

Systematic Review

Impact of Industry 5.0 on the Construction Industry (Construction 5.0): Systematic Literature Review and Bibliometric Analysis

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Special Issue

Towards Industry 5.0 in the Construction Industry: Techniques, Requirements, Energy, Maintenance Engineering, Challenges and Opportunities

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Abstract: The construction industry is undergoing a paradigm shift with the advent of Construction 5.0 (C5.0), which integrates artificial intelligence (AI), the Internet of Things (IoT), digital twins, blockchain, and robotics to enhance productivity, sustainability, and resilience. This study conducts a systematic literature review and bibliometric analysis of 78 scholarly sources published between 2022 and 2025, using data from Scopus and following the PRISMA method. Keyword co-occurrence mapping, citation analysis, and content review are utilized to identify key advancements, emerging trends, and adoption challenges in C5.0. Seven core technologies are examined through the lenses of sustainability, human–robot collaboration (HRC), and resilience, revealing a rapidly expanding yet still nascent research domain. While C5.0 presents transformative potential, its widespread implementation faces significant barriers. A critical evaluation of these challenges is conducted, alongside strategic pathways to facilitate adoption and maximize impact. Furthermore, the leading countries and seminal contributions in the field are highlighted to guide future research efforts. By addressing knowledge gaps and industry trends, this study provides practical insights for policymakers, researchers, and industry professionals, contributing to the development of innovative frameworks that enhance efficiency, sustainability, and resilience in the era of Industry 5.0.



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Keywords: construction 5.0; industrial 5.0; construction industry; sustainability; resilience; human centricity; HRC; artificial intelligence; IoT; digital twin; bibliometric

1. Introduction

The construction industry plays a vital role in the global economy, contributing significantly to the GDPs of major economies such as the United States, China, and the United Kingdom. In 2022, the construction sector contributed approximately USD 1 trillion, CNY 1.2 trillion, and GBP 110 billion to their respective national economies [1,2]. Globally, construction expenditures reached USD 11 trillion and are projected to increase to USD 14 trillion by 2025, accounting for nearly 9% of the world's GDP [3]. Technology in construction has led to increased productivity, efficiency, and economic growth [4].

Industrial transformations have historically shaped the construction sector, aligning with broader industrial revolutions. The First Industrial Revolution (Industry 1.0) spanned

centuries, transitioning into Industry 2.0 over a period of 100 years. The shift to Industry 3.0 required 70 years, followed by the emergence of Industry 4.0 (I4.0) approximately 30–40 years later [5,6]. Industry 4.0 first appeared at Hannover Messe in 2011 when Professor Wolfgang Wahlster introduced it, highlighting the need for industries to adapt to the Fourth Industrial Revolution. It emphasized digitalization, automation, and real-time data utilization to stay competitive in a high-wage, globalized market [7]. More recently, Industry 5.0 (I5.0) has emerged as an evolution of I4.0, emphasizing human centricity, resilience, and sustainability alongside advanced automation [8].

The transition from Industry 4.0 (I4.0) to Industry 5.0 (I5.0) represents a shift from automation-driven processes to a more collaborative and sustainable approach. While I4.0 focused on full automation and machine-driven efficiency, I5.0 integrates human expertise with intelligent systems such as Collaborative Robots (Cobots), the Internet of Things (IoT), artificial intelligence (AI), digital twins, blockchain, prefabrication modular, 6G, prefabrication, edge computing, augmented and virtual reality (AR/VR), and smart sensors [9–14]. These advancements, widely used in I4.0, are now evolving to prioritize human–machine collaboration, environmental responsibility, and adaptive resilience in industrial processes.

Following this global industrial transformation, the construction industry has begun its transition from Construction 4.0 (C4.0) to Construction 5.0 (C5.0). Construction 4.0, introduced alongside Industry 4.0 (I4.0), emphasized digitalization, automation, and modular construction. It is also noteworthy that Construction 4.0 (C4.0) first appeared in the literature in 2015, three years after the I4.0 initiative [15–17]. Construction 5.0 (C5.0), inspired by Industry 5.0 (I5.0), builds upon the foundations of Construction 4.0 (C4.0) while shifting toward a more human-centered, sustainable, and resilient approach [3]. Researchers are drawn to Industry 5.0 for its ability to address Industry 4.0 challenges, such as workforce displacement, human–machine collaboration issues, and ethical concerns. It aims to refine technological advancements for more balanced and sustainable integration. In the construction industry, Industry 5.0 serves as a supportive tool rather than replacing stakeholders.

The concept of C5.0 has recently gained scholarly attention. Marinelli's research, which is the first to use the term "Construction 5.0" (C5.0), explores its potential through human–robot collaboration (HRC) in construction, identifying key challenges such as technological readiness, workforce adaptation, and integration barriers. She provides a realistic assessment of the transition from Industry 4.0 to C5.0, emphasizing a human-centered approach [18]. Similarly, Kolaei et al. analyzed the role of augmented reality (AR) in different construction phases, highlighting its impact on real-time visualization, efficiency, and project management [19]. These studies indicate that while C5.0 is still in its early stages, it holds immense potential for reshaping construction methodologies through adaptive and intelligent systems.

This study presents a comprehensive mixed-method review that integrates bibliometric analysis and a qualitative assessment to examine C5.0's technological progress in recent years. By mapping the existing literature, identifying research trends, and outlining key challenges and opportunities, this paper provides a structured methodology for evaluating and synthesizing academic findings. The objective is to offer a clear framework for understanding C5.0's evolution, its practical applications, and its future research directions. This research aims to guide policymakers, industry professionals, and researchers in leveraging C5.0 innovations to enhance sustainability, efficiency, and resilience in construction.

2. Methodology

To investigate the knowledge domain concerning C5.0, which refers to the fifth-generation construction technologies integrating advanced computational methods and intelligent systems into construction, it is important to provide specific citations that support this definition. This study employs a mixed literature review technique, a method extensively utilized in prior research. The methodology is illustrated in Figure 1. The review process follows a structured sequence of steps to ensure transparency and reproducibility. First, relevant publications are systematically collected from a selected database. Then, a bibliometric analysis is conducted using VOSviewer 1/6.19 to map the scientific landscape of the existing literature. In this analysis, the following aspects are examined: co-citation analysis, co-cited authors, multinational co-authorship, and research cluster analysis. Following this, specific subtopics are analyzed qualitatively to provide a deeper understanding of the current research trends. Finally, based on the findings, potential directions for future research are proposed. Further details of the methodology are elaborated on in the subsequent sections.

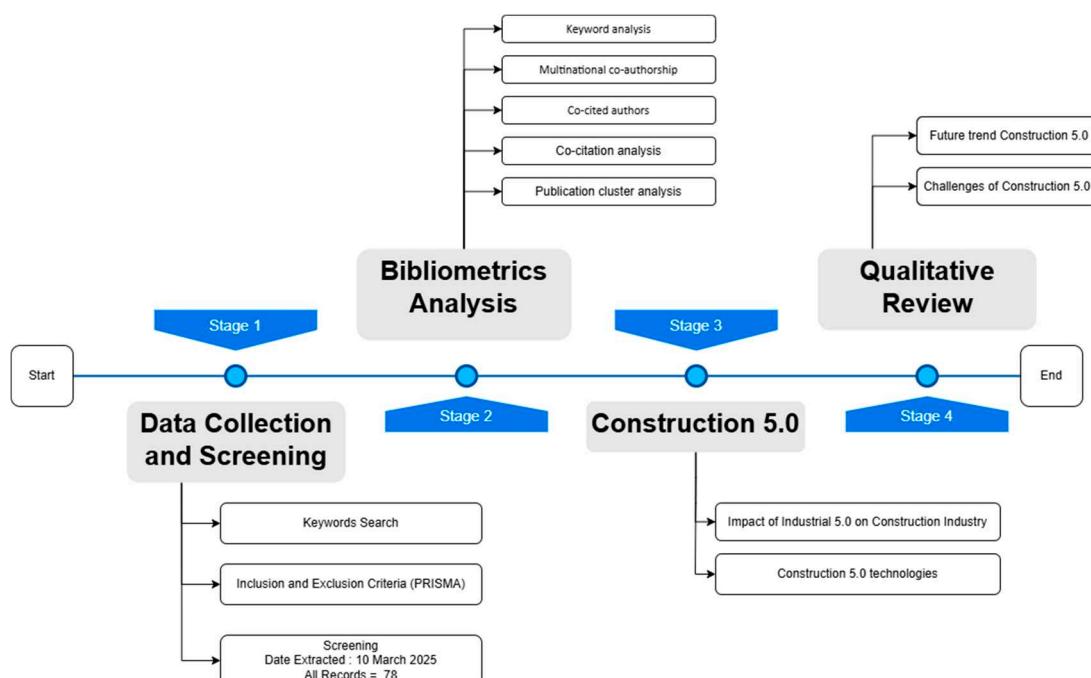


Figure 1. Research methodology framework.

The foundation of any literature review relies on the quality of the input data. Therefore, before conducting the bibliometric analysis and qualitative discussion, it is essential to establish a comprehensive database and a rigorous search strategy. In this study, Scopus was selected as the primary database for retrieving relevant publications due to its extensive coverage of engineering and technology and its frequent use in previous construction industry literature reviews. Additionally, Scopus offers broader coverage than many alternative databases in terms of interdisciplinary research and journal publications [20]. Regarding the search methodology, a set of keywords related to C5.0 technologies was defined to extract relevant publication details from Scopus (Table 1). The search period spans from 2022 to February 2025, aligning with the active development phase of C5.0 technologies. This timeframe, defined by the filters in Section 2.3, ensures data availability from 2022 onward, capturing recent advancements and emerging trends. Extending the period to 2025 provides a forward-looking perspective for a comprehensive analysis of ongoing developments.

Table 1. Keywords pertaining to C5.0.

| Construction 5.0 |
|---|
| "Construction 5.0" OR ("Operator 5.0" and "construction") OR("Industry 5.0" OR "Industrial 5.0") AND ("Construction industry" OR "Human-Centric in Construction" OR "HRC in Construction" OR "Robot in Construction" OR "Building" OR "AEC industry" OR "Resilience in Construction" OR "sustainability in Construction" OR "Automation in Construction" OR "3D printing in construction" OR "Blockchain in construction" OR "Digital twins in construction" OR "IoT in construction" OR "Augmented reality in construction" OR "Virtual reality in construction" OR "Mixed reality in construction" OR "Machine learning in construction" OR "machine learning in construction" OR "cloud computing in construction" OR "metaverse in construction" OR "AI in construction") |

2.1. Methods

The process of identifying and selecting the relevant literature for this study was meticulously structured in accordance with the 2020 revised guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement to uphold the principles of transparency, reproducibility, and methodological rigor [21]. This systematic framework facilitated the establishment of a comprehensive search protocol, incorporating a well-defined search strategy, stringent eligibility criteria, a structured selection process, and robust filtering mechanisms. These measures ensured the extraction of highly relevant and methodologically sound publications pertaining to C5.0 technologies within the construction sector, thereby reinforcing the validity and reliability of the subsequent bibliometric and qualitative analyses [22,23].

