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PRIORITISATION OF BIM-BASED SAFETY MANAGEMENT FEATURES USING THE ANALYTIC HIERARCHY PROCESS

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ABSTRACT

The construction industry is widely recognised as one of the most hazardous sectors due to its dynamic environment, complex processes, and high exposure to safety risks. Improving safety performance, therefore, requires effective management strategies supported by advanced technologies. Building Information Modelling (BIM) has emerged as a valuable tool for enhancing safety management throughout the building lifecycle. This study aims to prioritise key BIM-based safety management features using the Analytic Hierarchy Process (AHP). Three evaluation criteria, i.e. (i) importance, (ii) effectiveness, and (iii) ease of implementation, were used to assess three major BIM safety feature, including Prevention through Design (PtD), Automated Hazard Identification (AHI), and Emergency planning and simulation (EPS). Data were collected from ten BIM experts through pairwise comparisons, and the results were analysed using AHP. The findings indicate that importance is the most influential criterion. Among the features, PtD ranked highest, followed by Automated Hazards Identification (AHI), and Emergency Planning Simulation (EPS). The results highlight the significance of proactive design-based safety strategies and guide prioritising BIM-enabled safety interventions in construction safety practices.

Keywords: *Analytic Hierarchy Process; Automated Hazard Identification; Building Information Modelling; Emergency Planning and Simulation; Prevention through Design.*

1. INTRODUCTION

The construction sector is widely recognised as one of the most accident-prone industries due to its inherent complexity, dynamic work environment, and high exposure to occupational risks (Yiu et al., 2018). Construction projects involve multiple stakeholders, heavy machinery, working at heights, and constantly changing site environments, which significantly increase the likelihood of accidents and injuries (Bavafa et al., 2018). According to Rey-Becerra et al. (2021), the construction sector contributes to a substantial

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proportion of workplace accidents worldwide, particularly in developing countries where safety management practices may be less advanced. As a result, improving safety performance has become a critical priority for the construction industry.

Traditional safety management approaches in construction mainly rely on reactive measures, such as inspections, safety training, and incident reporting, after hazards have already emerged (Khosravi et al., 2020). This limitation highlights the need for more proactive safety management approaches that can identify and mitigate hazards during the earlier stages of the project lifecycle. Recent advancements in digital technologies have introduced innovative tools that can enhance construction safety management. Among these technologies, BIM has emerged as a powerful platform for integrating safety considerations into construction planning, design, and project management processes (Hire et al., 2024). BIM enables the creation of digital representations of building components and processes, allowing project stakeholders to visualise construction activities, identify potential hazards, and simulate safety scenarios before actual construction begins (Jaafar et al., 2018). Through capabilities such as hazard visualisation, design coordination, and simulation-based planning, BIM has the potential to significantly improve safety performance across the building lifecycle.

Despite the growing interest in BIM applications for construction safety, existing research has focused on individual BIM tools or specific safety applications, such as hazard visualisation or fall detection. However, limited studies have systematically evaluated and prioritised the most influential BIM-based safety management features that can effectively improve safety features and should receive attention and investment. This lack of prioritisation may lead to inefficient allocation of resources and limited adoption of the most impactful safety interventions. Therefore, there is a need for a systematic decision-making approach that can evaluate multiple BIM-based safety management features and determine their relative importance in improving construction safety performance. Multi-criteria decision-making methods provide a structured way to compare different alternatives based on expert judgement and multiple evaluation criteria. Among these methods, AHP is widely used for prioritising complex decision problems since it allows both qualitative and quantitative evaluation and includes a consistency verification mechanism to ensure reliable results.

This study aims to prioritise key BIM-based safety management features that contribute to improved safety performance in construction projects using the AHP method. To achieve this aim, the study pursues objectives: First, the study identifies key BIM-based safety management features relevant to construction projects through a literature review. Second, a framework for AHP analysis was developed to evaluate these features based on three criteria: importance, effectiveness, and ease of implementation. Third, Expert judgements from BIM professionals are collected and analysed through pairwise comparisons to determine the relative priority of the identified BIM-based safety features. Finally, the study provides practical insights for professionals and decision-makers by identifying the most influential BIM-based safety features that can support improved.

