Research on the Digital Technological Factors Influencing the Development of the Global Construction Industry under the Context of Digitalization—Based on Bibliometric Analysis and the Fuzzy Delphi Method

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Abstract. This research explores the digital technological factors influencing the development of the global construction industry in the context of rapid digitalization. Experts identified and evaluated key digital technologies using bibliometric analysis and the fuzzy Delphi method. The analysis identified eight critical digital technology factors impacting the construction industry: Artificial Intelligence (AI), Building Information Modeling (BIM), Digital Twins, Big Data and Cloud Computing, IoT and Smart Building Technology (SBT), Virtual Reality/Augmented Reality (VR/AR), Construction Robotics, and Blockchain Technology. After two rounds of expert evaluations, AI and Construction Robotics were ranked as the most influential factors shaping the industry's future. The research's findings guide policy-making, industry development strategies, and vocational education, emphasizing the need for interdisciplinary skills and innovation in construction technologies.

Keywords: Digitalization, Construction Industry, Fuzzy Delphi Method, Bibliometric analysis, Vocational education, Artificial Intelligence (AI), Construction Robotics, Building Information Modeling (BIM), Digital Twins, Digital transformation

1 Introduction

Currently, with the continuous development of global science and technology, the construction industry is undergoing a path of transformation and reform. The traditional construction industry model, due to issues such as low efficiency, slow technological progress, resource waste, and environmental impact, the traditional construction industry model can no longer meet modern society's growing demands. 1 Therefore, there is a need for optimization of development models and technological innovation to bring new vitality and direction to the construction industry.

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In contrast to the challenges faced by the construction industry, the rapid development of digital technologies has been evident since the German government introduced the concept of Industry 4.0 in 2011[2]. As a new structural model, Industry 4.0 relies on extensive shared data and communication networks to achieve the digitalization, automation, and intelligent transformation of various traditional industries. The wave of digital technology development has also greatly influenced the construction industry, to address the challenges faced by the traditional construction industry, many scholars and industry professionals have turned their attention to Industry 4.0. Oesterreich and Teuteberg were among the first to propose the adoption of digital technologies to create a new construction environment, exploring the impact of various digital technologies on the construction industry and introducing the concept of Construction 4.0[3]. Subsequent studies have further examined the application of core Industry 4.0 technologies such as artificial intelligence, BIM, IoT, cloud computing, etc. in areas like construction design, engineering management, material innovation, and project execution[4]. In this context, it is crucial for researchers in the construction industry to employ data-driven, rational research methods to analyze the development trends and directions of digital transformation in the industry, providing vital support for policymaking, business decision-making, and the development of vocational education for talent in the construction sector.

In this context, professionals and researchers in the construction industry need to adopt scientific and rational research methods to analyze the key digital technological determinants influencing the industry's development amidst the ongoing digital transformation. This will help to uncover the critical development pathways for the global construction industry under digitalization. The findings will provide essential support for policymaking, business decision-making, and vocational education for talent cultivation in the construction sector.

2 Research Question$Objective

The primary research question of this study is: How can an objective and rational analysis method be found to identify the key digital technological factors influencing the development of the global construction industry, in order to address the challenges in determining the industry's future direction? This is broken down into two sub-questions:

RQ1: How can relevant digital technological factors influencing the global construction industry be identified through an objective and rational analysis method?

RQ2: How can the key digital technological factors among the many relevant ones be identified as the most influential for the development of the global construction industry?

The main research objective is to identify the key technological factors influencing the development of the global construction industry based on objective and rational data. The sub-objectives are:

RO1: To identify the relevant digital technological factors affecting the global construction industry through bibliometric analysis.

RO2: To use the Fuzzy Delphi Method to evaluate and rank these factors, thereby identifying the key digital technological factors driving the development of the global construction industry.

3 Previous Research & Knowledge Gap

Previous studies in this field have primarily focused on review-type research exploring the development directions of the construction industry under digitalization, as well as application-based studies on how various digital technologies improve design, construction, project management, and materials[23]. However, there is a lack of research that uses quantitative methods to analyze the future development directions of the industry. Moreover, current studies suffer from poor cross-disciplinary correlation, with different scholars and institutions conducting research on the application of digital technologies in construction without much interconnection or collaboration. This highlights the need for more precise and rational studies to guide future collective research. Additionally, this study focuses on the technological factors influencing global construction development within the digital context, but lacks exploration of non-technological factors, which should be addressed by future research to provide a more comprehensive view.

