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INVESTIGATING THE INFLUENCE OF ICT APPLICATION IN CONSTRUCTION JOBSITES: A SYSTEMATIC REVIEW AND BIBLIOMETRIC ANALYSIS

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SUMMARY: *In recent years, the construction industry has witnessed a surge in the adoption and application of emerging technologies. Substantial evidence indicates the impact of these technologies on the lifecycle of construction projects. Among the notable categories of technologies embraced in construction, Information and Communication Technologies (ICTs) stand out. This category encompasses BIM models, reality capture, cloud computing, robotics, and more. However, a literature investigation that specifically focuses on the significant influence of these technologies on construction sites is lacking. To address this gap, this study conducted a systematic literature review, supported by a bibliometric analysis of published articles in the field of construction management. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, data was sourced from Scopus and Web of Science, covering the period from 2009 to 2023. The findings shed light on nine prominent ICT tools widely adopted on construction sites for project execution, with contributions from 113 countries emphasizing their profound impacts. Despite these positive aspects, this study also identifies notable challenges and provides recommendations for mitigating them. A smart site data integration framework was developed to facilitate the seamless integration of these technologies while ensuring data security. This study provides fundamental insights for future research in this field aimed at informing the construction industry about the importance of embracing cutting-edge technologies for enhanced efficiency on construction jobsites and for timely project delivery.*

KEYWORDS: *ICT, Construction management, Construction site, Emerging technologies, Wearables.*

REFERENCE: *James Olaonipekun Toyin, Salman Azhar, Anoop Sattineni, Ayodele Ambrose Fasoyinu (2024). Influence of Information and Communication Technology Application in Construction Jobsites: A Systematic Review and Bibliometric Analysis. Journal of Information Technology in Construction (ITcon), Vol. 29, pg. 444-479, DOI: 10.36680/j.itcon.2024.021*

1. INTRODUCTION

The construction industry plays a vital role in a country's economy and contributes significantly to its economic development (Chia et al, 2014, Olanipekun and Saka, 2019). In recent years, the construction sector has faced increased competitive pressure, driving rapid adoption of strategies to shorten project timelines, reduce costs, and enhance performance and efficiency. This pressure results from evolving market dynamics, in which clients and real estate developers seek greater value, higher quality, faster project completion, and access to up-to-date information throughout the project lifecycle (Aziz et al, 2009, Vlist et al, 2014, Asgari and Rahimian, 2017, Sezer and Bröchner, 2020). Nevertheless, it is widely acknowledged that innovative solutions are needed to overcome these challenges (Saridaki et al, 2019, Ogunseiju et al, 2021). The issues of delayed access to essential information that could improve construction and material management, enhance construction worker safety, and streamline communication among project participants have long been identified as areas in need of continuous improvement within the current construction processes (Lam et al, 2010, Svalestuen et al, 2017, Buer et al, 2018). The quality, quantity, and timeliness of information play a critical role as they can either hinder or facilitate successful outcomes. Information and Communication Technologies (ICTs) are rapidly advancing fields that affect numerous sectors, including the construction sector (Turk, 2023). ICTs encompass technologies for managing information, and their infrastructure includes components such as hardware, software, and networking for IT environments, whether on-site or in the cloud. These components enable IT services and solutions to be delivered. For over 40 years, the Architect, Engineer, and Construction (AEC) sector has been using ICT to streamline operations and transform industries (Isikdag et al, 2009). Notwithstanding this, significant advancements have been made in the recent years. The introduction of technologies such as BIM, artificial intelligence, drones, smart wearables, virtual and augmented reality, and data collection applications (DCA), among others, has revolutionized conventional practices in the construction industry, thus facilitating its advancement in the construction industry (Chatterjee et al, 2017, Jiang et al, 2022, Eliwa et al, 2023).

Currently, the industry is increasingly using ICTs in areas such as design, project scheduling and planning, budgeting, cost control, computer-aided facilities management, effective time management, improved construction safety, and on-time project delivery (Ikediashi and Ogwueleka, 2016, Hasan et al, 2018, Dixit et al, 2021, Toyin et al, 2023, Becerik-Gerber et al, 2012). This has created numerous opportunities in the industry to execute projects more effectively and efficiently. Information management and uninterrupted communication during the construction stage are vital, and attention should be paid to the management of information and communication during this stage (Adriaanse et al, 2010, Czart et al, 2017). This will assist in project cost management and effective safety control (Piroozfar et al, 2019, Spisakova et al, 2020, Eiris et al, 2020, Arowoiya et al, 2023) and effective collaboration among stakeholders (Mesároš and Mandičák, 2017, Turk, 2023). The interdisciplinary nature of the construction industry necessitates the rapid exchange of information among all participants, including project owners, design consultants, project managers, subcontractors, contractors, and suppliers (Lam et al, 2010, Linderoth and Elbanna, 2016). Azhar et al, (2015) testified that fast and reliable information exchange using ICT is necessary between all stakeholders for effective collaboration. Over the past two decades, project stakeholders have increasingly shared construction-related information electronically to boost efficiency because of ICT's growth (Sørensen et al, 2009). Li et al, (2010), Zekavat et al, (2015) reported that medium to large construction organizations frequently use intranets and some types of electronic document management to meet their internal communication needs, while web-based collaboration portals are quickly spreading to support information sharing and to launch workflow processes among multidisciplinary team members. Recently, the Internet has become a crucial medium for disseminating project data and has served as a modern communication platform (Eliwa et al, 2023, Ikediashi and Ogwueleka, 2016). This could be a result of advancements in network signal frequency from second-generation (2G) to fifth generation (5G) mobile networks. This has increased the use of portable personal computers (PPC), tablets, and phones onsite, which supports improved productivity and quality (Wu et al, 2018, Hasan et al, 2021, Mahdi and Afshar, 2022, Zhao et al, 2023).

While research on ICT in the construction industry has mostly focused on ICT promotion (Soon Ern et al, 2017) and contemporary uses (Ahuja et al, 2010, Ikediashi and Ogwueleka, 2016, Jiang et al, 2022), others have examined this concept from the perspective of industrialized countries, such as the United Kingdom, the United States of America (USA), Canada, and Japan. In addition, reviews have been conducted in areas such as the application of ICT in AEC organizations (Lu et al, 2015), construction organizations (Eliwa et al, 2023), and emerging technologies in industrialized construction (Qi et al, 2021). Nonetheless, there is a notable gap that requires immediate attention, and the absence of a comprehensive, systematic review assessing the influence of

ICTs in the building construction phase for building project execution and management. Such a review would provide valuable insights to researchers and project coordinators to optimize the utilization of diverse ICT tools that could enhance construction practices, productivity, safety, and time. Inspired by the insights mentioned above, this study introduces a systematic literature review (SLR) aimed at organizing various approaches. It specifically concentrates on the impact of key information and communication technology applications on construction jobsites during project execution and evaluates their effects on collaboration, cost control, safety and security measures, and likely challenges. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. The primary goal of SLR is to offer a comprehensive and state-of-the-art perspective on the influence of ICTs on building construction project management. This includes an examination of the research objectives, methodologies employed, and results obtained from articles published between 2009 and 2023.

Five research questions were posed to guide this systematic review (see Table 1). The remainder of this paper is organized as follows. Section 2 outlines the design of the systematic literature review and explains the research methodology. Section 3 presents and discusses the findings of the bibliometric analysis. Section 4 presents the insights discovered and responses to the research inquiries, drawing on the papers reviewed. Section 5 provides a synopsis of the review findings and presents the conceptual framework. Finally, Section 6 presents concluding remarks and recommendations for future research.

2. METHODOLOGY

A glance at this study's research methodology is shown in Figure 1. Various analyses, including bibliometric analysis and content analysis through a SLR, were employed to fulfill the objectives of the study.

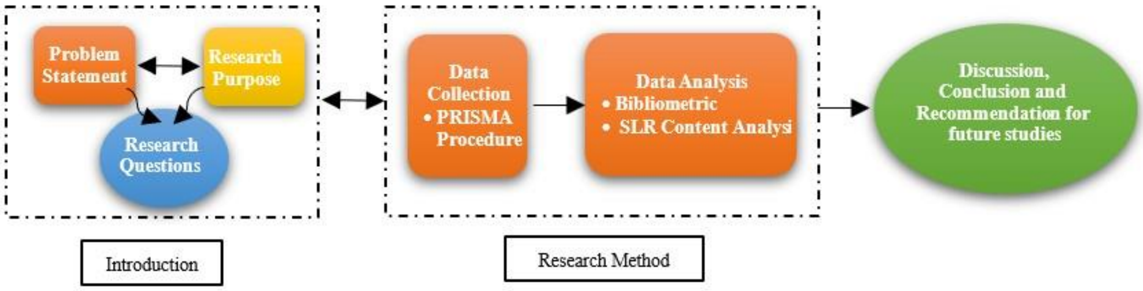

Figure 1: Research Methodology.

2.1 Systematic literature review design

A systematic literature review (SLR) provides a thorough examination of existing literature related to a specific research question. It combines prior research findings to enhance the foundational knowledge of a particular topic while emphasizing transparency and minimizing bias in the process (Williams et al, 2021, Deng et al, 2021, Hiebl, 2023).

2.1.1 Research question

Initially, the research question (RQ) was strictly defined in line with the PRISMA guidelines, focusing on the influence of emerging information and communication technologies during the construction stage. Surprisingly, no existing articles have comprehensively reviewed the articles published in this study's focus area. This gap extends beyond specific research, leading to an investigation tailored to the research questions. This represents a critical concern for researchers and practitioners aiming to enhance construction activity management. As the quest for dynamically improving the construction process persists, exploring various emerging technologies impacting the construction phase and understanding their impact on construction project management at construction sites is essential to prepare for advancements in future research.

Previous studies related to this study have revealed the following limitations:

- These studies did not extensively review the emerging technologies that have a substantial impact on the construction stage of building construction. This gap implies that critical advancements in construction technology, such as those related to scheduling, time management, safety and security control, cost management, and stakeholder collaboration, may not be adequately covered.
- The articles did not comprehensively address the various ICT tools adopted in the construction stage, which have a substantial influence on various aspects of on-site activity management. This omission leaves gaps in the understanding of how specific technologies impact construction processes.

These limitations highlight the need for more comprehensive and state-of-the-art information regarding the impact of emerging information and communication technologies during project execution, and their integration with knowledge management and other critical aspects of construction project management. Based on the above considerations, the research question (RQ) in Table 1 was defined. While focusing on these five objectives, this research also addresses the challenges identified in some of the articles. This analysis provides recommendations aimed at overcoming these challenges and justifies the impact of ICT during project execution.

Table 1: Research question and possible goals.

Index	Research Question	Goal
RQ1	How has ICT adoption evolved within the construction industry?	This research question aims to quantitatively analyze the data collected for the study using bibliometric network mapping.
RQ2	What are the emerging key ICT tools and systems that influence project execution at construction sites and how do they affect the management of building project?	The aim of the review section is to identify and analyze the trends and impacts of ICT tools and systems used in construction sites. The focus will be on how these technologies have influenced construction project execution over the years
RQ3	How does using ICT tools affect scheduling and time management during construction?	This question guides the assessment of how emerging ICT tools affect project scheduling and time management during the construction phase. The goal was to gain insights into their impact and identify potential improvements for better construction project management practices.
RQ4	How does ICT integration affect cost control and budget management in the construction phase?	The analysis focuses on how ICT tools and systems can improve cost management, optimize budgets, and enhance financial control processes in construction projects. Additionally, this study aims to identify the challenges that limit the adoption of ICT during the construction stage.
RQ5	How do ICT tools enhance communication and collaboration among project stakeholders during the project execution phase? And what are the challenges faced.	This question aims to assess how well ICT tools enhance information sharing, promote teamwork, and facilitate smoother interactions among different parties in construction projects.

2.1.2 Search strategy and information sources

The SLR was conducted using guidelines from the existing systematic review formats in the field of construction technology. The PRISMA framework, which includes a three-phase checklist and flowcharts, was followed to achieve the objectives (Newman and Gough, 2020, Cao et al, 2022, Huu, 2023). This SLR relies on methodological approaches from previous studies and does not involve conducting a meta-analysis. The SLR process is based on various criteria as described in the following subsections.

