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Evolution of Digital Transformation in Construction Research: Topic Modelling Analysis

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Abstract

This article examines digital transformation in the construction industry, which begins with adopting digital technologies and culminates in comprehensive organizational change. The diverse and often conflicting conceptualizations in this field have created ambiguity in the theoretical framework of digi-tal transformation in construction. Using topic modeling and pattern analysis, this study identifies key themes and trends in the domain. The article analyzes 1,308 articles published between 1990 and 2023 to review research areas related to digital transformation in the construction industry. It identifies six main topics: Security & Safety, Organization & Project Management, Digital Simulation & Interaction, Sustainability,

Innovative Building Materials, and Dynamic Monitoring Methods. The analysis reveals that Organization & Project Management is the most researched topic, while Sustainability receives the least attention. The article offers recommendations for advancing research in this field and serves as a valuable reference for researchers and practitioners interested in digital transformation in construction. By addressing existing criticisms, it provides a clear map of the field's structure and trends, comple-menting previous qualitative studies with a broader, more structured, and objective analysis.

Keywords: Topic Modeling; Digital transformation; Industry 4.0; Construction industry; Building; Disruptive Technology.

Introduction

The construction industry faces increasing competition and challenges due to the rapid advancement of information and communication technologies, necessitating digital transformation (DT) and the digitization of business processes (Gerbert et al., 2016; Stoyanova, 2020). Digital transformation in the construction industry encompasses a range of interdisciplinary technologies spanning cultural, organizational, and technological domains. It facilitates the digitization, automation, and integration of construction processes across all stages of the value chain, enabling innovative approaches to industry practices (Zulu & Khosrowshahi, 2021).

This study investigates how digital technologies can transform and enhance the construction industry. It advocates for the industry's adoption of DT, demonstrating its potential to benefit firms, workers, the environment, and the industry in multiple ways. The study identifies key objectives of implementing DT in the construction industry, including improving productivity, production efficiency, decision-making, and equipment longevity. Furthermore, it highlights that the adoption of these technologies can enhance safety, promote sustainability, and elevate the industry's reputation (Buisman, 2018; Oesterreich & Teuteberg, 2016; Phang et al., 2020).

Despite these advantages, the field of DT research in the construction industry continues to face significant challenges. Even years after the introduction of the DT concept, numerous unanswered questions remain regarding the nature of knowledge structures and research trends in this domain (Adekunle et al., 2021; Musarat et al., 2021). The growing complexity of the paradigm shift driven by DT suggests that previous efforts to develop theoretical or normative insights through a single perspective are no longer sufficient. For instance, researchers have criticized the prevailing mindset in the DT literature within the construction industry, noting that focusing solely on organizational changes, such as the adoption of information technology systems, is inadequate (i.e., Volkoff et al., 2007). Consequences of DT, such as the emergence of new digital business models even in non-digital industries such

as the construction industry, are beyond the previous stages of technology change, and usually appear in the form of incremental and dynamic changes (for example, Orlikowski (2000).

The rapid and expanding body of research on DT in the construction industry has contributed to structural incoherence and complexity in the field. This has resulted in confusion among researchers, hindering their ability to gain clear insights into the future direction of DT studies in this domain (Adekunle et al., 2021; Ghazanfari et al., 2009; Musarat et al., 2021). The diverse and often conflicting conceptualizations and studies in the field of DT in the construction industry have created ambiguity in its theoretical framework (Patil, 2018). This study reviews the literature on DT in the construction industry using topic modeling, a method that analyzes historical text data to group articles and reveal hidden patterns and relationships among topics. By addressing existing criticisms, it provides a comprehensive map and insights into the field's structure and trends. To achieve this, the study addresses three research questions:

This study addresses the following research questions:

1. What are the main topics constituting the knowledge structure of DT in the construction industry?

2. What research trends have emerged in the main topics of DT in the construction industry in recent years?

3. What are the existing gaps in the literature, and what are potential directions for future studies?

The study analyzes 1,308 articles on DT in the construction industry, published between 1991 and 2023, using text mining. By employing text processing techniques, it models a large volume of scientific documents to uncover patterns. This approach complements previous qualitative studies by providing a broader scope and more structured, comprehensive, and objective results. It reveals the knowledge structure and research trends of DT studies in the construction industry.

Literature Review

Prior reviews and syntheses on DT in construction literature

The background of this study encompasses all review-based studies, including meta-analyses, systematic reviews, meta-syntheses, and those employing text mining techniques to analyze the knowledge structure and research trends of DT and disruptive technologies in the construction industry. Previous studies on DT in the construction industry have explored a wide range of aspects, reflecting the diversity of research in this field. Earlier studies focused on topics such as the construction supply chain (Dallasega, 2018), smart cities (Reddy & Kone, 2019), or broader organizational strategies for adopting DT (Chanias et al., 2019; Warner & Wäger, 2019). A significant portion of prior studies have evaluated the potential of

DT in the construction industry (Berlak et al., 2021; Khahro et al., 2021; Rouhani & Ravasan, 2014; Stoyanova, 2020). Additionally, these studies have assessed the challenges, obstacles, and benefits associated with implementing DT in this industry (Atuahene et al., 2020; Berlak et al., 2021; Ernstsen et al., 2021).

