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ARTIFICIAL INTELLIGENCE IN CLOUD COMPUTING TECHNOLOGY IN THE CONSTRUCTION INDUSTRY: A BIBLIOMETRIC AND SYSTEMATIC REVIEW

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SUMMARY: *The integration and impact of artificial intelligence (AI) and cloud computing (CC) technology in the construction industry (CI) would support their implementation process and adoption. However, there is a lack of research in the extant literature, and recent advances in this field have not been explored. As such, the key research question focuses on the extent of existing literature, main research hotspots, and recent advances (i.e., research gaps and future directions) in AI in CC in the CI. To address this research question, this study aims to conduct a state-of-the-art review of AI in CC in the CI by providing a qualitative discussion of the main research hotspots, research gaps, and future research directions. This review study used a four-step bibliometric-systematic review approach consisting of literature search, literature screening, science mapping analysis, and qualitative dis-cussion. The results found four main research hotspots, namely (1) construction project performance indicators, (2) data analysis and visualization, (3) construction quality control and safety, and (4) construction energy efficiency. These findings would provide valuable insights for scholars and practitioners seeking to understand and integrate AI and CC technology applications in the CI. This review study will lay a better foundation for future developments in construction project management processes, data-sharing protocols, real-time safety monitoring, and ethical implications of AI and CC technologies.*

KEYWORDS: *Artificial Intelligence, Cloud Computing, Construction, Science Mapping, Literature Review.*

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1. INTRODUCTION

Artificial intelligence (AI) can be defined as the ability of a computer or digital comput-er-controlled machine to perform complex tasks that would normally require human intelligence (Chen and Ying, 2022). The construction industry's (CI) growth is severely constrained by the myriad of complex challenges such as health and safety concerns, productivity and labor shortages, and cost and time overruns (Abioye et al., 2021). The CI is undergoing a rapid digi-tal transformation as AI continues to develop and be widely used for improving construction operations and project performance (Pan and Zhang, 2021; Zhang et al., 2024). AI is revolu-tionizing the CI by automating processes, detecting potential risks, and improving efficiency (Abioye et al., 2021; Kyivska and Tsiutsiura, 2021). By analyzing large amounts of data, AI can detect patterns, predict outcomes, and optimize workflows. For example, AI can automate tasks such as scheduling and budgeting, saving time and resources for construction companies (Pan and Zhang, 2021; Gill et al., 2022). It can also detect potential risks such as equipment failures or safety hazards, reducing the likelihood of accidents and costly delays (Amodei et al., 2016; Soori et al., 2023). Additionally, AI can analyze data to identify patterns and trends, making it easier to optimize workflows and identify areas for improvement (Mintz and Brodie, 2019; Bohr and Memarzadeh, 2020). Taken together, AI can play an important role in the CI by improving health, safety, and productivity of construction resources.

The application of cloud computing (CC) in the CI has attracted increasing attention from re-searchers and practitioners around the world due to its benefits (Amarnath et al., 2011; Sunyaev, 2020; Oke et al., 2021), and there are many relevant empirical studies (Beach et al., 2013; Bello et al., 2021; Aghimien et al., 2022). CC is an enabler of innovation delivery for other emerging technologies (e.g., building information modeling (BIM), internet of things (IoT), virtual reality (VR), augmented reality (AR), big data analytics (BDA)) in the CI (Bello et al., 2021). CC technology is becoming increasingly popular in construction because it provides on-demand access to computing resources, making it easier to store and access data. This is particularly important in construction, where large amounts of data are generated daily. CC technology also provides a secure environment for storing data, reducing the likelihood of data loss (Subashini and Kavitha, 2011; Vurukonda and Rao, 2016). CC technology provides a more efficient and powerful mechanism for stakeholders in the CI to better collaborate and share data (Beach et al., 2013; Lokshina et al., 2019). The CI is already working on developing data and process models to enable greater interoperability of work between project participants (Beach et al., 2013). Ad-ditionally, CC technology provides the ability to scale resources up or down depending on pro-ject requirements, making it more cost-effective.

With the application and development of innovative/digital technologies such as BIM, IoT, dig-ital twin, blockchain, and AI (Gill et al., 2019; Sun et al., 2023; Mu and Antwi-Afari, 2024; Ye et al., 2024), CC has become a form of intelligent computing technology. Emerging digital technologies are being used at all stages of the building lifecycle, which play an extremely im-portant role in the CI (Hannon, 2007; You and Feng, 2020; Turner et al., 2021). While past re-search has highlighted the numerous benefits and advantages of integrating AI and CC applica-tions in the CI (Amarnath et al., 2011; Abioye et al., 2021; Kyivska and Tsiutsiura, 2021), no review study has integrated and conducted the impact of AI and CC in the CI. As such, this re-view study provides research gaps and recent advances in integrated applications of AI and CC that could enhance the understanding of researchers and practitioners in the CI.

Several existing review-based studies in AI-in-CI and CC-in-CI have identified many benefits of AI and CC technologies such as improving efficiency and stability in the CI (Abioye et al., 2021; Bello et al., 2021; Pan and Zhang, 2021; Rawai et al., 2013). However, no study has systematically reviewed the recent research advances of AI-in-CC-in-CI, to provide the current implications and practical contributions as well as recommendations for future research direc-tions in this field. Therefore, this review study aims to conduct a four-step biblio-metric-systematic review analysis approach to identify main research hotspots, potential re-search gaps, and future research directions in the domain of AI-in-CC-in-CI. In particular, this review study attempts to answer the following research questions:

1. What are the annual publication trends of research on AI-in-CC-in-CI?
2. What are the influential research journals, keywords, countries/regions, and documents in AI-in-CC-in-CI?
3. What are the research hotspots of AI-in-CC-in-CI?

4. What are the research gaps of existing research in AI-in-CC-in-CI?

5. What are the future research directions of AI-in-CC-in-CI?

The remaining parts of this review study are as follows. In section 2, a comprehensive literature review was conducted to review the relevant literature in this research area, mainly the AI-in-CI review and the CC-in-CI review. Next, the adopted four-step bibliometric-systematic review analysis approach was explained in the research methods section. Section 4 provided the results of the annual publication trends, influential journals, keywords, countries/regions, and docu-ments in AI-in-CC-in-CI. A qualitative discussion on the main research hotspots, research gaps, future research directions, and study implications in the field of AI-in-CC-in-CI was presented in Section 5. Lastly, the summary and limitations of this review are highlighted in the conclu-sions section.

2. REVIEW OF RELATED WORKS

2.1 AI-in-CI Review

Darko et al. (2020) presented one of the first comprehensive scientometric studies on AI-in-the-architectural, engineering, and construction (AEC) industry, highlighting the potential of AI to solve complex problems in AEC and identifying genetic algorithms, neural networks, fuzzy logic, fuzzy sets, and machine learning as the most widely used AI methods in AEC. Abioye et al. (2021) identified opportunities and challenges for AI applications in the CI and provided insights into key AI applications to overcome challenges such as cost and time overruns, health and safety, productivity, and labour shortages. Baduge et al. (2022) provided a comprehensive review of the applications of AI in the building construction industry, covering various domains such as design, construction management, and durability, and discussing data collection strategies, challenges, and future trends.

Bang and Olsson (2022) conducted a review of publications on AI in construction and found that the industry lags behind other sectors in adopting AI, identifying the need for further research and multidisciplinary approaches. Castro Pena et al. (2021) explored the application of AI to architectural conceptual design, noting an increase in papers since 2015, and employing evolutionary computing techniques to explore the requirements and possible solutions for generating new designs. A study by Chen and Ying (2022) analyzed 587 articles published between 1989 and 2021 to identify the main development trajectories of AI technologies in the CI and to suggest possible directions for further application to promote progress in architectural and engineering design, and construction services.