2.2. Search Strategy

Scopus was chosen as the primary database for this study due to its comprehensive coverage of engineering, technology, and interdisciplinary research and its consistent use in the bibliometric analyses and literature reviews related to construction and Industry 5.0.

The search settings in Scopus were configured to target publications within the "title/abstract/keywords" field, ensuring that only articles explicitly discussing C5.0 technologies in construction were included. A keyword-based search strategy was employed, starting with an initial set of terms derived from the literature review on C5.0 technologies and their application in construction. However, using a broad term like "construction" alone yielded an excessive number of irrelevant results.

To refine the search, a combination of keywords was used, incorporating C5.0 technology-related terms alongside construction-specific terminology. This strategy was informed by the previous literature review studies in Building Information Modeling (BIM) and smart construction, acknowledging that some influential research appears in interdisciplinary journals beyond the engineering domain.

2.3. Inclusion and Exclusion Criteria

A rigorous filtering process was implemented to ensure the selection of publications directly relevant to this study's focus.

Inclusion Criteria:

- Journal articles and books published between 2022 and 2025 to ensure up-to-date insights.
- Studies explicitly discussing C5.0 technologies and their application in the construction sector.
- Publications from engineering, computer science, technology, and interdisciplinary innovation domains.
- Documents in the English language to ensure accessibility and consistency in analysis.
- Document types: Articles, reviews, book chapters, and books.

- Publication stage: Only final publications were considered.
- Key focus: Studies emphasizing Construction 5.0 and Industry 5.0 applications in construction.
- Relevance to research aim: Studies that contribute significantly to understanding Construction 5.0.

Exclusion Criteria:

- Studies from non-engineering disciplines, such as arts, medicine, nursing, agriculture, biological sciences, health professions, microbiology, immunology, pharmacology, veterinary science, and dentistry, as they do not contribute to the technical and engineering focus of this review.
- Articles discussing C5.0 technologies in non-construction contexts, such as healthcare or education, unless they provide transferable insights applicable to construction innovation.
- Non-peer-reviewed sources, such as conference papers.
- Non-English publications to ensure consistency in language analysis.
- Conference proceedings were excluded.
- Articles in the press were omitted to ensure only finalized research was considered.
- Studies that do not specifically focus on Construction 5.0 or Industry 5.0 applications in construction were excluded.
- Studies with marginal relevance to the research aim were also eliminated to maintain a highly focused and coherent dataset.

Based on the mentioned criteria, 78 documents were selected for full-text evaluation from an initial set of 100 building documents.

2.4. Qualitative Review

While scientometrics analysis provides a broad and general perspective on research trends, this method alone is insufficient for uncovering nuances and conducting a deep analysis of the content of research studies. Therefore, in this study, a qualitative analysis of selected texts was conducted, as illustrated in Figure 1.

The qualitative analysis was based on a thematic analysis, aiming to identify the recurring patterns and dominant themes in the literature related to the application of Industry 5.0 in the construction sector (C5.0). The analysis process followed the three-stage framework of Bardin's content analysis, which includes pre-analysis, data exploration, and the interpretation of results. This approach enabled us to identify and classify the main challenges, limitations, research gaps, practical advancements, and future research pathways, which are detailed in Section 5. For this analysis, a structured manual coding process was employed to ensure the precise classification and interpretation of the data.

3. Bibliometric Analysis

Construction 5.0, driven by the digital revolution and supported by 78 publications from the Scopus database, has seen significant growth in construction-related research between 2022 and 2025, highlighting its increasing importance. However, a comparative analysis suggests that its adoption in the construction industry has been somewhat sluggish, indicating substantial potential for future expansion. To gain a comprehensive understanding of C5.0, a bibliometric analysis was conducted using the VoSviewer tool [24]. This software helps dissect bibliometric data and visualize it through tables and figures, providing insights into the scientific landscape of this subject. This approach has been used in previous quantitative literature assessments [24–26].

3.1. Publication Versus Citation

A study identified the primary sources of publications on Construction 5.0, summarized in Table 2. *Sustainability* (Switzerland) leads with eight publications, followed by *Buildings* with seven. *Applied Sciences* (Switzerland) ranks third with four publications. *Journal of Building Engineering* has three, while *Studies in Systems, Decision and Control*, *Automation in Construction*, *SpringerBriefs in Applied Sciences and Technology*, and *Drone Applications for Industry 5.0* each contribute two. The last contributors are *Environment, Development and Sustainability*, and *CFI Ceramic Forum International*.

Table 2. Journal publication related to C5.0.

| Journal Title | Documents |
|--|-----------|
| <i>Sustainability</i> (Switzerland) | 8 |
| <i>Buildings</i> | 7 |
| <i>Applied Sciences</i> (Switzerland) | 4 |
| <i>Journal of Building Engineering</i> | 3 |
| <i>Studies in Systems, Decision and Control</i> | 2 |
| <i>Automation in Construction</i> | 2 |
| <i>SpringerBriefs in Applied Sciences and Technology</i> | 2 |
| <i>Drone Applications for Industry 5.0</i> | 2 |
| <i>Environment, Development and Sustainability</i> | 1 |
| <i>CFI Ceramic Forum International</i> | 1 |

3.2. Co-Citation Analysis

Co-citation happens when two documents are cited together by a third document, suggesting that frequently co-cited papers represent fundamental concepts, methods, or experiments in a specific field and tend to have high individual citation numbers [27]. Moreover, when two papers are cited in numerous other papers, it can be inferred that these co-cited papers share a strong relationship and have a substantial impact on the research domain [28,29]. Using a co-citation network generated through a Scopus-based analysis with VOSviewer aids in visualizing connections between important publication sources, documents, and influential authors within the C5.0 domain [30].

This section presents a VOSviewer co-citation analysis to identify the influential authors in the field, as shown in Figure 2. To maintain consistency with the methodology, the co-citation analysis was conducted using data retrieved from Scopus, as reported earlier. A total of 78 works were selected based on predefined criteria, ensuring the comprehensive coverage of the research landscape. Using a minimum co-authorship threshold of 20, 41 authors out of 12,184 met the criteria. The results in Figure 2 reveal two main author clusters. The most prominent researcher is Zheng P., with the highest total link strength (2836) and 50 citations. Wang L. follows with a total link strength of 2668 and 70 citations. In third place, Zhang C. has a total link strength of 2591 and 35 citations. Other notable authors include Li X. (2277 total link strength; 53 citations), Wang Y. (1665 total link strength; 37 citations), and Li Y. (1651 total link strength; 48 citations). Table 3 provides a detailed analysis of additional co-cited authors, highlighting their collaborative contributions and influence in the research field. Figure 2 visually demonstrates the clustering and interconnections among these influential authors, offering a comprehensive view of their research collaborations and citation relationships.

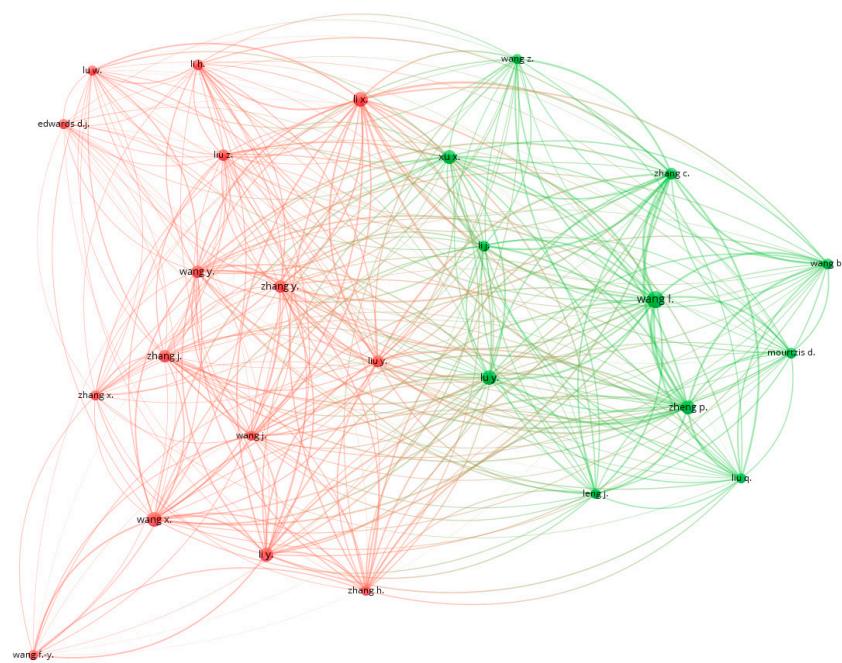


Figure 2. Co-cited authors network analysis.

Table 3. Top co-cited authors.

| Names | Total Link Strength | Citations |
|----------|---------------------|-----------|
| Zheng P. | 2836 | 50 |
| Wang L. | 2668 | 70 |
| Zhang C. | 2591 | 35 |
| Li X. | 2277 | 53 |
| Wang Y. | 1665 | 37 |
| Li Y. | 1651 | 48 |
| Xu X. | 1638 | 48 |
| Liu Y. | 1617 | 34 |
| Lu Y. | 1610 | 53 |
| Li J. | 1496 | 28 |
| Wang B. | 1488 | 30 |
| Zhang Y. | 1481 | 40 |

3.3. Multinational Co-Authorship

This section introduces a co-authorship analysis aimed at identifying collaboration networks based on the geographical location (country/region) of individual authors. For the analysis, bibliometric data were processed using VOSviewer's co-authorship function with a minimum publication threshold of one per country/region, resulting in the inclusion of 44 countries/regions that met this criterion.

Figure 3 presents the co-authorship network, where countries/regions sharing the same color belong to the same cluster, indicating stronger collaborative ties within those regions compared to others. For instance, researchers in the United Kingdom, Cyprus, and Portugal form a distinct cluster, suggesting a robust collaborative network within the Construction 5.0 (C5.0) research domain.