For this systematic literature review, two types of conventional databases (Scopus and Web of Science) and one search data source engine were used to search terms, as illustrated in Table 2. Paper sourcing began in the fall semester of 2023 (August) and continued until the end of December 2023, with finalization and formatting completed in January 2024. The search terms were integrated using Boolean operations in terms of title, keywords, text, and abstract as adopted in related reviews (Huu, 2023, Toyin and Mewomo, 2023c). The search process documentation and the search terms are listed in Table 2.

Table 2: Documentation of the search process.

Data source	Search process	Search query	Query search result
Scopus	Search date: September. 13 2023 – December 4 2023 All search results are saved and reserved in Zotero Evaluate and find abstracts that meet inclusion criteria. Evaluate and find full texts that meet inclusion criteria. Add studies to the final set based on content characteristics.	"ICT" OR "INFORMATION, COMMUNICATION AND TECHNOLOGY" AND "CONSTRUCTION" OR "CONSTRUCTION MANAGEMENT" OR "CONSTRUCTION AUTOMATION" AND PUBYEAR > 2008 AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA,"ENGI")) AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"ch")) AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO (EXACTKEYWORD,"Construction Industry") OR LIMIT-TO (EXACTKEYWORD,"Project Management") OR LIMIT-TO (EXACTKEYWORD."Construction Projects")	5,056
Web of science		Results for "ICT" OR "INFORMATION, COMMUNICATION AND TECHNOLOGY" AND "CONSTRUCTION" OR "CONSTRUCTION MANAGEMENT" OR "CONSTRUCTION AUTOMATION" (All Fields) and 2023 or 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014 or 2013 or 2012 or 2011 or 2010 or 2009 (Publication Years) and Article or Proceeding Paper or Book Chapters (Document Types) and Engineering Civil or Construction Building Technology or Management (Web of Science Categories)	6,428
Google scholar		"ICT" OR "INFORMATION, COMMUNICATION AND TECHNOLOGY" AND "CONSTRUCTION" OR "CONSTRUCTION MANAGEMENT" OR "CONSTRUCTION AUTOMATION"	15,200

2.2 Selection criteria

The paper selection process comprises four stages with various activities and follows an iterative approach. Initially, a search was conducted through over 15,000 articles, as shown in Table 2. Preliminary inclusion and exclusion criteria, such as the year range of 2009–2023, acceptable written language (English), and limitations on document types (journals, book chapters, and conference papers), were applied. The results of this study search are summarized in Table 2. The objective of this study is to identify recent trends in research articles concerning the influence of key ICT tools adopted in the construction stage and their impact on collaboration, cost control, challenges, safety, and security, with a focus on effective construction project management at construction sites.

2.2.1 Extended eligibility criteria

Criteria were established to answer the research question. The data collection process focused on the use of Scopus (5,056) and the Web of Science (WoS) (6,428); thereafter, duplicate documents were removed before screening. Google Scholar was used to find and download articles from the published domain; however, it was subsequently excluded owing to its non-traditional database status. The inclusion and exclusion criteria were as follows:

Title and abstract screening: This involved careful review of titles and abstracts, articles not addressing the research questions or failed to focus on construction project execusion were excluded. Articles lacking a full bibliography were excluded. Research articles were selected based on the availability of full English-language PDF, resulting in the deletion of 288 duplicate articles. The eligibility criteria for assessing the impact of ICT on construction site management were categorized into (1) key ICT tools and systems; (2) design, visualization, and scheduling; (3) cost control and budget management; (4) communication and collaboration; and (5) safety, monitoring, security measures, and challenges. These criteria were compared to the narratives in the search expressions presented in Table 2.

The term “ICT” was frequently used in these studies, and there was a consistent approach to defining the study population. Studies that used terms like “emerging technology” or modern technology” often featured similar aspects, including information technology (IT). This commonality in terminology resulted in a higher level of agreement regarding the eligibility criteria. ICT is a fundamental part of modern technology and IT, facilitating innovative solutions for enhancing information-sharing, monitoring, and management in construction projects. The primary focus was on assessing ICT’s influence within the framework of emerging construction information and communication.

2.3 Data extraction and analysis

Basic information about the study and its methods, such as document citation, research focus, study type, and significant findings, was collected. The main results were subsequently organized based on the study's objective and common themes identified through the analysis of selected articles. Rayyan and Zotero were utilized for data collection to summarize the findings. Data extraction was performed by two experts, and the accuracy was verified by a third expert.

2.4 Research procedure: PRISMA flowchart

The SLR approach is consistent with the suggestions made by (Prebanić and Vukomanović, 2021). This is compatible with the PRISMA method, which uses the schematic diagram in Figure 2, along with the PRISMA steps in Figure 3.

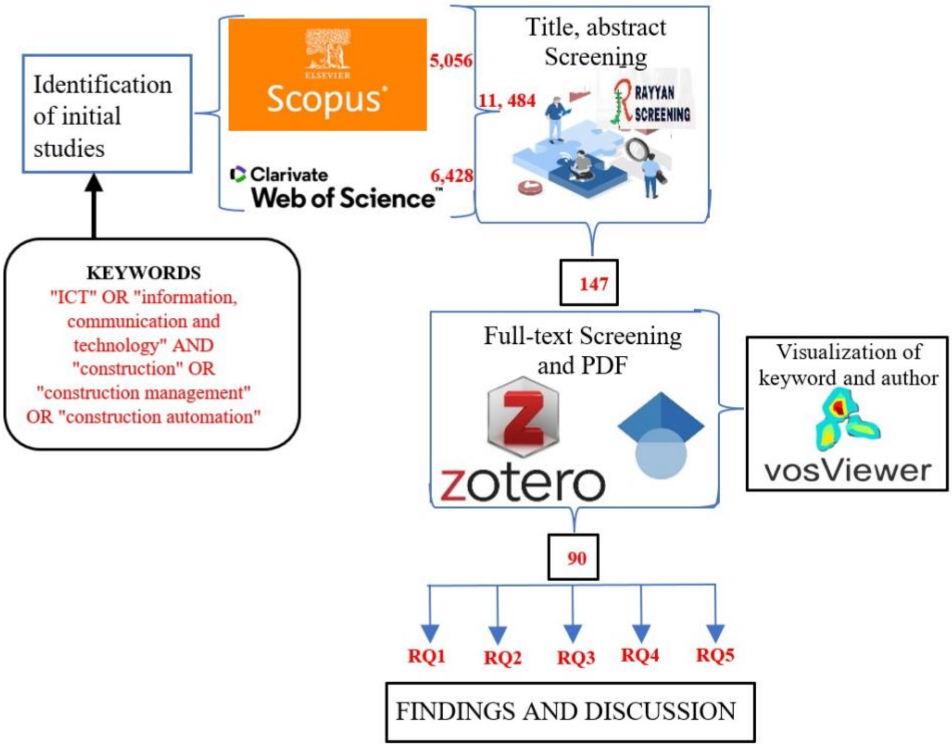

Figure 2: Study procedure schematic diagram.

Initially, a total of 5,056 articles were identified in Scopus and 6,428 articles in WoS. After considering factors such as the domain, index, period, and language, 11,484 articles were retained. These articles were imported into the Rayyan online tool, designed to assist researchers in efficiently screening and selecting studies for systematic reviews and similar projects. The documents from Scopus were saved in RIF format, totaling 5,056 documents, whereas those from WoS were downloaded in sets of 1,000, until they reached a total of 6,428 in RIF format. After importing the data into Rayyan, the duplicate detection process identified 288 duplicate documents and removed them. Subsequently, inclusion and exclusion criteria were applied in the system, marking 2,429 records as ineligible (less than three stars) and subsequently deleting them.

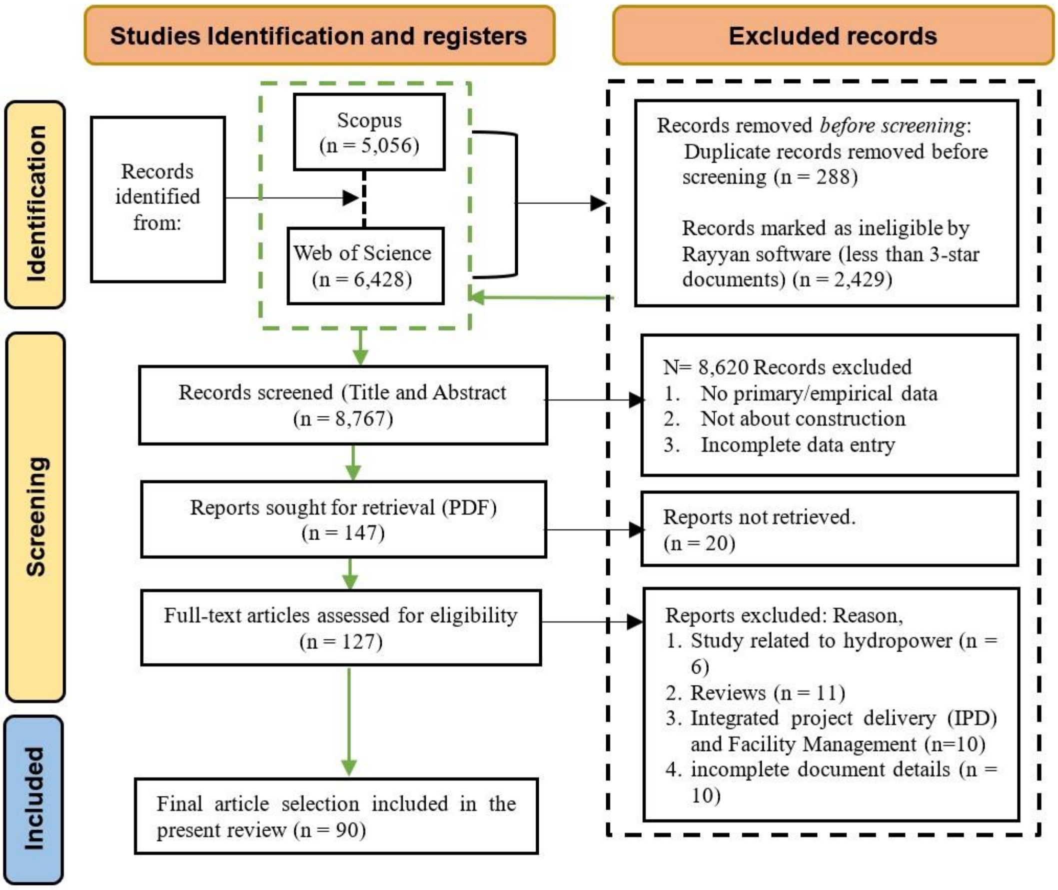

Figure 3: Study PRISMA flow diagram.

Following the PRISMA flowchart process (see Figure 3), a total of 8,767 documents remained for the "Title and Abstract screening." Among these, 8,620 articles were removed, leaving 147 for further consideration. The data for these 147 articles were exported in BibTeX format and imported into Zotero for document retrieval. Using Zotero's full-text finder, 75 articles were automatically located, whereas the remaining 72 documents were manually downloaded from the publisher's website. An additional 52 articles were retrieved from Google Scholar. However, access to 20 documents was restricted due to application fees and licensing restrictions in the publisher's domain. Consequently, 127 full-text articles were retained. After full-text screening, 37 documents were excluded for reasons outlined in Figure 2. The final review included 90 articles.

3. BIBLIOMETRIC MAPPING ANALYSIS

This section answers Research Question 1 (RQ1): How has ICT adoption evolved within the construction industry? Thus, explores the outcomes of the bibliometric analysis, illuminating trends in publications, co-occurring keywords, countries, and analysis of top impactful articles. Bibliometric analysis is a quantitative method commonly used in literature reviews and serves as a vital research tool that reveals various perspectives by mapping published articles across different fields. This method visually represents the interconnected relationships within a dynamic scientific knowledge system. While Zabidin et al, (2020) conducted a bibliometric mapping of Industry 4.0 in the construction industry, this study focused on Information and Communication Technology (ICT) in the same domain. Notably, the accessibility of extensive bibliometric data has been enhanced by databases such as Scopus and Web of Science, along with specialized software such as BibExcel, CiteSpace, Gephi, VOSviewer, and Leximancer, contributing to an increased scholarly interest in bibliometric analysis (Tariq et al, 2022, Toyin and Mewomo, 2023c).

