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Evolution and research trends in virtual reality and augmented reality technologies for the architecture, engineering, and construction (AEC) industry: a systematic review and science mapping approach

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This systematic review and bibliometric analysis examine the evolution and research trends of Virtual Reality (VR) and Augmented Reality (AR) technologies within the Architecture, Engineering, and Construction (AEC) industry to identify key research themes, application domains, and future directions. A comprehensive literature search was conducted using both Scopus and Web of Science databases covering publications from 2015 to 2025 to ensure robust multi-database validation. After applying engineering subject area filters, the Scopus search yielded 1,301 articles while Web of Science returned 898 articles. The methodology combined quantitative bibliometric analysis using Bibliometrix software with qualitative thematic analysis of the most-cited and relevant studies following PRISMA guidelines. Performance analysis, science mapping, and co-occurrence analysis were employed to identify research clusters and trends across both databases. Cross-database validation confirmed convergent patterns in publication growth, thematic structure, and collaboration networks, with both databases demonstrating exponential growth and similar dominant research themes centered on digital twins, virtual reality applications, and BIM integration. This study provides a comprehensive quantitative mapping of VR/AR research in the AEC industry with multi-database validation, revealing the intellectual structure and research fronts. The integrated approach combining bibliometric analysis with thematic synthesis offers insights for researchers and practitioners to understand current applications, identify research gaps, and guide future technology adoption strategies.

KEYWORDS

virtual reality, augmented reality, construction industry, research trends, digital twin, science mapping, bibliometric analysis, building information model (BIM)

1 Introduction

1.1 Digital transformation in the AEC industry

The Architecture, Engineering, and Construction (AEC) industry is undergoing a fundamental digital transformation aligned with Industry 4.0, characterized by the integration of Cyber-Physical Systems, Internet of Things (IoT), and cloud computing technologies (Hossain and Nadeem, 2019). This transformation aims to enhance productivity, improve collaboration, and address evolving construction demands through comprehensive digital solutions (Bou Hatoum et al., 2022).

Building Information Modeling (BIM) has emerged as a cornerstone technology, fundamentally redefining information management across project lifecycles and enabling efficient design, planning, execution, and maintenance processes (Azhar, 2011; Mannino et al., 2021). The integration of digital twin technologies further augments these capabilities by providing real-time data visualization and analysis, facilitating improved decision-making throughout building lifespans (Sepasgozar, 2020). This technological shift enhances project management while improving safety standards and operational efficiencies in construction environments (Sidani, Poças Martins and Soeiro, 2022).

Construction 4.0 embodies Industry 4.0 principles, illustrating how digital and physical realm convergence drives innovation through advanced technologies including robotics, artificial intelligence, and automated systems integrated into construction workflows (Klarin and Xiao, 2024). Organizations seeking modernization must navigate these digital transformation complexities to foster industry resilience and sustainability (Hossain and Nadeem, 2019; Bou Hatoum et al., 2022).

1.2 Immersive technologies landscape

Immersive technologies exist along the reality-virtuality continuum, a conceptual framework introduced by Milgram and Kishino (1994) that spans from completely real environments to fully virtual ones. Extended Reality (XR) serves as an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). VR provides fully immersive digital environments isolated from the physical world; AR overlays digital content onto real-world views; and MR enables interaction between physical and digital objects in real-time. These technologies have emerged as transformative tools offering innovative solutions for visualization, design collaboration, and training within the AEC sector, addressing complex challenges inherent in modern construction practices through enhanced spatial understanding and interactive experiences. While XR represents the complete spectrum of immersive technologies, VR and AR have achieved greater technological maturity and documented implementation within AEC contexts, forming the empirical focus of this review.

VR provides fully immersive environments enabling users to interact with digital representations of physical spaces, facilitating intricate detailed visualization before physical execution and supporting informed decision-making early in project lifecycles (Afzal et al., 2021). This technology enhances stakeholder communication and engagement by providing shared virtual spaces for real-time modifications and assessments, potentially reducing costly later-phase changes (Jacobsen et al., 2022).

AR complements VR by superimposing digital information onto real-world environments, proving particularly advantageous during construction phases through real-time project overlays that enhance work accuracy (Xu and Moreu, 2021). Multiple studies have highlighted AR's potential for construction safety enhancement by providing critical information in hazardous settings, enabling workers to visualize safety instructions within their operational context (Adami et al., 2022; Jacobsen et al., 2022).

Mixed Reality applications, while less prevalent in current AEC literature, demonstrate promising results in specific construction tasks. For instance, MR has been successfully applied to electrical construction design communication, showing higher productivity rates and fewer assembly errors compared to traditional methods (Chalhoub and Ayer, 2018). However, MR implementation remains limited due to higher hardware requirements and technological complexity compared to VR and AR solutions.

The integration of VR and AR with BIM significantly streamlines AEC workflows, enabling interactive BIM data visualization in immersive formats that enhance project collaboration and optimize workflow management (Chi et al., 2022; Li et al., 2024). Recent literature indicates expanding applications in civil engineering structure condition assessment, presenting paradigm shifts that enable virtual inspections and simulations previously requiring extensive time and resources (Catbas et al., 2022).

1.3 Research gaps and systematic review rationale

The rapid expansion of VR applications in civil engineering necessitates a comprehensive quantitative review to effectively map the growing knowledge base and elucidate emerging research trends. As an evolving field, VR has gained recognition for its potential to transform various civil engineering and construction aspects, from design processes to training and safety practices (Huang and Roscoe, 2021).

Bibliometric analysis provides systematic empirical methods utilizing statistical tools to quantify academic literature, offering insights into publication patterns, co-authorship networks, keyword trends, and citation dynamics (Agbo et al., 2021). Such analyses have been effectively employed across various domains to highlight trends and research gaps (Rashid et al., 2021). The noteworthy expansion of VR-related publications, coupled with increasing interdisciplinary collaboration, underscores the necessity of bibliometric approaches to efficiently synthesize this information wealth.

Current literature lacks comprehensive systematic reviews combining quantitative bibliometric analysis with qualitative thematic synthesis specifically focusing on VR and AR applications in the AEC industry context. Existing reviews tend to focus on narrow application areas or lack the temporal scope necessary to capture the recent technological advances and integration patterns.

