Automation in Construction 158 (2024) 105212

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Review

Digital technologies in architecture, engineering, and construction

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ARTICLE INFO

Keywords:
Industry 4.0
AEC sector
Technology
Digitalisation

ABSTRACT

Digitalization in the architecture, engineering, and construction (AEC) sector is slow due to significant challenges in technology adoption. The study aims to promote technology adoption by advancing the understanding of digital technologies in the AEC sector. This article presents the findings from a quantitative scoping review, encompassing 3950 technology-related abstracts retrieved from the *Scopus* database, providing a preliminary assessment of literature size, geographic innovation hotspots, research gaps, and key concepts in the AEC field. The results show that Building Information Modelling (1852 studies) dominates the literature, while topics like 3D Printing (311) and Internet of Things (227) are gaining traction. China (687 publications) and the United States (566) produce most research articles. Despite the increasing interest in emerging technologies, their implementation often necessitates acquiring specific skill sets. Academia needs to put a stronger focus on these technologies in education and tighter collaboration with the industry is needed.

1. Introduction

1.1. General background

The architecture, engineering, and construction (AEC) sector is known for its traditional methods and slow adoption of technological advancements and innovations. It is considered one of the least digitised industries, with significantly lower investments in research and development compared to other sectors [1] and is also facing severe labour shortages [2]. As a result, its productivity growth is lagging behind other more digitalised industry sectors, e.g., the manufacturing sector [3].

Multiple factors contribute to the slow adoption of technology, including the sector's fragmentation, the project-based nature of construction activity where buildings cannot be regarded as serial products, and the temporary nature of supply chains. These factors hinder frictionless communication and information management [4,5], which further causes timepass in construction projects [6]. Additionally, building construction usually takes place in uncontrolled environments that are exposed to shifting external influences and is carried out according to project-specific boundary conditions and stakeholder decisions. This makes the implementation of, e.g., automation, harder compared to other industries, for instance, manufacturing [4].

Although transforming the AEC sector with digital technologies is challenging, new knowledge about technology implementations can help research and practice. There is a greater need for a new kind of packaging of information about digital technologies in the academy and industry. This is evident through the increased research interest in digital technologies and the emergence of novel conceptualizations, such as digitalization, digital transformation, virtual design construction and Industry 4.0, aimed at better understanding the transformation. These conceptualizations confine a multitude of technologies and technological phenomena. Although previous research has used these conceptualizations, their application in AEC sector research is still quite limited. Thus, there is a need for a more precise definition and application of the terms. One such conceptualization is Industry 4.0, also known as the *Fourth Industrial Revolution* [7], which is taken as a framework for analysis in this review article.

Hofmann and Rüsch [8] describe *Industry 4.0* as a "[…] shift in the manufacturing logic towards an increasingly decentralised, self-regulating approach of value creation, enabled by concepts and technologies such as cyber-physical systems, internet of things (IoT), internet of services, cloud computing or additive manufacturing and smart factories, to help companies meet future production requirements". These innovations, when applied to the AEC sector, are continuously driving disruption in the industry, propelling it towards the concept of *Construction 4.0* [9]. Although there is no clear and agreed-upon definition yet, Construction 4.0 may be regarded as a "transformative framework" consisting of three main transformative

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https://doi.org/10.1016/j.autcon.2023.105212
Received 28 August 2023; Received in revised form 7 November 2023; Accepted 17 November 2023

trends [10,11], as based on the work by Tetik et al. [12] on direct digital construction:

1. Industrial production (e.g., prefabrication, 3D printing, modularization, robotics)
2. Cyber-physical systems (e.g., IoT, sensors, actuators, robots, drones)
3. Digital technologies (e.g., Building Information Modelling (BIM), Artificial Intelligence (AI), cloud computing, big data, blockchain, Virtual Reality (VR), simulation)

The Construction 4.0 concept is regarded as a substantial opportunity [2,9] for enhancing productivity and efficiency, and addressing the challenges regarding the AEC sector's immense environmental impact [13]. In the EU, the sector accounts for approximately 18 million jobs and contributes nearly 9% to the EU's gross domestic product [14]. The importance of increasing the competitiveness and digitalisation of the AEC sector is documented in several European policy initiatives, such as the *Digital Europe Programme* [15], the *Circular Economy Action Plan* [16], and the *Renovation Wave* [17]. The specific challenges inherent to the nature of the AEC industry require tailored solutions, technology advancements, and standardization frameworks to enable quick and comprehensive adoption of the Construction 4.0 technologies by all stakeholders.

While Industry 4.0 is still unfolding as a pathway to make manufacturing and production "smart", *Industry 5.0* is already conceptualized boosting the synergies of unique human expertise paired with powerful, smart and accurate machinery [18]. However, as the European Commission's Directorate-General of Research and Innovation stresses, "[…] Industry 5.0 should not be understood as a chronological continuation of, or alternative to, the existing Industry 4.0 paradigm", but rather as complementation and extension of it [19]. Industry 5.0 is characterised by highly skilled, intellectual professionals guiding high-speed and accurate machines to bring back the human character and creativity to manufacturing. One of the guiding principles frequently mentioned in this context is "mass customisation" or "mass personalisation" [18–20]. This should be achieved for instance by employing collaborative robots ('cobots') [21] in the production process [18–20,22]. However, *Construction 5.0* as an implementation of the Industry 5.0 paradigm remains a vision and developing concept to be explored in future studies [22]. Thus, this article focuses on the more – yet not fully – established Industry 4.0/Construction 4.0 concepts.

1.2. State of the art

This review article distinguishes itself from previous research in terms of its unique and holistic scope and methodology, thereby introducing new findings and discussions. In an earlier review, for example, Forcael et al. [23] focused on a bibliometric analysis of 257 research articles spanning 2014 to 2019 within the realm of Construction 4.0 technology-related scientific literature. They built their review around seven keywords used for identification, namely (1) *New materials related to industrialisation*, (2) *3D printing*, (3) *Internet of Things*, (4) *Artificial intelligence and robotics*, (5) *Computer-aided design technologies*, (6) *Big data*, (7) *Virtual and augmented reality*. They found that the number of publications in this field is growing exponentially, with the United States, United Kingdom, and China taking the front ranks. The most critical technologies for understanding the Construction 4.0 concept are 3D printing, big data, VR and IoT according to the authors.

Meanwhile, Schönbeck et al. [24] conducted a quantitative analysis of 2342 journal papers published between 2015 and 2019 to investigate the extent to which research on construction project management addresses Construction 4.0 technologies within information and communication, automatization or industrialisation. One of the key findings is that synergies between different technologies are underexplored in the investigated body of literature. As opposed to the findings in [23], Schönbeck et al. did not find a significant increase in journal publications on new technologies between 2015 and 2019.

Kozlovska et al. [25] explored the implementation status of Industry 4.0 technologies in the construction industry and analysed their impact on the Construction 4.0 concept, utilizing 195 research articles published between 2014 and 2020. In their findings, the authors write that the Industry 4.0 concept has the greatest impact on productivity growth in construction and that every year, interest in digital technologies is growing. However, their penetration into the construction industry is currently slow and limited, they found. Similar to Schönbeck et al. [24], they suggest that future research needs to focus on the synergies between different Construction 4.0 technologies.

In another vein, Chen et al. [26] conducted a systematic review of emerging technologies in the construction industry, drawing insights from 175 articles published between 2001 and 2020. In total, they identified 26 different technologies in these articles. The findings indicate that the technologies for data acquisition and visualisation dominate the application of technologies in the construction sector, with BIM being the single most common technology. They call for more research and cross-disciplinary studies on the barriers to the implementation of technologies within and outside of AEC organisations.

However, these studies focused on a manual and detailed screening of limited literature subsets [24], or notably smaller subsets of literature [23,25,26]. In all cases, a relatively narrow range for the publication years of included articles was set. This is mainly because these earlier studies aimed to look at Construction 4.0 from different and narrower angles than is done in the present research. Here, a more holistic approach is followed, including a wider spectrum of literature, both from a thematic and temporal point of view. Moreover, the previous reviews do not include an investigation of the topicality of technologies, possibly due to missing or non-established indicators for this purpose. Thus, a new indicator, the *Normalized-Year Index* (NYI) is introduced in this study. In conclusion, a new paper is needed on this topic to provide a more comprehensive and holistic examination of Construction 4.0 conceptualization in the AEC sector, which goes beyond the scope of previous studies that focused on limited subsets and narrower perspectives.

1.3. Objectives and structure

The primary objective of this study is to comprehensively investigate the challenges and potentials of technology adoption in the AEC sector, as introduced in the Construction 4.0 concept. By offering a holistic and comprehensive description of technological advancements, including the literature from the years before the term Construction 4.0 was coined, this research aims to unveil the dominant topics, identify regions that are represented and underrepresented in existing literature, and highlight the increasing interest in innovative technologies within the AEC sector.

By explaining how the AEC sector is currently facing significant challenges and opportunities due to technological advancements, this study contributes to understanding these challenges and the potential for addressing contemporary issues in the industry. The AEC sector plays a critical role in the economy and society, and technological innovation within this sector can lead to substantial societal and economic benefits. By examining the AEC sector's technology adoption capabilities over time, this article contributes to the advancement of technological innovation as contextualized by the Construction 4.0 concept in the future.

The following questions are of interest:

- What are the dominant, emerging, underdeveloped, and niche technologies within the context of Construction 4.0?
- What is the geographical distribution of Construction 4.0 technologies in scientific literature?

- How can various stakeholders collaborate to advance the Construction 4.0 concept, and what significance does access to information hold in fostering this collaboration?

To address these questions, the study relies on the results of a scoping review, the methodology of which is detailed in Section 2. The results are presented in Section 3, followed by a discussion in Section 4. The paper concludes in Section 5.

2. Methodology

2.1. Scoping review

This article employs a scoping review approach to identify and analyse Construction 4.0 technologies within an extensive body of scientific literature. Fig. 1 presents a flowchart of literature identification, screening and analysis methods applied in this study. The technologies used for literature screening are listed in Table 1. Altogether, 38 different technology categories were utilized in the analysis. These categories had been identified as relevant and comprehensive in previous research on digitalisation in the AEC sector [27], as well as during the process of literature identification and screening.

A scoping review is a suitable choice for this study due to the rapidly emerging nature of the literature and its lack of precise definition in previous research; conducting a systematic review at this stage would be premature [28]. Scoping reviews are similar to systematic reviews as both use "rigorous and transparent methods to comprehensively search for all relevant literature and to analyse and interpret the data" [29]. However, the two review types differ in terms of their purposes and aims. A systematic review, on the one hand, typically addresses a well-defined question, focuses on empirical studies, and aims to provide answers from a relatively small subset of quality-assessed studies of the literature body [29,30]. On the other hand, a scoping review addresses broader topics and is less likely to assess the quality of included studies [30]. It is of an exploratory nature and aims to draw up an overview of all relevant literature on a broad topic and identify recurring themes and key issues [29,31]. Consequently, a scoping review provides a "preliminary assessment of potential size and scope of available research literature" [28]. Furthermore, given their exploratory nature with a focus on sizing the breadth of relevant literature, scoping reviews are distinct from other types of reviews, which typically seek to conduct more in-depth analyses and draw conclusions about a phenomenon or the sampled literature. A scoping review can be used to identify a topic area for a future systematic literature review [31,32].

