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Keywords: Construction Digitalization, Bibliometric Analysis, VOS Viewer, Building Information Modeling, Automation, Blockchain, Smart Contracts.



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Article

A Bibliometric Review of the Trends of Construction Digitalization Research in the Last Decade

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Abstract: The integration of digital technologies into construction practices has emerged as a pivotal area of interest, reflecting its substantial influence on the future trajectory of the construction industry. This study undertakes a comprehensive bibliometric analysis of literature on construction digitalization spanning from 2013 to 2023, sourced from the Elsevier Scopus database. Employing key terms such as “construction digitalization,” “BIM,” “construction 4.0,” and “digital construction methodologies,” the research methodically extracts and scrutinizes relevant articles. Advanced tools like the VOS viewer were utilized to delve into the bibliometric networks, offering insights into prevailing research trends within the built environment sector. The findings reveal a pronounced emphasis on digital modeling, automation, blockchain technologies, and emerging paradigms such as smart contracts and modular construction. This investigation enriches the academic discourse by elucidating the varied subtleties, ongoing shifts, and prospective directions in the ever-evolving landscape of construction digitalization research.

Keywords: construction digitalization; bibliometric analysis; vos viewer; building information modeling; automation; blockchain; smart contracts

1. Introduction

The construction industry holds a pivotal role in shaping society, responsible for the creation of buildings, structures, and environments that link communities, provide employment opportunities, and elevate the overall well-being of society [1]. In the collective pursuit of global sustainable development by 2030, this industry has a critical role to play, particularly in prioritizing projects that emphasize environmental responsibility and social accountability [2–4]. Currently, the construction industry stands as one of the largest economic sectors globally, with construction-related expenditures constituting about 13% of the global economy and an estimated annual revenue of approximately \$10 trillion, projected to reach \$14 trillion by 2025 [5]. Construction digitization is a key concept ushering in this profound transformation within the construction industry, leveraging digital tools and processes to enhance efficiency, sustainability, and innovation. Construction digitization is a dynamic force reshaping the built environment, fostering improved designs, efficient processes, and sustainable practices to meet the industry's evolving needs [6,7]. Furthermore, this digital revolution is fundamentally altering the industry's traditional practices, with the adoption of smart construction sites enhancing connectivity and reducing miscommunication and errors. The benefits of construction digitization extend to project management, enabling real-time tracking of

progress, resource allocation, and cost management with the use of AI and intelligent decision support systems (DSS) [8].

Alongside these digital solutions, the construction industry is harnessing the power of technologies such as the Internet of Things (IoT), unmanned aerial vehicles (UAVs), 3D printing, augmented reality (AR), virtual reality (VR) and mixed reality (MR) [9,10]. Drones and sensors on construction sites are enhancing safety measures and data-driven decision-making. Innovative building materials that are both robust and eco-friendly are on the rise, promising sustainable and resource-efficient structures [11,12]. Construction digitization is also addressing environmental concerns by reducing waste and resource consumption, contributing to an eco-friendly approach [13]. Central to this transformation is Building Information Modeling (BIM), enabling the creation of detailed 3D models that facilitate improved design, planning, and collaboration [14,15]. These advanced digital representations provide stakeholders with valuable insights before construction begins, reducing errors and saving time and resources. Project management software, IoT sensors, and drones are optimizing project oversight, tracking, and safety [16]. The integration of the Internet of Things (IoT) is giving rise to smart construction sites, improving resource allocation and communication [17].

Innovations in building materials, stronger and more sustainable, are contributing to the longevity and eco-friendliness of structures. Moreover, construction digitization addresses environmental concerns by minimizing waste and resource consumption [18]. However, challenges, such as workforce upskilling and data security, must be met [19]. The opportunities for the construction industry are substantial, promising greater automation, efficiency, and the delivery of sustainable and resilient infrastructure. In recent years, the concept of construction digitalization has gained significant attention across the construction industry, with a growing emphasis on how digital technologies can transform and enhance construction processes [20,21]. Researchers, policymakers, and industry professionals have increasingly recognized the potential benefits of digitalization, not only in terms of efficiency and cost-effectiveness but also in improving the overall quality and sustainability of construction projects. As a result, there is a growing body of literature that explores various aspects of construction digitalization, including the use of Building Information Modeling (BIM), robotics, artificial intelligence, and data analytics in construction processes [16,22–24].

While previous studies on construction digitalization have made substantial contributions, there is a need for a comprehensive and systematic review of the existing research in this field. This paper employs bibliometrics to analyze articles on construction digitalization research published in the last decade (between 2013 and 2023). This method allows for the identification of research trends, key areas of focus, prominent publications, leading authors in the field, and levels of collaboration. Additionally, the paper explores the latest trends in this research area and offers practical recommendations to guide future research and industry practices. Construction digitalization research has gained significant momentum in recent years, reflecting the industry's growing recognition of the transformative potential of digital technologies. This bibliometric review aims to provide a comprehensive overview of the research landscape in this field, offering valuable insights into the trends and directions that have shaped construction digitalization research in the last decade. By understanding the current state of research and identifying emerging areas of interest, this paper contributes to the ongoing discourse on how digital technologies can revolutionize the construction industry.