Several studies on DT in the construction industry have specifically examined disruptive technologies, evaluating their technological implications. However, the maturity, adoption, application, benefits, and challenges of these technologies vary significantly across contexts. For instance, technologies such as Building Information Modeling (BIM) (Phang et al., 2020; Prodius et al., 2020) and the Internet of Things (IoT) (Dahanayake & Sumanarathna, 2021; Reddy & Kone, 2019) have been widely implemented in construction projects and adopted by numerous companies (Maskuriy, Selamat, Maresova, et al., 2019; Zabidin et al., 2020). Recent efforts in DT have focused on integrating emerging technologies into the construction process. Technologies such as augmented reality, virtual reality, cloud computing, blockchain, and artificial intelligence have gained attention in recent years, yet their full potential and role in the industry remain underexplored (Aibinu & Papadonikolaki, 2020; Dahanayake & Sumanarathna, 2021; Ferraz et al., 2020).

Adekunle et.al. (2021) reviewed 1,892 articles on DT in the construction industry from 2010 to 2020, identifying six main topics: Building Information Modeling (BIM), Internet of Things (IoT), artificial intelligence (AI), big data and analytics, cloud computing, and augmented reality (AR) and virtual reality (VR). Their study proposed a balanced model for DT in the construction industry, encompassing four dimensions: technology, process, people, and environment. However, it focused primarily on technology, omitting other aspects of DT, such as robotics and blockchain, and did not account for temporal and regional variations in DT adoption across different countries.

Another notable review by Ghobakhloo et al. (2021) analyzed 745 articles on DT in the construction industry over a decade. The study identified key success factors for DT and outlined its sustainability value and conditions. However, it overlooked the implications and challenges of Industry 4.0 in non-technical areas, such as social, ethical, environmental, and economic dimensions, which may limit the generalizability of its findings.

Chan (2020) reviewed 18 articles on digital platforms in the architecture, engineering, and construction (AEC) sector. The study recommended exploring the strategic potential of operating systems to gain a competitive advantage in AEC and identified four main topics in platform research: platform ecosystems, platform governance, platform innovation, and platform effects. Like many reviews of DT in the construction industry, this study is limited in scope, focusing on a specific aspect without contributing to a comprehensive theoretical framework.

Table 1 summarizes prior reviews, detailing their scope, period, and sample size. Most employed systematic review methods analyzed full-text articles and relied on qualitative approaches.

Table 1. Summary of prior Digital Transformation in construction reviews

Citation	Review period (sample size)	Review the focus area	Method
(Adekunle et al., 2021)	2010-2020 (1892 papers)	Exploring DT aspects in the construction industry and suggesting future research directions	Bibliometric review
(Ghobakhloo et al., 2021)	2010-2020 (745 papers)	Identifying the most important factors of success in DT	systematic literature review
(Lammers et al., 2018)	2010-2017 (58 papers)	Identifying drivers of DTs in key industries	
(Liboni et al., 2019)	2014-2018 (52 papers)	Identifying the possible impacts of Industry 4.0 on human resource management – with a focus on employment, job description, and the required conditions and skills of the workforce	
(Agyemang & Fong, 2019)	not reported (40 papers)	Identifying a comprehensive systematic review of the desired skills of future construction management students	
(Dahanayake & Sumanarathna, 2021)	2005-2018 (40 papers)	Examining the opportunities of integration of smart facility management based on IoT-BIM	Semi-systematic literature review
(Barata & Cunha, 2019)	not reported (37 papers)	An integrated solution for the adoption of wearable technologies in construction, occupational safety, and health	systematic literature review
(Musarat et al., 2021)	Up to 2021 (26 papers)	Evaluating the DT potential of different sectors of the construction industry	
(Ferraz et al., 2020)	2010-2019 (23 papers)	Evaluating BIM maturity models	
(Chan, 2020)	Up to 2020 (18 papers)	Reviewing the digital platform studies conducted in the field of architecture, engineering, and construction	literature review
(Khahro et al., 2021)	not reported	Assessing DT and e-commerce potential in the construction industry. Exploring the potential, benefits, and obstacles of DT and e-commerce.	
(Calvetti et al., 2020)		Creating a framework based on the use of future data, including electronic performance monitoring, building information Modelling, smart contracts, and artificial intelligence	systematic scoping review
(Andras Nick & Pongrácz, 2018)		Providing connections between the concepts of transformative innovation, smart city, and Industry 4.0	literature review
(Bhattacharya & Momaya, 2021)		Providing a strategy framework for DT of the value chain for architecture, engineering, construction, and operation and maintenance companies	
(Jackson & Dunn-Jensen, 2021)		Identifying planning methods for leadership succession	
This research	1991-Q1, 2023 (1308 papers)	Representing the background literature of DT in the construction industry as a whole entity without focusing on a specific sector	Topic Modelling

Table 1 indicates that prior studies on DT in the construction industry have employed review methods and text mining techniques to examine knowledge structures and research trends. However, these studies have not comprehensively analyzed the content of the literature using text mining methods. Moreover, none have sought to objectively classify and analyze DT literature over time, which is the primary objective of this study.

Methodology

This study employs text mining and topic modeling to address the research questions. These methods enable rapid and effective analysis of large document collections, offering distinct advantages over other approaches. The study compares text mining and topic modeling with review methods such as meta-synthesis and systematic review, providing a comprehensive overview of the research context. Additionally, topic modeling mitigates some limitations of traditional analyses (Lee & Kang, 2018). The methodology integrates manual and automated techniques for data collection, screening, preparation, topic modeling, visualization, descriptive analysis, and result dissemination. The main stages of this research are illustrated in Figure 1.

