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# UAV-based building condition assessment and safety diagnostics for lifecycle management: a scientometric analysis and systematic literature review

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## Abstract

**Purpose** – This study investigates the application of unmanned aerial vehicles (UAVs) in building condition assessment (BCA) and safety diagnostics, with the aim of informing future research and supporting practical implementation across the construction and operational lifecycle.

**Design/methodology/approach** – A comprehensive search of Scopus and Google Scholar identified thirty-three peer-reviewed empirical and conceptual studies on UAV-enabled building assessment and safety applications. Thematic synthesis was employed to identify key research directions, while scientometric mapping was conducted using VOSviewer.

**Findings** – Research on UAV applications in building diagnostics and safety has increased significantly since 2020, indicating a transition toward autonomous, data-driven monitoring and lifecycle-oriented risk management. Five core themes were identified: (1) hazard detection and pathology assessment, (2) building monitoring and condition assessment, (3) integration with artificial intelligence, Building Information Modelling, and Digital Twins, (4) safety and technical training and (5) regulatory and ethical considerations.

**Practical implications** – The study provides practitioners, academics, and policymakers with insights to enhance building safety performance, optimize condition monitoring processes, support evidence-based decision-making and promote sustainable lifecycle management (LCM) practices.

**Originality/value** – This study is among the few to integrate scientometric analysis with a systematic literature review to examine UAV applications in building diagnostics and safety. It advances the theoretical understanding of intelligent safety and building monitoring ecosystems and identifies future research priorities in governance, ethical deployment and cross-industry knowledge transfer.

**Keywords** Building condition assessment, Construction safety, Drone technology, Hazard detection, Systematic review

**Paper type** Literature review

## Introduction

Beyond its role in infrastructure, the construction industry accounts for 4.4–4.5% of U.S. GDP (BEA, 2025). Despite this contribution, it remains globally hazardous due to dynamic site configurations and concurrent work activities, with studies in emerging economies such as



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Ghana reporting particularly low levels of technology adoption for safety management (Pittri *et al.*, 2024). Digital technologies, particularly Unmanned Aerial Vehicles (UAVs), now offer significant opportunities for building condition assessment (BCA) and safety diagnostics. When integrated with computer vision and Building Information Modelling (BIM), UAVs provide high-resolution imagery that complements manual inspections, which are often constrained by limited visibility and restricted access (Guo *et al.*, 2018; Zhu *et al.*, 2022).

Despite growing research on UAVs in construction, existing studies largely emphasize surveying, monitoring, and logistics, with relatively limited attention to BCA and pathology-based diagnostics (Guo *et al.*, 2018; Gupta and Nair, 2024). Previous reviews often lack integration of scientometric mapping, which restricts understanding of intellectual structures and thematic interconnections within the field (Cheng *et al.*, 2023). Consequently, the literature remains fragmented, as UAV applications are rarely examined within a lifecycle framework that links safety diagnostics to building performance, maintenance, and adaptation. This study addresses these gaps through an integrated scientometric and systematic review of UAV-enabled building diagnostics from 2016 to 2024.

Beyond construction safety, this work contributes to building pathology and lifecycle adaptation theory. Traditional manual inspections are limited by access constraints and subjectivity; UAV-enabled diagnostics extend these methods by providing high-resolution, repeatable monitoring capable of generating precise datasets for structural assessment and deformation analysis (Truong-Hong *et al.*, 2022). Integrated with photogrammetry and thermal imaging, UAVs enable earlier detection of deterioration, strengthening evidence-based pathology assessment and supporting sustainable building management aligned with Sustainable Development Goal 8.

The study further advances adaptation theory by linking diagnostic data acquisition with lifecycle decision-making processes. Continuous monitoring facilitates a shift from reactive maintenance toward predictive, condition-based adaptation planning, where UAV-generated datasets serve as empirical inputs for interventions such as envelope retrofitting or structural reinforcement. By conceptualizing UAVs as diagnostic instruments within a broader adaptation ecosystem, this review extends safety-focused discourse toward a pathology-informed, lifecycle-oriented framework for intelligent building management.

The contributions are twofold. First, it synthesizes the intellectual structure of the field through an integrated approach, delineating key thematic clusters. Second, it advances monitoring theory by conceptualizing an intelligent diagnostic ecosystem in which UAVs enable predictive risk analytics. Finally, the study proposes a causal path model (Figure 5) illustrating the flow from UAV data acquisition to proactive safety performance, while accounting for mediating regulatory and human factors.

## Background

To position this study, a systematic assessment of existing review articles on UAV applications was conducted. Previous formal reviews are often limited by either a scope that is too broad or a methodology lacking quantitative rigour. Foundational studies typically employed non-systematic approaches (Guo *et al.*, 2018) or focused on narrow and application-specific technological domains (Zahari *et al.*, 2021). While higher-rigour systematic reviews exist, they generally cover the broader Architectural, Engineering, and Construction field rather than building-specific diagnostic applications (Guan *et al.*, 2022). Furthermore, existing bibliometric studies often address general construction management without focussing on safety diagnostics or condition assessment (Gupta and Nair, 2024).

