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Digital Technologies in Reducing Carbon Emissions in the Construction Industry: China, Heibei

Sun Jiachen[1], Khoo Terh Jing[1,*], Atasya Osmadi[1], Wang Jiao[1], Sun Hui[1], Zhang Xiaolu[2]

[1] School of Housing, Building and Planning, Universiti Sains Malaysia, 11800 Gelugor, Pulau Pinang, Malaysia
[2] CSCEC Science and Industry Building, Nanshan District, Shenzhen, Guangdong, China

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ABSTRACT

Global warming caused by carbon emissions has become the focal point of the international community, requiring global cooperation and proactive actions to deal with it. With the continuous development of digital technology, its presence in people's lives is getting higher. The development and application of these technologies are driving the arrival of the digital era. So far, there is still a gap in the application of digital technology in the field of carbon emission management in the construction industry and the application framework in different life cycles is still unclear. Therefore, this study intended to explore the application of digital technologies in the construction industry’s carbon emissions. Furthermore, this intended to study the role of digital technology in different life cycles of carbon emissions, aiming to provide reasonable suggestions for reducing carbon emissions in different life cycles of projects， such as planning, Operation & Maintenance, Tear Down. This systematic literature review uses PRISMA, identified 305 documents from ScienceDirect. A growing trend in publications on this topic was observed, indicating an increasing use of digital technologies in the study of carbon emissions. There is an important impact on reducing carbon emissions such as Artificial Intelligence, Internet of Things, Big Data, Blockchain, Digital Twin, Machine Learning, etc. Then we use mixed research methods to conduct analysis through Focus Group and AHP and obtain the results through weight ranking. The result of this study can be used as a guideline for digital technology in the process of managing carbon emissions. Driving the guideline, this research helps establish a digital technology carbon emissions in construction management system, which is crucial for promoting digital technology in carbon emissions.

1. Introduction

According to the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4), greenhouse gas emissions worldwide, resulting from human activities, have increased since the pre-industrial era [13]. Greenhouse gas emissions continue to rise. Desertification is severe, sea levels are rising, soil productivity is declining and the frequency of extreme weather events is increasing [31]. The Global Covenant estimates that if the above plans are fully implemented, more

* *Corresponding author.*
E-mail address: terhjing@usm.my

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than 9,000 urban construction projects are likely to commit to achieving a minimum carbon reduction target of 1.4 Gt CO2e per year in 2030 and 2.8 Gt CO2e per year in 2050 [31].

"Green environment" and "sustainable development" have been recognized across various industries for decades. However the construction industry, which is one of the largest sources of carbon emissions, has struggled to effectively control and manage these concepts [10]. According to the latest research, 30-40% of total global greenhouse gas emissions are caused by energy consumption in the construction industry [10]. Approximately 40% of the world's energy is consumed by the construction sector, contributing to 36% of global CO2 emissions. Carbon dioxide emissions are the primary driver of global climate change [14].

The application of digital technology can help reduce carbon emissions by lowering energy consumption and minimizing construction waste on a larger scale, ultimately reducing carbon emissions [18]. The development of computerization and digitalization has significantly influenced management methods across all areas of life [30]. The involvement of modern digital technology throughout the entire life cycle of various sectors has increased. Technologies such as: Artificial Intelligence (AI), Internet of Things (IOT), Big Data (BD), Blockchain, Digital Twin (DT), Machine Learning (ML), Information and Communication Technology (ICT), Building Information Modelling (BIM) are pivotal. Meanwhile, the advancement of information technology has enhanced industry productivity of the industry and both management and technology have made significant progress [28]. However, many studies suggest that the construction industry's reluctance to adopt new technologies stems from the complexity, immaturity, higher expertise requirements and management challenges of construction projects compared to the manufacturing, electronics and aerospace industries [28].

In addition, possible challenges and problems prior to digital transformation in the industry should be considered, such as: organizational and process changes, resistance to technological change and hesitation to adopt technology [28]. Currently, a comprehensive examination of the literature regarding the implementation of various digitally regulated technologies within the construction sector is lacking. Moreover, there remains an unaddressed gap in the utilization of digital technology for managing carbon emissions within this industry, with the application framework across different lifecycle stages remaining unclear. This study's importance lies in providing a thorough review of research pertaining to carbon emissions and digital technologies within the construction field. Furthermore, a pioneering framework is crafted to guide the regulating of carbon emissions in the construction sector. The first research objective of this study is to comprehensively review the relevant literature on the impact of digital technologies on carbon emissions in the construction industry. To achieve this aim, the following objectives have been formulated. Employing the PRISMA methodology to delineate the yearly publication patterns concerning carbon emissions and digital technology within the construction sector. This includes scrutinizing the origins of authors and their affiliated nations involved in carbon emissions and digital technology research in construction, ranking the prevalence of keywords and identifying the journals publishing these studies. Lastly, focus groups and the Analytic Hierarchy Process (AHP) will be used to evaluate the influence of diverse digital technologies on carbon emissions across various stages of the construction industry lifecycle.

2. Methodology

This study used systematic literature review (SLR) and mixed research methods. Mixed research methods including focus groups and AHP. The methodological framework is illustrated in Figure 1. Initially SLR was used to identify, appraise, retrieve and integrate the data sources to achieve the research objectives. The primary research object was to analyse the impact of different types of digital technology on carbon emissions across various building life cycles. The study comprised four phases, paper selection, system content analysis, analysis of research objects and research methods. In the first phase, articles were selected from ScienceDirect, which included peer-reviewed articles across related disciplines and interdisciplinary research. The second phase involved quality assessment to identify suitable publications. The third phase conducted system content analysis, focusing on the five information technologies most prevalent in selected journals to analyse their role in carbon emission processes. The fourth phase utilized mixed research methods: focus groups gathered information, followed by AHP analysis for weighting and prioritization. The main contribution of this study lies in identifying digital technologies with significant impacts on carbon emissions in construction, offering guidelines for effective carbon management and control in the industry.