4 Research Significance

The findings of this study will have significant implications for industry development, vocational education in the construction sector, and academic research in related fields. First, the study will identify the relevant technological factors influencing the global construction industry under digitalization. Clarifying these factors will help practitioners and companies better understand the challenges and solutions for practical work in the future. By using expert evaluations to identify the key technological factors among them, the study will provide governments and industry enterprises with a more comprehensive understanding of the importance of various digital technologies, supporting the formulation of reasonable and forward-looking development strategies.

Second, the research will guide vocational education and talent development in the construction industry. By revealing the key technological factors shaping the global construction sector in the digital context, the study will offer valuable insights for aligning future training programs with industry needs.

Finally, the study will contribute to theoretical knowledge and methodological innovation in related academic research. By adopting a mixed-methods approach to analyze the digital technological factors influencing the construction industry, the study addresses gaps in existing research and provides a methodological framework for future studies using quantitative or mixed research methods. This has significant methodological value, offering a template for future studies in this field.

5 Research Methodology

This research adopts an exploratory sequential mixed-methods approach, which consists of two research phases[5]. In the first phase, qualitative research will be conducted to collect relevant data. This will be followed by a quantitative analysis of the first phase's findings in the second phase. After defining the research questions and objectives, bibliometric analysis will be employed in the first phase. By analyzing core literature datasets related to the research topic from the WOS database, the study aims to identify the technological factors influencing the global construction industry in the context of digitalization. This phase involves a visual analysis of the dataset's characteristics, including key authors, institutions, and keywords, which is part of the qualitative research.

In the second phase, the identified digital technological factors will be structured into a survey questionnaire, which will be distributed to experts in the construction industry. The Fuzzy Delphi Method will then be used to analyze the results and determine the key digital technological factors influencing the global construction industry's development under digitalization.

Bibliometric Analysis. Bibliometric analysis is a method used to analyze data by treating literature as the primary object of study. It involves the statistical evaluation of multiple works under a specific research topic to understand the characteristics and trends of related studies[6]. Bibliometric analysis includes two specific approaches: analyzing the external features (such as document type, authors, institutions, and publication year) and the internal features (including titles, keywords, and abstracts) of the literature[14]. The final step is to visually represent the important researchers, institutions, and research themes through clustering or co-occurrence analysis. In this study, Cite-Space software will be used to analyze the WOS database's literature dataset to identify the various technological factors influencing the global construction industry in the digital age.

This research uses Web of Science (WOS) as the database and employs advanced search techniques, focusing on the Web of Science Core Collection. No restrictions were set on the time range, and the document types were limited to articles and conference papers. The search was conducted with the topic "Construction industry" and included literature related to "digitalization" "smart buildings" or "artificial intelligence", as well as works connected to "industry" or "development". This combined search strategy enabled the identification of research literature that covers technologies such as digitalization, smart buildings, and AI within the construction industry and their relevance to industry development. A total of 410 relevant research papers were identified based on these search criteria. After excluding literature published before 2000 and manually filtering out papers with low relevance to the construction industry, 387 papers were selected as the sample for this study. These papers were then input into the Cite-Space software for bibliometric analysis and visualization.

Fuzzy Delphi Method. In the second phase of this study, an expert survey will be conducted. The relevant technological factors influencing the development of the global construction industry, collected in the first phase, will be summarized and compiled into a questionnaire. The expert opinions will be gathered and analyzed through quantitative methods to reach a consensus and identify the key technological factors shaping the global construction industry in the digital context. For this, the Fuzzy Delphi Method (FDM), which combines traditional Delphi with fuzzy theory, will be employed.

Compared to the traditional Delphi method, FDM reduces the number of survey rounds required and minimizes uncertainty in expert evaluations[7]. In this study, the Triangular Fuzzy Number (TFN) method and defuzzification techniques will be used to model the uncertainty and vagueness in the experts' evaluations. This approach uses three parameters (lower limit, middle value, upper limit), allowing a broader range of expert input, which provides a more comprehensive reflection of their opinions[8]. FDM is widely applied in fields like technology forecasting, policy analysis, and decision-making, making it suitable for the multidisciplinary nature of this study's goal to identify key technological factors affecting the global construction industry under digitalization.