Table 1 summarizes key review studies, comparing their scope, methods, and limitations. It shows that most adopt broad construction perspectives or focus on specific technologies, with limited attention to integrated BCA and safety diagnostics. This gap highlights the need for an integrated study combining scientometric analysis and systematic literature review.

**Table 1.** Comparative summary of previous review studies on UAV applications in construction and the built environment

| Author | Year | Scope | Methodology | Limitation |
|---|---|---|---|---|
| Ham *et al.* | 2016 | Visual monitoring of civil infrastructure (buildings, bridges), streamlining aerial data collection and analysis | Review of related works | Broad civil infrastructure focus; lacks exclusive attention to construction safety diagnostics and lifecycle-oriented UAV assessment |
| Guo *et al.* | 2018 | General UAV applications in construction management (surveying, monitoring) | Narrative review | Does not focus on building condition assessment or safety diagnostics; lacks quantitative mapping of intellectual development |
| Zhou and Gheisari | 2018 | UAV applications in construction (inspection, surveying, safety monitoring, maintenance) | Systematic literature review | Broad application scope; older synthesis lacks quantitative mapping and lifecycle-focused safety assessment |
| Albeaino *et al.* | 2019 | AEC-related UAV applications (inspection, progress monitoring, city planning, construction safety) | Systematic literature review | Broad AEC coverage; limited focus on construction safety diagnostics and lifecycle management; lacks structural scientometric mapping |
| Vanderhorst *et al.* | 2019 | UAV implementation across the construction project lifecycle (progress, 3D modelling, low-cost measurements) | Systematic literature review | Focused on general lifecycle adoption but not specifically on safety monitoring and building condition assessment; lacks dual-method mapping |
| Zahari *et al.* | 2021 | UAV photogrammetry and 3D modelling | Systematic literature review | Narrow technological focus; does not map safety diagnostics or lifecycle-oriented condition monitoring |
| Videras Rodríguez *et al.* | 2021 | UAVs in architecture and urbanism (3D models, land mapping, building surveying, site monitoring) | Scientometric and bibliometric analysis | Uses dual-methods but broad scope; lacks exclusive focus on construction safety and lifecycle-focused diagnostics |
| Perera *et al.* | 2022 | UAV applications for construction site safety | Systematic literature review | Focused on safety but employs purely qualitative synthesis; lacks quantitative mapping and lifecycle assessment |
| Rachmawati and Kim | 2022 | UAVs integrated with digital technologies toward Construction 4.0, including safety | Systematic literature review | Broad integration focus; insufficiently deep analysis on safety diagnostics and building condition monitoring |

(*continued*)

**Table 1.** Continued

| Author | Year | Scope | Methodology | Limitation |
|---|---|---|---|---|
| Guan *et al.* | 2022 | UAV-based remote sensing for construction and civil applications | Literature review | Technology-centric; includes general risk factors but lacks exclusive focus on safety diagnostics and lifecycle management |
| Acero Molina *et al.* | 2023 | UAV research in construction management (inspection, surveying, safety) | Literature review | Broad focus; reviews methods and benefits but lacks dual-method mapping of intellectual structure and lifecycle-focused safety diagnostics |
| Gupta and Nair | 2024 | UAVs in construction site safety monitoring (PPE/ML algorithms) | Bibliometric and content-based analysis | Qualitative synthesis of specific technical methods; lacks detailed scientometric mapping of safety diagnostics and building condition monitoring |
| This study | 2026 | UAV-based building condition assessment and safety diagnostics across the construction lifecycle | Integrated scientometric and systematic review | First dual-method study providing quantitative structural mapping and deep thematic synthesis focused explicitly on construction safety, building condition assessment, and lifecycle management |

The present study represents one of the first focused investigations of UAV applications in BCA and safety diagnostics, combining quantitative mapping with qualitative synthesis to reveal the field's intellectual structure and provide evidence-based guidance for future research and practical lifecycle management (LCM) applications.

## Methodology

This study adopts an interpretivist paradigm, prioritizing phenomena within their contextual environments and recognizing that meaning occurs through interaction and interpretation. This supports a mixed-methods literature review integrating two complementary layers: a quantitative scientometric analysis mapping structural patterns, and a qualitative systematic synthesis interpreting scholarly perspectives.

The research followed a four-phase structure adapted from Al Horr *et al.* (2023): (1) database selection and search strategy, (2) screening and eligibility assessment, (3) scientometric analysis, and (4) systematic literature review. Phases were sequential, with quantitative mapping preceding interpretive synthesis to enhance conceptual clarity (Grant and Booth, 2009) (Figure 1). Scopus and Google Scholar were selected to balance reliability and coverage. Scopus provides curated, structured citation data suitable for scientometric analysis, while Google Scholar broadens coverage to include conference papers, reports, theses, and emerging studies, reducing publication bias.

