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BIM-Driven Safety Management for Enhancing Hazard Prediction: A Systematic Review

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Construction projects remain among the most hazardous workplaces, with high accident rates stemming from dynamic site conditions, complex scheduling, and limited foresight in hazard prediction. Traditional safety management practices often rely on reactive approaches and fragmented tools, which limit their effectiveness in preventing accidents. Building Information Modeling (BIM) offers new opportunities for integrating safety planning directly into project models. This paper presents a systematic review of recent developments in BIM-based safety management, with an emphasis on hazard prediction, visualization, and risk mitigation. The findings highlight that BIM can support Automated Hazard Identification (AHI), enhance safety communication through visual simulations, and improve decision-making in planning and execution phases. Studies demonstrate that BIM integration enables early detection of workspace conflicts, cost–time–safety trade-offs, and compliance with safety codes through automated rule checking. Addressing BIM roles in hazard prediction, the study identifies eight common workflows used in BIM-based safety management. However, challenges remain regarding interoperability, model standardization, and adoption in real-world project environments. This research provides insights into new trends in technology-driven safety strategies, indicating IoT, computer vision, and digital-twin integrations are transforming BIM from a static model into a dynamic, real-time safety monitor that tracks proximity and behavior.

Keywords: Building Information Modeling (BIM); Construction Safety; Hazard Prediction; 4D & 5D; Risk Assessment; Proactive Safety Management.

Introduction and Background

Construction is one of the most hazardous industries worldwide, consistently recording high rates of occupational accidents and fatalities (Emamialeagha et al., 2025; Tamanaeifar & Shahhosseini, 2025). According to the International Labor Organization (ILO), the construction sector is among the most hazardous industries and contributes a disproportionately large share of global workplace fatalities. Falls, electrocutions, caught-in/between, and struck-by incidents are identified among the leading causes of these fatalities (Warrier, 2024). These accidents are frequently linked to unsafe site conditions, limited hazard visibility, and fragmented information flow between design and field operations. In recent years, the adoption of digital technologies, particularly Building Information Modeling (BIM) within the Architecture, Engineering, and Construction (AEC) industry (Fountain & Langar, 2018; Ghaffarianhoseini et al., 2017; Langar & Pearce, 2014), has transformed how construction safety is managed, offering a proactive, data-driven, and visual approach to hazard identification and prevention. BIM is increasingly acknowledged as a powerful innovation for improving safety in construction and has been used in the industry (Azhar, 2017; Webb & Langar, 2019). Its ability to integrate geometric, semantic, and temporal data, centralize data, enable real-time collaboration, and combine various safety management methods within a single platform offers a viable alternative for addressing complex and dynamic risks presented on construction sites (Elrifaee and Zayed 2025).

Over the last decade, a large body of research has emerged focusing on BIM-integrated safety management systems, reflecting a steady evolution from static 3D modeling to dynamic, real-time safety analytics. Early studies demonstrated the feasibility of integrating rule-based checking and ontology frameworks within BIM to automate hazard identification and compliance checking against Occupational Safety and Health Administration (OSHA) standards (Kim et al., 2015). Subsequent developments incorporated sensor networks and Internet of Things (IoT) to create dynamic models capable of real-time monitoring of workers and equipment (Li et al., 2015; Park et al., 2017). These sensor-enhanced BIM frameworks enabled the transition from reactive incident reporting to predictive safety management, where potential risks are identified and visualized before accidents occur.

Recent research further extends the predictive potential of BIM through integration with Artificial Intelligence (AI), Machine Learning (ML), and Fuzzy Inference Systems (FIS) (Li et al., 2024; Parsamehr & Ruparathna, 2023; Wang & Yuan, 2024). These data-driven frameworks combine BIM's geometric intelligence with probabilistic reasoning to estimate the likelihood and severity of risk across construction phases. Similarly, ontology-based systems (Hwang et al., 2025; Speiser et al., 2025) leverage semantic interoperability (via OWL, SPARQL, and SWRL rules) to formalize safety knowledge and automate compliance checking. Meanwhile, AR/VR-integrated BIM environments (Afzal & Shafiq, 2021; Alirezaei et al., 2022; Yap et al., 2024) have enhanced situational awareness by visualizing hazards in real time, bridging the gap between digital models and job sites.