3.1 Publication trend

The analysis depicted in Figure 4 illustrates a notable increase in publications, indicating an increase in research efforts in the AEC sector. This surge is likely propelled by academia, research institutions, and industry stakeholders who acknowledge the significance of leveraging Information and Communication Technology (ICT) for enhanced outcomes in AEC practices. This upward trend points to a collective commitment to disseminating knowledge among academic and professional communities, with researchers actively contributing to understanding how ICT applications are transforming construction processes. This growing interest in publications has prompted educational institutions to adapt their curricula to align with the ICT requirements for AEC students, reflecting a broader shift towards scrutinizing the technological proficiencies of graduate students in response to industry demands (Kim and Irizarry, 2021, Uhm et al, 2017, Yap et al, 2022, Toyin and Mewomo, 2023b). This evolution acknowledges the imperative of a workforce equipped with ICT skills to effectively navigate the evolving technological landscape of the AEC industry.

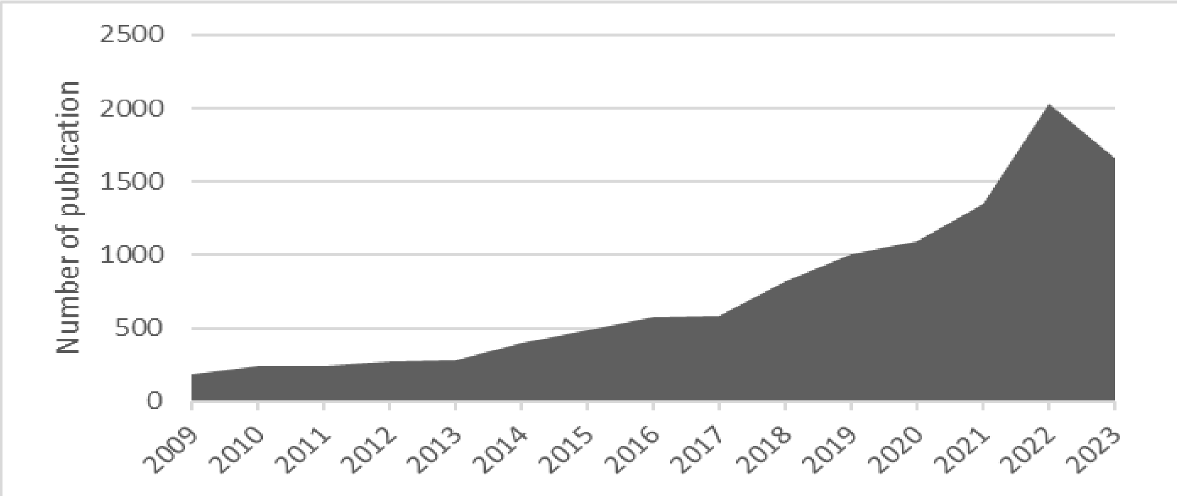

Figure 4: Publication per year on ICTs in construction management.

3.2 Co-occurring keyword

Among the 22,706 co-occurring keywords, the inclusion criteria were set to a minimum of 80 occurrences, resulting in 51 keywords meeting this threshold. A check was then conducted to eliminate redundant keywords, leading to the removal of 7 keywords such as "survey," "design/methodology/approach," and "building information model - BIM." Ultimately, 45 keywords were visualized, forming three clusters representing diverse areas of ICT applications in the Architecture, Engineering, and Construction (AEC) industry. Each cluster highlights the thematic groupings of keywords, with the dominant keywords describing core themes. From Figure 5, Cluster 1, "Integrated Construction Technology," features "Construction Industry" as the most frequent keyword, with 534 occurrences and a total link strength of 1345. Cluster 2, "Smart Sustainable Technology," is characterized by "Decision Making," with 259 occurrences and 721 total link strength. Cluster 3, "Technology in Learning and Building," showcases "Machine Learning" as the most occurring keyword, with 199 occurrences and 348 total link strength.

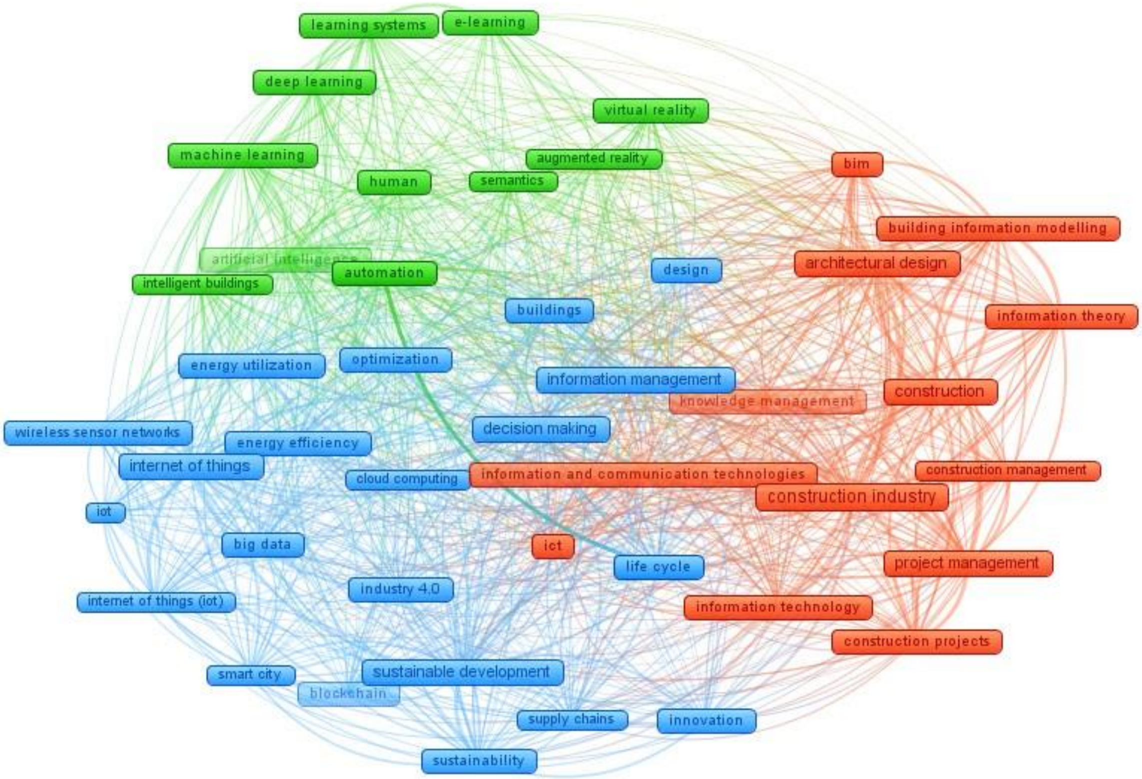

Figure 5: Co-occurringtop keywords from the ICTs publication.

3.3 Countries contribution

The bibliometric analysis of countries contributing to the ICT domain in construction involved a dataset comprising 113 countries. This section aims to explore the global research landscape within this domain, focusing on parameters such as documents per top-cited country and link strength in published literature, with a minimum citation benchmark of 500. As a result, 45 countries surpassed this threshold, highlighting the significant global contributions of ICT to construction. This widespread involvement signifies the collaborative and globally distributed nature of research efforts in this field, demonstrating a broad interest and engagement across continents. Adherence to a robust citation benchmark and the involvement of 113 countries reinforces the credibility and significance of the findings, providing valuable insights into the diverse contributions of nations to this dynamic and evolving field. Notably, the top five contributors include China, the United Kingdom, the United States, Australia, and India, with varying numbers of documents indicating their respective levels of involvement and influence in the domain, as shown in Table 3.

Table 3: Countries contributing to ICT in construction.

SN	Country	Documents	Citations	Total link strength
1.	Australia	283	10250	31753
2.	Bangladesh	14	545	2813
3.	Belgium	18	505	1521
4.	Brazil	65	2495	6800
5.	Canada	92	4348	11667
6.	Chile	25	937	2862

SN	Country	Documents	Citations	Total link strength
7.	China	621	13754	39710
8.	Denmark	37	1895	4571
9.	Egypt	44	881	3947
10.	Finland	62	2627	4827
11.	France	75	6162	6865
12.	Germany	73	4706	7864
13.	Greece	41	1357	2878
14.	Hong Kong	106	6412	14219
15.	India	221	4838	13658
16.	Indonesia	49	928	3203
17.	Iran	82	2178	8806
18.	Israel	15	1466	1527
19.	Italy	150	4493	9377
20.	Japan	67	1840	3118
21.	Lithuania	22	626	2588
22.	Malaysia	180	4101	18680
23.	Morocco	12	558	401
24.	Netherlands	78	2667	6655
25.	New Zealand	31	3021	4434
26.	Nigeria	64	840	7431
27.	Norway	47	1706	4037
28.	Pakistan	67	1859	9355
29.	Poland	65	1153	4612
30.	Portugal	65	2534	4646
31.	Qatar	15	831	3309
32.	Saudi Arabia	92	2016	13861
33.	Singapore	36	1336	4138
34.	Slovenia	23	802	1393
35.	South Africa	70	1111	8856
36.	South Korea	197	4000	11481
37.	Spain	193	4890	9975
38.	Sweden	93	2897	10532
39.	Switzerland	25	719	2147
40.	Taiwan	87	2567	7658
41.	Turkey	84	3489	6276
42.	United Arab Emirates	51	1245	8485
43.	United Kingdom	369	15528	45812
44.	United states	347	13458	32092
45.	Vietnam	28	562	2890

3.4 Analysis of top impactful document

VOSviewer was utilized to identify the top papers in the systematic literature review (SLR) research domain using bibliometric data from Scopus and Web of Science (WoS). The top ten papers cited in this article were considered. Cross-verification of citations was conducted across search engines and databases utilized for generating data for this study, with documentation of source details including journals and publishers. Notably, "Engineering," affiliated with the Chinese Academy of Engineering and Higher Education Press, emerged as the publisher of the most highly cited paper on Google Scholar, with 2708 citations. "IEEE Communications Surveys and Tutorials" topped the citations in both Scopus and WoS, with a CiteScore of 82.5 and an Impact Factor of 35.6, while the "International Journal of Production Economics" secured the third position across all three platforms, boasting a CiteScore of 19.3 and an Impact Factor of 12. The details of the top ten papers are listed in Table 4. The high citations accumulated by these articles signify the relevance and interest in promoting ICT for project execution.

Table 4: Top cited documents and their source. (updated 03/28/2024)

SN	Author	Paper Title	Citations			Journal	Journal Impact factor
			Google Scholar	Scopus	WoS		
1.	Khalighi and Uysal, 2014	Survey on free space optical communication: A communication theory perspective	2207	1760	1402	IEEE Communications Surveys and Tutorials	35.6
2.	Zhong et al, 2017	Intelligent Manufacturing in the Context of Industry 4.0: A Review	2708	1739	1241	Engineering	12.8
3.	Dalenogare et al, 2018	The expected contribution of Industry 4.0 technologies for industrial performance	2114	1195	863	International Journal of Production Economics	12
4.	Becerik-Gerber et al, 2012	Application areas and data requirements for BIM-enabled facilities management	1238	671	489	Journal of Construction Engineering and Management	5.1
5.	Gu and London, 2010	Understanding and facilitating BIM adoption in the AEC industry	1275	627	468	Automation in Construction	10.3
6.	Wu et al, 2018	A Survey of Physical Layer Security Techniques for 5G Wireless Networks and Challenges Ahead	762	569	468	IEEE Journal on Selected Areas in Communications	16.4
7.	Buer et al, 2018	The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda	898	543	393	International Journal of Production Research	8.8
8.	Dutta et al, 2020	Blockchain technology in supply chain operations: Applications, challenges and research opportunities	961	612	435	Transportation Research Part E: Logistics and Transportation Review	10.6
9	Han and Golparvar-Fard, 2016	Potential of big visual data and building information modeling for construction performance analytics: An exploratory study	248	180	138	Automation in Construction	10.3
10	Zollmann et al, 2014	Augmented Reality for Construction Site Monitoring and Documentation	208	122	84	Automation in Construction	10.3

4. FINDINGS PRESENTATION AND DISCUSSION

4.1 Construction site emerging technologies

This section addresses Research Question 2 (RQ2): What are the emerging key ICT tools and systems that influence project execution on construction sites and how do they affect the management of building projects?. In recent years, the construction industry has adopted various emerging ICT tools and systems to transform the management of building projects. The emerging information and communication technology that impacts the construction phase refers to innovative digital tools and systems adopted in the construction industry to improve communication, data management, and various jobsite construction processes (Turk and Klinc, 2017). These technologies are continually evolving and designed to enhance coordination, efficiency, safety, and productivity in construction projects (Sattineni and Khosrowshahi, 2011, Sorce and Issa, 2021, Seyman-Guray and Kismet, 2023). The construction industry is undergoing a transformative shift through the adoption of emerging ICT technologies during project execution. These innovations align the construction sector with other industries revolutionized by IT advancements on a global scale. By enhancing the efficiency, safety, and coordination of construction processes, these technologies empower professionals to manage projects more effectively and respond directly to the evolving demands of the industry. This study identified three key clusters of ICT tools and systems: Data and Information Management technology, Communication and Visualization; and Automation and Analytics. Figure 6 shows a graphical representation of these clusters and the ICT tools that resonate with them. In addition, it is appropriate to list other ICT tools and systems used during project execution that do not receive significant concentration in this study, as shown on the right-hand side of Figure 6.

