lower technical risk scores of 6 and 9, respectively. Overall, these results indicate that HIRARC effectively identifies hazards with potentially fatal consequences as the highest priority; however, the ranking remains primarily based on technical likelihood–severity scores.

Table 1. HIRARC Risk Assessment Results

No.	Code	Hazard	L	S	R = L × S	Category
1	H1	Fall from the rooftop edge	4	5	20	High
2	H2	Fall from a narrow canopy platform	4	5	20	High
3	H3	Slipping during the waterproofing application	3	4	12	Medium
4	H4	Falling objects into the lower area	3	4	12	Medium
5	H5	Chemical exposure	2	3	6	Low-Medium
6	H6	Postural fatigue/instability	3	3	9	Medium

The AHP weighting results presented in Table 2 show that the People dimension received the highest weight (0.60), followed by Profit (0.25) and Planet (0.15), with a Consistency Ratio (CR) of 0.07. This result indicates that the expert panel considered worker safety and health consequences to be the dominant concern, while still incorporating operational-economic and environmental dimensions into the prioritization process.

Table 2. AHP Weighting Results of TBL Criteria

Criterion	Weight	Interpretation
People	0.60	Highest priority
Profit	0.25	Secondary priority
Planet	0.15	Lowest priority

Notes: $\lambda_{max} = 3.081$, CI = 0.040, and CR = 0.070. The comparison matrix is considered acceptable because CR < 0.10.

The sustainability-based prioritization results are presented in Tables 3 and 4. Table 3 shows the average People, Planet, and Profit scores assigned to each hazard, together with the composite TBL score and its normalized value (NTBL). The results indicate that H1 obtained the highest NTBL value (1.000), followed by H2 (0.907) and H4 (0.868), whereas H6 had the lowest NTBL value (0.628).

Table 3. TBL Scores, Composite TBL Score, and Normalized TBL Value

No.	Code	Hazard	People	Planet	Profit	Composite TBL Score	NTBL
1	H1	Fall from the rooftop edge	5.000	3.000	4.571	4.593	1.000

2	H2	Fall from a narrow canopy platform	4.571	1.857	4.571	4.164	0.907
3	H3	Slipping during the waterproofing application	3.571	2.571	3.286	3.347	0.729
4	H4	Falling objects into the lower area	4.286	3.714	3.429	3.986	0.868
5	H5	Chemical exposure	3.429	4.571	4.429	3.849	0.838
6	H6	Postural fatigue/instability	2.857	1.857	3.571	2.884	0.628

Notes: People, Planet, and Profit represent the average expert scores on a 1–5 scale. The composite TBL score was calculated using the AHP-derived weights, and NTBL was obtained by normalizing the composite score against the maximum TBL value.

The final SRPI ranking is shown in Table 4. The results indicate that H1 and H2 remained the top two hazards, indicating that integrating sustainability dimensions did not alter the dominance of hazards with potentially fatal consequences. However, a different pattern appears among the medium-level hazards. Although H3 and H4 had the same HIRARC score ($R = 12$), H4 obtained a higher SRPI because it had a higher composite TBL score and a higher NTBL value. This result shows that hazards with the same technical risk magnitude do not necessarily have the same sustainability consequences and, therefore, should not automatically receive the same control priority.

Table 4. Sustainability Risk Priority Index (SRPI) and Risk Ranking

Rank	Code	Hazard	HIRARC Score (R)	NR	NTBL	SRPI
1	H1	Fall from the rooftop edge	20	1.00	1.000	1.000
2	H2	Fall from a narrow canopy platform	20	1.00	0.907	0.907
3	H4	Falling objects into the lower area	12	0.60	0.868	0.521
4	H3	Slipping during the waterproofing application	12	0.60	0.729	0.438
5	H6	Postural fatigue/instability	9	0.45	0.628	0.283
6	H5	Chemical exposure	6	0.30	0.838	0.251

Hazard H5 also provides an important finding. Although it has a relatively high NTBL value (0.838), its SRPI remains low because its technical risk score is comparatively low ($R = 6$; $NR = 0.30$). This pattern indicates that the SRPI model balances two components simultaneously, namely technical risk magnitude and sustainability consequences. Accordingly, hazards with relatively high sustainability implications but low technical risk do not disproportionately overtake hazards with potentially fatal outcomes.

From an analytical perspective, these findings indicate that SRPI does not replace HIRARC; rather, it extends HIRARC. HIRARC remains effective in identifying hazards with potentially fatal outcomes, whereas SRPI adds sensitivity to People–Planet–Profit consequences that are not captured by technical risk scores alone. In particular, the different rankings of H3 and H4 demonstrate the added value of the proposed model in distinguishing hazards with the same technical score but different sustainability implications. This result supports the use of SRPI as a more comprehensive basis for occupational safety risk prioritization in high-rise building maintenance.