2. Materials and Methods

The main objective of this study is to comprehensively investigate dominant research themes related to construction digitalization over the recent decade. Utilizing bibliometric methodology, this study endeavors to identify and graphically represent pivotal knowledge domains and recurring keyword trends, illuminating forthcoming research trajectories. As underscored by research conducted by [25,26], the employment of bibliometric techniques facilitates comprehensive and holistic scrutiny of the prevalent literary corpus, surpassing the constraints inherent to conventional manual evaluations. This bibliometric scrutiny adheres to a meticulously devised four-phase

strategy, resonating with the protocols articulated by [27,28]. These phases encompass data acquisition, data refinement employing bibliometric methodologies, data visualization and evaluation, culminating in an in-depth exploration of the insights gleaned from the bibliometric findings. The predominant repository for data procurement is the expansive Scopus repository. In contemporary times, Scopus has established its prominence, acclaimed for its extensive coverage spanning myriad scholarly disciplines, as acknowledged by [25]. The strength of Scopus lies in its rich reservoir of peer-reviewed content, including journals, books, and conference materials. It also boasts a quicker indexing mechanism compared to other renowned databases like Web of Science (ISI) and Google Scholar. This efficiency positions Scopus as a top choice for academic inquiries. Moreover, Scopus stands out for its exhaustive capture of abstracts and citations from scholarly literature across multiple domains, equipped with smart tools for monitoring and visualizing research progressions. In formulating the search criteria, we ensured a comprehensive search statement to encapsulate all relevant documents.

The retrieval schema used in Scopus was: (TITLE-ABS-KEY) ("Construction") AND ("Digitalization"), with a focus on content published between 2013 to October 2023. The "TITLE-ABS-KEY" indicates either a journal or conference article title, abstract, and keywords. The initial search produced 2,054 documents with the above-named keywords. The 2,054 documents extracted were then carefully refined based on three parameters – field (Engineering and Computer science), publication language (English), and publication/document type (Article, Conference paper, Book, Book chapter and Review). Manual screening was employed based on these three parameters (Strictly by excluding other irrelevant parameters instead of limiting to the desired parameters to give a precise search) which yielded 489 articles, which were subsequently extracted as a CSV file and used for the analysis. The CSV file contained the metadata of the extracted articles based on information such as the title of articles, year of article publication, author of articles, affiliation of authors, abstract information, article keywords, volume and page numbers of articles, citation information, references list and Digital Object Identifier (DOI) of extracted articles. To investigate the concept of construction digitalization and its research emphasis within the construction industry, this research utilized the VOS Viewer text-mining tool for an in-depth analysis of bibliometric relationships, drawing insights from specific findings. These include: (1) analysis of the number of publications (2) analysis of the publications per country; (3) analysis of publications per document source; (4) analysis of most cited publications; (5) analysis of co-occurrence of keywords; and (6) Focus areas based on year of publication as shown in Figure 1.

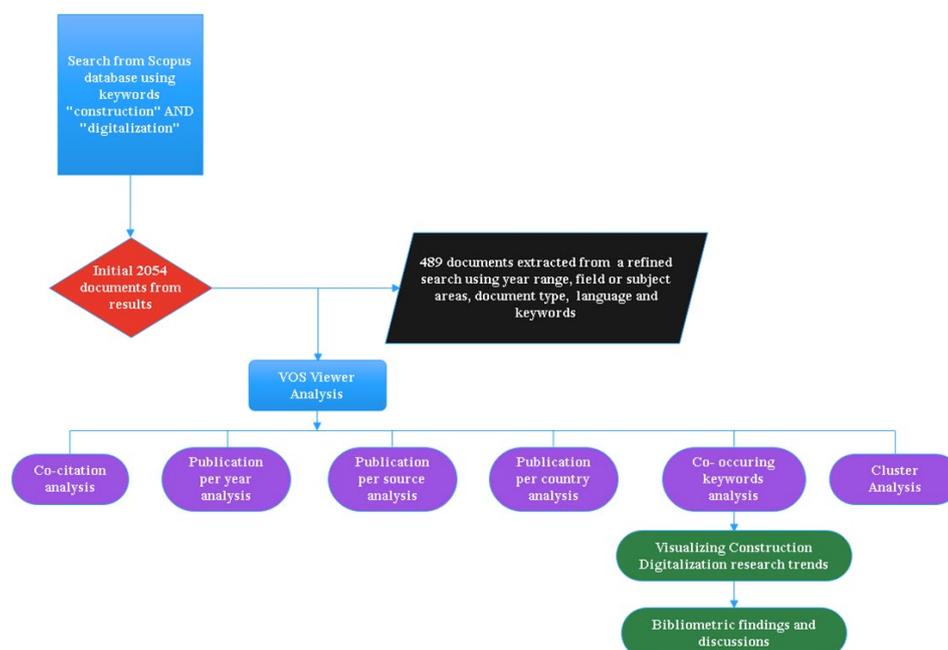


Figure 1. Outline of Research Methodology.

3. Bibliometric Results and Discussions

3.1. Publication per Year

Most publications of the 489 extracted articles on construction digitalization research were conference papers, accounting for 53% of the total. Journal articles, or simply articles, represented a significant 32% of the publications. Meanwhile, book chapters comprised 9%, reviews were 5%, and books made up a minimal 1% of the overall publications. The number of publications per year from 2013 to 2023 has been a clear upward trend. In 2013, only 6 articles were published, and this number steadily increased over the years, with some fluctuations in between. Significant growth is observed starting from 2020, with publications increasing to 62 that year, followed by 92 in 2021 and reaching its peak with 127 articles in 2023. This depicts an evolving interest in the topic over the decade. This data suggests that while the topic of construction digitalization has been gaining traction, most of the discourse has taken place in conference settings, followed by traditional journal articles.

Given the current trajectory, it is evident that there is growing interest in this area, emphasizing the potential for further research and exploration in the construction sector. This indicates an increase in interest in the subject, which may have been impacted by the adoption of 4IR technologies in construction (construction 4.0) in 2013 [29–31]. Nevertheless, considering how vast and intricate the concept is, there is currently only a little research on it in the building sector, and it is quite complex to gain a specific definition [32,33]. While the construction industry is making strides in embracing digital tools and methodologies, there remains a vast expanse of uncharted territory. This underscores the pressing need for more in-depth research in the hope of realizing a truly integrated digital transformation.