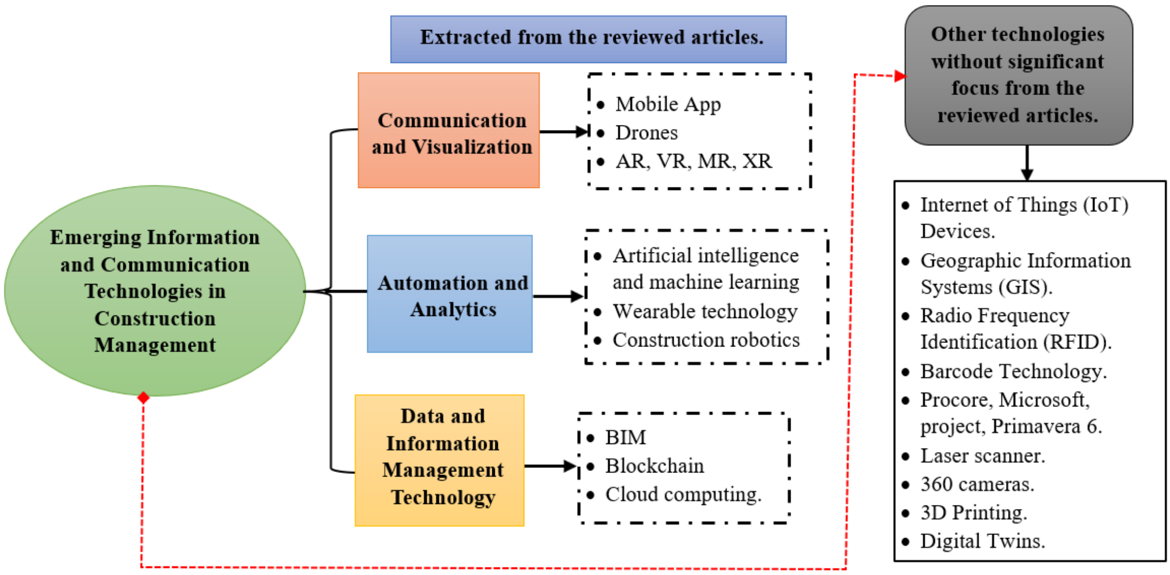

Figure 6: Clusters of the ICT tools.

4.2 Group 1: Data and information management technologies

Data and information management technology in the construction industry refers to an organized and smart way of handling data and information throughout the various phases of construction projects. This study focused on the key technologies that impact construction jobsite project execution. Based on the fragmented nature of the industry, effective data and information management are critical for the success of construction projects, as they ensure that accurate, up-to-date, and relevant information is available to all stakeholders. Figure 7 shows a graphical representation of these technologies (BIM, blockchain, and cloud computing).

Figure 7: Data and information management.

4.2.1 BIM

Substantial empirical research has been conducted with a focus on the BIM technology. Despite the traditionally slow diffusion of information and communication technologies (ICTs) in construction, BIM has revolutionized practices such as transitioning from 2D drafting to 3D design, clash detection, and automated quantity takeoffs through nD. Lindgren and Widén, (2018) investigated the extent and pattern of BIM diffusion in the U.S.A construction industry and understood the internal and external influences on BIM adoption. The authors used diffusion theory to study the adoption process and factors of BIM functions in the U.S. construction industry. They found that 3D visualization, clash detection, and constructability analysis were the most widely adopted BIM functions. Code validation, material tracking, delivery, facility management, and energy analyses were implemented less frequently. With these acknowledged functions, the industry is still looking for an improved and updated system. Nevertheless, Lindgren and Widén (2018) found that the diffusion of BIM functions is primarily influenced by internal rather than external factors, with government regulation being a significant external force. In the United States, the general services administration (GSA) promotes BIM use but lacks the strong governmental push observed in European and Asian countries for widespread BIM adoption in the building market (Gu and London, 2010). Ekholm and Molnár, (2009) studied how modern ICT can be introduced to support the industrialization of the building sector, with a focus on BIM. Lin et al, (2016) propose a BIM-based defect management (BIMDM) system to improve quality inspection and defect management processes in construction projects. Svalestuen et al, (2017) investigated how BIM devices, such as BIM stations and tablets, can improve information flow and collaboration on construction sites. Hasan and Rasheed (2019) investigated the benefits and challenges associated with the 5D BIM implementation in the Iraq construction industry. Hasan and Rasheed (2019) investigated the benefits and challenges associated with the 5D BIM implementation in the Iraq construction industry. Sehrawy et al, (2019) explore how the application of the 6D BIM approach can improve the planning and control of onsite carbon emissions during the construction phase. Liu et al, (2019) investigated BIM adoption in less BIM-ready regions, particularly in Chongqing, China, and explored the impact of organization features on individual perceptions regarding BIM. The authors found that two main factors, employer type and organization size, played significant roles in shaping how individuals perceived BIM adoption. They opined that BIM adoption in less BIM-developed regions might still be limited to visualization, and that there is a gap between the potential of BIM and its current applications in such regions. The research indicated that AEC practitioners in Chongqing considered external factors, such as project contracts and budgets, which are more critical for BIM implementation, than internal factors, such as having knowledgeable professionals. The lack of effective BIM training and acceptance by senior management have been identified as major barriers. Governmental employees had more conservative perceptions of BIM than industry practitioners, suggesting a gap between the government and industry views. Smaller-sized organizations had more positive views on certain BIM benefits, but faced challenges related to BIM investment and costs. Jensen and Jóhannesson, (2013) conducted research on BIM adoption and ICT deployment in the Nordic nations of Europe, with a particular emphasis on Denmark and Iceland. The author noted that all Nordic nations had low levels of manual drafting, and Iceland used CAD the most widely, but used BIM and IFC-compliant BIM the least.

In general, studies on BIM use at construction sites have focused on simplifying the construction process and expanding the value of capital. Various authors (Amuda-Yusuf and Mohamed, 2015, Agostinelli et al, 2019, Hamzeh et al, 2019, Hong et al, 2019, Shigaki and Yashiro, 2021, Bolsunovskaya et al, 2021, Toyin and Mewomo, 2023a) have described BIM features, benefits, and challenges such as better understanding of the project, updated production information, improved project coordination, reduced risk of errors, cost/benefit ratio, poor usability of the BIM, lack of trust in the BIM, and need for training and support among others. Notwithstanding, suggestions on some initiatives to better utilize the BIM model have been made, such as better training, more details in BIM, change of attitude, better location of BIM stations, and better-protected devices.

4.2.2 Blockchain

Blockchain technology is primarily used for secure and transparent data storage and transaction management (Dutta et al, 2020). In construction, it can be applied to ensure the integrity of documents, contracts, and transactions, thereby reducing disputes and enhancing trust among project stakeholders (Turk and Klinc, 2017). Adel et al, (2022) developed a new information exchange and management system for construction firms using blockchain technology and chatbots. The system was designed to address common challenges associated with Information and Communication Technologies (ICT) in construction management, such as security, privacy, and traceability. The system follows eight steps for data exchange with a blockchain-based network and demonstrates acceptable performance in terms of transfer latencies and storage size. It enhances real-time tracking, reduces waiting times for information confirmation, enables accurate status reporting, and facilitates effective stakeholder communication (Khalighi and Uysal, 2014). However, the limitations include handling only raw textual and numeric data on chain, excluding visuals and large data. Project management limitations include potential data duplication and misinterpretation, which can be mitigated through regular audits and disclaimers that govern legal and contractual aspects. Hijazi et al, (2022) developed a comprehensive methodology for integrating BIM and blockchain for the delivery of construction supply chain (CSC) data, creating a BIMSSoT model. This methodology, which combines business and management research with elements of information technology and computer science, includes innovative tools such as the BIMSSoT Data Flow Diagram (DFD), data taxonomy, and Entity-Relationship Diagram (ERD). The BIMSSoT DFD illustrates data transactions between external CSC entities and the main contractor for reliable data delivery in a handover. The taxonomy classifies CSC data as on- and off-chain, whereas ERD identifies entities within the physical BIMSSoT and its interface with BIM. Practically, this research advances BIM into digital engineering, moving beyond 3D modeling to structured and reliable datasets. This transition from isolated electronic files to a connected digital ecosystem of databases ensures that CSC data for operation and facility management are machine readable, contributing to the creation of digital twins for smart cities. Turk and Klinc (2017) explored how blockchain, a distributed and secure database technology, can be integrated with BIM to address some of the challenges in managing building information in the construction industry. The author found that some legal barriers and risks associated with BIM, such as ownership, liability, intellectual property, and data privacy, hinder the smooth implementation of this technology on jobsites. The author investigated the use of blockchain to store BIM transactions in four life scenarios.

4.2.3 Cloud Computing

Cloud computing involves the storage and sharing of project-related data and documents on remote servers that are accessible on the Internet. This technology enables secure and efficient data management, providing anytime and anywhere access to the project information (Hijazi et al, 2022, Zhong et al, 2017). Decades ago Redmond et al, (2011) envisaged the future of ICT in the construction industry with a focus on implementing a cloud service hosting interoperable applications. The author found that cloud computing should be considered for several reasons, such as its ability to increase efficiency and productivity throughout the construction industry. The advent of BIM has provided a common database (cloud) in which building components are modeled in disparate software programs. The main benefit of cloud-based as-built BIM is its ability to increase access to higher-quality information, resulting in faster business decisions. Although Abanda et al, (2018) explored the use of mobile/cloud BIM as a means to facilitate the adoption of an integrated approach to project delivery, they found that time and cost savings were the prominent benefits driving the application of mobile/cloud BIM. This involves employing automated or semi-automated dynamic information-sharing processes, all of which aim to enhance the construction performance. Czart et al, (2017) conducted a study on the use of ICT for resource management at construction sites. They proposed solutions based on the Google application framework, particularly for online collaboration among management staff. These solutions leverage versatile features in data processing, communication, workflow, and resource management. This framework facilitates the creation of an integrated collaboration environment in cloud computing environment. Furthermore, the proposed solutions can be integrated with Internet of Things (IoT) platforms to enhance monitoring and control tasks. This will assist civil engineers to ensure the quality of construction projects. This potential involves implementing a Wireless Sensor Network (WSN) for efficient asset and resource management, considering business objectives, technological constraints, and safety requirements.

4.3 Group 2: Communication and Visualization

Communication and visualization tools in the construction industry are technology-driven solutions that enhance the flow of information and facilitate the visual representation of construction projects. These tools are crucial for improving collaboration, decision making, on-site task coordination, and overall project management. The tools identified in the literature (are illustrated in Figure 8).