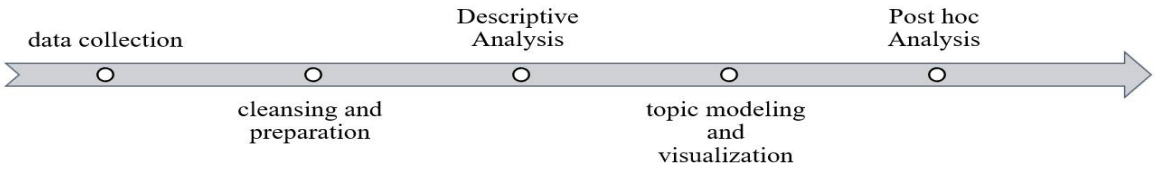


Figure 1. Research steps, employed applications, and libraries

Data Collection

This study utilized the Web of Science (WoS) database to identify literature on DT in the construction industry due to its extensive coverage and high-quality data. To ensure comprehensive retrieval, we searched the Title, Abstract, and Keywords fields of WoS articles using wildcards (*), Boolean operators (OR), and proximity operators (W/n, within n words). Keywords related to disruptive technologies in the construction industry were selected based on the 2019 report Digital Transformation in Transport, Construction, Energy, Government, and Public Administration (Baldini et al., 2019). The study focused on the construction sector, excluding articles with unrelated terms in their titles. It included journal articles published up to April 2023, filtering out non-indexed sources. Abstracts from the selected articles were used for text mining analysis. The search terms were defined as follows:

All data, including journal name, publication year, title, abstract, and keywords, were downloaded from WoS and recorded in a CSV file. The final dataset comprised 1,308 articles from 573 journals, authored by nearly 4,000 researchers. Of these, 142 articles were single-authored. Figure 2 illustrates the temporal distribution of articles and the geographical

distribution of authors. China, the United States, the United Kingdom, Malaysia, Australia, and South Korea were the leading countries in publishing articles on DT in the construction industry.

"Digital transformation" OR "Emerging technolog*" OR "Disruptive technolog*" OR digitaliz* OR digitiz* OR digitalis* OR digitis* OR "Industry 4" OR "construction 4" OR " Internet of Things" OR IoT OR "Mobile Internet" OR "Additive manufacturing" OR 3D OR Drones OR "Building Information Model*" OR "Building Information management" OR "Virtual reality" OR "Augmented reality" OR "Artificial intelligence" OR blockchain OR "smart contract" OR "Big data" OR Cloud OR "Robotic*" OR "Autonomous robots" OR "Global Positioning System" OR GPS OR "Radio Frequency Identification" OR "RFID" OR "Digital Twin" (Title) and "Building industr*" OR "construction industr*" OR "Building compan*" OR "construction compan*" OR "Building sector" OR "construction sector" OR "Building firm*" OR "construction firm*" OR "civil" (Abstract) not geotechnic OR geotechnical OR oil OR gas OR "bridge construction" OR subway OR transportation OR railroad OR railway OR highway OR road OR "road infrastructure" OR airport OR railway OR tunnel OR environment OR "road engineering" OR "coastal cities" OR cities OR "electrical construction" OR "plant construction" OR stations OR soil OR submarines OR asphalt OR "smart city" OR petrochemical OR "metro construction" OR "pavement engineering" OR geopolymer OR landscape OR "ship construction" (Topic) and English (Languages) and Article (Document Types) and Article or Early Access (Document Types)

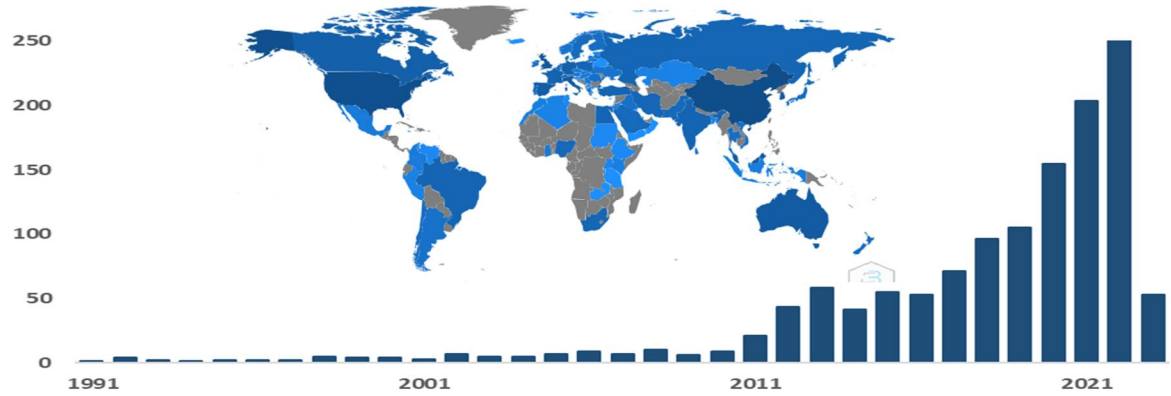


Figure 2. Distribution of published articles.