Despite these advancements, existing literature remains fragmented on how BIM-based workflows, tools, and integration methods are classified and assessed. Prior systematic reviews primarily focused on Automated Hazard Identification (AHI) and the identification of BIM applications in construction safety domains, often neglecting trends and offering a clear classification (Akram et al., 2019; Martínez-Aires et al., 2018). Additionally, while numerous studies have proposed BIM-based safety systems, few have systematically assessed the types and levels of integration. Therefore, this study conducted a comprehensive review of 38 peer-reviewed journal articles to develop a classification of BIM-based workflows, integration type, automation levels, and BIM roles in hazard prediction to answer:

- RQ_1: How can a BIM model be utilized to predict safety hazards on construction sites?
- RQ_2: What workflows exist for integrating BIM with safety planning?

Methodology

This study employed a Systematic Literature Review (SLR) to examine how a BIM model can be used to predict and mitigate safety hazards on construction sites, and to identify workflows and tools for integrating BIM with safety planning. An SLR was selected because it ensures a rigorous, transparent, and replicable approach to synthesizing evidence (Kitchenham, 2004; Tranfield et al., 2003). Unlike narrative reviews, SLRs minimize bias and enable comprehensive coverage of relevant studies, providing a robust foundation for identifying trends, gaps, and future directions in BIM-driven safety management (Moher et al., 2009; Snyder, 2019). Construction safety has successfully applied SLRs to establish evidence-based insights into BIM and safety integration previously (Martínez-Aires et al., 2018). For this study, the SLR methodology consisted of four sequential stages: 1) Database selection and keyword search; 2) Filtering criteria; 3) Abstract screening; 4) Full screening of articles.

In the first stage of the research, database selection and keyword search parameters were established. The Web of Science (WoS) database was selected as the primary source for this review because it is one of the most reputable, multidisciplinary citation indexes for high-quality peer-reviewed research. WoS provides comprehensive coverage of construction management, engineering, and safety journals. Prior systematic reviews in construction safety have also relied on WoS due to its reliability and broad coverage (Darko et al., 2019; Getuli et al., 2020; Gheisari & Esmaeili, 2019). The keywords defined on the research scope included *"Building Information Modeling, BIM, Safety Management, Hazard Prediction, Construction Safety Planning, Risk Assessment, and Proactive Safety Management"*. Accordingly, the query was formulated as: ("Building Information Modeling" OR BIM) AND ("Safety Management" OR "Construction Safety" OR "Construction Safety Planning") AND ("Hazard Prediction" OR "Hazard Identification" OR "Risk Assessment" OR "Proactive Safety Management"). The search was applied to the Topic field (titles, abstracts, and keywords) to capture the most relevant studies. No restriction was applied to the publication year, as the earliest relevant study appeared in 2013, followed by additional contributions from 2015 onward. At this stage, all document types were considered. The initial search yielded 100 papers (Figure 1).