The FDM in this study will involve professionals from the fields of construction industry research and vocational education. The number of participants will follow the guidelines of previous Delphi studies [9,10], with 15 experts selected for this study. The FDM process will be conducted in three stages:

Face Validity Testing (3 participants) to refine the questionnaire;

Pilot Testing (5 participants) to assess the distribution and collection methods;

Formal Survey (15 participants), where experts will anonymously evaluate the impact of various technological factors on the construction industry. Each factor evaluation criteria are 5 levels. The collected ratings will then undergo analysis.

Once the data from the formal survey is obtained, it will be processed using TFN and defuzzification techniques to derive the key technological factors. This process involves three calculation stages:

After collecting the evaluation results of the experts participating in the survey on the impact of various digital technology factors on the development of the construction industry, it is necessary to convert the evaluation of each expert on each relevant factor into triangular fuzzy number (TFN). Triangular fuzzy number is to set the fractional value of expert evaluation as the peak value, and then calculate the triangular fuzzy number of each evaluation through the following formula[11]. The triangular fuzzy number conversion formula (Eqs.1) is as follows:

$$\tilde{F}^{(i)} = \left(f_1^{(i)} \cdot f_2^{(i)} \cdot f_3^{(i)}\right) i = 1,2,3,\ldots,n. \quad (1)$$

After converting all the evaluation results into triangular fuzzy numbers, the following formula is used to calculate the average value of fuzzy numbers in the evaluation of each relevant factor by different experts[11]. The average value of fuzzy number is calculated (Eqs.2) as follows:

$$\widetilde{f_{ave}} = \left(l_j \cdot m_j \cdot u_j\right) = \frac{1}{n}\sum_{i=1}^{n}(f_1^{(i)} \cdot f_2^{(i)} \cdot f_3^{(i)}). \quad (2)$$

Finally, the defuzzification formula is applied to convert the average fuzzy number for each factor into a final score[11]. These scores are then used to rank the factors, and the key technological factors influencing the global construction industry under digitalization are identified. The defuzzification formula (Eqs.3) is as follows:

$$X_j = \frac{l_j + m_j + u_j}{3}. \quad (3)$$

6 Results and Analysis

6.1 Identification of Technological Factors Influencing Global Construction Industry Development in the Digital Context – Using Bibliometric Analysis

Various factors influence the development of the construction industry, including technological, environmental, economic, and organizational factors[12][13]. This study focuses on the digital technological factors in the context of digitalization, excluding traditional construction engineering, economic, organizational, or policy-related factors.

To identify the digital technological factors influencing the construction industry, this study applies bibliometric analysis using Cite-Space to analyze core literature from the Web of Science (WOS) database. The analysis includes external features (authors, institutions) and internal features (keyword clustering)[14].

Due to the large number of literatures in the sample literature data set and the long-time span, the K-value of g-index is selected as 15 in the setting of Cite-Space software, which is slightly lower than the K-value data set by default in the software. G-index index is used to determine the most influential literatures or authors in the analysis. A low K value helps to focus on core literature data with high citations.[15]

In the external feature analysis of the WOS core literature data set of related research, scholars and institutions that have made great contributions to the research in related fields will be mainly identified, and the relevant digital technical factors affecting the development of the global construction industry under the background of digitalization will be obtained by summarizing their research results.

In the co-occurrence analysis of authors, 227 author nodes, 216 node connections, and 0.0084 network density were generated in this study. In the co-occurrence graph of authors, authors marked with red asterisks were the core of the research team, and the font size of authors' names was proportional to the number of publications (Fig. 1). It can be intuitively found that within the scope of the research subject set in this paper, a number of small research teams have been formed, and these research teams are relatively independent in their research direction, and there are few studies on multi-specialty integration, and the correlation between the research teams is poor.