Databases such as Web of Science, IEEE Xplore, ASCE Library, and Engineering Village were excluded due to substantial overlap with Scopus, which would increase duplication without significantly expanding the dataset. Preliminary pilot searches indicated over 85% metadata overlap between Scopus and these repositories. This combination ensures methodological robustness, breadth of coverage, and efficient data screening.

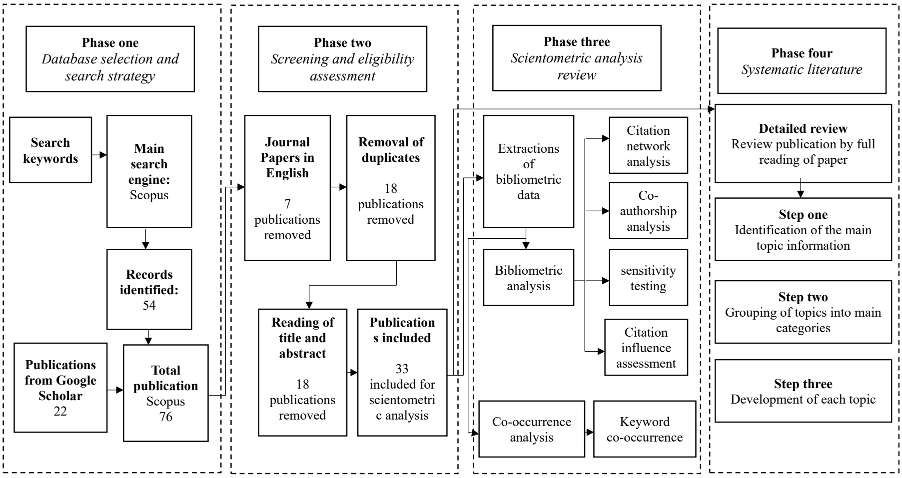


**Figure 1.** Research process

Boolean operators and carefully structured keywords were used to capture studies at the intersection of UAVs, construction, and safety. Synonyms across technological and built environment fields ensured comprehensive yet focused retrieval, enhancing transparency, reproducibility, and minimizing omission of relevant studies. The search spanned 2016–2024, reflecting regulatory expansions and digitalization in the Architecture, Engineering and Construction (AEC) sector (Cheng *et al.*, 2023).

The initial search returned seventy-six records. After duplicate removal, a three-stage screening process was applied: (1) title and abstract screening, (2) full-text assessment for methodological transparency, and (3) grey literature evaluation based on author expertise. Inclusion and exclusion criteria were defined to ensure methodological rigour. Studies were included if they addressed UAV applications in construction, inspection, or infrastructure monitoring with clear methodological approaches and contributions to safety, BCA, or LCM. Both empirical and conceptual works were considered. Studies unrelated to the built environment or lacking methodological transparency were excluded. This process yielded thirty-three high-quality studies.

Data extraction captured bibliographic information, study aims, methodologies, and contributions. Thematic analysis used concept-driven coding to identify clusters relevant to UAV-enabled building condition and safety diagnostics. Two independent reviewers coded a subset to ensure reliability, with discrepancies resolved through discussion.

VOSviewer keyword co-occurrence analysis was used to identify thematic structures. A minimum occurrence threshold of three was applied to balance inclusiveness and noise reduction. Full counting assigned equal weight to keywords, while association strength normalization measured term relatedness. Clustering used default algorithm and resolution settings to ensure stable and interpretable groupings, appropriate for identifying dominant themes in the dataset. This sequential integration ensures findings are grounded in high-quality literature, offering a comprehensive understanding of UAV applications in BCA, safety diagnostics, and LCM (Al Horr *et al.*, 2023).

## Results

Research on UAVs for BCA and safety diagnostics between 2016 and 2024 demonstrates a progressive but uneven expansion across three distinct waves (Figure 2). The foundational