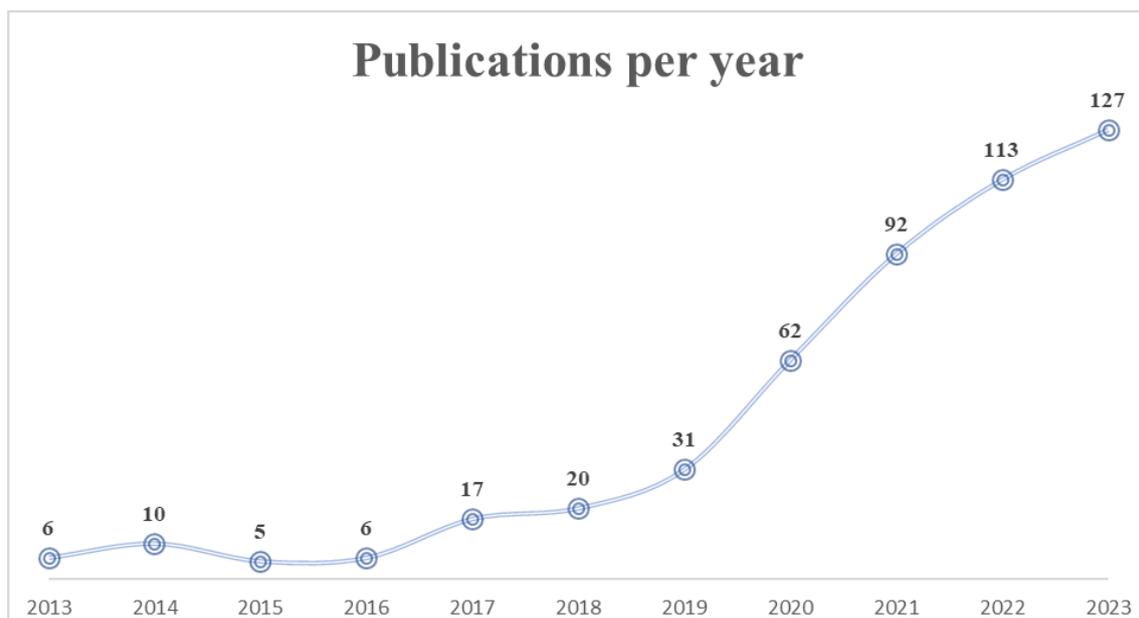


Figure 2. Number of Publications Per Year.

3.2. The Network of Publications per Year

To identify leading contributors in construction digitalization research, the study set criteria requiring countries to have a minimum of 5 publications and two citations, later adjusting to a stricter threshold of at least 12 publications and two citations per country. This methodology spotlighted thirty-two countries as significant contributors, emphasizing the global relevance of digitalization in construction. The foremost contributors were China (99 articles, 364 citations), indicating its leadership in the field, followed by the Russian Federation (61 articles, 77 citations), Germany (48 articles, 413 citations), the United Kingdom (48 articles, 649 citations), and Italy (36 articles, 207 citations), according to Figure 3. The United Kingdom, matching Germany in publications, stands

out for the higher citation impact of its research. The Russian Federation's substantial publication count contrasts with its lower citation numbers, suggesting varying international reception of its research.