To identify the body of literature, the Python package *elsapy* [33] was used. This package allows access to the *Elsevier* application programming interface (API) [34]. It was used to access titles within the Scopus database which is an abstract and citation database including >84 million records from >7000 publishers [35]. The advantage of using this method and database is the possibility of a fully automated process of identifying, bulk-downloading, structuring and managing vast amounts of metadata. Additionally, abstracts in the database are freely available independent of access limitations due to missing institutional subscriptions to publishers. This approach was chosen as there are strict limitations to an automated mass download of full texts via APIs today. Moreover, it can be reasonably assumed that the authors of the papers that this research article aims to identify, at least mention the addressed technology once in the abstract. With this approach not only a more comprehensive body of literature can be screened (automatically), but it is also less biased by random mentions of specific terminologies that might be related to the addressed topic of a study, but not its focus. This applies especially to the introduction or reference sections of such

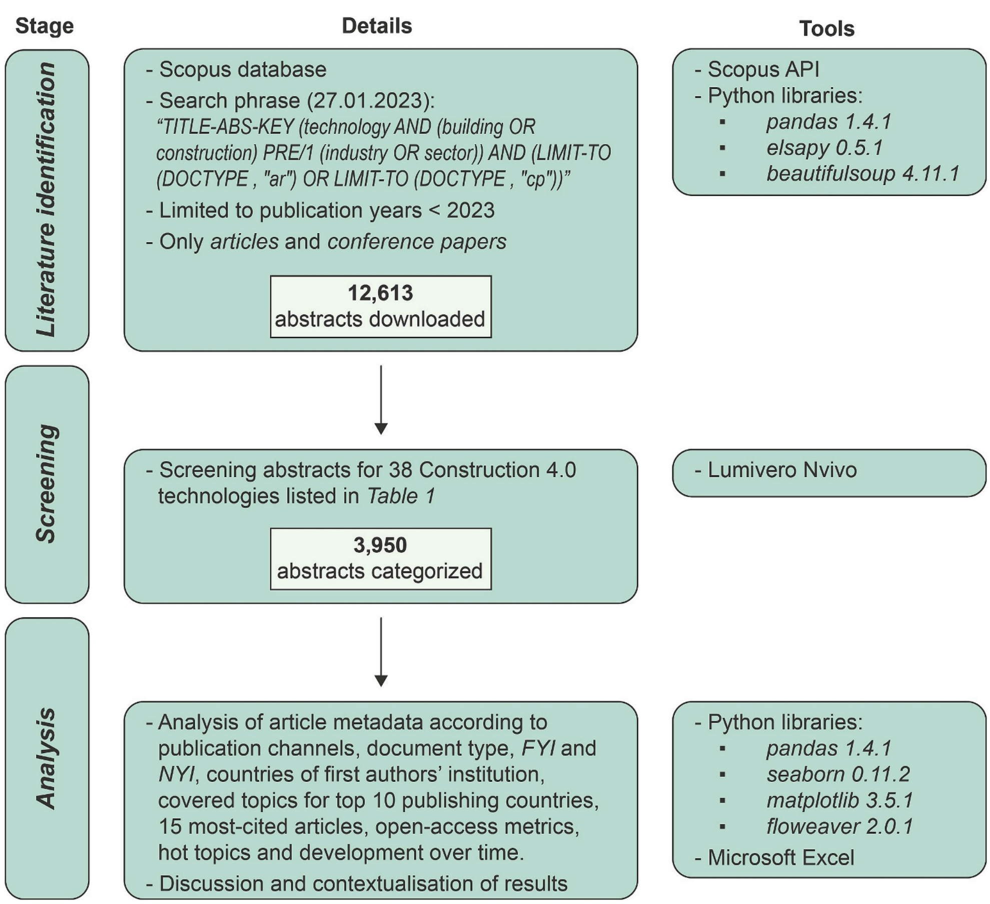

Fig. 1. Schematic visualisation of applied review methodology in this study.

Table 1
Construction 4.0 technologies, short definitions, and Nvivo search phrases.

Nr.	Construction 4.0 technology	Short definition	Nvivo search phrase
1.	3D modelling	3D modelling involves using software to create digital representations of objects.	(((“3D model” OR “3 D model”) OR (“3D models” OR “3 D models”)) OR ((“3D modeled” OR “3 D modeled”) OR (“3D modeling” OR “3 D modeling”))) OR ((“3D modelled” OR “3 D modelled”) OR (“3D modelling” OR “3 D modelling”))
2.	3D printing / Additive manufacturing	3D printing, also known as additive manufacturing, is a process of creating physical objects by adding material layer by layer based on a digital design.	((“3D print” OR “3 D print”) OR (“3D prints” OR “3 D prints”)) OR ((“3D printed” OR “3 D printed”) OR (“3D printing” OR “3 D printing”)) OR “additive manufacturing”
3.	5G	5G is the fifth generation of wireless technology, providing faster data speeds, lower latency, and improved connectivity for mobile devices and IoT devices.	5G
4.	Access control	Access control refers to the technologies used for managing who can enter or use specific areas, systems, or resources.	“access control”
5.	Artificial Intelligence (AI), Machine Learning (ML)	AI is computer intelligence that mimics human-like tasks. ML is a type of AI where computers learn from data.	(“artificial intelligence” OR “machine learning”) OR (AI OR ML)
6.	Automated Valuation (Model) (AVM)	AVM is software that estimates the value of real estate properties using mathematical algorithms and data analysis.	“automated valuation” OR AVM
7.	Big Data	Big Data refers to large and complex sets of digital information that require specialized tools and techniques for analysis and interpretation.	“big data”
8	Blockchain	Blockchain is a decentralized digital ledger technology used to record and verify transactions across multiple computers.	“blockchain” OR “block chain”
9.	Building Information Modelling (BIM)	BIM is a digital method for creating and managing detailed 3D models of buildings, including data about their parts and systems, for construction, design, and maintenance purposes.	((BIM OR “building information model”) OR (“building information modelling” OR “building information modeling”)) OR “building information models”
10.	Chatbot	A chatbot is a computer program designed to simulate conversation with human users.	(chatbot OR chatgpt) OR (“chat gpt” OR “chat bot”)
11.	Cloud technology	Cloud technology refers to the use of remote servers accessed through the internet to store, manage, and process data and applications.	Cloud
12.	Computer Aided Design (CAD)	CAD is the use of computer software to create detailed digital models and drawings of objects.	“computer aided design” OR CAD
13.	Crowdfunding	Crowdfunding is a method of raising funds for projects or ventures by collecting small contributions from many people.	((crowdfunding OR crowdsourcing) OR (“crowd funding” OR “crowd sourcing”)) OR ((crowdfunded OR crowdsourced) OR (“crowd-funded” OR “crowd-sourced”))
14.	Cryptocurrency	Cryptocurrency is a type of digital or virtual currency that uses cryptography for secure transactions.	Cryptocurrenc*
15.	Customer Relationship Management (CRM)	CRM is a technology and strategy used by businesses to manage interactions with customers.	“customer relationship management”
16.	Data analytics	Data analytics is the practice of analysing data to discover patterns and insights that inform decision-making.	“data analytics”
17.	Digital Twin	A digital twin is a virtual representation of a physical object, system, or process that allows for monitoring, simulation, and analysis.	“digital twin” OR “virtual twin”
18.	Drones, Unmanned Aerial Vehicles (UAV)	Drones, or UAVs, are aircraft operated without a human pilot on board, often used for purposes such as surveillance, photography, and data collection.	((Drone OR UAV) OR (“unmanned aerial vehicle” OR “unmanned aerial vehicles”)) OR (drones OR UAVs)
19.	Geolocation	Geolocation is the process of determining and identifying the physical location of a device or individual.	Geolocat*
20.	Geospatial/ Geographical Information Systems (GIS)	GIS refers to technologies that capture, analyse, and visualize geographic data.	(“geographic information system” OR GIS) OR (geospatial OR “geo-spatial”)
21.	Global Positioning System (GPS)	GPS is a satellite-based navigation system that provides accurate location and time information on Earth.	GPS OR “global positioning system”
22.	Internet of Things (IoT)	IoT is a network of interconnected devices and objects that can communicate and exchange data with each other through the internet.	“internet of things” OR IoT

(continued on next page)

Table 1 (*continued*)

Nr.	Construction 4.0 technology	Short definition	Nvivo search phrase
23.	Location analytics	Location analytics involves analysing and interpreting data based on geographic location.	"location analytics"
24.	Material science	Material science involves the study and development of materials to create products with improved properties and performance.	"material science" OR "material technology"
25.	Metaverse	A metaverse is a virtual world where people interact, socialize, and engage using digital avatars and immersive technologies.	Metaverse OR (("virtual world" ~ 2) OR ("virtual environment" ~ 2))
26.	Modular construction	Modular construction refers to using pre-made, standardized modules for construction that are manufactured off-site and then assembled on-site.	Modular AND (building OR construction)
27.	Parking	Parking technologies encompass various digital solutions and systems designed to optimize and manage parking spaces.	Parking
28.	Peer to Peer (P2P)	P2P refers to a decentralized network where participants interact directly with each other to share resources, information, or services.	"peer to peer" OR P2P
29.	Predictive analytics	Predictive analytics involves using data and algorithms to forecast future outcomes or trends, helping to make informed decisions and take proactive actions.	"predictive analytics"
30.	Pre-fabrication	Pre-fabrication is the process of constructing building components off-site in a controlled environment before assembling them on the construction site.	((("pre fabrication" OR "pre-fabrication") OR ("prefabrication" OR "prefabricated")) OR (("pre fabricated" OR "pre-fabricated") OR ("prefab"))) OR (("pre-fab" OR "prefabricating") OR ("pre fabricating" OR "pre-fabricating"))
31.	Robot/robotics	A robot is a machine or device programmed to perform tasks autonomously or semi-autonomously, often imitating human actions or functions.	Robot*
32.	Sensors	Sensors are devices that detect and measure physical or environmental changes.	Sensor*
33.	Smart Building	A smart building is a structure equipped with technology and sensors that enable automated control of various systems, such as lighting, heating, and security, to enhance efficiency, comfort, and sustainability.	(("smart building" OR "smart home") OR ("smart house" OR "smart office")) OR (("smart buildings" OR "smart homes") OR ("smart houses" OR "smart offices"))
34.	Smart City	A smart city is an urban area that uses technology and data-driven solutions to improve infrastructure, services, and quality of life for its residents, while promoting sustainability and efficient resource management.	((("smart city" OR "smart urban") OR ("smart town" OR "smart community")) OR ("smart municipality")) OR ((("smart cities" OR "smart urbanized") OR ("smart towns" OR "smart communities")) OR ("smart municipalities" OR "smart urbanised"))
35.	Urban mobility	Urban mobility refers to the movement of people and goods within urban areas, encompassing various transportation modes and systems that enable efficient and sustainable transportation.	((("urban mobility" ~ 5) OR ("town mobility" ~ 5)) OR (("municipality mobility" ~ 5) OR ("community mobility" ~ 5))) OR ((("urban transport" ~ 5) OR ("town transport" ~ 5)) OR (("municipality transport" ~ 5) OR ("community transport" ~ 5)))
36.	User Interface (UI)	UI is the point of interaction between a person and a digital device or software, allowing users to control and communicate with the system.	"user interface" OR "user interfaces"
37.	Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Extended Reality (XR)	VR, AR, MR, and XR are immersive technologies that blend the digital and physical worlds.	(("augmented reality" OR "mixed reality") OR ("virtual reality" OR "extended reality")) OR (("(AR)" OR "(MR)") OR ("(VR)" OR "(XR)"))
38.	Work Flow Management (WFM)	WFM technologies are digital tools and systems that facilitate the efficient design, automation, and monitoring of tasks and processes within an organization to enhance productivity and coordination.	("work flow management" OR WFM) OR WFMS

"∼*x*" is a proximity operator that looks for the occurrence of two words within a range of *x* words.

articles. Abstracts, on the other hand, tend to narrow down the specific focus of a study. Another key advantage of screening abstracts and not full texts is that in Scopus about 20% of indexed articles are written in languages other than English, but still have an English abstract [36]. The common limitation in many reviews of only looking at scientific literature in English language is thereby overcome.

The following search phrase was used to identify all relevant articles: "TITLE-ABS-KEY (technology AND (building OR construction) PRE/1 (industry OR sector)) AND (LIMIT-TO (DOCTYPE, 'ar') OR LIMIT-TO (DOCTYPE, 'cp'))".

Since Scopus applies word stemming, also plural and possessive forms of words in the search phrase are covered. Only documents of type "article" and "conference paper" were included. This excludes non-peer-reviewed documents like books, notes, short surveys, editorials, etc., but also review articles that might bias the results and thus interfere with the study's aim. The proximity operator "PRE/1" indicates that the search terms before and after this operator are searched for with at most one word in between. Through this approach, it is aimed at only identifying relevant literature for the building/construction industry/sector. The search was performed on 27.01.2023 and resulted in a total number of 12,678 elements. It should be noted that only complete years were included in the analysis so that 2022 was the most recent year an included article was published. Via the individual Elsevier-ID (eid) of each identified element and the Elsevier API, an XML file was parsed for metadata and the abstract. If the database contained an abstract, it was saved as a .txt file. Older elements occasionally did not have an abstract associated with the database entry. In total, it was possible to extract and download 12,613 abstracts with a speed of about 1.0 s/per element, or 3.5 h.