Sensitivity Analysis

A sensitivity analysis was conducted to examine the relative stability of the SRPI ranking under moderate changes in the expert-derived TBL weights. In this study, the People dimension was selected as the focus of the analysis because it received the highest weight in the baseline AHP results (0.60), indicating that it was the most dominant criterion in the weighting structure. The People weight was then varied by $\pm 10\%$ from its baseline value, while the Profit and Planet weights were adjusted proportionally to maintain a total weight of 1.00. The proportional adjustment was performed by maintaining the initial Profit: Planet ratio of 5:3.

Table 5. TBL Weight Scenarios for Sensitivity Analysis

Scenario	People	Profit	Planet	Adjustment Basis
Baseline	0.60	0.25	0.15	Weights obtained from AHP ($CR = 0.07$)
A (-10% People)	0.54	0.2875	0.1725	Remaining weight distributed proportionally using the 5:3 ratio

B (+10% People)	0.66	0.2125	0.1275	Remaining weight distributed proportionally using the 5:3 ratio
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Using these alternative weighting schemes, the SRPI values were recalculated while keeping the technical risk scores and hazard-level TBL scores unchanged. The results show that H1 remained ranked first across all scenarios, indicating that the primary priority decision is relatively stable under moderate changes in the weighting scheme. This finding suggests that the recommendation to prioritize fall-prevention controls for the most critical work-at-height hazard is not highly sensitive to reasonable variation in expert preference.

However, the effect of weight variation is more visible among the medium-level hazards than among the highest-priority hazards. This pattern indicates that the sensitivity analysis does not provide universal validation of the model; rather, it provides evidence of limited robustness for the top-ranked hazards, while confirming that SRPI remains sufficiently sensitive to differentiate hazards with similar technical risk magnitudes. In this sense, the analysis supports the role of SRPI as a prioritization tool that preserves the dominance of fatal hazards while allowing more refined discrimination among hazards with comparable technical scores.

Comparative Analysis, Managerial Implications, and Study Contribution

The findings show that integrating sustainability dimensions into occupational safety risk prioritization does not alter the dominance of hazards with potentially fatal consequences, but it does refine the priority structure among medium-level hazards. In the present case, H1 (fall from rooftop edge) and H2 (fall from narrow canopy platform) remained the highest priorities in both HIRARC and SRPI. This result is consistent with previous studies showing that fall-from-height hazards remain one of the most critical sources of severe injury and fatality in construction and other elevation-based activities, particularly when fall protection systems are inadequate [2]–[4].

However, the main added value of the proposed SRPI emerges among hazards with similar technical risk magnitudes. In this study, H3 (slipping during waterproofing application) and H4 (falling objects to the lower area) had the same HIRARC score ($R = 12$), yet H4 received a higher SRPI ranking because it had a higher composite TBL score and a higher NTBL value. This difference is important because it demonstrates that hazards with the same technical score do not necessarily produce the same sustainability-related consequences. From this perspective, the proposed model does not replace HIRARC; rather, it extends HIRARC by incorporating People–Planet–Profit consequences into the prioritization logic. This finding aligns with sustainability-oriented risk assessment studies showing that the inclusion of broader social, environmental, and economic dimensions may alter priority structures compared with purely technical approaches [17], [18], [20].

The result for H5 (chemical exposure) provides an additional conceptual insight. Although H5 has a relatively high NTBL value, its overall SRPI remains low because its technical risk score is relatively small. This pattern indicates that the proposed model balances two components simultaneously: technical risk magnitude and sustainability consequences. As a result, hazards with higher sustainability implications do not automatically overtake hazards with potentially fatal outcomes when their technical risk remains comparatively limited. This is a key distinction from conventional HIRARC ranking, which primarily reflects likelihood–severity combinations, and from broader sustainability assessment models that often operate at the project or managerial level rather than directly at the hazard level [8], [17], [22].

From a managerial perspective, the ranking results provide a clearer basis for selecting control priorities. Because H1 and H2 remained the highest-ranked hazards, the primary intervention priority should be directed toward engineering controls, particularly the installation of edge protection, the provision of safer temporary working platforms, and the use of adequate anchor and lifeline systems. These measures are directly aligned with the observed exposure conditions and with the well-established need to prioritize preventive fall protection in work-at-height activities [2]–[4].

For the medium-level hazards, the findings suggest the importance of stronger administrative controls once the dominant fall hazards have been addressed. In particular, the ranking of H3 and H4 indicates the need for permit-to-work procedures, pre-job briefings, routine inspection of work access and protection systems, and closer supervision during maintenance execution. Such measures are relevant because medium-level hazards are more sensitive to the broader operational and organizational context than the highest-priority fatal hazards [25], [26].

The result for H5 indicates that material handling, housekeeping, residue management, and rework prevention should receive greater attention than would be suggested by technical risk scoring alone. Although H5 does not become a top overall priority, its sustainability implications remain relevant, as chemical use and residue generation may affect environmental cleanliness, operational continuity, and

material efficiency [17], [22]. Similarly, the ranking of H6 highlights the importance of ergonomic improvements, including better workspace arrangement, more stable footing, and appropriate work-rest scheduling, to reduce postural instability and related productivity disruption [8], [27].