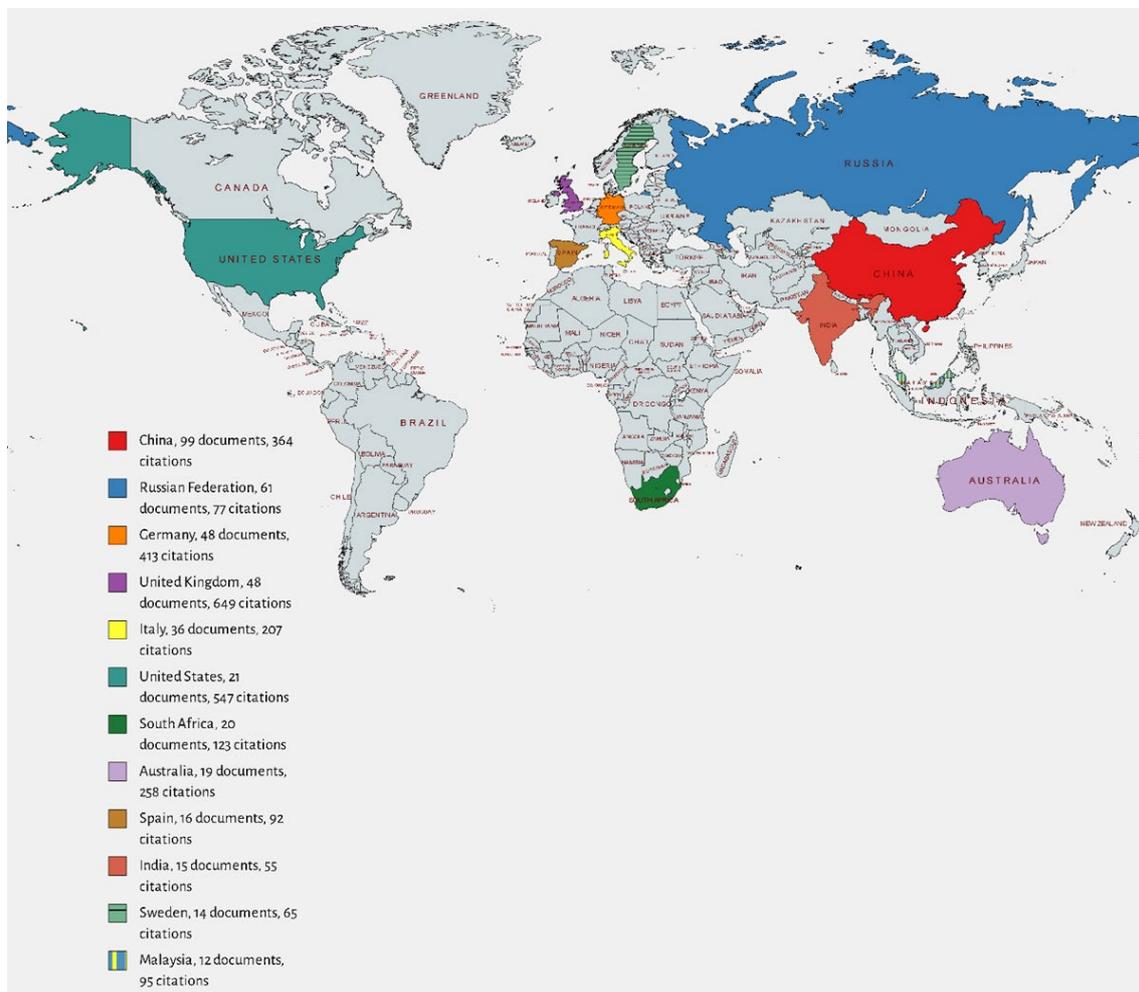


Figure 3. Number of Publications per country.

A closer look at the African landscape reveals that South Africa leads the continent with 20 articles and 123 citations in construction digitalization research. This indicates that South Africa is at the forefront of advancing this area of study within the African continent. However, with Malaysia having 12 articles and 95 citations, it is evident that there is a disparity in research output and influence between these two countries. Despite South Africa's contributions, the African continent is underrepresented in the domain of construction digitalization research [31,34]. Only South Africa has managed to make a notable mark on the global stage. This underscores a significant knowledge gap and suggests that there is a vast untapped potential for research in this domain within the continent. These findings highlight the global interest in construction digitalization, with certain countries emerging as predominant contributors and influencers in the research landscape.

3.3. The Publications per Document Source

Subsequently, an analysis was conducted to identify the number of documents based on their source titles, aiming to offer scholars a clearer view of the key journals and conferences concerning digital innovations and their applications in the construction realm. From a pool of 487 assessed articles, 12 satisfied the preset criterion of having a minimum of 7 documents and citations for a given source. These articles spanned 7 academic journals and 5 conference proceedings. Notably, one source title hosted as many as eight publications within the outlined duration. Of all the sources, the

“Automation in Construction” journal was notably prominent, boasting 25 articles and receiving a whopping 1205 citations.

This underscores its pivotal role in the research landscape. The journal is acclaimed for publishing groundbreaking studies centered around the integration of automation, robotics, and computational technologies in construction. It accentuates the significance of these advancements, not just in on-site construction tasks but across the comprehensive value chain encompassing varied stakeholders. Table 1 itemizes those source titles that have published a minimum of two articles. With an impressive impact factor of 10.52, “Automation in Construction” stands out, reinforcing its esteemed position within the academic community. Meanwhile, in terms of H-index, which indicates the citation influence in the research sector, the “Automation in Construction” journal, with an H-index of 157, clearly establishes its leadership. This speaks volumes about the impactful and qualitative content it consistently offers to the research community.

Table 1. Number of Publications per Sources.

Journal Articles/Book/Conference/Review Title	Number of Documents (2013-2023)	Number of Citations	Journal Impact factor	H-index
ACM International Conference proceeding series	26	21	0.50	137
Advances in intelligent systems and computing	9	12	0.63	58
Automation in construction	25	1205	10.52	157
Buildings	37	258	3.80	45
Ceur workshop proceedings	19	35	0.39	62
Construction innovation	17	154	0.83	42
Journal of information technology in construction	9	108	4.37	53
Lecture notes in civil engineering	26	20	0.13	18
Lecture notes in networks and systems	49	28	0.54	27
Procedia computer science	8	8	0.83	109
Proceedings of international structural engineering and construction	12	19	1.53	16
Proceedings of the international symposium on automation and robotics in construction	12	9	0.33	9

3.4. The Most Cited Publications

The bibliometric analysis highlighted the most frequently cited documents to discern the prevalent trends and focal points in construction publications that have had a significant influence within the given period. This examination centered on works cited 59 times or more, marking them as particularly impactful in their domain. Of the 489 assessed documents, 10 stood out based on this criterion, as illustrated in Table 2. The data suggests that the lion’s share of these extensively cited papers gravitates towards themes including digitalization and product innovation, the role of artificial intelligence and blockchain in construction, the significance of cyber-physical systems in Industry 4.0 education, and the evolving potential of technologies such as Building Information Modelling (BIM) and 3D printing in the construction environment.

Table 2. Most Cited Publications.

