Leveraging Virtual Reality (VR) to Enhance Construction Design Management (CDM)

Muhammad Yusuf Nordin*, Kherun Nita Ali, Ahmad Faiz Azizi Ahmad Fauzi

Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia

***Corresponding Author**

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ABSTRACT

This study presents a systematic and bibliometric review exploring how Virtual Reality (VR) enhances Construction Design Management (CDM) through improved visualization, collaboration, and safety integration. Using the Web of Science Core Collection as the primary database, 59 peer-reviewed publications from 1999 to 2025 were analyzed using VOSviewer for keyword co-occurrence, author and journal co-citation, and document clustering to map the intellectual and thematic structure of VR-CDM research. The analysis reveals that global interest in VR applications within CDM has accelerated significantly since 2017, driven by the industry's digital transformation under Construction 4.0. The United States, the United Kingdom, and Italy dominate the research landscape, while developing nations, including Malaysia, remain underrepresented. Four dominant research clusters were identified: (1) design visualization and collaborative review, (2) BIM–VR integration, (3) safety management and training, and (4) human–technology interaction. The findings underscore VR's transformative potential in supporting safe-by-design and prevention-through-design principles by enabling early hazard identification and participatory design reviews. However, adoption remains constrained by high costs, interoperability challenges, a lack of standardization, and limited empirical validation. This review concludes that VR serves as a pivotal enabler for proactive, data-driven, and safety-oriented design management in the Construction 4.0 era. Future research should integrate VR with Artificial Intelligence (AI), Digital Twins, and Extended Reality (XR) to create intelligent safety design ecosystems aligned with evolving regulatory frameworks such as Malaysia's Occupational Safety and Health (Construction Work) (Design and Management) Regulations 2024.

Keywords: Virtual Reality; Immersive Technology; Construction; Design; Collaboration

INTRODUCTION

The advent of Industry 4.0, characterized by the integration of technologies such as the Internet of Things (IoT), artificial intelligence (AI), immersive visualization, cyber-physical systems, and big data analytics, has significantly reshaped industrial sectors, including construction. This transformation has culminated in Construction 4.0, which represents a shift from conventional, fragmented practices to digitally enabled, interconnected, and automated processes (Hajirasouli et al., 2025; Halder, 2025; Rasheed et al., 2024). Within this paradigm, Virtual Reality (VR) has emerged as a pivotal technology, particularly in the context of Construction Design Management (CDM), a framework closely aligned with safe-by-design and prevention-through-design approaches. CDM emphasizes early-stage hazard identification and risk mitigation, ensuring that health and safety are embedded into design decisions (Yusoff et al., 2025). However, harmonizing multiple stakeholders and integrating safety considerations into design reviews remain persistent challenges. VR offers promising avenues to address these issues by creating immersive, data-rich environments that enhance spatial understanding, collaboration, and decision-making across project stages (Pham et al., 2025; Renganathan et al., 2025).

VR is often described as a computer-generated 3D environment that provides immersive, interactive experiences, usually mediated by head-mounted displays, enabling stakeholders to engage with digital prototypes in real time (Nikolić & Whyte, 2021; Rubio-Tamayo et al., 2017). In CDM processes, where reliance on 2D drawings often hinders the identification of safety risks, VR can facilitate iterative, participatory design reviews. By providing a shared virtual environment, stakeholders (architects, engineers, contractors, and clients) can collaboratively visualize complex construction designs, detect hazards, and assess safety implications before implementation (Afzal et al., 2021; Pham et al., 2025). Importantly, VR allows the simulation of construction sequencing, temporary works, and access planning, which are critical elements in CDM-related safety design reviews (Afzal et al., 2021; Hare et al., 2019). Such applications align with CDM's core objective of designing out risks at source, ensuring safer and more efficient project delivery.

Despite these advantages, several challenges impede the widespread adoption of VR in CDM. High equipment costs, intensive computational requirements, and limited expertise constrain its practical application (Pham et al., 2025; Turner et al., 2016). Additionally, integrating VR with Building Information Modelling (BIM), a central component of Construction 4.0, remains a technical and procedural challenge, particularly when adapting BIM datasets for immersive design review (Mastrolembo Ventura et al., 2019; Tariq et al., 2019). Issues of stakeholder acceptance and the absence of standardized protocols for incorporating VR into safety-driven design reviews also hinder implementation (Elbir, 2025; Karakhan & Gambatese, 2017). These barriers underscore the importance of systematic evaluation to identify effective adoption strategies.

To date, most bibliometric and systematic reviews of VR applications have focused on domains such as training, education, and design visualization (Angra et al., 2025; Korkut & Surer, 2023; Rojas-Sánchez et al., 2023). However, relatively few studies explicitly analyze VR's role in Construction Design Management and safety-by-design processes. This gap is significant, as leveraging VR within CDM not only supports hazard identification but also enhances regulatory compliance, communication efficiency, and stakeholder engagement in line with frameworks such as the UK CDM Regulations (2015) and Malaysia's CDM 2024 Regulations. By consolidating fragmented studies through bibliometric and systematic methodologies, this research aims to clarify key themes, trace research trajectories, and propose future directions for VR-enabled CDM. Specifically, the review addresses the following research questions: (RQ1) What are the most relevant keywords in VR and CDM research? (RQ2) Which journals and authors are most productive in advancing VR-CDM scholarship? (RQ3) What are the dominant thematic clusters in this field? And (RQ4) What emerging trends and gaps define the future of VR-CDM integration?

A systematic and bibliometric review methodology was employed, primarily using the Web of Science (WoS) database, to capture relevant literature on VR in CDM. Systematic reviews, as described by (Haddaway et al., 2015), provide structured and reproducible approaches for evaluating fragmented scientific outputs, while bibliometric techniques allow for the mapping of research interrelationships, influence, and impact (Pessin et al., 2022). Through this combined methodology, the study highlights critical insights into VR's transformative potential in enhancing safety-focused design management, while also identifying adoption barriers and opportunities for future investigation. Ultimately, this review contributes to both theoretical and practical knowledge, reinforcing the argument that VR-enabled CDM represents a paradigm shift in advancing safe, collaborative, and efficient construction practices.

METHODOLOGY

For this review, academic papers relevant to the application of Virtual Reality (VR) in Construction Design Management (CDM) were systematically collected from recognized scientific databases. The Web of Science (WoS) core collection was selected as the primary data source, as it provides comprehensive coverage of high-impact journals and ensures reliable indexing of peer-reviewed literature across engineering, construction, and technology domains (Marzouk et al., 2025). Clearly defining the scope of the research field is a critical step to reduce the risk of overlooking significant contributions and to establish the boundaries of analysis (Cao & Shao, 2020). Accordingly, this study adopts a systematic review methodology combined with science-mapping techniques to identify publication trends, thematic clusters, and emerging research directions in VR applications within CDM. Science mapping, often operationalized through bibliometric tools such as VOSviewer, enables the visualization of co-authorship networks, keyword co-occurrences, and citation linkages, thereby offering valuable insights into the intellectual and conceptual structure of the field

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(Petrovich, 2021; N. J. van Eck, 2011). The methodological framework guiding this research, including data collection, screening, and analysis procedures, is presented in Figure 1, which outlines the sequential steps employed to ensure rigor, transparency, and reproducibility in the review process.