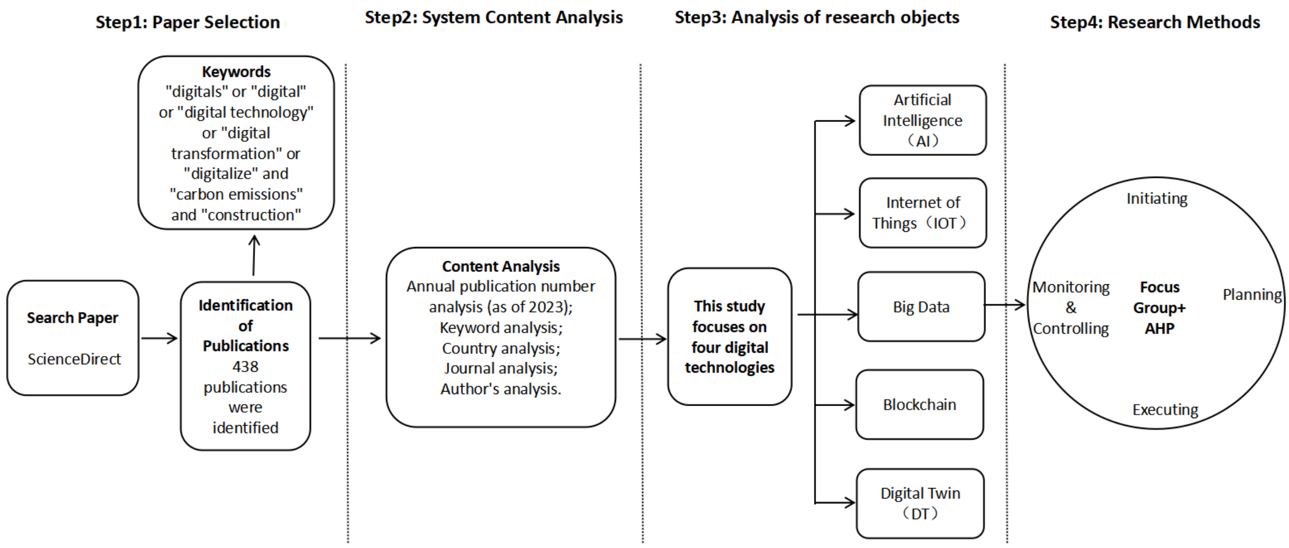

Fig. 1. Methodological framework

Focus Group is a common research method for qualitative research and usually consists of 6-10 participants [24]. The Focus Group needs to be guided by a moderator, aiming to gain an in-depth understanding of the opinions, views and attitudes of different participants on the research topic [32]. A total of 6 people took part in this study, all from Hebei Province, China. They are all between 33 and 45 years old. Their positions are Carbon footprint analysts, digital technology engineers, intelligent civil engineers, information technology practitioners, etc.; before the meeting, the research purpose and questions were determined and a discussion framework was formulated; after the meeting, data analysis of the meeting contents will be conducted and a report will be written.

These interviewees in the focus group discussed the topic of this study and analysed their perceptions, opinions, experiences and suggestions. The contribution of the six interviewees to this study was that they expressed opinions that were of great use to this study based on their field of work and work experience. They integrated and analysed the evaluation of five digital technologies in different life cycles, which is of great significance for the next round of AHP analysis.

AHP is a decision analysis method that combines qualitative and quantitative methods. It was proposed by the American business researcher Professor T. L. Saaty in the early 1970s. Its core logic is to compare the importance of items in pairs, use mathematical methods to calculate the relative importance of items at each level and perform weight sorting [26]. AHP enables people to make decisions that take multiple aspects into account. General statistics are objective, while the AHP expresses people's subjectivity and intuition through numbers and makes the analysis results objective [15].

In this study, the three levels of the AHP are the goal hierarchy, the criteria hierarchy and the alternative hierarchy. The details are shown in Figure 2. In addition, an evaluation standard for the pairwise comparison was developed in this study. “1” stands for equal direct influence, “3” for weak direct influence, “5” for moderate direct influence, “7” for strong direct influence and “9”” for very strong direct influence.

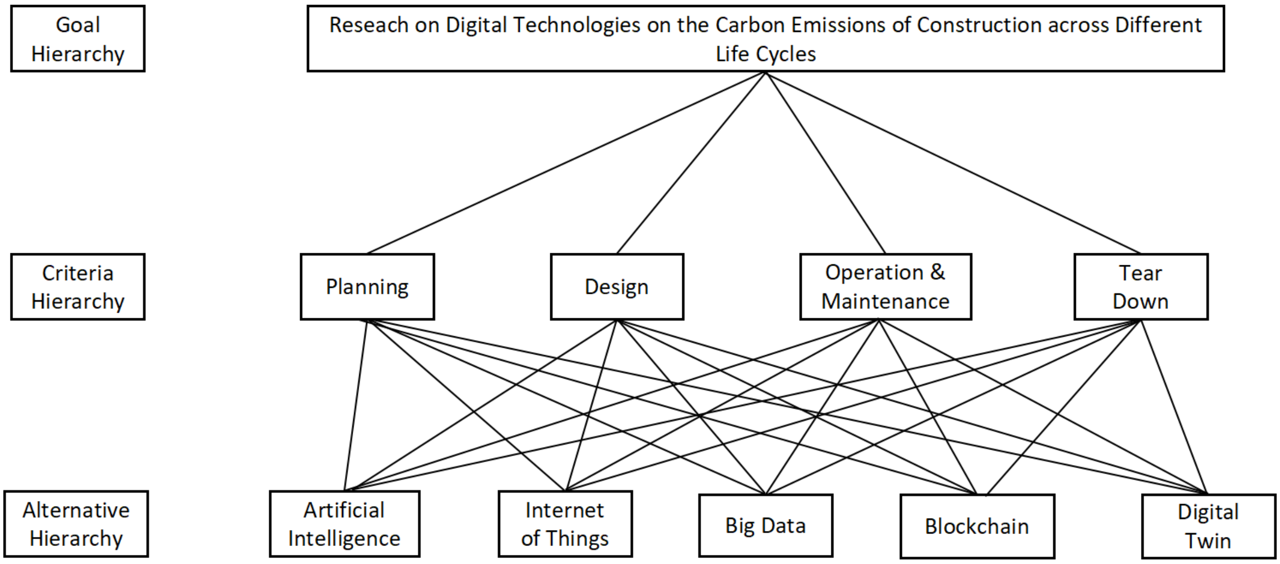

Fig. 2. AHP structure diagram

3. Result

First, this research involved sorting out relevant literature published previously through paper selection, quality assessment and system content analysis. Subsequently, data analysis was employed to create a literature review of the five digital technologies used in this study. The next step involved using a focus group for qualitative analysis. The information gleaned from the focus group was then inputted into the AHP to ultimately determine the weighting of the five information technologies.

