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Review

BIM Applications in Transportation Infrastructure: A Bibliometric and Systematic Literature Review

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Abstract: This study presents a comprehensive bibliometric analysis combined with a Systematic Literature Review (SLR) to examine the global research landscape of Building Information Modeling (BIM) applications in transportation infrastructure. The motivation of this study arises from the increasing complexity of modern infrastructure systems, including railways, tunnels, bridges, roads, and airports, which require advanced digital solutions to address challenges related to interoperability, lifecycle management, and data integration. A total of 1,615 peer-reviewed articles published between 2010 and July 2025 were retrieved from the Scopus database. Bibliometric techniques, including keyword co-occurrence and citation analysis, were applied using Visualization of Similarities viewer (VOSviewer), followed by an in-depth systematic review of the most influential publications. The results indicate a substantial increase in research activity after 2018, with railway infrastructure emerging as a major application domain. Five principal thematic clusters are identified: Geographic Information Systems (GIS) integration, Digital Twins (DT), tunnel and bridge engineering, lifecycle sustainability, and smart monitoring technologies. Keyword evolution analysis further reveals a transition from design-oriented studies prior to 2020 toward asset management and digital intelligence after 2022. The study also identifies leading journals and key technologies shaping current research trends, while recent publications in 2025 demonstrate increasing attention to immersive DT, robotic manufacturing, and multi-criteria decision-making frameworks. This study contributes by systematically mapping the development of BIM knowledge in transportation infrastructure and identifying underexplored areas, particularly in operation and maintenance applications and regional disparities in research output. Limitations include the reliance on Scopus-indexed, English-language publications and the use of citation-based selection criteria, which may introduce bias toward older, highly cited studies. Despite these limitations, the findings provide valuable insights for researchers, practitioners, and policymakers seeking to align future efforts with ongoing digital transformation in transportation infrastructure.

***Keywords*:** building information modeling, geographic information systems, transportation infrastructure, bibliometric analysis, systematic literature review, Visualization of Similarities viewer (VOSviewer), digital twin

1. Introduction

The digitalization of transportation infrastructure has become a strategic priority for enhancing efficiency, sustainability, and resilience in the built environment. Increasing demands for smart and low-carbon infrastructure systems have accelerated the adoption of advanced digital technologies, including Building Information Modeling (BIM),

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Geographic Information Systems (GIS), Digital Twins (DT), and the Internet of Things (IoT) [1]-[3]. These technologies facilitate integrated data environments, enabling improved decision-making across the entire lifecycle of infrastructure assets.

Transportation infrastructure-such as roads, bridges, tunnels, railways, and airports-is inherently complex, characterized by long service lifecycles, extensive spatial data requirements, and the involvement of multiple stakeholders. Conventional approaches to design, construction, and asset management are often constrained by fragmented data environments, limited interoperability, and reactive maintenance practices [4]. In this context, BIM has emerged as a key enabler of lifecycle-oriented infrastructure management by providing a unified digital platform that supports data integration, multidisciplinary coordination, and information continuity from design to operation [5].

While early applications of BIM primarily focused on 3D design coordination, clash detection, and 4D/5D simulations in vertical building projects [6], recent developments have expanded its applicability to linear and geographically distributed infrastructure systems, where integration with GIS and other digital technologies is essential [7], [8]. Existing studies have demonstrated the effectiveness of BIM across various transportation domains, including railways [9]-[12], tunnels [13], bridges [14], [15], and airports [16]. In addition, the convergence of BIM with DT, cloud computing, robotics, and Machine Learning (ML) has further extended its role toward Operation and Maintenance (O&M), enabling predictive strategies and more intelligent asset management [17]-[20].

Despite these advancements, several challenges remain. The integration of BIM with geospatial and sensor-based systems continues to be fragmented, particularly in Low-and Middle-Income Countries (LMICs) [21]. Moreover, BIM adoption across the full infrastructure lifecycle-particularly beyond the design and construction phases-remains limited in practice [22]. Many existing studies are case-specific and lack scalable frameworks or standardized approaches, thereby constraining interoperability and broader implementation [23]. Furthermore, the literature lacks a systematic consolidation of thematic and temporal trends, making it difficult to trace the evolution of BIM research and to identify emerging research directions.

Given the increasing complexity of transportation infrastructure systems and the ongoing shift toward digital transformation, a comprehensive synthesis of how BIM and related technologies are applied across the infrastructure lifecycle is required. Although BIM has been widely recognized for its contributions to design and construction processes, its application in long-term operation, maintenance, and infrastructure intelligence remains insufficiently explored in the academic literature [24]-[26].

To address these gaps, this study employs a combined bibliometric analysis and Systematic Literature Review (SLR) to map the scientific landscape of BIM applications in transportation infrastructure. By analyzing 1,615 Scopus-indexed publications published between 2010 and July 2025, the study examines the evolution of research in this domain, highlights the convergence of BIM with emerging technologies such as IoT and ML, and identifies key research gaps that warrant further investigation.

This study pursues four main objectives: (i) to map the evolution of BIM research in transportation infrastructure across key domains, including railways, tunnels, roads, bridges, and airports; (ii) to identify dominant technological themes, emerging trends, and temporal shifts, particularly the transition from 3D modeling to DT and smart sensing; (iii) to examine the citation landscape, with a focus on identifying the most influential authors, institutions, and journals; and (iv) to propose strategic directions and policy recommendations to support the advancement of BIM adoption, particularly in underrepresented regions.

The scope of this study encompasses: (i) Scopus-indexed, English-language journal articles published between 2010 and July 2025; (ii) BIM applications across the full infrastructure lifecycle, including design, construction, O&M, and decommissioning; and (iii) the integration of BIM with enabling technologies such as GIS, DT, IoT, robotics, and Artificial Intelligence (AI).

This study provides an up-to-date synthesis of BIM research in transportation infrastructure by integrating bibliometric mapping with a SLR. It traces the thematic evolution of BIM applications across three major stages-foundational applications, transitional expansion, and emerging innovations-while identifying underexplored yet high-potential areas, particularly in O&M, interoperability, and lifecycle-oriented digital infrastructure. In addition, the study presents a consolidated synthesis of influential publications, offering a comprehensive reference for researchers, practitioners, and policymakers.

To guide the analysis, the following Research Questions (RQs) are addressed:

RQ1: What are the dominant thematic clusters in the literature on BIM applications in transportation infrastructure?

RQ2: How have research themes evolved over time, particularly in relation to digital transformation technologies such as DT, GIS, and IoT?

RQ3: Which journals and institutions are the most active contributors to this research domain?

RQ4: Which publications have had the greatest academic impact, and what key topics do they emphasize?

RQ5: What research gaps remain, and what future directions can be proposed to advance BIM-enabled transportation infrastructure?