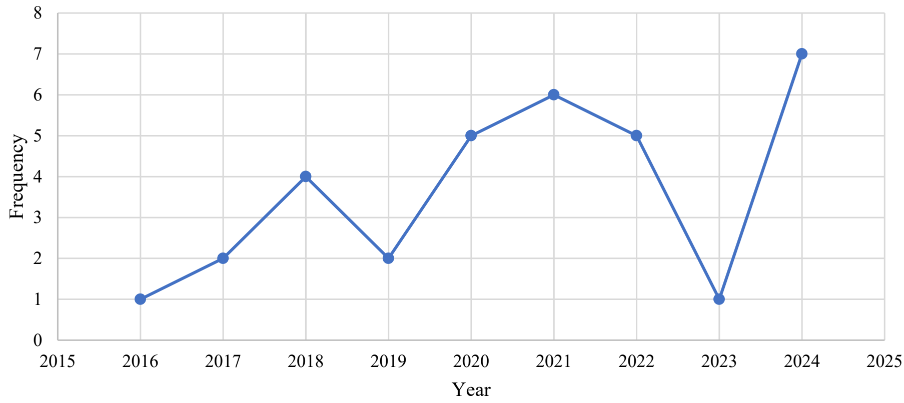


**Figure 2.** Publication trajectory (2016–2024)

wave (2016–2018) was characterized by early exploratory studies ($n = 7$). Following a brief stabilization in 2019, the growth wave (2020–2021) saw accelerated output ($n = 11$), likely catalyzed by the demand for contactless monitoring during the COVID-19 pandemic. The maturation wave (2022–2024), despite a 2023 dip, culminated in the highest annual output in 2024 (f = 7). This trajectory reflects a transition from isolated experimentation to more integrated, context-driven research orientations within building safety and lifecycle management (LCM) frameworks.

Methodological analysis (Figure 3) reveals a dominance of system development studies (f = 15), focussing on real-time hazard detection and design testing, followed by literature-based synthesis studies (f = 9) aimed at consolidating fragmented knowledge. Conversely, case studies (f = 5) and surveys (f = 2) remain moderate to low in frequency, although recent large-scale empirical surveys have begun to highlight significant barriers to adoption, such as technical challenges and high costs (Pittri *et al.*, 2024). The scarcity of modelling, simulation, and gap analysis studies (f = 2 each) indicates that predictive analytics and strategic optimization remain underdeveloped. Overall, the methodological distribution signals an ongoing shift from technology-centred experimentation toward more empirically grounded and building-centred inquiry.

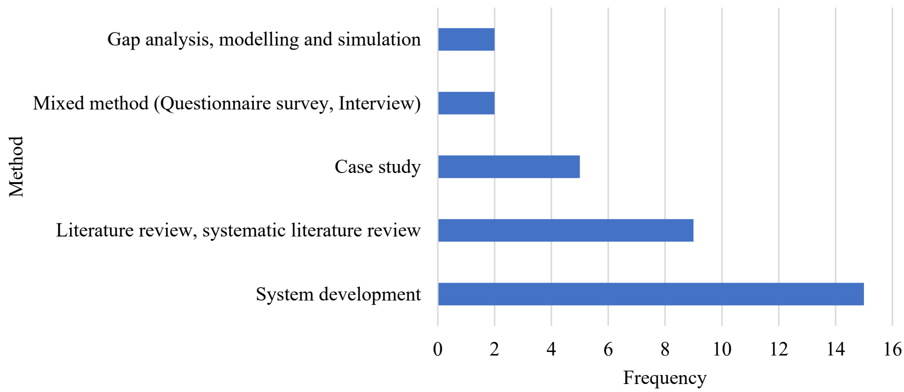


**Figure 3.** Method

*Influential publications*

Relevance-based citation analysis, balancing frequency and recency, identified foundational contributions shaping UAV integration in BCA and safety diagnostics (Table 2). A primary research stream focuses on UAV-enabled data acquisition to enhance situational awareness and safety-informed decision-making. Alizadehsalehi *et al.* (2020) demonstrated that coupling 4D BIM with UAV imagery supports dynamic hazard identification and scenario planning, while Martinez *et al.* (2020) highlighted UAV-captured visual data for improving coordination in building monitoring. Collectively, these works mark a transition from manual inspections toward data-driven and predictive condition management approaches.

A second stream involves the convergence of UAVs with artificial intelligence. Shanti *et al.* (2022) introduced deep-learning frameworks for work-at-height risk detection, while Wu *et al.* (2021) applied computer vision techniques to monitor foundation pit deformations for early-warning systems. These contributions advance the development of semi-autonomous diagnostic systems for proactive safety management. Complementing these technical approaches, Jeelani and Gheisari (2021) addressed cognitive and psychological risk factors, advocating for ethical governance and human-centred risk-aware design.

Among 127 authors, six emerged as intellectual leaders. Gheisari leads with three publications (298 citations) spanning UAV deployment and virtual-reality-based safety training (Martinez *et al.*, 2020; Cheng *et al.*, 2023). Other prominent contributors include Alizadehsalehi, Arditi, Celik, and Yitmen, whose collaborative work on UAV–BIM integration (Alizadehsalehi *et al.*, 2020) received 170 citations. Collaborative linkages between Gheisari and Jeelani further illustrate the emergent knowledge networks underpinning theoretical and applied advancement in the field.

*Keyword co-occurrence analysis*

VOSviewer keyword co-occurrence analysis (threshold $n = 3$) identified thirty-six frequent terms from a pool of 362, forming three dominant thematic clusters (Figure 4). The first cluster (Human-Centred Risk Management) focuses on mitigating human exposure through keywords such as workplace, accidents, and occupational risks. This reflects the field's origins in direct safety enhancement and visual intelligence, supporting real-time monitoring and automated compliance detection (Calantropio, 2019).