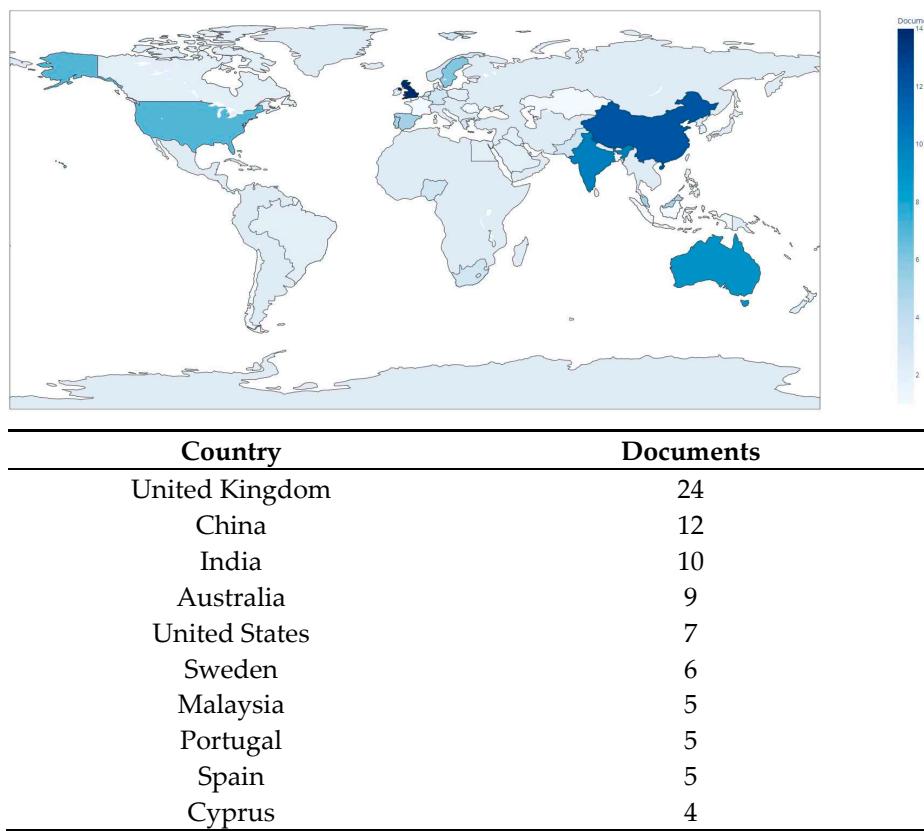


Figure 3. Global multinational co-authorship network.

The United Kingdom emerges as the most productive country (Figure 4), contributing fourteen published documents (Figure 3), followed by China twelve documents and India's ten documents. Australia produced nine documents, while the United States contributed seven. Sweden followed with six documents, whereas Malaysia, Portugal, and Spain each contributed five documents. Cyprus recorded four published documents. By comparing these findings with prior studies, this analysis contextualizes the role of multinational collaborations in C5.0 research and highlights evolving trends in global participation. The increasing involvement of specific countries suggests a shift in research focus. However, the United Kingdom had the highest contribution. Notably, China, the United Kingdom, and Sweden had the highest citations, emphasizing their significant influence on the research landscape within this domain. Additionally, other countries, including Hong Kong, Germany, Greece, the Netherlands, Nigeria, Norway, and Pakistan, have also contributed to this research, further demonstrating the widespread global engagement in this field.

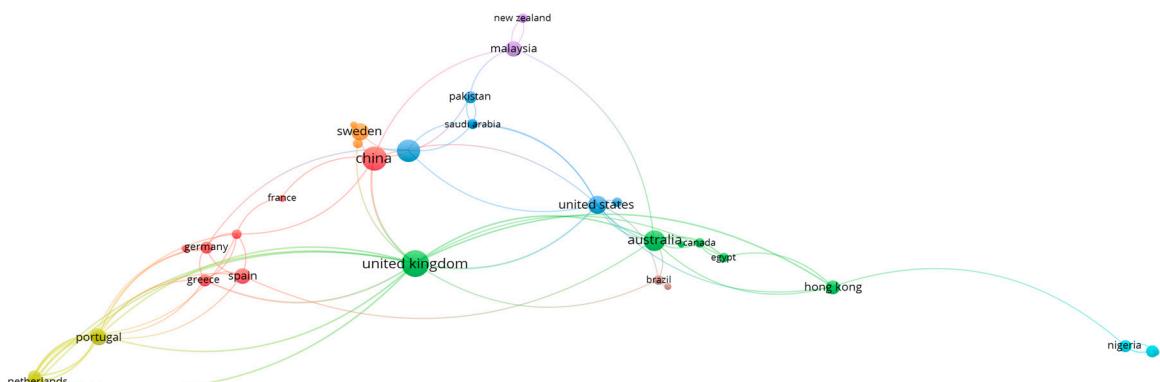


Figure 4. Visualization of the contributions of countries to the advancement of Construction 5.0.

Additionally, several institutions have played a leading role in advancing C5.0 research. The S.M.A.R.T. Construction Research Group at the Division of Engineering, New York University Abu Dhabi (NYUAD), United Arab Emirates, has made significant contributions. Other prominent institutions include the School of Architecture, Building and Civil Engineering, Loughborough University, United Kingdom, the School of Design, South China University of Technology, Guangzhou, China, and the School of Engineering of Bilbao, University of the Basque Country—UPV/EHU, Bilbao, Spain. Furthermore, the Victoria University Business School, Victoria University, Melbourne, Australia, the School of Civil Engineering, National Technical University of Athens, Greece, and the School of Engineering, University of Leicester, United Kingdom, have emerged as key research hubs driving advancements in this field.

3.4. Keyword-Based Research Cluster Analysis

Keywords designated by the authors have been suggested in numerous prior studies, for example, [31–34]. Author-specified keywords have been endorsed in previous studies as a crucial method for identifying vital research areas in a particular subject. Thus, this section presents the results of an inquiry into the co-occurrence of keywords using the VOSviewer tool. To create an interconnected network of keywords, bibliometric data related to C5.0 research were input into VOSviewer, aiming to provide a more comprehensive insight into current research trends and relationships [35]. The minimum keyword occurrence threshold was set at three. To create a clear and meaningful map, a further step involved consolidating keywords with similar semantic meanings. Additionally, we have ensured that the terms appear consistently in Figure 5 and Table 4 for accuracy. The co-occurrence map (Figure 5) presents keywords derived from 44 keywords in the analyzed publications. The size of each node corresponds to the frequency of the keyword's occurrence, with larger nodes indicating a higher frequency. Keywords in the same research cluster are depicted in matching colors, and the distance between the nodes signifies the strength of their connection (greater distance suggests weaker relationships) [36]. Figure 5 provides a comprehensive summary of the information.

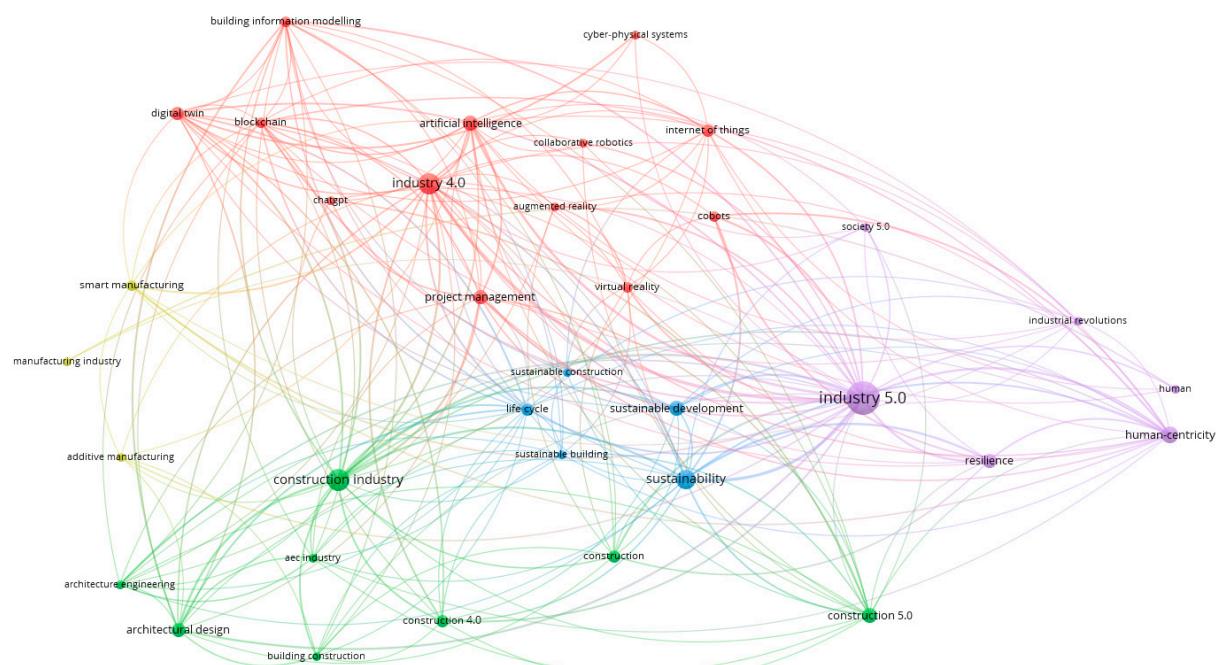


Figure 5. Research cluster analysis by the cited keywords.

Table 4. Keyword occurrences, total link strength, and average citations.

| Label | Cluster | Links | Total Link Strength | Occurrences | Avg. Citations |
|-------------------------------|---------|-------|---------------------|-------------|----------------|
| Industry 5.0 | 5 | 41 | 118 | 37 | 12.1 |
| Construction industry | 2 | 27 | 65 | 16 | 17.7 |
| Industry 4.0 | 1 | 33 | 61 | 15 | 21.9 |
| Sustainability | 3 | 23 | 48 | 13 | 5.2 |
| Human centricity | 5 | 26 | 44 | 9 | 10 |
| Artificial intelligence | 1 | 23 | 39 | 8 | 25.5 |
| Life cycle | 3 | 24 | 38 | 5 | 45.4 |
| Architectural design | 2 | 18 | 34 | 7 | 26.5 |
| Blockchain | 1 | 20 | 34 | 4 | 37 |
| Project management | 1 | 19 | 31 | 7 | 26 |
| Digital twin | 1 | 19 | 30 | 6 | 21.8 |
| Building information modeling | 1 | 20 | 26 | 4 | 30.5 |
| Construction 5.0 | 2 | 19 | 24 | 8 | 20.1 |
| Resilience | 5 | 9 | 24 | 7 | 3.9 |

The most prominent node in the diagram represents “Industry 5.0”, which is expected given its significance in both the construction and C5.0 research domains. It has an occurrence of 37, a total link strength of 181, and an average citation of 12.0811. The diagram also suggests that many researchers exploring C5.0 are actively seeking connections between the construction industry and Construction 5.0, which includes AI, Industry 4.0, and sustainability. The most prominent node in the diagram represents “Industry 5.0”, which is expected given its significance in both the construction and C5.0 research domains. It has an occurrence of 37, a total link strength of 118, and an average citation of 12.1. The diagram also suggests that many researchers exploring C5.0 are actively seeking connections between the construction industry and Construction 5.0, integrating concepts such as AI, Industry 4.0, and sustainability. Other key research areas include “Construction industry” (occurrence: 16, total link strength: 65, average citation: 17.7), “Industry 4.0” (occurrence: 15, total link strength: 61, average citation: 21.9), “Sustainability” (occurrence: 13, total link strength: 48, average citation: 5.2), and “Construction 5.0” (occurrence: 8, total link strength: 24, average citation: 20.1). Additional important topics include “Life cycle” (occurrence: 5, total link strength: 38, average citation: 45.4) and “Resilience” (occurrence: 7, total link strength: 24, average citation: 3.9). For human–robot collaboration research, “Human-centricty” has 9 occurrences, a total link strength of 44, and an average citation of 10. Further details are provided in Table 4, summarizing keyword occurrences, total link strengths, and average citations.