2. LITERATURE REVIEW

2.1 SIGNIFICANCE OF SAFETY

Safety is the preservation of positive value, "An ability for a system to perform its intended purpose, whilst preventing harm to persons" (Vandeskog, 2024, P.5). On the other hand, Ball and Frerk (2015), emphasised that, applying risk control across the workplace, individual and system, integrating it into the organisation to reduce risk as much as reasonably practicable to achieve sustainable action, accountability, and potential injury reduction. Improving safety is a continuous process requiring organisational initiatives such as structural safety training and ensuring the application of learned safety skills in daily work activities (Hutchinson et al., 2022). In high-risk work environments, unresolved health and safety issues may lead to reduced productivity, increased medical expenses, and overall strain on employees (Classen et al., 2020). Moreover, sharing safety information and adhering to safety procedures rely heavily on effective interpersonal communication and cooperation (Newnam & Goode, 2019). Some researchers have provided a clear elucidation regarding the significance of safety, as described in Table 1.

Table 1: Importance of safety

Importance	Authors
Safety directly influences work performance, enhancing workers' effectiveness and confidence.	Noor Arzahan et al. (2022)
Preventing workplace accidents is a core outcome of a strong safety system, and it improves the physical and mental health of workers, minimizing exposure to hazards.	Wachter & Yorio (2014)
Effective safety knowledge transmission must align with real working conditions, understanding task-related hazards and developing strategies to reduce risk.	Rémery (2022)
Inefficient planning negatively affects both productivity and safety performance, demonstrating that safety is not an isolated function but directly linked to overall project success.	Vinodkumar & Bhasi (2010)
Safety integration is critical requirement for construction firms to remain competitive, as high accident rates hinder productivity, quality outcomes, and financial performance.	Rodrigues et al. (2021)
Effective safety planning must span the entire project lifecycle from design and planning, through construction, to end-of-life to address hazards evolving over time.	Wetzel & Thabet (2015)
Safety directly influences work performance, enhancing workers' effectiveness and confidence.	Noor Arzahan et al. (2022)

As mentioned above, safety is important to the construction sector, and integration of advanced technologies can be used to enhance safety features and safety culture.

2.2 ENHANCING SAFETY FOR BUILDINGS THROUGH BIM

Enhancing safety for buildings through BIM is an advanced digital process that is transforming how construction projects are created, managed, and visualized (Thang Ngoc Nguyen, 2025).The United States National BIM standard for BIM is defined as " a shared knowledge resource, a sharing of information about the facility, to provide a reliable basis for the establishment of the facility from the construction to the demolition of the whole life cycle of the process"(National BIM Standard-United States, 2013, P.5). This definition highlights BIM not merely as a modelling tool, but as an integrated information management process that supports decision-making across the entire building lifecycle Borkowski (2023). In recent years, the use of BIM has increased significantly, not only in the design management of construction elements (Antwi-Afari et al., 2018), but also in activities related to the life cycle of buildings, such as hazard identification and safety assurance, maintenance of building assets, and their environmental performance (Fargnoli & Lombardi, 2020). The integration of BIM across multiple project stages enables proactive planning, improved visualisation, and early identification of potential design, construction, and operational challenges (Fargnoli & Lombardi, 2020).

2.3 PREVENTION THROUGH DESIGN

Prevention through Design is a proactive safety approach that aims to eliminate or reduce construction hazards during the design stage before construction activities begin (Collinge et al., 2022). BIM-based PtD addresses common on-site accidents caused by poor planning and weak risk management by embedding safety considerations into building and construction design (Aladayleh & Aladaileh, 2024). This enables early hazard identification, evaluates safer design alternatives, and improves communication and coordination among project stakeholders (Rodrigues et al., 2021). According to Johansen et al. (2024), PtD is closely related to the hierarchy of controls because it focuses on eliminating hazards at their source through design modifications rather than relying only on protective measures during construction. Furthermore, BIM-supported PtD tools can assist in detecting safety risks, analysing construction sequences, and providing safety-related information during the design stage, which contributes to reducing construction-site accidents and improving overall safety performance (Li et al., 2021).Automated hazard identification Traditional hazard identification requires extensive planning, monitoring, and coordination, which are challenging to maintain consistently across all phases of a construction project (Phinias, 2023). Among emerging technological tools, BIM has gained significant attention for its potential to improve safety outcomes on construction sites (Malik et al., 2021). One of the most valuable capabilities of BIM is its capacity to address safety hazards directly within the digital project environment (Akram et al., 2019). Hence, BIM supports the identification of potential risks by enabling the visualisation of site conditions, construction sequence, and spatial constraints (Kim et al., 2024).