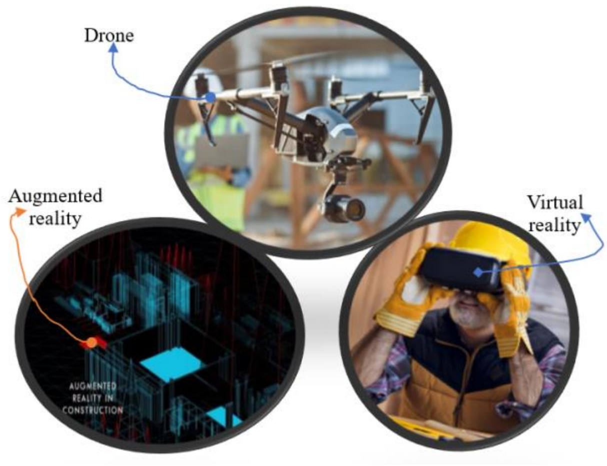

Figure 8: Communication and visualization technologies.

4.3.1 Mobile Apps

Mobile devices such as Apple and iPad have brought about transformative changes in the construction industry, and these devices have proven exceptionally valuable. Their daily use is marked by their capability to connect to the Internet, facilitating immediate access to and sharing of information among project stakeholders (Sattineni and Schmidt, 2015). Mobile applications are designed for use on smartphones and tablets, allowing onsite workers and project teams to access project data, update information, and communicate easily. They play a pivotal role in real-time communication and data-sharing. Consequently, the mobile device market is experiencing consistent growth, with smartphones and tablets recognized as convenient tools equipped with various computing services through numerous apps. Azhar et al, (2015) observed the abundance of mobile applications within the market designed for various construction-related activities, including quality control, safety measures, and annotating plans directly in the field. Despite the availability of numerous options, identifying the most suitable mobile app for a specific task remains challenging. However, Kim et al, (2017) developed a mobile application designed to streamline tasks related to the construction project management system, thereby enhancing the efficiency of construction management activities at construction sites. This mobile app serves as a valuable tool by providing access to inspection details, weather updates, contract information, various criteria, terminology, and photographic data. The intent was to offer a smart and accessible solution for construction professionals, allowing them to efficiently perform management tasks directly at construction sites by referencing essential information through a mobile application. These devices provide targeted communication, allowing concise and direct messaging between the users and their mobile devices. This communication method avoids unnecessary details in computer-based applications such as large file sizes and report headers. For construction workers, mobile computing offers a straightforward platform that is free from technical complexities, enabling the quick and simple communication of on-site information to stakeholders in different locations (Liu et al, 2019). In addition, smartphones provide portable camera functionality that is not always readily available on other desktop devices.

4.3.2 Drones

The emergence of advanced photo-capturing technologies, including affordable camera drones and depth-image cameras, has significantly eased and advanced the process of recording construction activities (Lee et al, 2023). In the virtual domain, drones operate autonomously without the need for human pilots and their lack of physical constraints allows multiple drones to gather data simultaneously during a single collection session (Rahimian et al, 2020). Drones equipped with cameras and sensors provide aerial surveys, project status reporting, project progress evaluation, productivity improvement, and real-time monitoring (Igwe et al, 2022). They support project communication by offering a bird's-eye view of the construction site and facilitating progress monitoring. The diverse applications of drones encompass the automation of elementary tasks, leading to a substantial reduction in labor costs. This is achieved by leveraging multiple sensors on a unified platform, thereby enhancing accuracy. In addition, drones facilitate real-time monitoring of project costs and progress (Ogunseiju et al, 2021). Drones with adjustable heights are particularly useful for monitoring ceiling elements and other buildings within a building. This adaptability enables drones to navigate efficiently and capture detailed information from various angles and distances. This capability ensures the thorough surveillance and assessment of ceiling structures. The height adjustability of drones enhances their versatility in inspecting various aspects of ceiling elements, making them a valuable tool for gathering data for construction and maintenance purposes (Zhao et al, 2023).

4.3.3 Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR) and Extended Reality (XR)

AR, VR, MR, and XR are immersive technologies that alter or enhance the perception of the real world through interactive experience. Together, these technologies offer new methods for project design, planning, collaboration, and execution, and also play a role in the digital revolution of the construction industry. They contribute to process simplification, mistake reduction, improved communication, and, ultimately, increased project efficiency in the construction industry. In construction, they are used for project visualization, design reviews, virtual walkthroughs, providing augmented information at construction sites, enhancing communication, and decision-making. Virtual information modelling (VIM) is a combination of virtual design, construction, and BIM concepts. Didehvar et al, (2018) investigated the benefits and challenges of VIM as a novel information and communication technology method for project management in the Iran construction industry. The author found that VIM had the most significant impact on project integration management, offering both substantial benefits and challenges. These benefits and challenges are related to project integration management. VIM can enhance coordination among various project elements and optimize efficiency across all project phases. Arowoiya et al, (2023) highlight that AR technology enhances the real world by providing access to digital information within the physical environment. The success of AR implementation in construction depends on its ability to improve the effectiveness and efficiency of the project execution. The authors identified 12 critical success factors for AR adoption in the Nigerian construction industry: innovativeness, awareness, advancements in computer design and hardware, social acceptance, and adherence to government policies. The authors found that the surveyed professionals had a high level of awareness of ICT, with approximately 50% having experience with mobile AR computing. Zollmann et al, (2014) introduced an approach for using AR for on-site construction site monitoring and documentation. The approach combines aerial vision with a mobile AR interface, thus allowing relevant information to be accessed directly on-site. Chalhoub and Ayer, (2019) explored how Augmented Reality (AR) can be used to enable point layout tasks for electrical construction and how different task attributes and model-related factors affect the accuracy and performance of AR devices. The authors used a marker-based approach to display the designs on a Microsoft HoloLens device, and measured the accuracy, time, and cognitive workload of the participants using AR for the layout tasks. The authors found that the accuracy of AR devices decreased as the distance from the marker increased and that the number and diversity of devices also affected the accuracy and time of the layout tasks. Gu and London, (2010) addressed the significance of BIM in VR research, emphasizing both technological development and practical applications. This study evaluates the industry's readiness in terms of products, processes, and people, and identifies technical and non-technical issues that influence BIM adoption.

4.4 Group 3: Automation and analytics

In the construction sector, automation and analytics are related to the application of technology-driven procedures and data analysis to enhance productivity, decision-making, and project management. These methods and instruments seek to decrease labor-intensive tasks, boost output, and offer insightful information to improve construction project results. These tools are used in this cluster:

4.4.1 Artificial intelligence and machine learning

With its predictive power, machine learning technologies have revolutionized construction management by adopting a data-driven approach to scheduling, cost forecasting, and decision making. In the construction industry, these applications help improve the overall project success, decrease risks, and boost efficiency (Sepasgozar et al, 2023). Karimi et al, (2023) adopted machine learning principles through deep learning networks to identify damages in the historical buildings within a short time and with the most accuracyduring remodification construction phase. Valero et al, (2019) used supervised machine learning algorithms to identify erosion, delamination, mechanical damage, and non-defective damage in a historical castle in Scotland. In their research Eom et al, (2022) found the optimal methodologies to maximize the accuracy of predicted dependent variables and critical determinants of ICT innovation performance using machine learning techniques.

Embracing construction automation and artificial intelligence (AI) has the potential to eliminate redundancy in information sharing. This is achieved by facilitating seamless collaboration among project participants, ensuring transparency, and providing ready access to essential information (Onososen and Musonda, 2022). The adoption of AI and ML during the project execution phase offers several advantages, including enhanced project quality, improved collaboration, streamlined data sharing and communication operations, increased productivity, simplification of construction tasks, and automatic self-learning processes. Onososen and Musonda (2022) emphasized that these technologies contribute to process improvement by executing tasks more efficiently, rapidly, and sustainably, with automated systems capable of self-learning, requiring minimal human intervention. Akinosho et al, (2020) highlight the relevance of AI and ML in addressing project delays and declining productivity in the built sector, further emphasizing their role in improving construction tasks and overall project quality.

4.4.2 Wearable technologies

Wearable devices include smart helmets, smart glasses, sensors, and exoskeletons that provide real-time data, enhance safety, and collect information for analysis. Wearable technology contributes to improving productivity within the jobsite (Okpala et al, 2021), and the use of helmet camcorders in the process of remote supervision of employees can be used to support technicians during their fieldwork (AL-Sahar et al, 2021). Ibrahim et al, (2023) discovered that construction organizations can derive significant benefits from the utilization of wearable safety devices in key areas such as preventing slips and trips, sensing environmental concerns, avoiding collisions, preventing falls from heights, and mitigating the risk of electrocution. Various sensors can be worn by construction workers to monitor the environmental conditions, vital signs, and safety compliance. These sensors provide data for safety and health-management purposes. Ryu et al, (2019) studied the feasibility of employing a wristband-type activity tracker with an embedded accelerometer for the automatic collection of field data to classify construction worker's activities. This research indicates that utilizing acceleration signals from a single accelerometer on the wrist may be sufficient to recognize various construction actions, particularly those involving both upper limb dominant and whole-body movements. Figure 9 presents the top wearables that impacted the construction jobsite activities. Patel et al, (2022) emphasized the paramount need to prioritize the well-being, safety, and efficiency of workers. This has become especially crucial amid post-pandemic challenges, including a scarcity of skilled labor, disruptions in the supply chain, global inflation, and rising medical costs. The authors advocate the effective utilization of smart wearable technologies to enhance the optimal utilization of labor resources.

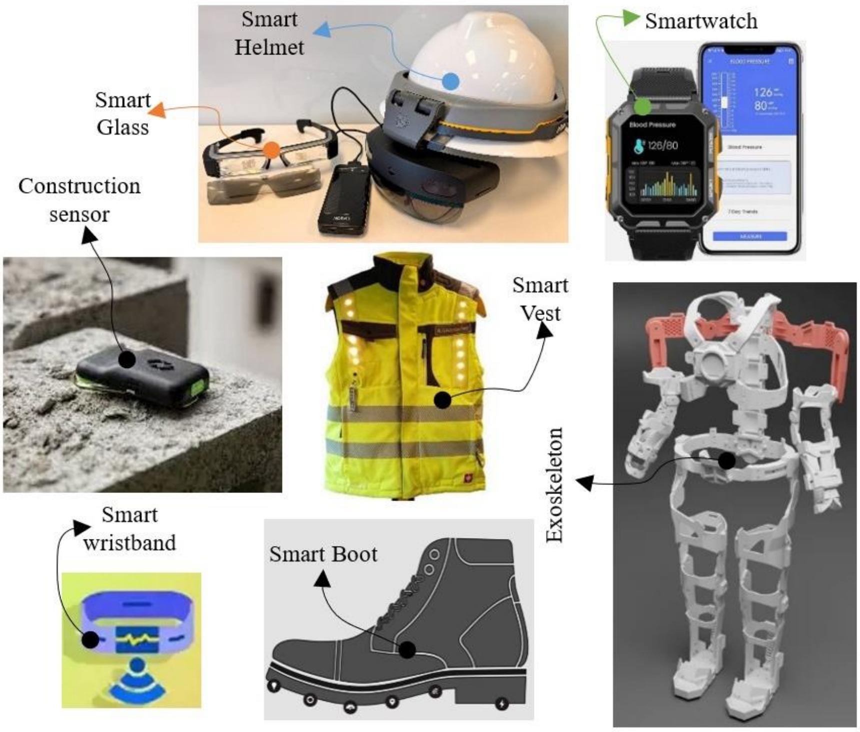

Figure 9: Top wearable technologies.

4.4.3 Construction robotics

Robotics in construction includes automated machinery and equipment used in tasks such as excavation, concrete pouring, and 3D printing. They automate physical construction processes and increase productivity (Hannan Qureshi et al, 2023). Figure 10 shows some robotics used in the construction process. Jung et al, (2013) conducted a study focusing on the development and implementation of a robotic system designed for assembling steel beams in high-rise buildings. Their research revealed that the robotic system was capable of inserting and tightening bolts using vision-based control and two types of bolting tools: primary and complete. To assess its practicality, the researchers tested this robotic system in a controlled testbed environment and on an actual construction site in Korea. Their findings indicated that the system consistently demonstrated an efficient, accurate, and safe performance. Based on their results, the researchers concluded that the robotic system has the potential to replace human workers in tasks involving the assembly of steel beams, particularly in situations where such tasks are risky and challenging. In doing so, it has the potential to enhance the overall quality and productivity of construction processes. Sun et al, (2023) investigated the capacity of robots on construction sites using the autonomous control system. The robots were assigned tasks such as safety monitoring, laying bricks, and capturing the condition of the construction site using a 360 camera and laser scanner. Jang et al, (2023) introduce a multi-camera approach for human activity recognition in construction's human–robot collaboration. The proposed method utilizes a particle filter to estimate 3D human poses from multiple cameras and employs Long Short-Term Memory (LSTM) to classify activities based on 3D joint locations. This study assessed the performance of human activity recognition models using one to four cameras. The findings demonstrate that employing multiple cameras significantly improves recognition performance, offering a more accurate and reliable method for identifying and distinguishing between various construction activities.