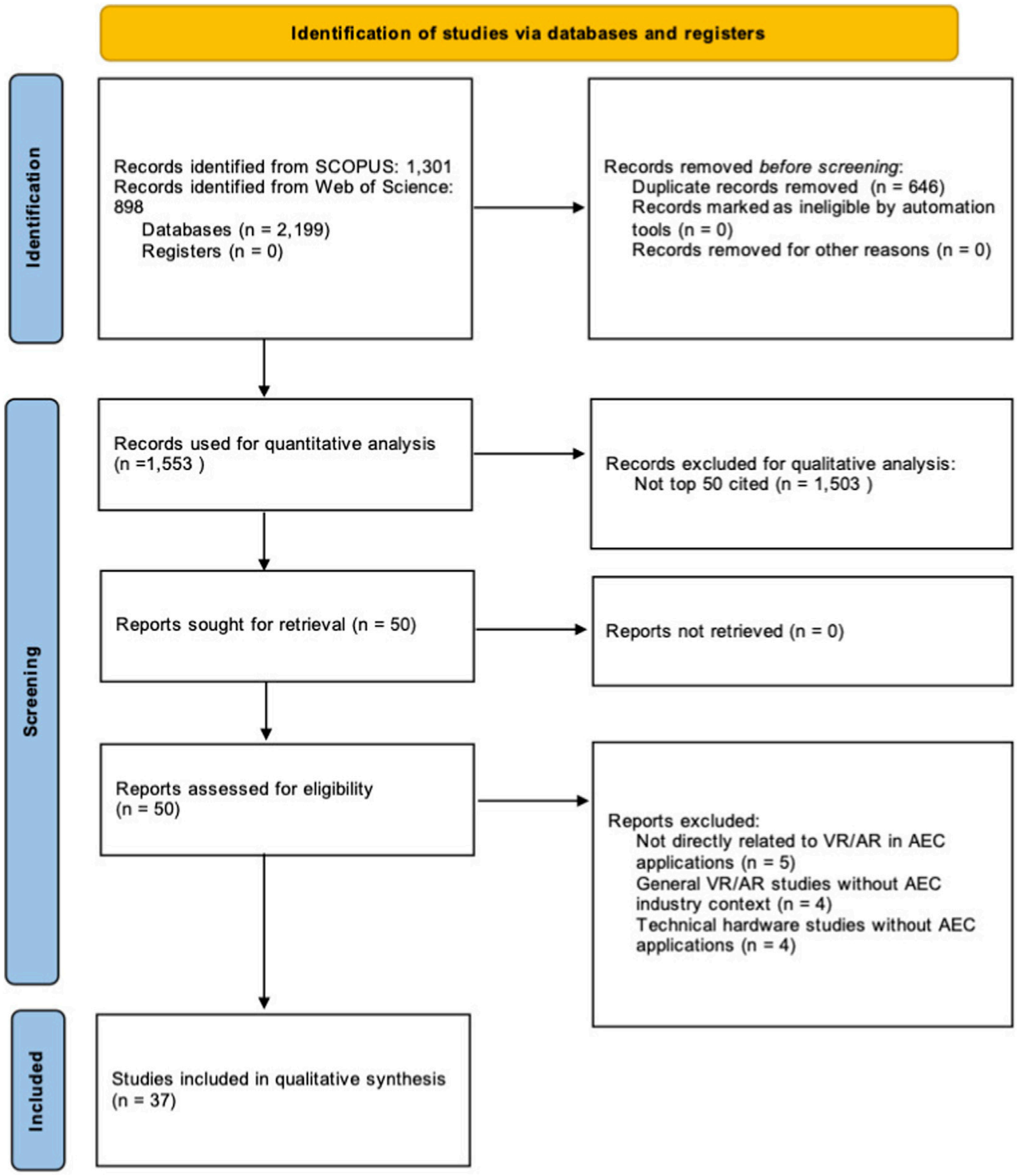

FIGURE 1
PRISMA flow diagram showing study selection.

1.4 Research objectives

This systematic review aimed to provide a comprehensive mapping of VR/AR research evolution in the AEC industry through an integrated bibliometric and thematic analysis. Specific objectives include.

1. Quantify publication trends, growth patterns, and collaboration networks in VR/AR research for AEC applications (2015–2025)
2. Identify main research clusters, thematic areas, and intellectual structure through science mapping techniques
3. Synthesize key application domains, technological integration patterns, and implementation challenges
4. Determine research gaps and propose future research directions for VR/AR technologies in the AEC industry

2 Materials and methods

2.1 Protocol and registration

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Figure 1) to ensure methodological rigor and transparency (Page et al., 2021). The review protocol integrated quantitative bibliometric analysis with qualitative thematic synthesis to provide a comprehensive mapping of Virtual Reality and Augmented Reality research in the Architecture, Engineering, and Construction industries.

2.2 Search strategy and database selection

A comprehensive literature search was performed using two major academic databases—Scopus and Web of Science—to ensure robust multi-database validation as recommended for bibliometric studies. Both databases were selected for their extensive coverage of engineering and technology publications, comprehensive citation tracking capabilities, and robust metadata for bibliometric analysis. The search strategy was designed to capture publications addressing VR/AR technologies specifically applied within the context of the AEC industry.

The inclusion of contextual terms such as 'building information model', 'BIM', and 'digital twin' alongside core AEC descriptors was a deliberate methodological choice to ensure comprehensive retrieval of VR/AR applications within established AEC digital workflows. Importantly, these terms were connected using the Boolean operator OR, meaning articles needed to match only one of these contextual terms rather than all of them, thereby expanding rather than restricting the search scope. These terms function as contextual anchors rather than thematic constraints, as preliminary searches using only VR/AR terms with general AEC descriptors yielded excessive noise from unrelated domains (e.g., medical VR, gaming applications). This approach aligns with bibliometric search strategies that recommend combining technology terms with domain-specific connectors to improve precision without sacrificing recall (Aria and Cuccurullo, 2017). Identical search queries were adapted to the syntax of each database to maintain consistency.

2.2.1 Scopus query

TITLE-ABS-KEY ((“virtual reality” OR “augmented reality” OR VR) AND (“civil engineering” OR “construction industry” OR “architecture engineering construction” OR “building information model*” OR BIM OR “digital twin*” OR “structural engineering” OR “construction management”)) AND PUBYEAR ≥ 2015 AND PUBYEAR <2026 AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (SUBJAREA, “ENGI”)).

2.2.2 Web of science query

TS=(“virtual reality” OR “augmented reality” OR VR) AND TS=(“civil engineering” OR “construction industry” OR “architecture engineering construction” OR “building information model*” OR BIM OR “digital twin*” OR “structural engineering” OR “construction management”) AND PY=(2015–2025) AND DT=(Article) AND LA=(English). Research Area Filter: Engineering.

The application of the Engineering subject area filter in both databases was a deliberate choice to maintain focus on technical implementation studies rather than purely theoretical or pedagogical works. While this filter is labeled 'Engineering,' it encompasses a broad range of AEC-related disciplines in both Scopus and Web of Science, including civil engineering, construction engineering, architectural engineering, and building technology. Analysis of the retrieved dataset confirmed that publications from construction management, architectural design, and related AEC disciplines were successfully captured, as evidenced by the diversity of source journals including Engineering, Construction and Architectural Management; Journal of Construction Engineering and Management; and Automation in Construction (Table 3). This filtering approach balanced comprehensiveness with relevance, reducing noise from non-technical domains while retaining the interdisciplinary breadth characteristic of AEC research.

The search encompassed publications from 2015 to 2025. This timeframe was selected to capture the period of significant technological advancement and increased adoption of immersive technologies in construction practices.

2.3 Eligibility criteria and selection process

This study employed strict inclusion criteria to ensure the relevance and quality of selected publications. The included studies were peer-reviewed journal articles published between 2015 and 2025 in English, focusing on VR and AR technologies applied within the context of the AEC industry. While the search strategy centered on VR and AR as the most established and documented immersive technologies in AEC literature, articles addressing MR applications were captured when indexed under VR or AR terminology, reflecting the overlapping nature of these technologies in current academic databases. Research was required to address applications in civil engineering, construction management, architectural design, or related disciplines while demonstrating the clear integration of immersive technologies within AEC workflows.

Exclusion criteria eliminated conference proceedings, book chapters, and grey literature, along with studies mentioning VR/AR technologies without substantial AEC application focus, purely technical hardware development studies without AEC implementation, and articles in languages other than English.

The selection process followed a systematic dual-database approach. The Scopus search yielded 1,301 articles after applying the engineering subject area filter, while the Web of Science search returned 898 articles, resulting in a combined total of 2,199 articles. Using the Bibliometrix mergeDbSources function with automatic duplicate detection, 646 duplicated documents were identified and removed based on DOI, title, and author matching algorithms, representing a 29.4% overlap between databases.