Data preparation

Abstracts were used for the text mining analysis, consistent with approaches in prior studies (e.g., (Papadouka et al., 2016)). The data preparation process involved several steps. First, duplicate references to the same term, such as "IoT" and "Internet of Things," were consolidated. Second, n-grams (multi-word phrases) were identified using Sketch Engine and standardized by replacing spaces with underscores. Third, stop words (e.g., "study," "design," "method") were defined based on a list of frequent single words generated by Sketch Engine. Fourth, terms from the search query, such as blockchain, big data, IPD, BIM, and AI, were removed to avoid bias. Finally, tokenization and lemmatization were performed to normalize the text.

Topic Modelling and Visualization

Topic modeling is a text mining technique used to extract semantic information from a corpus. Various algorithms have been implemented in programming languages such as Python, including libraries like Gensim and Scikit-learn (Sun et al., 2020). This study employs the LdaModel from Gensim, programmed in Python, to identify latent topics.

Following the recommendations of Griffiths and Steyvers (2004)We used Gibbs sampling to determine the optimal number of topics, testing values of T ranging from 5 to 15 with 1,000 iterations. This process identified six topics. Table 2 presents the top 10 keywords for each topic, along with the temporal distribution of articles, based on the frequency and percentage of each topic's prevalence in the corpus for each year.

Validation

To validate the adequacy and relevance of the identified topics, we applied the Scikit-learn library in Python, configured for six topics, and compared the results with those from Gensim. While the outcomes were similar, Gensim's results were more interpretable and coherent, making it more suitable for our dataset. Additionally, three academic experts and two practitioners, each with over five years of experience in DT in the construction industry, reviewed the topics and confirmed their alignment with the field's core disciplines.

Figure 3 visualizes the topic of "Organization and Project Management." The right panel displays the most frequent words associated with this topic, while the left panel presents all topics as numbered circles. Larger circles indicate greater topic prominence, and closer circles reflect higher topic similarity. The 2D plane, defined by principal components PC1 and PC2, illustrates the distances between topics. The six main topics are influenced by input parameters, which affect topic composition, word selection, and model sensitivity. A guide in the bottom-left corner of the figure indicates each topic's coverage within the corpus. The distance between topic clusters reflects their relationships, with greater distances indicating effective data separation. By selecting a topic on the left panel, users can view its associated words on the right panel, where bars next to each word display frequency metrics: blue represents the word's frequency across all articles, and red indicates its frequency within the selected topic. Clicking on a topic circle highlights its words and relationships with other topics.

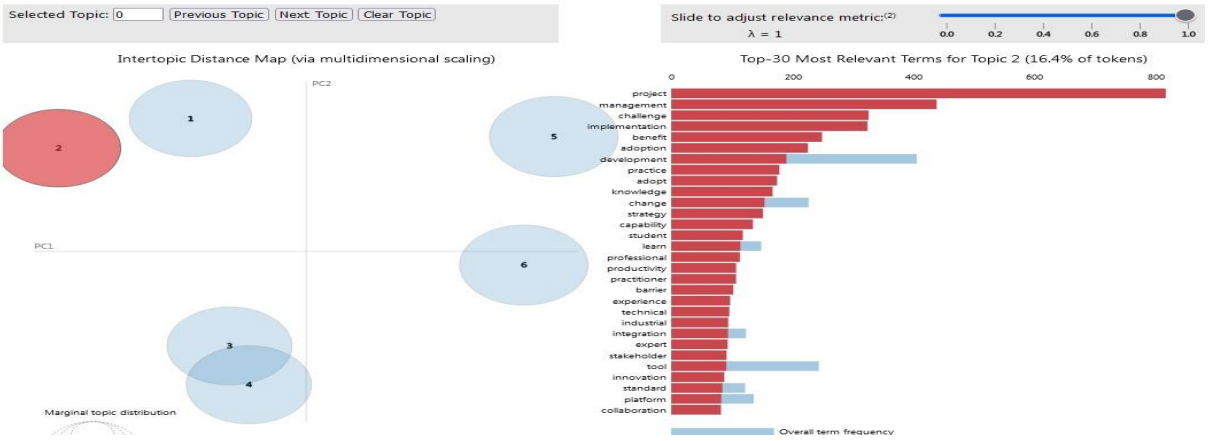
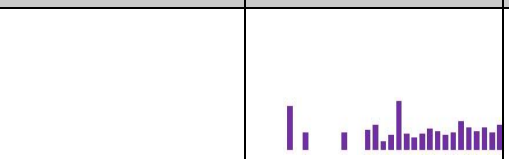
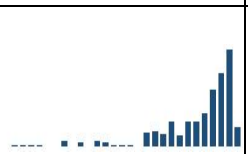
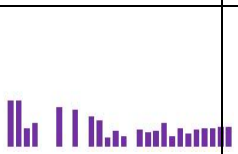
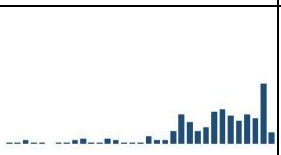
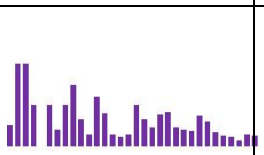
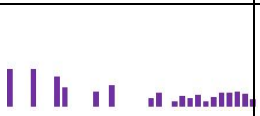
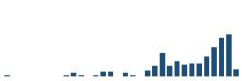
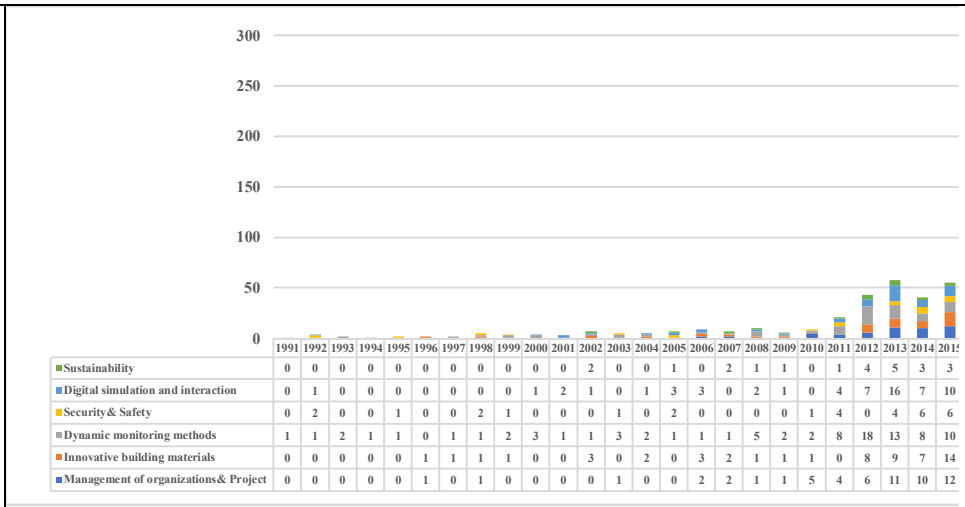