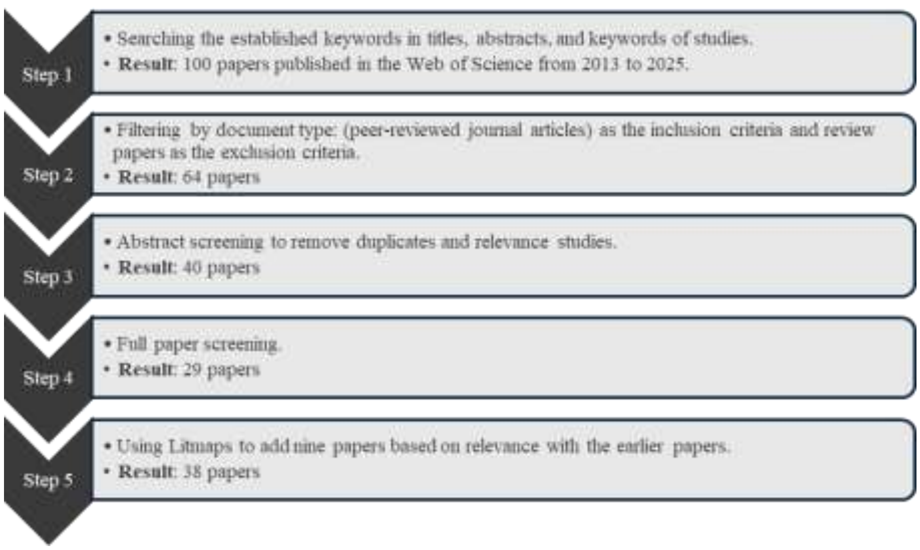

Figure 1. SLR process utilized for research

In the second stage, two filters were established to refine the dataset. The applied criteria included document type (peer-reviewed journal articles) as the inclusion criterion and review papers as the exclusion criterion. Review papers were excluded as they did not offer any new or innovative workflow in the target domain. After establishing the filters (inclusion and exclusion criteria), the data set was reduced to 64 articles (Figure 1). In the third stage, abstracts from 64 articles were manually screened to identify duplicates and relevance to the study. No duplicate records were found. This process refined the dataset to 40 papers deemed relevant for full-text screening. In the last (fifth) stage final set of 40 articles was subjected to manual screening, which included a comprehensive review of the full texts to ensure complete relevance to the research scope. This step resulted in a final set of 29 papers for detailed analysis. At this stage, the researchers used Litmaps to identify an additional 9 papers based on associations and relevance to the earlier-identified 29 papers, resulting in 38 articles (n) that were analyzed to examine the workflows, technologies, integration types, safety focus, and automation levels of existing BIM-based systems.

Data extraction to address the two research questions was performed manually by a single reviewer with experience in BIM-based safety systems. Given the interpretive nature of the analysis and the fact that most reviewed studies do not explicitly state such classifications, the categorization was developed as a structured qualitative synthesis based on predefined definitions and the reviewer's informed interpretation. Workflow type was classified based on the primary mechanism for linking BIM to safety-related functions. The integration level was defined by the degree of coupling between BIM and external systems, while the automation level was categorized as low (manual analysis), moderate (rule-assisted processes), or high automated (real-time or algorithm-driven execution without human intervention).

Results and Discussion

A total of 38 peer-reviewed journal articles were systematically analyzed using the SLR process. Approximately 90% of the reviewed studies were published after 2015, indicating rapid expansion of BIM-based safety research over the past decade (Figure 2). The most frequent publication outlets were Automation in Construction (9), Buildings (5), Safety Science (4), International Journal of Construction Management (3), and Sustainability (3) (Figure 3). In BIM-integrated safety research, fall hazards remain the predominant focus across studies, followed by struck-by and collision-related risks. These hazard categories align with the leading causes of construction fatalities reported by OSHA, confirming that BIM applications primarily focus on mitigating high-impact risks in dynamic site conditions.

BIM Role in Hazard Prediction

The analysis of literature indicates that BIM has evolved from a geometric coordination and 3D environment tool into an intelligent, data-driven platform that plays both predictive (by supporting real-time adjustments in design and schedule to mitigate hazards) and proactive (by visualizing and quantifying risks before they occur) roles in hazard prediction. Across 38 analyzed articles, BIM serves as the central environment that integrates design, scheduling, safety, and sensor data to identify, simulate, and mitigate potential hazards before and during construction. It supports predictive safety analysis, anticipating risks based on spatial–temporal and behavioral data, and proactive intervention, embedding safety design and control strategies early in the project. Overall, the BIM's roles could be divided into three main categories of predictive, proactive, and hybrid (Table 1).