Source	Source Title	Citations	Research Method	Research Focus
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Lyytinen, K et al. (2016)	Digital product innovation within four classes of innovation networks	412	Systematic Literature Review	Understanding the impact of digitalization on product innovation networks.
Pan, Y. and Zhang, L. (2021)	Roles of artificial intelligence in construction engineering and management: A critical review and future trends	319	Scientometric and Qualitative analysis	Analysis of AI's evolution and trends in AI application in CEM
Li, J et al., (2019)	Blockchain in the built environment and construction industry: A systematic review, conceptual models, and practical use cases	297	Systematic Literature Review, Focus Group Discussion and Expert Interview	Exploring the applications of Distributed Ledger Technology (DLT), specifically blockchain, in the built environment. Evaluating the state-of-the-art concerning these requirements and presenting the CONPrint3D concept for on-site, monolithic 3D printing as developed at the TU Dresden.
Mechtcheri, V et al. (2019)	Large-scale digital concrete construction–CONPrint3D concept for on-site, monolithic 3D-printing	189	Experimental approach and quantitative	Understanding how cyber-physical systems and 4.0 industry technologies under teaching factories will reshape manufacturing education
Mourtzis, D et al. (2018)	Cyber-physical systems and education 4.0–the Teaching Factory 4.0 concept	143	Case Study	Developing a BIM-based integrated technology model for MEP management in the O&M phase of projects
Hu, Z et al. (2018)	BIM-based integrated delivery technologies for intelligent MEP management in the operation and maintenance phase	126	Modelling/ Simulation	Scientific development of a maturity model concerning the digital transformation of companies within the manufacturing industry's supply chain.
Klötzer, C.and Pflaum, A. (2017)	Toward the development of a maturity model for digitalization within the manufacturing industry's supply chain	105	Modelling	Contribution to the iContract body of knowledge
Mcnamara, J. and Sepasgozar, E. (2021)	Intelligent contract adoption in the construction industry: Concept development	70	Systematic Literature Review	

Shahzad, M et al. (2022)	Digital twins in built environments: an investigation of the characteristics, applications, and challenges	60	Qualitative	Understanding the role of digital twins in the built environment
Aghimien, O et al. (2020)	Mapping out research focus for robotics and automation research in construction-related studies	59	Bibliometric approach	Discovering research areas and trends for robotics and automation in construction studies.

Additionally, some documents discuss the maturity models for the digital transformation of the manufacturing industry's supply chain, the concept of intelligent contracts, and the relevance and application of digital twins in built environments. There is a burgeoning emphasis on integrating digital advancements into construction, as seen by the prominence of such topics in leading nations. This underscores the escalating recognition of digital technologies and their transformative potential for the construction sector globally. Nonetheless, it also hints at existing knowledge gaps, emphasizing the need for broader research perspectives, including regions that are currently underrepresented in this discourse, such as Africa, with only source from [25] with 59 citations on the topic; mapping out research focus for robotics and automation research in construction-related studies.

3.5. Analysis of Co-Occurrence of Keywords

In an in-depth analysis of bibliographic data, a co-occurrence map was created to explore the interconnectedness of keywords within construction digitalization research, highlighting key focus areas and the evolution of scholarly discussion [25,35]. This approach, utilizing a threshold of five occurrences for keyword consideration, identified 170 relevant keywords from 3803 across 489 articles. This was later refined to 166 after manually excluding irrelevant terms such as 'current', 'survey' and 'students'.

The graphical representation in Figure 4, facilitated by VOS Viewer software, visually depicts the frequency and relationships of these keywords, where larger nodes represent more commonly cited keywords and thicker lines indicate stronger connections between them. This bibliometric method, esteemed for its analytical precision, has revealed the main themes and emerging trends in construction digitalization, demonstrating the software's utility in literature review and bibliometric studies [25].

Table 3. List of Clusters and Co-occurring Keywords.

Cluster Label	Keywords	Number of Occurrence	Total Link Strength
Cluster 1 (red)	Digitalization	113	495
	Decision making	30	192
	Big Data	17	61
	Virtual Reality	17	95
	E-learning	16	68
	Digital economy	14	47
	Computer-aided design	10	54
	Engineering education	10	69
	Product design	10	53
	Industrial Research	9	55
Cluster 2 (green)	Information Technology	10	44
	Automation	27	143
	Artificial Intelligence	25	130

	Internet of Things	24	105
	Digital Twin	19	70
	Office buildings	12	107
	Data handling	10	63
	Information services	9	35
	Intelligent buildings	8	44
	Intelligence systems	8	21
	Data mining	7	34
	Computation theory	7	23
	Project management	52	385
	Robotics	24	149
	Construction management	13	77
	Three-dimensional computer graphics	12	72
Cluster 3 (blue)	Environmental impact	11	55
	Human resource management	11	90
	Visualization	7	48
	3d printers	6	49
	Construction Equipment	5	52
	Concretes	6	48
	Architectural design	94	725
	Life Cycle	43	356
Cluster 4 (yellow)	Building Information Modelling	39	320
	Sustainable Development	27	157
	Structural Design	17	155
	Construction Companies	6	34
	Radiofrequency identification	6	59
	Construction industry	135	837
	Construction	53	402
Cluster 5 (purple)	Industry 4.0	26	139
	Digital devices	17	115
	Supply chains	15	80
	Productivity	11	66
	BIM	47	258
Cluster 6 (aqua (light blue))	Construction 4.0	11	69
	Embedded Systems	10	71
	Infrastructure	9	67
	Risk assessment	7	43
	Buildings	6	43
	Building information modelling (BIM)	10	81
Cluster 7 (orange)	Blockchain	15	106
	Construction sectors	14	93
	Smart contract	7	54