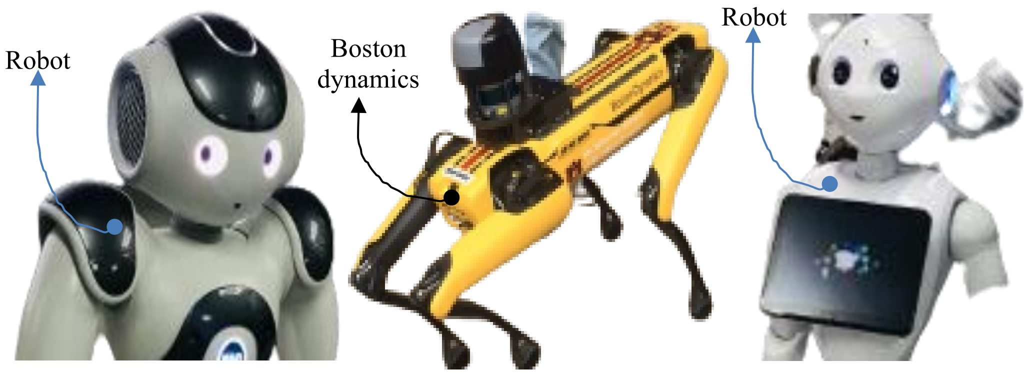

Figure 10: Robotics in construction.

4.5 Construction Technologies uses

Construction technology encompasses a wide range of tools, equipment, and software applications designed to enhance various aspects of construction projects. Table 5 shows the major uses of the identified emerging technologies revolutionizing the construction site.

Table 5: Key Uses of the technologies on construction site.

SN	Tools/Systems	On-site use of ICT tools	References
1.	BIM	Clash detection and resolution, Visualization for stakeholders, Construction management and collaboration and coordination	(Amuda-Yusuf and Mohamed, 2015, Agostinelli et al, 2019, Hamzeh et al, 2019, Hong et al, 2019, Shigaki and Yashiro, 2021, Bolsunovskaya et al, 2021, Alshorafa and Ergen, 2021)
2.	Blockchain	Tracking and managing construction equipment and machinery, supply chain management, secure project documentation, improves quality assurance.	(Turk and Klinc, 2017, Adel et al, 2022, Hijazi et al, 2022)

3.	Cloud Computing	Streamline construction data storage and accessibility, data security and backup, financial management and cost estimation, remote monitoring, and control	(Redmond et al, 2011, Abanda et al, 2018)
4.	AI &ML	Risk management, supply chain management, predictive construction tools and machinery maintenance, quality control, real time monitoring and reporting, energy efficiency, cost saving.	(Onososen and Musonda, 2022, Sepasgozar et al, 2023, Karimi et al, 2023)
5.	Construction Robotics	Surveying, remote controlling of equipment and machinery, task performance, handling of materials	(Jung et al, 2013, Jang et al, 2023, Sun et al, 2023, Hannan Qureshi et al, 2023)
6.	Wearable Technology	Safety monitoring, worker health tracking, hazard or accident prevention, tools and equipment monitoring and productivity tracking.	(Ryu et al, 2019, Okpala et al, 2021, AL-Sahar et al, 2021, Ibrahim et al, 2023)
7.	Drones	Progress and environmental monitoring, site surveying and mapping, safety Surveillance, transportation of lightweight materials, documentation and reporting and emergency response.	(Pour Rahimian et al, 2020, Ogunseiju et al, 2021, Igwe et al, 2022, Zhao et al, 2023, Lee et al, 2023)
8.	Mobile app	Project management, communication, quality control, materials, and equipment management, reporting and timekeeping	(Azhar et al, 2015, Czart et al 2017, Kim et al, 2017, Liu et al, 2019, Sattineni and Schmidt, 2015)
9.	AR, VR, MR, and XR	Site planning, remote collaboration, real-time data integration, interactive virtual design collaboration, safety guidance, training, and simulation	(Gu and London, 2010, Zollmann et al, 2014, Didehvar et al, 2018, Chalhoub and Ayer, 2019, V. A. Arowoiya et al, 2023)

4.6 Influence of ICT adoption on project scheduling and time management

This section addresses research question 3: RQ3: How has the adoption of ICT tools influenced project scheduling and time management in the construction stage? Here, we discuss how ICT tools influence project scheduling and time management during construction.

The adoption of ICT tools has a profound impact on project scheduling and time management during the construction stage. Kang et al, (2016) developed a project schedule management system that combines nD computer-aided design (CAD) object data, such as schedule and resource information, with a telepresence concept video management operation system. A system that integrates real-time videos from webcams and smartphones with nD computer-aided design (CAD) objects that contain information such as schedule, cost, and resources. This system allows users to monitor and compare their actual construction status with the planned design and simulation. This method synchronizes the coordinates of the video and the nD object based on the location information of the webcam, smartphone, and the digital map. The method also adjusts the angle, zoom, and error correction of the video and nD object to provide a consistent viewpoint. These technologies have significantly improved efficiency, accuracy, and collaboration, ultimately leading to improved project outcome. BIM allows for 3D to nD modeling of the project, which provides a visual representation of the construction process. This aids in better planning and scheduling by identifying potential clashes, optimizing construction sequences, and reducing rework (Gledson and Greenwood, 2016). Specialized project management software like "primavera," "microsoft project," "bexel manager" and "procore" streamline scheduling and time management. They enable real-time updates, task assignments, and progress tracking, ensuring that the project timelines are adhered to (Czart et al, 2017). ICT tools such as "microsoft project" and P6 provide the ability to create detailed Gantt charts and schedules that are easily adjustable as project conditions change (D. Li et al, 2022). This tool can accommodate unexpected delays and modifications. ICT tools facilitate communication and collaboration among project stakeholders, allowing instant updates, feedback, and issue resolution (Attencia and Mattos, 2022). This helps to avoid communication bottlenecks that can lead to scheduling problems. Construction project management apps enable on-site workers to access schedules and updates in real time, reducing the lag in information flow and improving decision-making (Ogunseiju et al, 2021). The IoT and sensors on construction equipment and materials provide real-time data, enabling remote monitoring and control. This helps to identify issues early and take corrective actions swiftly (Dosumu and Uwayo, 2023). ICT tools assist in resource allocation, ensuring that the right personnel, equipment, and materials are available when needed, thereby reducing project delays (Almarri et al, 2021). However, the vision for the future of construction supply chain management involves connecting manufacturers to multiple factories and suppliers, enabling instant collaboration, data sharing, and timely delivery.

Material management is a key phase of construction projects. An incorrect approach to this stage may result in capital loss, wastage of time, and a destructive environment that cannot be regained. Therefore, this phase should be carefully considered. Hijazi et al, (2022) looked at how BIM and blockchain can be integrated to facilitate the delivery of construction supply chain data by creating a BIM single source of truth (BIMSSoT) model. This model enables the adequate monitoring of the supply and usage of building materials at construction sites. Asgari and Rahimian, (2017) explored the need for automated project monitoring and control systems that can improve time management for the optimization of day-to-day activities within ordinary construction projects. The authors introduced a conceptual framework for creating a real-time intelligent observational platform supported by advanced intelligent agents. This platform is designed to manage various intelligent agents actively, autonomously, and seamlessly, such as cameras, radio-frequency identification (RFID) scanners, remote sensors, and other types of sensors capable of sensing their environment (Czart et al, 2017). The primary purpose is to identify, report, and document "high-risk" defects in construction projects.

4.7 Impact of ICT on construction cost and budget control

This section aims to answer research question 4 (RQ4): "How does ICT integration affect cost control and budget management in the construction phase? Additionally, what challenges and barriers are associated with ICT adoption in relation to addressing costs?".

4.7.1 ICT integration in construction: procurement and cost management

In the construction sector, procurement refers to the process of obtaining materials, supplies, and services required for a building project. This process encompasses all stages from initial planning to delivery and payment, and plays a critical role in shaping a project's budget, quality, and schedule. Various methods and strategies are employed for procurement in construction, and the choice of the method significantly affects project management. The conventional procurement method has disadvantages over e-procurement, primarily because it relies on manual processes and paperwork. Unlike e-procurement, which leverages ICT to streamline procurement activities, the conventional approach often suffers from inefficiencies, delays, and errors inherent in manual handling (Imoni et al, 2023). E-procurement systems offer several advantages over traditional methods such as improved transparency, reduced cycle times, enhanced accuracy, and lower administrative costs. By digitizing procurement processes, construction firms can access a wider pool of suppliers, compare prices and specifications more easily, and negotiate contracts more effectively, thereby additively managing the costs incurred (Addy et al, 2023). Moreover, e-procurement platforms enable the real-time tracking of procurement activities, providing stakeholders with greater visibility and control over project costs and timelines. Ibem and Laryea, (2015) studied the use of e-procurement in the South African construction industry. They identified four categories of e-procurement tools used in the industry: e-mail, static websites, Web 2.0, technologies, and portals capable of supporting intra- and inter-firm communication, and the exchange of project information and data. Although the adoption of e-procurement technologies was relatively low, these tools were primarily used for sharing information, exchanging bills of quantities, CAD drawings, and project requirements. The simplicity of use, reduced transaction costs, and faster transaction speeds are the key drivers of their usage. In their study, Hamma-adama and Ahmad, (2021) highlighted the potential benefits of e-procurement within the Nigerian construction industry, including increased transparency, reduced corruption, budget control, strengthened procurement processes, and the opportunity to explore innovations such as blockchain and BIM technology. Integrating e-procurement with BIM in construction offers a synergistic approach to enhancing project efficiency, collaboration, and cost management. Building Informatics is a field that leverages ICT, digital systems, BIM, and advanced software to address technical and management challenges in construction and building sectors. Amusan et al, (2019) investigated how artificial neural networks (ANNs) as a modern approach can be used for data forecasting and modeling, which offers advantages over traditional regression methods. The authors configured a neural network system to process the residential building cost data. The system was trained using the cost data to create an algorithm for cost prediction. The algorithm was designed to predict the cost range for office projects, considering economic factors, such as inflation and the building price index. Research by Vlist et al, (2014) on the Netherlands construction industry aimed to understand how ICT impacts the economic competitiveness of construction firms. Specifically, they investigate whether firms that invest in ICT gain a production-cost advantage. Initially, the economic literature suggested that ICT could bring cost advantages owing to its flexibility and improvements in planning, organization, and control of work. To test this hypothesis in the construction industry, researchers have formulated a production cost function that incorporates ICT into construction management. The results of the study revealed that construction firms that invested in ICT capital did indeed have a production cost advantage and the ability to control and manage costs effectively. ICT lowers a firm's cost structure and boosts operational performance. Additionally, firms must reach a minimum level of ICT capital to fully realize these cost advantages. Using a drone for job site assessment not only saves time and reduces costs, but also keeps technicians safe on the ground instead of dealing with the challenges of erecting scaffolding and navigating the hazards of a construction site. Like drone integration, the construction industry incorporates robotic and autonomous equipment.