3.1 Paper Selection

This study presents the latest research findings on carbon emissions and digital technologies in the construction industry, focusing on the role and contribution of various digital technologies to carbon emissions. For the literature review, documents were retrieved from prominent databases such as ScienceDirect, which are recognized by Scopus and Web of Science. This review uses "digitals" or "digital" or "digital technology" or "digital transformation" or "digitalize" and "carbon emissions" and "construction" to search. In this study, relevant journals were primarily selected by analysing titles, abstracts, keywords and content. This study presents the latest findings on carbon emissions and digital technologies in the construction industry, emphasizing the role and contributions of various digital technologies.

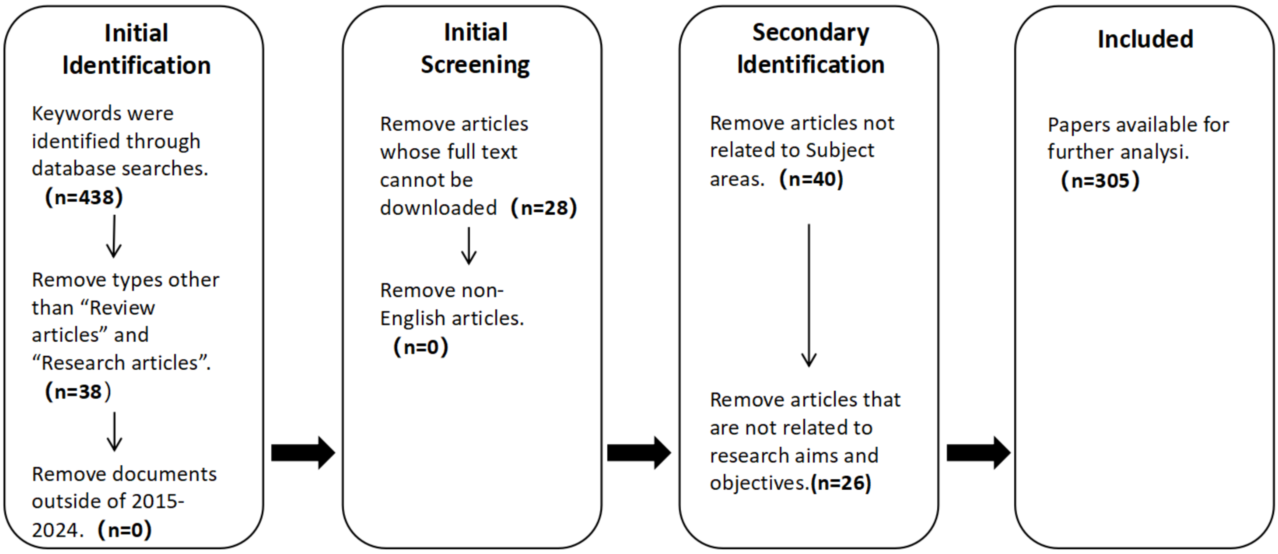

Fig. 3. Journal selection process

3.2 Quality Assessment

The analysis results in this section indicate that research on digital technology and carbon emissions in buildings began in 2017 and has demonstrated an upward trend since 2019, with significant growth after 2021 (Figure 4). The intersection of carbon emissions and digital technology in the construction industry is undergoing rapid development and has become a popular area of research. Contrary to previous assumptions, researchers and practitioners have recognized that the use of digital technology in construction does not increases but rather significantly impacts carbon emissions, offering substantial opportunities for environmental improvement.

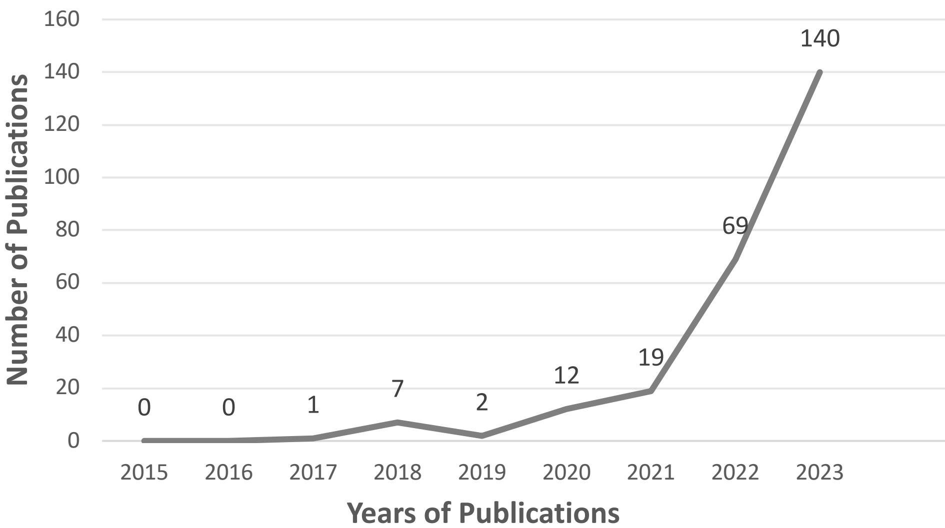

Fig. 4. Number of relevant publications published annually from 2015 to 2023

In databases and search engines, keywords serve as the primary basis for users to search and filter documents. Accurate keywords can enhance the likelihood of retrieved and can increase citation rates. The use of Keyword analysis and total link strength, as illustrated in Figure 5, facilitates a more precise understanding of the research topic and scope, enabling the capture of research focus. Moreover, this approach supports further analysis and data summarization. The link strength of keywords also acts as a crucial indicator to gauge the authority of web pages, the significance of keywords in search engine rankings and relevance of content between web pages. The focus of this research primarily focuses on digital transformation, digital economy and carbon emissions. Additionally, this study explores deeper dimensions such as sustainability, climate change, green innovation.