Debrah et al. (2022) conducted a comprehensive bibliometric and systematic analysis to identify major research hotspots, trends, knowledge gaps, and future research directions in the application of AI in green building (AI-in-GB), to enhance sustainability and efficiency in the AEC sector. Momade et al. (2021) reviewed 165 articles and found that AI tools, particularly artificial neural networks (ANNs) are widely applied in the CI, with increasing use of hybrid systems for better modeling abilities. Oluleye et al. (2023) conducted a systematic review of the application of AI for circular economy (CE) in the building CI, identifying thirteen application areas and proposing a holistic framework and future research directions to promote digital systemic circularity in the building CI. Pan and Zhang (2021) presented six hot research topics that demonstrate the advantages of AI in construction, engineering and management, as well as six key directions for future research.

Sacks et al. (2020) reviewed the growth of digital information tools in construction and their potential for future applications of AI, tracing their past, present, and future challenges. Sharma et al. (2021) reviewed the use of AI-based models for accurate prediction and estimation of construction cost, duration, and shear strength in geotechnical and construction engineering, discussing input parameters and challenges. Saka et al. (2023) presented a systematic review of conversational AI in the AEC industry to provide insights into the current development and conducted a focus group discussion to highlight challenges and validate areas of opportunities. Zandi et al. (2021) reviewed the use of AI algorithms in civil engineering applications, including construction, engineering and management, and compared the performance of ANNs with other soft computing methods. Zhang et al. (2022) conducted a systematic bibliometric analysis to review the integration of BIM and AI in the AEC/facility management (FM) industry and identified typical integrated modes, and proposed future directions for the development of BIM-AI integrations in AEC/FM. Table 1 shows a summary of reviews on AI-in-CI.

Table 1: Summary of reviews on AI-in-CI.

SN	Source	Timespan	Research method	Number of included articles
1.	Abioye et al. (2021)	1960-2020	Critical review	1,272
2.	Baduge et al. (2022)	Not specified	Literature review	200
3.	Bang and Olsson (2022)	2015-2020	Systematic scoping review	107
4.	Castro Pena et al. (2021)	Not specified	Literature review	75
5.	Chen and Ying (2022)	1989-2021	Main path analysis	587
6.	Darko et al. (2020)	1974-2019	Science mapping method	41,827
7.	Debrah et al. (2022)	2002-2021	Mixed-methods systematic review	383
8.	Momade et al. (2021)	2014-2020	Literature review	165
10.	Oluleye et al. (2023)	2018-2022	Systematic literature review	30
11.	Pan and Zhang (2021)	1997-2020	Literature review	4,473
12.	Sacks et al. (2020)	Not specified	Literature review	Not specified
13.	Saka et al. (2023)	2002-2022	Systematic literature review	21
14.	Sharma et al. (2021)	2005-2020	Literature review	Not specified
15.	Zandi et al. (2021)	Not specified	Literature review	Not specified
16.	Zhang et al. (2022)	Not specified	Systematic literature review	183

2.2 CC-in-CI Review

The application of CC in the CI has led to the rapid transformation and upgrading of the indus-try and attracted the attention of researchers. Fathi et al. (2012) suggested that implementing context-aware cloud computing information systems (CACCIS) can enhance collaboration, productivity, and efficiency in the construction supply chain processes. Rawai et al. (2013) conducted a literature review on the use of CC in construction management and found that it offers great potential for collaboration, sustainability, and financial benefits while reducing energy consumption and CO2 emissions. Wong et al. (2014) reviewed the literature on cloud-BIM integration and highlighted the need for more research on its application in building life cycle management, particularly in areas such as operation, maintenance, facility management, and energy efficiency, as well as on organizational and legal issues. Bello et al. (2021) con-ducted a systematic review and highlighted the current and future application areas of CC in the CI, as well as identifying barriers and strategies for broader adoption. Won et al. (2022) con-ducted a case study to identify the drivers, challenges, and strategies for CC adoption in the CI, as well as to investigate and analyze the status of its adoption. Table 2 presents a summary of reviews on CC-in-CI.

Table 2: Summary of reviews on CC-in-CI.

SN	Source	Timespan	Research method	Number of included articles
1.	Bello et al. (2021)	2009-2019	Systematic review	92
2.	Fathi et al. (2012)	Not specified	Literature review	Not specified
3.	Rawai et al. (2013)	Not specified	Literature review	Not specified
4.	Won et al. (2022)	Not specified	Literature review/Case study	100
5.	Wong et al. (2014)	Not specified	Literature review	Not specified

Overall, these review studies highlight the potential of AI to solve complex problems in the AEC industry and provide valuable insights for future developments. In addition, several stud-ies have identified the potential benefits and challenges of implementing CC technology in the CI, highlighting the need for further research on its application in building life cycle manage-ment, organizational and legal issues, and strategies for broader adoption. However, there is a gap in the literature regarding a comprehensive and systematic review of the latest advance-ments in AI-in-CC-in-CI research, and thus this review study aims to address this gap through a thorough investigation and discussion.

3. RESEARCH METHODS

This review study used a four-step bibliometric-systematic review analysis approach consisting of a literature search, literature screening, science mapping analysis, and qualitative discussion to answer the aforementioned research questions. These four major research steps are presented in Figure 1 and discussed in the following sections.

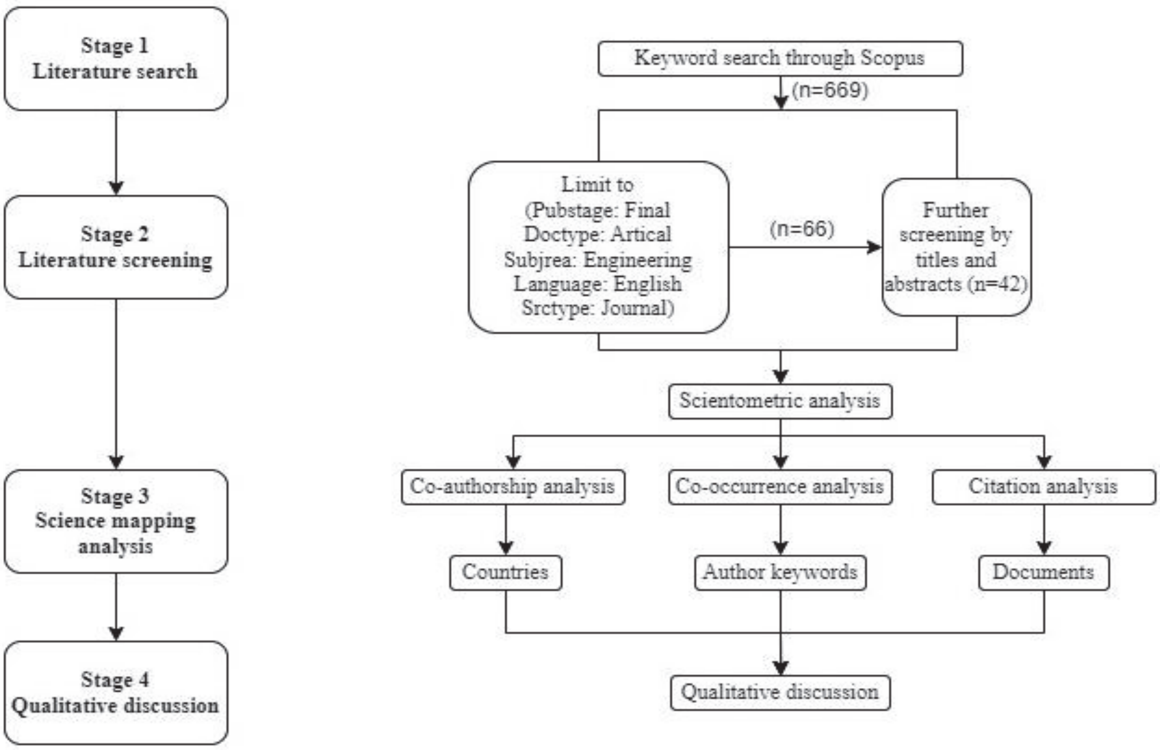

Figure 1: Flow diagram of the four-step literature review process.