2. Background

This section outlines the core digital concepts underpinning BIM applications in transportation infrastructure, with particular emphasis on their roles in lifecycle management, interoperability, and system-level integration. Rather than presenting isolated definitions, the focus is placed on how these technologies interact within a unified digital ecosystem to support data-driven infrastructure management.

BIM serves as the central digital backbone for managing infrastructure assets across design, construction, and operation phases. In transportation systems-characterized by linear networks such as railways and highways, as well as complex nodes including bridges, tunnels, and airports-BIM enables multidisciplinary coordination, structured data management, and lifecycle information continuity [26]. Compared to its early applications in vertical construction, BIM in transportation increasingly emphasizes scalability, interoperability, and integration with external data sources to support long-term asset performance and system-level decision-making [27]-[29].

GIS complements BIM by providing spatial context and georeferencing capabilities essential for large-scale and geographically distributed infrastructure systems. The integration of BIM and GIS enables corridor-level planning, route optimization, environmental analysis, and network-scale visualization. This synergy is particularly critical in transportation infrastructure, where assets are inherently spatial and interconnected, making BIM-GIS integration a foundational component of digital infrastructure systems [30]-[32].

IoT technologies extend BIM capabilities by enabling continuous, real-time data acquisition from distributed sensors monitoring structural, environmental, and operational conditions. These data streams provide dynamic inputs for infrastructure monitoring, including vibration, deformation, temperature, and traffic-related parameters. When integrated with BIM, IoT facilitates real-time visualization, anomaly detection, and condition-based maintenance, particularly during the O&M phase [33].

Building upon these integrations, DT represent an advanced evolution of BIM toward dynamic, data-driven infrastructure systems. By synchronizing BIM models with IoT data, historical records, and analytical models, DT enable continuous feedback loops between physical assets and their digital representations. This supports predictive maintenance, performance optimization, and scenario-based decision-making across the asset lifecycle. DT applications are increasingly prominent in transportation domains such as railways, bridges, and tunnels, where real-time monitoring and system reliability are critical [34]-[36].

The Level of Development (LOD) concept underpins the reliability and granularity of BIM information across different lifecycle stages. While LOD 300-350 is commonly applied during detailed design and construction, higher levels (LOD 400-500) are essential for asset handover, operation, and DT implementation. Extending LOD definitions beyond construction has become increasingly important for supporting inspection, maintenance, and lifecycle data integration in infrastructure systems [37].

In addition, emerging technologies such as blockchain have been explored to enhance data integrity, traceability, and secure information exchange within BIM-enabled ecosystems. Although current applications remain relatively limited in transportation infrastructure, blockchain shows potential in supporting trustworthy data management, particularly in multi-stakeholder environments and lifecycle-oriented digital workflows [37], [38]. Together, these technologies form an integrated digital ecosystem in which BIM acts as the central data model, GIS provides spatial context, IoT supplies real-time data, and DT enables intelligent decision-making across the infrastructure lifecycle.

Figure 1 illustrates the conceptual integration framework of BIM, GIS, IoT, and DT for transportation infrastructure systems. At the physical layer, infrastructure assets such as roads, bridges, tunnels, and railways generate real-time operational data through embedded IoT sensors. These data streams are continuously transmitted to the digital environment, where BIM serves as the central information model, integrating geometric, semantic, and lifecycle data.

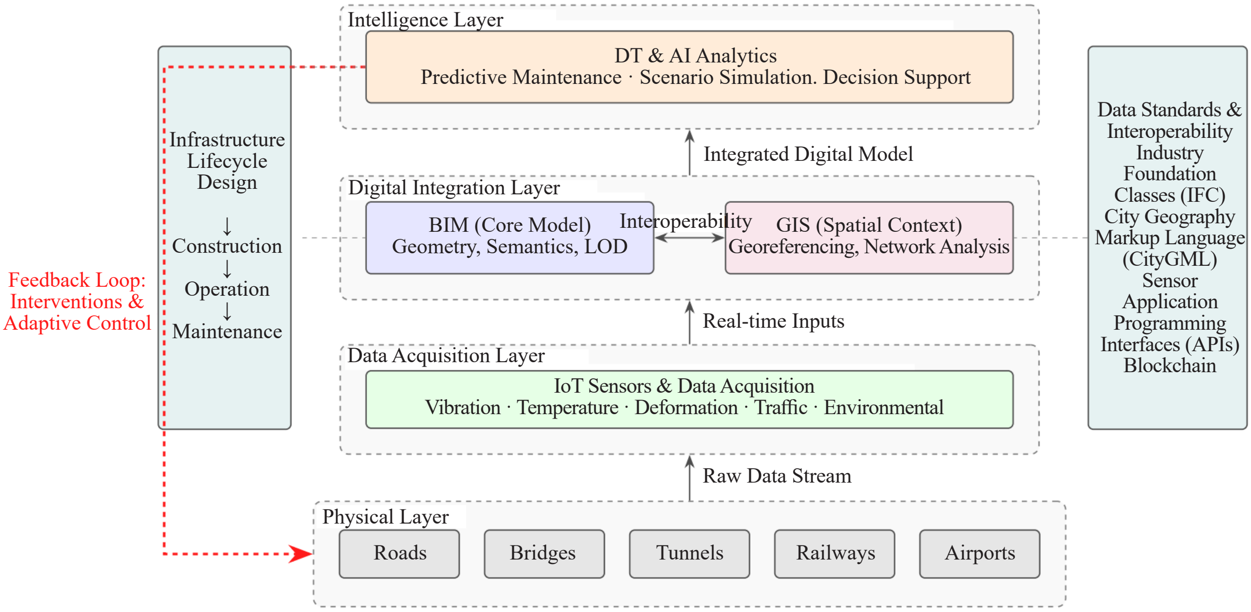

Figure 1. Conceptual framework of BIM-GIS-IoT-DT integration for lifecycle-oriented transportation infrastructure management

GIS provides spatial context by enabling georeferencing, large-scale visualization, and network-level analysis, particularly for geographically distributed infrastructure systems. The integration of BIM and GIS forms a unified digital representation that supports both asset-level and system-level understanding.

Building upon this integrated data environment, DT act as dynamic and intelligent replicas of physical assets by synchronizing real-time sensor data, historical records, and predictive analytics. This enables continuous monitoring, anomaly detection, and scenario-based decision-making. A bidirectional feedback loop between the physical and digital layers supports adaptive and data-driven infrastructure management across the entire lifecycle, from design and construction to O&M.

3. Materials and methods

This study adopts a hybrid methodological framework that integrates bibliometric analysis with a SLR to investigate the evolution, structure, and knowledge gaps in BIM applications for transportation infrastructure. This combined approach enables both macro-level identification of research trends and micro-level interpretation of thematic developments, thereby ensuring a comprehensive and methodologically robust analysis.