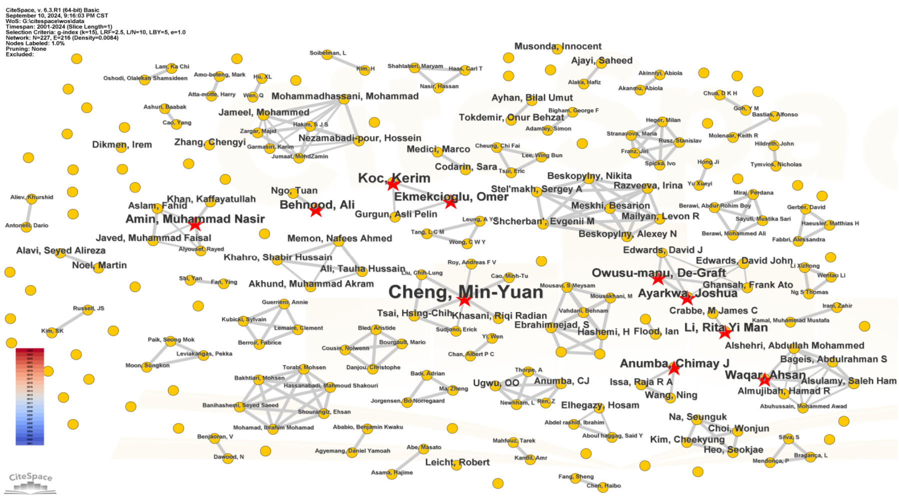

Fig. 1. The authors of relevant literature co-occurrence analysis Sources: The author (2024)

Among the existing researchers, the team with Cheng Min-Yuan as the core is the one that earlier applied digital technology to research related to the construction industry. In addition, there are other research teams composed of Koc, Kerim and Omer, and Amin Muhammad Nasir as the core. A research team composed of Waqar, Ahsan et al. Through reading the research results of these research teams, sorting out and summarizing their research directions and the digital technologies adopted in the research (Table 1), the selection of different digital technologies in the development of the construction industry by core scholars in relevant research fields is obtained, and this is taken as the relevant technical factors affecting the development of the construction industry in the digital background.

Table 1. Summary of the research direction of the core author team in the sample literature

Researchers and teams	Impact ranking	Main research direction	Digital technology factor
Cheng Min-Yuan, et al	1	Construction cost management; Evaluation of building materials.	Artificial intelligence.
K Kerim&Omer, et al	2	Construction project management (Safety Accident Management); Construction industry standard.	Artificial intelligence; Building Information Model(BIM).
Amin Muhammad Nasir,et al	3	Evaluation of building materials.	Artificial intelligence.
A Joshua& De-Graft,et al	4	Construction industry standard.	Smart building technology (SBT).
Waqar Ahsan,et al	5	Construction project management; Sustainable building.	Artificial intelligence; Building Information Model(BIM).

In the co-occurrence analysis of publishing institutions, a total of 164 nodes were generated in this study, 132 nodes were connected, and the network density was 0.0099. In the co-occurrence map of publishing institutions, the research institutions with the larger text font were the research institutions with the larger number of publishing institutions (Fig. 2), as shown in the figure, the institutions conducting relevant research mainly formed six obvious sets. Summary and analysis of the research direction of the issuing institution will also help to find the specific research direction of important research institutions in relevant research fields, and classify the digital technologies adopted by them (Table 2), and summarize the relevant technical factors affecting the development of the construction industry under the background of digitalization.

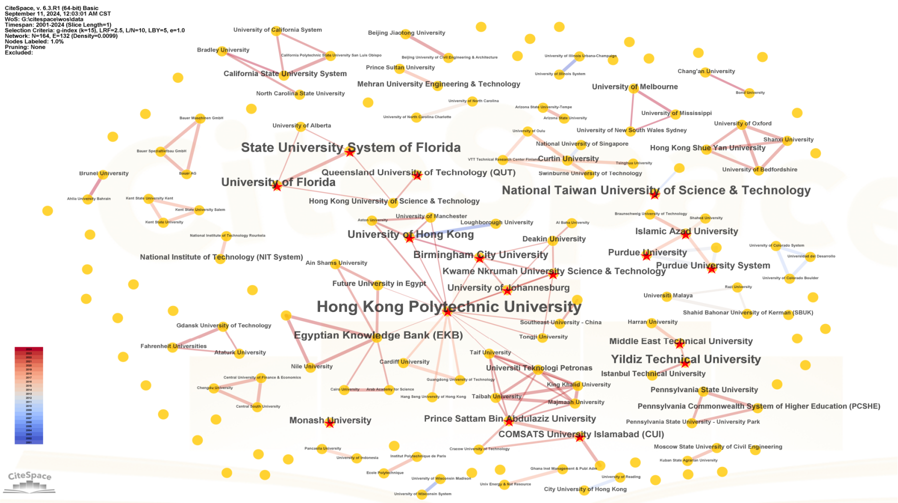

Fig. 2. The publishing institutions of relevant literature co-occurrence analysis Sources: The author (2024)