3.1 Literature Search

The first step of this review study was to conduct a bibliometric search in the Scopus database. The Scopus database was chosen because it is a widely known research database that provides broader journal coverage, interdisciplinary research outcomes, user-friendliness, and conven-ience as compared to other available databases such as Science Direct and Web of Science (Chadegani et al., 2013). To address the aforementioned research questions, some major key-words, such as “artificial intelligence”, “cloud computing” and “construction industry” were used as search terms in Scopus to retrieve bibliographic records related to published articles in the field of AI-in-CC-in-CI. All keywords used in the Scopus search are shown in Table 3. Lit-erature search was conducted using search keywords in the “title, abstract, and keywords” sec-tion, with no date range limitations (up to February 4, 2023), resulting in a comprehensive da-taset of 669 articles.

Table 3: Keywords used in Scopus and search results.

Nr.	String	Results
1.	TITLE-ABS-KEY ("AI" OR "Artificial intelligence" OR "Machine intelligence" OR "Machine learning" OR "Genetic algorithms" OR "Artificial general intelligence" OR "Computer vision" OR "Deep learning" OR "Reinforcement learning" OR "Transfer learning" OR "Image recognition" OR "Natural language processing" OR "NLP" OR "Supervised learning" OR "Unsupervised learning" OR "Robotics") AND TITLE-ABS-KEY ("Cloud computing") AND TITLE-ABS-KEY ("Construction industry" OR "Construction"))	669
2.	AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT- TO (SRCTYPE, "j") [a]	66
3.	Manual screening based on AI-in-CC-in-CI results [b]	42

Note: Literature search was performed on 4 February 2023.

[a, b] The further screening is described in Section 3.2.

3.2 Literature Screening

Initially, a total of 669 records were identified, and the literature samples were refined to “engi-neering” as a subject area and journal articles that were finally published in English. Conference papers were excluded due to their extensive quantity but relatively lower value in comparison to journal articles (Butler and Visser, 2006). Following the primary screening process, a total of 66 articles remained in the literature sample. These 66 articles were then subjected to further examination of their titles, abstracts, and full-texts, as illustrated in Figure 1. For example, some review articles (e.g., Jan et al. 2023) although mentioned keywords such as AI and CC were not focused on the construction industry. Other articles that did not focus on AI and CC in the CI were deleted. For instance, Lian's (2022) study was related to AI and CC in a construc-tion-related context but mainly focused on blockchain platforms and associated technologies. Some of these articles were excluded in this study. In addition, it should be noted that this re-view-based study focuses on the CI, covering aspects of construction materials, construction methods, and construction management. Therefore, areas that do not directly relate to the CI such as teaching model reform (Liang et al., 2021) were excluded. After a thorough screening process, a sample of 42 journal articles was ultimately selected for subsequent scientometric analysis.

3.3 Scientific Mapping Analysis

The third step of this review-based study is a scientometric analysis method using the text min-ing tool VOSviewer. The advantages of VOSviewer over other software tools for bibliometric mapping include its feasibility for constructing and visualizing bibliometric maps, ease of use, freely availability to the bibliometric research community (Sun et al., 2023; Antwi-Afari et al., 2023). It is also capable of handling large datasets and offers a wide range of visualization op-tions and customization possibilities (Eck and Waltman, 2009). The main process of scien-tometric analysis is to import the literature sample data obtained from the search in Scopus into VOSviewer software for scientific mapping analysis. In this study, results related to co-occurring keywords, co-occurring countries/regions, and the impact of documents/articles were generated in the field of AI-in-CC-in-CI.

3.4 Qualitative Discussion

After analysing the aforementioned 42 sample articles with the VOSviewer software, the fourth step involves qualitative discussion, which aims to provide a comprehensive evaluation of the prominent research topics on AI-in-CC-in-CI field, identify the current research gaps and limi-tations, and outline future research endeavours that need to be undertaken by AI-in-CC-in-CI scholars to advance this domain.

4. RESULTS

4.1 Annual Publication Trend of Articles

The present study encompasses a total of 42 articles published from 2012 to 2022, as illustrated in Figure 2, which displays the annual distribution of selected papers over 10 years. Notably, there were no publications before 2012, and also in 2013, 2015, and 2017. Furthermore, the average number of papers published on AI-in-CC-in-CI per year during the period between 2012-2018 was one, indicating a lack of attention to this topic. However, the number of publications on AI-in-CC-in-CI showed a significant increase from 2019, with a total of 7 papers published in that year alone, surpassing the total number of papers published before 2019. Additionally, the dashed line in Figure 2 represents the result of a third-order polynomial fit, which reveals a sig-nificant increase in the number of publications from 2019 to 2022. This trend highlights the growing interest in AI-in-CC-in-CI among practitioners, researchers, and stakeholders in the CI. The increasing trend in the number of publications over the past decade is justified, as AI and CC have the potential to revolutionize the CI by improving project management, productivity, cost-effectiveness, and safety. This emphasizes the relevance and necessity of this review, as more efforts are being made to understand AI-in-CC-in-CI.

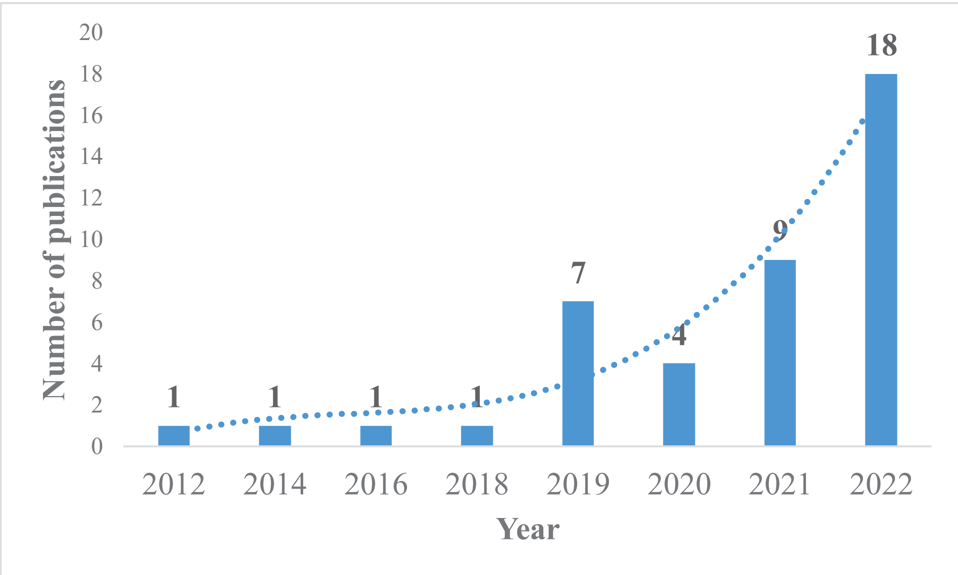

Figure 2: Annual publication trends of articles on AI-in-CC-in CI.

4.2 Selection of Relevant Peer-Reviewed Journals

The examination of the journal distribution of the 42 selected articles is significant as it reflects the caliber of the studies incorporated in this review. Table 4 illustrates the frequency distribu-tion of these studies across 34 distinct peer-reviewed journals. Combining the journals that have published only one article, a total of 27 journals were identified, with a cumulative publi-cation count of 27 articles. It is evident that the majority of these journals are highly reputable and influential academic journals in the field of architecture engineering and management, which highlights the inclusion of a diverse range of high-quality journal articles in this review.

