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Systematic Review

Applications of Building Information Modeling (BIM) and BIM-Related Technologies for Sustainable Risk and Disaster Management in Buildings: A Meta-Analysis (2014–2024)

Jiao Wang [1,2,*], Yuchen Ma [3], Rui Li [1] and Suxian Zhang [1]

[1] College of Urban Development and Modern Transportation, Xi'an University of Architecture and Technology, Xi'an 710055, China
[2] China Northwest Architecture Design and Research Institute Co., Ltd., Xi'an 710018, China
[3] Shannxi Provincial Transport Planning Design and Research Institute Co., Ltd., Xi'an 710065, China
* Correspondence: wangjiao624729@gmail.com

Abstract

Sustainable risk and disaster management in the built environment has become a critical research focus amid escalating environmental challenges. Building Information Modeling (BIM) is recognized as a key digital tool for enhancing disaster resilience through simulation, data integration, and collaborative management. This study systematically reviews BIM applications in sustainable risk and disaster management from 2014 to 2024, employing the PRISMA framework, literature coding, and network analysis. Five primary research clusters are identified: (a) sustainable construction and life cycle assessment, (b) performance evaluation and implementation, (c) technology integration and digital innovation, (d) Historic Building Modeling (HBIM) and post-disaster reconstruction, and (e) project management and technology adoption. Despite increasing scholarly attention, the field remains dominated by conceptual studies, with limited empirical exploration of emerging technologies such as artificial intelligence (AI). Four key challenges are highlighted: weak foundational integration with structural risk research, technological bottlenecks in AI and digital applications, limited practical implementation, and insufficient linkage between sustainability and risk management. Future trends are expected to focus on achieving Industry 4.0 interoperability, advancing AI-driven intelligent disaster response, and adopting multi-objective optimization strategies balancing resilience, sustainability, and cost-effectiveness. This study provides a comprehensive overview of the field's evolution and offers insights into strategic directions for future research and practical innovation.

Keywords: building information modeling (BIM); risk management; disaster management; digital twin (DT); artificial intelligence (AI); sustainability; Industry 4.0

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1. Introduction

1.1. Background and Importance of Sustainable Disaster Management

In recent years, the field of disaster and risk management in buildings has shifted beyond merely addressing functional issues to also focusing on the sustainability of these management strategies and applications [1–3]. Sustainable risk and disaster management for buildings refers to the adoption of sustainable strategies and technologies throughout the design, construction, operation, and maintenance of buildings to enhance their resilience against natural disasters (such as earthquakes, floods, typhoons, and fires) and human-induced risks (such as environmental pollution, resource depletion, and climate

change) [4–6], ensuring their long-term environmental [7], economic [8], and social sustainability [9]. Research and practice in this area is critical, as it not only helps to protect human life and property, but also has a significant impact on ensuring the sustainability and economic viability of construction projects [10].

1.2. The Role of Digital Tools and BIM in Disaster Management

Against this backdrop, the adoption of digital tools has become indispensable for accelerating the development and implementation of sustainable disaster management strategies. Building Information Modeling (BIM), in particular, serves as a cornerstone technology in this transformation. BIM refers to a 3D model-based tool for managing and communicating information in construction projects [11,12]; it makes project management more efficient and provides decision support by simulating the life cycle of a building, including the design, construction, and operation and maintenance phases [13–15]. By integrating automated measurement, visualization, and data processing technologies, BIM reduces misunderstandings and errors, optimizes resource allocation and time management, and ultimately enhances the sustainability of building projects [16,17]. There are many derivatives, such as Landscape Information Modeling (LIM) [18,19] for landscape use and HBIM for heritage buildings [20–22], and a wide range of applications including project management [23,24], facility operations and maintenance [25,26], and energy analysis [1,27].

1.3. Current State of Research

Current applications of BIM (and BIM-related technologies) in buildings' risk and disaster management include disaster simulation [28], emergency response planning [29], facility damage assessment [30], and strategic planning for recovery and reconstruction [31], which, in conjunction with technologies such as digital twins [32,33], artificial intelligence (AI) [34,35], machine learning [36,37], the Internet of Things (IoT) [38,39], and augmented reality (AR) [40,41], have led to a wider range of applications. However, this has also led to the complexity of the relationship between research methods and the scope of application, and thus the need to sort out past research methods and application scenarios to provide a basis for research positioning for subsequent research. In view of the importance of the research content and the complexity of the current research situation in this field, a certain number of review articles have been published to provide a systematic literature review on the research and application of BIM, or BIM-related technology applications and construction disaster management, specifically in the following categories:

(a) Comprehensive Reviews Aligned with the Field: Earlier comprehensive reviews, such as a seminal 2017 article [42], linked BIM with various stages of standard risk management workflows, including structural management and virtual reality. However, these reviews lacked coverage of recent advancements, such as machine learning and IoT. Since 2020, comprehensive reviews in this field have become scarce.

(b) Subfield-Specific Reviews: This category is subdivided into two specific categories of literature. The first is a review of research that emphasizes only a specific aspect of BIM for building disaster and risk management, for example, articles systematically summarizing the application of BIM for post-disaster strategies [43]. The second is a review of research on BIM for risk and disaster management in a specific building type, such as the use of BIM for risk and disaster management in industrial buildings [44]. The limitations of this type of research, however, are also evident, as limiting the focus to the application of BIM to a specific aspect of building disaster management

or to a specific type of building may lead to a lack of comprehensive and coherent understanding of the potential uses of the technology.

(c) Related Domain Reviews: This type of review mainly focuses on the application of BIM to areas related to sustainable risk and disaster management [2]; for example, the review of disaster management in heritage buildings mentions the unifying role that BIM or HBIM plays in it [21,45], and the application of BIM in construction cost management also mentions the possibility of its application in disaster management, disaster identification [46,47], and so on.

1.4. Research Gaps and Study Aims

Although prior reviews have examined the role of BIM in disaster and risk management, they tend to focus either on specific building types, particular phases of disaster management, or adjacent domains, and many are now outdated given the rapid evolution of digital technologies. A comprehensive, decade-spanning review that systematically maps technological inter-relationships, analyzes research trends, and identifies emerging challenges remains lacking.

To address this gap, the aim of this paper is to systematically analyze the literature to map the relationships and applications of BIM, BIM-related technologies, and other emerging technologies in sustainable architectural risk and disaster management while identifying trends and challenges in the field. This study seeks to address this gap by systematically analyzing the literature to map the relationships and applications of BIM, BIM-related technologies, and other emerging digital tools in sustainable architectural risk and disaster management. More specifically, the objectives of this study can be categorized as follows:

Sub-aim (a): To identify the bibliographic characteristics of the literature on the application of BIM in sustainable risk and disaster management for buildings, including the countries and regions involved, the journals in which the articles were published, and the publication trends over the past decade. To conduct clustering analysis to uncover the structural patterns and thematic inter-relationships among research topics in BIM-based sustainable risk and disaster management studies.

Sub-aim (b): To summarize the technologies involved in the research and application of BIM in sustainable risk and disaster management for buildings, clarify the relationships between these technologies (e.g., complementary or substitutive), and match them to their respective application scenarios.

Sub-aim (c): To systematically code the research themes in the literature on BIM in sustainable risk and disaster management for buildings and to analyze the inter-relationships among the identified thematic categories.

Sub-aim (d): To identify and assess the research challenges and development trends in the field of BIM-related studies on architectural risk and disaster management.

1.5. Expected Contributions

The expected contribution of this study is to provide a comprehensive and in-depth perspective on the application of BIM in sustainable risk and disaster management for buildings, and thus to contribute to the advancement of technology and improvement of practice in this area.

2. Materials and Methods

This study employs a four-step approach to literature analysis (Figure 1). First, the Web of Science (WoS) was utilized to search and collect the relevant literature, serving as the primary data source for subsequent analysis [48]. Second, the PRISMA framework (Figure 2) was applied to obtain a visual overview of basic information, such as annual publication trends and research coverage, through coding and statistical methods [49,50]. PRISMA was also employed to establish multiple criteria for classifying and identifying the specific content of the target literature. Third, conceptual network analysis through bibliometric mapping was conducted through a co-occurrence analysis using VOSviewer (Van Eck & Waltman, 2010) based on titles, abstracts, and keywords of the selected publications. This method enabled the identification of major research clusters, revealing conceptual groupings, thematic associations, and emerging trends across the field [51,52]. Last, literature coding was applied to analyze the literature in detail [29]. Systematic content analysis through thematic coding: Building upon the bibliometric results, a structured content analysis was performed to extract detailed information from each publication, focusing on three dimensions: (1) research themes, (2) technological applications (methods, tools, and data), and (3) research findings and challenges. This approach allowed for a more granular classification of study focuses, methodological practices, and identified research gaps, directly informing the study's objectives [53].