In addition to summarizing the external features of the core literature data set through co-occurrence analysis, this study will also analyze the internal features (keywords) of the core literature data set through cluster analysis, summarize the high-frequency keywords in related research through keyword clustering, identify the keywords related to digital technology and divide them into technical types. The more popular digital technology types in the field of construction industry development are taken as the relevant technical factors affecting the development of construction industry.

Table 2. Summary of the research direction of the core author team in the sample literature

The publishing institutions	Impact ranking	Main research direction	Digital technology factor
Hong Kong Polytechnic University,et al	1	Construction project management; Construction cost management; Building energy consumption evaluation;	Artificial intelligence; Building Information Model(BIM);

		Evaluation of building materials	Digital twin; Internet of Things.
State University System of Florida&University of Florida,et al	2	Building operations	Artificial intelligence; Intelligent construction & construction robots.
Yildiz Technical University&Middle East Technical University,et al	3	Construction project management (Safety Accident Management); Construction Project Management (Engineering Risk Assessment).	Artificial intelligence.
Islamic Azad University& Purdue University,et al	4	Evaluation of building materials.	Artificial intelligence.
National Taiwan University of Science & Technology,et al	5	Construction cost management; Evaluation of building materials.	Artificial intelligence.
Prince Sattam Bin Abdulaziz University,et al	6	Evaluation of building materials; Sustainable building.	Artificial intelligence.

In keyword cluster analysis, 264 nodes were generated in this study, 1003 nodes were connected, and the network density was 0.0289. The keyword cluster order shown in the analysis can explain the fields and technical factors that researchers focus on in current relevant research results (Fig. 3). In addition, Through the statistics of high-frequency keywords involved in the relevant literature data set, and the selection of keywords related to digital technology to make a list (Table 3), to supplement the relevant technical factors affecting the development of the construction industry under the background of digitalization in this study.

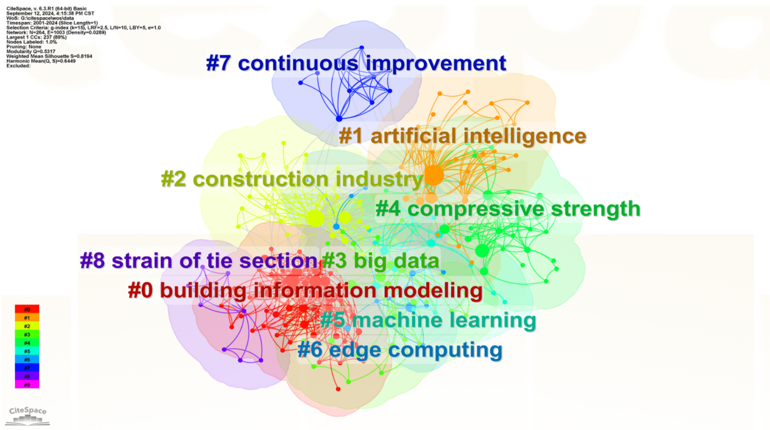

Fig. 3. Keywords cluster analysis of sample literature. Sources: The author (2024)

Based on the analysis of the external features (authors, institutions) and internal features (keywords) of the literature dataset collected in this study, along with the classification of different digital technologies in related research[16], it can be concluded that major researchers and their teams conducting studies in the construction industry are primarily influenced by digital technologies such as Artificial Intelligence (AI), Building Information Modeling (BIM), and Smart Building Technology (SBT). Similarly, the key institutions publishing research in this field are influenced by AI, BIM, Digital Twins, Big Data ， IoT & Smart Construction, and Construction Robotics.

Additionally, the analysis of keywords in the sample dataset, supplemented by research on the types of digital technologies impacting the construction industry[16], indicates that other influential technologies include Virtual Reality/Augmented Reality (VR/AR) and Blockchain technology.