3.1 *Bibliometric analysis*

Bibliometric analysis involves the quantitative assessment of scientific literature using statistical and network-based techniques to reveal patterns, collaboration structures, and thematic concentrations within a research domain [39]. This approach is particularly effective for mapping knowledge evolution, identifying influential publications, and detecting emerging research directions in rapidly evolving fields such as BIM and digital infrastructure [40].

Data were retrieved from the Scopus database, selected for its extensive coverage of peer-reviewed literature in engineering, construction, and technology. The following search query was applied to the Title, Abstract, and Keywords fields:

TITLE-ABS-KEY((“BIM” OR “Building Information Modeling” OR “Building Information Modelling”);
AND (“transportation infrastructure” OR “road” OR “bridge” OR “highway” OR “railway” OR “rail”;
OR “metro" OR “underground” OR “subway” OR “airport” OR “tunnel” OR “infrastructure project”));
AND (PUBYEAR > 2009) AND (LIMIT-TO(DOCTYPE, “ar”)) AND (LIMIT-TO(LANGUAGE, “English”)).

The search was conducted on 24 July 2025, yielding 1,615 records. Only peer-reviewed journal articles and reviews were included, while non-English publications, non-peer-reviewed documents, and irrelevant domains (e.g., biomedical uses of “BIM”) were excluded (Table 1). The dataset was exported in Comma-Separated Values (CSV) format for subsequent analysis.

Table 1. Criteria for the bibliometric dataset

Criteria	Inclusion	Exclusion
Publication period	2010-July 2025	Before 2010 or after July 2025
Language	English	Non-English
Document type	Peer-reviewed journal articles & reviews	Editorials, notes, retracted works
Research focus	BIM applications in transportation infrastructure	Non-relevant domains (e.g., biomedical “BIM”)

The selection of the 2010-July 2025 timeframe was based on both methodological and domain-specific considerations. Prior to 2010, BIM-related research was largely confined to vertical building applications, with limited and fragmented studies in transportation infrastructure. From 2010 onward, BIM adoption in infrastructure domains-particularly railways, tunnels, bridges, and highways-accelerated significantly, driven by advancements in digital design technologies, the introduction of national BIM mandates, and increasing infrastructure complexity. Accordingly, the selected timeframe captures the period of rapid growth, technological convergence, and methodological maturation in this field.

The resulting dataset of 1,615 publications is considered representative of the active development phase of BIM-enabled transportation infrastructure research. The consistent increase in annual publication output, together with the diversity of infrastructure types, technologies, and lifecycle stages covered, indicates a sufficiently comprehensive and robust dataset for both bibliometric and systematic analyses.

To ensure comprehensive coverage, the search query was iteratively refined through multiple trial searches. The final query incorporates both general BIM-related terms and a broad set of transportation-specific keywords, representing both linear assets (e.g., roads, railways, tunnels) and node-based infrastructure (e.g., bridges, airports, metro systems). This iterative refinement process minimized the omission of relevant studies while excluding non-relevant domains.

Following data retrieval, duplicate records were removed, and keywords were standardized to ensure consistency. For example, variations such as “building information modelling”, “BIM technology”, and “building information model” were consolidated under “BIM”, while terms such as “bridge engineering” and “digital twins” were normalized to “bridges” and “digital twin”, respectively.

Bibliometric analysis was conducted using multiple tools and techniques. Co-citation analysis, bibliographic coupling, keyword co-occurrence, and citation analysis of the top 20 most cited publications were employed as primary indicators. Visualization of Similarities viewer (VOSviewer) (v1.6.18) was used for co-authorship analysis, keyword co-occurrence mapping, and citation clustering, applying full counting and association strength normalization [41]. CiteSpace (v6.2) was utilized to detect citation bursts and emerging research clusters [42]. Biblioshiny (Bibliometrix R-package, v4.2.2) supported trend analysis and network visualization, while NVivo 14 was used to code qualitative themes during the SLR stage [43].

3.2 *Systematic literature review*

To complement the macro-level insights derived from bibliometric analysis, a SLR was conducted following the

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [44]. An initial set of 1,615 Scopus-indexed documents was retrieved, after which titles, abstracts, and keywords were screened to assess relevance.

A final sample of 20 highly cited publications was selected for in-depth analysis. This sample size reflects a balance between the depth of qualitative synthesis and representativeness, consistent with prior hybrid bibliometric-SLR studies in construction informatics. Eligibility criteria required that selected studies explicitly apply BIM to transportation infrastructure (e.g., railways, bridges, tunnels, roads, or airports), incorporate related digital technologies such as DT, GIS, or IoT, and address at least one stage of the infrastructure lifecycle (design, construction, or O&M).

Each selected article was subsequently reviewed in full text to extract key information, including research objectives, methodological approaches, infrastructure type, lifecycle phase, and reported contributions, limitations, and future research directions.

4. Results and discussion

4.1 *Publication volume and trends*

Figure 2 presents the annual publication output on BIM applications in transportation infrastructure from 2010 to July 2025, revealing a clear and sustained upward trend over time. Overall, the trajectory reflects the progressive development of the research field, transitioning from an initial exploratory phase to a period of rapid expansion and consolidation.

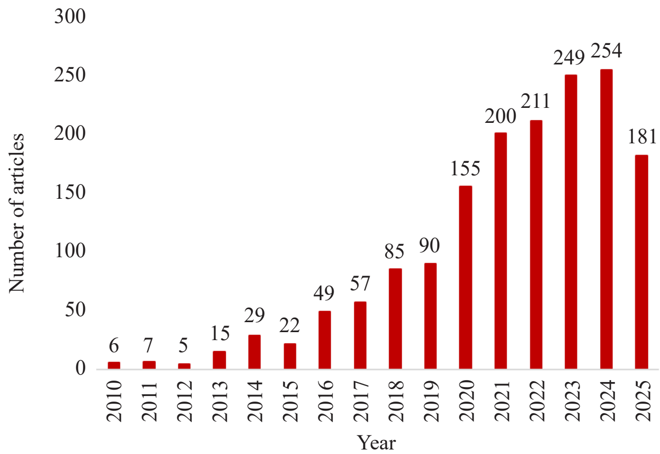

Figure 2. Annual publication output

During the early stage (2010-2013), publication output remained relatively low, with fewer than 16 articles per year. This period represents the initial exploration of BIM applications in transportation infrastructure, when research activity was limited, and the topic had not yet gained widespread academic attention.

A phase of emerging growth is observed between 2014 and 2017, during which the number of publications increased steadily from 29 in 2014 to 57 in 2017. This upward trajectory indicates increasing research interest and a gradual expansion of BIM-related studies within the transportation infrastructure domain.