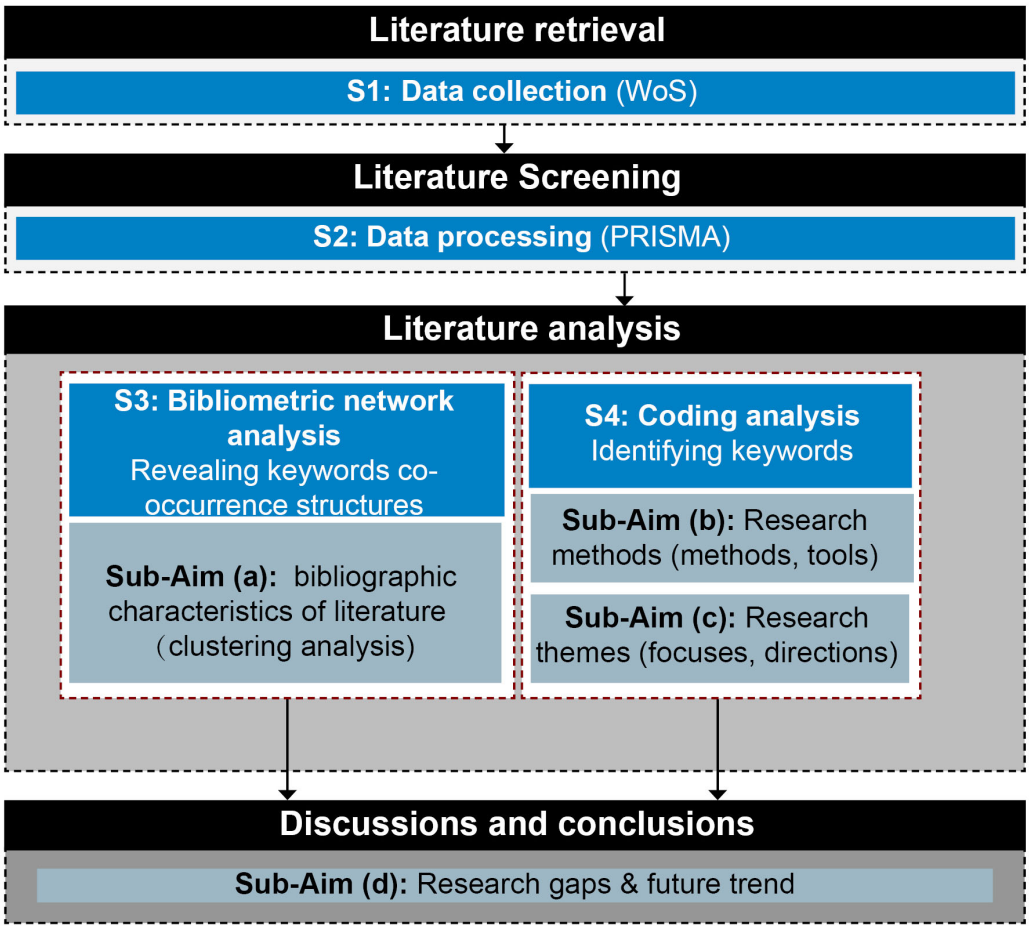


Figure 1. Multi-method analytical framework: Reviewing BIM-related research in sustainable building risk and disaster management contexts.

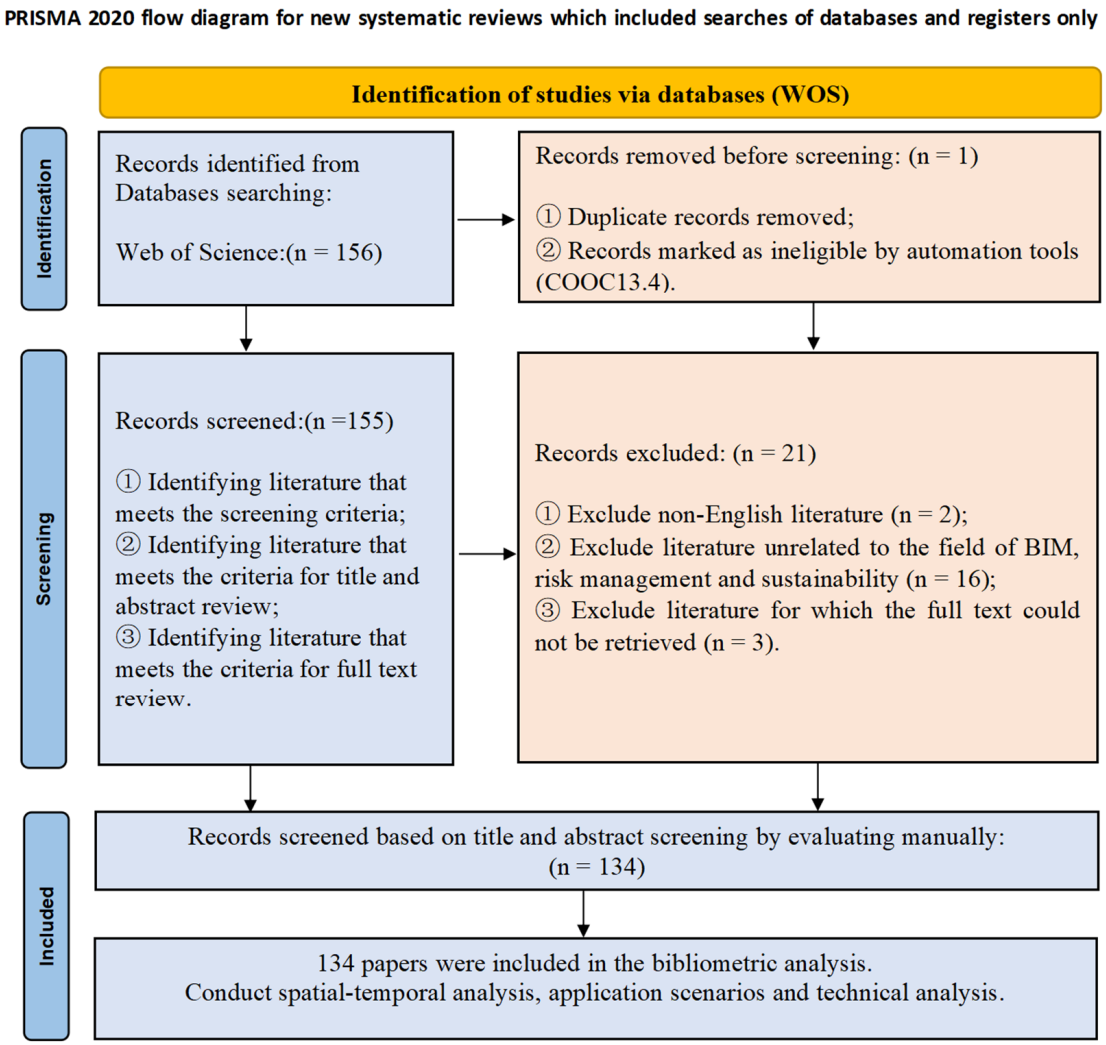


Figure 2. PRISMA flow diagram for paper screening.

2.1. Data Collection

The Web of Science (WoS) offers diverse and accessible databases that explicitly define and utilize digital methods for disaster protection during construction phases [54], encompassing architectural technology, archeology, engineering, and urban planning. This study selected data from the Conference Proceedings Citation Index—Social Sciences and Humanities, Emerging Sources Citation Index, Conference Proceedings Citation Index—Science, Science Citation Index Expanded, Social Sciences Citation Index, and Arts and Humanities Citation Index.

The selection of keywords was informed by the three primary aspects of this review: BIM, construction design, and disaster management. Additional reviews were referenced to identify specific keywords. Boolean operators were employed to combine three categories of keywords for the search, adhering to the following rules:

- "building information modeling" OR "building information modelling" OR "BIM" OR "Landscape Information modeling" OR "Landscape Information Modelling" OR "LIM";
- "sustainable" OR "sustainability";

- "risk management*" OR "disaster management*" OR "hazard management*" OR "risk*" OR "disaster*" OR "hazard*".

2.2. Data Processing

The search generated a total of 156 documents from the WoS Core Collection, following the PRISMA guidelines. Only peer-reviewed journal articles were considered for review to ensure the scientific rigor, validity, and reliability of the included studies. The literature type was initially limited to 'article' and 'review'. However, further manual screening was conducted to exclude non-research content, including editorials, conference abstracts, letters, and book reviews, as these types of publications generally do not provide full empirical research or comprehensive methodological frameworks. In addition, publications were filtered based on the following criteria:

(1) Non-English language papers were excluded to maintain consistency and ensure accessibility;
(2) Papers published prior to 2014 were excluded to focus on developments within the most recent decade;
(3) Studies not directly related to construction design, risk management, or disaster resilience were removed;
(4) Papers without accessible full text were excluded.

Following this filtering process, a final dataset of 134 articles was selected for in-depth analysis.

2.3. Literature Coding

Considering that keyword-based clustering analysis has inherent limitations in fully capturing the depth and nuance of research content, paper coding was applied for statistical and qualitative analysis, following the taxonomic and theme analysis methods of Onwuegbuzie et al. [53]. To enable a more structured evaluation, the classification system was redefined into three key coding dimensions: (1) research methods and analytical techniques (capturing the methodological approaches applied in the studies), (2) use of multi-methods (identifying studies that integrate multiple analytical approaches), and (3) research themes and findings (representing the conceptual development of the field and the reliability of the research outcomes). Each paper was systematically deconstructed along these dimensions using thematic analysis and constant comparison techniques, enabling the identification of recurring patterns and the grouping of studies under coherent thematic clusters. This combined analytical approach allowed for a more nuanced understanding of the evolving landscape of BIM-related research in sustainable risk and disaster management.