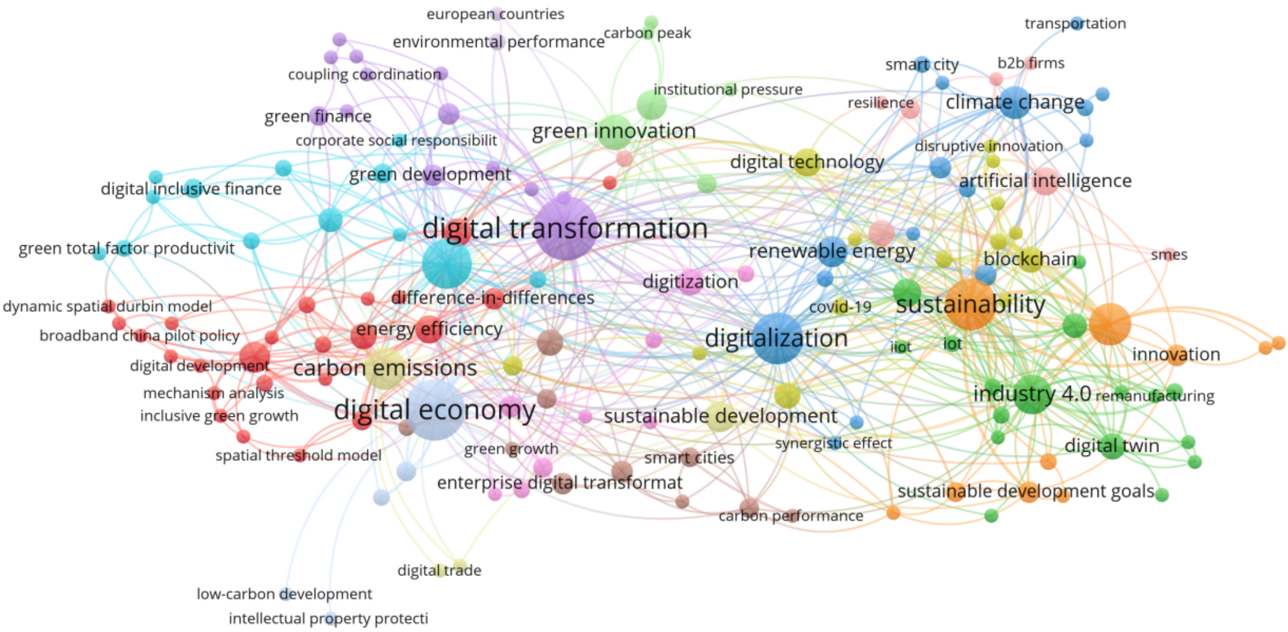

Fig. 5. Keywords and total link strength analysis

Table 1 organizes the frequency of keywords in this study. The most frequently occurring keyword is "digital transformation," appearing 41 times, followed by "digital economy," with 37 appearances. "Sustainability" and "digitalization" tie for third place. Other prominent keywords include "China," "carbon emissions," "circular economy," "Industry 4.0," "green innovation," and "climate change," each appearing 27 times. Keywords such as "appeared" 25 times, 18 times, 16 times, 13 times and 11 times are also noted. Many terms appear fewer than 10 times and are listed in each respective row; the minimum threshold for inclusion is six appearances, with any terms appearing fewer than six times omitted.

Table 1
Keywords frequency statistics table

Frequency	Keywords
41	Digital Transformation
37	Digital Economy
27	Sustainability, Digitalization
25	China
18	Carbon Emissions, Circular Economy
16	Industry 4.0
13	Green Innovation
11	Climate Change
10	Renewable Energy, Spatial Spillover Effect, Sustainable Development
9	Carbon Neutrality
8	Artificial Intelligence, Big Data, Digital Finance, Digital Technology, Energy Efficiency
7	Blockchain, Carbon Emission, Digital Technologies, Digital Twin, Digitization, Technological Innovation, Threshold Effect
6	Green Technology Innovation, Internet of Things

Figure 6 examines the countries where journals are published. China leads in publication volume, followed by the USA, Italy, Spain, England and Germany. Australia, Malaysia, Russia and Portugal also report significant numbers of publications. Additionally, Vietnam, Romania, Lithuania, Canada, Turkey, Thailand, Ireland, Norway, Brazil and other countries have contributed papers to related research fields.

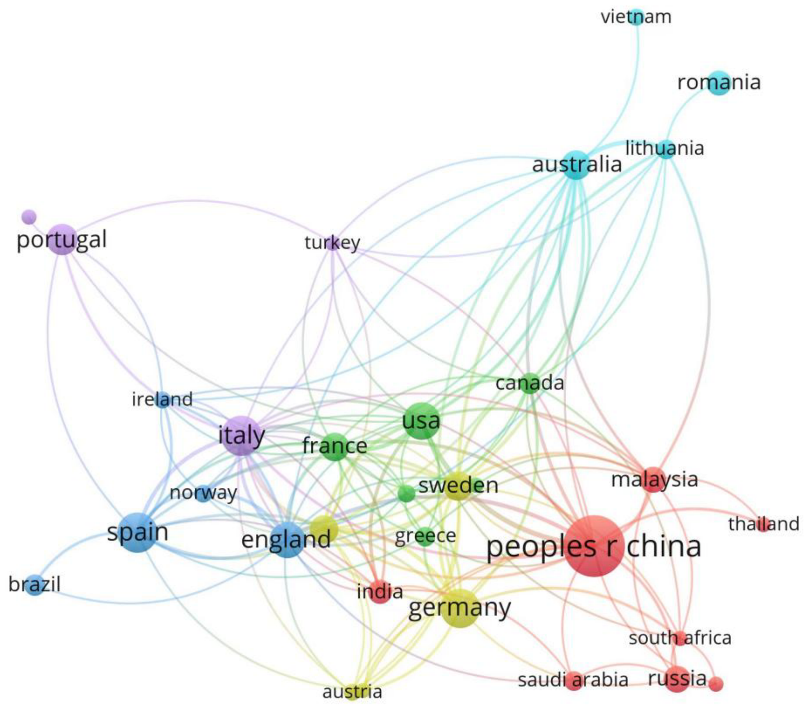

Fig. 6. Journal publication country analysis

As mentioned above, this study conducted a quantitative analysis of journal information, i.e. 305 articles published between 2015 and 2024 were analysed. As shown in Table 2. the 'Journal of Cleaner Production' has the most publications with 66 articles, which corresponds to about 22 % of the total circulation; 'Resources Policy' has the second highest number of publications with 28 articles, which corresponds to about 9 % of the circulation; 'Technological Forecasting and Social Change' follows closely behind in third place with 24 articles, which corresponds to about 7.8 % of the circulation;

Journal of Environmental Management' is in fourth place with 22 articles, which corresponds to about 7 % of the total circulation. 'Heliyon' is in fifth place with 15 articles, which corresponds to around 4.9% of the total circulation. In addition, 'Energy Economics', 'Energy', 'Economic Analysis and Policy' and 'Journal of Innovation & Knowledge' also have high circulation, all over 9 articles; there are three journals with 8 published articles; 1 journal has published 1 article; 5 journals have published 6 articles; 4 journals have published 5 articles; 3 journals have published 4 articles.