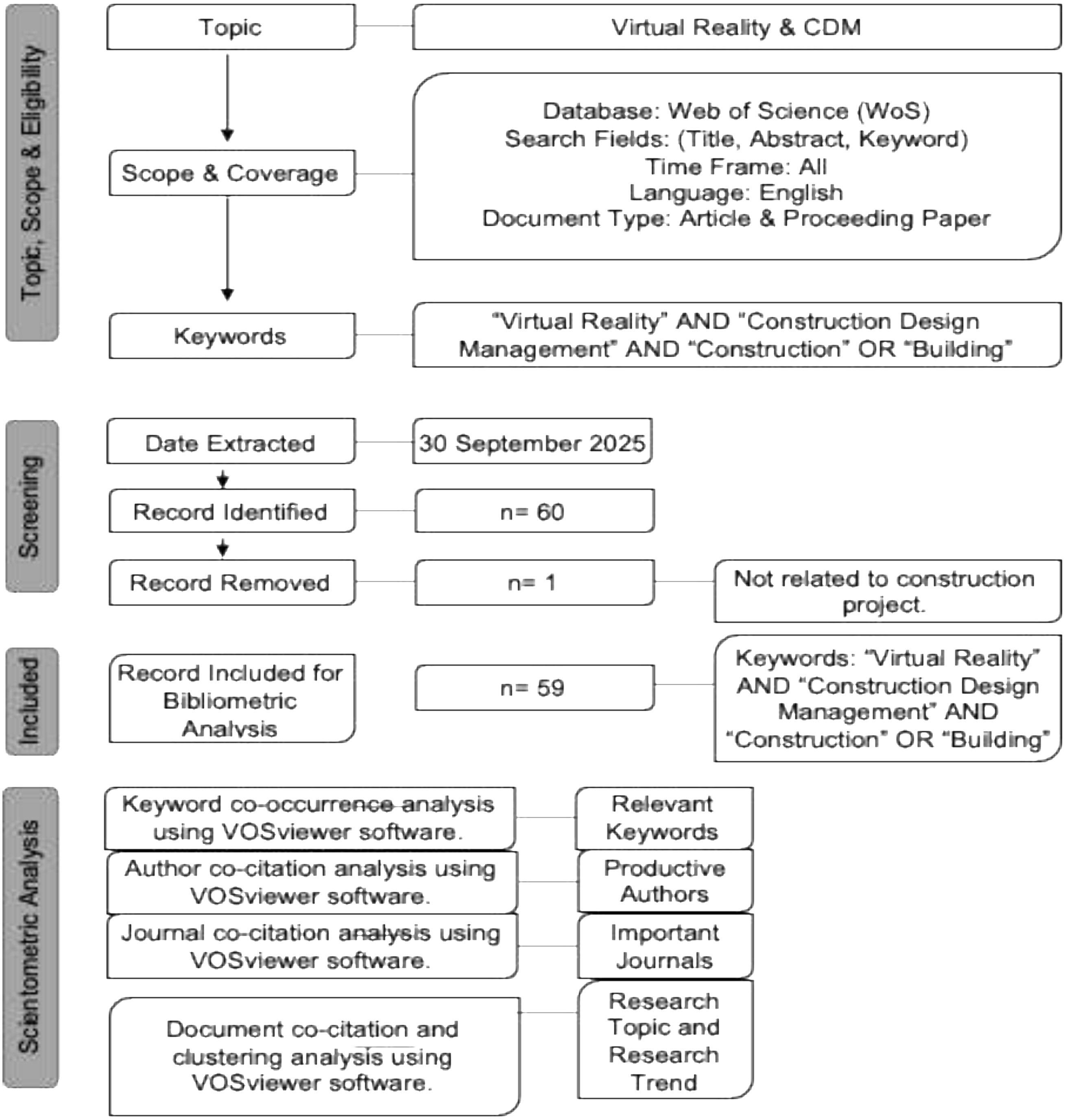

Figure 1 Diagrammatic representation of the search methodology process

Bibliometric Analysis

Bibliometric analysis is a widely adopted statistical method for evaluating the intellectual structure, academic impact, and research development of scientific fields through publication metadata. It typically involves analyzing indicators such as citation counts, co-authorship networks, keyword co-occurrence, and publication trends, which collectively illuminate the evolution of a field and the influence of leading scholars, journals, and institutions (Petrovich, 2021; N. J. van Eck, 2011). In this study, bibliometric analysis is employed to examine the academic landscape of Virtual Reality (VR) applications in Construction Design Management

(CDM). In this domain, VR is increasingly positioned as a transformative tool for embedding safety, risk mitigation, and collaborative decision-making into early-stage design processes (Pham et al., 2025; Robertson De Ferrari, 2023).

The Web of Science (WoS) Core Collection was selected as the primary database for this review, given its rigorous indexing standards, extensive coverage of high-quality peer-reviewed journals, and robust citation tracking capabilities (Pranckutė, 2021; Yan & Zhiping, 2023). Compared with alternatives such as Scopus and Google Scholar, WoS is considered exceptionally reliable for bibliometric studies due to its detailed citation linkages and advanced filtering tools that enhance the precision of literature retrieval (Yan & Zhiping, 2023). This is essential when mapping multidisciplinary research fields like VR-enabled CDM, which intersects with construction engineering, architecture, computer science, safety management, and sustainability research.

To maintain transparency and reproducibility, the review applied explicit inclusion criteria, restricting the dataset to English-language journal articles and conference proceedings. The finalized search query, conducted in September 2025, was designed to capture the breadth of VR applications within CDM-related contexts while minimizing irrelevant records. Following the initial database retrieval, the dataset underwent a two-stage screening process in which document titles and abstracts were manually reviewed to confirm relevance to VR in CDM. This rigorous procedure resulted in the selection of 59 documents, comprising 40 peer-reviewed journal articles and review papers and 19 conference proceedings. Such a dataset size is consistent with other bibliometric analyses in emerging domains, where research outputs remain fragmented yet rapidly expanding (Wen et al., 2021)

"Virtual reality" OR "vr" OR "immersive virtual reality" OR "IVR" OR "head-mounted device" (Topic) and "construction design management" OR "CDM" OR "safe-by-design" OR "sbd" OR "prevention through design" OR "ptd" OR "osheim" OR "design review" OR "safety design review" (Topic) and "construction" OR "building" OR "architecture" OR "AEC"

By applying bibliometric analysis alongside a systematic review, this study provides a robust foundation for identifying research clusters, knowledge gaps, and future directions for leveraging VR to enhance CDM. The methodological framework ensures not only the quantitative mapping of the field but also a critical qualitative synthesis of how VR is reshaping safety-oriented design management practices in the construction industry.

Below, we present the inclusion and exclusion criteria for studies in this review.

Inclusion Criteria

- Studies discussing various aspects of Virtual Reality (VR) in Construction Design Management (CDM), including its role in improving visualization, collaboration, and decision-making in construction projects.
- Studies focusing on the application of VR technologies such as Building Information Modelling (BIM) integration, Digital Twins, and immersive visualization within the Construction Design Management context.
- Studies analyzing the strengths, limitations, and potential applications of VR in CDM emphasize its benefits for design coordination, communication, and training, as well as challenges related to cost, interoperability, and evaluation metrics.
- Studies published in English.