The second cluster (Management Integration) indicates an expansion from isolated hazard detection toward comprehensive construction oversight, including construction management, inspection, and safety engineering. Studies here (Noh *et al.*, 2024; Qu *et al.*, 2017) demonstrate the convergence of safety diagnostics with lifecycle-based management, reflecting the integration of UAVs into broader digital construction ecosystems.

The third cluster (Technological Frontier) signals a shift toward autonomous systems through deep learning, computer vision, and object detection. Here, UAVs function as data acquisition nodes within intelligent analytics frameworks (Sharma *et al.*, 2021; Zhu *et al.*, 2022). Algorithmic interpretation enables proactive hazard forecasting and performance optimization.

These clusters reveal a clear maturation trajectory, progressing from reactive human-centred safety approaches, to managerial integration, and ultimately toward AI-driven predictive autonomy for building safety and LCM.

*Thematic synthesis*

The keyword clusters provide a quantitative foundation for interpreting UAV research in BCA and safety diagnostics, highlighting a shift toward intelligent, lifecycle-informed management. The systematic review identifies five principal themes summarized below.

(1) Hazard detection and pathology assessment

UAVs are deployed to detect site hazards and building defects such as structural cracks, moisture ingress, and thermal anomalies. Computer vision and deep learning enable

**Table 2.** Seminal publications

| Authors | Year | Title | Publication | Citation | CPY | Key finding |
|---|---|---|---|---|---|---|
| Jeelani and Gheisari | 2021 | Safety challenges of UAV integration in construction: Conceptual analysis and future research roadmap | Safety Science | 136 | 45.33 | UAVs pose physical, attentional, and psychological risks to construction workers, highlighting the need for empirical research and regulatory measures to ensure their safe integration into construction sites |
| Alizadehsalehi *et al.* | 2020 | The effectiveness of an integrated BIM/UAV model in managing safety on construction sites | International Journal of Occupational Safety and Ergonomics | 170 | 42.5 | Integrating 4D BIM with UAV monitoring significantly enhances hazard identification and mitigation, potentially reducing fatal, non-fatal, and property damage-causing accidents on construction sites |
| Martinez *et al.* | 2020 | UAV integration in current construction safety planning and monitoring processes: Case study of a high-rise building construction project in Chile | Journal of Management in Engineering | 151 | 37.75 | Integrating UAV-generated aerial visuals into safety planning and monitoring significantly improves hazard identification, especially for high-risk conditions at heights and reduces the time required for site inspections in high-rise construction projects with limited safety personnel |
| Shanti *et al.* | 2022 | Real-time monitoring of work-at-height safety hazards in construction sites using drones and deep learning | Journal of Safety Research | 57 | 28.5 | The integrated deep learning and drone-based system can accurately detect fall protection equipment and safety violations in real-time, achieving 90% accuracy and demonstrating strong potential for improving worker safety at heights on construction sites |
| Wu *et al.* | 2021 | Rapid safety monitoring and analysis of foundation pit construction using unmanned aerial vehicle images | Automation in Construction | 68 | 22.67 | UAV imagery combined with point cloud reconstruction enables accurate and efficient detection of local deformations in foundation pits, offering a reliable alternative to traditional safety monitoring methods |