2.4. Network Analysis

The network analysis was further expanded to analyze and visualize the connections between different studies. The widely recognized software tool, VOSviewer [51], was employed. A comprehensive database of collected studies was assembled for subsequent filtering and analysis. These Java-based programs facilitate the creation of color-coded bibliometric maps, providing insightful data visualizations. This approach highlights key terms within the literature and uncovers emerging trends and concepts in the research domain [55]. Additionally, the Pajek plugin was utilized to further support the identification of research frontiers and hotspots, employing time-slice analysis to reveal the temporal dynamics of the field's development. Through this bibliometric approach, the study effectively

presents the core research directions and their connections, tracks the evolution of research hotspots, and captures the pathways of knowledge dissemination across different time periods.

3. Results

This section systematically reviews the current state and developmental trends of BIM in architectural risk and disaster management, focusing on research quantity, core themes, and methodologies and tools. From 2014 to 2024, the number of publications in this domain has shown a steady growth trend, reflecting the increasing interest in this field. The research themes have evolved from foundational applications of BIM to deeper integration with risk management, construction safety, and intelligent technologies. Different periods exhibit distinct research focuses and hotspots. Additionally, clustering analysis reveals BIM's key applications in project management, risk assessment, and worker well-being. Methodologies and tools have progressed from basic data processing to intelligent technologies, driving innovation in architectural risk and disaster management [56]. Through quantitative and qualitative analyses, this section provides a systematic perspective on the field's research trends and future directions.

3.1. Preliminary Analysis Results

China and Australia are the leading contributors in this research field, forming a central hub with strong collaborations, particularly with Pakistan, Saudi Arabia, and Malaysia. England, Italy, and Saudi Arabia also play significant roles, with England closely connected to Egypt, Canada, and Greece, forming a European–Mediterranean research cluster. The U.S. and England exhibit strong ties with the UAE and Egypt, while Spain, the Netherlands, and the Czech Republic form a distinct collaboration group linked to Singapore (Figure 3a).

The publication trend in BIM-based sustainable risk and disaster management shows exponential growth (Figure 3b), particularly after 2017, when annual publications surged from 9 to 30 in 2024. The cumulative count surpassed 100 papers by 2023, reflecting increasing recognition of BIM's role in disaster resilience and sustainability. The post-2020 surge aligns with global efforts in climate resilience and digital transformation, indicating that BIM-driven risk management is becoming a key research focus.

Research in BIM for sustainable risk and disaster management is heavily concentrated in sustainability-focused journals (Figure 3c), with "Sustainability" leading at 26 publications, far surpassing others. Journals, such as "Journal of Cleaner Production" and "Applied Sciences Basel" also contribute, emphasizing environmental and interdisciplinary approaches. Other key journals, such as "Journal of Construction Engineering and Management" and "Automation in Construction", publish 2–3 papers each, reflecting a broad but scattered interest in BIM, digital tools, and construction risk management. The dominance of sustainability-related publications highlights a strong research focus on sustainable construction and digital resilience, while the fragmented distribution of BIM, digital twin, and AI studies suggests emerging opportunities in digital construction risk assessment.

3.2. Results of Network Analysis

In network analysis, the study presents the probability of keyword occurrences, classification, correlation, and temporal trends of BIM in sustainable risk and disaster management.

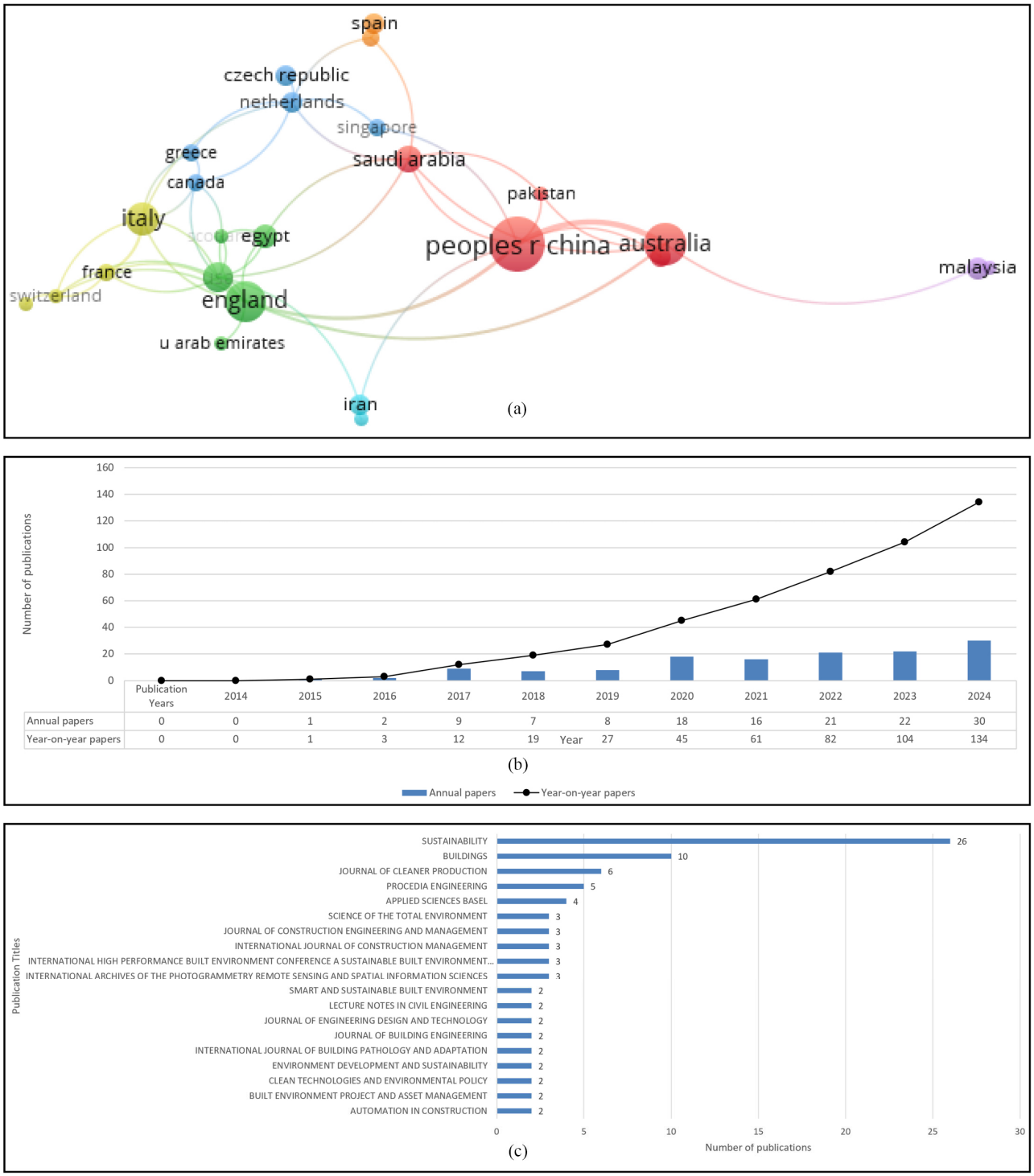


Figure 3. Literature characteristics: (**a**) national issuance of articles from 2014 to 2024; (**b**) annual publications and cumulative growth from 2014 to 2024; (**c**) journal publication from 2014 to 2024.

3.2.1. Clustering Analysis

A total of five research focus clusters were identified (Figure 4a):

(a) Sustainable Construction and Life Cycle Assessment (Blue Cluster): This cluster focuses on sustainability in construction, particularly life cycle assessment, material evaluation (e.g., concrete), and decision-making processes. The increasing application of blockchain technology suggests potential for decentralized data management, improving transparency and traceability in the construction industry. Additionally,

the cluster addresses sustainable construction practices and environmental impact assessment, promoting eco-friendly building methods.

(b) Performance Evaluation and Implementation (Green Cluster): This cluster explores performance evaluation, simulation techniques, and implementation strategies, particularly in heritage conservation and smart buildings. Studies highlight the role of IoT and social sustainability in optimizing building performance, while the integration of deep learning (AI) enhances data-driven analysis for more efficient building management. The research in this area contributes to the advancement of sustainable building technologies and the optimization of historic building preservation.

(c) Technology Integration and Digital Innovation (Red Cluster): This cluster focuses on BIM-GIS integration, digital twins, AI, and virtual reality (VR) in the construction industry. The strong connection between energy management, infrastructure development, and digital workflows underscores the potential of AI-driven risk assessment models in building management. Particularly in bridges and large-scale infrastructure, studies explore the use of digital twin technology for real-time monitoring and predictive maintenance, enhancing long-term sustainability and safety.

(d) HBIM and Reconstruction (Purple Cluster): This cluster is centered on Historic Building Information Modeling (HBIM) and reconstruction, emphasizing 3D modeling, photogrammetry, and risk assessment for historic buildings. The presence of the term "vulnerability" highlights the importance of disaster resilience and how digital transformation can enhance the adaptability and preservation of heritage structures. With advancements in HBIM technology, research is increasingly integrating BIM with cultural heritage conservation to support sustainable building management.