Exclusion Criteria

- Studies published in languages other than English were excluded.
- Studies that discuss Construction Design Management (CDM) without reference to Virtual Reality (VR) were excluded.

- Grey literature (e.g., conference abstracts, unpublished reports) was excluded to ensure the quality, reliability, and academic rigor of the bibliometric review findings.

Systematic Review Analysis

A systematic review is a rigorous research methodology designed to identify, evaluate, and synthesize all available evidence on a given topic in a structured, transparent, and replicable manner (Shaheen et al., 2023). Unlike traditional narrative reviews, which are often descriptive and potentially biased, systematic reviews adopt predefined protocols, inclusion and exclusion criteria, and reproducible search strategies to minimize subjectivity and ensure methodological rigor (Siddaway et al., 2019). This study conducts a systematic review to examine how Virtual Reality (VR) has been leveraged in Construction Design Management (CDM). CDM emphasizes early hazard identification, risk elimination, and safety integration in the design phase. In this area, immersive VR environments can significantly enhance visualization, stakeholder engagement, and decision-making (Balali et al., 2018; Gutierrez-Bucheli et al., 2025). The systematic review not only synthesizes evidence on VR-enabled CDM but also visualizes and maps the knowledge domain to capture thematic trends, research clusters, and emerging directions.

Within bibliometric studies, keywords, abstracts, and titles serve as analytical units that provide insight into the intellectual and conceptual structure of a research field (Zupic & Čater, 2015). In this review, bibliometric techniques were applied to systematically explore VR's role in CDM by analyzing publication metadata. This methodological choice is consistent with established scientometric practices, which employ keyword co-occurrence to identify core research themes. At the same time, citation-based analyses reveal influential works and scholarly collaboration networks (Donthu et al., 2021).

To uncover the prevailing patterns in VR-CDM scholarship, several analytical methods were utilized. First, keyword co-occurrence analysis was performed to highlight the frequency and relational patterns of core terms such as “virtual reality,” “safety in design,” and “BIM integration.” This was followed by author and document co-citation analyses, which identify key contributors, foundational works, and the field's intellectual lineage (Chen, 2017). Burst detection analysis was applied to track temporal shifts and identify emerging topics, thereby revealing the dynamic evolution of VR-CDM research over time (Kleinberg, 2002). Additionally, journal co-citation and bibliographic coupling were conducted to assess the connectivity among research outlets, allowing the identification of distinct clusters within the literature (Leung et al., 2017).

Before clustering analysis, keyword co-occurrence and co-citation results provided a broad overview of the VR-CDM knowledge landscape. Burst detection further enhanced this by tracing the evolution of research themes, highlighting emerging emphases such as VR for hazard visualization, collaborative design reviews, and integration with BIM for safety management (Han et al., 2016; Swallow & Zulu, 2024). The clustering of co-cited documents allowed the delineation of thematic areas, with representative terms assigned to each cluster to capture the underlying research direction. This combined methodological framework not only reveals the intellectual structure of VR in CDM but also facilitates a deeper understanding of how the field is developing, where research gaps exist, and what future opportunities can be pursued.

RESULT AND FINDINGS

Data Acquisition

Academic publications, journals, and conference papers on virtual reality in the construction industry were extracted using a keyword search strategy from the Web of Science database. The Web of Science database allows users to explore and sort required materials by subject, as shown in Figure 2. According to the statistics, 67% of the publications were linked to Engineering Civil & Construction Technology, and 33% were related to Computer Science.

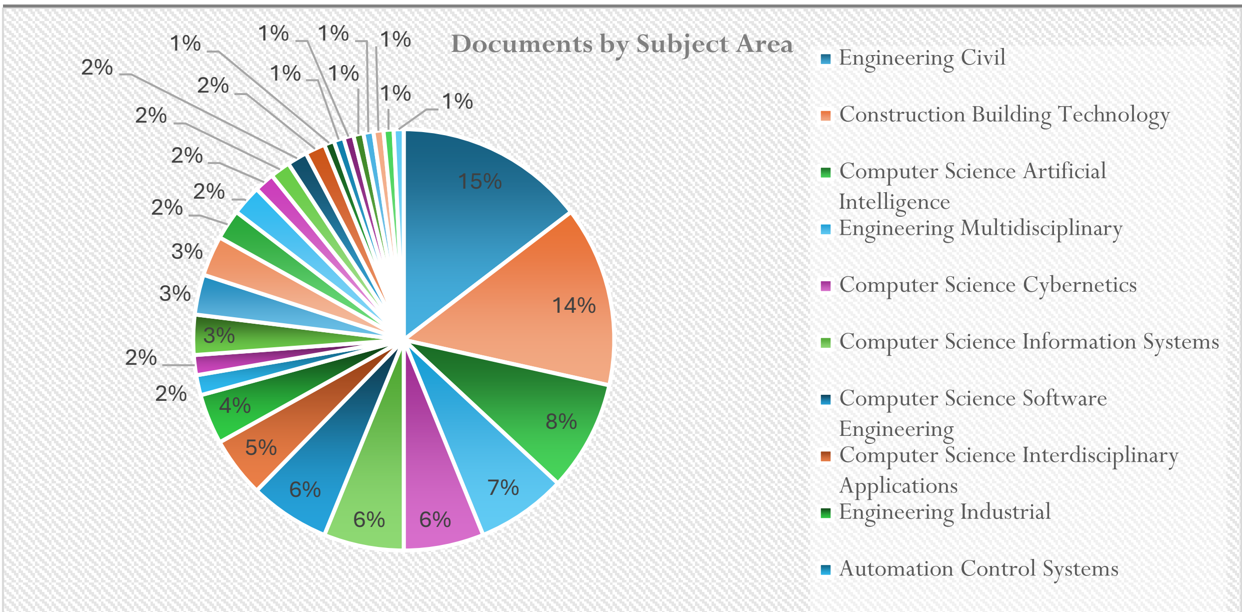

Figure 2 Documents by subject area.

Figure 3 presents the annual distribution of published documents about the application of virtual reality (VR) within the construction industry, as indexed in the Web of Science database. The data reveal a discernible upward trajectory in the number of publications from 2017 through 2025, with notable peaks in scholarly output in 2020 and 2021, each accounting for eight publications. This trend reflects the growing academic and practical interest in VR technologies as a transformative tool in construction, underscoring their increasing relevance and application in the field. It is crucial to acknowledge that the 2025 data cover only the first 9 months of the year. Given the established trend of increasing publication numbers in previous years, it is plausible to anticipate that the total number of publications for 2025 will exceed the current figures, thereby reinforcing the ongoing upward trajectory of VR research in enhancing CDM.