Based on these findings, the technological factors influencing the global construction industry in the context of digitalization include: (1). Artificial Intelligence (AI), (2). Building Information Modeling (BIM), (3). Digital Twins, (4). Big Data and cloud computing, (5). IoT and Smart Building Technology (SBT), (6). Virtual Reality/Augmented Reality (VR/AR), (7). Construction Robotics, (8). Blockchain technology.

These factors will serve as the foundation for the subsequent identification of key factors influencing the construction industry's development through the Fuzzy Delphi method. It is important to note that these conclusions are based on the analysis of the literature dataset collected for this study and may have some limitations in terms of comprehensiveness.

Table 3. The frequency table of keywords related to digital technology in the sample literature

Keyword	Keyword occurrence	% of the sample literatures	Digital technology factor
Artificial intelligence	116	29.97%	Artificial intelligence
Machine learning	42	10.85%	Artificial intelligence
Building information modeling/Model	41	10.59%	Building Information Model(BIM)
Neural networks/Neural network/Artificial neural network	32	8.26%	Artificial intelligence
BIM	26	6.71%	Building Information Model(BIM)
Digital twin	17	4.39%	Digital twin
Deep learning	16	4.13%	Artificial intelligence
Internet of Things	12	3.10%	Big data and Internet of Things technology
Big data	11	2.84%	Big data and Internet of Things technology
Classification	9	2.32%	Artificial intelligence
Augmented reality	8	2.06%	Augmented Reality (AR)/ Virtual Reality (VR)

Computer vision	7	1.80%	Artificial intelligence
Prediction	7	1.80%	Artificial intelligence
Genetic algorithm	6	1.55%	Artificial intelligence
Fuzzy logic	5	1.29%	Artificial intelligence

6.2 Identification of Key Technological Factors Influencing Global Construction Industry Development in the Digital Context – Using Fuzzy Delphi method

Description of Participants in the Survey. The purpose of this Fuzzy Delphi survey is to evaluate various digital technology-related factors influencing the development of the construction industry, ultimately identifying the key technological factors under digitalization. This will provide guidance for policymaking in the construction industry and for talent development in construction vocational education. Therefore, the participating experts must have relevant work experience in the construction industry or the field of digital technologies. The participants should include researchers, university professors in related fields, government officials, and industrial manager in construction projects. They are required to hold at least a master's degree and have a minimum of 10 years of work experience. Table 4 provides an overview of the experts participating in the Fuzzy Delphi survey. The evaluations gathered from these experienced industry professionals and researchers will be crucial in informing the study's conclusions.

Table 4. Overview of the experts participating in the Fuzzy Delphi survey

Expert background	No	%	education qualifications	No	%	Work experience	No	%
Researcher	4	26.6%	PhD	3	20%	Above 25years	1	6.6%
University professors in related fields	6	40%	Master's degree	12	80%	20-25years	1	6.6%
Government officials	3	20%				15-20years	5	33.3%
Industrial manager	2	13.3%				10-15years	8	53.3%

Explanation of Face Validity Test and Pilot Test. This study will select three experts to analyze and summarize the relevant technological factors influencing the development of the construction industry under digitalization and to provide feedback on the questionnaire design[17]. Based on the feedback collected from these three experts during the face validity test, the questionnaire will be revised to include more detailed classifications for the eight digital technology factors influencing the global construction industry.

In the pilot test, five experts will be chosen to review the Fuzzy Delphi survey process, to ensure the accuracy of the investigation process[17]. After discussions with the experts, it has been determined that the questionnaire will be distributed via an online platform, all surveys will be conducted anonymously. The distribution time will be coordinated, and participants will have one day to complete the survey. Before distributing the questionnaire, the researchers will communicate with the participants to ensure they have sufficient time to complete the survey.

Expert Questionnaire Setting. The questionnaire adopted in this survey is based on the above research results and the validity test of the experts. The final questionnaire will be composed of 8 major digital technology factors. The relevant technical factors selected in this study are comparable to the findings of the emerging building technology cognition study proposed by Jang et al., 2021[18].

When designing the questionnaire, the digital technology factors influencing the development of the construction industry, identified in this research, are treated as Independent Variable (IV). The degree to which each technological factor (IV) affects the development of the construction industry is considered the Dependent Variable (DV).