4.7.2 Enhancing efficiency, budget and cost control using ICT during construction

The pursuit of efficiency, budget and cost control has long been paramount in the dynamic domain of construction (Benjaoran, 2009, Musarat et al, 2021). Today, as the industry navigates a landscape shaped by technological innovation and global imperatives, ICT's integration of ICT emerged as a cornerstone for achieving these objectives. The convergence of digital tools and construction methodologies has ushered in a new era of possibility, in which ICT serves as a vehicle for optimizing processes, maximizing resource utilization, and driving sustainable outcomes (Zhu et al, 2022, Dalenogare et al, 2018). This introduction serves as a gateway to investigating the transformative potential of using ICT for cost control in construction. Isikdag et al, (2009) conducted research on the perception of the Turkish AEC industry on the strategic role of ICT in their construction industry. The authors found that the professional indicated a change in thinking about the value that ICT can offer to obtain strategic competitive advantage, as opposed to just supporting and enabling business operations. They also found that organizations make ICT investments to save present and future costs and the possibility of working within or below the budget or improvements upon present procedures. However, gaining a competitive edge is not connected to emphasis on investments. Moreover, ICT-related research and development is now conducted at a relatively low cost compared with the results. It is interesting to note that there is much enthusiasm for future involvement in ICT-related building research. Ruddock and Ruddock, (2011), assessed ICT development in the UK construction sector with an eye on growth and productivity. While the initial cost of incorporating ICT increased project costs, there was a considerable gain in productivity and industry growth over time. This was demonstrated by comparing projects that adopted ICT with those that did not, indicating that projects that adopted ICT have a significant advantage in budget management and cost control. Decade ago, the 'Oman Vision 2020' a long-term development strategy plan was launched by the government of the Sultanate of Oman, which focuses on ICT in the construction industry and the fundamental establishment of a knowledge economy. This move aligns the Oman construction industry with other developed countries' construction industries, with the aim of increasing productivity and reducing operational costs. Tibaut and Zazula, (2018) focused on innovative approaches to construction that encompass a wide range of disciplines, including computer science and informatics. The underlying goal is to improve construction project quality while optimizing costs with an eye on their long-term impact on both local and global economies. In essence, the authors sought to integrate various fields of knowledge to enhance the efficiency and sustainability of construction practices using bid visual data with a focus on effective cost control.

Hartmann et al, (2012) investigated the Benefit of two BIM-based tools: for automated cost estimating and a 4D model to aid risk management in Netherland. The extensions of BIM incorporate cost estimation (5D) and lifecycle management (6D). This extension enriches the data aspects of BIM, helping project managers better understand and control costs and plans for the long-term maintenance and operation of buildings, leading to improved cost savings. Narlawar et al, (2019) conducted a study on the utilization of BIM for planning, scheduling, and cost estimation in construction projects, focusing on a case study of a residential apartment building in India. The findings revealed that BIM application significantly expedited the planning process and led to more accurate budget estimates. Hong et al, (2019) explored the main factors influencing BIM adoption in small- and medium-sized construction organizations (SMOs) in Australia. The authors developed a BIM adoption model to assess the BIM implementation benefits, costs, and challenges faced by SMOs. The model captured the correlation between BIM adoption in SMOs and associated impact factors, including knowledge support and BIM adoption motivation. The authors found that the potential benefits of BIM, such as improved data accuracy and cost savings, played a significant role in motivating SMOs to consider adopting BIM.

4.8 Influence of ICT on communication and collaboration on construction site

The influence of Information and Communication Technologies (ICTs) on construction sites has been transformative, revolutionizing various aspects of the construction industry. This section addresses Research Question 5 (RQ5): How do ICT tools enhance communication and collaboration among project stakeholders during the project execution phase? And what are the challenges faced. The following are some key areas where ICT has a significant influence on construction sites during project execution, as extracted from the reviewed articles.

- **Scheduling, time management, and progress tracking**: ICT tools such as Primavera, Microsoft Project, Bexel Manager, and Procore facilitate efficient scheduling, time management, and progress tracking. These tools enable project managers to create and manage schedules, allocate resources effectively, and track project milestones in real-time, leading to improved project delivery timelines and enhanced overall efficiency.
- **Clash detection and constructability analysis**: 4D BIM technology enables clash detection and constructability analysis. By creating digital models of a project, stakeholders can identify and resolve clashes or conflicts between different building elements before construction, thereby minimizing errors and rework during the actual construction process.
- **Document integrity, storage, and sharing**: Technologies such as blockchain, chatbots, cloud computing, and BIM ensure the protection of document integrity while facilitating the secure storage and sharing of project-related data and documents. These tools provide a centralized platform for storing and accessing project information, enhancing collaboration among stakeholders, and streamlining document-management processes.
- **Real-time communication and data sharing**: Mobile Apps enable real-time communication and data sharing among project stakeholders, regardless of their physical location. By leveraging mobile devices, stakeholders can communicate updates, share documents, and collaborate seamlessly, thereby enhancing coordination and decision-making during project execution.
- **Job-site assessment and progress monitoring**: Drone, AR, and VR technologies facilitate job site assessment, progress evaluation, and real-time monitoring. These technologies provide aerial views of construction sites, enabling stakeholders to assess progress, identify potential issues, and make informed decisions to optimize project outcomes.
- **Collaborative virtual visualization and design reviews**: AR, VR, Mixed Reality (MR), and Extended Reality (XR) technologies enable collaborative virtual visualization and design reviews. By creating immersive virtual environments, stakeholders can visualize project design, conduct design reviews, identify design flaws or improvements, and enhance collaboration and decision-making processes.
- **Risk reduction**: Artificial Intelligence and machine learning (AI/ML) technologies help with risk reduction by providing predictive reports for tools and machinery used during the project execution phase. By analyzing historical data and patterns, AI/ML algorithms can predict potential equipment failures or maintenance needs, enabling proactive maintenance strategies and minimizing downtimes at construction sites.
- **Safety monitoring and information collection**: Wearable Technologies facilitate safety monitoring and the collection of information for safety analysis. These technologies, such as smart helmets or vests, can track worker movements, detect hazardous conditions, collect data for safety analysis, enhance jobsite safety, and reduce the risk of accidents.
- **Excavation, concrete pouring, and 3d printing**: Construction Robotics technologies automate tasks such as excavation, concrete pouring, and 3D printing, thereby improving the efficiency and accuracy of these processes. By deploying robotic systems, construction companies can streamline repetitive tasks, reduce labor costs, and enhance productivity at construction sites.
- **Material remote monitoring**: Internet of Things (IoT) and sensor technologies enable remote monitoring of materials by tracking parameters such as temperature, humidity, and location. By deploying IoT sensors on construction materials and equipment, stakeholders can monitor their conditions in real-time, optimize inventory management, and prevent theft or loss.
- **Budget control and administrative costs reduction**: Technologies such as Email, BIM, static websites, Web 2.0, AI, and ML contribute to budget control and administrative cost reduction. Construction companies can streamline operations, reduce overhead costs, and improve financial management during

project execution by automating administrative tasks, digitizing processes, and leveraging AI/ML algorithms for cost estimation and budgeting.

4.8.1 Harnessing ICT for communication and collaboration in construction

In the early stages of ICT adoption in the Taiwanese construction industry, Chien and Barthorpe, (2010) noted that ICT was mainly used for financial management, design, estimation, and project management. In addition, the author found that e-mail and intranet were major communication tools. Nishigaki et al, (2011), investigated how the use of ICT-based work management systems in the construction industry might improve teamwork and interactive communication at the Mt. Unzen-Fugen volcanic eruption site. This is to help post-disaster restoration using unmanned construction collaboration. According to the authors, this method makes it easier for supervisors, resident engineers, and others to collaborate effectively and manage routine construction jobs and fundamental data. Zekavat et al, (2015) developed a unified ICT-supported process control framework for holonic construction management (HCM). The author included multitype holons such as “(1) equipment, (2) human laborer/operator, (3) material, (4) three-dimensional (3D) space, and (5) information/supply logistics organized in resource clusters”. The HCM was successfully tested, demonstrating its effectiveness in facilitating a seamless interface among five distinct types of holons. Within this model, three communication links were established and integrated, following the HCM paradigm. Notably, one of these links introduced a novel communication and information channel between the rebar foreman and supplier. This channel enables the Foreman to request a preferred bundling scheme with each bundle tagged with RFID-based information. This establishes a continuous flow of data from the fabrication shop to the delivery truck and the staging area. The inherent flexibility of the holonic structure allows real-time collaboration and sharing of this information with other holons, including the crane operator, main office, and steel crew. Hasan et al, (2019) investigate the impact of using mobile ICTs in construction project management focusing on construction management professionals in Australia's construction industry. The author found that improved communication and collaboration among stakeholders were among the five key impacts of using mobile ICTs for construction project management. Qammaz and AlMaian, (2018) investigated the role of ICT in enhancing the successful implementation of risk management practices in the construction industry. The author highlights several advantages of incorporating ICT into risk management, including increased productivity, enhanced communication, integrated project information, more efficient decision-making processes, and better control of project performance. Underwood and Khosrowshahi (2012) analysis revealed the main role of ICT in the UK’s construction sector, highlighting its contribution to increased productivity and long-term competitiveness. Despite substantial investments, ICT expenditures in the construction industry remain low. In response to global economic conditions, UK organizations have prioritized assessing their business overhead, with ICT accounting for a significant proportion. Underwood and Khosrowshahi (2012) examined current ICT spending, coping strategies, and future trends in the construction industry in the UK. Their findings revealed that industry stakeholders recognize ICT as essential for process efficiency and flexible communication infrastructure, enabling collaboration with clients, consultants, and supply chain partners. Sustained investment and implementation of ICT are imperative for maintaining competitiveness on a global scale in the UK construction sector

Hasan et al, (2021) explores the impact of mobile information and communication technology (mICT) on construction management professionals in the Australian construction industry, particularly in the context of informal work during non-work hours. The author identified enhanced communication and collaboration as the key positive impacts of adopting mICT. Liu and Li, (2013) investigated the use of virtual construction (VC) as a tool for stakeholder and construction site communication throughout the building phase in the Chinese built environment. The idea was to produce a 4D model that automatically provided a clear notion and overview of the construction in various phases. The author developed a linking procedure based on the relevant Levels of Detail (LODs) of the 3D model and schedule. Nevertheless, VC will ultimately become a crucial component of construction management that must be employed during the construction phase, as technology develops (Liu and Li, 2013). Presently, the effect of COVID-19 has driven the construction sector to acclimatize themselves to a virtual environment that enhances real-time collaboration and communication. Han and Golparvar-Fard, (2016) explored the potential of using big visual data in conjunction with BIM for construction-performance analytics. The author introduced a model-driven visual analytics approach that utilizes images and BIM to address challenges related to communication inefficiencies and project control in construction. Ikediashi and Ogwueleka, (2016) examined the extent of ICT infrastructure usage in Nigeria’s construction sector, and evaluated its impact on the effectiveness of building projects. Based on the report, project managers, site managers, and quantity surveyors were the most frequent users of ICT in the Nigerian construction industry, whereas Foremen were the least frequent users. The three most frequently used systems are word processing/accounting, electronic communication, and project management systems. The ICT infrastructure has been identified as having the greatest impact on project performance in terms of effective stakeholder collaboration, quality of work improvement, real-time communication, and cost control.

4.8.2 Addressing challenges

Oke et al, (2018) investigated the challenges of digital collaboration and strategies to enhance the use of digital technologies in the Gauteng province of South African construction industry. The major challenges of digital collaboration in the South African construction industry include lack of training, cost barriers, adoption standards, and interoperability. To address these challenges and improve the use of digital tools, the authors recommend several strategies including government support, education and training, access to financing, and workplace encouragement. In a study conducted by Alaghbandrad et al, (2012) they examined the obstacles and challenges related to the utilization of ICT in Iranian construction sites. These barriers were categorized into seven groups: issues such as inadequate ICT infrastructure, lack of locally trained personnel familiar with ICT systems in remote construction sites, economic challenges in providing ICT training for staff in smaller construction sites, difficulties in effective communication through electronic tools such as video conferencing, limitations in the usability of software outputs, complex administrative processes for ICT development, and inadequate backup systems in remote construction sites. To address these challenges, the construction firm identified several key factors for overcoming these barriers. These include investing in ICT infrastructure, providing structured training for personnel, encouraging and mandating the use of electronic communication tools, establishing network connections for designers, justifying the streamlining of administrative processes, and implementing a comprehensive document management system. Adel et al, (2022) developed blockchain technology and chatbots to address common challenges such as security, privacy, and traceability associated with ICT in construction management. Czart et al, (2017) developed systems based on Google applications and Internet of Things (IoT) platforms capable of coordinating online collaboration and resource management in construction sites.