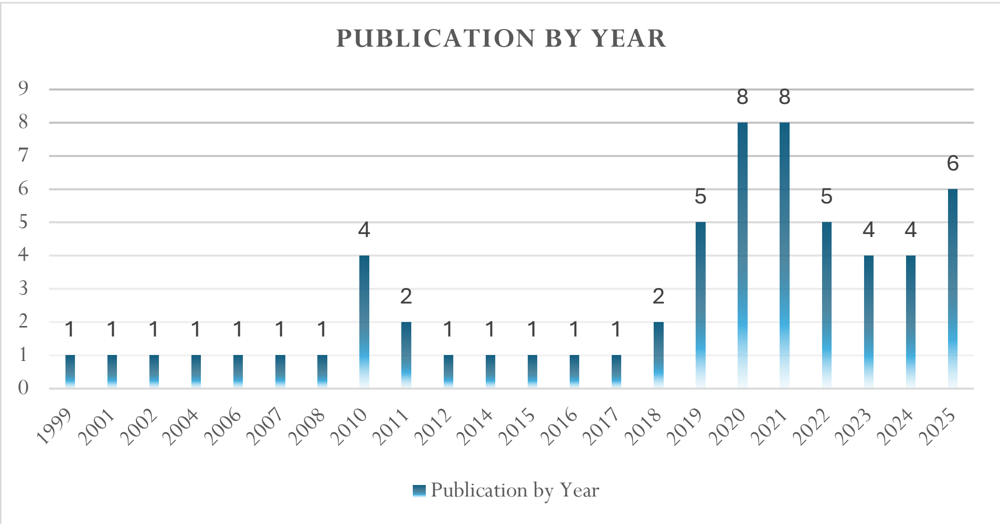

Figure 3 Publication by year

Figure 4 depicts the publishing profiles of the top 10 countries contributing to research on virtual reality (VR) in the Web of Science database. The United States leads globally, producing 20 published documents, which underscores its dominant position in advancing VR research. This significant output reflects the country's substantial investment in technological innovation and interdisciplinary research, which have facilitated the rapid development and application of VR technologies across various fields, including construction.

England follows with nine published documents, demonstrating its growing influence and commitment to research in emerging technologies. Italy ranks third, contributing eight published documents, highlighting its

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robust academic infrastructure and collaborative research environment that foster advancements in VR technology. Germany and China followed with seven published documents. China's rise in VR research output can be attributed to its strategic focus on digital transformation and innovation, supported by both government policies and industry-driven initiatives.

South Korea, with five published documents, and Australia, with 3, also feature prominently among the leading nations in VR research. South Korea's strong presence is likely driven by its advanced technological ecosystem and culture of innovation, particularly in sectors such as electronics and digital technologies, which overlap significantly with VR. Similarly, Australia's contributions reflect its active participation in global research networks and its focus on integrating VR into diverse applications, including construction and architectural design.

The data presented in Figure 4 not only illustrate the geographic distribution of VR research but also provide insights into international collaboration and the dissemination of knowledge within this rapidly evolving field. The global nature of VR research is evident, with contributions from diverse nations that bring unique perspectives and expertise to the development and application of VR technologies.

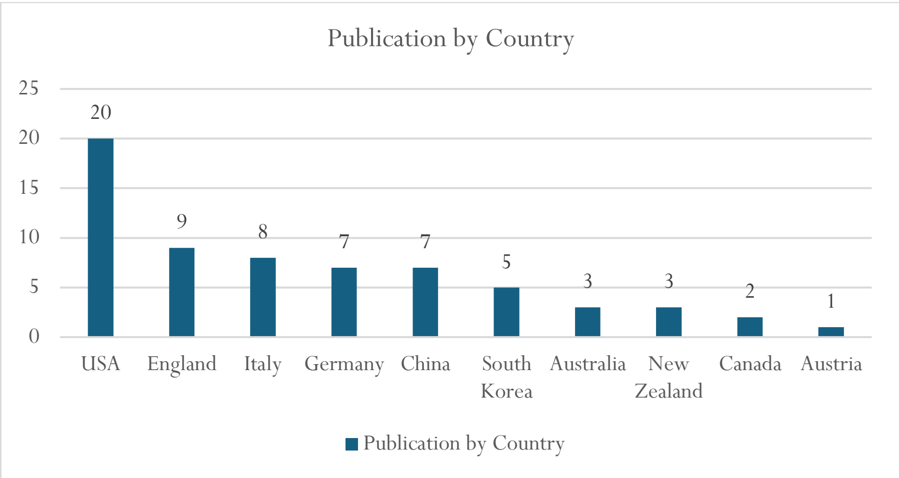

Figure 4 Publications per country

Keyword Co-Occurrence Analysis

Keywords serve as critical indicators of a document's thematic content, succinctly encapsulating the core concepts and research focus within the delineated boundaries of a specific academic domain. In this study, the bibliometric tool VOSviewer was used to perform a sophisticated keyword co-occurrence analysis, using data from the Web of Science database(N. Van Eck & Waltman, 2010). The resulting visualizations are distance-based network maps, in which the spatial proximity between nodes indicates the strength of the conceptual linkage between keywords; closer nodes signify a stronger conceptual linkage. The size of each node within these visualizations is directly proportional to the frequency with which a keyword appears across the body of literature, providing a visual metric of its significance within the research field (N. J. van Eck, 2011). Moreover, VOSviewer incorporates an advanced clustering algorithm that systematically groups related keywords into clusters, each represented by a distinct color. This clustering technique enhances the identification of coherent thematic subfields within the broader research landscape (N. J. Van Eck & Waltman, 2014).

For this analysis, a selective criterion was applied, selecting only keywords with high frequency in the network mapping. Specifically, the threshold for keyword inclusion was set at three occurrences, resulting in the identification of 23 qualifying keywords out of 290 total keywords in the Web of Science database. Table 1 provides a detailed summary of these frequently occurring keywords, including their respective occurrence counts and total link strengths, offering a comprehensive overview of prevailing research trends and focal points in the domain of virtual reality applications in the construction industry.

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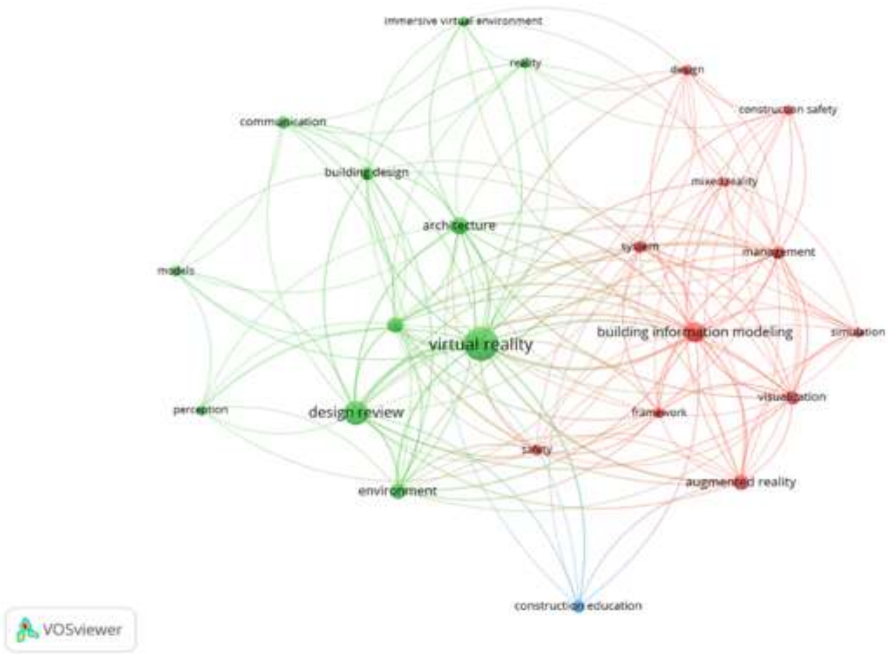

Figure 5 Keyword co-occurrence network

Using the VOSviewer statistical technique, Table 1 identifies "virtual reality" as the most frequently occurring author keyword in the literature, with 35 occurrences. "Design review" is the second-most prevalent keyword, with 18 occurrences, followed by "building information modelling," which appears 13 times. The links depicted represent the number of connections between a particular node and others, while the total link strength reflects the cumulative strength of these connections. Notably, the total link strength for "virtual reality" is 87, the highest among all nodes, indicating its significant interrelation with other keywords in the context of construction projects.