Furthermore, an analysis of Figure 5 and Table 4 is provided, identifying five key research clusters within the C5.0 domain. The thematic clustering of keywords further refines these clusters, highlighting their interconnections through key terms that emphasize C5.0’s interdisciplinary nature. These clusters are interconnected through key connection words, establishing links between them and highlighting the interdisciplinary nature of C5.0 research. Cluster 1: The Digital Technologies cluster includes topics related to digital and intelligent technologies, such as artificial intelligence, augmented reality, blockchain, Building Information Modeling, ChatGPT, Cobots, collaborative robotics, Cyber–Physical Systems, digital twin, Industry 4.0, Internet of Things, project management, and virtual real-

ity. Cluster 2: The integrating construction industry focuses on construction-related themes, encompassing the AEC industry, Architectural Design, Architecture Engineering, Building Construction, construction, Construction 4.0, Construction 5.0, and the construction industry. Cluster 3: Sustainability highlights sustainability-oriented research, covering life cycle, sustainability, Sustainable Building, sustainable construction, and Sustainable Development. Cluster 4: Smart Manufacturing is centered around manufacturing advancements, including Additive Manufacturing, Manufacturing Industry, and Smart Manufacturing. Cluster 5: This cluster addresses the Industrial Revolution aspects of industrial progress, featuring topics such as Human, human centricity, Industrial Revolutions, Industry 5.0, resilience, and society 5.0. The connection words linking these clusters indicate strong relationships between Industry 4.0 and 5.0, collaborative robotics and human centricity, and sustainability and digital transformation, highlighting the integrated evolution of C5.0 research. These clusters reflect the diverse and evolving nature of C5.0 research, combining technological, industrial, and sustainability-driven innovations.

3.5. Seminal Contributions and Influential Research in Construction 5.0

This study systematically reviews articles pertinent to Construction 5.0. The table (Table 5) presented below catalogs the most frequently cited publications within this field, detailing the article title, year of publication, and citation count. These works represent seminal contributions to the Construction 5.0 paradigm, offering critical insights into emerging trends and research priorities. For a comprehensive overview, including additional bibliometric details, readers are directed to Appendix A.

Table 5. Seminal contributions and influential research in Construction 5.0.

| Title | Year | Cite |
|--|------|------|
| Towards new-generation human-centric smart manufacturing in Industry 5.0: A systematic review [37] | 2023 | 100 |
| Investigating the Use of ChatGPT for the Scheduling of Construction Projects [38] | 2023 | 79 |
| BIM Information Integration Based VR Modeling in Digital Twins in Industry 5.0 [39] | 2022 | 73 |
| Construction 4.0, Industry 4.0, and Building Information Modeling (BIM) for Sustainable Building Development within the Smart City [40] | 2022 | 70 |
| Artificial Intelligence Enabled Project Management: A Systematic Literature Review [41] | 2023 | 48 |
| From Industry 4.0 to Construction 5.0: Exploring the Path towards Human–Robot Collaboration in Construction [7] | 2023 | 42 |
| Integrated practices in the Architecture, Engineering, and Construction industry: Current scope and pathway towards Industry 5.0 [42] | 2023 | 32 |
| Challenges and opportunities of augmented reality during the construction phase [19] | 2022 | 29 |
| Investigating the Causal Relationships among Enablers of the Construction 5.0 Paradigm: Integration of Operator 5.0 and Society 5.0 with Human-Centricity, Sustainability, and Resilience [43] | 2023 | 21 |
| Human–Robot Collaboration and Lean Waste Elimination: Conceptual Analogies and Practical Synergies in Industrialized Construction [18] | 2022 | 17 |

4. Impact of Industrial 5.0 on Construction Industry

Construction 5.0 marks a groundbreaking phase in industrialization, where humans collaborate seamlessly with advanced technology and AI-powered robots to optimize workplace processes. This paradigm unites the precision and efficiency of machinery with human creativity and personalization, resulting in a more resilient project delivery model. Building upon the technological foundation of Construction 4.0, Construction 5.0 (C5.0) introduces new dimensions by prioritizing sustainability, resilience, and human-centric innovation. It

utilizes cutting-edge technologies like the Internet of Things (IoT), big data, AI, robotics, digital twins, and blockchain to optimize efficiency within the construction industry (Figure 6). However, what truly sets C5.0 apart is its unwavering commitment to sustainability, as it actively seeks to minimize environmental impacts through resource-efficient practices [44]. This model ensures that advancements in technology serve environmental and societal goals, rather than just economic ones. In addition, C5.0 emphasizes cross-sector collaboration and innovation driven by real-time data analytics, ensuring a responsive and adaptive industry. Resilience integration forms another cornerstone, ensuring construction projects can withstand the rigors of a changing climate and unexpected disruptions by using real-time data and predictive analytics to anticipate and mitigate risks.

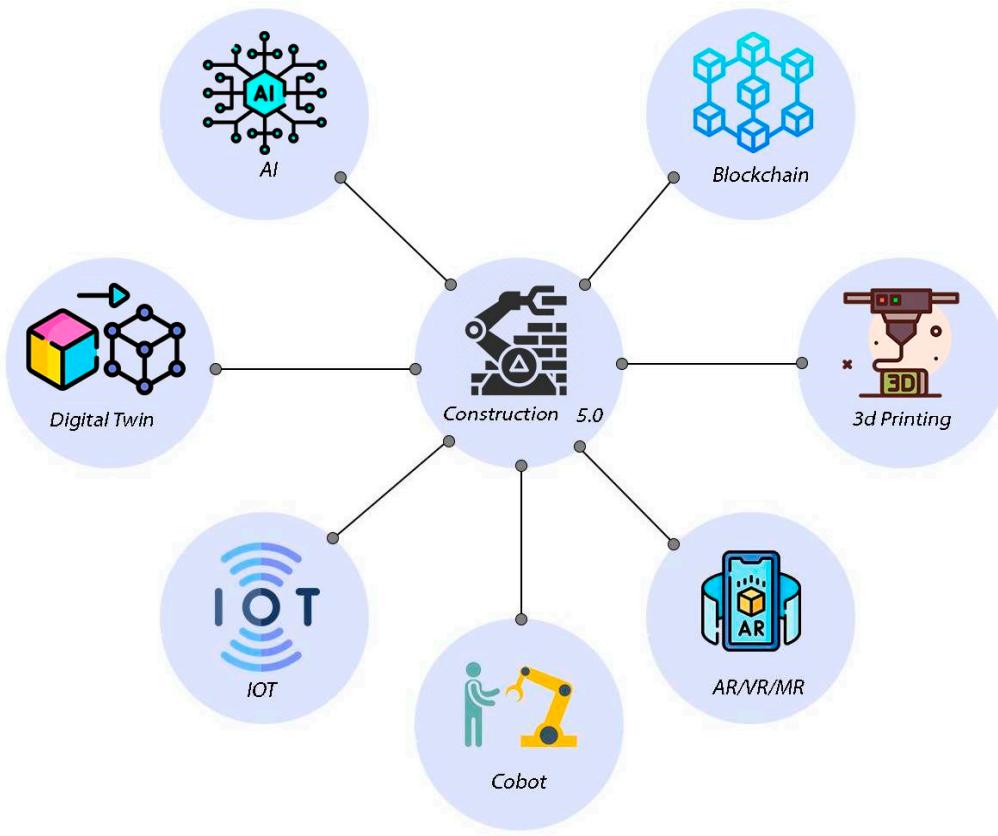


Figure 6. Core technologies used in the construction industry (C5.0).

In the evolving landscape of Industry 5.0, the centrality of humanity is crucial, with the needs of prosumers, consumers who are also producers, acting as a check on complete automation. Human-centric manufacturing emphasizes collaboration between humans and robots, enhancing both worker well-being and system efficiency. This approach combines critical socio-environmental data analysis with an AI-driven mindset, fostering Sustainable Development and societal trust. Compared to C4.0, where the focus was on automation and efficiency, C5.0 seeks to optimize worker engagement and integrate human expertise into decision-making processes. A notable shift is the introduction of a human supervisor responsible for overseeing and approving all executive actions across the system, ensuring a collaborative and safety-oriented construction environment. This shift highlights a more human-centric approach combining sustainability, resilience, and human well-being with technological innovation.

C5.0 aims to expedite green and digital transitions, redefining the construction industry's role in addressing global challenges. Sustainability is recognized as integral, aligning with UN Sustainable Development Goals (SDGs) [45]. C5.0 not only advocates for

decentralized resources and open products but also encourages innovation in delivering customized solutions to meet diverse environmental and societal needs. For instance, C5.0 utilizes blockchain technology to ensure the transparent tracking of resources across complex supply chains, improving accountability and supporting social sustainability goals [46]. In Industry 5.0, human-centered demands take precedence, emphasizing ethical considerations and social impacts. However, it is critical to balance social and environmental sustainability with economic viability, ensuring that technological advancements also deliver cost savings and productivity improvements. Financial sustainability is achieved by integrating smart construction methods, which not only reduce material waste but also optimize resource allocation and labor efficiency, contributing to lower project costs [47].

The global construction sector in C5.0 focuses on increased productivity, speed, and savings through environmentally responsible methods. Resilience in Industry 5.0 is vital for swift recovery from disruptions, whether they stem from supply chain vulnerabilities, natural disasters, or market fluctuations. C5.0 enhances adaptability by incorporating predictive analytics and dynamic system designs to better handle unforeseen challenges, ensuring a robust and future-proof industry. These predictive tools enable construction teams to anticipate risks, adjust workflows, and implement real-time mitigation strategies to maintain continuity.

Human-Centricity: This approach focuses on human–robot collaboration and emphasizes the role of human oversight in maintaining long-term system sustainability. It ensures that technological advances serve not just economic goals but also contribute to worker well-being and societal development. By placing a human supervisor in critical decision-making roles, C5.0 ensures that ethical considerations and worker safety remain central to project execution.

Sustainability: C5.0 integrates human, environmental, and social considerations, focusing on reducing the environmental impact of industrial activities and improving social welfare. By leveraging IoT, big data, and real-time analytics, C5.0 drives sustainable practices in resource-constrained environments, ensuring the efficient use of materials and energy. Additionally, innovations like decentralized energy systems and circular economy models promote sustainable construction methods, reducing dependency on finite resources.

