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From Exploration to Prioritisation: Advancing BIM-IOT Integration for Construction Health and Safety Improvement

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Abstract

The construction industry faces significant workplace safety-related challenges, with developing countries experiencing disproportionately high accident rates. While Building Information Modelling (BIM) and the Internet of Things (IoT) technologies show individual promise for enhancing safety, their integrated application remains underexplored in developing contexts. This study employs a mixed-methods approach combining a systematic literature review with quantitative survey validation to investigate the advantages of BIM-IoT integration for construction safety in South Africa. The literature review analysed peer-reviewed articles published between 2010 and 2025, while the empirical phase surveyed 252 South African construction professionals using a structured questionnaire. Statistical analysis employed exploratory and confirmatory factor analysis (EFA/CFA) using SPSS and AMOS to validate identified advantages. The systematic review identified 15 key advantages, with "improved safety monitoring" as the most cited, followed by "real-time decision-making" and "hazard identification". Quantitative validation confirmed strong alignment between the literature and practice, with the same three advantages ranking highest among practitioners (mean scores of 4.28, 4.22, and 4.19, respectively), confirming the universal applicability of the core advantages. Exploratory factor analysis identified five latent dimensions, accounting for 67.8% of the total variance: Real-time Monitoring & Control, Safety Planning & Design, Training & Communication, Investigation & Reporting, and Compliance & Economics. Confirmatory factor analysis validated the measurement model with strong fit indices (CFI > 0.90, RMSEA < 0.08), and all constructs showed high reliability (Cronbach's α > 0.70). Context-specific insights revealed that South African professionals prioritise regulatory compliance and cost considerations more than global literature suggests, while design-phase hazard elimination ranked lowest despite theoretical recognition. Despite moderate BIM familiarity (3.42) and low IoT familiarity (2.89), only 34.6% and 23.7% of companies have implemented these technologies, respectively, indicating substantial implementation gaps beyond awareness. This research provides comprehensive quantitative validation of BIM-IoT safety advantages in a developing country context, offering evidence-based priorities for technology adoption and policy development.

Keywords: Advantages, BIM-IoT, Integration, Construction Safety, South Africa

1. Introduction

Workplace safety has become a critical priority for industries due to its profound impact on employee health and overall productivity, with the construction industry experiencing a disproportionately high rate of workplace accidents (Kim and Chi, 2019). Occupational hazards are a persistent challenge in construction (Heidary Dahooie et al., 2020), as frequent accidents not only diminish workforce efficiency but also increase absenteeism. In South Africa, this challenge is particularly acute, with the construction industry recording 17.5 workplace fatalities per 100,000 workers annually and over 150 deaths in 2022 alone (Department of Employment and Labour, 2022; CIDB, 2022). Given the significantly higher accident frequency in construction compared to other industries, this sector faces heightened safety risks (Nadhim et al., 2016).

Integration of Digital technologies capable of analysing and effectively communicating safety issues is crucial

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for improving overall safety performance (Han et al., 2009). In the past decade, research has focused on using digital technologies to reduce health and safety risks on construction sites. Key advancements include computer vision, IoT sensors, wearable devices, BIM, and immersive technologies like augmented and virtual reality, all aimed at improving hazard detection and safety management (Zhang et al., 2017). Despite advancements, single-technology solutions fall short of optimal safety standards, and research shows that a multi-technology approach integrating various tools yields more reliable safety outcomes (Wang et al., 2021). Integrating BIM with real-time data from IoT devices enhances construction safety by linking IoT sensor networks to high-fidelity BIM models, enabling various applications (Tang et al., 2019).

In recent years, various studies have explored the application of BIM-IoT integration in safety management (Amiri et al., 2024); however, there is a lack of research that identifies and analyses the advantages of adopting BIM and IoT technologies to improve safety in the construction sector. Specifically, while qualitative studies have identified potential advantages, quantitative validation of these advantages using empirical data from developing countries like South Africa remains limited.

The key question is: "What are the advantages of BIM-IoT integration in construction health and safety, and how can these advantages be quantitatively validated in the South African construction context?" This study has two main objectives: first, to systematically identify and synthesise the advantages of BIM-IoT integration for construction health and safety through a structured literature review; and second, to empirically validate and model these advantages- conceptualised as five dimensions of real-time monitoring and control, safety planning and design, training and communication, investigation and reporting, and compliance and economics- using survey data from South African construction professionals.

2. Literature Review

Adoption of digital technologies in construction projects has grown due to the numerous benefits they offer in enhancing safety on construction sites. According to Luo et al. (2022), there is a growing trend in research utilising digital technologies to improve construction safety, with Virtual Reality, Augmented Reality, Digital Twins, BIM, and the IoT identified as the most effective technologies. While BIM and IoT have been applied in areas such as health and safety management, research on their integration is still in its early stages (Dave et al., 2018).

2.1. BIM and Construction Safety

Recent studies have shown that implementing the BIM methodology can improve the working conditions at construction sites (Cortés-Pérez et al., 2020). Azhar (2017) found that BIM can be utilised for better construction safety performance. BIM, a growing digital technology, is gaining attention for its role in enhancing safety design and improving construction safety management practices due to its object-oriented nature and effectiveness (Jin et al., 2019; Ding et al., 2014). Based on the literature reviewed, the main application of BIM in the safety management of the construction industry can be summarised into three areas: interactive worker training, site layout optimisation, and automated checks for safety issues (Chatzimichailidou and Ma, 2022).