(e) Project Management and Technology Adoption (Yellow Cluster): This cluster examines BIM adoption challenges, project management strategies, and sustainability considerations, focusing on how technology can improve construction efficiency and environmental adaptability. Notably, research on COVID-19 indicates that the pandemic has accelerated digital transformation in construction, leading to greater adoption of remote management, digital construction, and smart project management tools. Additionally, the cluster addresses thermal comfort and sustainable building technologies, providing valuable insights for the future of the construction industry.

3.2.2. Temporal Characteristics of Research Themes (Figure 4b)

The research in BIM-based sustainable risk and disaster management has evolved from foundational topics like life cycle assessment, resilience, and sustainability practices to more advanced, technology-driven approaches. Earlier studies focused on carbon emissions, prefabrication, lean construction, and disaster management, laying the groundwork for sustainability integration. Recent trends emphasize AI, digital twins, GIS integration, IoT, and blockchain technology, enabling real-time risk assessment, predictive analytics, and smart construction management. The emergence of urban green infrastructure, circular economy, and industrialized construction reflects a shift towards automation, waste reduction, and sustainable material use. As the field advances, AI-driven modeling, RFID tracking, and augmented reality applications are becoming key areas for future research, reinforcing BIM's role in climate resilience and digital transformation.

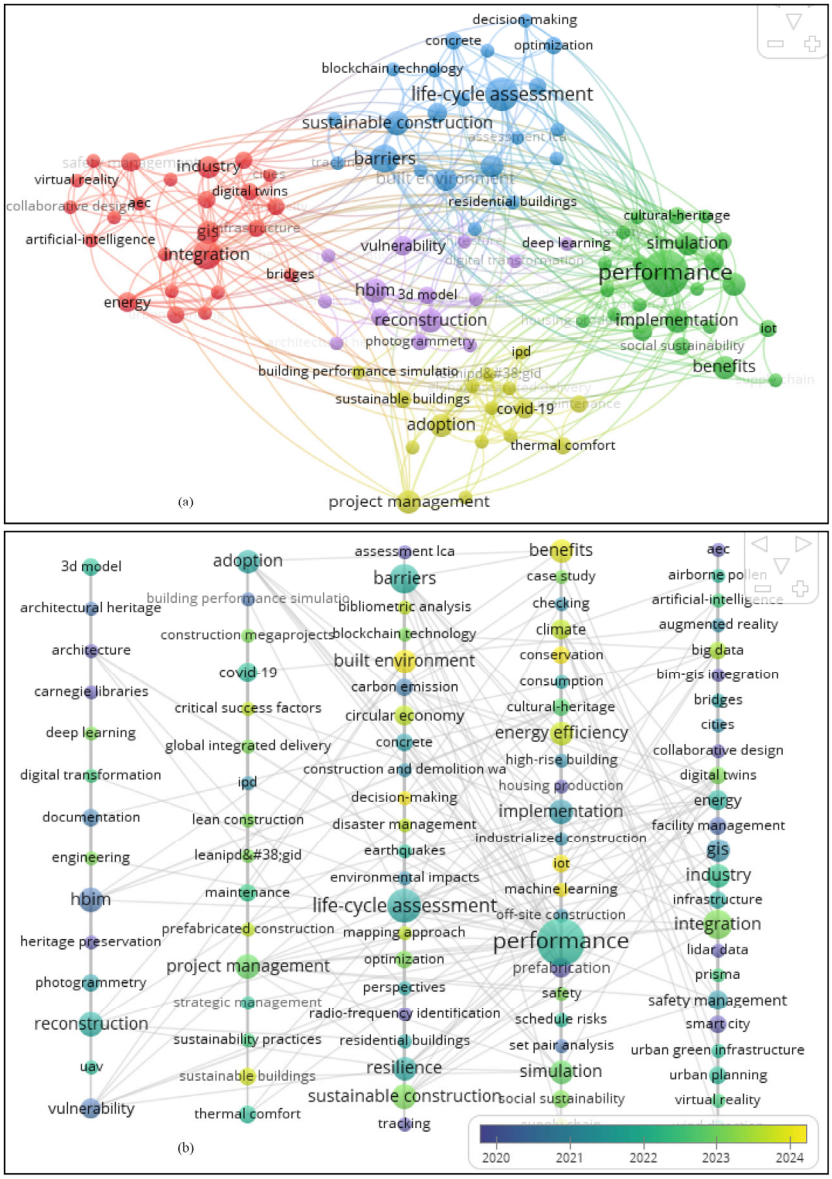


Figure 4. Network analysis for the keywords: (**a**) keyword co-occurrence analysis from 2014 to 2024; (**b**) the temporal characteristics of the keywords.

3.2.3. The Connections Among Research Clusters

The network analysis reveals strong interconnections among research clusters. Technology Integration (Red) and Performance Evaluation (Green) are closely linked through digital tools (AI, GIS, digital twins) and performance assessment (simulation, sustainability, benefits), highlighting the growing focus on data-driven risk decision-making. Similarly, Sustainable Construction (Blue) and Technology Integration (Red) are closely connected, reflecting the ongoing challenges of BIM adoption, digital transformation, and AI-driven risk management, emphasizing continuous efforts in BIM implementation and optimization.

When we incorporate key thematic terms such as sustainability, BIM, and risk, an interesting pattern emerges. Sustainability, despite being a central theme, does not have a direct connection to risk and risk management but is instead linked through BIM (Figure 5a). This suggests that BIM serves as a bridge, integrating sustainability principles into risk-related research rather than these concepts being naturally interconnected (Figure 5b,c). Furthermore, risk itself shows relatively weak connections with methodological clusters like GIS, indicating that BIM plays a crucial mediating role in integrating risk analysis with

digital tools. This highlights the growing importance of BIM as a convergence point for sustainability-driven risk assessment, reinforcing its role as an interdisciplinary enabler that connects risk management strategies with advanced digital technologies for sustainable built environments. Therefore, future research should focus on strengthening direct methodological linkages between sustainability and risk management, potentially through enhanced GIS-BIM integration, AI-driven predictive models, and digital twins for real-time risk monitoring in sustainable construction.

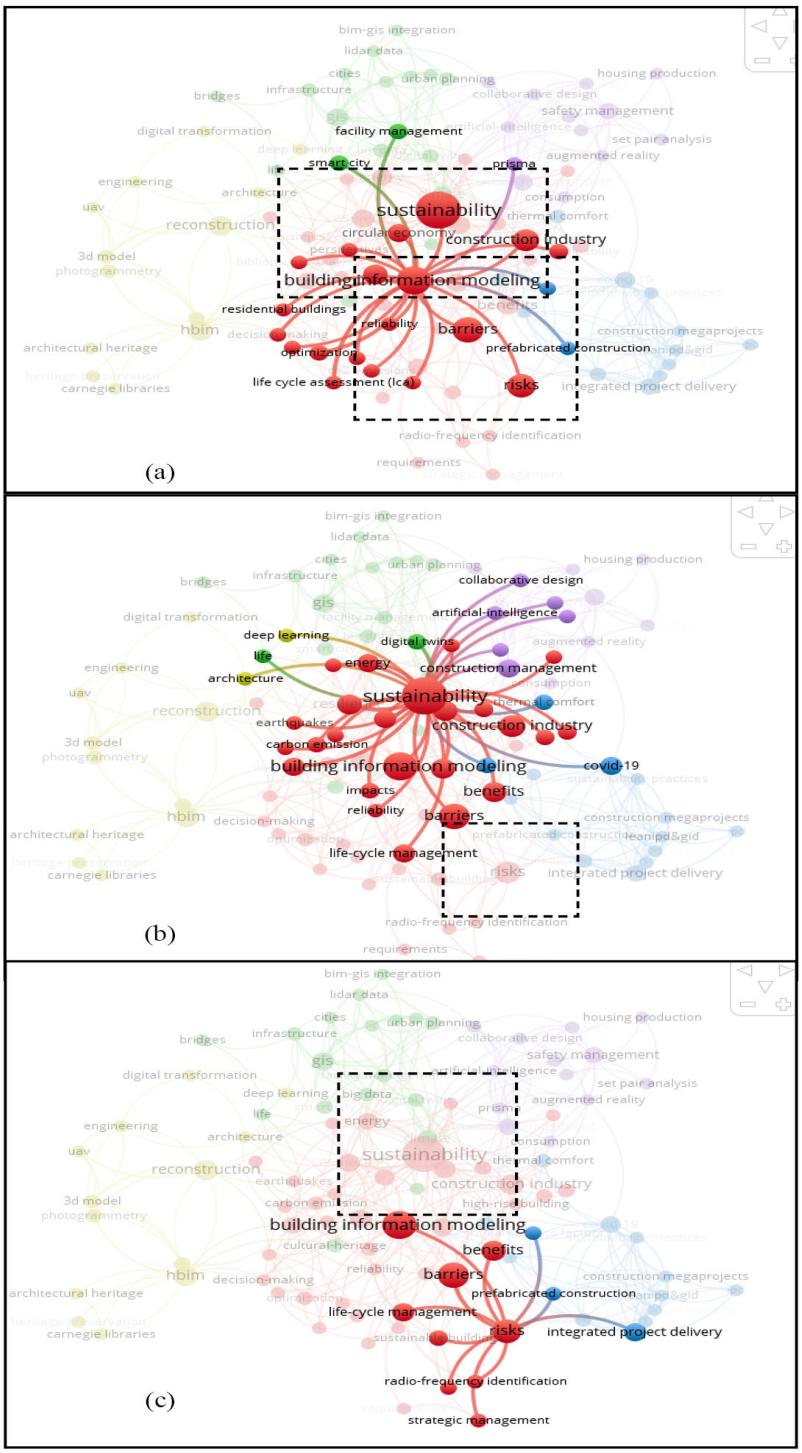


Figure 5. Network analysis for the keywords: (**a**) the green, red, blue clusters showcase strong connections; (**b**,**c**) the keyword "sustainability" and "risks" are connected indirectly by "BIM".