The final merged corpus comprised 1,553 unique articles, which formed the complete dataset for comprehensive bibliometric analysis. From this merged dataset, the top 50 most-cited articles were selected for detailed qualitative analysis. This citation-based threshold follows established bibliometric practices where “authors often exclusively use documents or journals that exceed some minimum citation threshold for the purpose of selecting only influential publications and limiting the core document set to a manageable size” (Zupic and Čater, 2015, p. 441). Accordingly, the selection of 50 highly-cited articles ensures comprehensive coverage of seminal works that have shaped the field's intellectual structure while maintaining analytical depth for rigorous qualitative synthesis.

Following rigorous title and abstract screening against inclusion criteria, 37 articles met the requirements for qualitative thematic synthesis, representing the most influential and relevant research in VR/AR applications for the AEC industry.

2.4 Data extraction and analysis methods

Comprehensive bibliometric data were extracted for all 1,553 articles to enable thorough quantitative analysis. This included publication metadata including titles, authors, journals, and publication years, alongside citation counts and patterns, author collaboration networks and institutional affiliations, keywords and subject classifications, and journal impact metrics with source distributions.

For the 37 selected articles subjected to qualitative analysis, detailed thematic data were extracted focusing on application domains within the AEC industry, technology integration approaches and methodologies, implementation challenges and limitations, future research directions and recommendations, and technological convergence patterns with other digital technologies.

2.5 Bibliometric analysis tools

Quantitative analysis was performed using the Bibliometrix R package, which provides comprehensive capabilities for bibliometric and scientometric analysis. The analysis encompassed performance analysis including annual publication trends and growth patterns, journal productivity and citation impact, author collaboration metrics and institutional analysis, and citation performance with temporal citation patterns.

Science mapping techniques included co-occurrence analysis of keywords and concepts, bibliographic coupling and co-citation analysis, thematic clustering and research front identification, and collaboration network visualization. Temporal analysis examined citation aging and knowledge diffusion patterns, whereas conceptual structure analysis using Multiple Correspondence Analysis revealed the intellectual organization of research themes and their dimensional relationships. This integrated methodology enabled comprehensive understanding of both quantitative research patterns and qualitative thematic developments within VR/AR applications in the AEC industry, providing robust foundations for identifying research gaps and future directions.

3 Results

3.1 Study selection and characteristics

The systematic dual-database search yielded 1,301 articles from Scopus and 898 articles from Web of Science, totaling 2,199 articles spanning 2015–2025. After applying the mergeDbSources function to eliminate duplicates, 646 overlapping documents were removed (29.4% duplication rate), resulting in a final merged corpus of 1,553 unique articles that formed the complete dataset for the quantitative bibliometric analysis (Table 1). The merged dataset encompassed publications from 453 different sources, with an average document age of 2.45 years. The collection included contributions from 4,707 authors, with an average of 4.42 co-authors per document. International co-authorships represented 17.41% of the total publications, indicating substantial global collaboration in VR/AR research within the AEC domain. The 29.4% overlap between Scopus and Web of Science databases demonstrates complementary coverage, with each database contributing unique articles while providing cross-validation for core influential research.

TABLE 1 Main information about merged dataset.

Description	Results
Databases	Scopus + web of science
Scopus articles	1,301
Web of science articles	898
Total before deduplication	2,199
Duplicates removed	646
Duplication rate	29.4%
Final unique documents	1,553
Timespan	2015:2025
Sources	453
Annual growth rate %	42.78
Document average age	2.45
Average citations per doc	29.75
Authors	4,707
Authors of single-authored docs	68
Single-authored docs	71
Co-authors per doc	4.42
International co-authorships %	17.41

3.2 Publication trends and growth patterns

As shown in Figure 2, temporal analysis of the merged 1,553-article dataset revealed exponential growth in VR/AR research within the AEC industry from 2015 to 2025. The number of publications increased dramatically from nine articles in 2015 to 331 in 2024, representing a nearly 37-fold increase over the last decade. The most significant growth occurred after 2018, with publications increasing from 48 in 2018 to 76 in 2019, followed by consistent year-over-year increases. The growth acceleration intensified after 2020, with publications increasing from 93 in 2020 to 147 in 2021 (58% increase), 229 in 2022 (56% increase), 263 in 2023 (15% increase), and peaking at 331 in 2024. The year 2025 recorded 317 articles, representing nearly complete annual output given the data collection timeframe. This sustained exponential growth pattern, reflected in the 42.78% annual growth rate, demonstrates the rapidly increasing research interest and maturation of VR/AR technologies for AEC applications.

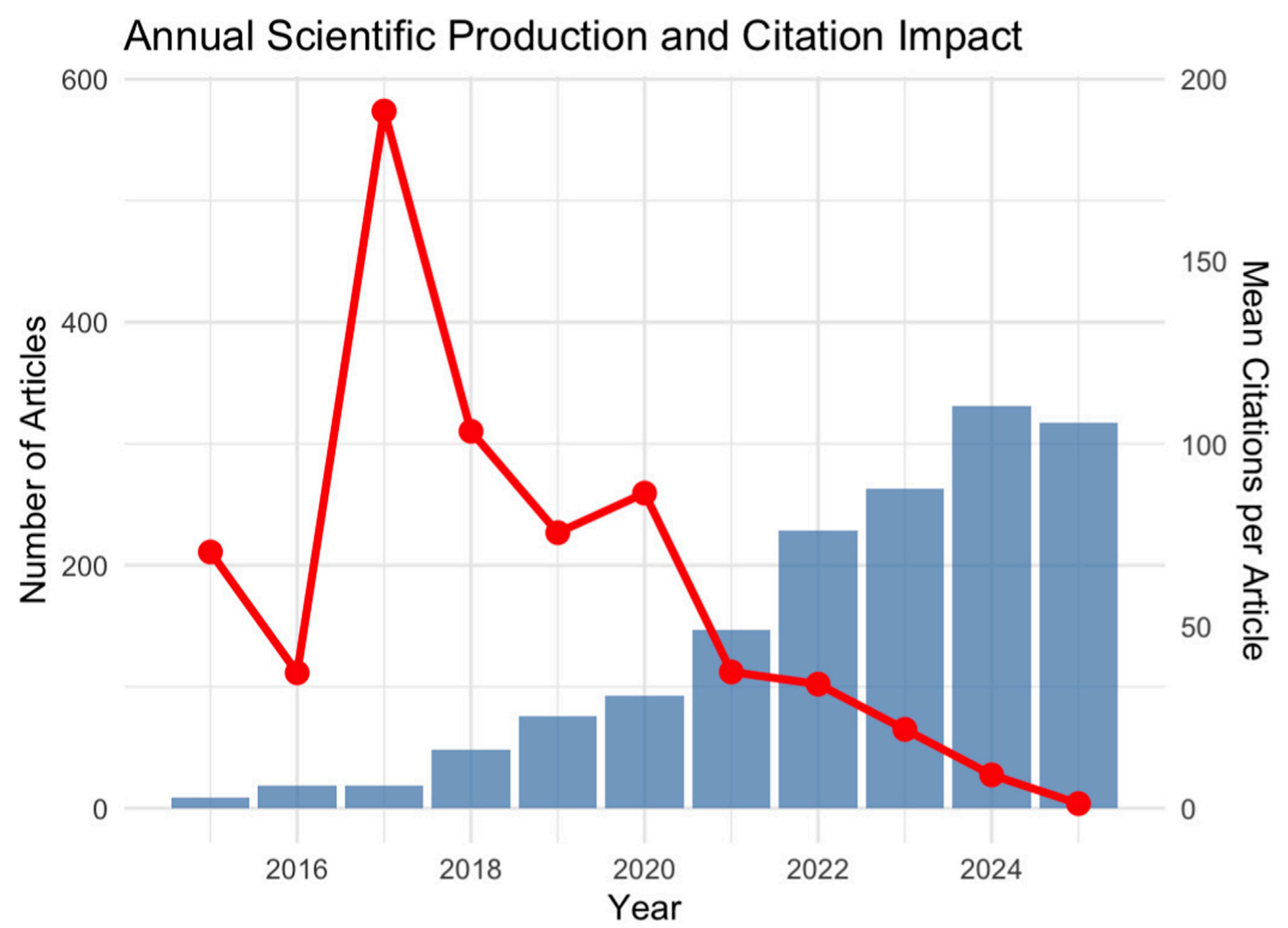

FIGURE 2
Annual publication growth (bars) and citation impact (line) of VR/AR research in AEC, 2015-2025.