The period from 2018 to 2022 is characterized by rapid expansion, with publication output rising significantly from 85 articles in 2018 to 155 in 2020 and reaching 211 in 2022. This acceleration reflects the broader diffusion of BIM research, likely influenced by global digitalization trends, the growing emphasis on data-driven infrastructure management, and the increasing availability of advanced computational and sensing technologies.

The upward trend continued into 2023 and 2024, with the number of publications reaching a peak of 254 articles in 2024. This peak suggests a high level of research activity and indicates that BIM has become an established topic within transportation infrastructure research.

As of July 2025, 181 publications have already been recorded. If this trajectory continues, the total publication output for 2025 is expected to be comparable to that of 2024, indicating sustained research momentum.

In summary, the observed publication trend reflects a clear shift from limited early-stage exploration to widespread research activity, aligned with broader developments in digital transformation, integrated data environments, and lifecycle-oriented infrastructure management.

4.2 *Leading journals analysis*

Figure 3 presents the top 10 journals with the highest number of publications related to BIM applications in transportation infrastructure. The distribution of publications across these journals provides insight into the primary dissemination channels and disciplinary orientation of research in this field.

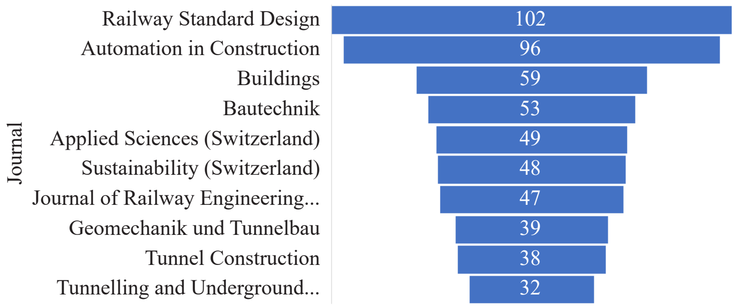

Figure 3. Top 10 journals with the highest number of publications on BIM applications in transportation infrastructure

Among the identified journals, Railway Standard Design (102 publications) and Automation in Construction (96 publications) exhibit the highest publication output, indicating their prominent roles as key publication venues. The strong representation of these journals reflects the technical and application-oriented nature of BIM research in transportation infrastructure, particularly within construction engineering and infrastructure design contexts. The prominence of journals such as Railway Standard Design suggests a substantial concentration of research on railway-related infrastructure within the broader BIM literature. This pattern indicates that railway systems constitute a major application domain in BIM-related transportation research, consistent with the complexity and data-intensive nature of such infrastructure systems.

Other journals, including Buildings, Bautechnik, and Applied Sciences (Switzerland), also contribute a significant number of publications. The presence of these journals highlights the interdisciplinary nature of BIM research, spanning construction engineering, applied sciences, and infrastructure management. In addition, the distribution of publications across multiple journals indicates that research in this domain is not confined to a single outlet but is instead disseminated across a diverse range of academic platforms. This diversity reflects the wide applicability of BIM and its relevance to multiple aspects of transportation infrastructure, including planning, design, construction, and asset management.

Overall, the journal distribution demonstrates that BIM applications in transportation infrastructure represent an active and interdisciplinary research domain, supported by a range of well-established journals in construction, engineering, and applied technology fields.

4.3 *Keyword co-occurrence analysis*

A keyword co-occurrence analysis was conducted to examine the thematic structure of BIM applications in transportation infrastructure. This method identifies relationships among frequently occurring keywords and groups them into clusters, thereby revealing dominant research themes and their interconnections. The results are presented in Figure 4, where node size represents keyword frequency and color denotes cluster membership. The co-occurrence network reveals five major thematic clusters, each corresponding to a distinct research focus within the field:

• The first cluster (blue) is associated with project management and BIM-GIS integration, including keywords such as project management, GIS, Industry Foundation Classes (IFC), construction, and railway engineering. This cluster reflects research emphasizing data interoperability, geospatial integration, and coordinated planning processes. The presence of GIS-related terms indicates the importance of spatial data in managing geographically distributed infrastructure systems and supports the integration of BIM with broader geospatial frameworks.

• The second cluster (red) focuses on bridge engineering and DT applications, with keywords including bridges, railway bridges, structural health monitoring, DT, IoT, and predictive maintenance. This cluster highlights studies focused on digital representation and lifecycle management of bridge assets. It demonstrates how BIM is applied to enhance asset reliability, inspection processes, and maintenance planning.

• The third cluster (green) represents tunnel and subsurface engineering, encompassing keywords such as tunnelling, railway tunnels, engineering geology, mechanized tunneling, numerical simulation, and construction. This cluster highlights research focused on modeling and managing underground structures, where BIM is integrated with simulation tools and geotechnical analysis.

• The fourth cluster (purple) relates to visualization and interoperability, including keywords such as visualization, interoperability, augmented reality, and parametric modeling. This cluster captures research aimed at improving model usability, data exchange, and user interaction across different platforms, highlighting ongoing efforts to enhance the accessibility and integration of BIM environments.

• The fifth cluster (yellow) is associated with lifecycle management and sustainability, featuring keywords such as infrastructure, asset management, sustainability, digitalization, and life cycle. This cluster reflects a growing emphasis on the use of BIM to support long-term infrastructure performance, environmental assessment, and lifecycle-oriented decision-making.