**Note(s):** Citations Per Year (CPY)
**Source(s):** Authors' own work

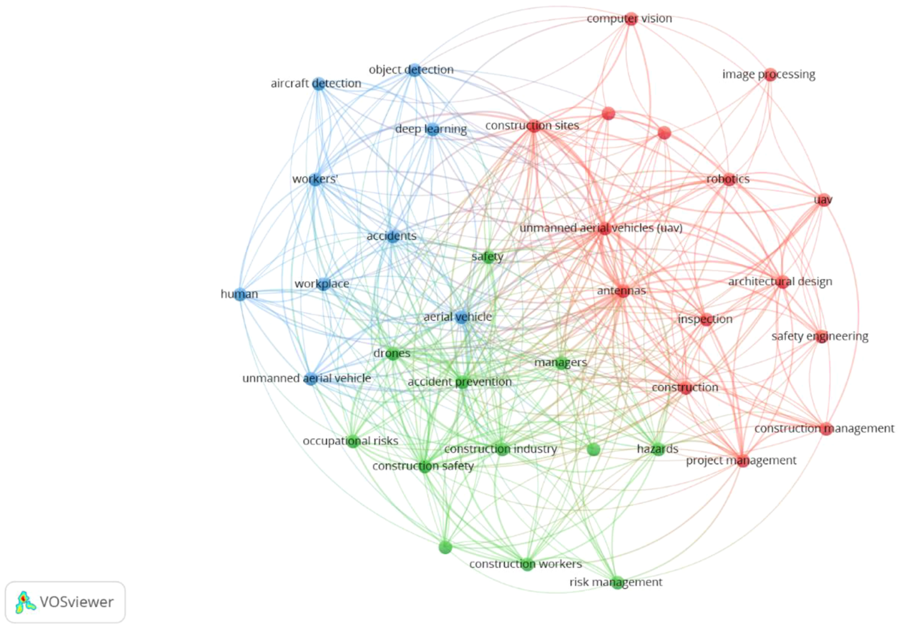


**Figure 4.** Keyword co-occurrence analysis

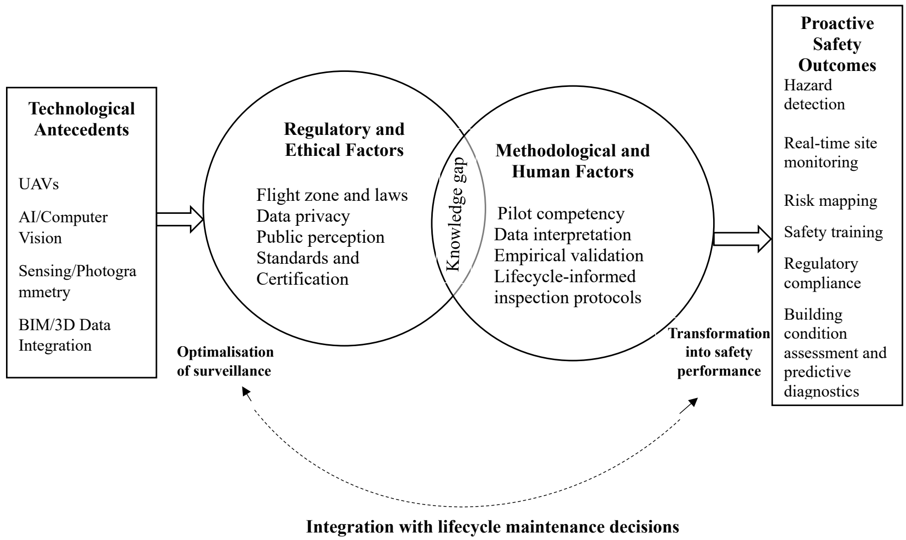


**Figure 5.** A sociotechnical causal path model

automated recognition, reducing reliance on manual inspection and thereby mitigating occupational risk exposure (Sharma *et al.*, 2021; Guo *et al.*, 2018). High-resolution imagery supports early detection of deterioration, facilitating preventative maintenance strategies and extending asset lifecycles.

(2) Building monitoring and condition assessment

Continuous UAV monitoring supports personnel safety and structural condition assessment over time. Integration with photogrammetry and thermal imaging allows for detailed surface mapping and temporal tracking of deterioration patterns (Zhu *et al.*, 2022). This dual function supports both immediate intervention for structural maintenance and longitudinal evaluation of building integrity, thereby bridging short-term safety monitoring with long-term LCM.

(3) Integration with AI, BIM, and Digital Twins

The convergence of UAVs with artificial intelligence, BIM, and Digital Twins (DT) enables predictive diagnostics. Hybrid UAV–BIM systems convert real-time spatial data into actionable insights for defect detection and forecasting (Alizadehsalehi *et al.*, 2020). Machine learning models applied to these datasets support degradation prediction and optimization of resource allocation within digital construction workflows.

(4) Safety and technical training

UAV-derived imagery enhances safety education through immersive virtual reality and augmented reality environments, improving hazard recognition and decision-making capabilities (Cheng *et al.*, 2023). UAV datasets also serve as pedagogical tools in building pathology training, enabling learners to interpret defects and understand condition-based maintenance strategies in realistic scenarios.

(5) Regulatory and ethical considerations

Adoption of UAV technologies is influenced by airspace regulations, privacy protection requirements, and liability frameworks (Jeelani and Gheisari, 2021). These factors significantly affect organizational readiness for sustainable integration. Clear governance structures addressing data ownership, privacy, and system interoperability are essential to ensure that UAV deployment effectively supports proactive LCM.

Across these themes, key limitations include high capital costs, operational complexity, and data security concerns. Emerging trends indicate increasing UAV autonomy and deeper integration into digital construction ecosystems for predictive LCM applications. The identified themes align with the quantitative clusters: hazard detection and monitoring correspond to human-centred and operational clusters, while AI–BIM–DT integration aligns with technological advancement clusters. Regulatory compliance and ethical governance function as enabling constraints, mediating the translation of UAV-derived data into actionable building safety and lifecycle outcomes.

## Discussion

The integration of scientometric mapping and thematic synthesis reveals a field transitioning from descriptive monitoring to more predictive and intelligence-driven building diagnostics. The surge in publications post-2019 reflects technological readiness and sector responsiveness to global disruptions, such as the COVID-19 pandemic, which accelerated the adoption of UAV-based inspection systems (Calantropio, 2019). This highlights the sociotechnical adaptability of construction operations and the potential of UAVs to support continuous lifecycle monitoring and data-driven maintenance strategies.