TABLE 2 Citation performance by year (merged dataset).

Year	Articles	Mean citations per article	Mean citations per year	Citable years
2015	9	70.33	6.39	11
2016	19	37.16	3.72	10
2017	19	191.26	21.25	9
2018	48	103.44	12.93	8
2019	76	75.63	10.80	7
2020	93	86.49	14.41	6
2021	147	37.39	7.48	5
2022	229	34.04	8.51	4
2023	263	21.65	7.22	3
2024	331	9.15	4.58	2
2025	317	1.26	1.26	1

Citation performance analysis (Table 2) revealed interesting temporal patterns in research impact across the merged 1,553-article dataset. Earlier publications demonstrated higher average citations per article, with 2017 showing the highest mean total citations per article (191.26), followed by 2018 (103.44) and 2020 (86.49). The mean citations per year metric

TABLE 3 Top publication sources.

Sources	Articles
Automation in construction	84
IEEE access	72
Buildings	69
Applied sciences-basel	67
Journal of information technology in construction	42
Sensors	42
Advanced engineering informatics	28
Journal of construction engineering and management	28
Engineering construction and architectural management	27
International journal of advanced manufacturing technology	22
Electronics	20
Journal of manufacturing systems	20
Journal of computing in civil engineering	19
Safety science	19
Smart and sustainable built environment	17
Construction innovation	16
International journal of computer integrated manufacturing	14
International journal of construction management	14
Applied sciences (Switzerland)	13
Journal of building engineering	13
Robotics and computer-integrated manufacturing	13
IEEE communications magazine	11
IEEE transactions on consumer electronics	11
Journal of industrial information integration	11
Multimedia tools and applications	11

indicated that 2017 publications had the highest annual citation rate (21.25).

3.3 Source analysis and journal distribution

The research landscape across the merged 1,553-article dataset was dominated by several key journals demonstrating sustained focus on VR/AR technologies in AEC applications (Table 3). Automation in Construction emerged as the leading publication venue with 84 articles, followed by IEEE Access with 72 articles and Buildings with 69 articles. Applied Sciences-Basel contributed 67 articles, while the Journal of Information Technology in Construction published 42 articles, establishing its role as a specialized venue for construction technology research. Sensors also contributed 42 articles, demonstrating strong interest in IoT and sensing technologies integration with VR/AR systems.

The diversity of publication venues reflects the interdisciplinary nature of VR/AR research in AEC, spanning construction management journals, engineering technology publications, and manufacturing systems outlets. Advanced Engineering Informatics (28 articles) and the Journal of Construction Engineering and Management (28 articles) demonstrated a sustained interest in construction and engineering informatics communities. Engineering, Construction and Architectural Management (27 articles) represent traditional construction management outlets embracing immersive technologies. The presence of manufacturing-focused journals such as the International Journal of Advanced Manufacturing Technology (22 articles) and the Journal of Manufacturing Systems (20 articles) indicated significant cross-pollination between the construction and manufacturing applications of VR/AR technologies.

Emerging interdisciplinary venues included Smart and Sustainable Built Environment (17 articles), Construction Innovation (16 articles), and Safety Science (19 articles), demonstrating the technology's application across sustainability, innovation, and safety domains. Specialized computing journals such as the Journal of Computing in Civil Engineering (19 articles) and electronics-focused outlets such as Electronics (20 articles) further illustrated the technological breadth of VR/AR research.

The merged dataset's source distribution of 453 unique journals demonstrates complementary coverage between Scopus and Web of Science, which captures both mainstream construction engineering journals and emerging interdisciplinary venues, providing comprehensive coverage of the VR/AR research landscape in AEC contexts.

3.4 Author collaboration networks

The analysis of author productivity (Table 4) across the merged 1,553-article dataset revealed concentrated research activity among leading scholars in the field. Yonghao Wang and Huazhen Zhang emerged as the most prolific authors with 22 articles each, followed by Steven K. Ayer (21 articles) and Yuxuan Zhang (20 articles). The fractionalized article counts, which account for multiple authorship, showed Steven K. Ayer leading with 6.44 fractionalized articles, followed by Yonghao Wang with 5.58 and Jong-Hyun Kim with 5.23, indicating substantial individual contributions and leadership roles in research publications.

Author collaboration patterns revealed both individual productivity and extensive collaborative research networks. The top 10 authors included Jae Yeol Lee, Yang Aron Liu, and Zining Liu (19 articles each); Xuewen Wang (18 articles), Jong-Hyun Kim and Jingwen Wang (17 articles each. The presence of multiple authors with the same surnames (Wang, Zhang, Li, Liu) reflects the strong representation of Chinese researchers in the field, which is consistent with the geographic distribution observed in collaboration network analyses.

The fractionalized article counts provide insight into authorship positions and research leadership. Authors with high fractionalization ratios relative to total articles (such as Steven K. Ayer: 6.44/21 = 0.31, Zining Liu: 4.78/19 = 0.25, and Jong-Hyun Kim: 5.23/17 = 0.31) demonstrated frequent first or corresponding author positions, indicating research leadership roles. Conversely,

TABLE 4 Most productive authors (top 10).

Authors	Affiliation	Articles	Articles fractionalized
Yonghao Wang	Birmingham City University	22	5.58
Huazhen Zhang	University of Science and Technology Beijing	22	4.10
Steven K. Ayer	Arizona State University	21	6.44
Yuxuan Zhang	Guangzhou University=	20	3.83
Jae Yeol Lee	Chonnam National University	19	3.62
Yang Aron Liu	Academy of Mathematics and Systems Science	19	3.69
Zining Liu	Electric Power Research Institute	19	4.78
Xuewen Wang	Taiyuan University of Technology	18	4.05
Jong-Hyun Kim	Inha University	17	5.23
Jingwen Wang	University of Alberta	17	3.36