Afterwards, the text files were imported into Nvivo [37], a qualitative data analysis software. Within Nvivo, the imported abstracts were searched for specific terms, allowing for their categorization according to the Construction 4.0 technologies listed in Table 1. The reason for the nested search syntax is that Nvivo only allows for two arguments in a single "OR" query. The search focused solely on "exact matches" of the search phrases. In total, it was possible to allocate 3950 out of the 12,613 abstracts (32.1%) to at least one category, with an average of 1.47 categories per abstract.

2.2. Publication year indicators

This study analyses various metrics, including the publication years of the articles under consideration. Two indicators, the *First-Year Index* (FYI) and the *Normalized-Year Index* (NYI, see also eq. 1), are utilized for this purpose. The FYI represents the earliest publication year for an article in a specific technology category from Table 1. The NYI is a novel indicator introduced in this study. In eq. 1, y represents a particular year, y_0 is the year of the earliest study in a certain category, and y_n is the year of the newest study investigated in this article. $f_{w,y}$ is a weighting factor for a particular year y, calculated from $f_{w,y} = n_{C,y}/n_{T,y}$, where $n_{C,y}$ is the number of publications in a specific category in that year, and $n_{T,y}$ is the total number of publications across all categories in a particular year. The NYI is related to the *Weighted-Year Index* in [38], but it does not indicate the average publication year of a category. Instead, it weights the publication years according to the relevance of each category in a given year.

$$NYI = \frac{\sum_{y_0}^{y_n} y^* f_{w,y}}{\sum_{y_0}^{y_n} f_{w,y}} \quad (1)$$

The normalization in the weighting factor $f_{w,y}$, results in a stronger weighting for years in which a particular category represents a larger share of the total publications. Utilizing the arithmetic average or median instead of the NYI would result in a shift towards more recent years of the index. This shift can be attributed to a substantial increase in the total number of publications in recent years. The normalization of the NYI prevents this shift.

The NYI can serve as a measure of the topicality of a specific category. For instance, *Category A* has an FYI of 1980 and an NYI of 1992, while *Category B* has an FYI of 1980 and an NYI of 2013. In the case of *Category A*, this indicates that publications in this category represent a larger share of total studies in earlier years. On the other hand, analysing the FYI and NYI shows that *Category B* gained significance since its inception and has become a more prominent topic in recent years.

2.3. Identification of dominant, emerging, underdeveloped, and niche technologies

In order to meet this study's objective to identify the dominant, emerging, underdeveloped, and niche technologies within the context of Construction 4.0, the following categorization methodology is applied. It is based on the NYI and share s of articles of a particular category of the total number of identified articles calculated from $s = n_C/n_T$, where n_C is the total number of publications identified for a specific category, and n_T the total number of publications across all categories. Categories are considered dominant if they have an NYI older than five years (≤ 2018.0 in this study) and a share of articles larger than the mean share $\bar{s}$ across all categories with at least one identified publication. Thus, they have neither emerged lately nor are currently trending, but managed to attract significant scientific interest over time. Emerging categories are those with an NYI less than five years old (> 2018.0 in this study) and an article share of $> \bar{s}/10$, meaning that a notable amount of articles was published relatively recently. Underdeveloped categories are those that stand for $\leq \bar{s}/10$ of articles, while niche categories are those not currently trending (NYI ≤ 2018.0 in this study), but not being considered dominant or underdeveloped either (share of all publications between $\bar{s}/10$ and $\bar{s}$), see also Table 2.

It needs to be highlighted that both the limit for the NYI (2018 in this case) and for the shares of publications ($\bar{s}/10$ as the lower and $\bar{s}$ as the upper limit) were selected based on the authors' experience and the specific nature of this study. For other topics, subsets of literature, number of categories, etc., different limits might be selected.

3. Results

3.1. Construction 4.0 technologies in scientific literature

Technology is a significant theme in AEC-related scientific literature. The Scopus database contains a total of 71,559 journal and conference articles published until 2022 within the AEC sector. This count was derived from a search query "TITLE-ABS-KEY ((building OR construction) PRE/1 (industry OR sector)) AND (LIMIT-TO (DOCTYPE, 'ar') OR LIMIT-TO (DOCTYPE, 'cp'))". Among these, 12,678 (or 17.7%) were found to be technology-focused, as determined by the previously outlined search approach.

Fig. 2 the yearly publication count of AEC articles and technology-focused articles, along with the respective share of technology-related content. The earliest publication associated with AEC dates back to 1927, whereas, for technology in AEC, it is from 1947. The trend demonstrates a gradual increase in the proportion of technology-focused articles within the overall AEC literature over time. In 2022, 21.9% of all AEC articles are related to technology. Overall, the number of scientific articles follows an exponentially rising trend in both categories (note the logarithmic y-axis in Fig. 2). The median publication year of the technology-related studies in AEC is 2016.

Overall, among the 12,613 elements that had an abstract, there were slightly more conference papers (6790, or 53.8%) than journal articles (5823, or 46.2%). As listed in Table 3, the *IOP Conference Series: Earth and Environmental Science* features most studies in the investigated subset of literature with 298 titles, followed by the two journals *Automation in Construction* (272 titles) and *Journal of Construction Engineering and Management* (268 titles).

A total of 3950 studies were categorized using the Construction 4.0 technologies listed in Table 1. Within this body of literature, *BIM* stood out with the highest count (1825 studies), followed by *VR, AR, MR,* and

Table 2
Applied methodology to identify dominant, emerging, underdeveloped, and niche topics.

	NYI	Share of articles
Dominant	≤ 2018.0	$> \bar{s}$
Emerging	> 2018.0	$> \bar{s}/10$
Underdeveloped	–	$\leq \bar{s}/10$
Niche/limited reach	≤ 2018.0	$\bar{s}/10 < s \leq \bar{s}$

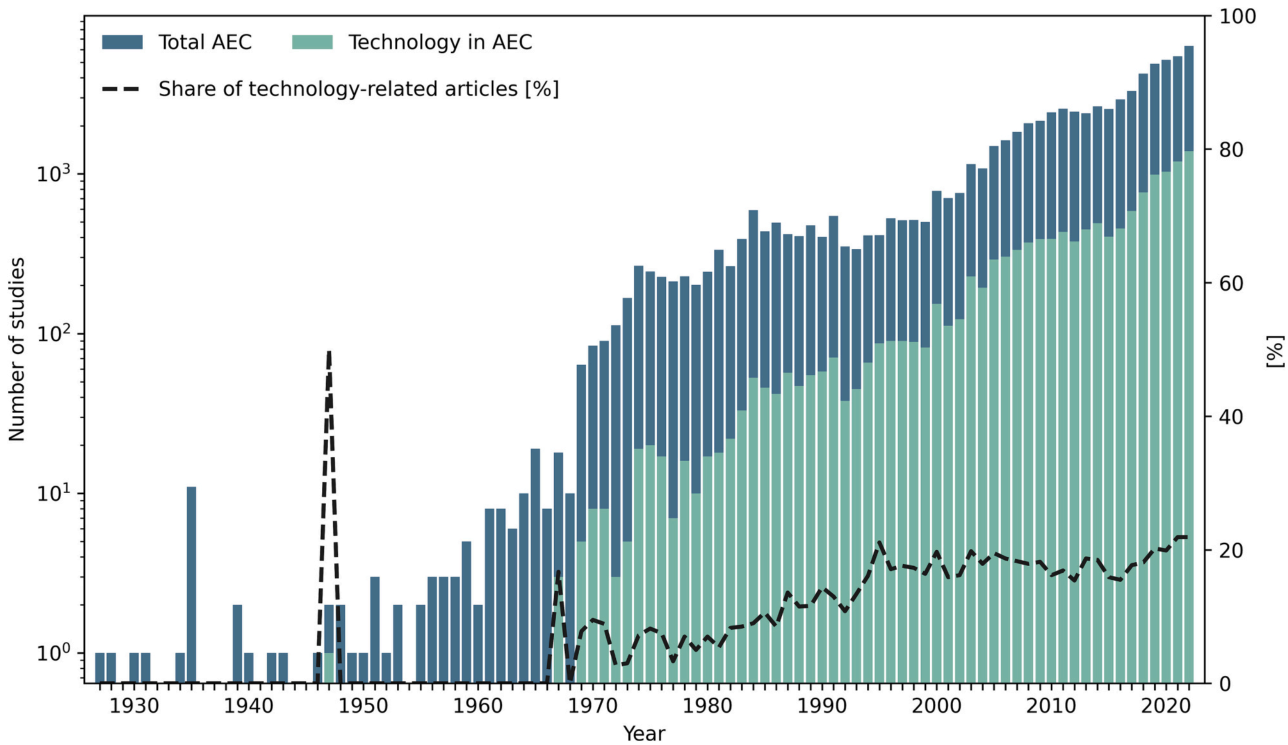

Fig. 2. Total number of articles in AEC and share of technology-related articles thereof per year as identified from the Scopus database.

Table 3
The top ten publication channels with most studies.

Nr.	Journal/Proceedings title	Count	Type
1	IOP Conference Series: Earth and Environmental Science	298	Journal (Conference papers)
2	Automation in Construction	272	Journal
3	Journal of Construction Engineering and Management	268	Journal
4	IOP Conference Series: Materials Science and Engineering	233	Journal (Conference papers)
5	Sustainability (Switzerland)	169	Journal
6	Construction Management and Economics	146	Journal
7	Engineering, Construction and Architectural Management	137	Journal
8	Proceedings, Annual Conference – Canadian Society for Civil Engineering	131	Conference proceedings
9	E3S Web of Conferences	119	Conference proceedings
10	MATEC Web of Conferences	113	Conference proceedings

XR (386), *Prefabrication* (367), and *3D printing* (311). Conversely, the least-addressed topics were *Location Analysis* (0), *Automated Valuation* (1), *Chatbot* (1), and *Geolocation* (1).

Fig. 3 illustrates the First-Year Index (FYI) and Normalized-Year Index (NYI, see also eq. 1) for each technology category. The FYI indicates the earliest publication year of a study within a specific category, while the NYI indicates the category's topicality. Notably, *Prefabrication* is the category with the lowest FYI (1971) and NYI (1985.4), indicating that publications in this category represented a larger share of studies in earlier years. In contrast, *Robots* has an FYI of 1984 and an NYI of 1993.4, which is a lower NYI than for instance *CAD* (NYI = 1996.7) or *Sensors* (NYI = 2002.9), despite having the same FYI of 1994 (see also Fig. 3). Thus, *Sensors* has received considerably more attention lately than *CAD* or *Robots*, *ergo* representing a more topical technology.

The development of the top ten technologies in terms of total publication numbers over time is shown in Fig. 4. Notably, *Prefabrication* was the initial technology covered in scientific literature and maintained dominance until the late 1970s. During the 1980s, *Robots* emerged as the prevailing technology, continuing through that decade. CAD represented a significant portion of the literature throughout the 1980s and 1990s, accounting for approximately one-fourth of the literature on average. However, its influence decreased ever since, partly due to the rapid increase in *BIM* publications from the early 2000s to the mid-2010s. Since then, *BIM*'s share declined, coinciding with the rise of two emerging technologies, *3D printing* and the *Internet of Things,* around 2015.

Moreover, a technology currently experiencing a 'revival' within this literature is *AI and ML*. While these technologies held a substantial presence from the mid-1980s to the early 2000s, the opposite is true for the period from 2005 to 2015. However, since 2015, there has been a renewed interest in *AI and ML* technologies and their share of publications is increasing again. *VR, AR, MR,* and *XR* emerged as a 'hot topic' during the second half of the 1990s and became the second most published topic in the early 2000s. Yet, despite the increasing number of publications, their relative importance has decreased over time.