Table 1 Selected keywords with network parameter.

Keyword	**Occurrences**	**Total Link Strength**
Virtual Reality	35	87
Building Information Modelling	13	56
Design Review	18	51
Architecture	10	40
Construction	8	37
Visualization	6	33
Augmented Reality	8	32
Environment	8	32
Management	5	30
Framework	4	27
Building Design	6	21
System	5	21
Safety	4	19
Mixed Reality	3	16

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Design	4	15
Simulation	3	15
Construction Safety	3	14
Construction Education	5	13
Communication	5	12
Reality	4	11
Immersive Virtual Environment	3	10
Models	4	9
Perception	3	9

Author Co-Citation Analysis

VOSviewer is a software tool utilized for bibliometric analysis, including Author Co-Citation Analysis (ACA). It can handle large datasets and provides network data mapping and visualization features (Pessin et al., 2022). ACA is a method for uncovering the intellectual structure of a scientific field by analyzing the frequency with which authors are cited together. VOSviewer facilitates the visualization of ACA by creating bibliometric networks, which can be analyzed quantitatively and visually (Wen et al., 2021). Interestingly, while VOSviewer is traditionally used for bibliometric data, its application has been extended to text analysis, demonstrating its versatility (Pessin et al., 2022). Moreover, VOSviewer's capabilities are not limited to ACA; it can also be employed for other bibliometric analyses, such as co-occurrence and citation analysis (Leung et al., 2017). The author's co-citation network is depicted in Figure 6. The node size represents each author's co-citation frequency, and connections between nodes reflect citation relationships created by the number of citations.

The top-ranked author for Web of Science is (Castronovo, F), with citation counts of 29. The second and third (Paes D; Heydarian, A), with 26 citation counts. Next, it was followed by (Dunston, PS) with 25 citation counts, (Sacks, R) with 16 citation counts, (Majumdar, T) with 15 citation counts, (Shen, WL) with 14 citation counts, (Du, J) with 13 citation counts, (Liu, YF) with 12 citation counts, and (Whyte, J) with citation counts of 11. The authors exhibiting the most pronounced citation bursts, defined by a rapid and substantial increase in citations over a brief period, have been identified and methodically ranked, as shown in Figure 7.

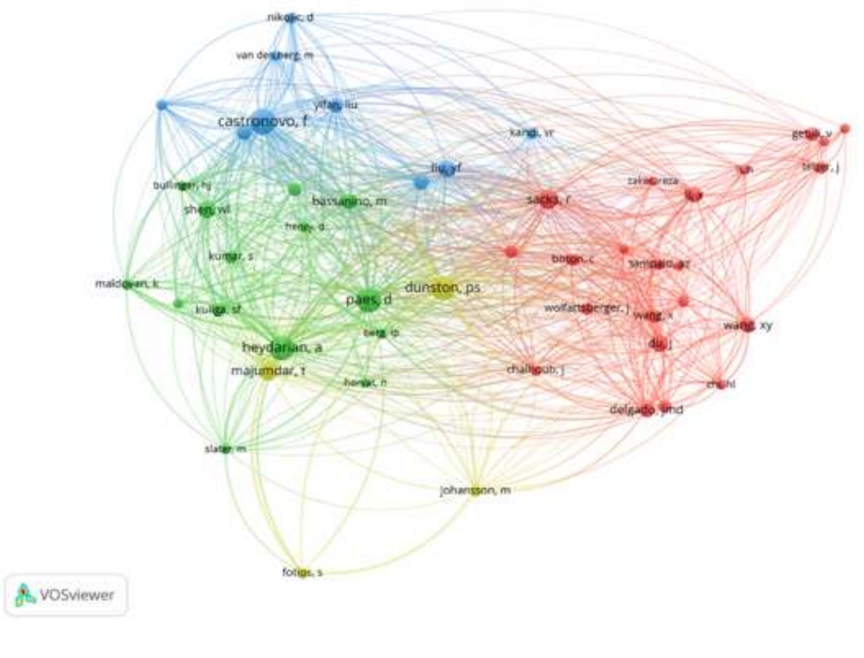

Figure 6 Author Co-Citation Analysis

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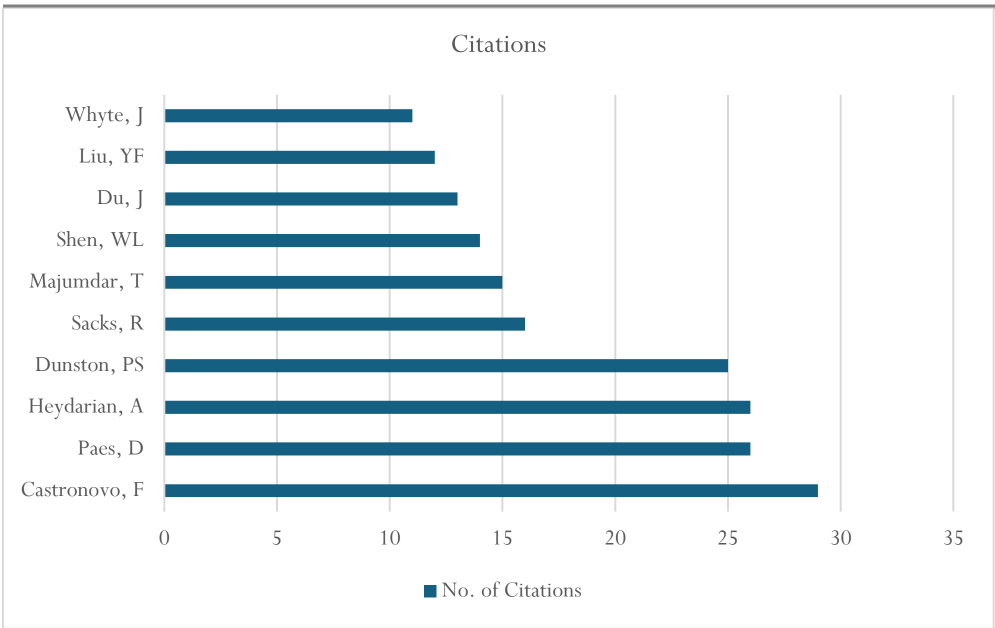

Figure 7 Authors with the strongest citation bursts

Journal Co-Citation Analysis

A journal co-citation analysis was conducted using VOSviewer, yielding a co-citation network comprising 68 nodes based on data from the Web of Science database. As illustrated in Figure 8, the size of each node corresponds to the frequency of citations, with more frequently cited journals represented by larger nodes within the network. The highest-ranked journal by citation count is Automation in Construction, with 253 citations. This is followed by the Journal of Information Technology in Construction, with 49 citations; the Journal of Advanced Engineering Informatics, with 43 citations; the Journal of Safety Science, with 40 citations; and finally, the Journal of Computing in Civil Engineering, with 40 citations.