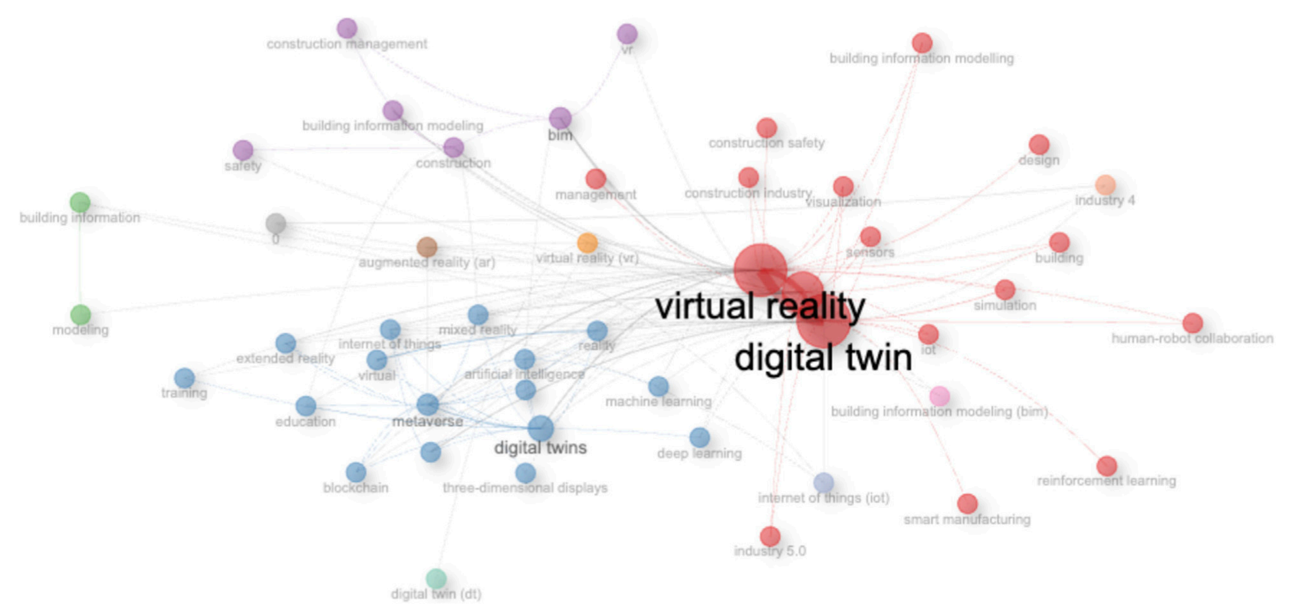

FIGURE 3
Keyword co-occurrence network showing two main clusters: digital twin applications (red) and emerging technologies (blue).

authors with lower fractionalization ratios indicated extensive collaborative partnerships. The presence of authors from diverse geographic regions, as evidenced by international co-authorship rates of 17.41%, demonstrated the global nature of VR/AR research in AEC applications, with the merged dataset capturing collaborative networks spanning multiple continents and research institutions.

3.5 Science mapping and co-occurrence analysis

The science mapping analysis of the merged 1,553-article dataset revealed distinct thematic clusters within VR/AR research for AEC applications. The keyword co-occurrence network (Figure 3) identified interconnected research areas spanning technical implementation, application domains, and integration approaches. Network Analysis revealed two primary clusters based on betweenness centrality metrics (Figure 3).

Cluster 1 (Red nodes) centered on "digital twin" forms the largest thematic group, encompassing core VR/AR technologies and their direct AEC applications. This cluster demonstrated the highest betweenness centrality values, with virtual reality (453.025), digital twin (319.240), and augmented reality (188.486) serving as the primary conceptual bridges connecting the different research sub-domains. Key nodes in this cluster included BIM (376 occurrences), building information modeling (327 occurrences), augmented reality (234 occurrences), and industry 4.0 (109 occurrences),

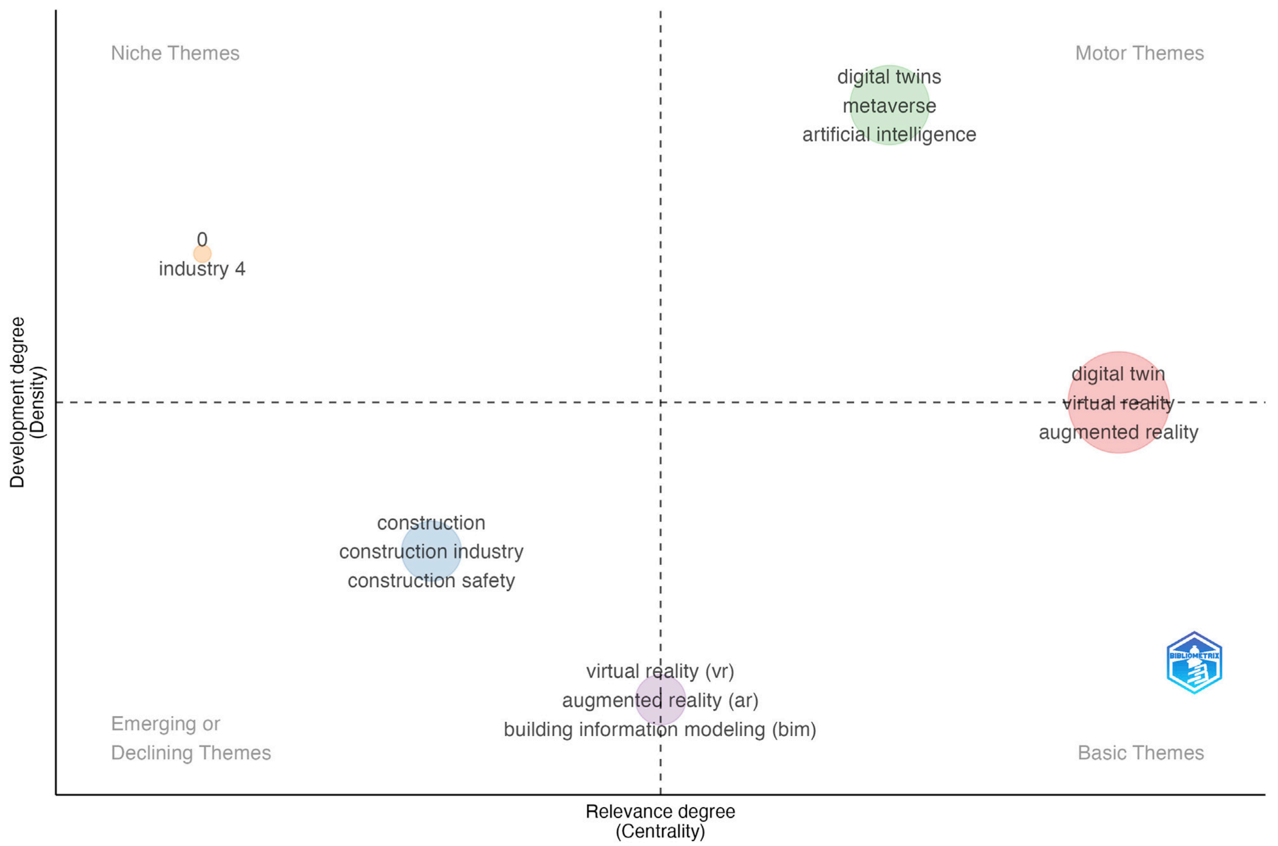

FIGURE 4
Thematic map displaying research themes by centrality and density.

indicating strong integration between immersive technologies and established AEC digital workflows. Application-focused keywords such as construction safety, simulation, visualization, and sensors demonstrated zero betweenness centrality, suggesting that they represent terminal application nodes rather than bridging concepts.

Cluster 2 (Blue nodes) centered on "digital twins" (plural form), "metaverse", and emerging technologies, represented a conceptually distinct but related research stream. This cluster showed substantial betweenness centrality for metaverse (175.723) and digital twins (19.649), indicating their role as bridges into emerging computational paradigms. Keywords in this cluster included artificial intelligence, Internet of Things, reality, and mixed reality, demonstrating the convergence of VR/AR technologies with advanced computational approaches and Industry 4.0/5.0 concepts.

Thematic map analysis (Figure 4) provided a complementary view of the field's intellectual structure organized across two dimensions: relevance degree (centrality) and development degree (density). The analysis identified four distinct quadrants revealing research maturation levels.

Motor Themes (upper-right quadrant) included "digital twins," "metaverse," and "artificial intelligence," representing well-developed and highly central research areas that drive the field forward. These themes demonstrate both internal cohesion (high density) and strong connections to other research areas (high centrality), positioning them as the strategic research fronts of the field.