Resilience: C5.0 aims to create adaptable, resilient systems capable of withstanding supply chain disruptions and other challenges. Resilience is achieved through the integration of real-time data systems, advanced simulation tools, and proactive risk management strategies, ensuring continuous operations despite external shocks. By utilizing predictive modeling, the construction sector can preemptively identify vulnerabilities and implement risk-aversion strategies, ensuring the longevity and sustainability of projects.

Moreover, the continuous evolution of digital and automation technologies plays a pivotal role in optimizing operational efficiency and fostering innovation in construction methodologies. In this section, Industrial 5.0 approaches in construction are systematically examined, with a focus on key technologies such as Collaborative Robots, blockchain, digital twin, Internet of Things, artificial intelligence, AR/VR/MR, and 3D printing, as well as their implications for the future of the construction industry [48].

4.1. Collaborative Robots

To address a construction labor shortage caused by an aging population and disengaged younger workers, Japan pioneered the use of construction automation and robotics during the 1970s and 1980s [49]. The early applications of robotics in construction focused on repetitive and labor-intensive tasks such as bricklaying and material handling, gradually evolving to more advanced systems capable of performing complex operations with higher

precision. Robots are transforming construction processes, from the effortless assembly of prefabricated components to the precise fixture installation and seamless connection of building elements [50,51]. This revolution in construction enhances both efficiency and accuracy. Notable milestones in this evolution include the development of robots capable of working in hazardous environments, like nuclear decommissioning sites, which has spurred further interest in their use in construction.

Robots play a crucial role in the inspection and monitoring of the built environment, including buildings and infrastructure, enhancing accuracy and efficiency. Unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) are the most commonly used systems, applied in maintenance inspection, construction quality control, progress monitoring, as-built modeling, and safety assessment [52]. In addition, advanced robotic systems such as Boston Dynamics' robot dog and Pictobot are increasingly being utilized in construction settings. Boston Dynamics' robot dog, with its agility and adaptability, proves invaluable for surveying construction sites, monitoring structural integrity, and assisting with tasks like carrying tools and materials in challenging environments. Meanwhile, Pictobot brings automation to the field of concrete construction, by utilizing robotic arms for the finishing of concrete in construction projects [53]. Integrating cutting-edge robotic technology, including diverse solutions like the robot dog and Pictobot, enhances the efficiency and safety of construction processes, showcasing the multifaceted applications of robots in infrastructure development [54,55].

Robotic technologies enhance construction efficiency and improve Resilience, Safety, and Environment (HSE) outcomes by automating hazardous tasks and facilitating human–robot collaboration, which reduces the risk of accidents [56]. Ensuring the safety of both workers and the public during collaborative work with construction robots necessitates robust safety regulations and standards. Additionally, developing frameworks for liability and responsibility in the event of accidents or damages caused by robots is critical for widespread adoption [57]. Robotics has successfully automated bricklaying, efficiently handling tasks such as brick selection, material bonding, and constructing double-leaf dry-stacked brick walls using specialized mobile robots [57].

Sustainability and resilience are also achieved with robotic innovations such as 3D printing, which minimizes construction waste, utilizes eco-friendly materials, and produces customized designs aligned with natural principles [58,59]. Three-dimensional printing robots further contribute to sustainability by enabling the construction of more energy-efficient buildings and reducing the need for the transportation of materials. Despite their potential, the limited adaptability of robots in construction projects, coupled with a resistance to change among workers and stakeholders, poses challenges to the effective integration of robotics and automation into traditional construction practices [60]. Developing modular and reconfigurable robots that can quickly adapt to different construction tasks may help mitigate these challenges, along with increasing training and awareness programs to reduce resistance.

The seamless fusion of Building Information Modeling (BIM) with robotics holds excellent promise. BIM is a comprehensive digital representation of a building's physical and functional attributes, enabling real-time data sharing, automated planning, and synchronized cooperation between robots and construction procedures [61,62]. Integrating robotics with BIM not only improves accuracy but also enhances collaboration across project stakeholders by providing a standard data environment. The construction industry's future lies in integrating AI, modular and reconfigurable robotic systems, 3D printing, Additive Manufacturing, and augmented reality (AR) and virtual reality (VR) technologies [61,63]. These advancements will allow robots to perform increasingly complex tasks, adapt to

dynamic environments, and work in close cooperation with humans, ultimately resulting in a more efficient, sustainable, and resilient construction industry.

4.2. Blockchain

Blockchain technology, proposed by Stuart Haber and W. Scott Stornetta in 1991, aimed to provide a secure and tamper-proof method for time-stamping digital documents through a system of cryptographically secured blocks linked together [64]. Blockchain's application in the construction industry began gaining traction in the mid-2010s, driven by the industry's increasing need for transparency, efficiency, and risk mitigation in project management and financial transactions. Notably, early pilot projects explored blockchain's role in streamlining procurement processes, resolving payment disputes, and improving supply chain transparency in construction workflows.

Blockchain technology has the potential to enhance human centricity in construction processes. By incorporating smart contracts and milestone tracking, it fosters transparency and trust among all stakeholders. This not only optimizes payment and contract management but also minimizes disputes, ensuring that the intended outcomes of executive actions are aligned with the satisfaction of all parties involved. However, it is crucial to recognize that, despite automation through smart contracts, human approval remains a key factor in ensuring ethical execution and overall stakeholder contentment [65,66].

Secure and decentralized data storage enables more efficient supply chain management and environmental monitoring. This ensures that the construction materials are sourced responsibly, promoting eco-friendly practices and reducing the environmental impact of construction projects. Moreover, the integration of blockchain with Internet of Things (IoT) devices facilitates the real-time tracking and monitoring of construction assets. This not only improves decision-making and operational efficiency but also contributes to sustainable practices by optimizing the use of resources. Sustainable construction practices, driven by blockchain technology, are aligned with environmental conservation efforts and the overall goal of reducing the ecological footprint of construction activities [67,68].

In addition to smart contracts, blockchain technology can also be used to provide secure and decentralized data storage [69]. In construction resilience, blockchain provides robust solutions by offering tamper-proof and secure documentation through cryptographically secured blocks. This ensures the integrity of project data, crucial for safeguarding against fraud and manipulation, and maintaining the credibility of construction records. Additionally, blockchain involvement in decentralized finance (DeFi) enhances financial resilience in construction. Transparent and secure blockchain transactions contribute to financial stability, mitigating fraud risks and ensuring the resilience of financial systems supporting construction projects [70]. A BIM-blockchain framework with smart contracts enhances asset tracking, delay analysis, and cost efficiency. Additionally, secure data storage and decentralized finance ensure transparency and financial stability in construction projects [71].

Data privacy and security are paramount in construction projects, given their frequent involvement in managing sensitive and confidential information such as financial data, intellectual property, and personal data [72]. This calls for more research into privacy-preserving techniques, such as zero-knowledge proofs, that can be applied within blockchain frameworks for the construction industry. Interoperability remains a critical issue in the construction industry, as it heavily relies on diverse software systems and platforms to carry out various processes. However, integrating these systems with blockchain technology poses a challenge. Achieving seamless data exchange and interoperability requires dedicated standardization efforts [73,74]. Blockchain technology can potentially revolutionize finance through decentralized finance (DeFi) [75].

Despite these advantages, achieving interoperability with diverse software systems poses challenges. Standardization efforts are crucial for seamlessly integrating blockchain, ensuring its resilience-enhancing features effectively contribute to the broader construction ecosystem. Future research should focus on developing frameworks that facilitate integration with widely used tools such as Building Information Modeling (BIM) and AI systems to optimize blockchain potential in real-time data sharing and decision-making. Overall, blockchain contributions align with the industry's evolving needs for secure, efficient, and trustworthy solutions in promoting sustainability and resilience [68,76].

4.3. Digital Twin (DT)

By 2006, the name of the conceptual model proposed by Grieves was changed from 'Mirrored Spaces Model' to 'Information Mirroring Model' in the construction industry [77]. Digital twins have evolved from a theoretical concept to a transformative tool in construction. Initially introduced in the aerospace and manufacturing sectors, digital twins gained traction in construction in the early 2010s, enabling a more precise digital representation of real-world structures [78]. Digital twins in construction utilize the virtual replicas of real-world objects or systems to optimize engineering systems and improve construction processes [79]. These simulations enhance planning processes, clash detection, construction logistics, scheduling, and overall project life-cycle management by integrating cyber-physical synchronicity, the semantic representation of building components, and artificial intelligence. Digital twins, in their application to construction, contribute to a human-centric approach by enhancing safety during the hoisting of prefabricated buildings. In addition to hoisting, digital twins also enable remote site monitoring, reducing workers' exposure to hazardous environments and improving real-time decision-making capabilities [80]. Through real-time monitoring and the identification of potential safety hazards, digital twins prioritize the well-being of construction workers. Moreover, as the industry moves toward Industry 5.0, digital twins enable workers to actively participate in a framework that fosters collaboration among project stakeholders. This aligns with a human-centric vision, improving overall project efficiency and worker engagement [81]. Digital twins play a significant role in promoting sustainability within the construction industry. The technology enables real-time building performance monitoring, allowing for predictive maintenance and identifying opportunities for sustainability and resilience improvements. By optimizing resource allocation through AI and ML algorithms, digital twins contribute to the efficient use of materials and energy, aligning with sustainable construction practices [82]. Integrating digital twins with BIM further enhances coordination and information sharing, streamlining processes and promoting environmentally conscious decision-making [83]. In terms of resilience, digital twins offer a robust solution by providing tamper-proof and secure documentation through their blockchain-like structure. Digital twins have also been implemented in post-disaster scenarios, where their predictive capabilities have enabled the rapid assessment of structural integrity following earthquakes or storms [84]. Despite the challenges in managing complex digital twin models, their role in predicting risks through AI and ML algorithms enhances overall project resilience. The future of digital twins in construction, especially with the integration of advanced visualization technologies, promises to further bolster resilience by providing stakeholders with immersive and intuitive experiences for better decision-making during unforeseen circumstances [85]. Moreover, digital twins can be used in the construction industry to enable real-time building performance monitoring, allowing for predictive maintenance and identifying opportunities for sustainability and resilience improvements. AR and VR technologies offer an immersive and realistic experience that enhances understanding, issue identification, and training for construction project stakeholders through the digital

representations of the project [86]. Furthermore, digital twins can be used in the construction industry to drive human-centric processes toward Industry 5.0, enabling workers to participate in the digital twin-based framework and improving collaboration among project stakeholders [87]. Artificial intelligence (AI) and machine learning (ML) algorithms enhance digital twins in construction by analyzing project performance, optimizing resource allocation, predicting risks, and enabling data-driven decision-making. This empowers construction professionals with accurate predictions, continuous learning, and improved efficiency for successful project outcomes [88,89]. The future of digital twins in the construction industry will be revolutionized by advanced visualization technologies like virtual reality and augmented reality, enabling stakeholders to have immersive and intuitive experiences that enhance understanding, collaboration, and decision-making in construction projects [90]. Additionally, integrating digital twins and Building Information Modeling (BIM) will enhance construction coordination, collaboration, and information sharing by seamlessly transferring data between virtual and physical environments, streamlining processes, optimizing decision-making, and improving project outcomes [81]. However, to ensure the scalability and broader adoption of digital twins in construction, the industry must address challenges such as high implementation costs, specialized training requirements, data privacy, and cybersecurity risks.