3.3. Analytic Results of Literature Coding

3.3.1. Research Methods

Given that BIM and BIM-related research methods are inherently linked to modeling and simulation, the modeling and simulation approaches summarized in this study exclude BIM's inherent modeling functions and instead focus on additional modeling or simulation techniques. Overall, the methods are categorized into single-method and multi-method approaches.

The analysis of research methods in sustainable building risk and disaster management reveals that a significant proportion of studies rely on literature reviews, case studies, and thematic research, primarily summarizing existing methods (Table 1). Specifically, 41 studies (30.60% of the total) employ only these methods, while over 44% of studies integrate such approaches as a foundation for further analysis. Following this, 21 studies (approximately 15%) focus on practitioner-based approaches, including interviews, surveys, and discussions, and 32 studies used a combination of multi-method applications (Table 2). This contradicts conventional expectations, as one would assume that a field centered on engineering and technology would predominantly feature technical methodologies. This suggests that technological advancements in the field have encountered resistance, leading scholars to focus on synthesizing past research and existing technologies to identify breakthrough opportunities. Furthermore, it indicates that core technologies and concepts in the field are still in development, necessitating continued research, expert discussions, and practical evaluations to determine pathways for technical breakthroughs.

In contrast, emerging research directions in BIM, such as information integration and AI-based methodologies, remain relatively underexplored, with only 7 and 5 studies, respectively, accounting for approximately 5% of the total publications. This highlights that research methods representing substantive technological breakthroughs receive comparatively little attention. Another technology-intensive category, simulation and modeling holds a significant proportion of studies; however, few of these focus on structural risk simulations, despite structural risks being one of the primary concerns in building safety. On the other hand, studies involving life cycle modeling and digital twins are relatively abundant, both of which demand high levels of technical expertise. Consequently, these areas may represent key directions for future technological advancements in the field.

Table 1. Summary of research methods and analytical techniques.

Methods Categories	Paper Coding	Counts	Tools/Softwares/Techniques
Literature review/Case study/Thematic analysis	1, 3, 7, 8, 9, 13, 26, 28, 30, 31, 32, 34, 35, 39, 43, 45, 49, 50, 52, 53, 54, 56, 57, 62, 69, 72, 73, 81, 86, 89, 92, 93, 100, 112, 116, 118, 124, 127, 128, 129, 133	41 (30.60%)	**Research Methodologies and Analytical Frameworks** - Case study analysis - Comparative safety assessment - Technology integration study - Cloud model - Knowledge mapping - Digital preservation analysis **Literature Review-Based Methods** - Literature review - Systematic literature review - Bibliometric analysis - Quantitative and qualitative bibliometric analysis - PRISMA framework (2020) - Bibliometric tools (VOSviewer 1.6.20, Citespace 6.2.R2)

Table 1. *Cont.*

Methods Categories	Paper Coding	Counts	Tools/Softwares/Techniques
Modeling/Simulation	5, 16, 18, 20, 25, 36, 37, 41, 42, 44, 51, 60, 61, 63, 64, 65, 67, 74, 84, 88, 96, 104, 108, 121	24 (17.91%)	**Building Performance and Energy Analysis** - Building energy modeling - Thermal resistance analysis - Energy simulation - Indoor climate evaluation - Building performance simulation - BIM-based parametric modeling - Sustainable interior design assessment - Energy consumption tracking **Life Cycle Modeling and Simulation** - Life cycle assessment (LCA) - Life cycle costing (LCC) - BIM-based life cycle analysis **Digital Twin and Simulation-Based Methods** - Digital twin modeling - BIM-based digital twin - Data-driven visualization - Computational fluid dynamics (CFD) - Monte Carlo simulation - Digital twin, IoT, Seismic behavior modeling **Structural and Other Risk Simulations** - Structural risk analysis - BIM-based reinforcement modeling - Structural analysis - BIM for risk analysis - BIM-based risk visualization - Shadow analysis - Stormwater management modeling - Road safety optimization - Evacuation simulation - Full-scale evacuation drill - BIM, Fire Dynamic Simulation (FDS) **Cultural Heritage and Archaeological Analysis** - HBIM - Stratigraphic analysis - Harris matrix modeling **Economic Decision-Making and Behavioral Analysis** - Probabilistic cost modeling - Evolutionary game theory - Moral hazard behavior modeling - Stakeholder incentive analysis - Economic impact analysis - Earned Value Management (EVM) - Time reduction analysis - Environmental, economic, and social risk modeling

Table 1. *Cont.*

Methods Categories	Paper Coding	Counts	Tools/Softwares/Techniques
Assessment/decision-making framework/system	6, 17, 21, 23, 24, 46, 58, 70, 76, 80, 117	11 (8.21%)	**Optimization and Decision-Making Methods** - Multi-objective optimization - Genetic algorithm (GA) - Pareto front optimization - Weighting method (Simo's procedure) - Multi-Criteria Decision-Making (MCDM) - Analytical Hierarchy Process (AHP) - Set pair analysis (SPA) - Improved Group-G1 (iG1) method - Fuzzy SWARA - Fuzzy COPRAS **Risk Assessment and Structural Performance Methods** - BIM-based risk modeling - Sensitivity analysis - Performance-Based Earthquake Engineering (PBEE) - Road Safety Audit (RSA) - BIM-based infrastructure assessment - Safety equipment selection - Thermal resilience analysis **Planning and Environmental Impact Assessment** - Environmental impact assessment - SCPM framework - Solar Envelope method - Performance-based design evaluation **Social and Corporate Responsibility Analysis** - Social Network Analysis (SNA) - BIM-IPD modeling - Corporate Social Responsibility (CSR) framework **Mixed and Systematic Approaches** - SWOT analysis - Mixed-method research - Taxonomy development - International collaboration assessment
GIS/LiDAR/Photo-grammetry	4, 14, 47, 75, 79, 102, 106, 119, 131	9 (6.72%)	**3D Data Acquisition and Modeling** - 3D laser scanning - UAV-based photogrammetry - Photogrammetry - Laser scanning - Scan-to-BIM process - 3D model reconstruction - UAV and LiDAR-based point cloud data - Hybrid Point Cloud-BIM data collection - Drone and LiDAR-based monitoring **BIM/HBIM-Based Methods** - HBIM-GIS integration - BIM-GIS integration - BIM, GIS, Smart management system

Table 1. *Cont.*

Methods Categories	Paper Coding	Counts	Tools/Softwares/Techniques
Survey/Interview	22, 48, 87, 107, 115	5 (3.73%)	**Survey-Based Methods** - Survey interviews - Online survey - Questionnaire **Interview-Based Methods** - Stakeholder interviews - Expert interviews - Semi-structured interviews **Statistical Analysis Methods** - Statistical assessment - Exploratory factor analysis - Descriptive statistical analysis
AI/Deep learning/Machine learning	2, 12, 40, 71, 85	5 (3.73%)	**Machine Learning and AI-Based Methods** - BP neural network - Bayesian Machine Learning - Deep learning (DNN) - AI forecasting - Multi-regression analysis **Digital Twin and IoT Integration** - Digital twin - IoT - Data-driven site characterization **Risk Analysis and Life cycle Assessment** - Life cycle analysis - Multi-hazard risk analysis - AI-based resilience modeling
Data integration and linkage	19, 68, 82, 110, 120, 122, 126	7 (5.22%)	**Data Integration and Standardization** - Linked data - BIM Integration - Environmental database management - Data integration framework - HBIM-based data integration - BIM-GIS merging - Geoscience data standardization **Performance and Standard Analysis** - BIM-based performance management tool - Environmental standard analysis - Knowledge-sharing framework - Software integration analysis (Revit, Navisworks, Tally, Green Building Studio) **Information Architecture** - Information system architecture **Smart Data Analytics and Geospatial Information** - EO (Earth Observation) data integration - Crowdsourced geospatial data integration - Smart device data analytics

Table 2. Summary of studies applying multi-method approaches.