Figure 3. Interactive LDAVis presentation of topics (topic#2 Management of organizations& Project)

Table 2. Topics in all years, with distribution in years

Row	Document-Count& % (in order of abundance)	Trend		Top 10 contributing terms to the topic	Topic (% of corpus)
		Frequency 1991 Q1,2023	Percentage 1991 Q1,2023		
1	292 (22.32 %)			project, management, adoption, strategy, implementation, challenge, benefit, barrier, productivity, adopt	:Topic 2 Management of organizations& projects
2	248 (18.96 %)			material, print, concrete, structure, element, structural, mechanical, printing, composite, manufacturing	Topic 5: Innovative building materials.
3	239 (18.27 %)			measurement, dimensional, dynamic, technique, structure, algorithm, prediction, detection, accuracy, position	Topic 6: Dynamic monitoring methods
4	195 (14.91 %)			security, issues, risk, protection, legal, regulation, society, worker, safety	Topic 1: Security & Safety
5	177 (13.53 %)			software, application, network, computer, reality, integrate, infrastructure, visualization, user, real	Topic 3: Digital simulation and interaction.
6	157 (12%)			sustainability, energy, environmental, performance, efficiency, process, requirement, plan, assessment	Topic 4: Sustainability

Overview



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Sustainability	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	2	1	1	0	1	4	5	3	3
Digital simulation and interaction	0	1	0	0	0	0	0	0	0	1	2	1	0	1	3	3	0	2	1	0	4	7	16	7	10
Security& Safety	0	2	0	0	1	0	0	2	1	0	0	0	1	0	2	0	0	0	0	1	4	0	4	6	6
Dynamic monitoring methods	1	1	2	1	1	0	1	1	2	3	1	1	3	2	1	1	1	5	2	2	8	18	13	8	10
Innovative building materials	0	0	0	0	0	1	1	1	1	0	0	3	0	2	0	3	2	1	1	1	0	8	9	7	14
Management of organizations& Project	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	2	2	1	1	5	4	6	11	10	12

Section 4 provides a concise overview of each topic identified in the field of DT in the construction industry, along with the temporal distribution of these topics. The topics are presented in order of their prevalence, based on the frequency of studies within each topic.

Results

Management of organizations& projects

This topic was titled “Management of organizations& Projects”. The topic covers 22.3% of the corpus and ranks first. It evaluates the processes, opportunities, advantages, challenges, benefits, and role of DT in the construction industry and project management (Demirkesen & Tezel, 2021; Phang et al., 2020). Since 2006, subjects of this topic have been considered more than before and have grown increasingly.

This group has a sub-topic that deals with creating new ways to cope with the digital-centered world in the construction industry. It also looks at how technology affects organizations and projects. It is argued that any technology that can change a project and keep it alive also changes the way project management works in that organization (Braun & Sydow, 2019; Iansiti & Lakhani, 2017; Jammulamadaka, 2020). All these innovations lead the construction industry and management of construction projects toward the digital era with more efficiency.

Therefore, true data on the progress and reports of the project will be available to the main agents (Jadidoleslami & Azizi, 2022). However, we can argue that the construction industry is not digitally mature enough to be affected by these positive changes. This immaturity means the existence of problems and obstacles in the use of digital technologies, as well as the lack of optimal use of available digital technologies (Demirkesen & Tezel, 2022). This topic encompasses subtopics such as evaluating the challenges, needs, requirements, and capabilities for adopting disruptive technologies in the construction

industry. It also explores the role of DT in facilitating performance development, enhancing productivity, and promoting organizational learning within the industry. The rapid advancement of technology in recent decades has generated new demands for organizations, clients, designers, contractors, and project managers (Agarwal et al., 2016; Waqar et al., 2023). Construction companies need a clear plan to go digital. They need to know their goals, investments, purchases, and schedules. The first step is to create a digital footprint that connects and shows everything. Then, they need to check and improve their digital footprint performance and measures. This will help them make their work more effective (Son et al., 2015). DT can change the organizational structure by looking at technologies independently. This helps to make decisions based on data, analyze patterns, and increase success.