Several studies have investigated the use of BIM in managing construction safety issues. A classification of BIM-based tools highlighted the use of Virtual Reality to enhance construction safety, particularly in training activities (Getulli et al., 2018). Another review compared BIM-based approaches with traditional risk management tools, emphasising BIM's potential in risk management, although it lacked a systematic selection of research published after 2015 (Zou et al., 2017). Research on the use of BIM and related technologies in the design phase focused on improving safety management and minimising design errors, with particular attention to Design for Safety (DfS) and its barriers (Xiaer et al., 2016). An investigation into BIM's shortcomings and its impact on safety involved a survey of field engineers in the construction industry (Alomari et al., 2017). Lastly, the relationship between BIM and worker safety performance was examined by identifying key factors and barriers through a literature review and a practitioner survey (Ganah and Godfaurd, 2015).

2.2. IOT and Construction Safety

IoT has demonstrated significant potential in high-risk Environment, Health, and Safety (EHS) industries, where human lives are at stake, offering safe, reliable, and efficient solutions through fine-grained operation and rich data collection (Wang et al., 2021). In construction, IoT automates safety monitoring and hazard detection, enabling connected devices to transfer and analyse data effectively, making it a suitable technology for facilitating seamless data transmission across systems (Tabatabaee et al., 2022). Several studies have investigated the use of IoT in managing construction safety issues. Yang et al. (2020) developed a tool based on IoT for detecting Personal Protective Equipment (PPE) to ensure that workers are provided with the appropriate PPE before beginning construction activities. Additionally, Kanan et al. (2018) created a protective IoT-based system to automatically monitor, localise, and warn construction workers in hazardous areas.

A detailed evaluation of the LoRa protocol demonstrated its suitability for IoT-based safety monitoring, provided battery-related constraints are addressed (Augustin et al., 2016). A Wi-Fi-based IoT safety surveillance system was proposed to connect field devices, such as cameras and smoke detectors, offering an innovative safety solution despite challenges in power supply and mobility (Jiang et al., 2013). Computer vision-based wireless sensing technology monitored workers' compliance with personal protective equipment (Park and Brilakis, 2012), while motion tracking systems detected unsafe postures to reduce musculoskeletal risks (Ray and Teizer, 2012; Seo et al., 2013).

2.3. BIM-IoT Integration

Over the past decade, the integration of BIM and IoT has attracted growing interest, as evidenced by a steady increase in scholarly publications on the topic. These technologies offer complementary strengths: BIM provides detailed, component-level visualisations of construction projects, while IoT enhances safety management by supplying real-time data on-site conditions (Mohd-Nor et al., 2019). By combining these capabilities, BIM-IoT integration supports data-driven decision-making and more proactive safety interventions (Mohammed et al., 2020).

2.3.1. BIM-IoT integration and construction safety

According to Tang et al. (2019), prevalent applications integrating BIM and IoT data for health and safety management include safety training and on-site monitoring. Numerous studies have explored BIM-IoT integration for managing construction safety, highlighting its potential to enhance hazard identification, real-time monitoring, and overall safety performance.

Li et al. (2015) developed the Proactive Construction Management System (PCMS) for real-time safety monitoring and feedback, improving safety awareness and efficiency on a Hong Kong site and demonstrating global applicability for workforce training. Riaz et al. (2014) developed a BIM and sensor-based safety monitoring solution for confined spaces. Cheng and Teizer (2013) developed a framework to stream real-time data to a VR platform to improve safety awareness. Kanan et al. (2018) introduced an IoT-based wearable system to provide real-time hazard alerts on construction sites. Ding et al. (2022) implemented an IoT-BIM system to manage hazardous energy on construction sites. Qian (2021) developed a tunnel monitoring system combining BIM, IoT, and GNSS to enhance safety and construction management. Kim et al. (2016) developed a BIM-based automated safety system to address scaffolding hazards by simulating worker movements and identifying potential risks. The system, integrated into commercial BIM software, successfully detected hazards and improved early safety communication in a real-world project. Scianna et al. (2022) integrated IoT sensors with BIM for real-time bridge deflection monitoring, linking the physical structure to its digital twin for continuous risk assessment.

3. Research Methodology

This study employs a mixed-methods research approach, combining a systematic literature review (SLR) with empirical survey validation, to provide comprehensive insights into the advantages of BIM-IoT integration. The SLR identifies and synthesises existing knowledge, while the quantitative survey validates these findings using data from South African construction professionals.

3.1. Phase 1: Systematic Literature Review

A Systematic Literature Review (SLR) synthesises past research through a structured process to identify key themes, gaps, and future research areas while minimising bias and ensuring consistency (Zhou et al., 2015). This study employs an SLR to examine BIM-IoT integration for construction safety management, following a seven-step approach (Figure 1).