Mixed-Methods Categories	Paper Coding	Counts
Literature review/Case study/Thematic analysis + Survey/Interview	15, 38, 83, 95, 97, 130	6 (4.48%)
Literature review/Case study/Thematic analysis + Assessment/decision-making framework	29, 55, 77, 78, 90, 98, 109, 114, 123, 125	10 (7.46%)
Literature review/Case study/Thematic analysis + Modeling/Simulation	59, 91	2 (1.49%)
Assessment/decision-making framework/system + Survey/Interview	27, 66, 94, 99, 105, 111, 132	7 (5.22%)
Assessment/decision-making framework/system + modeling/simulation	10, 11, 33, 101, 103, 113	6 (4.48%)
GIS/LiDAR/Photogrammetry + Simulation	134	1 (0.75%)

3.3.2. Research Themes

Based on the coding results, the current body of the literature can be categorized into 11 key research themes (Table 3). The following section summarizes the main insights and core conclusions for each category. At first glance, these research findings appear diverse and practically relevant; however, it is important to note that a substantial portion of these conclusions are derived from reviewing existing research or summarizing case studies, rather than from primary data or firsthand experimentation. For example, in the "Monitoring and Response Strategies" category—an area expected to be primarily driven by simulation and technological advancements—21 publications were identified, of which 11 were based on literature reviews or empirical case summaries, rather than on experimental measurements or computational simulations. Similarly, among the 36 studies focusing on "Construction and Design Optimization," 17 relied on literature reviews and case study synthesis, while 3 incorporated surveys and interviews. By contrast, greater technological challenges were observed in areas such as digitalization, data interoperability, and Industry 4.0. In this category, 13 studies were identified, with 8 relying on literature reviews or case analyses, 2 utilizing interviews and surveys, and only 3 engaging in practical implementation of data interaction, platform development, or IoT integration. This trend is counterintuitive, as building performance is inherently practical and should ideally be achieved through real-world applications or precise algorithmic modeling. This phenomenon underscores a critical gap between research and practice in the field, highlighting the disconnect between theoretical advancements and real-world implementation.

Table 3. Summaries of the research themes and key findings.

Categories of Research Themes	Paper Coding	Counts	Summaries of the Insights and Core Findings for Each Paper
Architectural Heritage and Culture: Sustainable Disaster and Risk Management	1, 6, 9, 14, 41, 61, 67, 68, 75, 88, 90, 133, 134	13 (9.70%)	**3D Scanning and Digital Tools** - 3D laser scanning and HBIM enhance structural analysis and sustainability. - UAV photogrammetry and 3D scanning improve heritage documentation. - Laser scanning surpasses photogrammetry in historical reconstruction. - AI and deep learning strengthen heritage disaster response.

Table 3. *Cont.*

Categories of Research Themes	Paper Coding	Counts	Summaries of the Insights and Core Findings for Each Paper
Architectural Heritage and Culture: Sustainable Disaster and Risk Management	1, 6, 9, 14, 41, 61, 67, 68, 75, 88, 90, 133, 134	13 (9.70%)	**Smart Maintenance and Sustainable Conservation** - Digital workflows enable proactive heritage preservation. - HBIM + IoT enhance conservation resilience. - Environmental standards in HBIM improve planning and sustainability. **Built Environment and Energy Efficiency** - Adaptive HVAC cuts energy use by 30% while preserving heritage integrity. - Digital tools optimize fire safety and conservation balance. **Future Research and Emerging Technologies** - Integrating non-destructive techniques, HBIM and digital twins is key to future heritage preservation. - Cloud models and ontology mapping enhance knowledge retrieval. **Sociocultural Sustainability** - BIM-IPD fosters sociocultural sustainability but needs better stakeholder integration. - HBIM and Harris matrix improve historical understanding and conservation.
Design Optimization and Construction Management Applied to Disaster Risk and Hazard Management	16, 17, 23, 27, 30, 31, 32, 33, 34, 36, 38, 39, 44, 51, 53, 57, 58, 62, 64, 65, 69, 70, 71, 73, 78, 79, 80, 81, 86, 94, 104, 107, 117, 123, 125, 128	36 (26.87%)	**BIM and Digital Twin for Risk Mitigation** - BIM improves risk management, reducing accidents, cost overruns, and reworks (4.6% time savings). - Neural network-based BIM enhances risk prediction for large projects. - Digital twin strengthens seismic resilience, life cycle management, and risk assessment. **Emerging Technologies and Collaboration** - BIM adoption needs better collaboration frameworks and tech integration. - BIM-IoT boosts efficiency but lacks industry awareness. - Hybrid Point Cloud and BIM improve accuracy and reduce delays. - Digital twin enhances underground station management. **Sustainable Construction and Environmental Impact** - Sustainable seismic design lowers environmental costs but needs policy support. - BIM-GIS minimizes shadow areas, improving road safety and sustainability. - Circular economy in bridge construction enhances material efficiency. - Integrated tech, policy and collaboration drive sustainability. **Construction Education and Industry Gaps** - Education–industry gaps require curriculum reform in technical and problem-solving skills. - A unified classification system improves global collaboration.

Table 3. *Cont.*

Categories of Research Themes	Paper Coding	Counts	Summaries of the Insights and Core Findings for Each Paper
Design Optimization and Construction Management Applied to Disaster Risk and Hazard Management	16, 17, 23, 27, 30, 31, 32, 33, 34, 36, 38, 39, 44, 51, 53, 57, 58, 62, 64, 65, 69, 70, 71, 73, 78, 79, 80, 81, 86, 94, 104, 107, 117, 123, 125, 128	36 (26.87%)	**Decision Support and Optimization** - Genetic algorithm models optimize project delivery. - Decision-support tools enhance sustainable PDM selection. - BIM adoption faces moral hazard risks, needing better incentives. - ABM reduces project delays by 15%.
Economic Benefits and Supply Chain Sustainability	3, 7, 25, 26, 48, 59, 85, 91, 99, 103, 105, 115, 132	13 (9.70%)	**Blockchain and Supply Chains** - Blockchain and Blockchain–BIM integration improve transparency, efficiency, and security in construction supply chains. - Challenges include cost overruns, slow payments, and financial instability, requiring modern solutions. **Digital Transformation and Risk Management** - AI, IoT, and blockchain enhance asset monitoring and risk management. - Monte Carlo simulation and BIM improve economic risk assessment in tunneling projects. - Data-centric geotechnics will drive digital transformation in engineering. **Barriers to Digital Adoption** - High workforce costs hinder digital twin (DT) adoption in lean construction (LC), while waste reduction is a key enabler. - Social and economic barriers (e.g., high costs, low demand) require financial incentives and BIM integration. **Sustainable and Industrialized Construction** - Systematic policies and financial mechanisms are needed for sustainable construction financing. - Enterprise collaboration is key to industrialized construction sustainability. **Supply Chain** - PPP research should focus on sustainability, innovation, and case studies. - MORDA algorithm optimizes supply chain efficiency under uncertainty, reducing delays.
Energy Sustainability	10, 18, 20, 29, 74, 76, 93	7 (5.22%)	**BIM for Energy Efficiency and Sustainability** - BIM (ISO 19650) enhances sustainability and risk management. - BIM-CFD and BIM-LCA integration improve hazard analysis, energy efficiency, and carbon footprint reduction. - BIM-Database integration enhances energy assessment accuracy across climates.

Table 3. *Cont.*

Categories of Research Themes	Paper Coding	Counts	Summaries of the Insights and Core Findings for Each Paper
Energy Sustainability	10, 18, 20, 29, 74, 76, 93	7 (5.22%)	**Performance-Based and Passive Design** - Performance-based design boosts energy efficiency but faces urban shadowing challenges. - Thermal resistance strategies cut energy consumption and emissions. - BIM-based reinforcement improves structural safety and efficiency in renovations.
Integrated Informatization and Industry 4.0	19, 24, 43, 55, 82, 87, 95, 97, 98, 111, 114, 118, 127	13 (9.70%)	**Digitalization and Smart Technologies** - Digitalization boosts sustainability and efficiency but faces adoption challenges. - Smart FM and Construction 4.0 drive sustainability but encounter cost, data, and cybersecurity risks. **BIM Integration and Data Management** - Linked data and CBIM enhance coordination and sustainability but require better data management. - BIM-based model checking improves risk management, with future focus on automation. **Adoption Barriers and Strategies** - Key barriers: high costs, lack of BIM standards, and industry resistance. - Solutions: government support, lean BIM integration, and stakeholder collaboration. **BIM-IoT and Cybersecurity** - BIM-IoT improves automation but raises cybersecurity concerns. - BIM tools enhance data integration and efficiency. **Strategic BIM Implementation** - Optimizing BIM adoption minimizes risks and maximizes cost, time, and sustainability benefits. - Success depends on collaboration, stakeholder engagement, and process optimization.
Monitoring and Response to Sustainable Risks and Disasters	2, 4, 8, 11, 15, 35, 37, 45, 50, 56, 84, 92, 100, 101, 110, 112, 116, 119, 120, 121, 129	21 (15.67%)	**BIM and Digital Twin for Urban and Infrastructure Management** - 3D BIM and LiDAR improve urban planning by visualizing exposure risks. - GIS-BIM integration enhances building health assessment with a focus on safety. - BIM-GIS-based railway risk assessment improves infrastructure resilience against natural disasters. - Satellite SAR-based mapping identifies high-risk zones, aiding sustainable urban planning. - Digital twin + BIM + cadastral maps enhance urban management, land use, and real-time monitoring.