Another sub-topic of this group studies how to develop and use new ways to measure the effect and value of DT in the construction industry. These ways help managers and leaders to make better and faster decisions (Hwang et al., 2022; Ngo et al., 2020). The analytical methods and reports help managers to move projects along the determined path. With the help of these reports, managers and stakeholders can easily analyze a wide range of data (Dolla & Delhi, 2023).

Innovative building materials

The second main topic with 248 articles (18.9% of the corpus) is "Innovative building materials". It began in 1996 and grew faster after 2017 due to digital technologies for new or improved materials. It covers new materials (e.g., concrete, composites, nanomaterials) and their use in the construction industry. It also covers new technologies and methods (e.g., additive manufacturing, self-healing concrete) to achieve sustainability and strength (Grabowska & Kasperski, 2020). On the other hand, DT includes the use of technology to improve efficiency, productivity, and sustainability in the construction industry (Sinka et al., 2020). Another sub-topic addressed in this subject is predicting and diagnosing failures of engineering structures in the construction industry. The development of materials science, advanced processing, forming and mechanization, and advanced digital materials Modelling and design techniques, all are considered in this topic. They help to improve the performance of the value chain and increase the predictability of this science (Ranjan et al., 2022; Sinka et al., 2020). By using sustainable materials and methods alongside digital tools and technologies, stakeholders can improve the efficiency, productivity, and sustainability of construction projects.

Dynamic monitoring methods

This topic (18.2% of corpus) is about "Dynamic monitoring methods" for disruptive technologies in construction. It started in 1999 and covers:

- Measuring and Modelling structural features and properties
- Testing construction materials in the lab and numerical studies

- Using image processing and laser signal algorithms to monitor, predict, and diagnose failures (Hadavandsiri et al., 2019; Kim et al., 2018; Ko, 2010).

This group has a sub-topic that uses techniques like 3D laser scanning, photogrammetry, holography, and interferometry etc. to measure and analyze structures in the construction industry. Another sub-topic uses techniques to measure and analyze structures' shape, size, position, and movement in the construction industry. For example, it studies how to use image processing and laser signal algorithms to get data from structures' images and laser signals. Then, it uses this data to get and understand information about their shape, size, and position (i.e.,(Ballaben & Rosales, 2018; Kumar et al., 2022)).

Security& Safety

The "Security and Safety" topic, comprising 195 articles and accounting for approximately 14.9% of the corpus, ranks fourth among the six main topics identified in the field of DT in the construction industry. This topic first emerged in 1992 with Preiss's article, which explored the legal and civil implications of using the Global Positioning System (GPS) in construction. At the time, GPS, a military satellite-based radio navigation system, was planned for civilian use upon completion. The study highlighted the gap between legal frameworks and technological advancements, addressing the legal and societal impacts of civilian GPS adoption in the construction industry (Preiss, 1992). This subject had an important subtopic. No study was done on this topic after this study until 2011. After 2011, more studies were done on this topic. The "security and safety" topic became more serious because of the new and changing technologies in the construction industry. Another sub-topic of this group is identifying the challenges and practical solutions to preserve the security of data and information for trust building in digital transformations, and the use of disruptive technologies and their adoption. Some of these studies have addressed DT in the construction industry in terms of legislation and physical cyber systems under cluster security (Maskuriy, Selamat, Ali, et al., 2019).

According to the studies of this topic, some of the disruptive technologies, such as IOT (Zhang et al., 2022) or blockchain (Jadidoleslami & Azizi, 2022; Xu et al., 2022), can be useful in protecting information security or improving the sharing mechanisms used in data. On the other hand, some of these technologies, such as drones (Mokoena et al., 2022) have raised security, safety, and privacy concerns for citizens. Data security is one of the critical aspects of DT in the construction industry. Although protocols and contracts related to the adoption of certain technologies such as BIM, IoT, and AI have been developed, most construction experts still don't have enough knowledge about their legal implications (Fan et al., 2019; Nair & Mathew, 2022). The security and safety issues faced by DT in the construction industry are not only limited to data ownership in platforms and technologies, but also include system security and data safety related to cyber planning, physical system security, software, and hardware. The main objectives include cyber-physical system security, confidentiality, integrity, availability, and accuracy (TEO, 2021; Tschider, 2018).

This sub-topic talks about the environment and labor safety issues with using digital platforms and disruptive technologies. These studies are not as numerous as the data security studies. But these studies have become more important recently. This is because some of these technologies can make safety better and reduce accidents. This is important because the construction industry has a lot of accidents in many countries (Melzner et al., 2013). The articles of this topic, by introducing digital technologies such as BIM, Big Data, exoskeletons, AR glasses, and wearable monitoring devices, have examined the achievability of higher security standards (for example (Guo et al., 2023; Plioutsias et al., 2018)).