2.3 EMERGENCY PLANNING AND SIMULATION

Effective emergency planning in buildings increasingly relies on the integration of BIM and simulation tools to ensure safe evacuation routes, efficient fire response zoning, and well-defined safety zones (Abir et al., 2022). According to Hassanpouret al. (2022), BIM models allow dynamic, agent-based evacuation simulations that account for human movement patterns, response delays, obstacle interactions, and route preferences. This integration is essential for analysing emergency exit performance, identifying congestion points, and assessing alternative evacuation strategies under varying conditions (Gao et al., 2022). The simulation framework incorporates key behavioural mechanisms, such as agents' speed, body radius, perception of nearby obstacles, path weighting, and emergency response activation once alarms are triggered (Makinoshima et al., 2022). Methodology This study aims to prioritise key BIM-based safety management features for improving safety performance in construction practices in the building industry. A literature review was conducted to identify relevant BIM safety features and determine their relative importance using AHP. The selection of BIM features was based on their relevance to different phases of the building lifecycle. And represent proactive hazard prevention, automated hazard detection, and emergency preparedness, which are considered major dimensions of BIM-enabled safety management in construction projects. AHP provides a structured multi-criteria decision-making approach that accommodates both qualitative and quantitative assessments (Szabo et al., 2021). AHP decomposes complex problems into hierarchical levels, enabling systematic comparison and prioritisation (Wong & Li, 2023). Furthermore, AHP includes a consistency verification mechanism, ensuring the reliability of expert evaluations. Therefore, AHP was considered the most suitable method for prioritising BIM-based safety management features in this study.

3. METHODOLOGY

Although BIM supports a wide range of applications in construction safety management, this study focuses on three major BIM-based safety management features: prevention through design supports proactive risk elimination during the design stage and is widely recognised as a fundamental strategy for reducing construction hazards (Chris et al., 2024). Automated hazard identification leverages BIM-based analysis tools to detect and visualise potential hazards, enhancing safety monitoring and decision-making during construction activities. Moreover, emergency planning and simulation were selected since BIM-enabled simulation technologies support evacuation planning, emergency response analysis, and safety preparedness in building operations (Sidani et al., 2023). Together, these three features represent safety prevention, hazard identification, and emergency preparedness across different stages of the building lifecycle.

The AHP method was employed to rank the identified BIM-based features according to their relative contribution to improving building safety performance. The hierarchical structure developed for this study consists of three levels. This study focuses on applying a direct comparison approach among the three primary BIM- based safety features and structures to ensure clarity and focuses on identifying the most influential feature from the BIM experts' perspective. The application of AHP includes the following steps.

Step 1: Problem definition

The first step involved clearly defining the decision problem, which is to prioritize the selected BIM-based safety management features in improving overall safety performance.

Step 2: Construction of pairwise comparison matrix

Four 3×3 matrices were created,

- One for importance
- One for effectiveness
- One for ease of implementation
- One for identified criteria

Saaty's scale was used to perform pairwise comparisons between features. This scale allows experts to express the relative importance of one feature over another using numerical values ranging from one to nine. The use of Saaty's scale provides a systematic and standardised approach for converting subjective expert judgement into quantitative values, thereby, enhancing the reliability and consistency of the decision-making process in AHP. Table 2 presents Saaty's scale used for pairwise comparisons.

Table 2: Saaty's scale

Intensity of importance	Definition
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance

Each matrix satisfies the reciprocity condition:

$$a_{ij} = \frac{1}{a_{ji}} \qquad (01)$$

Where, a_{ij} = importance of element of i compared with element j, a_{ji} = importance of element j compared with element i,1= reciprocal relationship between the two comparisons, i, j= criteria and factors being compared.

Step 3: Aggregation of Expert Judgements

The geometric mean method was used to combine expert responses:

$$a_{ij} = \left(\prod_{K=1}^{N} c_{ij}^{(k)}\right)^{1/N} \qquad (02)$$

Where, $a_{ij} =$ the aggregated pairwise comparison value, $c_{ij}^{(k)}$= the pairwise comparison value provided by respondants, K= index of experts, N= total number of experts,1/N= geometrix mean calculation.

Step 3: Derivation of local weights

Each matrix was normalized:

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \qquad (03)$$

Where, n_{ij}= Normalized value,a_{ij}= pairwise comparison value, n= total number of criteria and features being compared.

The row average method was then used to determine the local weight of each feature:

$$w_i = \frac{\sum_{j=1}^{n} n_{ij}}{n} \qquad (04)$$

Where,w_i = priority weight, n_{ij}= normalized value, j= index of column, n=total number of criteria and features being compared.