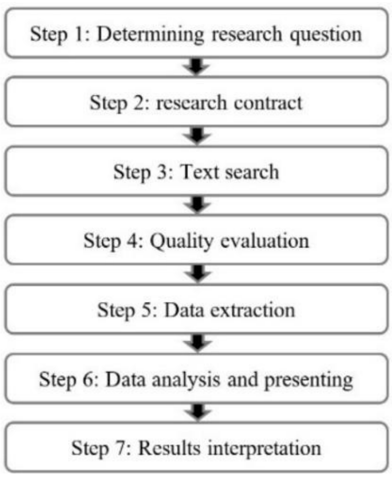

Figure 1: The SLR steps (Wright et al., 2007)

To ensure reproducibility, the SLR focused on peer-reviewed journal articles published between 2010 and 2025, written in English, and explicitly addressing BIM-IoT integration for construction health and safety. Articles were retrieved from three major databases-ScienceDirect, Scopus, and Web of Science (WoS) Core Collection-using combinations of the keywords “BIM”, “IoT”, “safety”, and “advantages/benefits”. The inclusion and exclusion criteria are summarised in Table 1, while the distribution of articles across databases is presented in Table 2.

Table 1: The criteria for inclusions and exclusions

Criteria	Inclusions	Exclusions
Publication timeline	• Between 2010 and 2025	• Before 2010
Document type	• Peer-reviewed journal research articles	• Books, book chapters, reports, theses, conference papers, editorials
Type of domain	• BIM-IOT integration in safety management only	• BIM-IOT integration in other domains (e.g. Facility management) and single-technology studies without integration
Language	• English	• Non-English

Table 2: BIM-IOT initial search results

Databases	Science direct		Scopus		Web of Science	
Search BIM-IOT	Total articles	Selected articles	Total articles	Selected articles	Total articles	Selected articles
Numbers	315	142	124	32	103	24

In Step 1, the research question is defined to establish scope and relevance, ensuring a balanced focus (Glasziou et al., 2001). In Step 2, an SLR protocol is developed to provide a structured selection process that covers the background, research question, and strategy (Henderson et al., 2010). In Step 3, a comprehensive literature search is conducted, using defined search terms and strict inclusion/exclusion criteria to ensure consistency (Wright et al., 2007). In Step 4, selected studies are evaluated using the CASP checklist to assess quality and relevance. In Step 5, data extraction is carried out using tailored forms to avoid duplicates, with a two-stage screening of titles, abstracts, and key sections. In Step 6, data analysis groups key findings by similarities in BIM-IoT integration for construction safety across design and construction. Finally, in Step 7, the results are presented through descriptive analysis, categorising text data to reveal patterns, and pattern coding, identifying themes to refine insights and develop a theoretical framework (Saldaña, 2021; Miles & Whitehouse, 2013).

3.2. Phase 2: Quantitative Validation Survey

While the systematic literature review successfully identified key advantages of BIM-IoT integration, this study extends the methodology through a quantitative validation phase to provide empirical evidence from the South African construction context. This approach enhances the reliability and generalizability of findings by combining qualitative synthesis with statistical validation.

3.2.1. Research design

A cross-sectional survey design was adopted to validate the identified advantages and explore implementation factors specific to the South African construction industry. This approach allows for the collection of standardised data across different construction organisations while maintaining the statistical rigour necessary for factor analysis and structural equation modelling.

3.2.2 Questionnaire Development

The survey instrument was developed based on the 15 advantages identified through the SLR (Appendix 1). Each advantage was operationalised into multiple measurement items using established scales from technology acceptance and construction safety literature. The questionnaire comprised five main sections:

Section A: Demographics - Participant and organisational characteristics, including age, experience, education, company type, size, and CIDB grading.

Section B: Technology Familiarity - Current knowledge and experience with BIM and IoT technologies using 5-point Likert scales.

Section C: Benefit Assessment - Evaluation of each identified advantage across three dimensions: importance for projects, potential safety impact, and implementation likelihood (5-point scales: 1=strongly disagree to 5=strongly agree).

Section D: Implementation Context - Assessment of organisational readiness and success factors.

Section E: Open-ended Questions - Qualitative insights on specific safety challenges and additional advantages.

The questionnaire underwent content validation by three construction technology experts and pilot testing with 35 industry professionals to ensure clarity and relevance.

3.2.3 Sampling strategy

The target population comprised construction professionals from companies registered with the Construction Industry Development Board (CIDB) at Grades 4-7, representing contractors capable of implementing advanced technologies. Using Cochran's formula with a 95% confidence level and 5% margin of error, a minimum sample size of 252 was calculated.

A stratified sampling approach was employed based on:

- **Geographic distribution:** 60% Gauteng Province, 20% Western Cape, 10% KwaZulu-Natal, 10% other provinces
- **Company size:** 40% Small (5-50 employees), 35% Medium (51-200), 25% Large (200+)
- **CIDB grading:** Proportional representation across Grades 4-7

3.2.4 Data collection procedure

Data collection was conducted using an online survey platform distributed via email, professional networks, and industry conferences to CIDB-registered contractors. This study received ethics approval from the University of Witwatersrand Research Ethics Committee (Approval No: H25/07/02). Informed consent was obtained from all participants. Participation was voluntary and anonymous, with responses stored securely and reported in aggregate form to ensure confidentiality. Average completion time was 15-20 minutes.