Applying the methodology from Section 2.3, the categories can be assigned to dominant, emerging, underdeveloped or niche technology as shown in Table 4. Resulting of the number of categories with at least one identified publication (37) the average share of publications $\bar{s}$ is 4.0%. Consequently, all categories with $s > 4.0\%$ and NYI $\leq$ 2018 are considered to be dominant, and all with $s \leq 0.40\%$ underdeveloped. Technology categories with an NYI > 2018 and $s > 0.40\%$ are considered emerging, while those with an NYI $\leq$ 2018 and $0.40\% < s < 4.0\%$ are considered a niche technology with limited reach in the AEC sector. Table 4 also shows that for dominant, emerging, underdeveloped, and niche technologies the average number of publications is 454.2, 145.9, 5.7, and 66.4, average NYI is 2002.4, 2019.2, 2007.1, and 2006.6, respectively. Note, that the average number of publications and the average share of the total expressed as a percentage in the third column in Table 4 does not add up to 3950 and 100%, respectively, as some publications were assigned more than one category (see Section 2.1).

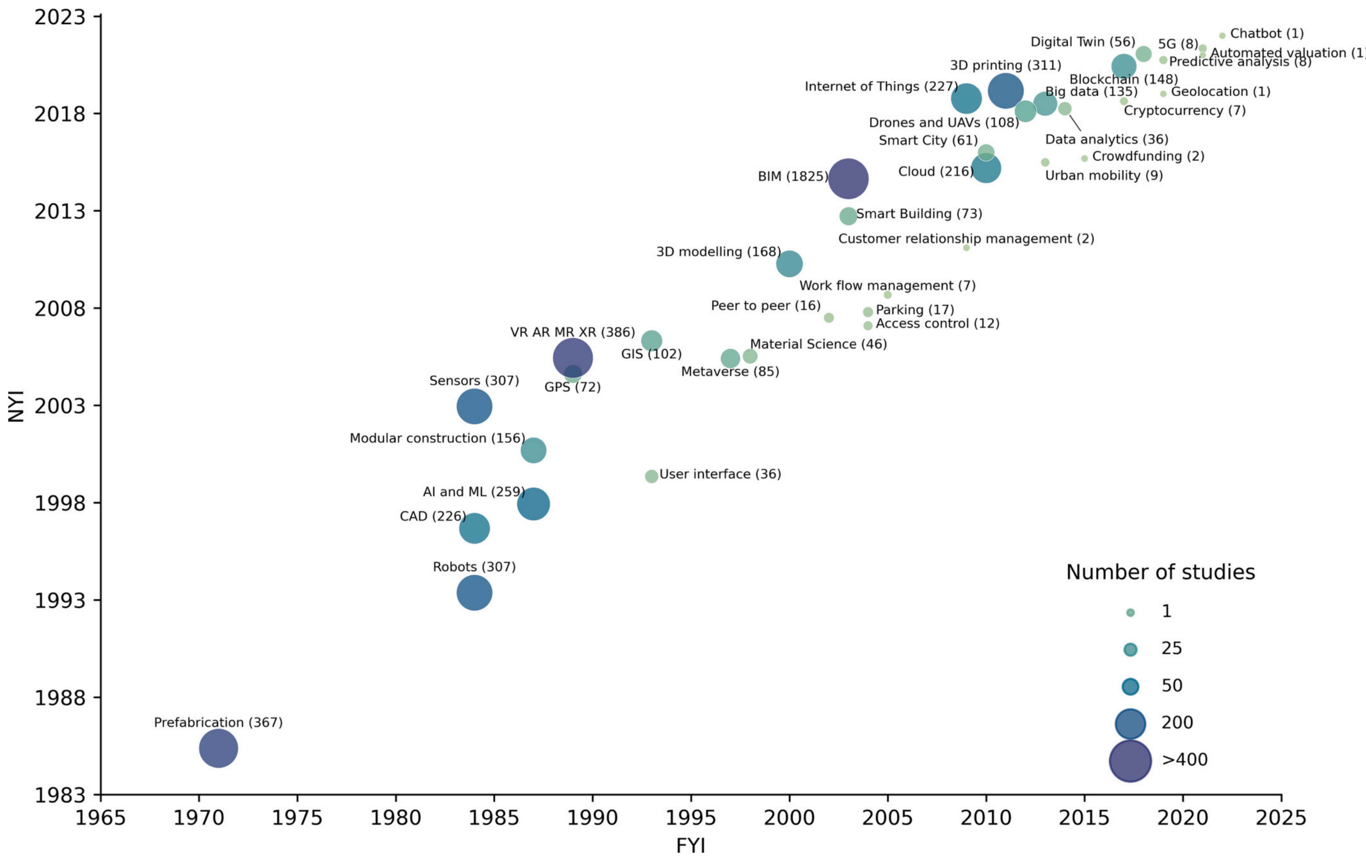

Fig. 3. First-Year Index (FYI) and Normalized-Year Index (NYI) for all categories (number of studies in respective category in parentheses).

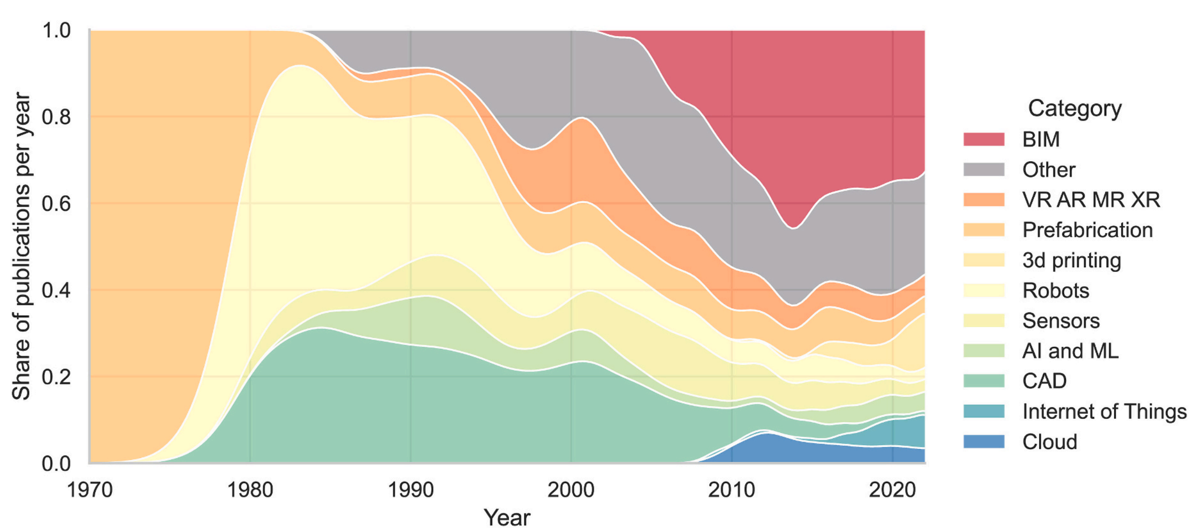

Fig. 4. Share of the top ten technologies/categories with the most publications over time (in order from the highest absolute number of publications at the top to lowest at the bottom). All other technologies/categories are summarized in 'Other'.

3.2. *Geographical context of the construction 4.0 technologies in scientific literature*

Fig. 5 presents the distribution of publications included in this study based on the country of the first author's institution. A three-colour scale is used to enhance differentiation for countries with lower numbers of publications. The countries with most publications are China (1068), the United States (827), the United Kingdom (396), Malaysia (272), and Australia (229), as shown in Table 5. Table 5 shows that the predominant category for each of these top countries is *BIM*. Together, the top ten productive countries contribute to 61.4% of the total literature subset analysed in this study. First authors from in total of 86 different countries were represented (excluding Yugoslavia as a separate country). Notably, 98 publications (2.5% of all included articles) lacked country metadata, particularly evident in earlier or anonymously written articles. Additionally, Fig. 4 underscores the underrepresentation of African countries.

The area diagram shown in Fig. 6 illustrates the distribution of total

Table 4
Distribution of categories among dominant, emerging, underdeveloped, and niche technologies.

	Categories	Average number of publications (% of total)	Average NYI
Dominant	*3D modelling, AI and ML, BIM, CAD, Cloud, Prefabrication, Robots, Sensors, VR, AR, MR, and XR*	454.2 (11.5%)	2002.4
Emerging	*3D printing, Big data, Blockchain, Data analysis, Digital Twin, Drones and UAVs, IoT*	145.9 (3.7%)	2019.2
Underdeveloped	*5G, Access control, AVM, Chatbot, CRM, Crowdfunding, Cryptocurrency, Geolocation, Predictive analysis, Urban mobility, WRM*	5.7 (0.1%)	2007.1
Niche technology	*GIS, GPS, Material science, Metaverse, Modular construction, Parking, Smart Building, Smart City, UI, P2P*	66.4 (1.7%)	2006.6

publications over time among the top ten countries. All other countries are summarized in *Other,* which collectively accounted for most publications analysed in this study (1844). Notably, The United States dominated the scientific literature landscape in this field from 1980 to 2010, but China assumed this position in 2015. Due to the exponential growth in the number of publications over time shown in Fig. 2 (note the logarithmic y-axis), China's larger share of total publications in more recent years results in an overall higher number of publications than from the United States. South Korea experienced a peak in productivity around 2008–2012, ranking as the fourth most productive country during that period. However, although South Korea's absolute productivity has continued to rise, its share of total publications in the investigated technologies has declined since then.

The Sankey diagram in Fig. 7 establishes connections between countries and technologies, providing a visual representation of each country's contributions to specific technologies in terms of publication numbers. Thicker flows and more intensive colours within the diagram indicate a higher number of publications.

3.3. Most cited construction 4.0 articles in scientific literature

Table 6 shows the 15 most-cited articles, showcasing their respective citation counts and open access status. The most-cited article with 1245 citations was written by Azhar [39] in 2011 on *BIM*. Among the top 15, eight articles were categorized under the *BIM* category. Notably, three of the articles were categorized under more than one technology, while only one article (authored by Hager et al. [52]) is a conference article, published in *Procedia Engineering.* Out of the 15 most-cited articles, five are open access (OA) publications, corresponding to 33.3%. This proportion is slightly higher compared to the overall share of 27.2% for all 3950 articles in this study. In total, the 3950 articles collectively received 58,463 citations, averaging around 15.8 citations per article. Remarkably, OA articles received an average of 13.4 citations, while non-OA articles received 16.7. Interestingly, the median citation count for OA articles (4 citations) is higher than for non-OA articles (3 citations), as depicted in Fig. 8. The visualisation also shows an increase in the share of OA publications, particularly since about 2010. In 2022, approximately half of the articles analysed in this study were published as OA articles.

Table 5
Top 10 countries with the most publications and the most dominant technology category per country.