Basic Themes (lower-right quadrant) contained the largest cluster with "digital twin," "virtual reality," and "augmented reality" as core concepts. Despite their lower density, these themes showed high centrality, indicating that they serve as fundamental, transversal concepts that connect multiple research streams but lack specialized development within specific niches. This positioning suggests these are mature and widely, adopted technologies serving as foundations for more specialized applications.

Niche Themes (upper-left quadrant) included "industry 4.0″as a specialized but peripheral research area. The single term in this quadrant demonstrated high internal development but limited connection to mainstream VR/AR research, suggesting industry-specific applications that remain somewhat isolated from core technological developments.

The Emerging or Declining Themes (lower-left quadrant) encompassed "construction," "construction industry," "construction safety," "virtual reality (VR)," "augmented reality (AR)," and "Building Information Modeling (BIM)." The positioning of these application-focused terms in this quadrant indicates that they represent either emerging application areas still developing conceptual coherence or declining research interests superseded by more integrated approaches such as digital twins and metaverse applications.

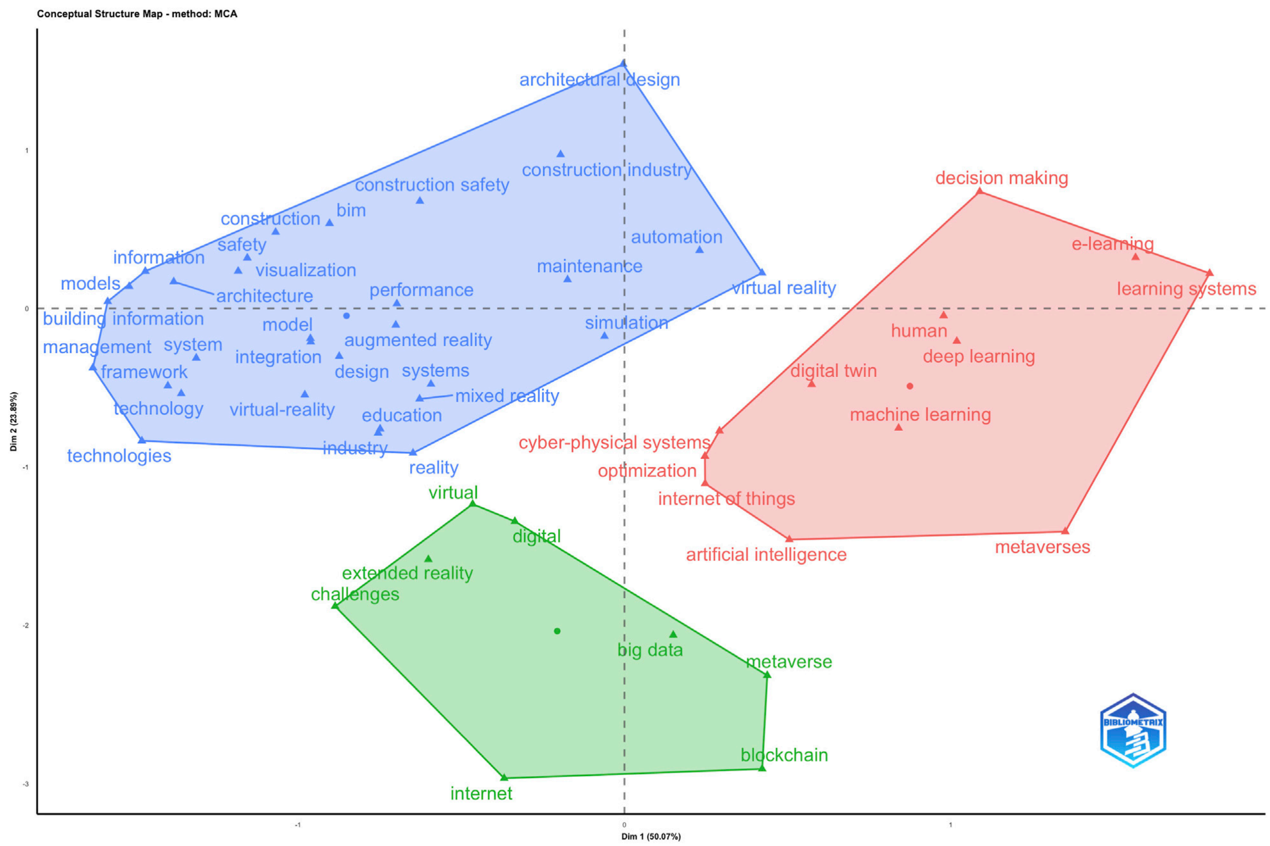

FIGURE 5
Conceptual structure map revealing three research clusters: traditional AEC (blue), intelligent systems (red), and frontier technologies (green).

Conceptual structure analysis using Multiple Correspondence Analysis (Figure 5) revealed the dimensional organization of the research field across two principal components explaining 73.96% of the total variance in keyword associations (Dim 1: 50.07%; Dim 2: 23.89%). The analysis identified three distinct thematic clusters representing different research trajectories within VR/AR applications for the AEC industry.

Cluster 1 (Blue) encompasses traditional AEC applications and core immersive technologies, including “construction,” “bim,” “construction safety,” “visualization,” “architecture,” “design,” “building information,” “augmented reality,” and “virtual-reality.” This cluster occupies the upper-left region of the map, representing established application domains where VR/AR technologies have achieved substantial implementation maturity.

Cluster 2 (Red) centers on emerging intelligent systems and learning technologies, featuring “digital twin,” “machine learning,” “deep learning,” “decision making,” “e-learning,” “learning systems,” and “human.” Positioned in the right region of the map, this cluster demonstrates the convergence of VR/AR technologies with artificial intelligence and advanced computational approaches for enhanced decision support and training applications.

Cluster 3 (Green) represents frontier computational paradigms, including “metaverse,” “blockchain,” “big data,” “artificial intelligence,” “extended reality,” “internet of things,” and “cyber-physical systems.” Located in the lower region of the map, this cluster indicates emerging research directions exploring the integration of immersive technologies within broader digital transformation frameworks.

The spatial organization demonstrates that core VR/AR concepts serve as conceptual bridges connecting these three domains, with terms such as “simulation,” “virtual reality,” and “mixed reality” positioned at cluster intersections. This three-cluster structure reveals a field simultaneously advancing along complementary trajectories: Consolidating established AEC applications, integrating intelligent decision-support capabilities, and expanding toward comprehensive cyber-physical ecosystems.

3.6 Citation performance metrics

The overall citation performance of the merged 1,553-article dataset indicated a substantial research impact, with an average of 29.75 citations per document across the entire collection. Temporal citation analysis revealed that documents from 2017 to 2020 achieved the highest citation impact, with 2017 publications showing the highest mean total citations per article (191.26) and the highest annual citation rate (21.25 citations per year), suggesting that this year produced particularly influential research that shaped subsequent developments in the field. Publications from 2018 (103.44 mean citations, 12.93 per year) and 2020 (86.49 mean citations, 14.41 per year) also demonstrated strong citation performance, establishing these years as foundational periods for VR/AR research in AEC applications.

The citation patterns reflected both the growing recognition of VR/AR technologies' potential in AEC applications and the increasing maturity of research methodologies and practical implementations. Earlier publications (2015–2017) demonstrated higher average citations per article due to longer citation windows, with 2015 showing 70.33 mean citations (6.39 per year) and 2016 showing 37.16 mean citations (3.72 per year). The consistently high citations per year for 2017–2020 publications, despite varying publication volumes, indicate sustained research quality and impact during this period of field establishment.