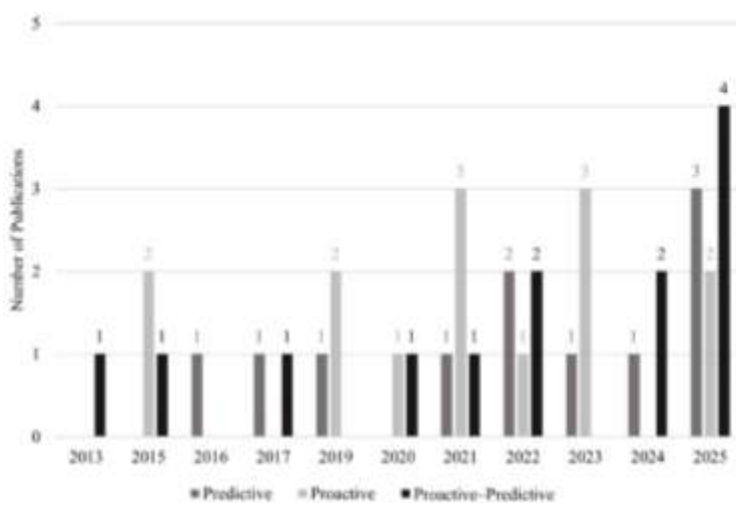

Figure 2. Annual distribution of BIM-based safety studies across proactive, predictive, and hybrid BIM roles (n = 38)

Figure 3. Distribution of reviewed BIM-based safety studies by journal outlet (n = 38)

Table 1. BIM Role Classification in Hazard Prediction

No.	Category	Phase	Purpose	Publications
1	Predictive	Construction / Execution	Predict hazard emergence through time-dependent or sensor-based modeling	Enshassi et al., 2016, Park et al., 2017, Lee et al., 2019, Afzal and Shafiq 2021, P. Li et al., 2022, Bao et al., 2022, Nasab et al., 2023, Z. Wang & Yuan, 2024, Wang et al., 2025, Elrifaee & Zayed, 2025, Hossain et al., 2025
2	Proactive	Design / Pre-construction	Prevent hazard creation through design-stage intervention and schedule planning	Kim et al., 2015, H. Li et al., 2015, Jin et al., 2019, Yuan et al., 2019, Cortés-Pérez et al., 2020, Lu et al., 2021, Wen & Liang, 2021, Rodrigues et al., 2021, Rafindadi et al., 2022, Parsamehr & Ruparathna, 2023, Xu et al., 2023, Singh et al., 2023, Emamialeagha et al., 2025, Speiser et al., 2025
3	Hybrid (proactive–predictive) workflow	Design / Execution	Integrate preventive planning & predictive visualization to enhance safety awareness, forecast hazards, & ensure compliance throughout the lifecycle	Zhang et al. 2015, Choe & Leite, 2017, Pham et al., 2020, Tran et al., 2021, Alirezaei et al., 2022, Rodrigues et al., 2022, Sorbi et al., 2024, W. Li et al., 2024, Tamanaeifar & Shahhosseini, 2025, Checca et al., 2025, Hwang et al., 2025, Aunwong & Hadikusumo, 2025

i) Predictive

Predictive category includes anticipating risks before they occur. BIM functions as an analytical and visualization engine that transforms project data into dynamic hazard forecasts. Early studies (Zhang et al., 2015; Zhang et al., 2013) demonstrated that BIM can encode OSHA and International Organization for Standardization (ISO) safety standards as digital rules, enabling automatic identification of fall or struck-by hazards through ontology reasoning or rule-based checking. Later frameworks, such as Hazard Identification through spatial–temporal exposure analysis (HISTEA) (Tran et al., 2021) and voxel-based detection models (Li et al., 2022; Wang et al., 2025), used BIM to analyze spatial and temporal overlaps of tasks. Likewise, knowledge-graph models (W. Li et al., 2024) and Fuzzy/FAHP-based methods (Parsamehr & Ruparathna, 2023; Wang & Yuan, 2024) quantified probability–severity relationships, transforming BIM into an intelligent predictive hub that learns from past accidents. During the construction phase, BIM–IoT and computer-vision integrations (Elrifaee & Zayed, 2025; Hossain et al., 2025; Park et al., 2017) extend prediction into real time. By fusing location tracking (BLE, GPS, RFID) or visual recognition (YOLOv8, RGB-D) with BIM geometry, these systems detect unsafe proximity and automatically issue alerts.