Nr.	Country	Number of publications	Top category
1	China	687	BIM
2	United States	566	BIM
3	United Kingdom	283	BIM
4	Malaysia	187	BIM
5	Australia	146	BIM
6	Germany	116	BIM
7	South Korea	115	BIM
8	Russian Federation	114	BIM
9	India	112	BIM
10	Italy	101	BIM

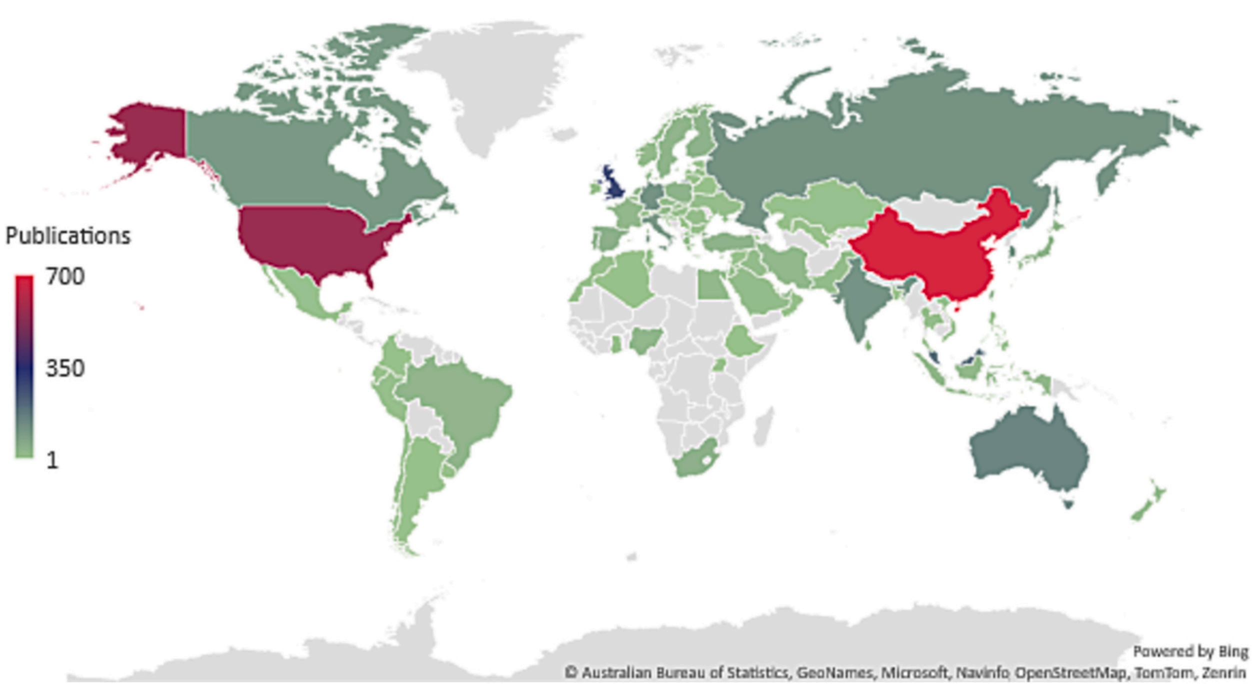

Fig. 5. Number of publications included in this study for each country.

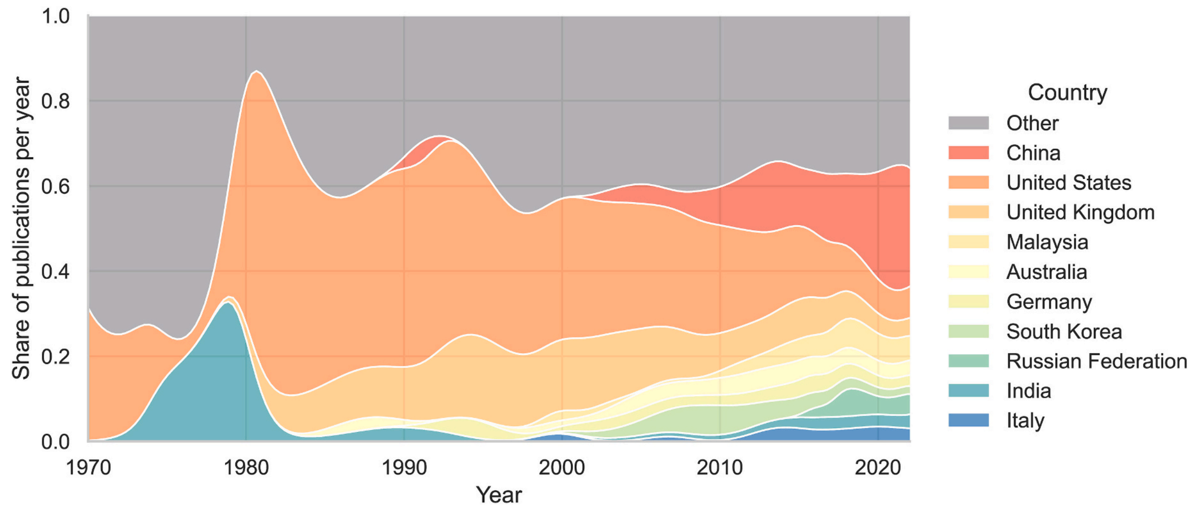

Fig. 6. Share of the top ten countries with the highest number of publications included in this study over time (in order from highest absolute number of publications at the top to lowest at the bottom). All other countries are summarized and grouped under 'Other'.

4. Discussion

4.1. The dominant, emerging, underdeveloped, and niche research topics related to digital technologies

The rapid evolution of digital technologies has brought forth an era of constant change and innovation. To navigate this dynamic landscape effectively, this article identifies dominant, emerging, underdeveloped, and niche research topics related to digital technologies.

Dominant research topics represent the established areas where substantial work has been done. This article shows that *BIM, 3D modelling, AI and ML, CAD, Cloud, Prefabrication, Robots, Sensors, VR, AR, MR,* and *XR* have dominated the research landscape over the years. In these topics, future research can focus on finding new perspectives, and some of the research directions have likely reached their maturity.

Emerging research topics highlight the cutting-edge areas where novel research is currently unfolding. Exploring these topics provides valuable insights into the future direction of digital technologies in the AEC sector. This article shows that *3D printing, Big data, Blockchain, Data analysis, Digital Twin,* and *Drones and UAVs* represent emerging topics.

Underdeveloped research topics signify areas that have received relatively little attention. They present untapped potential for breakthroughs. Identifying and focusing on these topics can lead to groundbreaking discoveries and solutions, propelling digital technologies into uncharted territories. This article's findings identified *5G, Access control, AVM, Chatbot, CRM, Crowdfunding, Cryptocurrency, Geolocation, Predictive analysis, Urban mobility*, and *WRM* as underdeveloped topics.

Niche topics in this study are considered neither dominant, emerging, or underdeveloped. However, similar to the dominant research topics, they likely have reached their maturity, while they have not been covered in scientific literature just as much. Niche topics still hold significant potential for future research to identify new perspectives and application areas. In this article, *GIS, GPS, Material science, Metaverse, Modular construction, Parking, Smart Building, Smart City, UI,* and *P2P* were identified as niche topics.

Classifying research topics into dominant, emerging, underdeveloped, and niche categories serves as a roadmap for research and development in the digital technology domain. The classification helps in resource allocation, prioritization, and collaboration among academia, industry, and government. Moreover, it fosters a holistic approach to digital transformation. We see that further analyses in different technology categories are desirable, and possible topics for structured literature reviews. However, it should be noted that any such categorization is indicative.

4.2. Geographical contextualisation of the results

The main geographic regions of innovation identified in this study are the United States and China. Notably, China has emerged as a focal point for scientific production in the investigated technologies, particularly since the mid-2010s. This increase has been fuelled by the country's tremendous economic growth [54]. Significantly, around one-fifth of China's enormous greenhouse gas emissions (accounting for 28% of the total global emissions [55]) originate from buildings [56]. This factor likely acts as a strong incentive to promote scientific activity aimed at supporting the formulation of policies that enhance the efficiency of the world's largest AEC sector [57].

Unfortunately, the analysed literature strongly underrepresents Central and South America, and even more notably, Africa. Due to the higher-than-average population growth and improving living standards in all three regions, the potential market for the application of these technologies is substantial. However, these regions continue to struggle with unregulated construction practices and face challenges in adopting these technologies rather than focusing on their development or research. This is particularly evident in the case of *BIM*, which aligns with findings from previous reviews [58,59]. For instance, Olatunde et al. [60] surveyed 129 construction professionals in Osun State, Nigeria, and concluded that the awareness and adoption readiness of Construction 4.0 technologies are *moderate* and *at the initial level*, respectively. The authors argue that the main challenges included a lack of standardization, insufficient investment in research and development, and the cost of implementation.

4.3. Visualisation-related technologies are the most investigated

The results show a significant thematic emphasis on *BIM*, supporting the findings from previous studies [24,26]. In a similar vein, Forcael et al. [23] also identified *IoT*, *BIM*, and *3D printing* as the most prominently published topics between 2014 and 2019, albeit not in the same order. However, *BIM* has various levels of maturity and areas of application which in this study are collected in one term. How extensively *BIM* is implemented and used within a project or organization can differ significantly as *BIM* can serve different purposes. These range from, for instance, basic *BIM* modelling for visualisation and clash detection to more advanced applications like scheduling, cost estimation, energy analysis, facility management, and beyond. The choice of which *BIM* applications to use depends on the specific project requirements, the available technology, the objectives of the stakeholders, as well as the skills of the user [61].

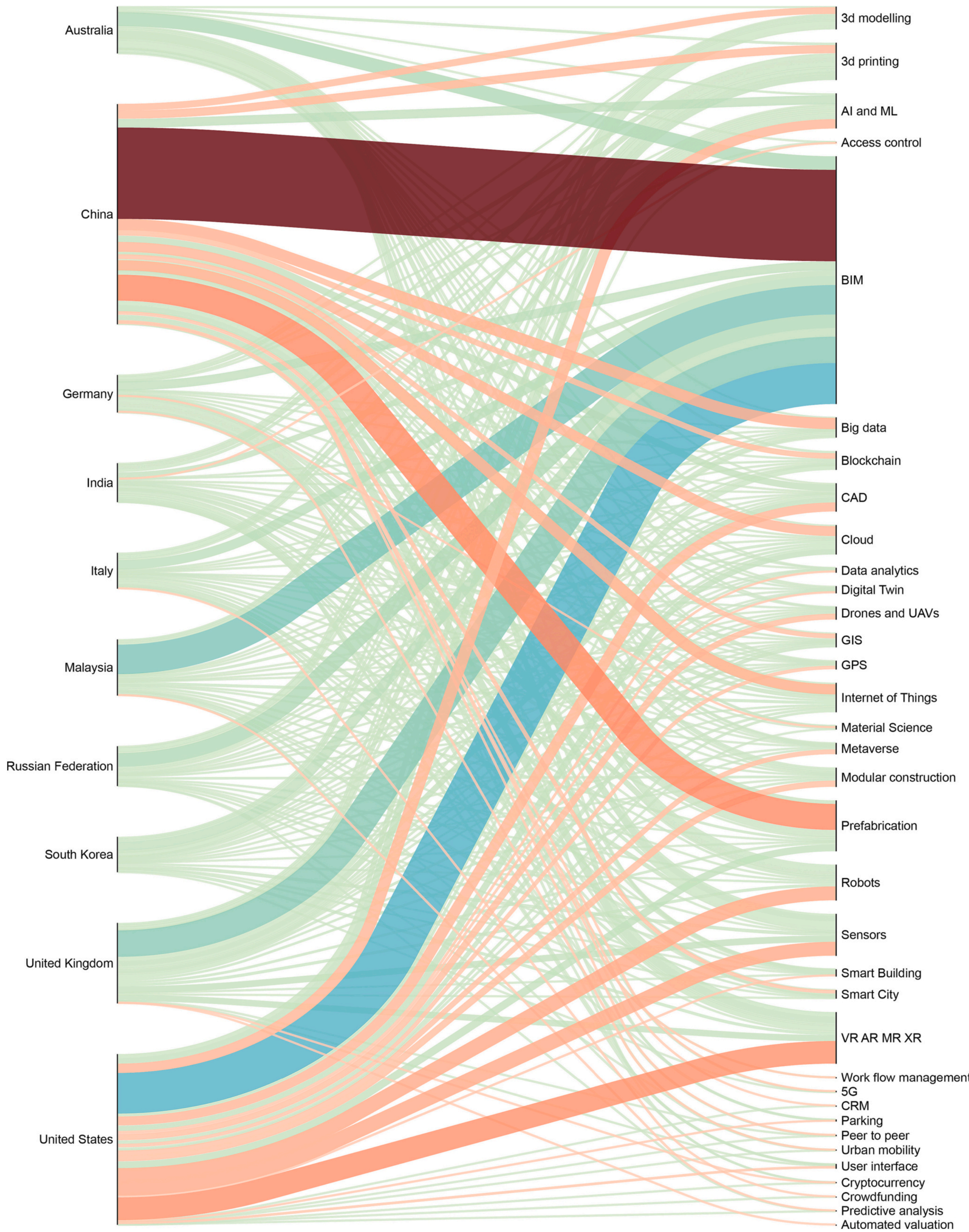

Fig. 7. Sankey diagram linking the ten countries with the most publications to technologies. The thickness of the links and intensity of the colours indicate the number of studies from each respective country addressing a technology. The top contributing link to each technology is represented by a red colour scheme, others are shown in blue/green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
The 15 articles with the most citations among the included publications in this study.