Step 4: consistency verification

To verify the consistency of the judgments, the consistency Index (CI) and consistency Ratio (CR) were computed:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (05)$$

Where, CI= Consistency Index,λ_{max}= the maximum eigenvalue, n= number of criteria and factors, n-1 = adjustment factor.

$$CR = \frac{CI}{RI} \qquad (06)$$

Where, CR=Consistency Ratio, CI=Consistency Index, RI=Random Index.

Table 3: Random index value

Random index	n	3	4	5	6	7	8	9	10
	RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Forn = 3, RI= 0.58.

A CR value below 0.10 indicates acceptable consistency.

Step 5: Calculation of Global weights

The Global weights of each BIM-based safety feature were calculated by multiplying the criterion weight by the local weight of the feature under that criterion:

$$\textit{Global weight} = \textit{Criteria weight} \times \textit{Local weight} \qquad (07)$$

The final ranking of the features was determined based on the calculated global weights.

Data were collected through semi-structured interviews with ten BIM experts who have 5-15 years of experience in BIM-based construction projects across pre-construction, and post construction phases. The summary of the responders is presented in Table 4.

Table 4: Profile of respondents

Expert	Designation	Work experience	Most familiar building lifecycle
E1	BIM Manager	12	Pre-construction
E2	BIM Engineer	5	Pre-construction
E3	BIM Director	12	Pre-construction and construction
E4	BIM Manager	9	Pre-construction and construction
E5	BIM Manager	7	Pre-construction and post -construction
E6	BIM Architect	9	Pre-construction
E7	BIM manager	10	Pre-construction
E8	BIM Modeler	7	Pre-construction
E9	BIM Manager	11	Pre-construction and post-construction
E10	BIM Modeler	6	Pre-construction

4. RESULTS AND DISCUSSION

The results of this study are consistent with the literature presented in sections 2.3 to 2.5, which highlights the theoretical and practical importance of Prevention through Design, Automated Hazard Identification, and Emergency Planning and Simulation in BIM-based safety management. The literature supports AHI as an effective tool for early hazard detection through BIM visualisation and analysis, while EPS is widely recognised for enhancing emergency preparedness and evacuation planning. The findings of this study, therefore, reinforce existing research by empirically prioritising these BIM safety features. The pairwise comparisons were performed by evaluating the relative importance, effectiveness, and ease of implementation of the three BIM-based safety features. Prevention through Design (PtD) was considered more important and effective because it eliminates hazards during the design phase, thereby preventing risks before construction begins. Automated Hazard Identification was ranked next, as it enables early detection of potential hazards through BIM-based visualisation and rule-based analysis. Emergency Planning and Simulation was ranked lower in comparison because it mainly focuses on emergency preparedness rather than hazard prevention. In terms of ease of implementation, Automated Hazard Identification and Emergency Planning and simulation were considered relatively easier to implement than PtD, since PtD requires deeper integration with design processes and may involve design modifications and multidisciplinary coordination.

4.1 BIM-BASED SAFETY MANAGEMENT FEATURES IN IMPROVING OVERALL BUILDING SAFETY PERFORMANCE

The pairwise comparisons were performed by evaluating the relative importance, effectiveness, and ease of implementation of the three BIM-based safety features. PtD was considered more important and effective because it eliminates hazards during the design phase, thereby preventing risks before construction begins. Automated Hazard Identification was ranked next, as it enables early detection of potential hazards through BIM-based visualisation and rule-based analysis. Emergency Planning and Simulation was ranked lower in comparison because it mainly focuses Emergency preparedness rather than hazard prevention. In terms of ease of implementation, Automated Hazard Identification and Emergency Planning and simulation were considered relatively easier to implement than PtD, since PtD requires deeper integration with design processes and may involve design modifications and multidisciplinary coordination.

4.2 FRAMEWORK TO PRIORITISE BIM-BASED SAFETY MANAGEMENT FEATURES

A conceptual AHP hierarchical model for prioritising BIM-based Safety management features was developed based on the literature review and input from industrial experts. The hierarchical framework consists of three levels. The first level represents the overall goal of the study, which is to prioritise BIM-based safety management features for improving safety performance. The second level includes the evaluation criteria used to assess the identified features. These criteria were selected because they reflect both the practical applicability and the potential impacts of BIM safety features in real environments. The third level consists of the main BIM safety management features identified from the literature. This hierarchical structure enables systematic pairwise comparison among the identified features under each criterion and supports the calculation of relative priorities using AHP. The pairwise comparison results for the evaluation criteria used in this study are presented in Table 5, while the corresponding normalised comparison matrix is shown in Table 6. The calculated local weights and ranking derived from the AHP analysis are summarised in Table 7, and the hierarchical model developed for this study is illustrated in Figure 1. The results obtained from the calculations indicate the three evaluation criteria for assessing BIM-based safety management features.