3.2.5 Statistical analysis plan

Data analysis followed a systematic approach using SPSS v29 and AMOS v29:

- **Phase 1: Descriptive Analysis -** Frequency distributions, descriptive statistics, and normality testing
- **Phase 2: Exploratory Factor Analysis (EFA)** - Kaiser-Meyer-Olkin measure (>0.7), Bartlett's test, Principal component analysis with Varimax rotation
- **Phase 3: Confirmatory Factor Analysis (CFA)** - Assessment of measurement model fit using multiple indices ($\chi^2/df < 3.0$, CFI > 0.9, RMSEA < 0.08)
- **Phase 4: Reliability and Validity Assessment** - Internal consistency (Cronbach's $\alpha > 0.7$), convergent validity (AVE > 0.5), discriminant validity

This study focused on validating the measurement model through EFA and CFA. Structural Equation Modelling (SEM) is recommended for testing hypothetical relationships between factors and adoption outcomes in future research. The quantitative findings are integrated with the SLR results to provide comprehensive insights into the advantages of BIM-IoT for construction safety management in the South African context.

4. Findings and Results

4.1. Systematic Literature Review finding

To identify the advantages of BIM-IoT integration in construction health and safety, the systematic review steps are applied as follows.

Step 1: Determining research questions

- "What are the advantages of BIM-IoT integration in construction health and safety?"

Step 2: research contract

The protocol developed to guide the selection of studies used in this research includes the following steps:

- Background

Since the research explores BIM-IoT integration in construction safety and its advantages, this foundation informs the inclusion and exclusion criteria in the review protocol.

- Research question

The overarching objective of conducting an SLR is to address the following question:

"What are the advantages of BIM-IoT integration in construction health and safety?"

- Research strategy and data sources

To identify the most relevant answers to the research question, the strategy outlined in Figure 2 is applied throughout the SLR process.

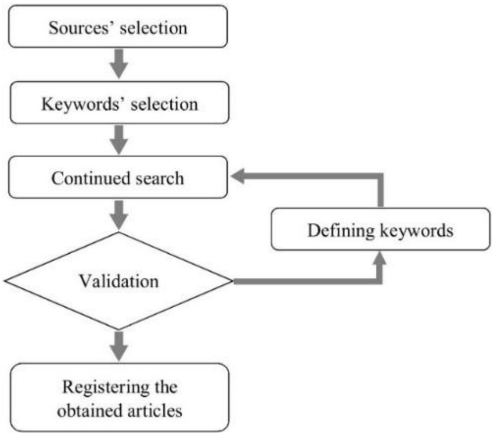

Figure 2: Research strategy

The keywords for the SLR were derived from the research question, focusing on "BIM", "IoT", "safety", and "construction". The following Boolean search strings were executed across three major indexed databases (ScienceDirect, Scopus, and Web of Science Core Collection):

[("BIM" OR "Building Information Modelling" OR "Building Information Modelling")
AND ("IoT" OR "Internet of Things" OR "Internet of Things")
AND ("safety" OR "health and safety" OR "OSH" OR "occupational safety" OR "workplace safety")
AND ("construction" OR "building" OR "construction site")]

Step 3: Text search

The authors utilised the following input and output criteria to select articles for the SLR, as illustrated in Table 1.

The search, conducted from August 2024 to January 2025 using keywords, yielded 542 articles (315 from ScienceDirect, 124 from Scopus, and 103 from WoS). After removing duplicates and irrelevant studies, 198 articles remained (Table 2).

At this stage, 198 papers were reviewed based on keywords, abstracts, and full texts, resulting in the selection of 94 articles (Table 3).

Step 4: Quality evaluation

In this section, the codes are classified as outlined in the results presentation step (Figure 3).

The final evaluation used the CASP instrument, which assessed 10 criteria, including research design and methodology. Articles were rated on a 5-point scale and categorised into quality groups. The qualitative scores

Table 3: Keywords and reviewing abstracts

Databases	Science direct	Scopus	Web of Science
Search keywords	51	20	23
Final selected articles	94		

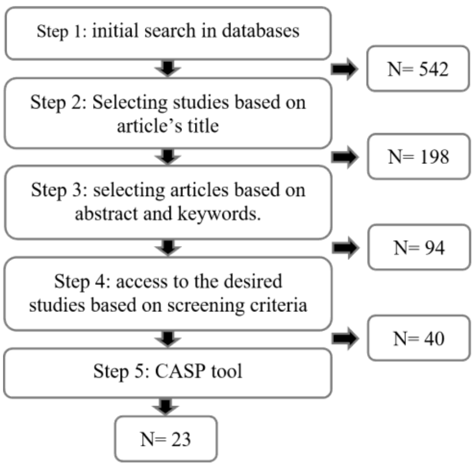

Figure 3: Steps for selection of the articles

were then categorised into very good (41-50), good (31-40), medium (21-30), poor (11-20), and very poor (0-10). Those scoring below 20 were excluded, leaving 23 articles for analysis.