Of these 34 journals, it was discovered that 7 had published at least 2 articles on AI-in-CC-in-CI within the last decade. This finding highlights the level of interest and research activity in this topic among a subset of the academic community. Among these journals, Build-ings (7%), Construction Innovation (5%), IEEE Access (5%), IEEE Transactions on Industrial Informatics (5%), Mathematical Problems in Engineering (5%), Safety Science (5%), and Wireless Communications and Mobile Computing (5%) are included. The total number of arti-cles published in these journals is 15, accounting for 37% of the total research sample. It is reasonable that Buildings has the highest number of published articles, as the main area of re-search in this review is in the field of the building industry. Therefore, Buildings can be consid-ered as a suitable research outlet for AI-in-CC-in-CI studies. Among the remaining 27 journals, each contributed one article, accounting for a total of 27 articles (63%) of the total articles uti-lized in this study.

Table 4: Distribution of selected articles by journal.

Journal	Number of publications
Buildings	3
Construction Innovation	2
IEEE Access	2
IEEE Transactions on Industrial Informatics	2
Mathematical Problems in Engineering	2
Safety Science	2
Wireless Communications and Mobile Computing	2
Other journals	27
Total	42

4.3 Keywords Co-Occurrence Analysis

Analyzing co-occurring keywords is essential for revealing the underlying structure of research themes and hotspots and gaining insights into the development trends and future directions of a field (Su and Lee, 2010). In this study, co-occurrence keyword analysis was conducted using the VOSviewer software, recommended by Eck and Waltman (2009). VOSviewer generates a map with connecting lines. The length of the line connecting two keywords indicates the strength of the relationship. The shorter the connecting lines, the stronger the relationship. The size of the keyword indicates the number of occurrences.

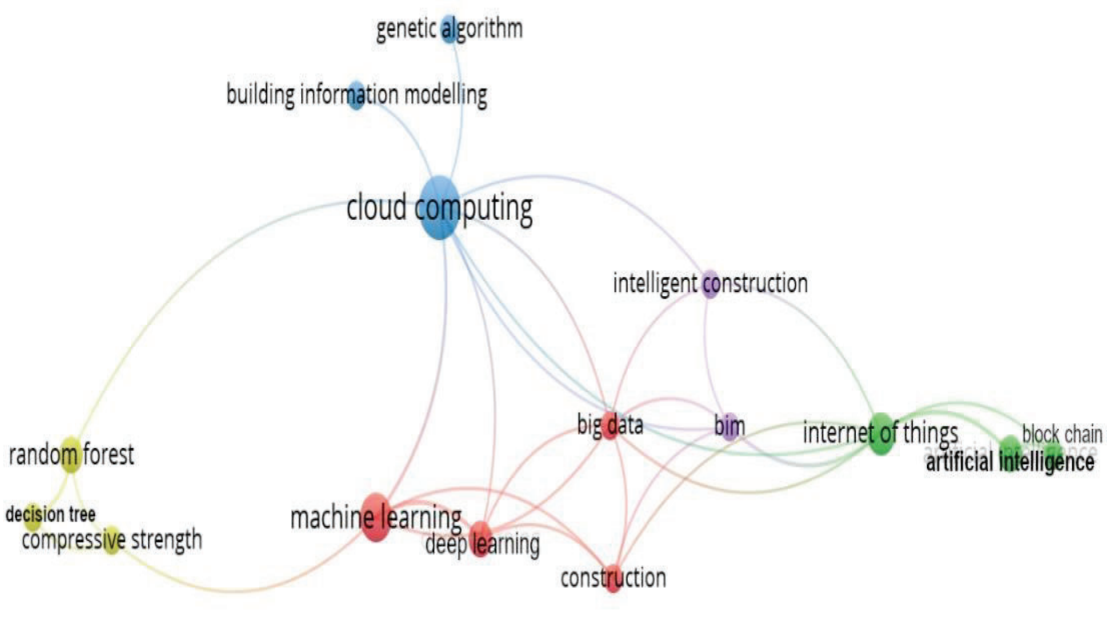

Figure 3: Visualization of author keywords from the literature sample.

As mentioned previously, the AI-in-CC-in-CI research area is not yet a hot spot for scholars, with only 42 valid and relevant articles available through a Scopus search. For these articles, the “Author Keywords” under the “Co-occurrence” category and “Fractional Counting” options were selected and by setting the minimum number of occurrences of a keyword at 2 in the software, only 15 out of 175 keywords were found to meet the threshold. As shown in Figure 3, the final map network obtained consisted of 15 items, 4 clusters, and 30 links. Given that the keywords "BIM" and "Building Information Modelling" have the same conceptual meaning, and that "BIM" is simply an abbreviation of "Building Information Modelling", the two keywords are combined and presented in Table 5. Table 5 shows all keywords in descending order according to their average normalized citations. The table also contains information on occurrence, average publication year, and average citation.

Table 5: Quantitative summary of the influence of keywords in AI-in-CC-in-CI research.

Keywords	**Occurrences**	**Average Publication Year**	**Average citations**	**Average normalized citations**
Construction	2	2021	38.5	4.14
Blockchain	2	2022	17.0	3.80
Building information modeling (BIM)	4	2022	10	3.11
Compressive strength	2	2022	6.5	2.02
Deep learning	3	2019	39.3	1.89
Internet of things	4	2022	8.0	1.69
Machine learning	5	2019	35.2	1.64
Big data	2	2021	30.0	1.50
Artificial intelligence	3	2021	12.0	1.19
Cloud computing	8	2020	15.4	0.50
Random forest	3	2021	2.7	0.33
Genetic algorithm	2	2020	3.0	0.30
Decision tree	2	2022	1.5	0.25
Intelligent construction	2	2022	0.5	0.16

The following is a summary of several important elements shown in Table 5:

1. Deep learning, machine learning, AI, and CC are the most popular keywords in the field of AI-in-CC-in-CI, showing that the use of these technologies in the CI is attracting more and more attention (Li et al., 2018; Li et al., 2020; Li et al., 2021; Shah et al., 2022).
2. Aside from AI technology, the Internet of Things, blockchain, big data, and other cut-ting-edge technologies are also extensively used in the CI (You and Feng, 2020; Abunadi et al., 2022).
3. Keywords such as construction, deep learning, blockchain, and machine learning have high and average normalized citation counts in this table, indicating the significance and impact of research on these technologies in AI-in-CC-in-CI.
4. The majority of the keywords in this table have an average publication year of 2021 or 2022, revealing that the study on AI-in-CC-in-CI is still in its early stages and has an extensive amount of space for further development.

4.4 Countries/Regions Co-Occurrence Analysis

For the country co-occurrence analysis, VOSviewer software was used to create a network of influential country collaborations in AI-in-CC-in-CI research to provide a clearer picture of re-search and collaboration across countries (see Figure 4). "Co-authorship" was selected as the type of analysis, "countries" as the unit of analysis, and "fractional counting" as the counting method. The minimum number of documents of a country and the minimum number of citations of a country were set to 1 and 10, respectively. This resulted in 18 out of 29 countries meeting the requirements. From Figure 4, it can be seen that the most influential countries in this studied topic include China, United States, and United Kingdom, all of which have strong research links with several countries. However, no AI-in-CC-in-CI research has been carried out yet in other countries like Germany, Slovenia, or Sweden.