Methodological analysis indicates a dominance of system-development and literature-based studies, reflecting a conceptual and prototyping emphasis. However, the limited number of field-validated and mixed-method studies reveals a persistent research-to-practice gap. While UAV systems demonstrate technological feasibility, particularly through YOLO and Faster-RCNN models for personal protective equipment compliance and helmet detection (Abbas *et al.*, 2016; Sharma *et al.*, 2021), few studies validate performance under real-world operational constraints. Predictive analytics and lifecycle-informed modelling remain underdeveloped, necessitating further research into operational reliability across the building lifecycle (Umar, 2021).

Thematic synthesis confirms an evolving field in which human-centred safety remains foundational. UAVs enable automated recognition of work-at-height risks and structural deficiencies while facilitating continuous assessment of building integrity, including cracks, moisture ingress, and thermal anomalies (Shanti *et al*., 2022). Integration with artificial intelligence, BIM, and digital twins reflects a shift toward intelligent ecosystems where UAV-derived insights enable proactive hazard anticipation and optimized intervention scheduling (Alizadehsalehi *et al*., 2020; Zhu *et al*., 2022). Furthermore, UAV data is increasingly used as a pedagogical tool in virtual reality and augmented reality training environments to enhance hazard recognition and address technical and organizational barriers identified in recent empirical studies (Truong-Hong *et al*., 2022; Cheng *et al*., 2023; Pittri *et al*., 2024).

Regulatory and ethical considerations highlight a dual-risk paradigm in which UAVs improve monitoring capability while simultaneously introducing operational, privacy, and governance vulnerabilities (Jeelani and Gheisari, 2021). The foregoing is consistent with empirical evidence identifying lack of training and limited institutional support as primary inhibitors to UAV integration (Pittri *et al*., 2024). Although no formal country-level bibliometric analysis was conducted, the reviewed literature suggests that UAV research in construction is concentrated in North America, Europe, and parts of Asia due to stronger regulatory frameworks, funding availability, and higher levels of digital adoption. Primary empirical contributions are largely associated with the United States of America, China, the United Kingdom, and South Korea, which together account for approximately 70% of the identified studies. In contrast, developing regions demonstrate limited adoption, constrained by cost barriers, regulatory uncertainty, and limited technical capacity. This disparity underscores the need for context-specific implementation strategies, and future research should incorporate explicit regional scientometric analyses to better capture global variation in adoption patterns. Ultimately, the convergence of UAVs with artificial intelligence and BIM underscores the emergence of aerial intelligence as a core enabler of situational awareness and sustainable LCM of building assets.

### *Causal path model for UAV-integrated safety management*

The conceptual framework synthesizes the scientometric findings into a sociotechnical causal path model (Figure 5), illustrating how UAV technologies enable proactive safety performance and BCA throughout the construction lifecycle. UAVs, combined with AI, computer vision, and sensing systems, serve as technological antecedents providing high-resolution, real-time data. The transition from raw aerial data to actionable outcomes is mediated by regulatory, ethical, and methodological factors, including flight regulations, data privacy, pilot competency, and empirical validation. Addressing these mediating factors enables proactive outcomes, such as automated hazard detection, risk mapping, and lifecycle-informed building condition diagnostics. A continuous monitoring and learning loop illustrates how longitudinal data acquisition facilitates a shift from reactive inspections toward predictive, data-driven management of both safety and structural performance.

The model can be operationalized by structuring UAV-assisted inspections into sequential stages. UAVs capture high-resolution imagery and sensor data from building envelopes, facades, roofs, and other hard-to-access elements. Data are processed via photogrammetry, computer vision, or artificial intelligence to detect cracks, deterioration, deformation, or safety hazards. Outputs can be integrated into maintenance or asset management systems, enabling prioritized interventions, targeted inspections, and preventive maintenance, thereby supporting safer inspections and proactive LCM.

### *Theoretical implications*

This research shifts the UAV discourse from a technology-centric view toward a socio-technical perspective in construction safety and BCA. By positioning UAVs as proactive agents within integrated risk governance systems, the proposed causal path model links real-time monitoring, safety training, and lifecycle-informed diagnostics. Key constructs, including real-time situational awareness, aerial hazard detection, and the convergence of UAVs with AI, BIM, and DT (Alizadehsalehi *et al*., 2020; Sharma *et al*., 2021), form the foundation of an "intelligent safety ecosystem." This paradigm emphasizes continuous data acquisition, predictive analytics, and adaptive learning to support structural performance throughout the building lifecycle. Furthermore, human–machine interaction remains central; UAVs function as cognitive collaborators that extend human perception, while ethical considerations necessitate theoretical models addressing autonomy, accountability, and cognitive ergonomics (Jeelani and Gheisari, 2021). These contributions reposition safety and BCA theory within the broader domains of adaptive risk governance and digital ethics.

### *Practical implications*

The findings provide actionable guidance for three primary stakeholder groups. Construction executives and safety managers should integrate UAV-derived data into BIM and DT workflows, formalize standard operating procedures, and enforce robust data privacy protocols. These measures reduce human exposure to hazards while enhancing inspection accuracy and supporting longitudinal condition assessment.