Nr.	Citations	Author(s)	Year	Title	Journal	Ref	Categories	Open Access
1	1245	Azhar S.	2011	Building Information Modelling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry	Leadership and Management in Engineering	[39]	*BIM*	Yes
2	972	Soong T. and Spencer B.	2002	Supplemental energy dissipation: state-of-the-art and state-of-the-practice	Engineering Structures	[40]	*Sensors*	No
3	618	Bos F. et al.	2016	Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing	Virtual and Physical Prototyping	[41]	*3D printing*	Yes
4	581	Gu N. and London K.	2010	Understanding and facilitating BIM adoption in the AEC industry	Automation in Construction	[42]	*BIM, VR AR MR XR*	No
5	500	Li X. et al.	2018	A critical review of virtual and augmented reality (VR/AR) applications in construction safety	Automation in Construction	[43]	*VR AR MR XR*	No
6	444	Singh V. et al.	2011	A theoretical framework of a BIM-based multi-disciplinary collaboration platform	Automation in Construction	[44]	*BIM, CAD*	No
7	437	Azhar S. et al.	2012	Building Information Modelling (BIM): Now and Beyond	Australasian Journal of Construction Economics and Building	[45]	*BIM*	Yes
8	417	Sacks R. et al.	2010	Interaction of lean and building information modelling in construction	Journal of Construction Engineering and Management	[46]	*BIM*	No
9	367	Arayici Y. et al.	2011	Technology adoption in the BIM implementation for lean architectural practice	Automation in Construction	[47]	*BIM*	No
10	326	Golparvar-Fard et al.	2009	D^4AR-A 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication	Electronic Journal of Information Technology in Construction	[48]	*Metaverse, VR AR MR XR*	Yes
11	301	Miettinen R. and Paavola S.	2014	Beyond the BIM utopia: Approaches to the development and implementation of building information modelling	Automation in Construction	[49]	*BIM*	No
12	286	Leung C.K.Y. et al.	2015	Review: optical fiber sensors for civil engineering applications	Materials and Structures/ Materiaux et Constructions	[50]	*Sensors*	No
13	284	Lee G. et al.	2006	Specifying parametric building object behavior (BOB) for a building information modelling system	Automation in Construction	[51]	*BIM*	No
14	283	Hager I. et al.	2016	3D Printing of Buildings and Building Components as the Future of Sustainable Construction?	Procedia Engineering	[52]	*3D printing*	Yes
15	269	Hong J. et al.	2018	Barriers to promoting prefabricated construction in China: A cost–benefit analysis	Journal of Cleaner Production	[53]	*Prefabrication*	No

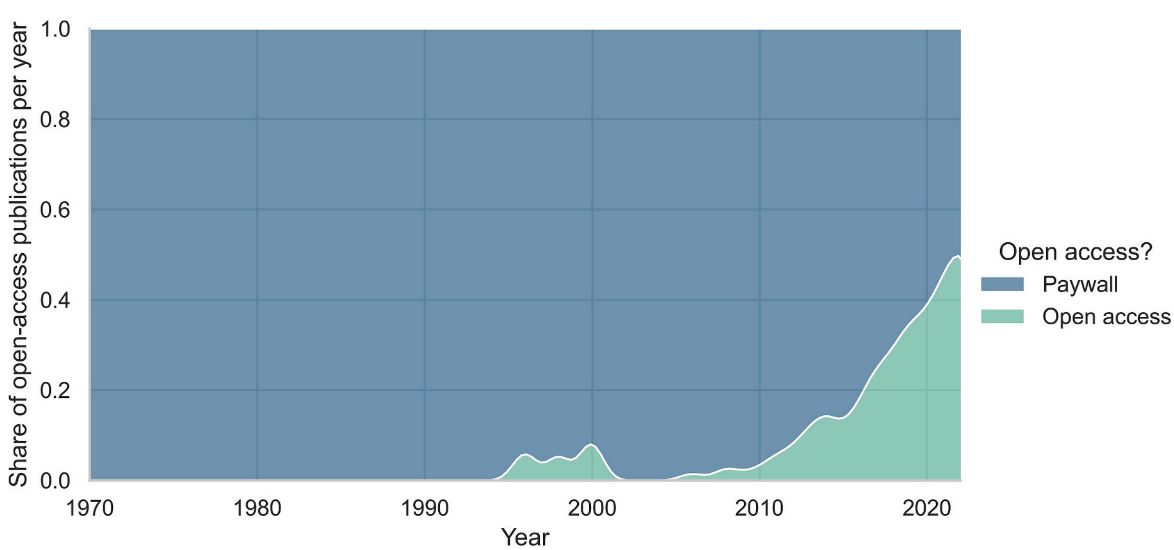

Fig. 8. Share of OA publications included in this study's analysis over time.

Moreover, there has been a surprising decline in the relative interest in *VR, AR, MR,* and *XR* in recent years. Although these technologies accounted for around 20% of the academic literature landscape in 2000, and despite the significant advancements in *VR, AR, MR,* and *XR* technology, along with a notable increase in overall publication numbers on the topic, the interest has not grown as strongly as it has for *IoT* or *3D printing*. However, a specific area of VR-related research and application is anticipated to gain a substantial rise in importance: education and training. Rojas-Sanchez et al. [62] have identified a significant rise in this interest, attributable to the COVID-19 pandemic and major developments in the technology since the mid-2010s. VR has proven to be a valuable asset not only in school classrooms but also for training AEC workers and engineers [63–65]. Particularly in the context of gamification for training and education purposes, VR can be regarded as a central element in future development, forming the foundation for a fully immersive training environment tailored to the complex nature of the construction industry [66,67]. Furthermore, in combination with *BIM*, the *VR, AR, MR,* and *XR* technologies open up an entirely new dimension for construction site management, allowing for digital construction site visits, virtual stakeholder meetings (in the *Metaverse*), and conflict identification (e.g., built vs. planned), among other applications.

4.4. "Smart AEC" is emerging as an enabling context for successful Digital Twin realisations

Digital Twin was surprisingly underrepresented in the analysed literature, with only 56 articles addressing the topic. The concept of a digital twin, which functions as a digital copy of a physical asset and its systems, holds immense potential for facilitating real-time decision-making throughout a building's life cycle. However, achieving this ambitious goal presents significant challenges. Its main value lies in its ability to provide accurate information, essential for tasks like building maintenance, energy efficiency management, and indoor environmental conditions [68]. The concept shares a strong connection to *BIM* and is expected to become one of the hottest topics in the coming years. This growth will be driven by its integration with other technology categories discussed in this paper, such as *Sensors*, *5G, IoT*, *Cloud technology*, *Smart Building,* as well as *AI and ML* [69].

This technological convergence arises from the benefits of integrating and utilizing common data platforms across different technology domains. While it presents numerous opportunities for enhancing the overall performance of digital infrastructures, it also brings about challenges, as researchers and practitioners need to acquire expertise in multiple technologies and their seamless integrations.

An illustrative example is *5G*, a pivotal enabling technology that catalyses various technology domains, including *Digital Twins,* smart homes, *Smart Buildings*, smart infrastructures, smart cities, and even smart construction sites [70,71] (collectively referred to as *smart AEC*). 5G offers superior peak data speeds with minimal latency, enhanced reliability, greater capacity, and improved availability compared to its predecessors [72]. Of paramount significance within the realm of smart AEC is the synergy between IoT and *Cloud technology*, which generate substantial volumes of data [73]. This necessitates seamless data transfer among sensors, actors, and diverse cloud services and databases. However, only a limited number of articles (8) in the present review address the subject of *5G*. Nevertheless, future research will be needed to develop suitable electronic infrastructures (or e-infrastructures). Simultaneously, it's worth noting that much of the framework development for *5G* may be published in articles not specifically related to the AEC industry (and consequently, not identified in the article search). This is because 5G primarily falls within the realm of *information and communication technology,* or ICT.

Other complementary technologies, including *AI and ML*, *Big Data*, *Blockchain,* facilities management encompassing *predictive maintenance* and *energy management*, *traffic analysis*, and *urban environmental monitoring*, among others [74], play a significant role in future developments. This is because they rely on digital infrastructures, which generate the necessary data needed by these technologies and facilitate their intended applications.

4.5. Drones and Robots are important enablers for automation

Drones and UAV technologies are closely intertwined with *Robots* and robotics, both experiencing a significant increase in interest lately as part of efforts to automate construction sites, capture geometries, detect damages or deviations from the BIM model, and perform various tasks to enhance workplace safety [75,76]. When coupled with robots, drones have the potential to increase productivity on construction sites and effectively operate in challenging and hazardous environments [77]. In fact, autonomous ground-based robots, including four-legged robots, are now capable of successfully navigating complex and typically cluttered construction sites. These robots can climb stairs, step over obstacles such as pipes, and navigate through metal meshes used in concrete reinforcement.

4.6. Chatbot not yet a key enabling technology in 2022

As of 2022, *Chatbot* remained a niche topic. However, in the coming years, generative, text-based AI models like ChatGPT (Chat Generative Pre-Trained Transformer) [78] and GPT-4 [79], which incorporates both text and image inputs, are expected to play a pivotal role across various industry sectors. AI stands out as a *key enabling technology* prioritised by the EU [80] and its potential applications within the AEC sector are extensive. When posed with the question of how ChatGPT and GPT-4 can support AEC professionals, ChatGPT provided the following ten bullet points:

1. Design assistance: ChatGPT can help architects and designers generate design options, providing suggestions and alternative ideas based on input criteria and preferences.
2. Conceptualization and visualisation: The language model can assist in converting rough sketches or verbal descriptions into visual representations, helping stakeholders better understand and visualize proposed designs.
3. Material selection: By providing information on various building materials, their properties, and performance characteristics, ChatGPT can aid architects and engineers in selecting suitable materials for specific projects.
4. Code compliance: The language model can assist in identifying and interpreting relevant building codes, regulations, and standards, ensuring designs comply with safety and legal requirements.
5. Cost estimation: ChatGPT can support cost estimation processes by providing insights into material costs, labor expenses, and other project-related expenses based on historical data and market trends.
6. Project management: The language model can assist with project planning, scheduling, and resource allocation by providing recommendations and insights based on historical project data and industry best practices.
7. Knowledge sharing and documentation: ChatGPT can help in creating and maintaining project documentation, including writing reports, generating meeting minutes, and answering questions regarding project details.
8. Collaborative design reviews: The language model can facilitate virtual design reviews by providing real-time feedback and engaging in discussions with project stakeholders to evaluate design options and address concerns.
9. Energy efficiency analysis: ChatGPT can assist in analysing and optimizing building designs for energy efficiency, suggesting strategies for reducing energy consumption and improving sustainability.
10. Safety analysis: By analysing design plans and identifying potential safety hazards, ChatGPT can aid in proactive risk assessment and suggest mitigations to enhance construction safety.

However, ChatGPT also emphasized that "human expertise and judgement will remain crucial to ensure safety, compliance and successful project outcomes". Especially for non-experts, such as building owners or those intending to acquire property, considering renovation, or looking for synthesized advice from multiple sources, the GPT tools can serve as quick sources of information, particularly in the early stages of decision-making. While their potential is vast, the utilization of ChatGPT, GPT-4, and similar technologies and models demands comprehensive research within the AEC sector and across all industries in the forthcoming years.

4.7. Research, education, and industry have to collaborate more closely

The results indicate that the AEC sector is exposed to increasingly rapid and dynamic technological advancements. The exponential acceleration of technological change, also known as the "Law of Accelerating Returns" as described by Ray Kurzweil [81,82], presents a growing challenge in keeping up with the emergence of new technologies, trends and tools. Notably, the lack of awareness and understanding of digital technologies, coupled with a shortage of a skilled workforce, has been recognized as the main obstacles to the uptake of digital technologies in the EU [2].

Academia bears a great responsibility to remain at the forefront of the developments and educating tomorrow's AEC practitioners and researchers. The rigid and well-established structures in academia often pose challenges in consistently acquiring the necessary new skill sets for applying innovative technologies, especially for practitioners with limited access to education. This notion is supported by Bolpagni et al. [11], who emphasized academia's pivotal role in training the required professionals to drive the transition towards Construction 4.0.