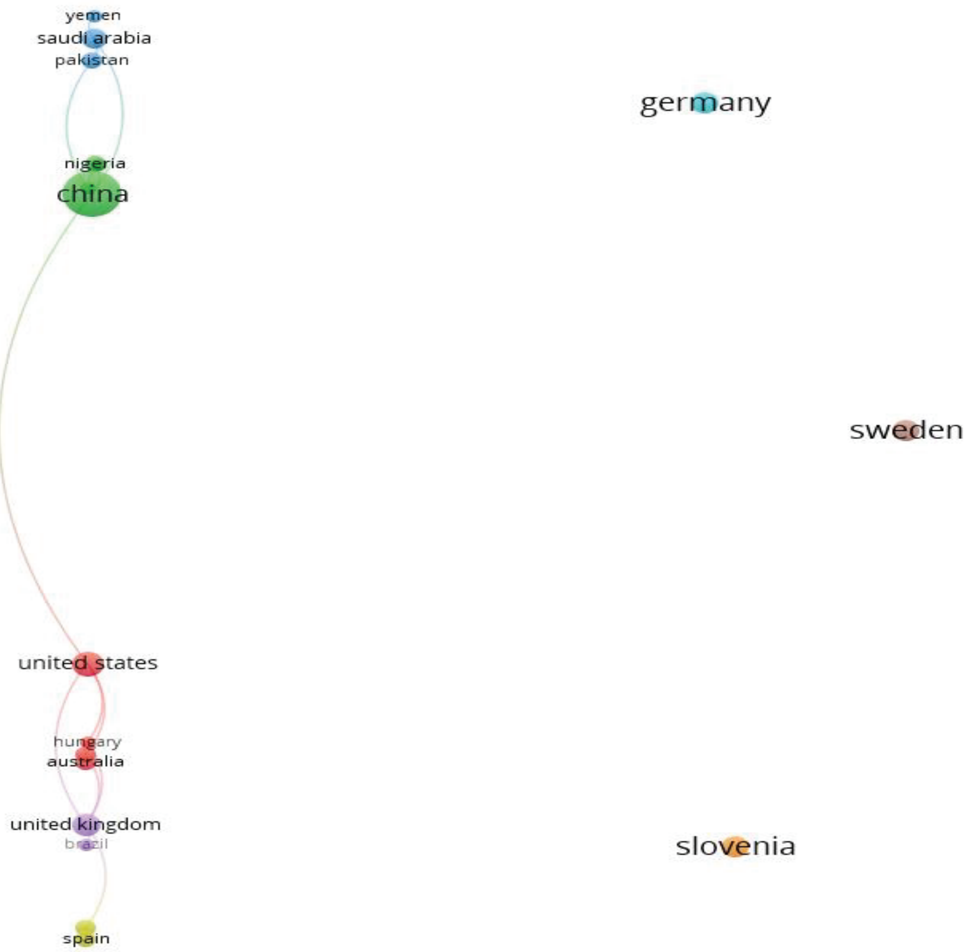

Figure 4: Network of influential countries collaborating to research AI-in-CC-in-CI.

Table 6 provides a quantitative summary of the countries active in AI-in-CC-in-CI research. As seen from the table, China is the number one contributor with 20 articles in this study. In addi-tion, China had the highest number of total citations, normalized citations, and total link strength. However, the average number of citations for China is 9.8, slightly lower than that for the US and UK. This may be due to the high number of articles from China having slightly lower av-erage quality or relevancy. In terms of average citations, Hungary, Spain, and Iran contribute to only one or two articles, but their average citations are high. For instance, the average citations (i.e., 60) for Hungary may be explained by publishing high quality articles that could be widely cited by their peers. Most of the articles have been published from 2018 onwards, indicating that the research in AI-in-CC-in-CI has been accelerating in recent years. Countries like Slove-nia, Brazil, and France had fewer articles and a lower average number of citations, which may be due to the relatively low level of research in the studied field. Sweden, Slovenia, and Ger-many all had a total link strength of 0, which may mean that their research results in AI-in-CC-in-CI are not yet widely recognized by their peers.

Table 6: Quantitative summary of countries/regions in research related to AI-in-CC-in-CI.

Country/ Region	Number of articles	Total citations	Normalized citations	Average publication year	Average citations	Average normalized citations	Total link strength
China	20	196	12.54	2021	9.80	0.63	6
United Kingdom	4	91	8.75	2021	22.75	2.19	5
Iran	2	79	3.95	2019	39.50	1.98	4
United States	5	139	6.47	2018	27.80	1.29	4
Saudi Arabia	3	33	10.24	2022	11.00	3.41	4
Hungary	1	60	3.00	2019	60.00	3.00	3
Pakistan	2	13	4.03	2022	6.50	2.02	3
Turkey	1	21	2.08	2021	21.00	2.08	2
Nigeria	2	29	2.87	2021	14.50	1.43	2
United Arab Emirates	2	17	5.28	2022	8.50	2.64	2
Spain	2	90	1.00	2018	45.00	0.50	1
Yemen	1	20	6.21	2022	20.00	6.21	1
Brazil	1	14	0.47	2020	14.00	0.47	1
Australia	2	25	1.54	2020	12.50	0.77	1
France	1	11	1.09	2021	11.00	1.09	1
Sweden	1	23	2.27	2021	23.00	2.27	0
Germany	1	18	1.00	2016	18.00	1.00	0
Slovenia	1	14	1.38	2021	14.00	1.38	0

4.5 Document Analysis

The objective of this study is to gain a better understanding of the highly cited journal articles in AI-in-CC-in-CI research through a network analysis of the journal articles. To achieve this, VOSviewer software was employed to summarize the highly cited journal articles. After choosing "citation" as the type of analysis and "documents" as the unit of analysis, the mini-mum number of citations for a document was set to 7. This resulted in 20 documents out of the 42 sample documents meeting the threshold. Table 7 lists a few of the influential articles that were arranged according to their normalized citations. It is worth noting that only representative articles with normalized citations greater than 2 are listed in Table 7.

Based on Table 7, it is apparent that the total citations and normalized citations counts vary sig-nificantly among the articles in the field of AI-in-CC-in-CI. Some articles have garnered a sub-stantially higher number of citations than others. For instance, a study by Mohammadzadeh et al. (2019) had the highest total citations (i.e., 60), but its normalized citations are 3.00, implying that its citations are not remarkable when normalized by the number of years since publication. Conversely, Abunadi et al. (2022) obtained lower total citations (i.e., 20), but its normalized ci-tations are much higher (i.e., 6.21), indicating that it has gained a higher level of attention rela-tive to its publication year.

A closer examination of the articles shows that some of the most cited articles concentrate on specific applications of AI-in-CC, such as predicting the properties of concrete or enhancing traffic control systems. On the other hand, some articles, such as Bosch-Sijtsema et al. (2021), have a broader focus on the hype surrounding digital technologies in the industry. Table 7 also reveals that some more recently published articles, such as Abunadi et al. (2022) and Shahzad et al. (2022), have already received a significant level of attention. These findings indicate that the field is evolving rapidly, and new developments are being closely monitored.

Table 7: Summary of highly cited journal articles in AI-in-CC-in-CI.

Article	Title	Total citations	Normalized citations
Abunadi et al. (2022)	Federated Learning with Blockchain Assisted Image Classification for Clustered UAV Networks	20	6.21
Shahzad et al. (2022)	Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges	17	5.28
Shah et al. (2022)	Machine Learning Modeling Integrating Experimental Analysis for Predicting the Properties of Sugarcane Bagasse Ash Concrete	12	3.72
Mohammadza-deh et al. (2019)	Prediction of Compression Index of Fine-Grained Soils Using a Gene Expression Programming Model	60	3.00
Bosch-Sijtsema et al. (2021)	The Hype Factor of Digital Technologies in AEC	23	2.27
Shengdong et al. (2019)	Intelligent Traffic Control System Based on Cloud Computing and Big Data Mining	44	2.20
Malami et al. (2021)	Implementation of Hybrid Neuro-Fuzzy and Self-Turning Predictive Model for the Prediction of Concrete Carbonation Depth: A Soft Computing Technique	21	2.08

5. DISCUSSION

After the scientific mapping of the chosen literature records, a thorough qualitative discussion was undertaken to summarize the mainstream research topics related to AI-in-CC-in-CI. From the keywords and document analyses, the main research hotspots were determined and the re-search gaps and directions for future research were identified. Based on the analyses of the keywords and selected sample literature, the current research hotspots in the field of AI-in-CC-in-CI are classified into four, as shown in Figure 5.