Table 2
Analysis of journal circulation quantity

Publication title	Number of publications
Journal of Cleaner Production	66
Resources Policy	28
Technological Forecasting and Social Change	24
Journal of Environmental Management	22
Heliyon	15
Energy Economics	12
Energy	10
Economic Analysis and Policy	9
Journal of Innovation & Knowledge	9
Computers & Industrial Engineering	8
Science of The Total Environment	8
International Review of Economics & Finance	8
Sustainable Cities and Society	7
Energy Policy	6
Applied Energy	6
Resources, Conservation and Recycling	6
Finance Research Letters	6
Sustainable Production and Consumption	6
International Journal of Production Economics	5
Environmental Impact Assessment Review	5
Renewable and Sustainable Energy Reviews	5
Ecological Indicators	5
Computers in Industry	4
Journal of Business Research	4
Industrial Marketing Management	4

Figure 7 analysed the relationship between the authors. The distribution of authors mostly appears in groups, which shows that there is more collaboration between the same country and less collaboration between foreign countries.

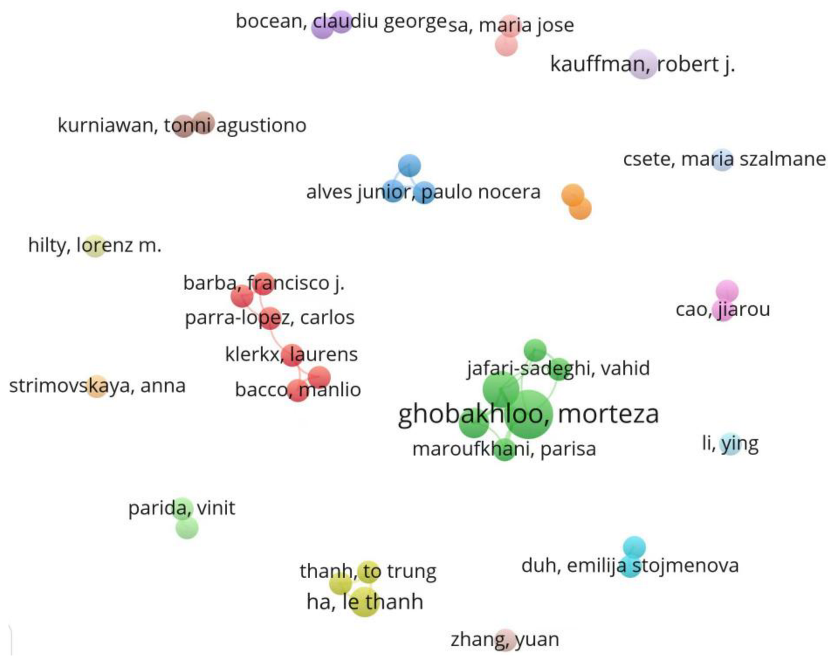

Fig. 7. Journal publication author analysis

3.3 System Content Analysis

Digital technology involves using computers and digital tools to process, transmit and store information, encompassing fields such as science, information technology and communication technology. It enables the application of various functions through the integration of hardware and software. Digital technology contributes to controlling carbon dioxide emissions via energy management, traffic optimization, urban architectural improvements and the management and trading of carbon dioxide emission data. This study analysed 305 documents, identifying 36 different types of digital technologies. It primarily focused on analysing five major digital technologies: Artificial Intelligence, Internet of Things, Big Data, Blockchain and Digital Twin.

3.4 Data Analysis

In total, 36 digital technologies were analysed across 305 documents that remained after screening for this study. Figure 8 was generated following the content analysis. It details the distribution of articles: 37 on AI, 30 on the IoT, 26 on BD, 19 on Blockchain and 15 on DT research. Additionally, significant numbers of articles focus on ML, ICT and BIM. This chapter provides an overview of the top five digital technologies