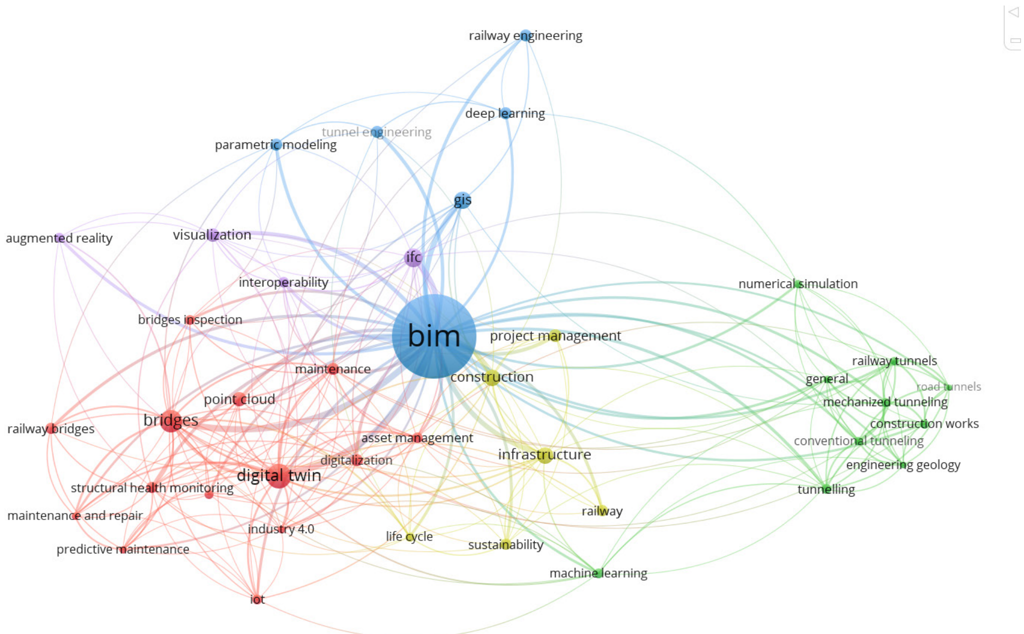

Figure 4. Keyword co-occurrence map by thematic clusters

Beyond the descriptive clustering results, the observed thematic structure reflects several underlying drivers shaping BIM research in transportation infrastructure. The strong presence of railway-related keywords across multiple clusters is closely associated with the scale, complexity, and safety-critical nature of rail systems, which require high levels of design coordination, lifecycle integration, and digital monitoring. Compared with road infrastructure, railway projects often involve dense urban environments, underground construction, and strict operational constraints, making them particularly suitable for BIM-GIS integration and DT applications.

The prominence of interoperability-and visualization-related keywords further reflects persistent technical challenges in integrating heterogeneous data sources across design, construction, and operation phases. As transportation assets are spatially distributed and managed by multiple stakeholders, research increasingly focuses on addressing data exchange, semantic alignment, and platform integration issues. These factors contribute to the emergence of clusters centered on GIS integration, DT, and lifecycle management, indicating a shift from isolated modeling processes toward integrated digital ecosystems.

Notably, Figure 4 shows that four out of the five identified thematic clusters include railway-related BIM applications. This strong presence highlights the growing importance of BIM in both the construction and operation of railway infrastructure. These findings suggest that countries, particularly those in the early stages of developing urban rail and high-speed rail systems, may benefit from adopting BIM from the initial planning stage through to full lifecycle operation. Early integration of BIM can provide a strategic foundation for improving efficiency, coordination, and asset management throughout the project lifecycle.

Overall, the keyword co-occurrence analysis demonstrates the interdisciplinary and evolving nature of BIM research in transportation infrastructure, with a strong emphasis on digital integration, asset performance, and long-term sustainability.

4.4 *Thematic evolution by time*

Figure 5 and Table 2 illustrate the co-occurrence of keywords based on their average year of appearance, using a color gradient from blue (earlier topics, ~2020) to yellow (more recent topics, ~2023). This temporal visualization reveals the evolving focus of research on BIM applications in transportation infrastructure. By examining the distribution and progression of keywords over time, distinct thematic transitions can be identified, reflecting both technological development and shifting research priorities in the field. The keyword distribution can be categorized into three main thematic phases:

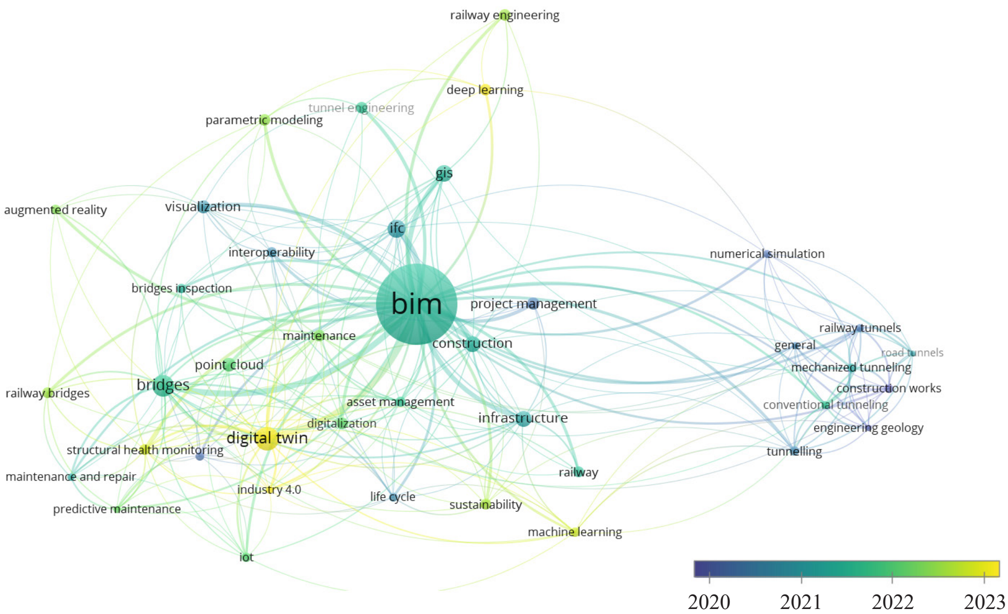

Figure 5. Keyword co-occurrence by average year of appearance

• Established foundations (Before 2021-Blue nodes): These keywords represent core BIM concepts and traditional applications that form the basis of early research, particularly in design, modeling, and project coordination. Key terms include BIM, construction, GIS, project management, interoperability, tunnel engineering, and numerical simulation.

These terms are closely associated with studies on BIM adoption in tunnels, bridges, and road design, emphasizing foundational practices in design coordination and modeling efficiency.

• Transitional expansion (2021-2022-Greenish nodes): These keywords reflect an expanding interest in the potential of BIM to support sustainability, asset lifecycle management, and operational efficiency. Representative terms include infrastructure, railway, asset management, bridges, sustainability, lifecycle, maintenance, structural health monitoring, and railway bridges. This phase highlights the progressive extension of BIM applications into O&M, particularly in rail and bridge infrastructure.

• Emerging innovations (2022-2023-Yellow nodes): More recent research emphasizes digital intelligence and automation, marking a transition toward smart infrastructure and real-time management. Key terms include DT, IoT, Industry 4.0, predictive maintenance, ML, point cloud, and augmented reality. These topics indicate a shift toward intelligent BIM ecosystems enabled by data analytics, AI, and immersive technologies.

The observed temporal transition in BIM research reflects broader technological and institutional developments in transportation infrastructure. The transitional phase around 2021-2022 corresponds to the accelerated adoption of digital transformation strategies, increased availability of sensing technologies, and growing interest in data-driven asset management. During this period, BIM research expanded from design-oriented applications toward sustainability assessment, asset management, and lifecycle optimization.

The emergence of keywords related to DT, IoT, and machine learning after 2022 indicates a shift toward intelligent and predictive infrastructure systems. This development is associated with the need to manage aging infrastructure assets, enhance operational resilience, and support real-time decision-making under increasing uncertainty. The temporal patterns observed in Figure 5 therefore reflect not only academic developments but also evolving priorities among infrastructure stakeholders and policymakers.