Digital simulation and interaction

The "Digital Simulation and Interaction" topic, comprising 177 articles and accounting for approximately 13.5% of the corpus, ranks fifth among the six main topics in the field of DT in the construction industry. This topic encompasses subtopics that explore how digital tools and technologies enhance construction processes, as well as the impacts, solutions, advantages, and challenges of adopting disruptive technologies in the industry. It focuses on the use of computational methods to simulate and test various aspects of construction projects and the application of software, programs, networks, infrastructure, visualization tools, and interfaces to enable user interaction with simulated environments. Notably, a significant portion of studies within this topic have focused on Building Information Modeling (BIM) technology. Over the past decade, the construction industry has increasingly prioritized BIM implementation (Aibinu & Papadonikolaki, 2020; Locatelli et al., 2021; Phang et al., 2020; Prodius et al., 2020). However, recent efforts of DT in the construction industry have seen the integration of other emerging technologies with BIM and the construction process (Aung et al., 2022; Lin et al., 2022). Yet, other technologies such as VR or augmented reality, cloud computing, drones, blockchain, and AI have also received attention in recent years (Hamledari & Fischer, 2021; Sampaio et al., 2004; Yang et al., 2020). The subtopics combine technologies and explore new opportunities and challenges for DT in the construction industry. They need more research on their role and potential. The studies first focused on technology, but later realized that DT affects many aspects of the industry.

Sustainability

This topic, "Sustainability", has 157 articles (12% of the corpus) and ranks sixth. It started in 2002 and has grown faster since 2012 due to environmental concerns. It covers economic, social, and environmental sustainability in construction projects affected by DT. It also examines the challenges, opportunities, and resource use of the industry's technologies. The main issues are:

- Assessing and improving buildings' sustainability, energy efficiency, and environmental performance with DT
- Creating tools to optimize designs and costs with DT goals and criteria

- Lowering energy use and optimizing construction processes for environmental sustainability
- Optimizing sustainable buildings' design and performance based on environmental and social needs (de Almeida Barbosa Franco et al., 2022; Orzeł & Wolniak, 2022).

The relationship between sustainability and DT involves the use of digital technologies to enhance sustainable practices in various industries. DT can reduce waste, increase efficiency, and optimize the use of resources. For example, in the energy sector, digital technologies such as intelligent networks and energy management systems can reduce energy consumption, carbon emissions, and improve energy supply (Jiménez-Roberto et al., 2017). Generally, integrating DT in sustainable practices can lead to more efficient and environmentally friendly operations.

In the following, we try to evaluate the main topics of the field of DT in the construction industry during different periods and analyze the gaps in the literature and possible future studies.

Discussion

Figure 4 shows the subtopics related to each subject and the analysis of future directions for the dominant subjects.