4.4. Internet of Things (IoT)

The term “Internet of Things” (IoT) refers to the concept of a groundbreaking creation that emerged in 1999 from MIT, which has since become a prominent field in future technology with widespread interest from different industries [91]. The early applications involved the use of sensors for material tracking and remote site management, which paved the way wider adoption in various construction processes. Concerning C5.0, implementing IoT technologies such as RFID, wireless sensor networks, middleware, cloud computing, and IoT application software enables the monitoring and control of construction processes, equipment management, safety and security measures, supply chain management, and energy efficiency optimization within the construction industry. These IoT solutions enable real-time tracking, remote monitoring, and optimization for improved productivity, safety, and cost savings [92,93].

In embracing IoT technologies in construction, a human-centric approach is evident through improved safety measures and worker well-being. IoT solutions enable real-time tracking, remote monitoring, and optimization, contributing to enhanced productivity and safety. Practical examples include the use of wearables for construction workers, which monitor vital signs and provide real-time alerts if a worker is in danger. With sensors on construction equipment collecting data on various parameters, there is a focus on optimizing equipment usage, tracking maintenance requirements, improving overall efficiency, and prioritizing the well-being and safety of construction workers [94]. The adoption of IoT technologies in construction contributes significantly to sustainability practices. Monitoring energy use and reducing energy demand are key aspects where IoT plays a crucial role. Additionally, the widespread adoption of digital twins, created through IoT-connected sensors, enables the real-time monitoring, analysis, and simulation of physical assets, enhancing performance evaluation. Integrating IoT with Building Information Modeling (BIM) further promotes sustainability by improving collaboration, project coordination, and facility management through seamless data exchange across different phases of building projects [92]. By minimizing material waste, ensuring accurate energy consumption forecasts, and reducing the carbon footprint of construction operations, IoT contributes to long-term sustainability efforts. These technologies enable sustainable practices by monitoring energy use and reducing energy demand [95,96]. IoT technologies

in construction contribute to resilience by providing real-time data on the location and status of workers and equipment. This information is vital for decision-making, enhancing overall project resilience. For instance, IoT-enabled systems can quickly alert managers in case of a structural failure or hazardous material exposure, ensuring rapid responses to potential crises. Using advanced analytics with AI capabilities and IoT-enabled autonomous equipment fosters resilience through improved efficiency, safety monitoring, collaboration, and decision-making. However, challenges such as data security and privacy, interoperability, and scalability complexities need to be addressed for robust resilience in IoT implementation within the construction industry [97,98]. In the construction industry, the widespread adoption of digital twins, created through IoT-connected sensors, will enable the real-time monitoring, analysis, and simulation of physical assets for improved performance evaluation, while integrating IoT with Building Information Modeling (BIM) will enhance collaboration, project coordination, and facility management through seamless data exchange across the different phases of building projects [99]. Emerging within Industry 5.0, predictive maintenance quality control is garnering popularity in the construction sector. This strategy leverages data analytics and the Internet of Things (IoT) to observe and anticipate machinery deterioration before breakdowns occur preemptively [100]. This empowers construction firms to curtail downtime and circumvent extensive repairs, saving time and costs. The maintenance quality control framework entails continual equipment monitoring, data analysis, and forward-looking strategies. Embracing predictive maintenance quality control enables construction enterprises to proactively enhance equipment upkeep, ensuring optimal operation and minimizing accidents or downtime from machinery failures [81].

Future research must address the cybersecurity risks associated with the vast amounts of data generated by IoT devices. Additionally, managing the scalability of IoT networks and reducing the costs associated with implementing IoT systems in construction are vital research directions to ensure IoT's continued success and adoption across the industry.

4.5. Artificial Intelligence (AI)

Artificial intelligence (AI) primarily empowers machines and systems with intelligence similar to humans [101]. AI first entered the construction industry in the early 21st century, with initial applications focused on automating simple tasks like scheduling and resource management. Over time, as machine learning techniques evolved, AI's role expanded into more complex areas such as predictive analytics and risk management. AI-driven predictive analytics can optimize project planning and scheduling by analyzing historical data and using machine learning [102,103]; AI technologies contribute to human-centric processes in construction by reducing human errors and enhancing safety monitoring and training. The integration of AI-driven predictive analytics ensures that decision-making aligns with the well-being of workers, optimizing project life cycles, reducing costs, and preventing schedule overruns. A key aspect of AI's human-centric approach lies in ensuring a smooth transition for the workforce, addressing the skills gap through upskilling or reskilling [104,105]. Additionally, AI-powered design tools can enable more human-centric building environments, allowing for the customization of spaces that adapt to user needs in real time, further enhancing the end-user experience.

In the realm of sustainability, AI plays a pivotal role in optimizing energy-efficient building design and retrofitting. The incorporation of AI into construction processes contributes to considerable reductions in energy consumption and greenhouse gas emissions. AI algorithms not only optimize the supply chain but also facilitate efficient material procurement and logistics planning, aligning construction practices with environmentally conscious principles [102,106]. Furthermore, optimizing energy efficiency through AI

supports the integration of renewable energy sources into the power grid, reinforcing the industry's commitment to sustainable practices while significantly reducing overall energy consumption by minimizing waste, optimizing load distribution, and improving demand forecasting [99,107,108]. By applying predictive analytics to energy usage data, AI enables proactive adjustments in building systems, reducing waste, and improving the overall environmental impact. AI algorithms optimize the supply chain by analyzing data for efficient material procurement and logistics planning [109–111]. AI enhances resilience in construction by contributing to risk management and asset management through predictive maintenance. By analyzing sensor and equipment data, AI algorithms enable proactive decision-making, minimizing downtime, and ensuring optimal equipment performance. This approach not only enhances the overall resilience of construction projects but also supports the longevity and reliability of assets [112,113]. AI-driven risk assessment models can also predict potential hazards during construction, allowing teams to implement preventive measures ahead of time, improving site safety and reducing project delays. In addition to these advantages, AI technologies can benefit the construction industry by reducing human errors and enhancing human-centric processes, such as safety monitoring and training. AI can also optimize project life cycles, reducing costs and preventing schedule overruns [114,115]. To successfully adopt AI in the construction industry, addressing the skills gap by upskilling or reskilling the workforce to use and manage AI technologies effectively is crucial [106]. Ensuring a smooth transition for workers is essential for successfully implementing AI in construction [116]. In future research, the construction industry will need to address challenges such as the ethical implications of AI, including job displacement and the transparency of AI decision-making processes. Additionally, managing the vast amounts of data generated by AI systems and ensuring data privacy will be critical considerations for AI's broader adoption. Finally, as AI implementation can be costly, future studies should focus on making AI solutions more affordable and scalable for small- and medium-sized construction enterprises.

4.6. AR/VR/MR

Mixed Reality (MR), encompassing both augmented reality (AR) and virtual reality (VR), has had transformative effects on the construction and architectural engineering industries. MR combines physical and digital worlds, enabling intuitive 3D interactions [117,118]. AR and VR technologies first began to appear in construction workflows in the early 2000s, initially limited to visualization tools for design review and project walkthroughs. MR technologies had rapidly evolved, and the construction sector began integrating these tools for more complex applications such as training and on-site simulations. MR technologies have quickly evolved, bridging the gap between the physical and digital realms and revolutionizing a traditionally tech-averse construction sector. These technologies offer significant advantages, including virtual site visits, enhanced stakeholder communication, and improved visualization for better project understanding [119]. MR technologies contribute to human-centric processes in construction by providing immersive experiences for workers. VR and AR enhance safety training, allowing workers to visualize and simulate tasks, identify potential issues, and make informed decisions. For example, construction teams can train using immersive VR scenarios that simulate hazardous environments, enabling workers to practice safety procedures without risk [120]. In the real estate sector, VR offers potential buyers immersive property exploration experiences, reducing costs, improving efficiency, and enhancing client satisfaction. The focus on user experience and engagement aligns MR with a human-centric approach, enhancing safety, efficiency, and overall satisfaction in construction processes [121]. Beyond human-centric applications, MR contributes to sustainability in construction through various avenues. BIM-enabled VR

optimizes energy efficiency and reduces energy management costs. This integration assists in sustainability, life-cycle assessment, and cost optimization. VR and XR technologies support construction project management, providing visualization and communication tools that enhance decision-making and reduce execution errors. For instance, VR is being used to visualize energy consumption patterns in building designs, allowing architects to make proactive adjustments that reduce the carbon footprint of projects. The efficient use of resources and enhanced project management capabilities align with sustainable construction practices [121,122]. In terms of resilience, MR plays a role in risk management and decision-making by allowing workers to visualize and simulate tasks, contributing to overall project resilience. For example, MR tools allow construction teams to rehearse emergency response scenarios, improving preparedness for real-world challenges such as structural failures or on-site accidents. Looking ahead, the integration between XR and BIM technologies holds promise for enhanced industrial applications and novel design collaboration modes in the Architecture, Engineering, and Construction (AEC) industry. This future integration aims to further enhance the resilience of construction projects through improved collaboration and decision-making processes [123,124]. Looking to the future, there is promise in the effective integration between XR and BIM technologies, fostering enhanced industrial applications and a novel design collaboration mode for the Architecture, Engineering, and Construction (AEC) industry [125]. However, there are challenges to overcome, including costs, technical complexity, data integration, content limitations, user acceptance, safety concerns, scalability, and legal considerations [126]. Despite these hurdles, MR's potential for reshaping the construction industry remains promising [122]. Looking forward, addressing the high costs associated with MR hardware and software, as well as developing more intuitive user interfaces, will be key to ensuring widespread adoption. Additionally, future research could focus on leveraging AI to enhance MR simulations, allowing real-time adjustments to project conditions, and enabling more accurate predictions of project risks.