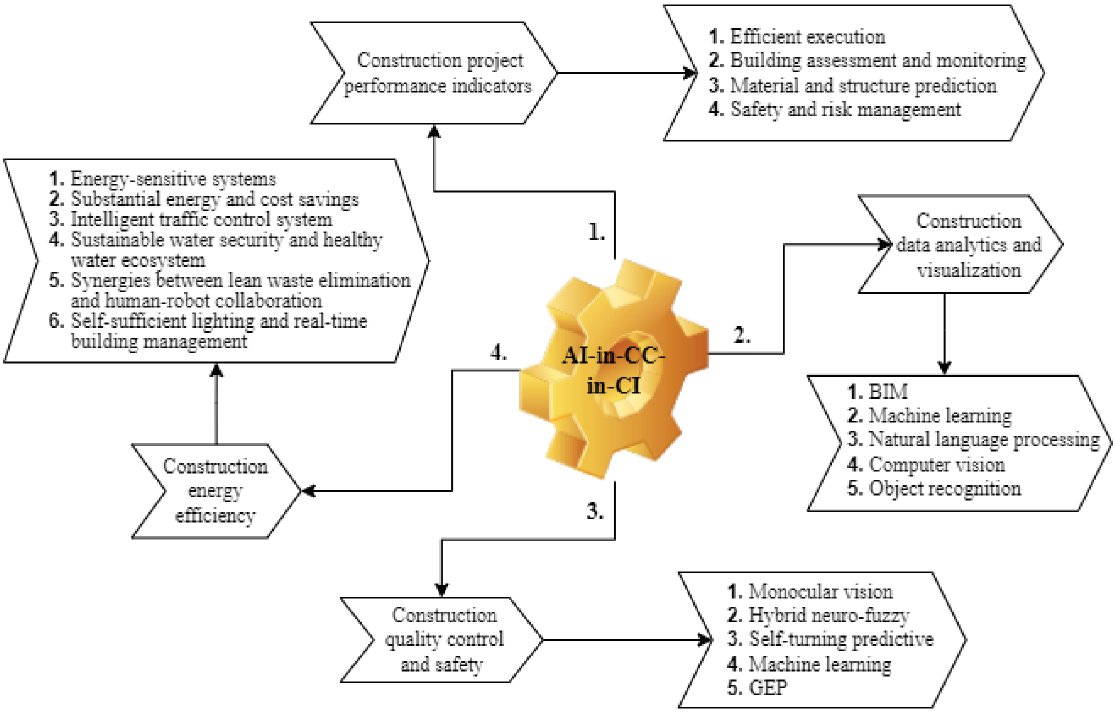

Figure 5: Diagram of AI-in-CC-in-CI research hotspots.

5.1 Summary of the Research Hotspots in the Field of AI-in-CC-in-CI

5.1.1 Construction Project Performance Indicators

AI in CC technology has enormous potential to improve the performance and efficiency of construction projects. Using CC can help construction companies manage their projects more effectively, reduce costs, promote quality, foster sustainability, ensure safety, increase produc-tivity, build stakeholder satisfaction, enhance environmental performance, and improve collabo-ration between project stakeholders. By categorizing and analyzing the selected literature, it was revealed that AI in CC has been implemented in different parts of the CI, including efficient ex-ecution, building assessment and monitoring, material and structure prediction and safety and risk management (Guo et al., 2019; Xu and Liu, 2022; Malami et al. 2021; Ray and Teizer, 2016).

In terms of efficient execution, the use of CC can improve the computational power of robots and enhance their performance. For example, Guo et al. (2019) have proposed an ener-gy-sensitive system framework for cloud robotic networks, which can prolong the lifetime of the network by reducing the execution time and energy loss of computational tasks. To manage the cost of data-intensive applications and maximize resource usage, Kumari et al. (2019) pro-posed an algorithm using particle swarm optimization and genetic algorithms to optimize task scheduling in CC. For construction assessment and monitoring, based on monocular vision, Xu and Liu (2022) introduced a high-precision and high-efficiency 3D reconstruction method for buildings. The method provides new solutions for damage detection, assessment, and monitor-ing, thus, facilitating the intelligent development of the CI. Liu and Tian (2019) proposed a construction risk assessment and early warning construction mechanism based on distributed machine learning algorithms. Their study contributes to a practical and effective method to quantitatively evaluate the safety conditions at construction sites and to identify safety hazards based on information feedback. For the prediction of materials and structures, Malami et al. (2021) developed an AI model to estimate the carbonation depth of reinforced concrete struc-tures, which could improve their durability and longevity. Shah et al. (2022) also developed a machine learning model to predict the compressive strength of bagasse ash concrete, which could lead to safer, faster, and more sustainable buildings. Mohammadzadeh et al. (2019) pro-posed a gene expression programming (GEP) model for predicting the compression index (Cc) of fine-grained soils, which could greatly benefit the CI. Al-Ghrery et al. (2021) proposed a GEP model for predicting the compressive strength of reinforced concrete beams with fi-bre-reinforced polymer (FRP) concrete cover separation

(CCS), which could help improve the flexural capacity of existing concrete structures. In safety and risk management, Ray and Teizer (2016) proposed a new method using machine learning algorithms to dynamically measure the blind spots of construction equipment operators in real-time, which has the potential to improve safety on construction sites and contribute to the design of equipment cabins.

5.1.2 Construction Data Analytics and Visualization

In the fields of AEC/FM, AI has been acknowledged as a revolutionary technique. BIM, a dig-ital technology that enables construction professionals to create and manage building infor-mation throughout a facility's life cycle, has seen a rise in recent years. Mansouri et al. (2020) discussed how data analytics combined with new building trends like BIM could revolutionize AEC/FM industry practices. They recognized two major potential areas such as process effi-ciency and productivity improvement. This indicates that BIM and AI technologies like machine learning and natural language processing could be combined to further improve the efficiency and accuracy of the construction process. Zhou et al. (2022) suggested a novel cloud-based building fire alarm system utilizing BIM. It tackles the challenges of private data sharing and alignment of fire sensors in the BIM model. This suggests that AI technologies could be used to improve BIM's usability and interoperability, which could eventually result in increased safety and security in the CI. From the viewpoint of BIM-based project contractors in the Ma-laysian CI, Wan Mohammad et al. (2022) examined the significant uses of BIM, emphasizing the top BIM uses as 3D coordination and record model creation for facility management pur-poses. This indicates that BIM-based project coordination and facility management could bene-fit from the application of AI technologies, computer vision, and object recognition to increase accuracy and speed. The studies described above demonstrate the potential of combining AI and data analytics with BIM to increase process productivity and efficiency as well as to address issues with private data sharing and sensor alignment. BIM has also been used to create cloud-based building fire alarm systems, showing that AI technologies can improve BIM's usa-bility and interoperability while also enhancing safety and security in the CI.

5.1.3 Construction Quality Control and Safety

The CI has always been one of the backbone of the global economy, providing buildings and infrastructure necessary for both social and economic growth. However, maintaining construc-tion quality has always been a significant industry problem. The use of AI has the potential to greatly enhance infrastructure safety and durability while also improving construction quality control. An analysis of the available research on the use of AI in building quality control was conducted using the data from the chosen literature.