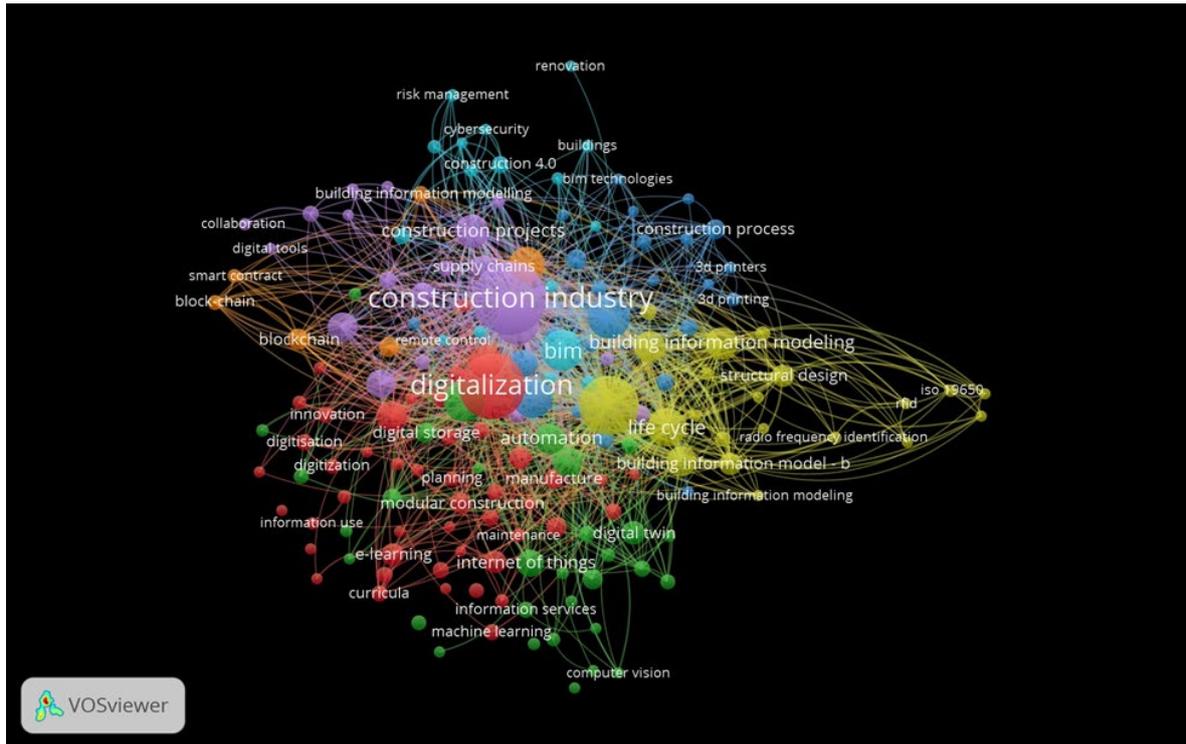


Figure 4. Network visualization map for co-occurring Keywords.

Cluster 1 - Technological Advancements in Modern Engineering and Design: The red cluster is composed of 12 significant keywords. This cluster, titled “Technological Advancements in Modern Engineering and Design”, delves deeply into the progressive technological landscape of the construction and engineering industry. The keywords, which range from digitalization, and digital technologies, to e-learning, and computer-aided design, underline the transformative nature of today’s engineering realm. This cluster explores the significant impact of digitalization and other digital technologies in the construction and engineering sectors. It highlights how innovations such as virtual reality, big data, and advanced decision-making processes are revolutionizing product design, industrial research, and engineering education. Key studies, including those by [36] on digital technologies and computer-aided design, and research by [37,38] on smart technologies in the digital economy, highlight the shift towards more integrated and innovative approaches in engineering. This shift not only meets functional requirements but also addresses the evolving demands of the digital age, making engineering education more accessible and aligning it closely with real-world challenges.

Cluster 2 - Integrated Intelligence and Automation in the Built Environment: The green cluster encompasses 11 essential keywords. The theme “Integrated Intelligence and Automation in the Built Environment” emphasizes the transformative role of artificial intelligence, automation, and data-centric technologies in reshaping the modern built environment. It highlights a significant shift towards automation and intelligent systems, including the Internet of Things (IoT), which are transforming office buildings into ‘intelligent buildings’. Research, including studies by [39,40], illustrates the use of digital twins for both design simulations and real-time operational feedback in building management. This integration of data handling, mining, and computational theory is opening new pathways in information services, turning buildings into data-driven entities with capabilities for self-regulation, predictive maintenance, and dynamic adaptability. The role of AI and data mining in efficient energy management and user-centric adaptations is underscored by research from [41,42]. Further studies by [43,44] indicate that intelligent systems, supported by advanced computation theories, are leading to smarter, more efficient, and sustainable built environments. This cluster presents a future where the fusion of intelligence and automation fundamentally changes our

interaction with and expectations of the built environment, highlighting the growing importance of creating harmonized, intelligent spaces.

Cluster 3 - Innovative Techniques and Management in Modern Construction and Design: This blue cluster is composed of 10 keywords, with the theme “Innovative Techniques and Management in Modern Construction and Design” illustrating the interplay of modern technology, management practices, and innovative techniques reshaping the construction landscape. Robotics and 3D graphics are revolutionizing the construction industry, enhancing project planning, execution, and environmental sustainability. Robotics are increasing precision and safety, while 3D printing, and new materials promote eco-friendly construction. Studies by [45,46] show how these technologies help mitigate environmental impacts. The shift towards strategic human resource management and advanced project management, supported by digital tools [47,48] is improving efficiency and stakeholder coordination. This trend towards technological integration and innovation is making the construction industry more sustainable, efficient, and prepared for future challenges.

Cluster 4 - Sustainable Architectural and Structural Practices in Contemporary Construction: This yellow cluster is represented by 7 integral keywords. The trend in architectural design is increasingly aligning with sustainable development, aiming to produce structures that are both visually attractive and environmentally friendly. Ref. [49] emphasize the significance of life cycle analysis in assessing a building’s environmental impact from start to finish. Building Information Modelling (BIM) is pivotal in integrating sustainability early in the design process, supported by research from [50–52], which shows BIM’s role in making construction more transparent and efficient. Structural advancements and technologies like RFID for asset management are improving the construction industry’s transparency, efficiency, and environmental consideration, as noted by [53,54]. This blend of innovation and sustainability is guiding modern construction towards ecological integrity without sacrificing architectural aesthetics, setting a precedent for future construction practices and research.