The final structure of the questionnaire is set to evaluate the influence of each independent variable (IV) on the dependent variable (DV). Experts are required to assess each technological factor (IV) along with its sub-factors. The evaluation criteria are 5 levels, including: very low impact, low impact, moderate impact, high impact, very high impact. After collecting expert evaluations, the evaluation grades are converted into fuzzy values. This research method refers to the research of Sadeghi, Jalal et al., and Norhanisha Yusof et al. [111920]. After collecting the necessary evaluation information from the experts, the fuzzy quantity table is made according to the triangular fuzzy number formula (Eqs1) mentioned above (Table 5). Finally, the final defuzzification evaluation value of each relevant factor is obtained through statistical analysis.

Table 5. Triangular fuzzy quantity table of expert evaluation value (5 scales).

The degree of influence of expert evaluation (IV)	**Fuzzy Scale** (l, m, u)
very low impact	(0, 0.1 ,0.3)
low impact	(0.1, 0.3 ,0.5)
moderate impact	(0.3, 0.5 ,0.7)
high impact	(0.5, 0.7 ,0.9)
very high impact	(0.7, 0.9 ,1)

Collection and Processing of Survey Results. The Fuzzy Delphi expert survey was conducted in two rounds. If the difference in expert opinions is within 0.2 after two rounds, it meets the minimum standard for consensus among experts, fulfilling the requirement for agreement in a Fuzzy Delphi survey[21]. During the collection process, the researchers did not interfere with the opinions of the participants to ensure that each respondent's view was accurately represented.

The expert evaluation results after the first round are shown in Table 6. For the four sub-factors of Artificial Intelligence (AI), experts rated each sub-factor individually, and the average values were calculated. For the remaining seven digital technology factors influencing the development of the construction industry, respondents directly rated each factor, and the average value for each question was calculated for every expert.

After the first round of the Fuzzy Delphi expert survey, most of the experts rated the impact of various digital technology factors on the development of the construction industry as high. Some evaluations indicated a very high impact or a moderate impact, while a few responses indicated a low impact. Since the threshold deviation between the evaluation values did not exceed 0.25, all the relevant factors were retained and included in the next round of the expert survey[11].

Table 6. Defuzzification number evaluation results after the first phase of FDM expert survey

Major factor	**Secondary factor**	**Triangular fuzzy Average with experts' opinions**			**The expert evaluation of secondary factors in the first phase of the survey was defuzzified**	**The expert evaluation of major factors in the first phase of the survey was defuzzified**
		u	**m**	**l**		
Artificial Intelligence (AI)	Machine Learning (ML) & Algorithms	0.973	0.847	0.647	0.822	0.723
	Knowledge-Based System (KBS)	0.887	0.713	0.513	0.704	
	Natural Language Processing (NLP)	0.833	0.633	0.433	0.633	
	Computer Vision (CV)	0.913	0.74	0.54	0.731	
Building Information Modeling (BIM)	/	0.867	0.687	0.487	/	0.68
Digital Twins	/	0.86	0.673	0.473	/	0.669
Big Data and cloud computing	/	0.833	0.647	0.447	/	0.642
Internet of Things (IoT) and Smart Building Technology	/	0.867	0.673	0.473	/	0.671

(SBT)						
Virtual Reality/Augmented Reality (VR/AR)	/	0.813	0.62	0.42	/	0.618
Construction Robotics	/	0.893	0.727	0.527	/	0.716
Blockchain technology	/	0.78	0.58	0.38	/	0.58

Before the second round of the expert survey, the researchers provided a brief explanation of the ranking results from the first round to the participating experts and collected feedback on the discrepancies in the first-round responses. After discussions, the primary factors related to Internet of Things (IoT) and Smart Building Technology (SBT) in the first-round questionnaire were split into two secondary factors. This adjustment was made because, although SBT has developed based on IoT technology, there are some differences between the two. As a result, minor adjustments were made to the second-round questionnaire. The evaluation results from the second round of the expert survey are shown in Table 7. Expert consensus was achieved when the difference between the second-round and first-round results was less than 0.2[21].