A high-precision and effective monocular vision-based 3D reconstruction technique for build-ings was put forth by Xu and Liu (2022) and can be used for quality assurance and construc-tion monitoring. Ray and Teizer (2016) demonstrated the use of AI in the CI for intelligent alert systems, which can increase safety on construction sites. Darminto et al. (2021) developed a machine learning-based landslide susceptibility mapping technique to detect infrastructure damage from landslides and enhance construction quality control. An AI-based predictive mod-el was proposed by Malami et al. (2021) to determine the carbonation depth of reinforced con-crete buildings, which can increase their durability and service life and help with construction quality control. To predict the compressive strength of sugarcane bagasse ash concrete, Shah et al. (2022) created machine learning models. These models allow designers, researchers, and practitioners to assess the compressive strength of environmentally friendly waste manage-ment-based concrete, resulting in safer, quicker, and more environmentally friendly construc-tion. A gene expression programming (GEP) model was proposed by Mohammadzadeh et al. (2019) to forecast the compression index (Cc) of fine-grained soils, which can help with con-struction quality control. Attempting to predict concrete cover separation in reinforced concrete beams strengthened with fibre-reinforced polymers (FRPs), Al-Ghrery et al. (2021) suggested a GEP model. This model can increase the safety and dependability of FRP-strengthened RC structures in construction projects. In conclusion, there are several studies on the use of AI in building quality control. AI-based solutions can deliver precise and real-time data, foresee pos-sible risks, and forecast material behavior, all of which contribute to the creation of intelligent construction solutions.

5.1.4 Construction Energy Efficiency

Another area of study in the chosen literature sample is AI in CC technology for building ener-gy efficiency. For cloud robotics networks, Guo et al. (2019) developed a framework for ener-gy-sensitive systems to increase the performance and lifespan of robots used in the CI. To achieve substantial energy and cost savings, Li et al. (2018) used deep reinforcement learning algorithms on CC and home smart grid systems. The concept of AI and CC in the transporta-tion sector was demonstrated by Shengdong et al. (2019) to create an intelligent traffic control system based on big data mining and the cloud to optimize real-time traffic flow control strate-gies. Jiang et al. (2021) also highlighted the significance of utilizing new information and communication technologies, such as CC and AI, to guarantee sustainable water security and a healthy water ecosystem. In the context of industrialized construction, Marinelli (2022) investi-gated the conceptual parallels and practical synergies between lean waste elimination and hu-man-robot collaboration, highlighting the significance of Industry 4.0 technologies such as AR, VR, wearables, sensors, CC, and machine learning for enhancing human-robot collaboration. In an attempt to advance the process of urban modernization resulting in a more effective use of land value, Kang (2022) examined the spatial layout of urban and rural structures under mul-ticriteria constraints using AI technologies such as machine learning algorithms and CC. Ac-cording to Zhou et al. (2022), the Xiong'an railway station in China was successfully built us-ing a variety of smart construction techniques, including AI, CC, and BIM technology, in order to achieve self-sufficiency in lighting energy and real-time building management. Taken togeth-er, previous studies on AI in CC technology for construction energy efficiency have reported potential results. According to the studies, the use of AI and CC technologies can significantly improve energy efficiency in the CI by employing a variety of cutting-edge strategies, including intelligent traffic control systems, smart construction methods, and energy-sensitive system frameworks.

5.2 Research Gaps in the Current AI-in-CC-in-CI Research

In the CI, AI and CC have become transformative technologies that present new opportunities to boost sustainability, productivity, and safety. There is still work to be done to completely realize the potential of AI and CC in applications related to construction, even though a growing body of research has explored these topics. Based on reviewing the selected literature, this study identifies some of the major research gaps in the field of AI-in-CC-in-CI.

5.2.1 In-Depth Studies on AI-in-CC for Construction Project Performance Indicators

The analysis of the data from the selected literature demonstrates that although the use of AI in CC technology is still in its early stages, it has an enormous impact on the CI. Guo et al. (2019) and Kumari et al. (2019) developed relevant system frameworks and optimization algorithms to achieve efficient execution in project management, respectively. However, it is important to fo-cus not only on efficiency but also on the management of costs in project management. For example, AI in CC can optimize resource utilization and reduce cloud spending, thereby facili-tating cost management. Xu and Liu (2022) and Liu and Tian (2019) conducted in-depth stud-ies on building damage detection assessment and construction risk assessment, but lacked a focus on building sustainability, which has a significant impact on the performance of construc-tion projects. AI in CC can help organizations improve sustainability by integrating renewable energy and reducing carbon emissions. In terms of predicting building materials and structures, studies have been conducted on the prediction of carbonation depth of reinforced concrete structures, compressive strength of bagasse ash concrete and compression index of fine-grained soils (Malami et al. 2021; Shah et al. 2022; Mohammadzadeh et al. 2019). However, limited research has been conducted on the environmental performance of construction materials. AI in CC can help improve the environmental performance of construction materials by analyzing their impact on the environment, optimizing their utilization, and reducing waste. Concerning safety and risk management, previous studies have focused on the management of construction site equipment (Ray and Teizer, 2016). However, research on improving collaboration between project stakeholders has not been fully explored. Collaboration and communication among the various project stakeholders, including owners, designers, contractors, oversight committees, and governing authorities are crucial. This is because the combined efforts and cooperation of all stakeholders can effectively contribute to successful project completion.

5.2.2 Limitations in Construction Data Analytics and Visualization

From previous studies (Mansouri et al., 2020; Zhou et al., 2022), there are a few research gaps in CC and AI technologies for the analysis and visualization of construction data. There has been little research on how to effectively integrate AI technologies like machine learning, natural language processing, computer vision, and object recognition with BIM to improve AEC/FM practices, despite their potential benefits. In the AEC/FM sector, private data exchange is a sig-nificant problem. Zhou et al. (2022) proposed a cloud-based building fire alarm system that us-es BIM to handle the issues of private data sharing and sensor alignment. However, the in-compatibility of BIM with other systems and technologies may be hampered by the absence of standardized data sharing methods. There has been little study into the use of AI-in-CC for BIM-based facility management, even though BIM has been widely used for 3D coordination and records model creation. For facility management, Wan Mohammad et al. (2022) empha-sized the value of developing records models, but they didn't consider how AI techniques can be applied in this process. In summary, even though the integration of AI techniques with BIM has a tremendous potential to transform AEC/FM practices, there are still unresolved issues that call for more future studies. Investigating efficient integration techniques, creating standardized data sharing procedures, and examining the use of AI-in-CC for BIM-based facility manage-ment are some potential research gaps worth conducting in the future.

5.2.3 Gaps in Construction Quality Control and Safety

Xu and Liu (2022) and Ray and Teizer (2016) proposed a 3D reconstruction method based on monocular vision and showed the use of AI in an intelligent alarm system, and other AI-based approaches for building quality control and safety. To build an integrated AI-based system, CC techniques must be incorporated. Integrating these technologies could result in a method for building quality control and safety that is more holistic and efficient. Numerous previous stud-ies on AI in building quality control and safety have been centered around simulations or lab tests. Consequently, the use of AI-based technologies on real-world construction sites needs to be conducted. For instance, Darminto et al. (2021) proposed a machine learning-based tech-nique for mapping landslide susceptibility, but it needs to be verified for efficacy on real-world construction scenarios. While some previous research, like Ray and Teizer's (2016) intelligent warning system, has addressed worker safety, more studies are still required for smart safety alerting systems. For instance, AI techniques in CC could be used to track employees' locations and send out instant warnings to prevent accidents.

5.2.4 Lack of Research in Construction Energy Efficiency

Li et al. (2018) used deep reinforcement learning algorithms on home and cloud smart grid systems to save energy. AI-in-CC technology has not been applied in their research to integrate renewable energy, optimize energy storage systems, improve energy efficiency, and thus con-tribute to the advancement of renewable energy in construction. Additionally, Marinelli (2022) investigated how Industry 4.0 innovations can enhance human-machine cooperation in indus-trialized structures. However, little is known about how AI and CC technologies might be uti-lized in this context, suggesting the actual use of these technologies in the CI. The practical ap-plication of AI-in-CC-in-CI research has been unexplored yet. Although previous studies (Shengdong et al., 2019; Jiang et al., 2021) have shown how AI and CC technologies can be used to optimize traffic flow and guarantee sustainable water security, there are still restrictions in every case, though. To understand how these technologies will scale and adapt in various environments, geographical locations, and building types, more future studies are required.