Steps 5 and 6: Data extraction and Data analysis

To extract relevant data, the following questions guide the data extraction process:

- Does the article address BIM-IoT integration in construction safety?
- Are the research objectives clearly stated?
- Does the article provide insights relevant to the research questions?

The results of the data extraction process and data analysis are presented in Table 4 (see Appendix 1).

Step 7: Results presentation and interpretation

The integration of BIM and IoT offers significant advantages for OSH management (Figure 4). The bar chart visualises the number of references for each advantage of BIM-IoT integration in the OSH management. The findings highlight improved safety monitoring as the most cited advantage (17 references), reinforcing the role of real-time data collection and hazard detection in construction safety. Enhanced real-time decision-making and emergency response, referenced by 12 sources, further highlight the dynamic nature of BIM-IoT integration in preventing accidents and managing emergencies more efficiently. Additionally, enhanced hazard identification and risk assessment are strongly supported by 11 references, underscoring the proactive role of BIM-IoT in identifying and mitigating risks before incidents occur. Among design-phase benefits, hazard elimination during design received comparatively fewer references, indicating the need for broader adoption despite its recognised potential. Similarly, hazard visualisation (11 references) is frequently cited, underscoring its role in enhancing situational awareness and proactive safety planning. Additionally, improving workers' safety awareness and warning workers of workplace hazards were frequently noted, demonstrating the technology's role in fostering a safety-conscious culture. However, advantages such as enhanced near-miss reporting and compliance with safety regulations were less frequently referenced, suggesting areas for further exploration and improved implementation.

Overall, the results confirm that BIM-IoT integration enhances real-time monitoring, decision-making, and risk mitigation in construction safety. However, further research is needed to optimise its application in hazard prevention during the design phase and regulatory compliance.

4.2. Quantitative validation results

To validate the advantages identified through the systematic literature review and provide empirical evidence from the South African construction industry, a comprehensive survey was conducted among local construction professionals. This section presents the results of the quantitative analysis, including participant demographics, statistical validation and factor analysis of the advantages, and discussion of key findings.

4.2.1 Demographic Profile of Respondents

A total of 275 responses were collected, yielding 252 usable responses (91.6% response rate). The sample included a diverse range of company sizes, roles, and geographic locations within South Africa:

- 67% of respondents were in the 25-45 age range.
- Company size: 39% small (5-50 employees), 37% medium (51-200), 24% large (>200).
- Geographic distribution: 58% from Gauteng, 23% from the Western Cape, 10% from KwaZulu-Natal, and 9% from other provinces.

4.2.2 Technology familiarity & implementation

Respondents' familiarity and experience with BIM and IoT were assessed using 5-point Likert scales:

- BIM familiarity: Mean = 3.42 (SD = 1.18); 68% rated themselves moderate to high.

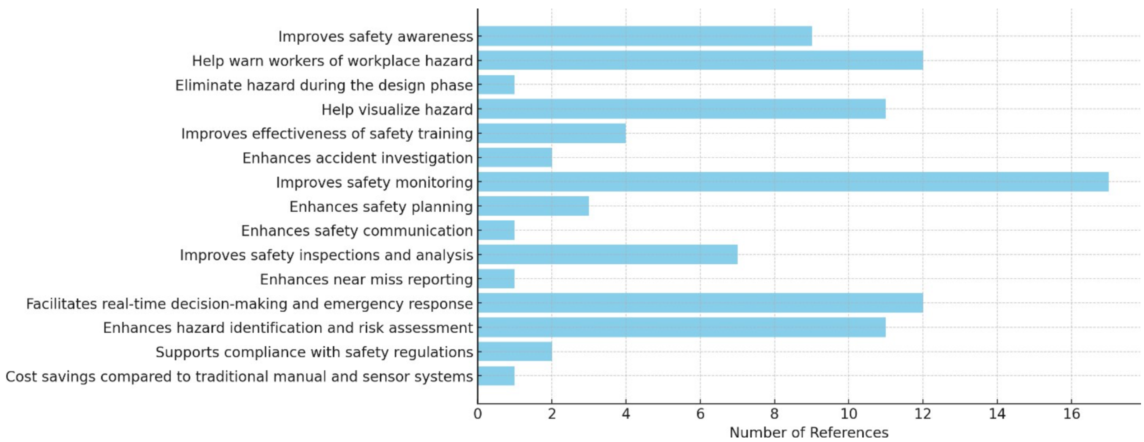

Figure 4: Advantages of BIM-IOT integration for OSH management

- IoT familiarity: Mean = 2.89 (SD = 1.24); 51% rated themselves moderate to high.
- 34.6% of companies reported implementing BIM in some projects; 23.7% reported using IoT devices for safety monitoring.

4.2.6 Reliability and Validity

All factors had Cronbach's α > 0.7, indicating good internal consistency (Table 7).

Table 7: Reliability and Validity Results

Factors	Cronbach's α	Mean	SD
Real-time Monitoring & Control	0.856	4.15	0.72
Safety Planning & Design	0.798	3.76	0.82
Training & Communication	0.821	3.92	0.72
Investigation & Reporting	0.776	3.72	0.85
Compliance & Economics	0.743	3.88	0.87

These findings indicate moderate BIM adoption while IoT implementation remains limited, suggesting significant potential for growth and integration.