4.7. Three-Dimensional Printing

Initially, when this technology emerged around 1980, its applications were primarily limited to prototyping [127]. The first applications of 3D printing in construction appeared in the early 2000s, with notable projects like the 3D-printed Canal House in Amsterdam and later developments in China, where entire houses were printed using this technology. By the late 2010s, 3D printing had transitioned from small-scale projects to being used for full-sized structures, driven by advancements in materials and printing technology. A rapid increase in the use of 3D printing has been identified since the end of 2000, thanks to a rise in sales of relatively affordable 3D printers [15]. The progression of 3D printing in construction involves advancing Modular 3D Printing (M3DP) systems. This inventive method integrates 3D printing with modular construction techniques, enabling the on-site printing and assembly of customizable housing components. M3DP not only boosts social acceptability but also enables the creation of intricate structures with minimized waste, enhancing overall construction efficiency. Distinctive design elements, such as honeycomb air-pocket walls, play a role in potentially fortifying climate resilience in constructed environments [128]. The evolution of 3D printing in construction has witnessed a shift toward human centricity. Modular 3D Printing (M3DP) systems, a notable development, allow the on-site printing and assembly of customizable housing components. This not only improves social acceptability but also enables the fabrication of structures that meet individual needs, enhancing the overall satisfaction of end users. The integration of unique design features, such as honeycomb air-pocket walls, not only adds to structural innovation but also contributes to potential climate resilience, creating spaces that

prioritize human well-being in various environmental conditions [129,130]. An example of this is the 3D-printed housing projects in Mexico, where customized homes are built for low-income families, demonstrating how this technology can meet specific user needs while maintaining construction efficiency [131,132]. Beyond its technical evolution, 3D printing in construction contributes significantly to sustainability goals. The ability to customize designs reduces material waste, and the technology is known for its energy-efficient processes. The accelerated construction timelines associated with 3D printing also contribute to resource efficiency. Moreover, the potential for 3D printing to integrate with sustainable materials further positions it as a key player in advancing environmentally conscious construction practices [128,133]. For instance, 3D printing with recycled materials or low-carbon concrete has been demonstrated in various pilot projects, further enhancing the sustainability profile of this technology. Nonetheless, 3D printing in construction offers several benefits [134]. In terms of resilience, 3D printing holds promise in constructing resilient structures, especially with the incorporation of innovative design features. The ability to fabricate complex and customized structures aligns with the resilience needed in the face of diverse environmental challenges. For example, 3D-printed shelters have been proposed for disaster-prone areas, where the technology can rapidly produce homes that are resistant to flooding, earthquakes, or extreme weather [135]. Looking ahead, the integration between 3D printing and Construction 5.0 technologies holds potential for enhancing the overall resilience of construction projects. This may involve the incorporation of advanced materials and techniques, further reinforcing the industry's ability to adapt and endure in changing circumstances [127,136]. According to experts, integrating 3D printing in Construction 5.0 is anticipated to facilitate transformative advancements. These advancements may include techniques like 3D printing and the incorporation of advanced materials, ultimately leading to full industry adoption by 2030 [134,137]. Additionally, research into new composite materials that combine the strength of traditional building materials with the efficiency of 3D printing is likely to drive the future of this technology in construction.

5. Qualitative Discussion

5.1. Challenges of Construction 5.0

Construction 5.0 (C5.0) marks a new era of technological revolution in the construction industry, focusing on green and digital transitions (Figure 7). While it holds promise for a resilient and sustainable society and economy, challenges must be addressed to realize its full potential. One of the critical aspects of C5.0 is its ability to offer several cost-saving measures and technologies for the construction industry. These include prefabrication, automation, Building Information Modeling (BIM), energy-efficient design, lean practices, and value engineering [138]. However, firms often find it challenging to justify the initial financial investment. For instance, a large-scale construction project in Singapore experienced a 25% increase in upfront costs due to the implementation of BIM and automation technologies [139]. Despite this, a long-term analysis demonstrated a 10–15% reduction in operational costs and a 20% reduction in project timelines within five years, showcasing the long-term value of such technologies [140]. Addressing cost overruns remains a significant industry challenge. Another challenge is the construction industry's historical reluctance to embrace emerging technologies that could enhance workplace efficiency fully. Despite recognizing the potential benefits, budget allocation for new software and gadgets remains limited within construction firms [141].



Figure 7. Fundamental principles of Construction 5.0.

The construction industry has been facing a prolonged labor shortage, lacking skilled professionals for global infrastructure projects. This scarcity poses a challenge for adopting Construction 5.0 (C5.0), which relies on a skilled workforce to handle advanced technology and robots. In response, several countries, including Germany and Japan, have launched training initiatives focused on equipping workers with skills in robotics and AI to meet the demands of C5.0. For instance, Germany's 'Build Smart' program has seen a 25% increase in productivity among trained workers, highlighting the importance of upskilling. Moreover, C5.0 aims to improve sustainability and community well-being but faces significant environmental challenges, including high energy consumption and waste generation, leading to greenhouse gas emissions and habitat disruption. Water management is crucial in water-scarce regions, and carbon emissions from materials and construction activities are substantial [142]. Addressing these challenges, adopting low-carbon materials, and mitigating the impact on biodiversity and communities are essential for more sustainable construction practices. Unlike C4.0, which did not address sustainability concerns, C5.0 recognizes the importance of addressing these issues. Balancing technological advancements with workforce stability, ethical labor practices, and responsible AI implementation is essential to ensure that C5.0 supports both industry progress and social well-being [143]. C5.0 places emphasis on the need for seamless human-machine communication; however, this presents challenges given the industry's intricacies. Human-robot collaboration (HRC), while promising, requires careful integration to avoid disruptions in workflows. For example, on a large infrastructure project in Dubai, integrating robots with human teams led to a 15% reduction in manual labor hours [144]. However, resistance from workers initially slowed the implementation of HRC, which was eventually addressed through dedicated training programs focusing on trust building and safety. A study by the Robotics Institute of Italy found that construction projects using HRC saw a 12% increase in efficiency, but human resistance to working alongside robots remains a challenge that must be addressed through proper training and trust-building initiatives [145]. To overcome the challenge of a labor shortage, the construction industry must focus on nurturing a skilled workforce, implementing training programs, making specialized and efficient robots in the field of construction, and leveraging construction software to increase efficiency and eliminate

labor-intensive activities [146]. By leveraging the principles of Industry 5.0, with a strong focus on human–robot collaboration (HRC), resilience, and sustainability, the Builtrobotics Construction Company effectively addressed the labor shortage challenge. The adoption of advanced technologies not only boosted the efficiency of construction processes but also fostered a more sustainable and socially responsible approach to infrastructure development. This example highlights the construction industry's potential to achieve significant benefits through the strategic integration of human expertise and cutting-edge technologies in the Construction 5.0 era. For example, By using techniques and low-carbon materials, construction waste can be reduced by 30%, while completing projects 20% faster than the industry average. By doing so, the industry can harness the full potential of C5.0 and achieve improved productivity, enhanced safety, and sustainable construction practices [7,48].

5.2. Future Trends and Gaps in C5.0

The integration of robotics into the construction industry represents a pivotal step in the technological evolution of this traditionally labor-intensive sector. Robotics holds significant potential for improving competitiveness, creating new employment opportunities, and fostering economic growth. However, despite the burgeoning interest in robotic technologies within construction, the industry lags in terms of research and practical implementation. The complexity of construction projects, involving heavy components, intricate assembly techniques, and dynamic environments, presents unique challenges compared to traditional manufacturing. Robotics in construction still face limitations in standardization, cost effectiveness, and adaptability to complex site conditions, which must be addressed through further research and development [147].

One critical research gap is the limited maturity of human–robot collaboration (HRC) technologies in construction. While interest in HRC is growing, most current technologies are designed for controlled environments like manufacturing, rather than the unpredictable and non-linear nature of construction projects [7]. Moreover, HRC research in manufacturing cannot always be directly applied to construction due to differences in scale and stringent safety requirements. To bridge this gap, further research should focus on developing adaptable HRC systems tailored to construction, addressing human safety, collaborative robot integration, and task complexity. Robotics can serve as efficient tools alongside human workers by automating repetitive tasks, enhancing precision, and improving safety in hazardous environments, significantly boosting project resilience. However, for HRC to fully mature in construction, the development and deployment of advanced robots are essential to overcoming current challenges and maximizing automation's potential.

Cybersecurity has emerged as a critical concern with the increasing digitalization of the construction industry. Construction projects are now more vulnerable to cyber threats, including data breaches, hacks, and unauthorized access. Blockchain technologies offer a promising solution for improving data security throughout the project's life cycle [148]. By developing industry-specific blockchain protocols, construction companies can ensure secure transactions, safeguard sensitive project data, and enhance overall resilience. Further research in cybersecurity should focus on quantum computing's role in securing future construction projects, exploring advanced encryption methods to protect large-scale data systems [149].

Looking ahead, the construction industry must also embrace AI-driven solutions to optimize resource allocation, improve decision-making, and enhance project outcomes. AI and machine learning can help automate project management, improving efficiency by predicting potential delays and optimizing construction schedules. Further research is required to develop AI models that can integrate real-time construction data from multiple sources (such as IoT sensors and BIM systems) to deliver dynamic project insights.

Additionally, developing machine learning algorithms that are capable of optimizing sustainability metrics will play a pivotal role in achieving low-carbon construction and reducing waste.

In conclusion, Construction 5.0 offers tremendous opportunities for technological advancement, but there remain significant gaps in robotic collaboration, workforce upskilling, cybersecurity, and AI adoption. Addressing these gaps requires coordinated efforts between academia, industry, and government bodies to foster a culture of innovation and collaboration. By investing in research and development, the construction industry can fully leverage the potential of Industry 5.0, leading to improved productivity, sustainability, and resilience in the face of future challenges in the construction industry.

6. Conclusions

The evolution of Construction 5.0 (C5.0) marks a significant shift in the construction industry, emphasizing resilience, sustainability, and human-centric approaches. Biblio-metric analysis underscores the growing academic interest in this domain, with 78 publications recorded in Scopus between 2022 and 2025. While the literature on C5.0 has expanded rapidly, its adoption within the industry remains slow, suggesting a gap between research advancements and practical implementation. Co-citation and co-authorship analyses highlight key contributors and influential research clusters, demonstrating the multidisciplinary and collaborative nature of C5.0 research. Notably, the United Kingdom, China, and India emerged as leading contributors, reinforcing the global significance of this field.

The cluster analysis of the literature shows five important thematic clusters within C5.0 research. The 'Digital Technologies' cluster explores cutting-edge technologies such as AI, blockchain, and IoT, which drive the digital transformation of the construction industry. The second cluster, 'Construction Industry', focuses on the ongoing evolution of the AEC sector, emphasizing the integration of Construction 4.0 and 5.0 paradigms. The third cluster, 'Sustainability', highlights the importance of sustainable construction practices, addressing life-cycle analysis and eco-friendly building methodologies. The 'Smart Manufacturing' cluster explores advancements in robotics and manufacturing technologies, such as Additive Manufacturing and Smart Manufacturing, that contribute to enhanced productivity and automation in construction. The 'Industrial Revolution' cluster examines the human-centric and societal aspects of industrial progress, focusing on the resilience, well-being, and societal impacts associated with Industry 5.0 and related concepts.

This paper reviewed advanced technologies like AI, IoT, digital twins, blockchain, 3D printing, Cobots, and VR/XR, exploring their applications in construction through the concept of Industry 5.0. This study identified key areas, such as artificial intelligence, human–robot collaboration, and sustainability, emphasizing the need for adaptive frameworks for collaboration and workforce training. However, significant research gaps remain in robotics integration, human–machine collaboration, and regulatory frameworks for large-scale C5.0 adoption. Challenges like energy consumption, waste management, and environmental impacts also persist. Future research should address these issues while considering economic, social, and regional factors, especially in developing economies.