Table 2. Keyword categorization by thematic period

Thematic group	Keywords	Research focus
Established (Before 2021)	BIM, GIS, construction, project management, interoperability, tunnelling	Design modeling, clash detection, coordination
Transitional (2021-2022)	Railway, bridges, asset management, lifecycle, infrastructure, maintenance, sustainability	Extension of BIM into O&M and lifecycle asset management
Emerging (2022-2023)	Digital twin, IoT, industry 4.0, predictive maintenance, machine learning, Augmented Reality (AR), point cloud	Smart infrastructure, AI integration, real-time monitoring

Overall, the results demonstrate a clear progression in BIM research, from foundational applications in design and interoperability toward integrated, data-driven systems supporting smart maintenance, real-time monitoring, and digital twin environments. This trajectory aligns with broader efforts to modernize transportation infrastructure through the adoption of advanced digital technologies. Moreover, the consistent presence of railway-related keywords across multiple temporal stages highlights this domain as both well-established and continuously evolving within BIM research.

4.5 *Citation analysis*

Citation analysis plays an important role in academic research by enabling the identification of influential studies within a given domain. By examining the number of citations received by individual publications, it is possible to assess their academic impact and contribution to the development of research directions. This form of bibliometric evaluation provides insights into both the evolution of the field and the priorities of the scholarly community.

It is acknowledged that selecting a limited number of highly cited articles may introduce citation-age bias, as earlier publications have had more time to accumulate citations than more recent studies. However, in this study, citation analysis is not used as a standalone indicator for identifying research trends. Instead, it is complemented by keyword co-occurrence analysis (Section 4.3), thematic evolution analysis based on average publication year (Section 4.4), and the review of recent influential publications (Section 4.7).

By integrating citation-based indicators with temporal overlay visualization and thematic analysis, the adopted framework captures both well-established foundational studies and emerging research directions that may not yet have accumulated high citation counts. This combined approach reduces potential selection bias and ensures a more balanced representation of the evolving research landscape in BIM applications for transportation infrastructure.

Table 3 presents the 20 most cited articles related to BIM applications in transportation infrastructure, providing insight into publications that have had a substantial influence on the field.

Table 3. Top 20 most cited articles

#	Article title and publication year	Journal	Cited by
1	BIM for transportation infrastructure-Literature review, applications, challenges, and recommendations (2018) [45]	Automation in Construction	403
2	BIM, machine learning and computer vision techniques in underground construction: Current status and future perspectives (2021) [46]	Tunnelling and Underground Space Technology	299
3	Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration (2022) [47]	Sustainable Cities and Society	230
4	Digital twin aided sustainability-based lifecycle management for railway turnout systems (2019) [48]	Journal of Cleaner Production	215
5	Potential of big visual data and building information modeling for construction performance analytics: An exploratory study (2017) [49]	Automation in Construction	207
6	Digital twinning of existing reinforced concrete bridges from labelled point clusters (2019) [50]	Automation in Construction	201
7	Integrating BIM and gaming for real-time interactive architectural visualization (2011) [51]	Automation in Construction	197
8	Integration of BIM and GIS: Geometry from IFC to shapefile using open-source technology (2019) [52]	Automation in Construction	179
9	Bim Inhibits Autophagy by Recruiting Beclin 1 to Microtubules (2012) [53]	Molecular Cell	178
10	Framework for automated UAS-based structural condition assessment of bridges (2019) [54]	Automation in Construction	176
11	Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites (2015) [55]	Advanced Engineering Informatics	174
12	A real-time construction safety monitoring system for hazardous gas integrating wireless sensor network and building information modeling technologies (2018) [56]	Sensors (Switzerland)	164
13	Digital twin for sustainability evaluation of railway station buildings (2018) [57]	Frontiers in Built Environment	153
14	Comparative Analysis on the Adoption and Use of BIM in Road Infrastructure Projects (2016) [58]	Journal of Management in Engineering	147
15	Integrating three-dimensional road design and pavement structure analysis based on BIM (2020) [59]	Automation in Construction	146
16	A Natural-Language-Based Approach to Intelligent Data Retrieval and Representation for Cloud BIM (2016) [60]	Computer-Aided Civil and Infrastructure Engineering	141
17	SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition (2018) [61]	Automation in Construction	140
18	Teaching construction project management with BIM support: Experience and lessons learned (2011) [62]	Automation in Construction	139
19	Integration of BIM and GIS: IFC geometry transformation to shapefile using enhanced open source approach (2019) [63]	Automation in Construction	135
20	Geospatial data management research: Progress and future directions (2020) [64]	ISPRS International Journal of Geo-Information	129

Several observations can be drawn from the citation analysis. The most cited article, titled "BIM for transportation infrastructure-Literature review, applications, challenges, and recommendations", published in Automation in Construction (2018), has received 403 citations. This study provides a comprehensive overview of BIM applications and has served as a key reference for subsequent research.

A considerable proportion of highly cited studies focus on the integration of BIM with emerging technologies. These include digital twin applications (e.g., entries #2, #4, #7, and #13), BIM-GIS integration (e.g., entries #3, #10, and #19), and the application of artificial intelligence and computer vision in infrastructure monitoring (e.g., entries #2 and #6). This pattern indicates a strong research interest in extending BIM from static modeling toward data-driven and intelligent infrastructure management.

The journal Automation in Construction accounts for a substantial share of the top 20 most cited articles, confirming its role as a major publication outlet for BIM-related research in construction and infrastructure informatics. It is also notable that several relatively recent publications (2021-2022), such as entry #3 (BIM-GIS integration for smart city design) and entry #2 (integration of BIM with machine learning and computer vision in underground construction), have already accumulated more than 200 citations. This observation suggests that influential contributions continue to emerge in response to contemporary challenges, including digital transformation, urbanization, and sustainability. One outlier article (entry #9), which is related to cell biology, appears in the dataset due to acronym overlap, where "BIM" refers to a biological term (Bcl-2-interacting mediator). This highlights the importance of contextual filtering in bibliometric analyses, particularly when dealing with acronyms that are used across multiple disciplines.

Overall, the citation profile indicates that BIM research in transportation infrastructure has developed into a technically mature and increasingly interdisciplinary field. The growing integration of BIM with DT, artificial intelligence, and sensing technologies is evident in many of the most influential studies. It should be noted that citation counts alone do not fully reflect the significance of research contributions, particularly for recently published studies. Therefore, citation indicators in this study are interpreted in conjunction with keyword co-occurrence patterns and temporal evolution analysis to ensure a balanced assessment of both established and emerging research directions.