4.2.3 Individual Advantage Rankings

Survey respondents evaluated each of the 15 advantages identified in the systematic literature review on a 5-point importance scale. Table 5 (see Appendix 1) presents the ranking based on mean scores.

4.2.4 Exploratory Factor Analysis (EFA) of BIM-IoT Advantages

EFA was performed on the 15 identified BIM-IoT advantages to explore the underlying factor structure. Results indicated high adequacy:

- Kaiser-Meyer-Olkin (KMO) = 0.892; Bartlett's Test of Sphericity: $\chi^2 = 3{,}247.8$, $p < 0.001$
- Five principal factors were identified with eigenvalues greater than 1.0, explaining 67.8% of total variance: Table 6 (see Appendix 1)
    1. Real-time Monitoring & Control
    2. Safety Planning & Design
    3. Training & Communication
    4. Investigation & Reporting
    5. Compliance & Economics

4.2.5 Confirmatory Factor Analysis (CFA)

CFA was performed to validate the measurement model using AMOS v29. The five-factor model demonstrated acceptable fit indices:

- $\chi^2/df = 2.47 < 3$(Threshold), CFI = 0.923 > 0.9 (Threshold), TLI = 0.908 > 0.9(Threshold), RMSEA = 0.076 < 0.08(Threshold), SRMR = 0.065 < 0.08(Threshold).
- All factor loadings were significant ($p < 0.001$) and exceeded the recommended threshold of 0.6, confirming the validity of the measurement model.

4.2.7 Key Findings Interpretation

The quantitative analysis validates the advantages identified through a systematic literature review while revealing important insights:

- Strong Literature-Practice Convergence: The top three ranked advantages in the survey ("Improve safety monitoring", "Real-time decision-making", and "Hazard identification") directly correspond to the most cited advantages in the SLR (17, 12, and 11 citations, respectively), demonstrating remarkable alignment between academic research and industry perceptions.
- Context-Specific Insights: Several advantages ranked higher in the survey than their literature citation frequency suggests, particularly "Supports compliance with safety regulations" (ranked 7th with only two citations) and "Cost savings" (ranked 11th with only 1 citation). This indicates that South African construction professionals place greater value on regulatory and economic benefits than the global literature suggests.
- Implementation Gap: "Eliminate hazard during design phase" ranked lowest (15th) despite being recognised in literature, suggesting implementation challenges in translating design-phase benefits into practice.
- Factor Dominance: "Real-time Monitoring & Control" emerged as the dominant factor, accounting for 18.7% of variance and containing the four highest-ranked individual advantages, confirming the central importance of dynamic safety management capabilities.
- The five-factor structure provides a validated framework for understanding BIM-IoT safety benefits, with strong statistical evidence (67.8% variance explained, excellent reliability, and good model fit) supporting the

theoretical categorisation of advantages into distinct but related dimensions.

5. Discussion

The integration of systematic literature review findings with quantitative validation provides comprehensive evidence for BIM-IoT advantages in construction safety management. This mixed-method approach strengthens the evidence base while revealing important patterns and contextual considerations.

The survey results demonstrate remarkable alignment between global research emphasis and South African professional perceptions, with the top-ranked advantages- "Improve safety monitoring" (4.28), "Real-time decision-making" (4.22), and "Hazard identification" (4.19). These findings confirm that the most cited benefits in international literature (17, 12, and 11 references, respectively) are equally valued by local construction professionals.

These validated advantages highlight BIM-IoT's capability to transform safety management from a reactive to a proactive approach, particularly through real-time hazard detection and emergency response systems (Riaz et al., 2014; Ding et al., 2022). The five-factor statistical structure- Real-time Monitoring & Control (18.7% variance), Safety Planning & Design, Training & Communication, Investigation & Reporting, and Compliance & Economics- provides a validated framework explaining 67.8% of total variance.

Context-specific insights reveal important divergences. "Supports compliance with safety regulations" ranks significantly higher locally (7th) than its limited literature presence (2 citations) suggests, reflecting South Africa's stringent regulatory environment and the critical importance of compliance in the local construction industry. Conversely, "eliminate hazard during design phase" received the lowest ranking (15th, mean 3.47), indicating implementation barriers despite theoretical recognition (Hu et al., 2024). This under-prioritisation likely reflects contractual fragmentation that limits the transfer of safety knowledge between design and construction teams, limited early involvement of safety professionals in design phases, and the absence of Design for Safety (DfS) mandates in local regulations. BIM-IoT systems could address this by functioning as early-stage risk identification tools during virtual construction simulation, with real-time IoT feedback validating design assumptions on actual sites. Regulatory adoption of DfS frameworks could further incentivise design-phase integration.