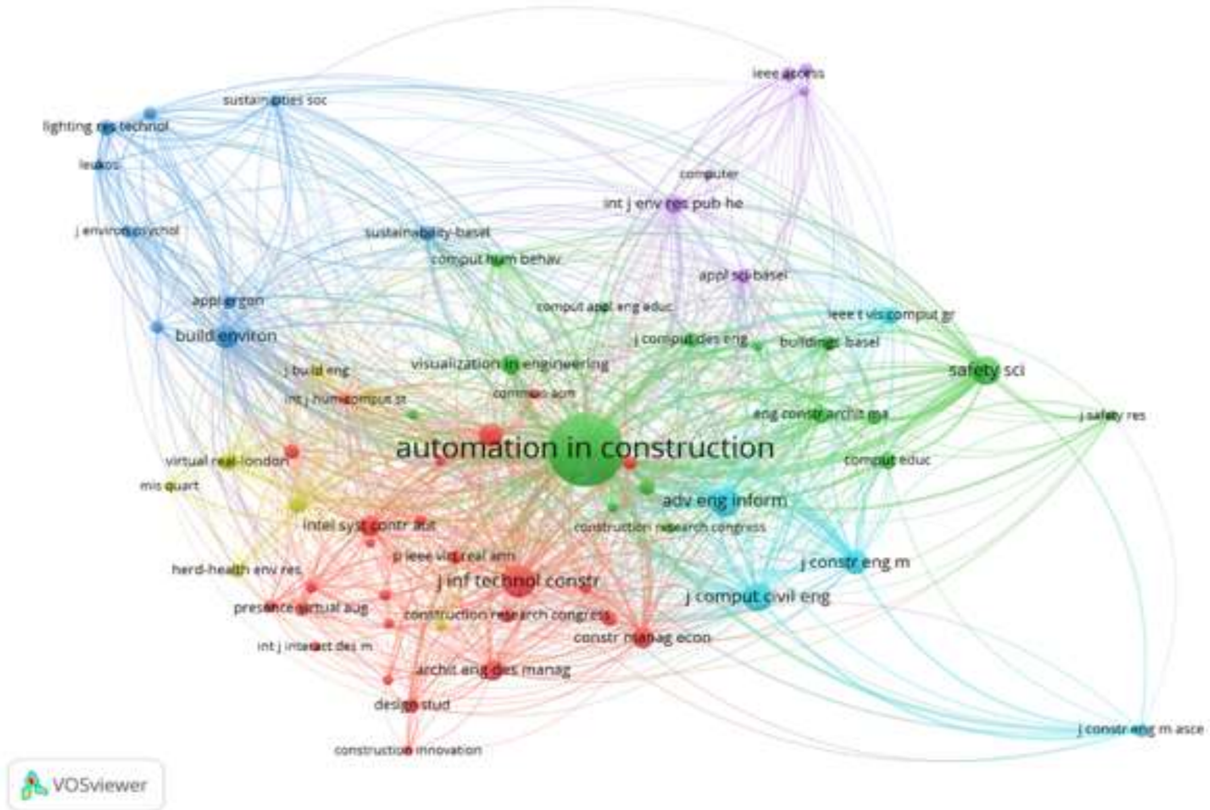

Figure 8 Journal co-citation network

Document Co-citation and Clustering Analysis

The document co-citation network serves as a valuable tool for visualizing and understanding the structure of research fields by clustering documents based on shared citation patterns. This approach helps to identify emerging trends and key research clusters within a given field (Chen, 2017; Small, 1973). In the present analysis, a co-citation network with 29 nodes and 117 links was constructed, as demonstrated in Figure 9. Each node represents a distinct document, and node size reflects its co-citation frequency, while links denote co-citation relationships between documents (Small, 1973). The network's structural properties are assessed using two key metrics provided by VOSviewer: modularity (Q) and silhouette score (S). According to Newman (2006), a modularity score exceeding 0.3 is generally considered high, indicating that the network consists of loosely connected clusters. Furthermore, a silhouette scores greater than 0.5 means that the network exhibits heterogeneous clustering, implying well-defined, distinct clusters (Rousseeuw, 1987; N. Van Eck & Waltman, 2010). Such structural assessments are essential for understanding the overall organization and coherence of the research field.

As depicted in Figure 10, a co-authorship network was constructed to map significant contributors to virtual reality research and its evolving trends. The network was generated using a threshold that required each author to have at least one publication with at least one citation to be considered noteworthy. Out of the 207 authors analyzed, 173 met these inclusion criteria. Table 2 presents the leading authors in this research domain, ranked by the number of publications, citation counts, and link strength. These bibliometric indicators are widely recognized for assessing both the productivity and impact of researchers within academic networks(Aksnes et al., 2019; Wagner & Leydesdorff, 2005). Citation scores reflect an author’s influence in the field, while link strength denotes the frequency and intensity of collaborations between authors, which is critical for understanding co-authorship dynamics (Glänzel & Schubert, 2004). Such metrics are frequently used to analyze the structure of scientific collaboration and the formation of research communities (Katz & Martin, 1997; Newman, 2004).