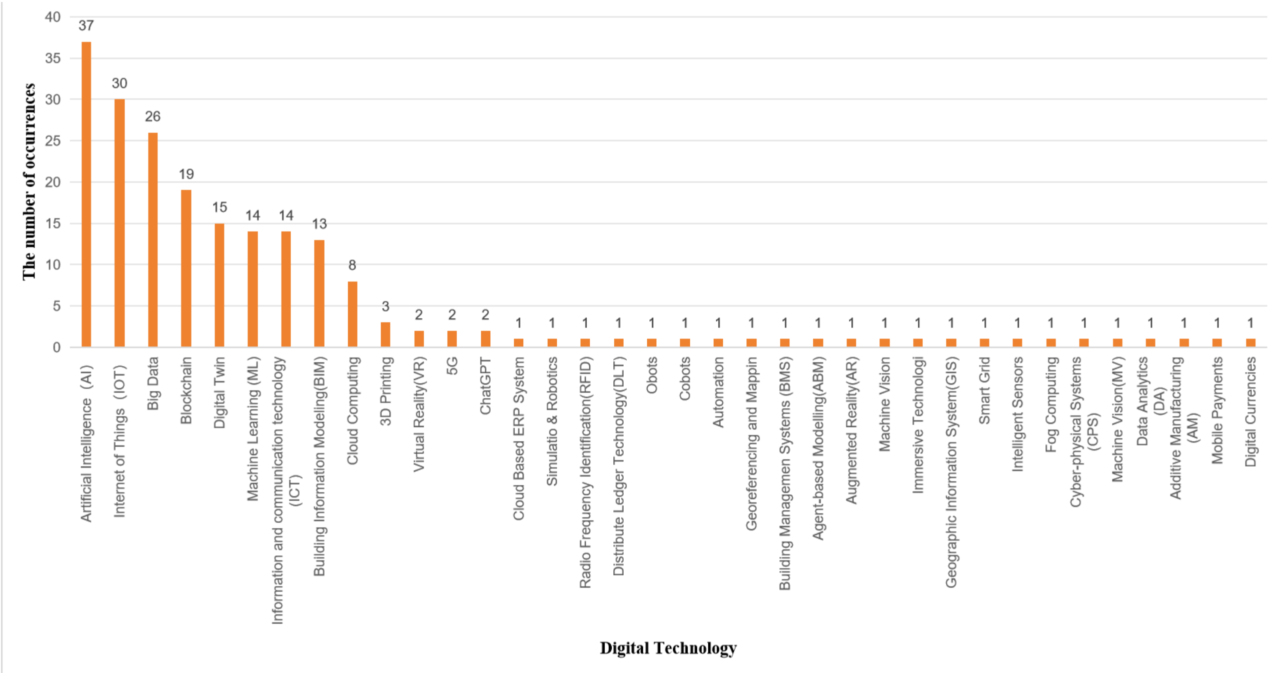

Fig. 8. Content analysis

3.4.1 Artificial intelligence

AI refers to technology where computer systems emulate human intelligence to perform tasks such as learning, reasoning and problem-solving [6]. AI is a new discipline that explores theoretical application design to simulate, extend and enhance human intelligence [30]. This technology can effectively replace human physical labour and cognitive labour in some aspects, while providing users with efficient auxiliary functions [29]. In recent years, AI has played an important role as one of the key digital technologies in improving business processes, optimizing service processes and increasing productivity in industry [1]. As a subfield of computer science, AI enables machines to emulate human perception and learning capabilities. These capabilities include knowledge representation, perception, problem-solving, logical reasoning and planning. AI empowers computers to address complex and ambiguous issues with awareness, intelligence and adaptability [5]. Rich and Knight's definition characterizes AI as a field concentrated on creating techniques for machines to execute tasks where humans currently excel. They categorize artificial intelligence into three primary groups: "narrow artificial intelligence (NAI), general artificial intelligence (GAI) and super artificial intelligence (SAI)." These groupings illustrate varying degrees of artificial intelligence proficiency [5].

The construction industry's failure to meet current projected infrastructure needs is largely due to the inadequate adoption of digital technologies and an excessive reliance on manual labour [4]. The challenges in the construction industry often stem from a lack of expertise and underutilization of technology, leading to cost inefficiencies, project delays, poor quality, inadequate decision-making, low productivity and suboptimal health and safety outcomes.

The use of artificial intelligence solutions has significantly increased today, particularly in manufacturing and construction processes aimed at enhancing operational efficiency within the construction industry [11]. Due to the slow performance growth of the construction industry, many companies and individuals have started using AI to improve productivity and optimize processes. This initiative has brought many benefits, such as more efficient project planning and management, increased safety on site and control of cost overruns, driving productivity gains in the construction industry [5]. Empirical evidence shows that the integration of AI technology into the industrial construction sector has great potential for increasing the degree of automation in the manufacture of finished products [11].

In addition, studies on individual buildings assess the carbon footprint during the entire life cycle of the building, i.e. in the planning, design, operation, maintenance and demolition phases [36]. The planning phase is very important and plays a crucial role in the entire life cycle of a construction project, as it affects quality, quantity, time, cost and other factors that all influence the success of the project. The use of AI in recent years has optimized planning and scheduling during the construction process [5]. The process of material preparation is an important aspect in the construction of a building. Using artificial intelligence and machine learning data as input to create visualizations of the quantity and progress of the template can minimize template design resources [5].

During the operation and maintenance phase, clients often face limited control over project progress. Therefore, obtaining data becomes a challenge. The integration AI and ML presents extensive opportunities across various domains, including asset management, supply chain monitoring, tracking, energy performance simulation and maintenance management AI improves the efficiency of project operations by enabling the capture of real-time data [5]. The integration of AI into demolition and refurbishment processes has received less attention than other project phases in the construction industry. Ensuring the sustainability of the construction industry depends on getting the most financial and environmental benefit from buildings before they are retired, including the deconstruction and demolition processes [5]. Wang and Wu introduced a theoretical framework to aid in evaluating the carbon emissions produced throughout the entirety of building waste demolition. Additionally, Wang and Li presented a groundbreaking prototype, driven by AI, for the effective sorting and gathering of construction waste. This phase is pivotal in the recycling of construction and demolition waste [5].

3.4.2 Internet of things

IoT is a network system that connects various devices and sensors via the Internet, facilitating data exchange and remote control. The technological revolution, ushered in by the IoT, represents the future of computing and communication. Progress in this domain is contingent upon dynamic technological advancements in several key areas [23]. IoT is a network that leverages the internet to facilitate information exchange between customers and goods. This multidisciplinary concept is realized through the integration of technologies from communication, networking, data collection, data fusion, cloud computing and security. These elements collectively enable intelligent identification, management, monitoring, tracking and positioning [23]. The IoT-based real-time monitoring platform leverages identifiable, capturable and shareable data for early warnings and decision-making. It also employs Internet technology to handle the storage, querying, analysis, mining and interpretation of massive sensor data [35].

In the 5G era, the rapid advancement of the IoT has accelerated the development of smart cities globally. Investigating carbon reduction strategies through IoT technology is a crucial aspect of studying global low-carbon cities. Both governments and urban designers are tasked with researching and promoting methods for smart carbon management, which has emerged as a significant contemporary issue [35].

IoT has embedded itself into numerous aspects of human existence, including transportation, construction and the energy industry. Internationally, air conditioning and lighting systems serve as primary electricity consumers within buildings, collectively accounting for approximately 40% and 20% of total electricity consumption, respectively [8]. Due to the rising energy costs, there have been endeavours to implement intelligent energy management systems, which encompass smart metering and monitoring frameworks utilizing the IoT and interconnected sensors [2]. IoT can manage the energy usage within buildings while ensuring users' comfort in terms of visual and thermal aspects. The IoT can identify anomalies in smart home functionalities based on user interactions and household conditions, thus facilitating the identification and replacement of malfunctioning home devices [8]. Furthermore, leveraging IoT in buildings allows for complete management of the connected devices, which helps in cutting down both investment and maintenance expenses of the building. IoT systems encompass wireless sensor networks that automatically manage devices. These systems employ a computing mechanism that follows a series of predefined rules to manage sensors and switches linked to household appliances [8].

3.4.3 Big data

BD refers to the process and methods of extracting valuable information from large, complex and diverse data through advanced technology. Economic growth is significantly driven by the development of the BD industry and the reduction of carbon dioxide emissions, which serve as key objectives. The future of green development transformation hinges on whether the two related policies can deliver a "win-win" outcome [7]. Characterized by its vast capacity, diverse types, rapid access and significant application value, this dataset initially found its utility within the IT sector and underwent rapid expansion. Key underpinnings encompass distributed processing, distributed databases, cloud storage and the virtualization of BD. The academic realm widely acknowledges the benefits afforded by the BD sector, with a predominant focus on its economic implications. Research indicates that the BD industry can drive economic expansion, elevate production efficiency and bolster innovation capacities [7]. Studies indicate that the advancement of the BD sector significantly contributes to the reduction of carbon dioxide emissions. Furthermore, the analysis of mechanisms reveals that the substantial enhancement in CO2 emission reduction driven by the BD industry is largely due to the optimization of the industrial structure, advancements in technology and more efficient resource distribution [7]. IoT can manage the energy usage within buildings while ensuring users' comfort in terms of visual and thermal aspects.”