However, achieving large-scale penetration of technological innovation that may revolutionize current practice requires the involvement of market actors. Consequently, collaboration between academia, research, and industry is crucial. In an unpublished survey of 89 AEC startups from 20 different countries carried out by the authors of this study, about two-thirds of the respondents emphasized the importance of future collaboration with academia. However, when asked about the main obstacles to collaboration with academia, the most common challenges cited were slow processes within academia, finding the right collaboration partners, bureaucracy, and high costs for hiring researchers (in that order). These results highlight the divergence between academia and industry. Creating more incentives and platforms to foster collaboration and information exchange would certainly yield multiple co-benefits and synergies on both sides.

Research indicates a noticeable gap between industry and academia in the adoption and adaptation of emerging technologies [83]. Furthermore, there is a greater need for a new kind of packaging of information in the academy and industry. This can be seen in the increasing popularity of general concepts, such as digitalization, digital transformation, or virtual design construction, which confine a multitude of technologies and technological phenomena. The results from this study can help identify current misalignments of academia's and industry's focus areas and needs for new conceptualizations and categorizations in terms of emerging or Construction 4.0 technologies. A better alignment of focus areas and novel conceptualizations are important, as academia not only has the responsibility of developing and identifying innovative technologies, but also to educate the next generation of professionals working in the industry. A more informed collaboration between the two will therefore enable a faster and more efficient digitalisation process of the AEC sector.

4.8. Open access publications facilitate technology penetration

The share of OA articles of the investigated subset of literature (27.2%) is higher than in Piwowar et al.'s [84] study on the prevalence and impact of OA articles in different fields of science. In their study, the OA share among almost 15,000 articles in the *Engineering and Technology* domain was below 20%. Although several studies (e.g., [84,85]) have shown that OA articles commonly have a citation advantage over non-OA articles, the same was not observed in the subset of literature analysed in the present study. Non-OA articles had in total 44,940 citations (on average 16.7 per article), while OA articles had 13,523 (on average 13.4 per article). The difference in citations may be because OA articles are generally newer and therefore receive fewer citations than non-OA publications, the majority of which were published earlier. However, the studies in [84,85] also concluded that differences between different fields exist.

Regarding the development of the share of OA articles for technology-related articles in the AEC sector, the trend is moving towards an OA publishing option. If the trend continues, more articles will soon be published OA than behind a paywall. Further increasing the number of OA publications will help create a larger readership, particularly from developing countries. This will facilitate a faster penetration of innovative technologies, methodologies, and frameworks into the market and provide valuable insights for researchers and practitioners.

4.9. Limitations and future research

This study constitutes a review of a highly dynamic field that is continuously changing and evolving. As a result, the presented results offer a momentary snapshot of the subject. Furthermore, since scoping reviews are primarily designed for a preliminary assessment of the potential size and scope of available research literature and do not incorporate formal quality assessments, they are generally considered inadequate for drawing far-reaching conclusions, such as making recommendations for policy or practice [28]. Additionally, other factors may introduce bias to the data and influence conclusions:

- Only one academic literature database, Scopus, was used, as it provides a scriptable API allowing for automated searching and downloading of relatively large amounts of metadata and abstracts. While this literature identification process certainly is not exhaustive and most probably not all relevant studies are included in this study, we believe that including other databases that do not allow for automizing the literature identification process would introduce disproportionate manual effort to identify, download, structure, manage and check the literature for duplicates. Therefore, we did not extend the scope of this article by including other scientific databases or publishers.
- The selected search terms impact the composition of the literature subset which is analysed. In this article, it was aimed to keep the search terms as broad as possible, while within the limits imposed by the API (e.g., max. 5000 hits at a time per search and an upper limit of API abstract retrieval requests of 10,000 per week).
- Technology screening in Table 1 was conducted automatically due to the large number of abstracts retrieved using the applied search phrase (12,613 in total). There is a potential risk that some abstracts may have been missed due to the selection of search phrases (see Table 1), while others might have been categorized incorrectly. The extent of this risk is unknown.
- The sufficient quality of the identified studies was assumed based solely on the peer-review process inherent to their publication. The authors did not conduct any additional quality evaluations.
- The list of Construction 4.0 technologies used in the analysis is based on previous research on digitalisation in the AEC sector [27] and they were found as relevant and comprehensive during the process of literature analysis. However, different experts might have different opinions on keywords and methods.

In conclusion, every literature review method has inherent limitations stemming from the review's scope and methodological decisions. This review has aimed to encompass a comprehensive dataset, a choice reflected in the methodological approach. Nevertheless, the material covered is not exhaustive and there are limitations in the analysis methods. However, as Booth et al. [86] note, achieving a state of complete exhaustiveness in any review is unnecessary for its intended purpose, and practical constraints, such as keyword combinations and the selection of scientific databases, impose limitations. The methodological choices have been guided by this "fit-for-purpose" principle, ensuring that the material aligns with the research goals, a success demonstrated by the conducted analyses.

Future research could involve the examination of different literature samples and adopt a systematic review approach, which typically addresses well-defined questions, focuses on empirical studies, and aims to derive answers from a relatively small subset of quality-assessed literature [24,25]. The discussion section provides many topics and preliminary research questions for systematic reviews. Additionally, it is recommended for future research to establish new technology categories (Table 1), as technologies and their applications continue to evolve rapidly.

Furthermore, expanding the search to Industry 5.0/Construction 5.0 at a later point in time when these terms are more established is recommended. Moreover, an even broader subset of literature could be screened in future studies. This could be achieved by including abstracts from databases other than Scopus and not limiting those to the occurrence of the term "technology". In another research approach, the methodology could be applied to full texts instead of abstracts in the future. For that, however, the publishers' restrictions on full-text downloads must be overcome, possibly by including them in the review process.

5. Conclusion

The primary contribution of this study is the comprehensive identification and categorization of existing research on digital technologies in the AEC sector, furthering our understanding of this field. The scoping review identified current trends, the coverage of different technologies in scientific literature over time, geographic hot spots of innovation/contribution, research gaps, and key concepts. In total, 12,613 abstracts were screened for 38 Construction 4.0 technologies, resulting in the analysis of 3950 abstracts.

The results showed that the most extensively covered topic by far was *BIM*, which supports previous review findings in the field. Currently, the booming topics are *IoT* and *3D printing*. Additionally, several topics received relatively little attention before 2022, but they are expected to become "hot" in the coming years. These include *AI and ML*, *Chatbot* (incl. Topics like ChatGPT or GPT-4), as well as *VR, AR, MR,* and *XR*. Furthermore, the United States and China have been the two centres of academic literature production. China's importance is still increasing, and it has become the leading country in terms of the number of publications on the investigated technologies in the AEC sector since around 2015, after decades of dominance by the United States. However, Russia and Malaysia have also significantly increased their output of scientific literature in recent years. Particularly African and South American countries are underrepresented in the examined body of literature. Finally, while non-OA articles represented the majority of included articles in this study (72.8%) and received, on average, more citations than OA articles (16.7 compared to 13.4), the trend is moving towards the OA publishing option in recent years.

Furthermore, the identification and categorization of existing research represents a vital step in improving research, policy and practice. The discussions on dominant, emerging, and underdeveloped research topics related to digital technologies provide theoretical implications for future research. Additionally, the discussions on the geographical distribution of scientific activity, industry-academia collaboration, education, and the role of open-access publications in promoting technology adoption offer pathways to improve policy and practice. A practical implication of the increased digitalization opportunities is the necessity for tighter collaboration between research and industry. This collaboration faces several obstacles, especially related to the inherently different structures of the two domains, as previous research has shown. The main concern for start-ups aiming to penetrate the market with Construction 4.0 technologies is the longer time horizons in academia, as well as bureaucracy and a lack of platforms to find the right research partners. Furthermore, academia should strengthen its focus on new and emerging technologies to better align with industry needs. Its responsibility extends beyond research and development to include the education of the next generation of industry professionals. This study shows promising future prospects as it encompasses several potential directions, such as the following:

- It can be used for continuous trend monitoring, tracking the evolution of trends in Construction 4.0 technologies and academic production. This helps to stay up-to-date with emerging technologies and regions of focus and understand how academic publishing patterns change over time.
- The identification of dominant, emerging, and underdeveloped research topics related to digital technologies helps to guide future research.
- The results have the potential to inform policy decisions and industry practices as they adapt to the digitalisation of the AEC sector. Insights from this article can guide policymakers, industry leaders, and researchers towards more effective strategies and investment in technology adoption.
- From the identified underrepresented regions, international collaboration between academia and industry can help bridge knowledge gaps and disparities in technology implementation, contributing to knowledge exchange and a more efficient global AEC sector.
- The article facilitates the identification of educational needs to equip students with the necessary skill sets for the successful adoption of emerging technologies in the industry, thereby bridging the academia-industry gap.
- Finally, the results allow for the identification of research topics for further assessments to measure the impact of digitalisation and new technologies on the AEC sector's efficiency, sustainability, and agility. This can be of particular interest to developing countries experiencing high population growth and increasing living standards.

In conclusion, this article offers insights that contribute to the understanding of digital technologies in the AEC sector. Particularly notable are the categorization of research topics into dominant, emerging, underdeveloped, and niche areas, providing a contemporary overview for research design. Additionally, the identification of the need for research on complementary technologies can serve as a guide for further exploration. The main limitation of the study is its reliance on a rapidly changing technological landscape. We encourage future research to continue similar trend analyses. The conclusions drawn regarding an increased necessity for industry-academia collaboration in Construction 4.0 technologies and the urgency to integrate these technologies into education challenges academic institutions to reconsider collaborative forms and the substance of their teachings.

Declaration of Generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work, the authors used *ChatGPT* in order to demonstrate the tool's functionality and labelled the AI-produced section clearly as such. However, the tool's output has not been checked for its validity as this relatively new technology has not been researched extensively enough for a conclusive validation. This has also been stated in the text. The authors reviewed the content and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Johannes Brozovsky: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Nathalie Labonnote:** Conceptualization, Writing – review & editing, Project administration. **Olli Vigren:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study was written within the BIMprove project (https://www.bimprove-h2020.eu/), funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 958450. Additional funding was received from Lars Erik Lundbergs Stipendiestiftelse under grant number 974884 and from Formas with grant number 2022-00102. Open access funding from Sikt – Norwegian Agency for Shared Services in Education and Research.

References

[1] R. Agarwal, S. Chandrasekaran, M. Sridhar, Imagining construction's Digital Future. https://www.mckinsey.com/capabilities/operations/our-insights/imagining-constructions-digital-future#/, 2016. (Accessed 28 March 2023).

[2] European Construction Sector Observatory, Digitalisation in the Construction Sector: Analytical Report. https://ec.europa.eu/docsroom/documents/45547, 2021. (Accessed 9 October 2023).

[3] W. Modery, P. Lopez-Garcia, M. Albani, C. Baccianti, R. Barrela, K. Bodnár, M. Bun, J. de Mulder, B. Lopez, V. Labhard, J. Le Roux, A. Linarello, I. Moder, K. Oja, C. Ragacs, R. Oke, A.S. Justo, R. Serafini, R. Setzer, I.S. Lopez, J. Vanhala, Key factors behind productivity trends in EU countries, SSRN Electron. J. (2021), https://doi.org/10.2139/ssrn.3928289.

[4] B. García de Soto, I. Agustí-Juan, S. Joss, J. Hunhevicz, Implications of construction 4.0 to the workforce and organizational structures, Int. J. Constr. Manag. 22 (2022) 205–217, https://doi.org/10.1080/15623599.2019.1616414.

[5] K. McHugh, B. Dave, L. Koskela, On the role of lean in digital construction, in: M. Bolpagni, R. Gavina, D. Ribeiro (Eds.), Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills, Springer International Publishing, Cham, 2022, pp. 207–226 (ISBN: 978-3-030-82429-7).

[6] S. Xu, H. Luo, The information-related time loss on construction sites: a case study on two sites, Int. J. Adv. Robot. Syst. 11 (2014) 128, https://doi.org/10.5772/58444.

[7] K. Schwab, The Fourth Industrial Revolution: what it means, how to respond, 2016. https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/ (accessed 28 March 2023).

[8] E. Hofmann, M. Rüsch, Industry 4.0 and the current status as well as future prospects on logistics, Comput. Ind. 89 (2017) 23–34, https://doi.org/10.1016/j.compind.2017.04.002.