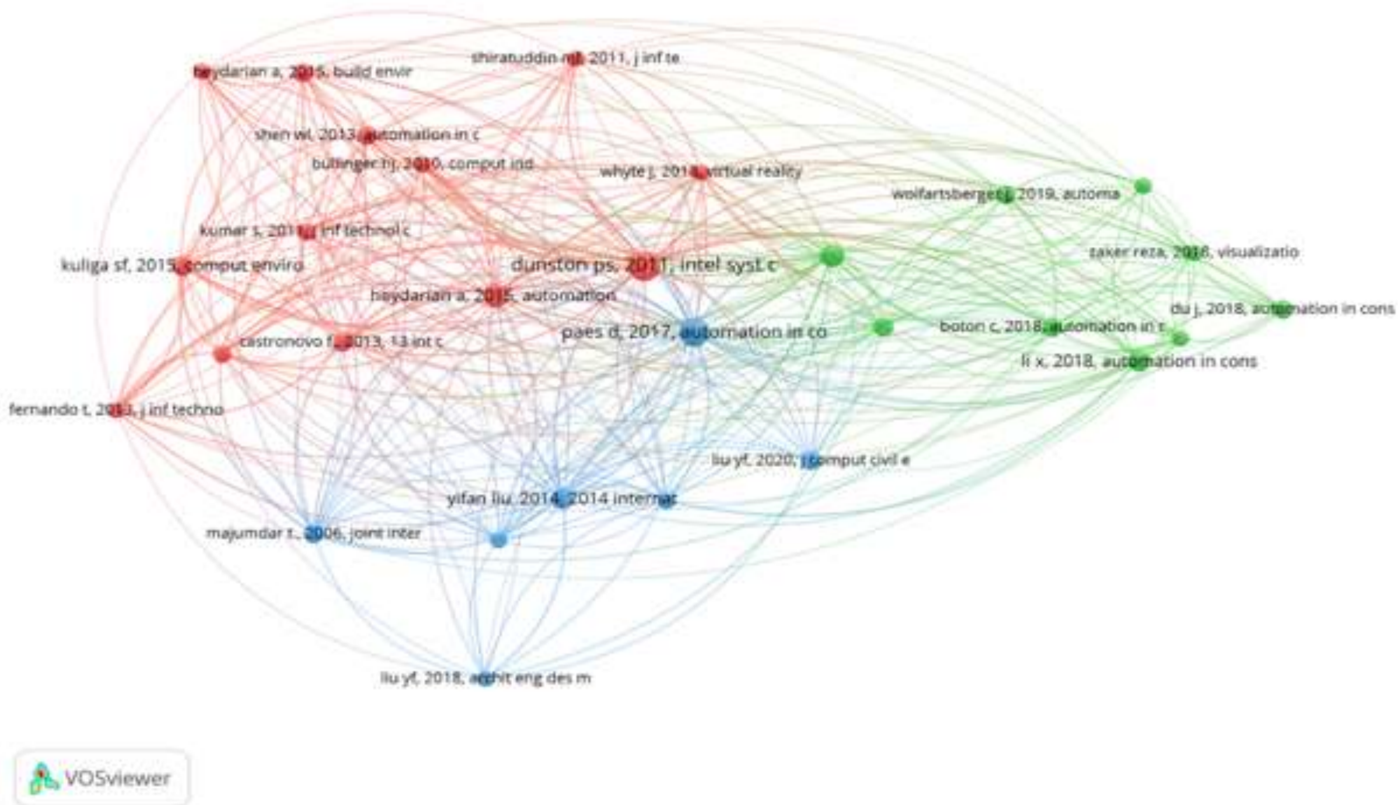

Figure 9 Network of document co-citation analysis

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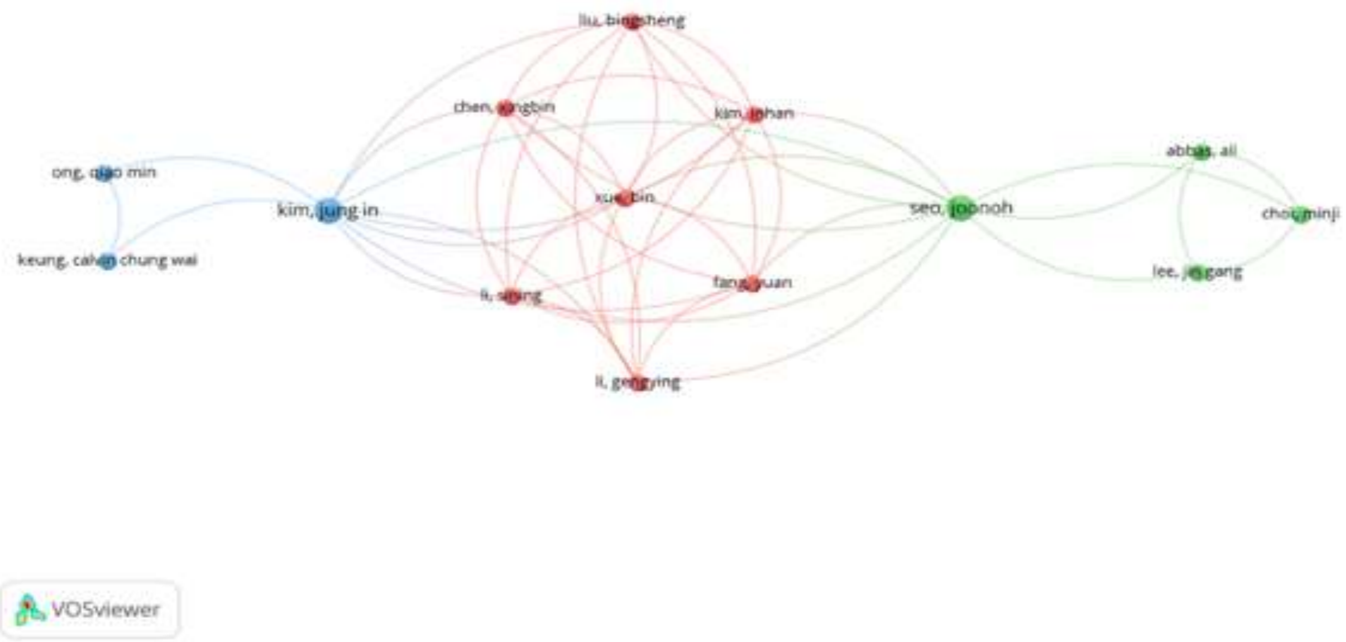

Figure 10 Network visualization of the co-authorship network

Table 2 Leading authors in virtual reality

Author	Documents	Citations	Total Link Strength
Seo, Joonoh	2	38	11
Kim, Jung In	2	22	10
Abbas, Ali	1	35	3
Choi, Minji	1	35	3
Lee, Jin Gang	1	35	3
Keung, Calvin Chung Wai	1	19	2
Ong, Qiao Min	1	19	2
Chen, Xingbin	1	3	8
Fang, Yuan	1	3	8
Kim, Inhan	1	3	8
Li, Gengying	1	3	8
Li, Sining	1	3	8
Liu Binsheng	1	3	8
Xue, Bin	1	3	8

DISCUSSION

This section synthesizes and interprets the bibliometric and systematic review findings, focusing on how Virtual Reality (VR) is leveraged to enhance Construction Design Management (CDM). The analysis explores the trajectory of research development, intellectual structures, thematic evolution, and the implications of integrating VR into safety-driven design processes. In line with the research questions, this discussion situates the findings within the broader context of Construction 4.0, highlighting both advances and persisting challenges in realizing VR's potential as a transformative design management tool.

Research Development and Global Research Dynamics

The upward trajectory in annual publications from 2017 to 2025 signifies VR's growing importance in construction design and safety research. The surge during 2020–2021 corresponds with increased digital transformation efforts catalyzed by Industry 4.0 initiatives, which emphasized automation, real-time visualization, and integrated project delivery (Oesterreich & Teuteberg, 2016; Swallow & Zulu, 2024). The dominance of the United States, England, and Italy in publication output reflects regions with strong technological infrastructures and funding ecosystems conducive to VR adoption in construction (Fakoyede et al., 2024).

Conversely, developing economies, including Malaysia and other Southeast Asian nations, remain underrepresented. This uneven geographic distribution reveals a digital divide in VR research and implementation, often linked to high equipment costs, limited technical expertise, and insufficient regulatory incentives (Selvaprasanth et al., 2021). Nevertheless, Malaysia's forthcoming Occupational Safety and Health (Construction Work) (Design and Management) Regulations 2024 present a unique opportunity to advance VR adoption for hazard visualization and risk management during early design stages. This regulatory evolution aligns with international CDM practices, emphasizing proactive safety integration and design accountability (Hussain et al., 2025).