Cluster 5 - Industry 4.0 and Digital Advancements in Modern Construction Practices: Represented by the purple cluster, this theme has been characterized by 6 crucial keywords. Industry 4.0 is transforming the construction industry, moving from traditional methods to digital integration, enhancing efficiency, precision, and innovation. Key contributions include [55] on the adoption of digital technologies, and [56] on the use of interconnected systems for improved operations and resource efficiency. This shift has made construction sites more connected to digital supply chains, leading to just-in-time delivery and less waste. The results are higher productivity, shorter project times, and better quality. [57] also highlights digital tools’ role in improving safety and project management. This blend of modern technologies with traditional methods is preparing the industry to tackle modern challenges more effectively, promising further advancements in construction practices.

Cluster 6 - Technological Integration and Risk Management in Advanced Building Infrastructure: This cluster, symbolized by the aqua (light blue) hue on the map, encapsulates 6 defining keywords. The AEC industry is evolving through Building Information Modeling (BIM) and Construction 4.0, integrating technology with infrastructure for enhanced functionality and sustainability. Studies like those by [58,59] highlight this trend, with embedded systems playing a key role in smart building automation. BIM facilitates the visualization, analysis, and optimization of built assets’ lifecycles [60]. However, this technological leap forward introduces risks, necessitating robust risk assessment and management strategies to ensure the integrity of smart systems and address vulnerabilities [61]. As urban spaces become more complex, the importance of technology in ensuring building safety, longevity, and efficiency becomes paramount. The AEC industry’s journey is thus characterized by a dual focus: embracing innovation while maintaining caution to create resilient, sustainable, and safe built environments [62], presenting rich opportunities for ongoing and future research.

Cluster 7 - Digital Innovations and Trust Mechanisms in Construction Management: The seventh cluster, represented by the orange hue on the map, comprises 4 essential keywords. Building Information Modeling (BIM) remains central to this theme, offering a diverse platform for architects,

engineers, and construction professionals. BIM enhances construction through streamlined design and the integration of technologies like blockchain, as identified by [63]. Blockchain in construction ensures transparency and secure documentation, particularly when combined with BIM, creating a reliable project record [64]. The theme extends to the “constructors sectors,” highlighting the vast network of construction stakeholders from contractors to regulators. Smart contracts, supported by blockchain, simplify and secure agreements, reducing disputes [65]. The core of this cluster is trust, aiming to authenticate documentation, ensure contract execution, and maintain stakeholder transparency through BIM, blockchain, and smart contracts. This marks a shift towards a construction management system that values reliability and efficiency. The emphasis on digital innovations and trust mechanisms suggests a future where technology enhances not only operational aspects but also ethical and trust foundations in construction, steering the industry towards a trust-centric paradigm.

3.6. Research Trends Based on Year of Publication

The overlay visualization network map, as shown in Figure 5, reveals the evolution of construction digitalization research through the interrelation of keywords over time, with a focus on publications from 2019 to 2022. Initially, research concentrated on building information modeling (BIM), digitalization, and automation, highlighted by blue clusters for the years 2019 and 2020, with key topics including BIM, digital tools, automation, digital twins, and the Internet of Things. Moving into 2020 and 2021, the research scope widened to encompass smart contracts, blockchain, and construction 4.0, depicted by green clusters, alongside emerging interests in modular construction, digital storage, and remote control. By 2022, the focus shifted towards innovative technologies such as radio frequency identification (RFID), ISO 19650, and computer vision, indicated by yellow clusters, pointing to advancements in construction efficiency, data interoperability, and visual computing applications. RFID's inclusion signals an increasing reliance on technology for asset tracking and inventory management.

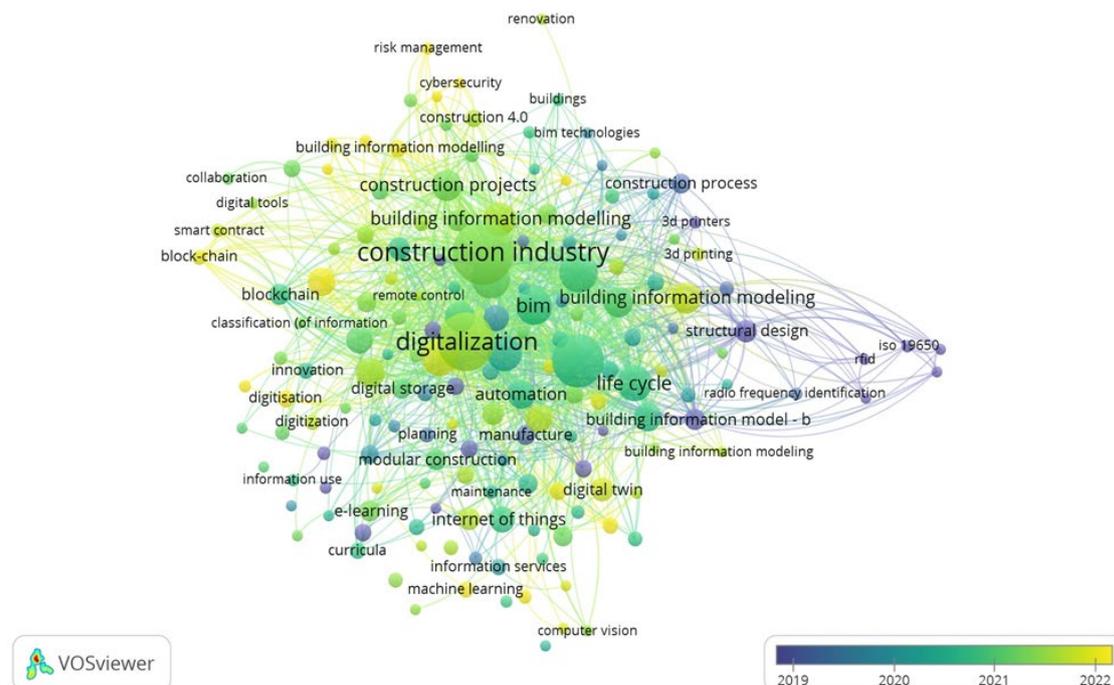


Figure 5. Overlay visualization for co-occurring keywords.