To address these gaps, research should prioritize adaptable human–robot collaboration (HRC) systems for construction, focusing on safety, task complexity, and integration with human workers. Additionally, standardizing robotics for cost effectiveness and scalability on construction sites is crucial. Cybersecurity concerns can be addressed with blockchain and quantum computing to secure transactions and data. AI-driven solutions should optimize project management, integrate real-time data, and improve sustainability metrics. Workforce upskilling is necessary for the effective interaction of robotics and AI. Finally, collaboration between academia, industry, and government is vital for the successful

implementation of Industry 5.0, leading to increased productivity, sustainability, and resilience in future construction projects.

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Appendix A

Table A1. List of articles related to Construction 5.0 and the applications of Industry 5.0 in the construction industry.

| Title | Year | Cite |
|---|------|------|
| Enhancing sustainable construction decisions: integrating BIM and VR for circular economy assessment [150] | 2025 | 1 |
| Empowering Sustainable Infrastructure and Sustainable Development Goals Through Industry 5.0 Implementation [151] | 2025 | 0 |
| A Framework for Modeling the Decarbonization of the Economy Based on Energy Innovations in the Context of Industry 5.0 and Sustainable Development: International Perspective [152] | 2025 | 0 |
| A novel human-centered methodology for assessing manual-to-collaborative safe conversion of workstations [153] | 2025 | 1 |
| The Impact of Digital Technology Applications on Construction Industry Project Performance [154] | 2025 | 0 |
| Integrating large language model and digital twins in the context of industry 5.0: Framework, challenges and opportunities [155] | 2025 | 0 |
| Digital Twin Approach in Buildings: Future Challenges via a Critical Literature Review [156] | 2024 | 9 |
| Developing a proof-of-concept curriculum foundation model for industry 5.0: A primary data survey of built environment academics [157] | 2024 | 3 |
| Supply chain resilience in the construction industry: A bibliometric review on operations management practices from Industry 4.0 to Industry 5.0 [158] | 2024 | 0 |
| Resilient Scheduling Heuristic for Single Machine Systems to Minimize Variance of Job Completion Time [159] | 2024 | 0 |
| Facilitating Construction 5.0 for smart, sustainable and resilient buildings: opportunities and challenges for implementation [160] | 2024 | 1 |
| A knowledge empowered graph learning feature selection method based on variation propagation effect representation and analysis for human-centric manufacturing systems | 2024 | 0 |
| Unlocking Blockchain in Construction: A Systematic Review of Applications and Barriers [161] | 2024 | 3 |
| Industry 5.0 and the future of work in manufacturing in Australia [162] | 2024 | 0 |
| Eco epo-seal, versatile ancillary construction material: pathway to circularity in Industry 5.0 [163] | 2024 | 0 |
| Drone swarms in industry 5.0 [164] | 2024 | 0 |
| Ethics-Aware Application of Digital Technologies in the Construction Industry [165] | 2024 | 1 |
| Industry 5.0 concepts and enabling technologies, towards an enhanced conservation practice: systematic literature review protocol [166] | 2024 | 2 |
| Digital Twin Technology and Social Sustainability: Implications for the Construction Industry [167] | 2024 | 2 |
| Integration of Industry 5.0 Principles in Stealth Construction: Leveraging Emerging Technologies for Efficiency and Sustainability [168] | 2024 | 0 |
| ETHNOGRAPHY FOR CONSTRUCTION 5.0 [169] | 2024 | 0 |
| Industry 5.0, towards an enhanced built cultural heritage conservation practice [170] | 2024 | 4 |
| Architecting net zero: from drawings to bytes [171] | 2024 | 1 |

Table A1. *Cont.*

| Title | Year | Cite |
|---|------|------|
| Metaverse for Industry 5.0 [172] | 2024 | 1 |
| Toward sustainability and resilience with Industry 4.0 and Industry 5.0 [173] | 2024 | 0 |
| Multimodal Perception and Decision-Making Systems for Complex Roads Based on Foundation Models [174] | 2024 | 1 |
| Printing the Future Layer by Layer: A Comprehensive Exploration of Additive Manufacturing in the Era of Industry 4.0 [175] | 2024 | 5 |
| A State-of-the-Art Review and Bibliometric Analysis on the Smart Preservation of Heritages [176] | 2024 | 0 |
| Breaking down to build up: how deconstruction and carbon finance foster sustainable, resilient construction in the industry 5.0 era [177] | 2024 | 0 |
| Bamboo industrialization in the era of Industry 5.0: An exploration of key concepts, synergies and gaps [178] | 2024 | 0 |
| BIM Policy Trends in Europe: Insights from a Multi-Stage Analysis [179] | 2024 | 4 |
| Innovative horizons in drone technology for construction during industry 5.0 [180] | 2024 | 0 |
| Quality Assurance and Control in Welding and Additive Manufacturing [181] | 2024 | 1 |
| ARCHITECTURE, ENGINEERING, AND CONSTRUCTION (AEC) INDUSTRY 4.0 AND BEYOND: Building Construction Automation through 3D Printing and Additive Manufacturing Toward Lower Environmental Impacts [182] | 2024 | 0 |
| Construction 5.0 and Sustainable Neuro-Responsive Habitats: Integrating the Brain–Computer Interface and Building Information Modeling in Smart Residential Spaces [183] | 2024 | 0 |
| Research trends in industry 5.0 and its application in the construction industry [45] | 2024 | 3 |
| Enhancing Drone Operator Competency within the Construction Industry: Assessing Training Needs and Roadmap for Skill Development [184] | 2024 | 3 |
| Human Digital Twin in Industry 5.0: A Holistic Approach to Worker Safety and Well-Being through Advanced AI and Emotional Analytics [185] | 2024 | 11 |
| Towards Enhanced Built Cultural Heritage Conservation Practices: Perceptions on Industry 5.0 Principles and Enabling Technologies [186] | 2024 | 0 |
| Society 5.0: social implications, technoethics, and social acceptance [187] | 2024 | 0 |
| Gender diversity in construction: demystifying the pipeline leaks in Australia, United States, United Kingdom and Brazil [188] | 2024 | 0 |
| Human-robot collaboration for building deconstruction in the context of construction 5.0 [189] | 2024 | 4 |
| Multi-Objective Optimization of an Assembly Layout Using Nature-Inspired Algorithms and a Digital Human Modeling Tool [190] | 2024 | 1 |
| Korea’s Citizen-Centric Smart City Development by Adopting Living Labs and Design Thinking Methodologies and Their Implications for ASEAN Countries [191] | 2023 | 0 |
| Thematic evolution and trends linking sustainability and project management: Scientific mapping using SciMAT [192] | 2023 | 9 |
| From Industry 4.0 to Construction 5.0: Exploring the Path towards Human–Robot Collaboration in Construction [7] | 2023 | 42 |
| Digital Twin Approach for Maintenance Management [193] | 2023 | 4 |
| Explainability as the key ingredient for AI adoption in Industry 5.0 settings [194] | 2023 | 6 |
| Perspectives on Digital Transformation Initiatives in the Mechanical Engineering Industry [195] | 2023 | 0 |
| A Review on the Way Forward in Construction through Industrial Revolution 5.0 [196] | 2023 | 27 |
| Integrated practices in the Architecture, Engineering, and Construction industry: Current scope and pathway towards Industry 5.0 [42] | 2023 | 32 |
| The resurgence of augmented reality and virtual reality in construction: Past, present, and future directions [197] | 2023 | 2 |

Table A1. *Cont.*

| Title | Year | Cite |
|--|------|------|
| Investigating the Causal Relationships among Enablers of the Construction 5.0 Paradigm: Integration of Operator 5.0 and Society 5.0 with Human-Centricity, Sustainability, and Resilience [43] | 2023 | 21 |
| Investigating the Use of ChatGPT for the Scheduling of Construction Projects [38] | 2023 | 79 |
| Application of artificial intelligence and machine learning for BIM: review [198] | 2023 | 16 |
| Assessing the Accuracy of ChatGPT Use for Risk Management in Construction Projects [199] | 2023 | 10 |
| Building Contract in the Fifth Industrial Revolution: Embedding Sustainable Design and Construction Practices [200] | 2023 | 0 |
| A novel evolution model to investigate the collaborative innovation mechanism of green intelligent building materials enterprises for construction 5.0 [201] | 2023 | 10 |
| University and Education 5.0 for Emerging Trends, Policies and Practices in the Concept of Industry 5.0 and Society 5.0 [202] | 2023 | 12 |
| Artificial Intelligence Enabled Project Management: A Systematic Literature Review [41] | 2023 | 48 |
| A Review on Challenges and Solutions in the Implementation of Ai, IoT and Blockchain in Construction Industry [203] | 2023 | 13 |
| Towards new-generation human-centric smart manufacturing in Industry 5.0: A systematic review [37] | 2023 | 100 |
| On Intelligent Mining with Parallel Intelligence [204] | 2023 | 5 |
| Modelling the adoption of Internet of things (IoT) for sustainable construction in a developing economy [205] | 2023 | 11 |
| Evaluation of Lean Off-Site Construction Literature through the Lens of Industry 4.0 and 5.0 [206] | 2023 | 15 |
| Reviewing and Integrating AEC Practices into Industry 6.0: Strategies for Smart and Sustainable Future-Built Environments [207] | 2023 | 40 |
| Application of BIM Methodology in Public and Private Electricity and Telecommunications Projects in Peru [208] | 2023 | 0 |
| Influence of 3D-printable sustainable concrete and industrial waste on Industry 5.0 [209] | 2022 | 0 |
| Human–Robot Collaboration and Lean Waste Elimination: Conceptual Analogies and Practical Synergies in Industrialized Construction [18] | 2022 | 17 |
| Greening Construction Transport as a Sustainability Enabler for New Zealand: A Research Framework [210] | 2022 | 7 |
| Process View to Innovate the Management of the Social Housing System: A Multiple Case Study [211] | 2022 | 6 |
| Challenges and opportunities of augmented reality during the construction phase [19] | 2022 | 29 |
| BIM Information Integration Based VR Modeling in Digital Twins in Industry 5.0 [39] | 2022 | 73 |
| Comparative Study of Digitalization in the Spanish Ceramic Sector from a Marketing Perspective over the Period 2017–2021 [212] | 2022 | 0 |
| Construction 4.0, Industry 4.0, and Building Information Modeling (BIM) for Sustainable Building Development within the Smart City [40] | 2022 | 70 |
| Achieving stepwise construction of cyber physical systems in EX-MAN component model [213] | 2022 | 0 |
| An optimal construction of smart aged homes based on SDLC using smart sensors and agent networks [214] | 2022 | 2 |
| A Scientometric Analysis of Studies on Risk Management in Construction Projects [215] | 2022 | 24 |

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