Table 3. *Cont.*

Categories of Research Themes	Paper Coding	Counts	Summaries of the Insights and Core Findings for Each Paper
Monitoring and Response to Sustainable Risks and Disasters	2, 4, 8, 11, 15, 35, 37, 45, 50, 56, 84, 92, 100, 101, 110, 112, 116, 119, 120, 121, 129	21 (15.67%)	**BIM for Risk Management and Sustainability** - BIM enhances risk management, supporting bridge construction sustainability. - 4D BIM improves communication, scheduling, and constructability, despite software challenges. - Life cycle cost analysis evaluates trade-offs in costs, emissions, and earthquake resilience for sustainable design. - Digital twin-based sustainability audits optimize subway station energy use and risk mitigation. - Deep learning models enhance accident prediction accuracy over traditional methods. **BIM in Structural and Construction Management** - BIM integration improves structural analysis but lacks standardization. - Bridge O&M should be planned early, incorporating digital asset management and eco-friendly maintenance. - BIM adoption reduces project life cycle costs by improving planning, collaboration, and resource management. - BIM across the life cycle enhances efficiency but faces management and technological hurdles. **Adoption Challenges and Future Directions** - Digital twin adoption needs structured frameworks for effective implementation. - BIM-FM interoperability issues hinder building handover, requiring better information fidelity and process streamlining. - Structural engineers face marginalization and need to embrace technology, legal protections, and redefine roles. - Resilient building stock management needs transdisciplinary frameworks beyond sustainability alone. - Green BIM is underutilized in IEQ assessments, needing more research for better implementation. **BIM for Health and Safety** - Health impact assessment framework integrates BIM and risk evaluation to assess worker safety (HAVS risks).
Risk and Disasters management and Smart Cities, Transportation, and Infrastructure	21, 47, 52, 72, 89, 102, 122, 124, 126	9 (6.72%)	**GIS-BIM Integration for Smart Cities and Infrastructure** - GIS-BIM integration supports smart city energy planning and data-driven decision-making. - BIM-GIS integration enhances 3D visualization, real-time monitoring, and data accuracy for underground infrastructure. - Theoretical development is needed to improve GIS-BIM decision-making and sustainability applications.

Table 3. *Cont.*

Categories of Research Themes	Paper Coding	Counts	Summaries of the Insights and Core Findings for Each Paper
Risk and Disasters management and Smart Cities, Transportation, and Infrastructure	21, 47, 52, 72, 89, 102, 122, 124, 126	9 (6.72%)	**BIM for Sustainable and Resilient Infrastructure** - Geotechnical engineering integrates BIM and sustainability to reduce environmental impact and improve affordability in transport infrastructure. - Standardizing geotechnical and hydrogeological data enhances BIM for infrastructure, ensuring better underground and environmental data integration. - 4D BIM-Infra + EO data improves disaster resilience and long-term asset management. **Digital Tools for Infrastructure Resilience** - Digital asset management tools strengthen infrastructure resilience but need better integration. - Railway LIM leverages 3D digital data and AI clustering for environmental analysis.
Risk and Disaster Management in Prefabrication and Modular Construction	22, 28, 49, 63, 66, 83, 96, 106, 108, 113	10 (7.46%)	**Collaboration and Policy Support** - Builder-supplier collaboration is key to prefabrication success. - BIM adoption requires cost–risk balance, policies, and stakeholder collaboration. - China's barriers: high transport costs, regulations, and market resistance need systematic strategies. **BIM and Digital Tools** - BIM-based MiC risk management needs AI and automation. - Scan-to-BIM enhances sustainability, energy efficiency, and cost reduction. - Digital modular construction requires life cycle management integration. **Design and Efficiency** - DfMA + BIM improves sustainability, cost efficiency, and rapid modular production. - Interface management enhances sustainability and operational efficiency. **Adoption Barriers** - High costs, lack of expertise, and poor collaboration hinder BIM in modular construction. - Cost, regulations, and industry perception remain major barriers to prefabrication.
Sustainable Architectural Responses to Pandemics	12, 54, 109	3 (2.24%)	- Digital twin-based ventilation monitoring enhances safety and efficiency in pandemic scenarios. - COVID-19 disrupted civil engineering projects, but digitalization and automation support recovery. - A strategic framework improves building operations, sustainability, and disease prevention with potential software applications.

Table 3. *Cont.*

Categories of Research Themes	Paper Coding	Counts	Summaries of the Insights and Core Findings for Each Paper
Sustainable Climate Risk and Disaster Management	40, 42, 60	3 (2.24%)	**BIM and Digitalization for Climate Resilience** - BIM-based stormwater modeling enhances NbS in landscape planning. - BIM and digitalization improve railway resilience to climate hazards. **AI and Digital Twins for Infrastructure** - AI and Digital twins boost infrastructure resilience against climate risks.
Sustainable Post-Disaster Management and Response (including Reconstruction/Renovation)	5, 13, 46, 77, 130, 131	6 (4.48%)	**BIM and Digital Tools for Reconstruction** - BIM-GIS aids post-conflict reconstruction with strategic planning and collaboration. - Post-disaster resilience relies on automation, AI and digital twins. **Adoption Barriers and Risk Mitigation** - BIM adoption in refurbishment faces social, cost and stakeholder barriers. - Multi-level risk mitigation (government, organizational, project) enhances adoption. **Sustainability and Safety** - Sustainable housing must balance economic, environmental and social factors. - Energy-efficient refurbishment cuts cooling energy by 61%, aiding elderly resilience. - BIM-FDS improves evacuation strategies and fire risk reduction.

3.3.3. Summaries for the Insights and Findings

The coding of the literature in BIM applications in sustainable risk and disaster management has revealed several key thematic insights across different research areas. The key aspects are summarized below (Table 3):

(a) In architectural heritage and cultural sustainability, studies emphasize the role of cloud models and ontology mapping in improving knowledge retrieval for heritage preservation. Additionally, HBIM (Historic BIM) combined with IoT and digital twins enhances conservation resilience by providing real-time monitoring and predictive maintenance capabilities. However, a major challenge in this domain is the integration of non-destructive techniques, such as 3D laser scanning and photogrammetry, with BIM frameworks to enable precise documentation and risk assessment for heritage structures. While digitalization has improved structural analysis and sustainability assessments for heritage buildings, practical implementation remains limited, requiring stronger interdisciplinary collaboration between historians, architects, and engineers.

(b) In the realm of design optimization and construction risk management, the integration of BIM with decision-support tools like SWARA (Step-wise Weight Assessment Ratio Analysis) has shown potential in reducing construction reworks, cost overruns, and delays. AI-powered models for risk prediction and project management optimization are also gaining traction, particularly in high-risk infrastructure projects. However, despite these advancements, the adoption of BIM-GIS integration for real-time hazard assessment remains slow, largely due to data interoperability challenges and resistance

from the construction industry. Studies highlight that hybrid methodologies, such as combining BIM with neural networks and IoT sensors, can enhance proactive risk mitigation strategies. However, regulatory frameworks and industry standards need to be refined to facilitate broader adoption.

(c) The economic benefits and supply chain sustainability aspect of BIM research underscore the need for systematic policies and financial mechanisms to support sustainable construction practices. Blockchain technology has emerged as a potential solution to improve transparency, traceability, and accountability in supply chain management, particularly for prefabrication and modular construction. However, research suggests that high implementation costs and lack of industry-wide digital standards remain key barriers. Additionally, financial modeling studies indicate that integrating BIM-based life cycle costing with multi-objective optimization can significantly improve the cost-effectiveness of sustainable infrastructure projects. To enhance the economic feasibility of BIM adoption, future research should focus on incentive-driven policies and public–private partnership models.

(d) In the domain of energy sustainability, studies highlight the importance of BIM-driven energy modeling for optimizing thermal efficiency, carbon footprint reduction, and environmental impact assessments. A simplified BIM–database integration framework has been proposed to enhance energy consumption tracking and sustainability evaluations. Moreover, emerging trends suggest that BIM-enabled energy simulations combined with AI-driven predictive analytics can significantly improve energy efficiency in both new and existing buildings. However, standardized environmental data integration across different platforms remains a challenge, requiring further developments in cloud-based BIM energy assessment systems.

(e) In the integrated informatics and Industry 4.0 category, linked data technologies are seen as a crucial advancement for improving environmental data accessibility and disaster resilience. Research suggests that IoT-enabled BIM systems and real-time data monitoring can transform risk management strategies by allowing predictive maintenance and automated response mechanisms. Despite these benefits, cybersecurity concerns and data ownership issues remain key barriers to large-scale adoption. Future research must focus on developing robust data-sharing protocols, enhanced security frameworks, and standardized interoperability models to fully harness Industry 4.0 capabilities in sustainable disaster and risk management.

Overall, the review highlights significant technological advancements, research gaps, and future opportunities in BIM-driven risk and disaster management. While AI, digital twins, and IoT integration hold great promise, their practical implementation remains limited due to data interoperability, industry resistance, and high costs. Future research should emphasize multi-disciplinary collaboration, policy-driven incentives, and advanced data integration methodologies to ensure that BIM transitions from a theoretical tool to a fully operational industry standard for sustainable disaster resilience.