4.6 *Regional disparities and BIM adoption patterns*

Based on the keyword co-occurrence patterns (Figure 4), thematic evolution analysis (Figure 5 and Table 2), and citation profiles discussed in Sections 4.2 and 4.5, regional differences can be observed in both the research focus and maturity of BIM applications in transportation infrastructure. Although a formal country-level collaboration network analysis is beyond the scope of this study, qualitative patterns derived from keyword clusters and case study contexts suggest the presence of regional variation.

In Southeast Asia, the literature shows a strong concentration on railway-and metro-oriented projects. This pattern is reflected in the frequent occurrence of railway-related keywords, such as railway, metro, railway tunnel, and railway bridge, across multiple thematic clusters in the keyword co-occurrence network (Figure 4), as well as their consistent presence across the thematic phases identified in the temporal evolution analysis (Figure 5 and Table 2). The association of these keywords with themes such as GIS integration, DT, asset management, and lifecycle management suggests that BIM research in this region has increasingly extended beyond design and construction toward more integrated and lifecycle-oriented applications. This trend is consistent with broader developments such as rapid urbanization, expansion of mass transit systems, and policy-driven digital transformation initiatives observed in several Southeast Asian countries.

In contrast, studies explicitly associated with African contexts appear more limited in both volume and thematic diversity. This observation is supported by the relatively lower representation of advanced lifecycle-related keywords, such as digital twin, predictive maintenance, and real-time monitoring, within the overall keyword co-occurrence network (Figure 4), as well as their weaker presence in the emerging thematic phase after 2022 (Figure 5). The citation profile analysis (Section 4.5) further indicates that highly cited studies are less frequently associated with African case contexts. Existing studies from this region tend to focus more on road infrastructure, feasibility assessment, construction efficiency, and cost control, with comparatively limited integration across the full infrastructure lifecycle.

The observed regional variation also reflects differences in BIM maturity levels and policy environments. Southeast Asian countries with established BIM strategies and ongoing investments in rail and metro systems appear to demonstrate a more advanced transition toward integrated and data-driven infrastructure management, as reflected in the prominence of lifecycle-and digital twin-related themes in Figures 4 and 5. In contrast, BIM adoption in many African contexts remains at an earlier stage, characterized by fragmented implementation, limited interoperability, and constraints related to institutional capacity and data availability.

These findings suggest that global BIM research trends in transportation infrastructure are shaped, in part, by regional infrastructure priorities and governance contexts. Consequently, future research and policy strategies may benefit from adopting region-specific approaches rather than uniform implementation models. For low-and middle-income regions, incremental BIM adoption-focusing on standardized data environments, capacity development, and policy alignment-may provide a more feasible and sustainable pathway toward advanced digital infrastructure applications.

4.7 *Emerging methodological directions in recent 2025 publications*

Table 4 presents selected highly cited articles published in 2025 (as of July 24, 2025), highlighting emerging methodological directions in BIM applications for transportation infrastructure. Although citation counts are commonly used to assess academic impact, early citation metrics for recently published studies should be interpreted with caution. Therefore, the 2025 publications presented in Table 4 are considered as illustrative examples of emerging thematic and methodological directions identified through temporal overlay analysis (Figure 5), rather than being selected based on strict citation thresholds.

Rather than providing detailed summaries of individual studies, this section synthesizes broader methodological patterns observed in recent publications. Three prominent directions can be identified. First, immersive and operational digital twin environments are increasingly being developed for bridges and tunnels, integrating scan-to-BIM workflows, point cloud processing, and real-time visualization platforms. These approaches reflect a shift toward interactive and feedback-driven asset management systems in the O&M phase. Second, sustainability-oriented and simulation-integrated BIM frameworks are emerging, particularly in underground and tunnel engineering. These studies combine multi-LOD modeling with hydro-mechanical simulations and lifecycle assessment, indicating a convergence between analytical modeling and BIM-based decision-support environments. Third, cross-platform integration frameworks linking BIM with GIS, Multi-Criteria Decision-Making (MCDM), and robotic manufacturing systems demonstrate a transition from model-centric workflows toward decision-support and automated execution ecosystems.

Table 4. Top cited articles in 2025 (as of July 24, 2025)

Article reference	Journal	Cited by	Focus	Core BIM use	Tools	Application phase	Novelty
[65]	Computers in Industry	8	Bridge monitoring & damage assessment	Digital twin, scan-to-BIM	Unity3D, LiDAR	Operation & Maintenance	Immersive inspection
[66]	Tunnelling and Underground Space Technology	5	Tunnel simulation & sustainability	Analytical coupling	LqQD, FEM	Design & Sustainability	Sustainability coupling
[67]	Engineering, Construction and Architectural Management	5	Site planning decision support	MCDM + spatial data	GIS, AHP, TOPSIS	Pre-Design Planning	GIS-BIM fusion
[68]	Tunnelling and Underground Space Technology	4	Automated excavation modeling	Parametric modeling	Dynamo	Construction Execution	Modular staging
[69]	Computers in Industry	4	BIM-to-robotic manufacturing	Robotic integration	Revit API, RobotStudio	Manufacturing/ Prefabrication	Robotic prefabrication

These emerging directions are consistent with the thematic evolution identified in Section 4.4, particularly the shift toward intelligent, lifecycle-oriented, and automation-driven infrastructure systems after 2022. Accordingly, the inclusion of 2025 publications serves to illustrate ongoing research trajectories rather than to redefine the core bibliometric findings of this study.

4.8 *Methodological reflection and justification*

The combined use of bibliometric analysis and SLR is well aligned with the research objectives of this study and with the characteristics of BIM-enabled transportation infrastructure research. As demonstrated in Sections 4.1-4.5, bibliometric analysis enables macro-level mapping of publication trends, thematic structures, keyword evolution, and citation patterns across a large body of literature. This quantitative perspective is essential for identifying dominant research clusters, emerging technological directions, and the overall development trajectory of the field.

However, the results also indicate that bibliometric indicators alone are insufficient to capture the methodological depth, application contexts, and practical implications of individual studies. To address this limitation, the SLR complements the bibliometric findings by providing a qualitative synthesis of selected influential publications, as presented in Sections 4.5 and 4.7. This approach enables a more detailed examination of how BIM is applied across different infrastructure types, lifecycle stages, and technological configurations, which cannot be fully inferred from citation metrics or keyword patterns alone.

The integration of bibliometric analysis and SLR therefore provides both breadth and depth of insight, enhancing the robustness and interpretability of the results. This hybrid methodological framework is particularly suitable for rapidly evolving and interdisciplinary domains such as BIM-enabled transportation infrastructure, where understanding both global research patterns and detailed implementation practices is essential.