The sensitivity analysis further supports this interpretation. The fact that H1 remained ranked first across all weighting scenarios indicates that the main fall-prevention decision is relatively stable under moderate changes in expert preference. At the same time, the greater responsiveness of the medium-level hazards confirms that the proposed SRPI is particularly useful in differentiating hazards that cannot be adequately distinguished by technical scores alone. Accordingly, the sensitivity analysis should be interpreted as evidence of limited robustness in the top-priority decision and of useful analytical sensitivity among hazards with similar technical risk levels, rather than as universal validation of the model.

Overall, this study contributes in two main ways. First, it provides a methodological contribution by developing the Sustainability Risk Priority Index (SRPI) as a measurable framework that integrates HIRARC-based technical risk with AHP-based TBL weighting and hazard-level sustainability impact assessment. Second, it provides a practical contribution by offering a more transparent basis for sustainability-oriented maintenance decision-making in high-rise building contexts. In this sense, the model helps decision-makers move beyond purely technical rankings toward a more comprehensive prioritization logic that accounts for worker safety, environmental impacts, and operational-economic consequences.

Limitations and Future Work

This study has several limitations that should be acknowledged when interpreting the findings. First, the proposed SRPI framework was demonstrated through a single case study, which means that the resulting rankings are context-specific and should not be interpreted as universally generalizable to all types of high-rise buildings or maintenance settings. The contribution of the study, therefore, lies primarily in the proposed framework and analytical logic, rather than in claiming universally transferable numerical weights or ranking outcomes.

Second, the AHP weighting and hazard-level TBL scores were derived from the judgments of seven experts, which introduces a degree of subjectivity. Although this limitation was mitigated by purposive expert selection, geometric mean aggregation, and consistency testing, the results still reflect contextual expert judgment rather than population-based inference. Accordingly, the weighting structure should be understood as a reasoned decision-support input for the specific case rather than as a statistically generalizable parameter set.

Third, the study did not incorporate historical incident data, near-miss records, or detailed cost data, including direct accident costs, downtime losses, and rework expenses. As a result, the Profit dimension and some aspects of the sustainability consequences were assessed through expert judgment rather than empirical operational records. In addition, the sensitivity analysis examined only moderate variation in the dominant People weight, which provides limited evidence of robustness but does not constitute universal validation of the model across broader scenarios.

Future research should therefore extend the present study in several directions. First, the SRPI framework should be applied across multiple case settings, including different building types, maintenance tasks, and organizational contexts, to assess its transferability and compare how ranking patterns vary across environments. Second, future studies should incorporate more objective empirical inputs, including incident records, near-miss data, downtime information, waste generation data, and cost components, so that the sustainability dimensions—particularly Profit and Planet—can be assessed with stronger evidential support. Third, further studies may compare the present framework with alternative or hybrid MCDM approaches to examine whether similar prioritization patterns emerge under different weighting and aggregation techniques. Finally, future work should explore how the SRPI framework can be integrated into operational occupational safety management practices, such as permit-to-work systems, routine inspections, maintenance planning, and safety monitoring, so that it can function not only as an analytical model but also as a practical decision-support tool for sustainability-oriented maintenance management.

Conclusion

This study develops a Sustainability Risk Priority Index (SRPI) as a sustainability-based framework for prioritizing occupational safety risks in high-rise building maintenance activities. By integrating HIRARC-based technical risk scores with the People, Planet, and Profit dimensions using AHP

weighting, the study shows that risk prioritization can be more comprehensive than conventional technical approaches that rely solely on likelihood and severity.

The findings show that hazards with potentially fatal consequences, namely falls from rooftop edges and narrow canopy platforms, remain the highest priorities. However, integrating sustainability dimensions provides additional differentiation among medium-level hazards. In this case, hazards with the same technical risk score may receive different priorities because they carry different People–Planet–Profit consequences. This finding confirms that SRPI does not replace HIRARC; rather, it extends HIRARC by adding sensitivity to sustainability-related consequences that are not captured by technical risk scores alone.

The main contribution of this article lies in three aspects. First, it develops the SRPI as a sustainability-based risk prioritization index. Second, it integrates technical risk magnitude and sustainability dimensions into a single measurable prioritization framework. Third, it provides methodological and practical support for sustainability-oriented maintenance decision-making, particularly in the context of occupational safety for high-rise building maintenance.

Nevertheless, the boundary of generalization should be clearly stated. The primary generalization from this study is the SRPI analytical framework, rather than the specific weights, scores, or numerical rankings generated in this case study. The AHP weights and prioritization results remain context-dependent because they are influenced by the hazard characteristics, work conditions, and expert judgments of the studied case. Therefore, application in other contexts still requires contextual data, expert assessment, and field-based verification.

Overall, this study shows that occupational safety risk prioritization can be made more transparent, more informative, and better aligned with sustainability principles without weakening HIRARC's ability to identify fatal hazards. Accordingly, SRPI may be positioned as a useful decision-support framework for more comprehensive occupational safety risk management in high-rise building maintenance activities.

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