5. SYNOPSIS OF THE REWIEW FINDINGS

This study provides an in-depth exploration of the profound influence of ICTs applications on project management at construction sites. The focus was on how ICTs tools significantly shaped project coordination and scheduling, time management, construction cost monitoring, and budget control. The key aspects discussed include the integration of various ICTs tools on construction jobsite, 3D to nD modeling through Building Information Modeling, and the utilization of specialized project management software such as Primavera and data security.

5.1 Overview of the findings

This study documents key challenges related to nD model integration by highlighting the importance of overcoming inefficiencies in geometry control to prevent schedule delays and maintain design integrity. Most studies on BIM have focused on simplifying construction processes, improving value for capital, and addressing challenges encountered onsite with the application of ICTs. Studies on Blockchain have focused on improving data security and transparency. Cloud-computing studies have focused on the storage and sharing of project-related data on remote servers. Mobile app studies have focused on how project management can be improved through real-time communication and data-sharing. Drones were captured on how activities could be automated by reducing labor costs through aerial surveys, project monitoring, and progress evaluation. Reality capture families focus on improving their perception of the real world through project visualization, design reviews, and virtual walkthroughs. AI and ML have focused on improving construction management through their predictive power. Wearable technology adoption has centered on preventing accidents, monitoring workers and environmental conditions, and improving worker productivity. The idea of adopting construction robotics is to define ways to improve the quality of work, save time, and execute difficult or repetitive tasks that may be hazardous to humans by automating physical construction processes.

A critical evaluation of ICTs tool applications at construction sites is presented, outlining their impact on project effectiveness. Challenges to ICT adoption, such as cost constraints, a lack of awareness, and training gaps, have been explored. This study also investigates the growth and productivity potential associated with the adoption of these technologies, emphasizing the need for a strategic approach to ICT investments. The challenges of digital collaboration are analyzed with a focus on strategies to enhance the use of digital technologies. The paper concludes with an exploration of the impact of mobile ICTs on construction project management, highlighting improved communication, collaboration, and work relationships among construction management professionals. Figure 11 presents a flowchart of the key findings of the study.

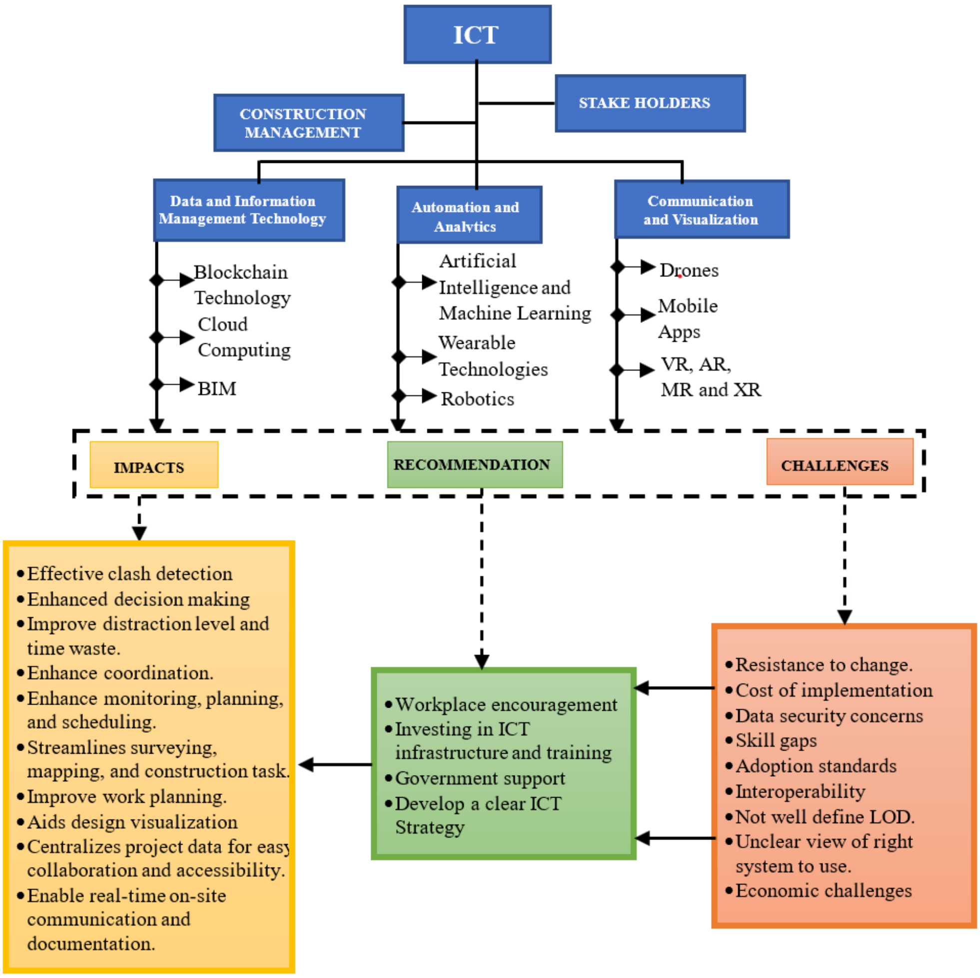

Figure 11: Findings flow chart.

5.2 Conceptual framework

The construction industry in its present form in developed countries such as the United States, the United Kingdom, and Australia, where ICTs adoption has gained significant maturity, cannot attempt any project without using two or more ICT tools identified in this study. Moreover, evidence shows that they are willing to explore its adoption throughout the building lifecycle. Based on the trending ICT technologies elicited from the literature, a conceptual framework that facilitates stakeholder collaboration and information sharing was developed, as shown in Figure 11. This will provide guidance for those willing to advance the adoption of these tools and a guide template for securing and protecting data sharing during the construction phase.

As shown in Figure 12, BIM serves as the central hub connecting all the technologies and ensuring data consistency. Blockchain secures transactions and data integrity across the framework. Cloud computing facilitates seamless data exchange and collaboration. AI and ML enhance decision-making based on data-driven insights. AR, VR, MR, and XR enhanced visualization and collaboration. Drones provide real-time data monitoring and mapping. Robotics automates and enhances the precision of construction tasks. Wearable technologies ensure on-site safety and communication.

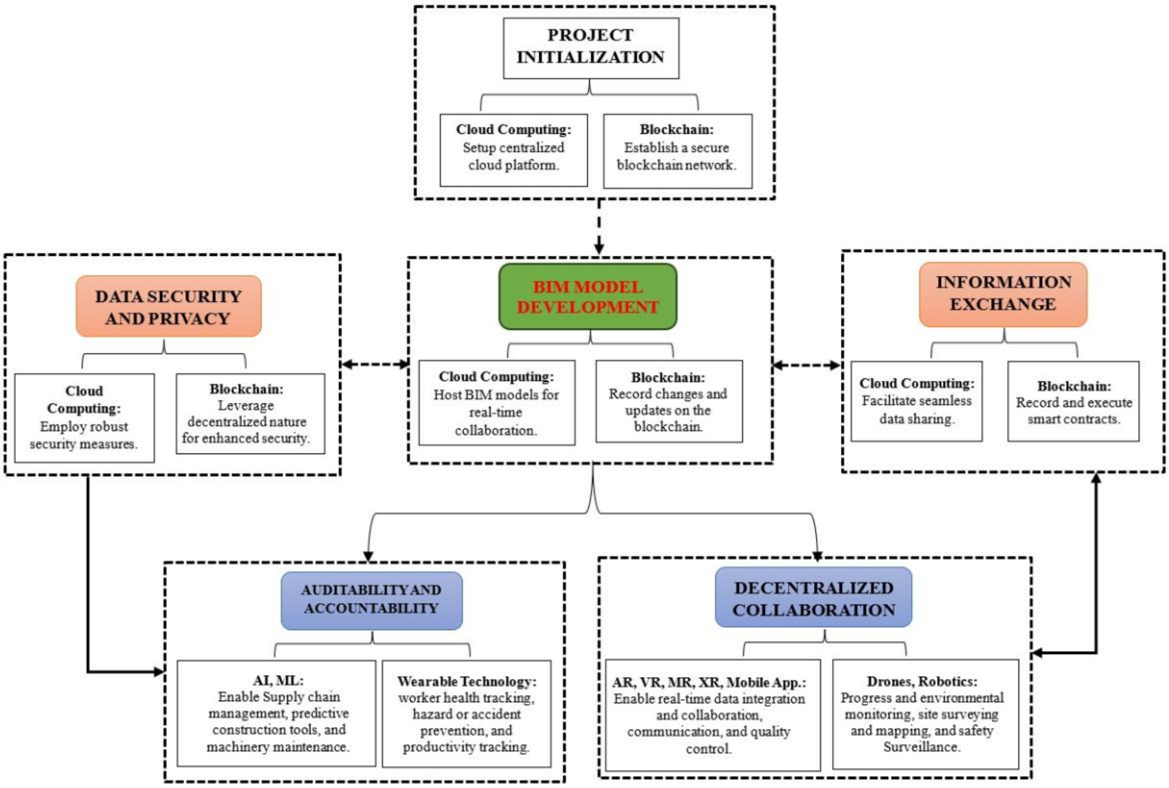

Figure 12: Smart-Site Data Integration Framework.

6. CONCLUSION AND RECOMMENDATIONS FOR FUTURE STUDY.

This study investigates the profound influence of Information and Communication Technologies (ICTs) on construction jobsites for project execution through an analysis of articles published between 2009 and 2023. By employing a systematic literature review and bibliometric network mapping, publication trends, co-occurring keywords, and global contributions were explored. Nine key technology families were identified and categorized into three clusters. A comprehensive systematic review and analysis has explored their diverse applications, impacts, challenges, and potential solutions. The results document ICT's key role in modern construction, as evidenced by its widespread adoption globally, with contributions from 113 countries. A bibliometric analysis revealed the intricate nature of these technologies as a global phenomenon, with substantial citations in published articles. Building information Modeling (BIM) has emerged as a transformative technology that acts as a central hub for shared information and integration with other technologies. The current technology trends shaping construction jobsites include reality technologies, Drones, Mobile Apps, Wearables, Cloud computing, blockchains, robotics, AI, and ML. These technologies significantly affect various facets of on-site construction activities, including coordination, safety, virtualization, data storage, material tracking, and overall work quality.

This study enriches the existing body of knowledge by documenting key information and communication technologies, clarifying their significant impacts resulting from widespread adoption, addressing the recent challenges faced during ICT adoption, and providing recommendations to overcome these challenges. A smart-site data integration framework is presented as a guide for the seamless application of these technologies, emphasizing robust data security. This framework aimed to empower the construction industry to make informed decisions while undertaking projects. The research findings offer valuable insights, aiding researchers and practitioners in better understanding the current research trends related to ICT applications on construction jobsites.

Based on the findings of this study, potential gaps exist. The recommendations for future research are as follows:

- In-depth studies on user experience and maturity level of each emerging technology on construction jobsites through surveys, interviews, or a mix of both globally require urgent attention among technology users. To understand their perspectives, challenges, and recommendations for improving the usability of these technologies. Obtaining feedback from users will strengthen and improve technology acceptance and its subsequent use.

- Addressing cybersecurity concerns by exploring ways in which construction companies can enhance measures to protect sensitive data.
- Investigate the environmental impacts of advanced construction technologies and assess their contributions to sustainability goals and environmentally friendly practices.
- Conduct a comprehensive cost-benefit analysis of ICT implementation in construction projects and explore the financial implications and potential cost savings.
- Explore the interaction between construction professionals and technology on jobsites, focusing on training programs, user interfaces, and support systems.

These research directions contribute to advancing our understanding of the role of technology in the construction industry. Nevertheless, the study's comprehensive approach, utilizing a systematic literature review and bibliometric analysis, provides a solid foundation for understanding the influence of ICTs during construction project execution. Despite the potential limitation of database selection, publication year limitation “2009 to November 2023,” the rigorous methodology employed enhanced the reliability and validity of the findings. Additionally, this study's identification of key technology trends and recommendations for future research directions offer valuable insights for both academia and industry. Therefore, while acknowledging the limitations regarding database coverage and year, the study's contributions remain significant in advancing knowledge and informing practices in the construction management field.

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