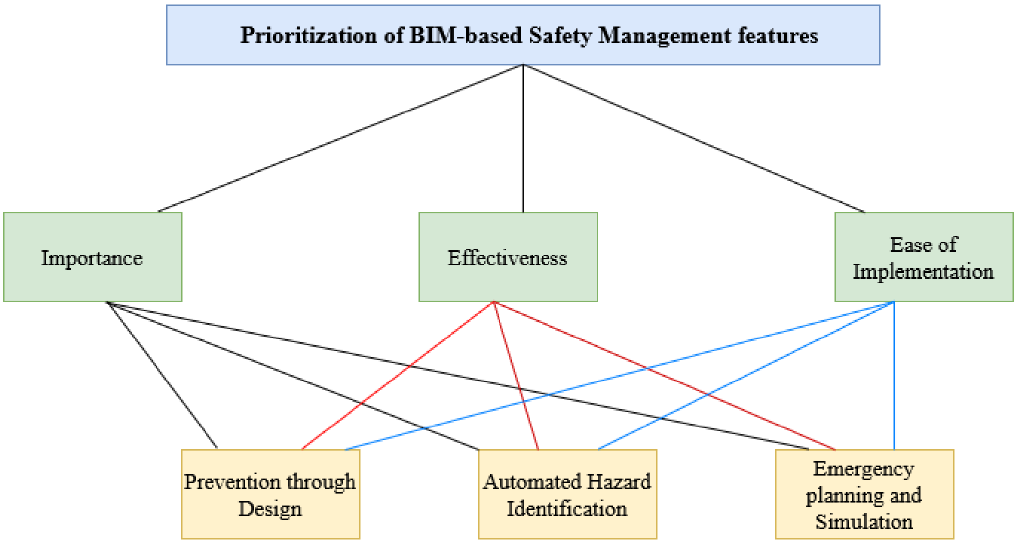

Figure 1: Hierarchical model of BIM-based features

Table 5 presents the pairwise comparison matrix of the evaluation criteria. The values in the matrix represent the relative preference of one criterion over another based on expert judgement using the AHP scale. For instance, the value 3.62 indicates that importance is moderately more significant than effectiveness, while 5.57 suggests that importance is strongly preferred over Ease of Implementation. The reciprocal values (0.276 and 0.179) represent the inverse comparisons. This matrix forms the basis for determining the relative priority of the ease evaluation criterion.

Table 5: Criterion-to-criterion pairwise comparison matrix for evaluation criteria

	Importance	Effectiveness	Ease of implementation
Importance	1	3.62	5.57
Effectiveness	0.276243094	1	5.8
Ease of implementation	0.179533214	0.172413793	1

Table 6 shows the normalised pairwise comparison matrix, which is obtained by dividing each value in the pairwise comparison matrix by the sum of its respective column. This normalisation process converts the values into comparable proportions, allowing the relative influence of each criterion to be evaluated. The normalised values indicate the contribution of each criterion in relation to the others.

Table 6: Matrix normalization for evaluation criteria

	Importance	Effectiveness	Ease of implementation
Importance	0.686918722	0.755360484	0.450282943
Effectiveness	0.189756553	0.208663117	0.468876314
	0.123324726	0.035976399	0.080840744

	Importance	Effectiveness	Ease of implementation
Ease of implementation	0.686918722	0.755360484	0.450282943

Table 7 presents the priority weights and ranking of the evaluation criteria derived from the normalised matrix. The results show that importance has the highest weight 0.63085, and is ranked first, followed by effectiveness 0.2891 and Ease of Implementation 0.08005. Additionally, the table includes the consistency evaluation of the AHP matrix, where the Consistency Index (CI) and Consistency Ratio (CR) are calculated. The CR value of 0.021966, which is below the acceptable threshold of 0.1, indicates that the expert judgments are consistent and reliable.