Thematic and Conceptual Insights from Keyword Networks

The keyword co-occurrence analysis highlights "virtual reality," "design review," and "building information modelling (BIM)" as dominant clusters, reflecting the strong interconnection between immersive technologies and data-driven design management. The prevalence of "safety," "simulation," and "collaboration" underscores a thematic shift toward VR applications that prioritize communication and risk awareness across multidisciplinary teams (Patel et al., 2012; Truong et al., 2021). This aligns with CDM's preventive ethos, which emphasizes eliminating early risks through design interventions rather than post-construction controls.

Furthermore, the emergence of keywords such as "mixed reality," "augmented reality," and "digital twin" signals a convergence toward integrated extended-reality (XR) ecosystems (Kostadimas et al., 2025). These technologies collectively expand the cognitive and perceptual dimensions of design management, offering enhanced visualization of complex construction environments and dynamic safety scenarios. Such integration of XR technologies supports the broader Construction 4.0 paradigm by bridging gaps between digital design, on-site execution, and post-occupancy performance evaluation (Donthu et al., 2021).

Intellectual Structure and Core Scholarly Contributions

The author's co-citation and journal co-citation analyses reveal a concentrated intellectual foundation, shaped by key contributors such as Castronovo, Paes, Dunston, and Sacks, who are known for pioneering VR applications in collaborative design and safety visualization. Journals like Automation in Construction and Advanced Engineering Informatics serve as primary platforms for disseminating high-impact research in this domain, demonstrating their centrality within the bibliometric network (Chen, 2017).

The modularity (Q) and silhouette (S) indices of the document co-citation network indicate a well-defined clustering structure, suggesting that VR-CDM research has matured into several coherent thematic areas. These include:

1. VR for Design Visualization and Review – focusing on real-time design validation and spatial cognition (Korkut & Surer, 2023; Lepola et al., 2020);

2. BIM–VR Integration – addressing data interoperability and model synchronization (Mastrolembo Ventura et al., 2019);

3. Safety Management and Training – leveraging immersive environments for hazard recognition and procedural rehearsal (Vercelli et al., 2024); and

4. Human–Technology Interaction – exploring usability, ergonomics, and behavioral adaptation in virtual environments (Paes & Irizarry, 2018).

Collectively, these clusters illustrate the progression from early visualization-focused VR applications toward integrative, safety-oriented, and human-centered frameworks consistent with CDM principles.

Integration of VR into Construction Design Management

VR's potential in CDM lies in its ability to create immersive, interactive spaces that simulate construction processes and safety-critical scenarios before physical implementation. Through such simulations, stakeholders can collaboratively identify hazards, assess constructability, and evaluate design alternatives, supporting the preventive intent of CDM frameworks (Korkut & Surer, 2023). When integrated with BIM, VR enhances the accuracy and accessibility of safety information, promoting early intervention and informed decision-making throughout the project lifecycle (Park et al., 2018; Pishdad-Bozorgi et al., 2018).

However, the review also identifies persistent barriers to full-scale VR adoption in CDM. Chief among these are interoperability challenges, inconsistent data exchange standards, and the absence of formal guidelines for embedding VR into design review workflows (Mastrolembo Ventura et al., 2019; Zhou et al., 2012). Furthermore, resistance to technological change, lack of training, and unclear return-on-investment metrics constrain adoption, particularly among small and medium-sized enterprises (SMEs) (Selvaprasanth et al., 2021). Overcoming these challenges requires coordinated efforts in standardization, upskilling, and alignment of institutional policies to ensure that VR tools complement regulatory frameworks.

Research Gaps and Future Directions

Although the bibliometric evidence reveals increasing scholarly engagement, the literature remains heavily concentrated in conceptual and pilot-based studies, with limited empirical validation in live project environments. Future research should employ longitudinal and mixed-method designs to evaluate the quantitative and qualitative impacts of VR-CDM integration on safety performance, collaboration efficiency, and design quality (Swallow & Zulu, 2024). Additionally, there is a need to incorporate socio-technical and behavioral dimensions examining user acceptance, cognitive workload, and inter-organizational collaboration to complement the current technology-centric discourse (Balali et al., 2018)

Another emerging research direction involves integrating VR with Artificial Intelligence (AI) and Digital Twins to enable real-time risk forecasting, automated hazard detection, and data-driven safety optimization (Kostadimas et al., 2025). Such integration could transform CDM from a reactive compliance mechanism into a proactive, intelligent design governance framework. Moreover, context-specific research in Malaysia should explore how VR applications can support compliance with OSHMP25 and the national Construction 4.0 Strategic Plan, advancing the local industry toward safer and more sustainable digital transformation.

CONCLUSIONS

This study conducted a comprehensive systematic and bibliometric review to explore the evolving role of Virtual Reality (VR) in enhancing Construction Design Management (CDM). The analysis reveals that VR has emerged as a pivotal technology in Construction 4.0, supporting early-stage hazard identification, collaborative design review, and decision-making processes that align with safe-by-design and prevention-through-design principles. By examining 59 key publications indexed in the Web of Science, this research mapped the intellectual landscape, identified thematic clusters, and traced the trajectory of VR-CDM integration across global and regional contexts.

The findings indicate that scholarly interest in VR-enabled CDM has accelerated over the past decade, with research increasingly focusing on immersive visualization, BIM–VR interoperability, and safety management applications. Developed economies such as the United States, the United Kingdom, and Italy lead this research domain, reflecting their technological readiness and institutional support for digital construction innovation. However, developing nations, including Malaysia, have yet to leverage VR's potential within their local regulatory frameworks fully, despite policy developments such as the Occupational Safety and Health (Construction Work) (Design and Management) Regulations 2024 and the Construction 4.0 Strategic Plan. This gap underscores the need for targeted research and policy support to translate VR innovations into practical, safety-driven design practices across varying industrial contexts.

The bibliometric analyses revealed four dominant thematic clusters: (1) VR for design visualization and collaborative review; (2) integration of BIM and VR for data-driven design management; (3) safety management and virtual training; and (4) human–technology interaction in immersive environments. These clusters collectively demonstrate VR's capability to transform CDM into a more proactive, evidence-based, and human-centered process. However, challenges related to interoperability, standardization, and organizational readiness continue to hinder widespread adoption.

From a theoretical standpoint, this review contributes to the body of knowledge by framing VR-CDM integration as a multidimensional construct encompassing technology, human factors, and regulatory alignment. Practically, the study highlights VR's potential to reduce design-related risks, improve stakeholder collaboration, and enhance compliance with emerging safety design regulations. For Malaysia and similar developing economies, the insights gained can guide policymakers and industry practitioners in embedding VR-based approaches into national safety management frameworks.

Future research should extend beyond conceptual and prototype-based studies to incorporate empirical, project-based validations of VR's impact on design safety performance, communication efficiency, and cost-effectiveness. Moreover, cross-disciplinary studies integrating Artificial Intelligence (AI), Digital Twins, and Extended Reality (XR) could enable intelligent, predictive, and real-time safety design systems. As the construction industry transitions toward digital and sustainable transformation, VR-enabled CDM represents not merely a technological innovation but a paradigm shift in how safety, design, and collaboration are conceived and operationalized.

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