Table 7. Defuzzification number evaluation results after the second phase of FDM expert survey

Major factor	**Secondary factor**	**Triangular fuzzy Average with experts' opinions**			**The expert evaluation of secondary factors in the second phase of the survey was defuzzified**	**The expert evaluation of major factors in the second phase of the survey was defuzzified**
		u	**m**	**l**		
Artificial Intelligence (AI)	Machine Learning (ML) & Algorithms	0.98	0.86	0.66	0.833	0.731
	Knowledge-Based System (KBS)	0.9	0.727	0.527	0.718	
	Natural Language Processing (NLP)	0.827	0.633	0.433	0.631	
	Computer Vision (CV)	0.927	0.753	0.553	0.744	
Building Information Modeling (BIM)	/	0.893	0.713	0.513	/	0.706
Digital Twins	/	0.887	0.713	0.513	/	0.704

Big Data and cloud computing	/	0.853	0.66	0.46	/	0.658
Internet of Things (IoT) and Smart Building Technology (SBT)	Internet of Things (IoT)	0.847	0.647	0.447	0.647	0.683
	Smart Building Technology (SBT)	0.9	0.727	0.527	0.718	
Virtual Reality/Augmented Reality (VR/AR)	/	0.813	0.62	0.42	/	0.618
Construction Robotics	/	0.913	0.753	0.553	/	0.74
Blockchain technology	/	0.807	0.607	0.407	/	0.607

The Result of Expert Consensus. After two rounds of expert surveys, the mean differences in the experts' evaluations of all digital technology factors influencing the development of the construction industry were less than 0.2 (see Table 8), indicating that consensus was reached among all experts. The researchers then ranked all the digital technology factors influencing the construction industry and determined the final ranking as follows: (1). Artificial Intelligence, (2). Construction Robotics, (3). Building Information Modeling, (4). Digital Twins, (5). IoT and Smart Building Technology, (6). Big Data and Cloud Computing, (7). Virtual Reality/Augmented Reality, (8). Blockchain Technology. This ranking provides direct support for the final conclusions of the research.

Table 8. The difference between the first stage and the second phase expert evaluation of the defuzzification average

Major factor	**The first phase of expert evaluation defuzzification average**	**The second phase of expert evaluation defuzzification average**	**Mean difference**	**The rankings**
Artificial Intelligence (AI)	0.723	0.731	0.008	1
Building Information Modeling (BIM)	0.68	0.706	0.026	3
Digital Twins	0.669	0.704	0.035	4
Big Data and cloud computing	0.642	0.658	0.016	6
Internet of Things (IoT) and Smart	0.671	0.683	0.012	5

Building Technology (SBT)				
Virtual Reality/Augmented Reality (VR/AR)	0.618	0.618	0	7
Construction Robotics	0.716	0.74	0.024	2
Blockchain technology	0.58	0.607	0.027	8

7 Conclusion

This research explores the digital technology-related factors influencing the global development of the construction industry in the context of ongoing advancements in digitalization, as well as the key technological factors impacting the industry's development. The study begins with bibliometric analysis, using a dataset of core research literature from the Web of Science (WOS), to identify the relevant technological factors affecting the construction industry. These factors include: (1). Artificial Intelligence (AI), (2). Building Information Modeling (BIM), (3). Digital Twins, (4). Big Data and cloud computing, (5). IoT and Smart Building Technology (SBT), (6). Virtual Reality/Augmented Reality (VR/AR), (7). Construction Robotics, (8). Block-chain technology.

Based on this research, a Fuzzy Delphi Method expert survey was conducted. Through two rounds of evaluation and the defuzzification of expert assessments, the final ranking of these eight factors was established. The top two factors were selected as the key technological factors influencing the development of the construction industry: Artificial Intelligence (AI) and Construction Robotics (see Table 8).

With these key factors identified, the findings of this study will help the construction industry adapt vocational education and talent development strategies to meet future market demands. This will enhance students' interdisciplinary skills, particularly in AI and Construction Robotics, while continuing to emphasize the application of other digital technologies like BIM, Digital Twins, IoT, and SBT in the construction industry. Furthermore, it will promote collaboration between academia, industry, and research institutions, opening up new pathways for the integration of education and industry. This will ensure that future professionals are equipped to handle the digital transformation of construction, improving both efficiency and sustainability through technological innovation and application.

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