Regulatory authorities should establish construction-specific frameworks, including data exchange standards, liability assignment, and operator certification, to enable reliable lifecycle monitoring. Finally, educational institutions must revise curricula to include UAV data interpretation and immersive safety simulations, ensuring workforce readiness for human-centred digital environments. Integrating UAVs with cloud computing, wearable sensors, and AI can transform BCA practices, fostering sustainable, data-driven adoption across the construction lifecycle.

### *Limitations and directions for future research*

Methodological limitations include reliance on Scopus and Google Scholar, English-language restrictions, and potential keyword indexing inconsistencies. Future reviews should integrate additional databases such as IEEE Xplore, ASCE Library, and Web of Science, alongside multilingual sources and controlled vocabularies to enhance retrieval accuracy. Analytically, citation-based measures are limited; complementary indicators, including altmetrics and network centrality, could provide more balanced assessments of scholarly impact. Conceptually, while this study focuses on UAV-specific applications, future research should explore synergies with wearable sensors, argumented reality/virtual reality, and Digital Twins to strengthen lifecycle-informed diagnostics. Furthermore, deeper examination of organizational and behavioural dimensions, such as trust, safety culture, and worker perception, is critical for sustainable adoption.

The final dataset of thirty-three studies reflects the specialized nature of UAV applications in building diagnostics. While sufficient for qualitative synthesis and targeted scientometric analysis, the combined use of Scopus and Google Scholar ensured a balance between structured indexing and broader coverage, thereby mitigating the exclusion of relevant grey literature and emerging studies. The consistency of themes across the dataset supports a robust interpretation; however, future research could expand the corpus using additional databases to further reduce potential bias.

### *Future research roadmap and conceptual contribution*

This study proposes a three-pronged research roadmap for UAV-enabled construction safety and BCA throughout the building lifecycle. The first axis focuses on large-scale, multi-site empirical validation to generate reproducible performance metrics, including precision, recall, latency, and operational robustness. Such evidence supports standardized testing protocols, realistic return-on-investment calculations, and broader industry confidence in system reliability. The second axis emphasizes the human–drone interface, encouraging investigations into the psychological and cognitive effects of continuous aerial monitoring, such as trust in automation and perceived surveillance pressure. Conceptualizing UAVs as cognitive collaborators ensures ethically responsible and operationally effective deployment while informing the design of safety and technical training systems.

The third axis underscores the necessity of coherent regulatory and governance frameworks addressing data security, liability, and operator certification. Establishing these frameworks enables scalable and adaptive integration of UAVs for proactive safety and lifecycle-informed diagnostics. This roadmap transitions the field from fragmented experimentation toward empirically validated, ethically governed, and human-centred deployment. It offers a clear conceptual contribution to guide both scholarly inquiry and industrial practice in UAV-enabled building monitoring and condition assessment.

## Conclusion

This study synthesizes scholarly research on UAV applications for building monitoring, condition assessment, and safety diagnostics across the construction and operational lifecycle. A systematic review of studies from 2016 to 2024 identified five dominant themes: hazard detection and pathology assessment; building monitoring and condition assessment; integration with artificial intelligence, BIM, and digital twins; safety and technical training; and regulatory and ethical considerations. These themes indicate a shift from reactive inspection toward more proactive and increasingly autonomous monitoring paradigms. The convergence of UAVs with AI and BIM positions aerial intelligence as a key enabler of real-time situational awareness, predictive maintenance, and informed decision-making in asset-critical environments.

Beyond safety benefits, the review demonstrates that UAV-enabled monitoring can contribute to reduced costs associated with building adaptation and maintenance. Early detection of envelope deterioration and serviceability issues supports timely, minimally invasive interventions, thereby preventing escalation into major rehabilitation works that typically incur higher capital costs and operational downtime. Improved inspection frequency and enhanced access to hard-to-reach components reduce reliance on scaffolding and manual surveys, enabling condition-based maintenance planning and optimized resource allocation.

The findings reveal a dual-risk paradigm in which UAVs strengthen diagnostic capability while simultaneously introducing operational, regulatory, and privacy challenges that necessitate integrated governance and human–machine collaboration protocols. Theoretically, this study advances building pathology by transitioning from subjective manual surveys to high-resolution, evidence-based defect characterization. Practically, it offers guidance for embedding UAVs within inspection workflows and predictive maintenance regimes. Aligned with sustainable construction principles and Sustainable Development Goal 8, UAV-enabled systems enhance worker protection, reduce asset risk, and improve overall lifecycle performance. Future research should prioritize interdisciplinary frameworks addressing governance, behavioural implications, and empirically validated outcomes to ensure ethically grounded and operationally integrated UAV deployment.

### Data availability statement

The processed bibliometric datasets are available from the corresponding author upon request.

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