5.3 Future Research Directions

Table 8 presents future research directions for AI-in-CC-in-CI based on the qualitative discussion of the identified research hotspots and research gaps. It is crucial to remain conscious that the study themes depicted in Table 8 are not independent but rather connected. For instance, all four themes revolve around construction project management, which is supported by data analysis and vis-ualization in this field, quality control and safety, and building energy efficiency. In other words, the identified themes are crucial to the success of projects and the long-term viability of con-struction projects. Based on the gaps identified in these four themes, the following research di-rections are proposed for future research:

1. Integrating AI and CC technologies to improve construction project management processes such as project planning, resource allocation, stakeholder collaboration, and cost manage-ment.
2. Creating effective merging strategies and standardized data-sharing protocols for AI-based technologies and BIM to advance AEC/FM practices.
3. Examining the application of AI technologies in model creation, upkeep, and updates in BIM-based facility management.
4. Examining how AI-based technologies can be used for real-time safety monitoring, such as tracking workers' locations and sending out prompt warnings to avoid accidents, to im-prove construction quality control and safety.

5. Investigating how to combine renewable energy with AI and CC technologies to maximize building performance.
6. Exploring the scalability and adaptability of CC and AI technologies in various settings, such as building types and geographical areas.
7. The integration of AI with other digital technologies such as IoT, big data, blockchain, ro-botics, and BIM requires a special focus on project management improvements, cost con-trol, and efficiency gains.
8. Full consideration of the ethical implications of CC and AI technologies.

In general, future studies should concentrate on filling the gaps and overcoming the obstacles found for the integration of CC and AI technologies in the CI. Additionally, to further advance the capabilities of AI and CC in the CI, concentrated attention must be given to the integration of AI with other digital technologies like IoT, big data, blockchain, robotics, and BIM. Finally, although CC and AI have the potential to enhance the construction process, their ethical ramifi-cations have not received enough consideration. For instance, data security and privacy may arise from the use of AI and CC in the CI. A study by Marinelli (2022) pointed out that it is crucial to think about the ethical consequences of these technologies in the CI.

Table 8: Future research directions for AI-in-CC-in-CI.

Research themes	Research hotspots	Future research directions	References
Construction project performance indicators	1. Efficient execution 2. Building assessment and monitoring 3. Material and structure prediction 4. Safety and risk management	1. Developing cost management index 2. Improving construction sustainability in practice 3. Enhancing environmental performance 4. Promoting stakeholder collaboration	Ray and Teizer (2016); Guo et al. (2019); Kumari et al. (2019); Liu and Tian (2019); Mohammadzadeh et al. (2019); Al-Ghrery et al. (2021); Malami et al. (2021); Shah et al. (2022); Xu and Liu (2022)
Construction data analytics and visualization	1. Building information modeling (BIM) 2. Machine learning 3. Natural language processing 4. Computer vision 5. Object recognition	1. Creating effective merging strategies 2. Developing standardized data-sharing protocols 3. Improving AI-assisted BIM facility management	Mansouri et al. (2020); Wan Mohammad et al. (2022); Zhou et al. (2022)
Construction quality control and safety	1. Monocular vision 2. Hybrid neuro-fuzzy 3. Self-turning predictive 4. Machine learning 5. Gene expression programming (GEP)	1. Developing more AI-based technologies tests on sites 2. Exploring AI-based tools in CC for worker safety 3. Real-time AI-based safety monitoring	Ray and Teizer (2016); Al-Ghrery et al. (2021); Darminto et al. (2021); Malami et al. (2021); Shah et al. (2022); Xu and Liu (2022)
Construction energy efficiency	1. Energy-efficient systems 2. Cost-effective energy savings 3. Smart traffic control 4. Sustainable water management 5. Lean waste elimination and human-robot collaboration 6. Self-sufficient lighting and building management	1. Improving renewable energy integration with AI and CC 2. Developing scalability and adaptability of CC and AI 3. Full consideration of the ethical implications of CC and AI	Li et al. (2018); Guo et al. (2019); Shengdong et al. (2019); Jiang et al. (2021); Marinelli (2022); Kang (2022); Zhou et al. (2022);

5.4 Study Implications and Contributions

From the policy perspective, the results of this research have significant ramifications for the formulation and application of current and potential policies in the CI. The industry's increasing interest in CC and AI technologies highlights the need for policymakers to establish regulatory frameworks and mandates that will encourage ongoing innovation and the adoption of cut-ting-edge technologies. Additionally, the results of this study will help make it easier for the government and other relevant organizations to fund and support research and development in the field of AI-in-CC technologies in the CI, thereby enhancing certain aspects of the AEC in-dustry's current environmental sustainability efforts. This will help to a certain degree with the goals of the European Union Digital Strategy for the CI.

For the policy theory, through a thorough analysis of the literature, this study contributes to a deeper theoretical understanding of the latest advances in research on AI-in-CC-in-CI. The study identifies the main research hotspots, gaps in existing research, and offers insights into future research directions. It highlights the growing importance of the field and the need for further research in various areas, such as cost management, sustainability, stakeholder collabo-ration and AI-assisted facility management strategies. The results of this study serve as a foun-dation for future research and contribute to a more systematic and comprehensive understand-ing of AI-in-CC-in-CI.

From the practical perspective, the implications of this study are of great importance to the CI. This study provides valuable insights into the potential applications of AI and CC in construc-tion projects for relevant practitioners in the CI, including architects, engineers, and project managers. Construction industry practitioners can utilize the findings of AI in existing CC technologies to improve project efficiency and reduce costs, thereby maximizing the outcomes of construction projects. In addition, by identifying and addressing barriers to implementation, this study encourages researchers and practitioners to invest additional efforts in overcoming obstacles, thereby improving overall performance and outcomes in the CI.

6. CONCLUSIONS

This review study aims to provide a theoretical overview of the main research hotspots, gaps in existing research, and future research directions of AI-in-CC-in-CI. To achieve this goal, 42 journal articles in the field of AI-in-CC-in-CI were reviewed in this study using a four-step bib-liometric-systematic review analysis approach, including literature search, literature screening, scientific mapping analysis, and qualitative discussion. Based on the results, research articles in AI-in-CC-in-CI have been published from 2012 onwards, and since 2019, there has been a no-table rise in the number of publications. An analysis of the keywords reveals that the popular research keywords in the field include construction, blockchain, BIM, compressive strength, deep learning, internet of things, and machine learning. The qualitative discussion of the select-ed literature sample revealed that the current research hotspots in the field of AI-in-CC-in-CI are focused on (1) construction project performance indicators, (2) construction data analytics and visualization, (3) construction quality control and safety and (4) construction energy efficiency. However, more research is needed to implement AI-in-CC in the areas of cost management, sustainability, stakeholder collaboration, standardized data sharing protocols, AI-assisted facility management strategies, real-time safety monitoring and the integration of renewable energy with AI and CC in the CI.

The above-mentioned future research directions will enable scholars in the field of AI-in-CC-in-CI to gain a better understanding of the current research gaps in order to bridge the gaps and lay a better foundation for a rapid development in the future. Furthermore, it should not be overlooked that there are still some limitations in this study, as it was limited to literature samples published in the Scopus database, and only includes journal articles written in English. Consequently, some publications that are indexed in other databases (e.g., Web of Science), written in other languages (e.g., Chinese), and other types of sources (e.g., conference proceedings) could be omitted. Moreover, it is conceivable that the keywords used in the litera-ture search might not completely encompass the subject matter. Additional keywords could be included in future research.

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