The trajectory of construction digitalization research reflects the industry's gradual adoption of advanced digital technologies, inspired by the digitization successes in other sectors. The prominence of blockchain in 2021 emphasizes the construction industry's push for transparency, security, and traceability, drawing parallels to its utility in finance and logistics [66]. The emergence of computer vision as a key topic in 2022 highlights its potential to transform site monitoring, defect detection, and project management. The consistent mention of 'risk management' throughout the visualization underscores the growing focus on identifying and mitigating digitalization risks, including cybersecurity and system malfunctions, with 'cybersecurity' and 'construction 4.0' strongly associated with this theme [67–69]. This evolution indicates the construction sector's proactive approach to embracing digital innovations while addressing the inherent challenges and risks of digital transformation. The lighter hues representing the years 2019 and 2020 underscore a concentration on the elemental facets of digital evolution, including 'building information modelling' and 'digital storage'. The visualization notably intensifies its hues when approaching the years 2021 to the present, revealing a significant pivot towards advanced and trending subjects within the construction sector.

Dominating this shift are technologies such as 'smart contracts' and 'blockchain', which signify the industry's burgeoning interest in leveraging innovative solutions. Furthermore, there is a nuanced amalgamation observed between 'BIM' and 'construction 4.0', hinting at the evolving sophistication and integration of digital modelling techniques with the broader paradigm of industrial automation and data exchange [9]. This period also highlights a close association between 'construction projects' and 'construction process', indicating a consolidated perspective that emphasizes a seamless digital workflow [70,71]. This pattern, where projects are visualized from beginning to end using digital perspectives, underscores the construction sector's dedication to utilizing technology to enhance efficiency and foster innovation. The inclusion of terms like 'e-learning', 'machine learning', and 'computer vision' further underscores the sector's exploration into diverse technological avenues, reflecting a proactive approach to adopt and adapt to the digital age's offerings. 2021 to these contemporary times, mark a period of rapid technological assimilation and forward-thinking strategies in the construction sector and research. However, these trends require progression and refinement in both academic inquiry and pragmatic implementations. This alignment indicates that with the escalating adoption of digital solutions, there is a heightened accentuation on their utility throughout the entire span of construction endeavors, from the inception and design phases through to finalization and subsequent maintenance. The trajectory of digitalization in construction suggests an industry-wide commitment not merely to competition with other industries, but to pioneer innovations and reshape the digital future of the construction sector.

4. Conclusions

This research underscores the construction sector's pivotal role in societal advancement through digital technology integration, observing a significant increase in digitalization-related research over the past decade. Utilizing bibliometric analysis, it explores trends, key knowledge areas, and prevalent keywords in construction digitalization, with a focus on Scopus-indexed data. This period coincides with the industry's evolution amidst the fourth industrial revolution, marked by the adoption of innovations like Building Information Modeling (BIM), digital twins, and the Internet of Things. These advancements have led to a surge in construction digitalization research, particularly in 2019 and 2020, reflecting a growing interest in automation, digital tools, and blockchain technologies. This period's research intensity mirrors the broader shift towards the fourth industrial revolution and its impact on construction, highlighting the emerging need for professionals in the field to adapt by gaining new knowledge and skills. The research illuminated leading countries in construction digitalization research, such as the USA, UK, and China, and points out the lack of contributions from Africa, suggesting areas for future research and collaboration.

Key forums like the International Journal of Construction Digitalization Research have become pivotal in this field, with a focus on smart contracts, blockchain, and construction 4.0. There is a notable trend towards digital modeling and industrial automation, indicating a shift to integrated

digital workflows for improved efficiency and innovation. Emerging technologies like e-learning and machine learning show the sector's forward-thinking approach. The construction industry is not just adapting to digital innovations but is at the forefront of them. However, the study's reliance solely on the Scopus database is a limitation, advocating for a broader research scope in the future to provide a more comprehensive view of construction digitalization. The findings underscore the importance of enhancing academic discourse, especially in underrepresented regions like Africa, through international collaboration and educational initiatives like conferences and workshops. Additionally, updating educational curricula in the built environment to include digitalization concepts is crucial for equipping students with relevant skills and knowledge. As the fourth industrial revolution gains momentum, embedding digital literacy in educational programs is crucial for preparing graduates for the complexities of the modern construction industry. This study, while offering comprehensive insights into construction digitalization, acknowledges its limitation due to sole reliance on the Scopus database.

Future research is encouraged to incorporate data from various databases such as Web of Science for a more rounded understanding and to uncover any discrepancies in the current discourse on construction digitalization. Expanding research to include multiple databases could provide a more complete view of the field, identifying overlooked areas or gaps, thereby strengthening future scholarly work. The findings significantly contribute to academia, guiding scholars, industry professionals, and policymakers towards untapped areas for research and innovation. These insights outline probable future directions for the construction industry, emphasizing the need for collaboration among stakeholders to navigate the sector's digital transformation. Integrating academic research with practical application is key to driving the industry forward, ensuring it remains resilient, sustainable, and innovative in the face of digital advancements.

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