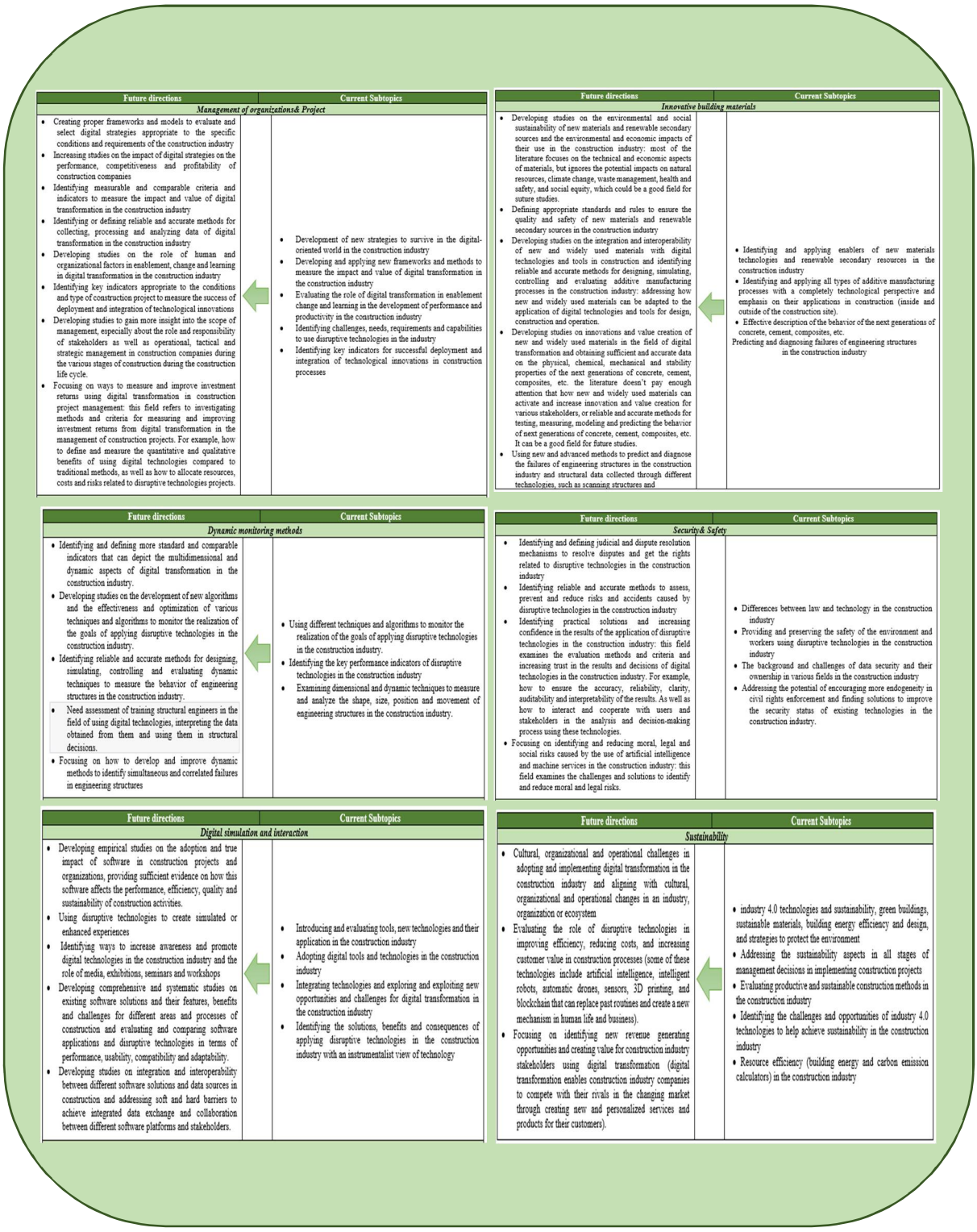


Figure 4. Subtopic and Future directions

Figure 4 shows current subtopics of each labelled topic, which are specific aspects of DT in construction industry, identified in classified articles for each topic. They are subsets of each main subject that reflect current and emerging issues and challenges in this field. For example, security and safety topic has 4 subtopics with various aspects and issues of DT security and safety in construction. Also, future directions in the table show research gaps and possible directions to facilitate and realize DT in the construction industry. They relate to the topic and are identified through analysing inclusive and non-inclusive cases in studies of each topic.

Implications for research and practice

This study employed topic modeling to analyze concepts of DT in the construction industry. This method offers an innovative and efficient approach to reviewing and categorizing literature by tracing the historical development of DT in the construction sector. It enables researchers to identify and visualize hidden patterns and relationships among concepts and topics using text data. Topic modeling can complement other literature analysis methods, such as systematic reviews, enhancing the depth of analysis. The study yields significant implications for both research and practice in the field of DT in construction, as outlined below:

- It supports industry stakeholders in developing and implementing effective strategies for adopting digital technologies by providing a clearer understanding of current trends and future directions.
- It enhances comprehension of the current and future landscape of digital technologies in the construction industry. By offering a comprehensive and analytical overview of existing literature, the study establishes a coherent conceptual framework for DT research in construction, serving as a theoretical and practical foundation for researchers and practitioners engaged in DT.
- It identifies future research opportunities and gaps for those pursuing DT in construction, including exploring innovative business models and value creation through DT, evaluating methods to measure and optimize return on investment in DT initiatives, addressing challenges and solutions in managing construction projects with DT, and developing enhanced or simulated experiences using disruptive technologies.
- It provides a framework for advanced investigation and sustained engagement in DT within the construction industry, encouraging deeper exploration for researchers and practitioners..

Conclusion

This study investigates the knowledge structure and research trends of DT in the construction industry using topic modeling, a text mining technique. It analyzes 1,308 journal articles published from 1991 to April 2023 through topic modeling and pattern analysis, identifying six main topics in the DT literature: Organization and Project Management, Digital

Simulation and Interaction, Sustainability, Innovative Building Materials, Dynamic Monitoring Methods, and Security and Safety. Additionally, it delineates subtopics and future research directions for each topic.

As the first study to employ topic modeling on a large literature sample to map the knowledge structure and research trends of DT in the construction industry, it extends beyond technological aspects to encompass diverse dimensions and levels of DT implementation in the sector.

For example, compared to the leading studies in this field, such as the study conducted by Adekunle et.al. that analyzed this issue in terms of technologies (Adekunle et al., 2021) mentioned in Table 1, the results of this study cover a wider range of aspects of DT in construction. It is because undoubtedly, the main issues, such as DT, will not lead to transformation just by a single-level view, such as a purely technological view, and it requires a more comprehensive view. Unlike the topics introduced in the study conducted by Adekunle et.al, which have only focused on disruptive technologies of the construction industry, the topics identified in this study reflect the most innovative transformations and the process of DT in construction, such as digital interaction and simulation, innovative building materials, and dynamic monitoring methods. Moreover, compared to the study conducted by Ghobakhloo et.al. (2021), this study has used a larger sample of literature (1310 vs. 745 articles) during a longer period (30 years vs. 10 years) and applied a more complex method for text analysis (topic Modelling vs. bibliometrics). In addition, it could analyze a large number of studies and a relatively large part of the literature.

When interpreting the findings of this study, the following limitations should be considered:

1. The research scope was limited to the Web of Science (WoS) database. This restriction may have introduced bias into the sample, as it may have excluded relevant articles or emerging concepts of DT in the construction industry published in other sources.
2. The analysis relied solely on article abstracts. Although abstracts provide more detailed information than titles or keywords, analyzing full texts could yield additional topics or insights in topic modeling.
3. The topic modeling analysis utilized the Gensim library in Python and was not compared with other topic modeling algorithms. Furthermore, results may vary slightly due to the inherent limitations of the Gensim algorithm, representing a constraint of this study.

To address these limitations, the following recommendations are proposed for future studies:

1. Expand the scope of literature searches to include additional databases and resources, such as Scopus, Google Scholar, and scientific society publications, to ensure a more comprehensive collection of DT literature in the construction industry.

2. Incorporate full-text content, including references, to enrich the dataset and enhance the accuracy of topic modeling.
3. Compare the performance of different topic modeling algorithms and optimize their parameters to achieve more robust and reliable results.
4. Conduct in-depth, qualitative analyses of each topic and sub-topic through independent studies to develop a more systematic and comprehensive understanding of DT in the construction industry

Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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