The significance of BD technology is found in its ability to expertly handle vast and valuable data, combined with its proficiency in conducting efficient, real-time interactive analyses [33]. Advancing the BD industry enhances industrial structure and reduces carbon dioxide emissions. BD facilitates the optimization of industrial structure through the growth of digital industries and the digital transformation of traditional industries. Initially, the extensive use of advanced technologies in the digital economy has spurred the emergence of new industries. At the same time, the BD industry will spawn many new business models and promote the development of emerging industries, thereby promoting the expansion of the digital industry. Secondly, the use of BD capturable can help reshape the rules of traditional industries. For example, integrating BD with traditional production models has enhanced efficiency and output, significantly transforming traditional industrial models. The digital transformation of traditional industries is driven by the BD industry through mechanisms such as industrial integration and technology dissemination [25]. Current research indicates that enhancing industrial structure can significantly mitigate CO2 emissions through various mechanisms [7].

3.4.4 Blockchain

According to Rodrigo *et al.,* [20], blockchain is characterized as a distributed and decentralized ledger that records all transactions. This technology is attracting significant attention from various entities, including startups, tech developers, businesses, government bodies and the academic community. Initially, blockchain was used primarily to document cryptocurrency transactions. However, the focus has shifted towards employing blockchain for diverse applications across multiple sectors such as science, real estate and construction [20]. Blockchain technology offers multiple benefits to the construction industry, including improvements in the construction supply chain (CSC), building information modelling, design management, sustainability enhancement, waste management, property and land ownership and asset management and maintenance [20]. In recent years, a novel approach to organizing data and services has emerged in the form of blockchain technology [27]. Emerging from Industry 4.0, blockchain technology represents a novel advancement that has captured the attention of numerous startups, tech developers, businesses, government bodies and academic researchers.

Additionally, blockchain technology offers a distributed shared database and computing infrastructure that safeguards data against tampering and modification. To ensure security, prevent erroneous transaction recordings and avoid double spending, blockchain employs a consensus algorithm that autonomously verifies transactions before their approval. Initially developed as a decentralized platform for digital currency exchange, the applications of blockchain technology have now extended to various other sectors [20]. The secure operation of blockchain technology supports various sectors, fostering a highly dynamic and extensive ecosystem. Blockchain secures diverse data types through encryption and enables their direct exchange, thereby establishing a novel data credit system. An increasing number of researchers are exploring ways to apply blockchain principles to develop government big data platforms, with the goal of supporting modern smart city initiatives. This system employs a decentralized approach to distribute the government big data platform, redistributing centrally located servers and storage units across various service nodes [27]. Key elements of blockchain include decentralization, distribution and consensus. A public blockchain typically comprises thousands of computer nodes that interact over a decentralized network, eliminating the need for a central authority to oversee the system [21]. Consequently, leveraging blockchain technology, this paper benefits from features such as decentralization, enhanced security, reliability, immutability and the ability to trace transactions [27]. As highlighted by Rodrigo *et al.,* [20] blockchain technology possesses the potential to establish a novel form of trust across various services, while simultaneously transforming industries, overhauling financial markets, supply chains, consumer and B2B services and public sectors.

3.4.5 Digital twin

DT are virtual models of physical entities designed to simulate, monitor and optimize their performance and operations in real time. As information technology progresses, DTs are increasingly becoming integrated into everyday life. This concept encompasses the fundamental tools that have spearheaded emerging technologies for many years [31]. It can be understood as a digital version of a physical product Shyr *et al*., [23]. The proposed definition of a DT is as follows: A DT is a dynamic and self-updating virtual or digital representation that mirrors a real-world entity (such as a component, machine, process or human). It continuously updates to accurately reflect the current state of its physical counterpart by exchanging real-time data and retaining historical data. The DT not only duplicates its physical counterpart but also mirrors any changes made to the digital representation in the physical entity [3,25]. Ontologically, a DT is a set of digital information that represents both the dynamic physical state and static physical attributes of the built environment. It functions as a real-time data sensor and a system model, continuously adapting to environmental changes [3]. DT can observe the function and life of individual products and optimize sustainability

[3]. In general, DT can be understood as digital representations of the real world. In addition to this, DT can provide modelling capabilities and the ability to analyse the real world. DT requires data management and analysis, as well as a combination of simulation, visualization and information sharing functions [31]. DT has the capabilities to analyse complex models and simulations. DT can also meet the needs of different groups, such as service users and citizens [31]. DT can help with urban development and urban planning and achieve decarbonization. Especially the calculation of carbon emissions and total energy consumption.

In summary, DT can help with maintenance and decision-making for visualization and prioritization [16]. The use of DT is instrumental in achieving carbon neutrality. This technology can replicate nearly any physical system and is effectively a digital counterpart of the entire real world [34]. DT plays different functions and roles in different life cycles. It helps create zero-carbon communities and can optimize each life cycle from planning, design to construction and operation management. DT provides a new perspective on the creation of zero-carbon communities [31]. DT can capture and monitor real-time building conditions, which is helpful for building operations [3]. DT can contribute to achieving zero-carbon communities in various ways. They enable a cross-sector digital representation of communities by utilizing data from buildings, energy networks, transportation infrastructure, environmental systems, community demographic indicators, planning decisions and more [31].

3.5 Case Analysis

The applications of AI, IoT, BD, Blockchain and DT in the construction industry are diverse. Table 3 introduces practical cases of each digital technology in carbon reduction in the construction industry through example analysis.

Table 3
Case analysis

	Case	Citation
AI	An example is the approach taken by Skanska Norway, which uses GPS, machines, vibration data and drone maps to optimize road construction processes. This reduces idle time, optimizes tipper traffic, minimizes unnecessary driving and improves driving style. All of this helps increase sustainability and reduce CO_2 emissions.	[19]
IoT	Monitor and manage energy consumption using IoT-based energy management systems and big data analytics to significantly improve energy efficiency and reduce carbon emissions.	[4,9]
BD	The application of intelligent big data technology combined with algorithms such as Apriori can conduct a comprehensive analysis of the entire life cycle of a building and convert energy consumption data into carbon footprint indicators. This approach can not only assess environmental impacts but also inform the design and implementation of energy conservation policies.	[22]
Blockchain	A major application of Blockchain is in construction and demolition waste management (CDWM), where Blockchain can streamline processes and improve information management, thereby promoting sustainable practices and reducing waste-related carbon emissions.	[12]
DT	A practical example is the application of DT platforms in the construction of foundation pits for subway stations. This method facilitates the quantitative calculation of total carbon emissions.	[17]

3.6 Focus Group

Based on the content discussed in the Focus Group, the significant roles of five digital technologies of AI, IoT, BD, Blockchain and DT in the four life cycle stages of planning, design, operation & maintenance and teardown were analysed and organized. The finding is presented in Table 4.