ii) Proactive

The proactive category aims to prevent risks by design, embedding safety thinking into the design and planning stages through the Prevention-through-Design (PtD) framework. Studies such as Yuan et al. (2019), Jin et al. (2019), and Rodrigues et al. (2022) have demonstrated that linking PtD knowledge bases or safety databases to Revit models enables the automatic detection of unsafe configurations (unguarded edges, steep roof slopes) before construction. These rule-based plug-ins, developed through Revit API (Application Programming Interface) or Dynamo scripts, visualize hazards directly in the model and suggest corrective measures. Through 4D BIM integration, proactive workflows simulate construction sequences to visualize when and where temporary safety systems (scaffolding, nets, guardrails) must be installed or removed (Pham et al., 2020; Rodrigues et al., 2022; Tamanaeifar & Shahhosseini, 2025). At a strategic level, BIM facilitates proactive management by embedding Safety Leading Indicators (SLIs) and behavior-based data (Lee et al., 2019; Xu et al., 2023). It transforms safety monitoring from reactive inspection into data-driven foresight, enabling project teams to visualize unsafe behaviors, prioritize high-risk tasks, and dynamically update mitigation measures.

iii) Hybrid (Integration of Predictive and Proactive)

The Hybrid Category integrates the predictive and proactive categories and is one of the most recent frameworks. Hybrid BIM–AR/VR systems combine predictive modeling with proactive field visualization, color-coding hazard intensity (Risk Priority Numbers) within BIM, and projecting it through AR for real-time awareness and training (Afzal & Shafiq, 2021; Alirezaei et al., 2022). Ontology-driven systems further automate reasoning: BIM provides geometric and temporal context, while ontology-based safety rules predict hazards and automatically recommend preventive actions (Hwang et al., 2025; Speiser et al., 2025).

Common Workflows for BIM and Safety Planning Integration

Based on the 38 reviewed articles, eight primary workflows were identified for integrating BIM with safety planning and hazard prediction. Each workflow demonstrates a distinct combination of modeling, data analysis, and visualization tools that transform BIM from a 3D model into an intelligent, data-driven safety management environment, and their features are summarized in Appendix I.

1. *Algorithmic Workflow:* An algorithmic workflow involves encoding rules, logic, or conditions into algorithms or scripts to perform specific tasks or analyses. In this cluster, BIM is integrated with safety, scheduling, a historical accident database, IoT sensing, and vision to predict live hazard monitoring and risk updates (Appendix I).
2. *Ontology-Based Workflow:* Workflow represents safety knowledge in a machine-interpretable format (ontology). These workflows encode safety knowledge in formal semantic structures to enable automated reasoning, rule checking across BIM environments (Appendix I).

3. *Tabular workflow:* The workflow is defined as approaches in which safety-related information is captured, analyzed, and reported primarily through spreadsheets or statistical tables, with limited computational automation or model-based reasoning. It's the simplest among workflow types, and less dynamic than algorithmic or ontology-based workflows (Appendix I).
4. *Conceptual Workflow:* The workflow is a visual or descriptive representation of the logical process. It is abstract & serves as the first step before translating the idea into workflows (Appendix I).
5. *Rule-Based Computational Workflow:* The workflow operates through a set of predefined logical rules that link conditions (triggers) to actions (responses) (Appendix I).
6. *Hybrid Process–System Architecture Workflow:* The workflow is a dual-layer BIM workflow combining process modeling (how tasks and safety procedures flow) and system architecture design (how digital tools, databases, and technologies interact). It integrates process logic (the workflow) with system architecture (the technology stack).
7. *Process Map Workflow:* The process map is a visual flowchart depicting task sequence, decision points, serving as a bridge between conceptual understanding and implementation (Appendix I).
8. *Quantitative–Analytical Workflow:* The workflow systematically uses quantitative data and analytical methods to evaluate Safety Performance Indicators (SPI) (Appendix I).