More recent publications naturally showed lower absolute citation counts owing to limited citation windows, with 2024 articles averaging 9.15 total citations (4.58 per year) and 2025 articles averaging 1.26 citations. However, the annual growth rate of 42.78% in publication output demonstrates the field's rapid expansion, suggesting that while individual article citations may be lower for recent works, collective knowledge production and dissemination has accelerated substantially. The multi-database validation approach, with a 29.4% overlap between Scopus and Web of Science, ensured comprehensive citation tracking across complementary indexing systems, providing robust citation metrics for the merged corpus.

The science mapping and bibliometric analysis of the 1,553-article dataset established a comprehensive quantitative foundation for understanding the research landscape of VR/AR technologies in AEC applications. The identified patterns of growth, collaboration, and thematic development, validated across two major databases, provide essential context for the qualitative thematic analysis that follows in the discussion section.

4 Discussion

4.1 Main application domains in AEC

The qualitative analysis of the 37 most influential studies reveals four primary application domains where VR/AR technologies demonstrate transformative potential within the AEC industry. These domains represent mature areas of implementation with demonstrated benefits and established research foundations.

Design and architectural visualization have emerged as the most developed application area, with VR providing superior conditions for collaborative decision-making and problem-solving during conceptual design phases (Paes et al., 2017). Users can experience materials, lighting, furniture, and architectural details from multiple perspectives on a real-world scale, thereby addressing the fundamental limitations of traditional BIM presentations (Alizadehsalehi et al., 2020). These immersive environments enhance spatial perception and understanding of 3D architectural models, enabling more suitable solutions for spatial problems through experiential interaction.

This technology has been specifically explored for specialized applications such as signage visibility analysis and optimization within BIM-enabled virtual reality environments (Dávila Delgado et al., 2020; Dávila Delgado et al., 2020). Despite these advantages, there remains a recognized scarcity of comparative, quantitative, and user-centered research demonstrating the effectiveness of immersive VR systems over traditional non-immersive approaches in architectural design (Paes et al., 2017).

Construction planning, monitoring, and assembly represent the second major application domain with demonstrated quantitative benefits. Experimental studies on Mixed Reality applications for electrical conduit construction design communication have revealed substantially higher productivity rates, reduced design comprehension time, fewer assembly errors, and increased accuracy in constructed conduits compared to traditional paper-based plans (Chalhoub and Ayer, 2018). AR visualization in piping assembly operations achieved remarkable improvements including a 50% reduction in task completion time, 50% decrease in assembly errors, 55% reduction in original time requirements, 46% decrease in rework time, and 66% reduction in error correction costs (Hou et al., 2015). Progress monitoring capabilities have been enhanced through frameworks integrating image processing, machine learning, BIM, and VR technologies for the on-demand automated simulation of construction projects (Rahimian et al., 2020).

Safety training and human-robot collaboration constitute the third critical application area, addressing workforce development and hazard mitigation challenges. VR applications in the Human-Robot Collaboration workspace design enable the comprehensive testing of workstation layouts, skill-based task distribution, virtual commissioning procedures, and safety protocol validation (Oyekan et al., 2019; Malik et al., 2020). Construction safety and health education benefit substantially from social and collaborative VR platforms that allow students to identify hazard scenarios, correct unsafe conditions through simulation tools, and acquire comprehensive safety knowledge through experiential learning (Le et al., 2015). The iCRT system captures detailed information from complex and hazardous construction activities such as underground excavation and piling operations, reproducing authentic practices in immersive virtual environments (Sepasgozar, 2020).

Facility management and urban planning applications represent the fourth domain, extending the VR/AR impact beyond construction phases into building operations and broader urban contexts. AR applications support the BIM-based inspection and maintenance of critical building systems, particularly fire safety equipment, enabling real-time access to system information and maintenance protocols (Chen et al., 2021). Urban planning and smart city development benefit from the integration of Geographic Information Systems and BIM as fundamental components for developing comprehensive 3D urban models, facilitating intelligent city planning processes, and managing complex urban infrastructure networks (Xia et al., 2022).

4.2 Technology integration patterns

The analysis revealed sophisticated integration patterns between VR/AR technologies and complementary digital systems that amplify their effectiveness within AEC workflows. These integrated approaches represent critical success factors for practical implementation and sustained adoption.

Digital Twins and Extended Reality convergence emerges as a fundamental integration pattern, with Digital Twins representing digital environments maintaining bidirectional linkages with physical counterparts, enabling advanced simulation capabilities and data-centric decision-making processes (Shahzad et al., 2022). XR technologies serve as critical interfaces for visualizing and interacting with Digital Twin systems, creating immersive bridges between virtual models and physical assets (Mourtzis et al., 2022; Alizadehsalehi and Yitmen, 2023). The Digital Twin-Reality Capture-to-Extended Reality system represents advanced integration, combining reality capture and XR technologies to create, capture, generate, analyze, manage, and visualize construction progress data and comprehensive reports (Alizadehsalehi and Yitmen, 2023).

Building Information Modeling integration serves as the foundational technology for VR/AR implementation, acting as a comprehensive source of geometric and building information (Du and Shi, 2018; Du and Zou, 2018; Alizadehsalehi et al., 2020). While interoperability between BIM and VR/AR tools remains fundamental, it has been identified as a primary obstacle owing to manual conversion processes and information loss during data transfer (Du and Shi, 2018; Rahimian et al., 2020). Despite these challenges, BIM-VR/AR integration enables the visualization of building designs in interactive, human-scale, and immersive formats, allowing users to interact with 3D models superimposed onto physical spaces while accessing additional contextual information.

The synergies of IoT, AI, and cloud computing synergies create comprehensive intelligent systems that enhance VR/AR capabilities through real-time data integration and advanced processing. IoT sensors provide real-time data from physical environments, which are integrated into BIM models and visualized through AR and VR applications, improving capabilities including fire safety monitoring and situational awareness (Tao and Zhang, 2017; Chen et al., 2021; Mihai et al., 2022). Artificial Intelligence and Machine Learning technologies enhance VR/R and Digital Twin system capabilities through advanced algorithms and automated processes, enabling intelligent systems through advanced control algorithms and sophisticated data processing capabilities (Schluse et al., 2018).

4.3 Current challenges and limitations

Despite significant demonstrated potential, the widespread adoption of VR/AR technologies in AEC remains constrained by numerous technical, economic, and human factors that require systematic attention for technology maturation.

Technical infrastructure and performance limitations are primary obstacles to practical implementation. High processing and equipment requirements demand specialized high-performance computing equipment and sophisticated algorithms operating under substantial computational loads to deliver satisfactory immersive experiences (Li X., 2018; Dávila Delgado et al., 2020). Building Information Modeling data conversion for visualization creates exceptionally large files that challenge even powerful computing systems, resulting in significant file size limitations that constrain model complexity and detail levels (Zaker and Coloma Pico, 2018; Alizadehsalehi et al., 2020). Hardware limitations persist across display technologies, with current head-mounted displays suffering from inadequate resolution and restricted fields of view, whereas commercial AR headsets demonstrate reliability issues including low refresh rates and resolution problems (Dávila Delgado et al., 2020; Chen et al., 2021).

Industry adoption and economic barriers constitute the most significant obstacles to the widespread implementation of VR/AR. High costs associated with hardware acquisition and comprehensive training consistently rank as the primary limiting factors (Zaker and Coloma Pico, 2018; Dávila Delgado et al., 2020). Industry perceptions continue to view AR and VR as expensive and immature technologies that are unsuitable for complex engineering and construction tasks (Dávila Delgado et al., 2020).

Construction firms frequently lack comprehensive knowledge of AR and VR market dynamics and capabilities, while skill shortages and difficulties accessing qualified graduates and expert knowledge in these technologies persist throughout the industry. Resistance to technological change represents a fundamental barrier, particularly among personnel and firms demonstrating aversion to adopting innovative technologies (Zaker and Coloma Pico, 2018).