While BIM familiarity (mean = 3.42) was moderate, only 34.6% of companies reported implementing BIM, and despite lower IoT familiarity (mean = 2.89), just 23.7% have adopted IoT devices for safety monitoring. This implementation gap indicates that limited familiarity is not the only barrier; cost concerns, insufficient digital infrastructure, and low organisational readiness also hinder adoption. For BIM, phased training programmes targeting project managers and site engineers, combined with integration into existing project workflows, could help translate familiarity into actual use. For IoT, pilot projects demonstrating clear return on investment and low-cost sensor solutions are essential to reduce perceived risk and uncertainty. Policymakers and industry bodies should therefore prioritise subsidised training, technology demonstration projects, and capacity-building initiatives to accelerate BIM-IoT adoption in the South African construction sector. Overall, while BIM-IoT demonstrates strong capabilities in real-time monitoring, further advancement is needed in design-phase safety and regulatory compliance applications.

6. Conclusion and Further Research

This study successfully addresses the research gap in the advantages of BIM-IoT integration through a mixed-methods approach combining a systematic literature review with quantitative validation from 252 South African construction professionals. The research provides both theoretical understanding and practical evidence for developing country contexts.

The systematic literature review identified fifteen advantages of BIM-IoT integration, with "improved safety monitoring" as the most cited benefit (17 references), followed by "enhanced real-time decision-making and emergency response" (12 references) and "enhanced hazard identification and risk assessment" (11 references). The quantitative validation strongly confirmed these findings, with the same advantages receiving the highest importance ratings from industry professionals (means 4.28, 4.22, and 4.19, respectively).

The statistical analysis revealed five underlying dimensions of advantages explaining 67.8% of total variance, providing a validated framework for understanding integrated technology advantages. All factors demonstrated excellent reliability (Cronbach's $\alpha > 0.7$), and the measurement model showed good fit indices, confirming the validity of the theoretical framework. The convergence between literature citations and professional ratings validates the global applicability of core BIM-IoT safety advantages.

However, despite these advantages, certain areas, such as hazard elimination during the design phase and regulatory compliance support, reveal implementation challenges. The limited emphasis on design-phase applications in literature, combined with the lowest survey ranking (15th, mean 3.47), suggests that while BIM-IoT holds promise for improving safety from the early design stage, practical adoption and implementation barriers persist. Conversely, regulatory compliance received a higher local priority than in the global literature, reflecting context-specific needs in developing economies.

The technology implementation gap, where IoT familiarity (2.89) significantly lags behind BIM familiarity (3.42), indicates substantial opportunities for growth and innovation in the South African construction sector. Only 23.7% of surveyed companies have implemented IoT for safety monitoring, suggesting significant potential for competitive advantage through early adoption.

6.1. Practical Implications and Prioritisation Framework

The five-factor structure identified in this study- Real-time Monitoring & Control, Safety Planning & Design, Training & Communication, Investigation & Reporting, and Compliance & Economics- provides a validated prioritisation framework that organisations can use to stage BIM-IoT investments strategically. Rather than implementing all advantages simultaneously, companies can adopt a phased approach: (1) **Phase 1 (Foundation):** prioritise Real-time Monitoring & Control and Safety Planning & Design, which account for the largest variance (18.7% and 14.1%) and address immediate safety concerns; (2) **Phase 2 (Enablement):** introduce Training & Communication systems to build workforce capability alongside technology deployment; (3) **Phase 3 (Optimisation):** develop Investigation & Reporting protocols to capture lessons learned and continuously improve safety; (4) **Phase 4 (Strategic):** integrate Compliance & Economics considerations to demonstrate ROI and secure ongoing stakeholder support. This staged approach allows organisations to distribute implementation costs, build internal expertise progressively, and accumulate evidence of safety improvements- particularly relevant for companies in developing country contexts with limited initial capital investment capacity. The framework thus serves not only as a theoretical model but as an actionable decision-support tool for construction industry practitioners.

6.2. Study Limitations

This study has several limitations that should be acknowledged. First, the survey sample was geographically concentrated in urban provinces, which may not fully represent rural or remote construction practices in South Africa. Second, the study relied on self-reported perceptions of BIM-IoT advantages rather than objective performance measures or longitudinal tracking of actual safety improvements. Third, while the SLR focused on three major indexed databases (ScienceDirect, Scopus, Web of Science) to ensure quality and consistency, this approach may have excluded relevant grey literature, regional practitioner reports, and industry publications from developing countries that were not indexed.

6.3. Recommendations for Future Research

Future research should focus on enhancing BIM-IoT integration for design-phase hazard prevention, optimising predictive safety analytics, and standardising safety compliance frameworks. Specific research priorities include: longitudinal studies tracking actual safety performance improvements following BIM-IoT implementation, investigation of barriers preventing design-phase integration, development of automated regulatory compliance tools, exploration of advanced applications including AI-driven safety monitoring and predictive hazard identification, and comparative analyses across demographic subgroups to identify whether implementation strategies should be tailored differently for small vs. large companies or novice vs. experienced BIM/IoT users.