4. Discussion

This section will build on the above literature analysis results to identify the current challenges and future development trends in the application of BIM for sustainable building disaster and risk management research.

4.1. Identification of Research Challenges

The network analysis and coding results of this study reveal that the current research landscape in this field faces significant challenges. While many concepts and frameworks have been proposed, the integration of technologies and breakthroughs in critical areas

remains at a bottleneck stage. These challenges can be categorized into the following four key aspects:

(a) Weak Foundations: Disconnection from Traditional Civil and Structural Risk Research. One of the fundamental issues in this field is its lack of a strong foundation in traditional civil engineering, structural risk assessment, and disaster resilience studies [12,42,55]. Many studies focus heavily on "sustainability" as a conceptual framework, but fail to integrate insights from well-established structural and geotechnical engineering disciplines [56–58]. As a result, research on sustainable risk and disaster management in buildings often lacks the rigorous engineering-based methodologies needed for robust assessments [59], leaving sustainability-driven studies theoretically rich but technically ungrounded. This disconnect from core engineering principles limits the practical applicability of sustainability research in real-world building performance and risk mitigation.

(b) Stalled Technological Advancements: Challenges in AI, Digital Twins, and Architectural Information Infrastructure. Despite the growing interest in AI-driven methods, digital twins, and the development of architectural information infrastructure, most research in these areas is still in an exploratory phase [60,61], with limited success in actual implementation. Studies often focus on how these technologies could be integrated, but concrete solutions for their seamless adoption and interoperability remain underdeveloped. For instance, AI applications in risk prediction, real-time hazard monitoring, and automated disaster response are still in their infancy [62]. Similarly, digital twin technologies have been widely discussed but are rarely fully operationalized within built environments [63], often lacking real-time data integration and predictive capabilities. The development of architectural information infrastructures—which should serve as the backbone for effective data interoperability [64], real-time risk monitoring [12], and multi-stakeholder collaboration—also remains fragmented [65]. The field, therefore, continues to struggle with moving from conceptual research to scalable technological deployment.

(c) Lack of Practical Implementation: Research Stagnates at the Conceptual Stage. Although many studies incorporate case analyses, a closer examination of these case studies reveals that sustainability-driven risk and disaster management strategies remain largely conceptual rather than practically implemented. Many studies describe theoretical response strategies and sustainability measures [66,67], yet few demonstrate tested methodologies, field experiments, or validated models that can be readily adopted in real-world scenarios. This lack of practical application suggests that the field has not yet bridged the gap between research and implementation, leading to a scenario where proposed frameworks are rich in theory but lack demonstrable effectiveness. For sustainable risk and disaster management to become actionable, future research must prioritize real-world testing, empirical validation, and industry collaboration to ensure feasibility and scalability.

(d) Weak Linkages Between Core Domains: Risk and Disaster Management Remain Loosely Connected to Sustainability. Risk management and disaster resilience studies have traditionally operated as distinct fields [68], and their direct connection to sustainability remains weak. In most studies, the link between sustainability and risk/disaster management is not inherently established, but rather created artificially through BIM or BIM-based technologies. This suggests that BIM serves as a bridge, rather than risk management and sustainability being naturally integrated concepts. The field lacks a holistic framework that seamlessly ties risk, disaster resilience, and sustainability together, leading to fragmented research efforts rather than a unified approach. Strengthening the intrinsic connections between these domains—beyond

relying solely on BIM—will be critical for advancing research and ensuring that sustainability is proactively incorporated into risk and disaster management strategies.

4.2. Future Research Directions

Based on the summary of the existing literature and the identification of current research gaps, this study identifies the following key future research directions and trends in the field:

(a) Achieving Industry 4.0 for Data and System Interoperability: One of the most critical advancements needed in BIM-based sustainable risk and disaster management is the full realization of Industry 4.0 principles [69], which emphasize integration, digitalization, and seamless interoperability [70]. Future research should focus on developing integrated frameworks that enable different devices (e.g., sensors, probes, monitoring equipment), diverse data formats, and multiple platforms to interact effectively. Achieving this level of interoperability will require advancements in cloud computing, real-time data sharing, and standardized communication protocols, ensuring that traditional civil engineering technologies can be seamlessly connected with modern digital tools. Additionally, this development must facilitate the interaction between supply chains, the Internet of Things (IoT), and digital twins, creating a more automated, responsive, and interconnected built environment. By breaking down data silos and enabling cross-disciplinary integration, risk management and disaster resilience strategies can become more adaptive, real-time, and predictive. Achieving data and system interoperability based on Industry 4.0 principles will allow construction and disaster management practitioners to implement real-time monitoring, predictive maintenance, and adaptive disaster response more efficiently. It will facilitate cross-platform communication, enhance collaboration across stakeholders, and enable integrated decision-making processes, thus improving the responsiveness and resilience of the built environment against evolving risks.

(b) Advancing AI-Based Technologies for Intelligent Systems: As smart technologies continue to evolve, the integration of AI-driven methods into BIM-based risk and disaster management will be a key breakthrough area. AI's ability to process large-scale data, identify patterns, and optimize decision-making makes it particularly suitable for disaster prevention, urban resilience, and emergency response planning. Future research should focus on developing AI-powered solutions for intelligent cities, smart transportation systems, and multi-objective optimization in construction, design, and management. AI will enable automated risk assessment, predictive modeling, and adaptive response strategies, reducing manual intervention and enhancing efficiency. Furthermore, deep learning and reinforcement learning models could enhance disaster forecasting, resource allocation, and infrastructure resilience, making risk management more proactive rather than reactive. Integrating AI-driven technologies into risk and disaster management will significantly enhance predictive capabilities, automate hazard detection, and optimize resource allocation. For practitioners, this means more accurate early warning systems, reduced operational costs, and improved adaptive management strategies, ultimately leading to safer, smarter, and more resilient infrastructures.

(c) Multi-Objective Optimization for Comprehensive Sustainability: While traditional disaster management focuses on risk mitigation and structural resilience, future research must adopt a multi-objective optimization approach that balances disaster risk reduction with ecological, economic, and energy sustainability. This means that disaster preparedness, hazard buffering, and emergency response strategies should be integrated with climate resilience, energy efficiency, and cost-effectiveness considera-

tions. For instance, disaster-resistant buildings should not only be structurally sound but also designed with sustainable materials, optimized energy consumption, and minimized environmental impact. Additionally, economic factors such as long-term maintenance costs, material life cycle performance, and sustainable financing models must be incorporated into decision-making frameworks. The transition towards a multi-objective approach will require advanced computational models, AI-driven simulations, and digital twin-based scenario planning, ensuring that sustainability and disaster resilience are holistically optimized rather than treated as separate concerns. Applying multi-objective optimization frameworks will enable decision-makers to simultaneously address disaster risk reduction, environmental sustainability, and economic viability. In practice, this integrated approach can guide the design of disaster-resilient and energy-efficient buildings, inform sustainable urban planning policies, and support more balanced, long-term investment strategies in construction and infrastructure development.

In a word, to advance BIM-based sustainable building disaster and risk management, future research must address interoperability challenges through Industry 4.0 principles, enhance AI-driven intelligence, and adopt multi-objective optimization for sustainability. These directions will ensure that the field moves beyond theoretical discussions and fragmented implementations, driving real-world impact, technological innovation, and long-term resilience in the built environment.

5. Conclusions

This study systematically reviews the application of BIM in sustainable risk and disaster management, identifying five major research clusters: sustainable construction and life cycle assessment, performance evaluation and implementation, technology integration and digital innovation, HBIM and reconstruction, and project management and technology adoption. Through network and coding analysis, the study finds that BIM serves as a bridge between sustainability and disaster risk management, as these two fields remain weakly interconnected. Additionally, literature reviews dominate existing research, with over 45% of studies relying on theoretical summaries rather than empirical testing or technological advancements. While AI, digital twins, and information integration hold great potential, practical implementations remain limited, highlighting a gap between theoretical discussions and real-world applications.

To advance this field, three key research trends are identified. First, achieving interoperability through Industry 4.0 is essential for integrating BIM with IoT, cloud computing, and real-time monitoring, enabling seamless data exchange. Second, AI-driven intelligent risk management must be further explored, particularly in areas such as hazard prediction, automated risk assessments, and AI-powered digital twins for real-time disaster response. Third, multi-objective optimization should be adopted to balance structural resilience, environmental sustainability, and cost efficiency, ensuring a comprehensive approach to disaster preparedness and response.

This study makes several contributions to the field. It provides a comprehensive knowledge mapping of BIM applications in sustainable disaster risk management, spanning a decade of research. By identifying methodological and thematic gaps, it highlights the over-reliance on literature reviews and the limited real-world adoption of AI and digital twins. Finally, the study proposes a strategic research roadmap, emphasizing interoperability, AI integration, and multi-objective sustainability optimization, which can guide future research and technological advancements. These insights will help transition BIM from a conceptual framework to an industry-standard tool for enhancing disaster resilience and sustainability in the built environment.

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