Human factors and user experience challenges significantly impact VR/AR technology effectiveness and user acceptance. Users frequently report unrealistic interactions in virtual environments, such as multiple attempts to operate virtual door handles, leading to reduced efficiency and inconsistent experiences (Chen et al., 2021). VR training systems, while beneficial, may result in loss of the real-life experience and fail to replicate authentic mental load and stress levels compared to actual environments (Li X., 2018). Cognitive overload and distraction represent ongoing concerns, as AR and VR technologies can potentially increase cognitive loads and cause user distraction (Dávila Delgado et al., 2020).

4.4 Research gaps and future directions

The analysis identified significant research gaps that require systematic investigation for technology advancement and practical implementation improvement. Current research demonstrates a notable scarcity of comparative, quantitative, user-centered research demonstrating the effectiveness of immersive VR systems compared to traditional non-immersive approaches in architectural design applications (Paes et al., 2017). Empirical investigations requiring larger, more diverse participant groups, including expert practitioners, are necessary for comprehensive technology validation (Sepasgozar, 2020; Chen et al., 2021).

Methodological and technological limitations require future research, including improved calibration accuracy between real movements and virtual animations (Shi et al., 2019). VR training systems need development of sophisticated human-environment interaction capabilities to enhance immersive experiences (Chen et al., 2021), while automatic evaluation processes and methods for VR/AR applications require development (Li Z., 2018). Research approaches predominantly focus on technical development and individual risk factors rather than adopting multi-disciplinary system-thinking approaches that consider various risk types across complete project lifecycles (Zou et al., 2017).

Digital Twin research requires investigation into appropriate and realistic fidelity levels for different use cases, balancing implementation benefits with costs and technical complexity (Jones et al., 2020). Data ownership and integration between virtual entities represent critical but under-researched areas for Digital Twin development, while ethical considerations including privacy, transparency, and security value system encoding in socio-technical Digital Twins require further investigation (Mihai et al., 2022).

4.5 Implications for practice and research

The integrated analysis revealed both immediate opportunities and long-term strategic directions for VR/AR technology adoption in the AEC industry context. For practitioners, evidence supports focused implementation in proven application areas including design visualization, construction safety training, and progress monitoring, where quantitative benefits have been demonstrated. Organizations should prioritize BIM-VR/AR integration capabilities while addressing interoperability challenges through standardized data exchange protocols.

For researchers, this analysis indicates the critical need for user-centered evaluation methodologies, standardized performance metrics, and interdisciplinary collaboration frameworks. Future research should emphasize practical implementation studies over purely technical development, with particular attention to economic justification models and change management strategies that address industry adoption barriers.

4.6 Study limitations

This systematic review acknowledges several limitations that may have influenced the interpretation of findings. Despite the dual-database approach using both Scopus and Web of Science, the study's reliance on these two databases, while comprehensive for engineering publications, may have excluded relevant research, published in specialized construction industry venues or emerging interdisciplinary journals. The focus on English-language publications potentially limited the geographic and cultural diversity of the included studies. The citation-based selection approach for qualitative analysis inherently favors established publications with longer citation windows; consequently, although 317 articles from 2025 were included in the quantitative bibliometric analysis, none met the citation threshold for qualitative synthesis due to insufficient time for citation accumulation. This methodological trade-off prioritizes analysis of demonstrably influential research that has shaped the field's intellectual structure, while the quantitative analysis comprehensively captures recent publication trends and emerging topics. The rapid evolution of VR/AR technologies means that the technical limitations identified in the literature may not reflect current capabilities, requiring ongoing monitoring of technological developments and practical implementations.

5 Conclusion

This systematic review and science mapping analysis addresses the research objectives by providing a comprehensive quantitative assessment of Virtual Reality and Augmented Reality within the Architecture, Engineering, and Construction industry through robust multi-database validation. The dual-database approach using Scopus (1,301 articles) and Web of Science (898 articles) yielded a merged corpus of 1,553 unique publications spanning 2015–2025, with 29.4% overlap demonstrating complementary coverage and cross-validation of core influential research across both indexing systems.

The bibliometric analysis revealed exponential growth with publications increasing 37-fold from nine articles in 2015 to 331 in 2024, with a sustained annual growth rate of 42.78%, establishing VR/AR technologies as the mainstream research focus within AEC applications. The analysis identifies concentrated expertise among leading researchers, with Yonghao Wang and Huazhen Zhang (22 articles each), Steven K. Ayer (21 articles), and Yuxuan Zhang (20 articles) demonstrating sustained productivity, whereas international co-authorships (17.41%) indicate substantial global collaboration spanning multiple continents and research institutions.

The conceptual structure analysis reveals a two-dimensional intellectual organization spanning from emerging computational technologies (metaverse, artificial intelligence, and blockchain) to established AEC applications (BIM, construction safety, and visualization), with VR/AR concepts serving as conceptual bridges between technological innovation and practical implementation. The identification of the main research clusters through science mapping techniques reveals mature application domains including design visualization, construction planning and monitoring, safety training, and facility management, each demonstrating quantifiable benefits such as 50% reductions in task completion time and assembly errors in experimental studies.

The synthesis of key application domains and technological integration patterns shows sophisticated convergence with Digital Twins, BIM, IoT, and AI systems, thereby establishing comprehensive frameworks for practical deployment. The thematic map analysis identified motor themes (digital twins, metaverse, artificial intelligence), basic themes (digital twins, virtual reality, and augmented reality), and niche themes (Industry 4.0), revealing the field's maturation and strategic research directions. However, significant barriers including technical infrastructure limitations, economic constraints (hardware costs and training requirements), and human factors (user experience challenges and cognitive overload) continue to impede widespread industry adoption.

The analysis revealed critical research gaps requiring systematic attention, particularly the scarcity of comparative, quantitative, user-centered evaluation studies demonstrating immersive the effectiveness of VR systems compared to traditional approaches, and insufficient interdisciplinary collaboration frameworks addressing complete project lifecycles. Future research directions should prioritize practical implementation studies over purely technical development, standardized evaluation methodologies, economic justification models that address real-world adoption challenges, and Digital Twin research investigating appropriate fidelity levels balancing benefits with implementation costs.

For practitioners, the evidence supports strategic implementation in proven application areas (design visualization with 37-fold publication growth, construction safety training with demonstrated 50% error reductions, and BIM-integrated progress monitoring) while developing comprehensive change management strategies. Organizations should prioritize BIM-VR/AR integration capabilities while addressing interoperability challenges through standardized data exchange protocols. The multi-database validation approach ensures the robustness of these recommendations across complementary academic indexing systems.

This integrated quantitative and qualitative analysis, validated across Scopus and Web of Science databases with 453 unique journal sources and 4,707 contributing authors, provides essential guidance for researchers and practitioners navigating immersive technology adoption within the construction industry. The established research clusters, application domains, and integration patterns offer stable frameworks for continued innovation, while the identified limitations and research gaps define clear pathways for advancing both technological capabilities and practical implementation strategies in the rapidly evolving VR/AR landscape. The 29.4% database overlap confirms that both Scopus and Web of Science capture core influential research while contributing unique perspectives, strengthening the validity and comprehensiveness of the findings to guide future research directions and technology adoption strategies in AEC applications.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DS-P: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing. GB: Funding acquisition, Project administration, Validation, Writing – original draft, Writing – review and editing. MP: Project administration, Resources, Supervision, Writing – original draft, Writing – review and editing. TM-P: Data curation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing.

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