Addressing these gaps requires further research and industry-driven innovations to optimise BIM-IoT frameworks for holistic safety management. The evidence base established in this study provides a foundation for evidence-based investment decisions while highlighting the potential for BIM-IoT integration to transform construction safety management from a reactive to a proactive paradigm in developing country contexts.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Appendix 1

Table 4: Advantages of using BIM-IOT integration for OSH Management

N	Advantages	References
1	Improve safety awareness	Fan et al (2021), Ding et al (2013), Cheng and Teizer (2013), Kiani et al (2014), Li et al (2015), Ding et al (2022), Parn et al (2019), Chen et al (2021), Riaz et al (2014)
2	Help warn workers of workplace hazard	Fan et al (2021), Ding et al (2013), Kiani et al (2014), Li et al (2015), Parn et al (2019), Liang and Liu (2022), Chen et al (2021), Qian (2021), Hossain et al (2023), Yuan and Anumba (2020), Cheung et al (2018), Riaz et al (2014)
3	Eliminate hazard during the design phase	Hu et al (2024)
4	Help visualize hazard	Sakr and Sadhu (2023), Scianna et al (2022), Fan et al (2021), Ding et al (2013), Cheng and Teizer (2013), Kiani et al (2014), Zhang and Bai (2015), Li et al (2015), Parn et al (2019), Hossain et al (2023), Hu et al (2024)
5	Improves effectiveness of safety training	Fan et al (2021), Cheng and Teizer (2013), Li et al (2015), Teizer et al (2013)
6	Enhancing accident investigation	Scianna et al (2022), Li et al (2015)
7	Improve safety monitoring	Sakr and Sadhu (2023), Scianna et al (2022), Cheng and Teizer (2013), Fan et al (2021), Kiani et al (2014), Zhang and Bai (2015), Li et al (2015), Ding et al (2022), Liang and Liu (2022), Chen et al (2021), Qian (2021), Hossain et al (2023), Riaz et al (2017), Yuan and Anumba (2020), Hu et al (2024), Jiang and Jiang (2024), Cheung et al (2018)
8	Enhancing safety planning	Scianna et al (2022), Fan et al (2021), Pang et al (2024)
9	Enhancing safety communication	Yuan and Anumba (2020)
10	Improve safety inspections and analysis	Sakr and Sadhu (2023), Scianna et al (2022), Fan et al (2021), Li et al (2015), Ying et al (2021), Yuan and Anumba (2020), Riaz et al (2014)
11	Enhancing near miss reporting	Li et al (2015)
12	Facilitating real-time decision-making and emergency response	Sakr and Sadhu (2023), Ding et al (2013), Cheng and Teizer (2013), Zhang and Bai (2015), Li et al (2015), Parn et al (2019), Chen et al (2021), Qian (2021), Yuan and Anumba (2020), Pang et al (2024), Cheung et al (2018), Riaz et al (2014)
13	Enhancing hazard identification and risk assessment	Scianna et al (2022), Kiani et al (2014), Zhang and Bai (2015), Li et al (2015), Qian (2021), Riaz et al (2017), Yuan and Anumba (2020), Hu et al (2024), Jiang and Jiang (2024), Pang et al (2024), Cheung et al (2018)
14	Supports compliance with safety regulations	Ding et al (2022), Liang and Liu (2022)
15	Cost savings compared to traditional manual and sensor systems	Hossain et al (2023)

Table 5: Ranking of BIM-IoT Safety Advantages (Based on Survey Results)

Rank	Advantage	Mean Score	SD	SLR Citation
1	Improve safety monitoring	4.28	0.68	17
2	Facilitating real-time decision-making and emergency response	4.22	0.71	12
3	Enhancing hazard identification and risk assessment	4.19	0.73	11
4	Help warn workers of workplace hazards	4.12	0.76	12
5	Improve safety awareness	4.08	0.78	9
6	Help visualise hazard	3.98	0.82	11
7	Supports compliance with safety regulations	3.94	0.85	2
8	Improves the effectiveness of safety training	3.91	0.79	4
9	Improve safety inspections and analysis	3.87	0.83	7
10	Enhancing safety planning	3.84	0.86	3
11	Cost savings compared to traditional systems	3.81	0.88	1
12	Enhancing safety communication	3.76	0.84	1
13	Enhancing accident investigation	3.68	0.89	2
14	Enhancing near miss reporting	3.61	0.93	1
15	Eliminate hazards during the design phase	3.47	0.97	1

Table 6: Factor Analysis Results - Five-Factor Solution

Factors	Advantages	Factor Loading	Eigenvalue	Variance Explained
Factor 1: Real-time Monitoring & Control			**4.23**	**18.7%**
	Enhances safety monitoring	0.834		
	Facilitating real-time decision-making and emergency response	0.789		
	Enhancing hazard identification and risk assessment	0.756		
	Help warn workers of workplace hazards	0.678		
Factor 2: Safety Planning & Design			**3.18**	**14.1%**
	Enhancing safety planning	0.812		
	Eliminate hazards during the design phase	0.745		
	Help visualise hazard	0.698		
Factor 3: Training & Communication			**2.89**	**12.8%**
	Improve safety awareness	0.823		
	Improves the effectiveness of safety training	0.756		
	Enhancing safety communication	0.689		
Factor 4: Investigation & Reporting			**2.67**	**11.8%**
	Improve safety inspections and analysis	0.798		
	Enhancing accident investigation	0.734		
	Enhancing near miss reporting	0.687		
Factor 5: Compliance & Economics			**2.34**	**10.4%**
	Supports compliance with safety regulations	0.812		
	Cost savings compared to the traditional system	0.745		