Conclusion

The review analyzed how BIM contributes to hazard prediction and safety management. The study conducted an SLR of 38 peer-reviewed journal articles, selected through a structured, multi-stage filtering process. The findings indicate that BIM serves as the intelligent backbone for hazard prediction, acting simultaneously as a data integrator, reasoning engine, and visualization medium. By fusing BIM with advanced analytics, construction safety management shifts from reactive compliance to predictive, knowledge-driven risk prevention. Studies show that BIM-anchored planning shifts hazard discovery upstream, before mobilization, cutting redesign, and last-minute controls. 4D/VR/AR visualizations enhance communication among site teams by making risks visible and improving the timing of safety interventions. IoT, computer vision, and digital-twin integrations transform BIM from a static model into a dynamic, real-time safety monitor that tracks proximity and behavior. Workflows range from rule/ontology reasoning to knowledge graphs, ML/AI, digital twins, VR/AR. Toolchains commonly pair Revit/Tekla and Synchro/Navisworks, Protégé/Pellet/SWRL, Dynamo/C# APIs, Python/Neo4j/SQL, Unity/Unreal, and IoT/CV/ROS. Among reviewed methods, algorithmic workflows dominate, enabling automated, multi-hazard detection. However, interoperability issues and uneven coverage of diverse hazards remain challenges for fully integrated, intelligent safety ecosystems.

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Appendix I

Appendix I. Table 1. Common Workflows for BIM and Safety Planning Integration

Workflow Typology	**BIM platform**	**Integration Tech.**	**Automation level**	**Primary safety function**
Algorithmic Workflow	P3, P4, P8, P9, P10, & P11	Rule-based scripting; BIM APIs; voxelization algorithms; AI/ML models; database linkage; IoT & vision integration	AL2-AL3	Automated hazard identification (AHI); Safety facility allocation; Safety scheduling; Real-time hazard monitoring & risk updates
Ontology-Based Workflow	P3, P7, & P9	Ontology modeling & semantic reasoning; Rule languages; Semantic query; Ontology editors & validators; Standards-based schema mapping	AL2-AL3	AHI; JHA; Consistency checking; Knowledge-based safety compliance & decision support
Tabular Workflow	P8 & P9	Spreadsheet-based analysis; statistical analysis tools; manual data entry & interpretation	AL1	Safety awareness assessment; BIM safety applications and adoption barrier identification; Descriptive reporting & comparison
Conceptual Workflow	P1, P2, & P9	Process modeling; Visual workflow; Simulation-assisted visualization; Dashboard-based integration	AL1 to AL2	Structuring safety planning logic; Supporting preventive & predictive safety analysis through visual understanding & decision support
Rule-Based Computational Workflow	P9 & P12	Rule-checking algorithms; open BIM APIs; IFC-based interoperability; Knowledge-base linkage; 4D simulation environments	AL3	AHI; PtD; Compliance checking; Safety measure recommendation across design and construction
Hybrid Process–System Architecture Workflow	P9 & P13	IoT sensing; mobile applications; cloud-based platforms; real-time data streaming; BIM–database synchronization; Dashboards for visualization and alerting	AL3	Continuous safety monitoring; Proximity-based hazard detection; Real-time alerting; Dynamic visualization of worker–hazard interactions
Process Map Workflow	P5 & P9	Process flowcharts; BIM-based coordination & interference detection; Visual mapping of data exchange	AL1 to AL2	Clarifying safety-related task sequences; Supporting fall prevention & risk communication; Improving coordination & decision-making across project stages
Quantitative–Analytical Workflow	P6 & P9	Statistical & analytical methods; Survey-based analysis; BIM-linked visualization	AL1 to AL2	Safety risk assessment; Prioritization of hazards & technologies; and decision support

AL1 = Low Automation Level; AL2 = Moderate Automation Level; AL3 = High Automation Level; P1= 2D digital drawings; P2 = 4D; P3= ArchiCAD; P4 = AutoCAD; P5 = BIM-based coordination platforms; P6 = BIM-based visualization platforms; P7 = IFC-based BIM environments; P8 = Navisworks; P9= Revit; P10 = Rhinoceros; P11 = Synchro PRO; P12 = Tekla Structures; P13 = Web-based BIM environment