Table 7: Ranking of the criteria value

Criteria	W	Rank	AW	λ	CI	RI	CR
Importance	0.63085	1	3.626787053	3.025466 45	0.01273 5	0.58	0.0219 66
Effectiveness	0.2891	2	5.57379242				
Ease of implementation	0.08005	3	5.809061438				

Table 8: Final findings of the criteria and BIM-based features

Criteria	Features	LW	Rank	GW	Rank	λ	CI	RI	CR
Importance	PtD	0.618035	1	0.38987148	1	3.090141	0.045	0.58	0.077
	AHI	0.296956	2	0.18736542	2				
	EPS	0.085009	3	0.0536231	5				
Effectiveness	PtD	0.622502	1	0.17996475	3	3.09268494	0.046343	0.58	0.079897
	AHI	0.300506	2	0.08687455	4				
	EPS	0.076992	3	0.00616308	9				
Ease of implementation	PtD	0.622521	1	0.049825	6	3.02546645	0.012735	0.58	0.021966
	AHI	0.295365	2	0.023644	7				
	EPS	0.082114	3	0.006571	8				

The AHP analysis evaluates the Local Weights (LW) and Global Weights (GW) of the identified BIM-based safety features under three main criteria i.e. (i) importance, (ii) effectiveness, and (iii) ease of Implementation. The results clearly indicate that PtD is the most influential safety feature across all criteria. Under the importance criterion, PtD obtained the highest local weight (LW=0.618035) and a global weight (GW=0.38987, ranked 1st), highlighting the critical role of integrating safety considerations during the early design stage of construction projects. Automated Hazard Identification (AHI) ranked second (LW= 0.296956, GW=0.18736542, ranked 2nd), indicating its significance in detecting potential hazards through the BIM visualisation and analysis tool. Meanwhile, Emergency Planning and Simulation (EPS) ranked third with the lowest local weight (LW=0.085009, GW=0.0536231, ranked 5th), suggesting that although it contributes to safety preparedness, its impact is relatively lower compared with the other features.

For the effectiveness criterion, PtD again achieved the highest weight (LW= 0.622502, GW= 0.17996475, ranked 3rd), emphasising that design-stage risk elimination is the most effective strategy for improving construction safety performance.

AHI ranked second (LW=0.300506, GW=0.08687455, ranked 4th), reinforcing the value of automated detection systems in identifying hazards before construction activities commence. EPS remained in the third position (LW=0.076992, GW=0.00616308, ranked 9th), indicating that while simulation tools support safety planning, their effectiveness is comparatively limited when measured against proactive design and hazard detection approaches.

Similarly, under the Ease of Implementation criterion, PtD maintained the highest ranking (LW=0.6225, GW=0.049825, ranked 6th), suggesting that incorporating safety consideration within BIM during the design stage can be readily implemented in project workflows. AHI ranked second (LW=0.295365, GW=0.023644, ranked 7th), demonstrating moderate implementation feasibility due to the technological requirements associated with automated hazard detection systems. EPS ranked third (LW=0.082114, GW=0.006571, ranked 8th), indicating comparatively lower ease of implementation.

Overall, the findings highlight that PtD is the most critical BIM-based safety management feature, followed by AHI, while EPS plays a supportive role in improving construction safety performance. These results emphasise the importance of integrating safety considerations at the early design stage and utilising BIM technologies to proactively identify and manage potential hazards in construction practices in the industry.

5. CONCLUSIONS

This study developed a structured framework to prioritise BIM-based safety management features in building construction projects using AHP. The proposed hierarchical model integrates three evaluation criteria i.e. (i) importance, (ii) effectiveness, and (iii) ease of implementation to systematically assess key BIM-based safety features identified from the literature and validated through expert input. The results indicate that importance is the most influential criterion with a weight of 0.63085, followed by effectiveness 0.2891, and ease of implementation. The consistency ratio obtained from the AHP analysis was below 0.1, confirming that the expert judgements used in the pairwise comparisons are reliable and acceptable.

Among the BIM-based safety management features evaluated in this study, PtD achieved the highest priority across all evaluation criteria, highlighting its significant role in integrating safety considerations during the early design stage. Automated Hazard Identification ranked second, demonstrating the importance of BIM technologies in identifying potential hazards through digital visualisation and analysis. Emergency Planning and Simulation received the lowest priority, indicating that although it supports safety preparedness, it is perceived as less influential compared with proactive design and hazard identification strategies.

Overall, the developed AHP-based framework provides a systematic and transparent approach for prioritising BIM-based safety management features in building projects. This study contributes to the academic field by providing a validated AHP framework to prioritise BIM-based safety features, advancing theoretical understanding of safety management in the building lifecycle. The framework assists decision-makers, project managers, and safety performance during project planning and execution. Emphasising supports improved risk management and contributes to safer construction practices in the building industry.

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