By combining quantitative mapping with qualitative interpretation, the adopted approach reduces methodological bias and supports a more comprehensive identification of research gaps and future directions. Overall, this methodological integration strengthens the validity of the findings and provides a reliable basis for advancing research and practice in BIM-based transportation infrastructure systems.

5. Conclusion and recommendations

5.1 *Conclusion*

This study presents a comprehensive bibliometric and SLR of BIM applications in transportation infrastructure, including roads, railways, tunnels, bridges, and airports. Based on an analysis of 1,615 Scopus-indexed publications (2010-July 2025), the study maps publication trends, thematic structures, leading contributors, and the evolution of research in this domain. The main conclusions are summarized as follows.

First, BIM research in transportation infrastructure has experienced significant growth since 2014, reaching a peak in 2024 and continuing into 2025. This trend reflects the increasing recognition of BIM as a key enabling technology for digital transformation in infrastructure systems.

Second, railway-related applications are prominently represented across multiple thematic clusters and throughout the identified stages of thematic evolution. This pattern suggests that the railway sector constitutes a major area of BIM application, particularly in the context of high-speed and urban rail systems.

Third, recent studies demonstrate increasing convergence between BIM and complementary digital technologies, including DT, GIS, IoT, machine learning, and robotic automation. This convergence reflects a transition from design-oriented BIM applications toward lifecycle-oriented intelligence and data-driven decision-making.

Finally, recent publications in 2025 indicate growing interest in advanced methodological approaches, including immersive digital twin environments, sustainability-integrated BIM modeling, automated construction staging, and robotic prefabrication. These developments highlight emerging directions in the evolution of BIM-enabled infrastructure systems.

5.2 *Research gaps*

Despite the increasing integration of BIM with GIS, DT, and IoT platforms, interoperability remains a critical and unresolved challenge in transportation infrastructure applications. A primary technical barrier lies in the incompatibility of data schemas between BIM and geospatial standards. For instance, IFC models are typically object-oriented and building-centric, whereas CityGML and other GIS data models are spatially hierarchical and optimized for large-scale geographic representation. This fundamental difference complicates data exchange, model synchronization, and semantic consistency across platforms.

Another major limitation is the lack of standardized and open APIs to support real-time, bidirectional data exchange among BIM, GIS, and digital twin systems. Many current implementations rely on proprietary software environments, resulting in fragmented workflows, limited scalability, and vendor lock-in. These constraints are particularly significant during the O&M phase, where continuous integration of sensor and monitoring data is required.

Interoperability challenges are further exacerbated by the limited availability of lifecycle-oriented semantic structures within existing BIM models. While BIM standards are relatively well developed for design and construction stages, semantic representations for O&M processes-such as inspection records, degradation patterns, and maintenance histories-remain insufficient. This limitation restricts the use of BIM as a long-term asset information model and constrains its integration with digital twin systems for predictive maintenance.

From a standardization perspective, regional differences also affect interoperability outcomes. For example, the United Kingdom's Publicly Available Specifications (PAS) 1192 framework emphasizes Common Data Environments (CDEs) and collaborative information management, whereas China's GB/T 51235 standard focuses on structured BIM implementation aligned with national infrastructure practices. Although both frameworks support BIM adoption, their differences in data governance and lifecycle integration present challenges for cross-regional interoperability.

These unresolved issues highlight the need for future research on semantic harmonization between BIM and GIS standards, the development of open and standardized APIs, and the extension of BIM schemas to better support O&M and digital twin applications. Addressing these challenges is essential for enabling scalable, interoperable, and lifecycle-oriented digital infrastructure systems.

5.3 *Practical, policy implications, and limitations*

The findings of this study provide practical insights for policymakers, infrastructure authorities, and industry practitioners seeking to advance digital transformation in transportation infrastructure. By synthesizing bibliometric trends and thematic gaps, the results highlight the role of emerging technologies, such as DT and IoT-enabled BIM, in supporting lifecycle-oriented asset management.

Despite the well-documented benefits of BIM-enabled O&M-including improved asset condition monitoring, predictive maintenance, and lifecycle cost optimization-its adoption in practice remains limited. This gap between research potential and real-world implementation can be attributed to a combination of institutional, technical, and economic factors.

From an institutional perspective, transportation infrastructure assets are often governed by fragmented ownership structures, where responsibilities for design, construction, and operation are distributed across multiple stakeholders. This fragmentation reduces incentives for early BIM investment, as the entities responsible for implementation are not always those that benefit from long-term O&M outcomes.

From a technical and economic perspective, integrating BIM with sensing technologies and digital twin platforms requires substantial initial investment. These include costs associated with IoT deployment, data acquisition systems, model updating processes, and skilled human resources. Such requirements present significant barriers, particularly in low-and middle-income regions, where legacy infrastructure systems were not originally designed for digital integration.

In addition, legacy infrastructure constraints further complicate BIM adoption. Many existing assets lack reliable as-built digital records, necessitating extensive data reconstruction before BIM-based O&M applications can be implemented. As a result, BIM adoption is often prioritized in new construction projects rather than in the retrofitting of existing infrastructure.

Policy and regulatory frameworks also significantly influence the adoption and maturity of BIM implementation across different regions. While BIM adoption is increasingly supported in design and construction phases through national guidelines and mandates, explicit requirements for BIM implementation in O&M remain limited. The absence of standardized deliverables and long-term data governance frameworks reduces incentives for lifecycle-oriented BIM adoption.

These findings suggest that accelerating BIM implementation in O&M requires coordinated policy actions, including clearer lifecycle-based mandates, incentives for digital retrofitting of existing assets, and the development of long-term data governance strategies. Aligning contractual structures, data standards, and asset management objectives is essential to bridge the gap between research advancements and practical implementation.

To illustrate these challenges in a developing-country context, Vietnam provides a relevant example. Ongoing investments in large-scale transportation projects, including high-speed rail and urban metro systems, demonstrate increasing demand for BIM-enabled planning and asset management. Existing studies indicate the feasibility of BIM-GIS integration for metro infrastructure in Vietnam, highlighting its potential for lifecycle-oriented applications. However, the limited number of large-scale implementations also reflects broader challenges related to regulatory maturity, data standardization, and institutional capacity, which are common across many low-and middle-income countries. This example underscores the importance of aligning policy frameworks, technical standards, and capacity-building efforts to support sustainable BIM adoption.

Despite these contributions, several limitations should be acknowledged. This study relies on Scopus-indexed, English-language publications, which may introduce database and language bias. Future research should expand the data sources to include multiple databases, such as the Web of Science Core Collection and China National Knowledge Infrastructure (CNKI), as well as multilingual publications to improve coverage and representativeness.

Conflict of interest

The authors report there are no conflicts of interest to declare.

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