Table 4
Analysis of focus group results

	Planning	Design	Operation & Maintenance	Tear Down
AI	Helps control costs, improve project planning efficiency.	Helps with design visualization, optimize resource allocation.	Can improve the operational efficiency of the modular construction industry, especially during manufacturing and construction.	AI can monitor and evaluate the safety situation on site and identify dangerous factors; it can monitor noise, vibration, dust, etc. during the demolition process; it can use robots to improve accuracy and reduce human errors.
IoT	By analysing electricity, water and energy consumption, planners can identify energy saving opportunities during the planning stage Take appropriate measures.	Can help the design team better assessment of buildings. Sustainability can be carried out continuous design and intelligently optimized design.	For monitoring of air conditioning, lighting and other systems. It is an important way to reduce energy consumption.	Track and manage various materials and components during the demolition process for sorting, recycling and reuse. Noise, particulate matter, etc. during the demolition process can also be monitored.
BD	The main method is traditional industry, digital transformation mainly occurs in planning stage.	In trend analysis and prediction, behaviour understanding, energy efficiency optimization. It plays an important role in other aspects and is beneficial to the design stage.	Remote monitoring and data analysis of construction equipment can be carried out, discover equipment by monitoring operating status and indicators abnormalities and failures.	The scheduling of manpower, materials and equipment during the demolition process can be optimized to achieve optimal utilization and cost savings.
Blockchain	The relevance of this life cycle and low attention.	Can be used for building information model management, design management.	The relevance of this life cycle and low attention.	Can be used for building sustainability and Waste management, asset management and maintenance.
DT	Visual presentation, contributes to asset and system planning.	This technology can represent any physical system and can improve the system and select the alternative path.	Real-time building status can be captured and monitored to promote building operations.	Virtual models of buildings, including structures, materials and environments, can be created to help plan optimal demolition strategies.

3.7 Analytic Hierarchy Process

Based on information obtained from the Focus Group, we compared various digital technologies across their life cycles and assigned scores which are displayed in Table 5.

Table 5
Life cycle score sorting

Alternative	Planning	Design	Operation & Maintenance	Tear Down
AI	7	9	9	9
IoT	5	7	7	5
BD	9	5	3	7
Blockchain	1	1	1	3
DT	3	3	5	1

Table 6 ranks the impact of each life cycle stage on carbon emissions throughout the entire life cycle of the building.

Table 6
Criteria hierarchy weight sorting

Criteria	Weight
Planning	0.057
Design	0.122
Operation & Maintenance	0.558
Tear Down	0.263

Subsequently, Table 7 presents the rankings of the weights of the five digital technologies across different life cycles.

Table 7
Alternative hierarchy weight sorting

Alternative	Planning	Design	Operation & Maintenance	Tear Down
AI	0.244	0.521	0.497	0.539
IoT	0.119	0.249	0.247	0.118
BD	0.508	0.122	0.076	0.255
Blockchain	0.037	0.038	0.038	0.055
DT	0.092	0.069	0.142	0.034

Based on the results of Criteria Hierarchy weight sorting and Alternative Hierarchy weight sorting, the MMULT (a function in Microsoft Excel) function calculation is performed and the following results are obtained, see Table 8. According to the results, the impact of AI on carbon emissions during the entire life cycle of the building is the effect is the greatest.

Table 8
Final results

Alternative	Weight of Alternative
AI	0.497
IoT	0.206
BD	0.153
Blockchain	0.043
DT	0.102

4. Discussion

This study provides a comprehensive review of the literature on the adoption of various digitally driven technologies in the construction industry and their contributions to controlling carbon emissions. It concludes that AI is the digital technology that has the greatest impact on carbon emissions throughout the entire life cycle of the construction industry, which is consistent with the conclusions drawn from the systematic literature review in the first half of this study. This research offers valuable insights for decision-making in the construction industry regarding carbon emissions and facilitates the strategic integration of digital technology at different stages of the life cycle.

After this study, it is concluded that AI has the greatest contribution in the tear down stage, which is mainly used to monitor and evaluate the safety situation on site, as well as monitor pollution conditions, etc.; it also makes a relatively large contribution in the operation & maintenance stage, mainly in improving Operational efficiency in the modular construction industry. IoT has the greatest contribution in the operation & maintenance stage, mainly reflected in equipment monitoring, which helps reduce energy consumption; Secondly, the contribution in the design and tear down stages is also large; the planning contribution is less effective. The role of BD is mainly reflected in the planning stage, mainly used for the digital transformation of traditional industries; the contribution of BD is also relatively large in the tear down stage, mainly reflected in the dispatch of manpower, materials and equipment during the demolition process. Blockchain's overall contribution to the four life cycles is small. The design stage is mainly used for building information model management and the tear down stage is mainly used for sustainable waste management. DT contributes greatly in the operation & maintenance stage, which is reflected in monitoring the status of the building and promoting the use of the building; followed by the design stage and planning stage.

5. Conclusion

First of all, this study used the PRISMA research method to research and analysis relevant articles on Digital technologies in reducing carbon emissions in the construction industry. The top five publications after searching for keywords are AI, IoT, BD and Blockchain, DT. Then analyse and research these five digital technologies, including: Year of Publications Analysis, Keywords and Total Link Strength Analysis, Journal Publication Country Analysis, Journal Circulation Quantity Analysis, Journal Publication Author Analysis. Then using a mixed research method, we first collected information from 6 stakeholders through Focus Group; then used AHP to conduct data analysis and compared the role of each information technology in the 4 life cycles in pairs and obtained the weight ranking. The results AI is the highest, followed by IoT, BD, DT and Blockchain. This research has certain guiding significance for the combination of digital technology and carbon emissions in the construction industry and is crucial to promoting the application of digital technology in carbon emissions.

However, the results of this study are subject to certain limitations, particularly due to time constraints, technology and the knowledge and experience level of the Focus Group participants. Furthermore, given the complexity of the construction industry and its nascent integration with information technology, each construction project has unique models and characteristics require that integration with information technology be tailored to the specific circumstances. Therefore, a generalized simulation may not be meaningful.

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