[9] K.-S. Schober, P. Hoff, K. Nölling, Digitization in the Construction Industry: Building Europe's Road to "Construction 4.0", Munich, Germany. https://www.rolandberger.com/publications/publication_pdf/tab_digitization_construction_industry_e_final.pdf, 2016.

[10] A. Sawhney, M. Riley, J. Irizarry, C.T. Pérez, A proposed framework for construction 4.0 based on a review of literature, EPiC Ser. Built Environ. 1 (2020) 301–309, https://doi.org/10.29007/4nk3.

[11] M. Bolpagni, R. Gavina, D. Ribeiro, I. Pérez Arnal, Shaping the future of construction professionals, in: M. Bolpagni, R. Gavina, D. Ribeiro (Eds.), Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills, Springer International Publishing, Cham, 2022, pp. 1–26 (ISBN: 978-3-030-82429-7).

[12] M. Tetik, A. Peltokorpi, O. Seppänen, J. Holmström, Direct digital construction: technology-based operations management practice for continuous improvement of construction industry performance, Autom. Constr. 107 (2019), https://doi.org/10.1016/j.autcon.2019.102910.

[13] P.R. Shukla, J. Skea, A.A.K. Slade, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Eds.), Climate Change 2022: Mitigation of Climate Change, Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, New York, NY, USA, 2022, ISBN 9781009157926, https://doi.org/10.1017/9781009157926.

[14] European Commission, The European Construction Sector: A Global Partner. https://ec.europa.eu/docsroom/documents/15866/attachments/1/translations/en/renditions/pdf, 2016. (Accessed 14 July 2023).

[15] European Commission, Regulation (EU) 2021/694 of the European Parliament and of the Council of 29 April 2021 establishing the Digital Europe Programme and repealing Decision (EU) 2015/2240 (Text with EEA relevance). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R0694, 2023 (accessed 29 March 2023).

[16] European Commission, A New Circular Economy Action Plan: For a Cleaner and more Competitive Europe. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:98:FIN, 2020. (Accessed 29 March 2023).

[17] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Renovation Wave for Europe - Greening our Buildings, Creating Jobs, Improving Lives, Belgium, Brussels, 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662 (accessed 10 November 2020).

[18] P.K.R. Maddikunta, Q.-V. Pham, P.B.N. Deepa, K. Dev, T.R. Gadekallu, R. Ruby, M. Liyanage, Industry 5.0: a survey on enabling technologies and potential applications, journal of industrial information, Integration 26 (2022), 100257, https://doi.org/10.1016/j.jii.2021.100257.

[19] M. Breque, L. de Nul, A. Petridis, Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry. https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1/, 2021. (Accessed 10 November 2023).

[20] S. Nahavandi, Industry 5.0—a human-centric solution, Sustainability 11 (2019) 4371, https://doi.org/10.3390/su11164371.

[21] International Federation of Robotics, Industrial Robots. https://ifr.org/industrial-robots (accessed 11 October 2023).

[22] M. Marinelli, From industry 4.0 to construction 5.0: exploring the path towards human–robot collaboration in construction, Systems 11 (2023) 152, https://doi.org/10.3390/systems11030152.

[23] E. Forcael, I. Ferrari, A. Opazo-Vega, J.A. Pulido-Arcas, Construction 4.0: a literature review, Sustainability 12 (2020) 9755, https://doi.org/10.3390/su12229755.

[24] P. Schönbeck, M. Löfsjögård, A. Ansell, Quantitative review of construction 4.0 technology presence in construction project research, Buildings 10 (2020) 173, https://doi.org/10.3390/buildings10100173.

[25] M. Kozlovska, D. Klosova, Z. Strukova, Impact of industry 4.0 platform on the formation of construction 4.0 concept: a literature review, Sustainability 13 (2021) 2683, https://doi.org/10.3390/su13052683.

[26] X. Chen, A.Y. Chang-Richards, A. Pelosi, Y. Jia, X. Shen, M.K. Siddiqui, N. Yang, Implementation of technologies in the construction industry: a systematic review, Eng. Constr. Archit. Manag. 29 (2022) 3181–3209, https://doi.org/10.1108/ECAM-02-2021-0172.

[27] O. Vigren, Digitalization, Sustainability, and Ecosystems: An Application of Social Network Analysis to the Real Estate Sector, Doctoral Thesis, KTH Royal Institute of Technology, Stockholm, Sweden. ISBN: 978-91-8040-155-5, https://www.diva-portal.org/smash/get/diva2:1641423/FULLTEXT01.pdf, 2022. (Accessed 20 August 2023).

[28] M.J. Grant, A. Booth, A typology of reviews: an analysis of 14 review types and associated methodologies, Health Inf. Libr. J. 26 (2009) 91–108, https://doi.org/10.1111/j.1471-1842.2009.00848.x.

[29] A. DiCenso, R. Martin-Misener, D. Bryant-Lukosius, I. Bourgeault, K. Kilpatrick, F. Donald, S. Kaasalainen, P. Harbman, N. Carter, S. Kioke, J. Abelson, R. J. McKinlay, D. Pasic, B. Wasyluk, J. Vohra, R. Charbonneau-Smith, Advanced practice nursing in Canada: overview of a decision support synthesis, Nursing leadership (Toronto, Ont.) 23 Spec No 2010 (2010) 15–34, https://doi.org/10.12927/cjnl.2010.22267.

[30] H. Arksey, O'Malley L, Scoping studies: towards a methodological framework, International Journal of Social Research Methodology 8 (2005) 19–32, https://doi.org/10.1080/1364557032000119616.

[31] Z. Munn, M.D.J. Peters, C. Stern, C. Tufanaru, A. McArthur, E. Aromataris, Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach, BMC medical research methodology 18 (2018) 143, https://doi.org/10.1186/s12874-018-0611-x.

[32] A.C. Tricco, E. Lillie, W. Zarin, K. OBrien, H. Colquhoun, M. Kastner, D. Levac, C. Ng, J.P. Sharpe, K. Wilson, M. Kenny, R. Warren, C. Wilson, H.T. Stelfox, S. E. Straus, A scoping review on the conduct and reporting of scoping reviews, BMC medical research methodology 16 (2016) 15, https://doi.org/10.1186/s12874-016-0116-4.

[33] Elsevier Inc., elsapy v0.5.0: A Python Module for Use with api.elsevier.com. https://github.com/ElsevierDev/elsapy, 2019 (accessed 30 March 2023).

[34] B.V. Elsevier, Elsevier Scopus APIs. https://dev.elsevier.com/sc_apis.html. (Accessed 30 March 2023).

[35] B.V. Elsevier, Scopus: Expertly Curated Abstract & Citation Database. https://www.elsevier.com/solutions/scopus, 2023. (Accessed 30 March 2023).

[36] B.V. Elsevier, Content Coverage Guide. https://www.elsevier.com/_data/assets/pdf_file/0007/69451/ScopusContentCoverageGuideWEB.pdf, 2023. (Accessed 12 July 2023).

[37] QSR International Pty Ltd, NVivo (Released in March 2020). https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home, 2020. (Accessed 12 July 2023).

[38] Y. Toparlar, B. Blocken, B. Maiheu, G. van Heijst, A review on the CFD analysis of urban microclimate, Renew. Sust. Energ. Rev. 80 (2017) 1613–1640, https://doi.org/10.1016/j.rser.2017.05.248.

[39] S. Azhar, Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry, Leadersh. Manag. Eng. 11 (2011) 241–252, https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127.

[40] T.T. Soong, B.F. Spencer Jr., Supplemental energy dissipation: state-of-the-art and state-of-the-practice, Eng. Struct. 24 (2002) 243–259, https://doi.org/10.1016/S0141-0296(01)00092-X.

[41] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing, Virtual Phys. Prototyp. 11 (2016) 209–225, https://doi.org/10.1080/17452759.2016.1209867.

[42] N. Gu, K. London, Understanding and facilitating BIM adoption in the AEC industry, Autom. Constr. 19 (2010) 988–999, https://doi.org/10.1016/j.autcon.2010.09.002.

[43] X. Li, W. Yi, H.-L. Chi, X. Wang, A.P. Chan, A critical review of virtual and augmented reality (VR/AR) applications in construction safety, Autom. Constr. 86 (2018) 150–162, https://doi.org/10.1016/j.autcon.2017.11.003.

[44] V. Singh, N. Gu, X. Wang, A theoretical framework of a BIM-based multi-disciplinary collaboration platform, Autom. Constr. 20 (2011) 134–144, https://doi.org/10.1016/j.autcon.2010.09.011.
[45] S. Azhar, M. Khalfan, T. Maqsood, Building information modeling (BIM): now and beyond, Australas. J. Constr. Econ. Build. 12 (2012) 15–28, https://doi.org/10.5130/AJCEB.v12i4.3032.
[46] R. Sacks, L. Koskela, B. Dave, R. Owen, Interaction of lean and building information modeling in construction, J. Constr. Eng. Manag. 136 (2010), https://doi.org/10.1061/(ASCE)CO.1943-7862.0000203.
[47] Y. Arayici, P. Coates, L. Koskela, M. Kagioglou, C. Usher, K. O'Reilly, Technology adoption in the BIM implementation for lean architectural practice, Autom. Constr. 20 (2011) 189–195, https://doi.org/10.1016/j.autcon.2010.09.016.
[48] M. Golparvar-Fard, P.-M. Feniosky, S. Savarese, D^4AR-A 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication, Electron. J. Inf. Technol. Constr. 14 (2009) 129–153. http://www.itcon.org/2009/13.
[49] R. Miettinen, S. Paavola, Beyond the BIM utopia: approaches to the development and implementation of building information modeling, Autom. Constr. 43 (2014) 84–91, https://doi.org/10.1016/j.autcon.2014.03.009.
[50] C.K. Leung, K.T. Wan, D. Inaudi, X. Bao, W. Habel, Z. Zhou, J. Ou, M. Ghandehari, H.C. Wu, M. Imai, Review: optical fiber sensors for civil engineering applications, Mater. Struct. 48 (2015) 871–906, https://doi.org/10.1617/s11527-013-0201-7.
[51] G. Lee, R. Sacks, C.M. Eastman, Specifying parametric building object behavior (BOB) for a building information modeling system, Autom. Constr. 15 (2006) 758–776, https://doi.org/10.1016/j.autcon.2005.09.009.
[52] I. Hager, A. Golonka, R. Putanowicz, 3D printing of buildings and building components as the future of sustainable construction? Proc. Eng. 151 (2016) 292–299, https://doi.org/10.1016/j.proeng.2016.07.357.
[53] J. Hong, G.Q. Shen, Z. Li, B. Zhang, W. Zhang, Barriers to promoting prefabricated construction in China: a cost–benefit analysis, J. Clean. Prod. 172 (2018) 649–660, https://doi.org/10.1016/j.jclepro.2017.10.171.
[54] The World Bank, GDP (Current US$) - China: 1960–2022. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?contextual=default&end=2022&locations=CN&start=1960&view=chart, 2023.
[55] United Nations Environment Programme, Emissions Gap Report 2022: The Closing Window: Climate Crisis Calls for Rapid Transformation of Societies, Nairobi, Kenia. https://www.unep.org/resources/emissions-gap-report-2022, 2022.
[56] China Association of Building Energy Efficiency, China Building Energy Consumption Research Report (2019). https://www.sohu.com/a/367415540_505899, 2019 (accessed 9 May 2023).
[57] International Trade Administration - U.S. Department of Commerce, China - Country Commercial Guide: Design and Construction. https://www.trade.gov/country-commercial-guides/china-design-and-construction, 2023 (accessed 7 July 2023).
[58] A. Balbola, S. Musa, M.T. Akinlolu, T.C. Haupt, A bibliometric review of advances in building information modeling (BIM) research, J. Eng. Des. Technol. 21 (2023) 690–710, https://doi.org/10.1108/JEDT-01-2021-0013.
[59] A.B. Saka, D.W.M. Chan, A Scientometric review and Metasynthesis of building information modelling (BIM) research in Africa, Buildings 9 (2019) 85, https://doi.org/10.3390/buildings9040085.
[60] N.A. Olatunde, A.M. Gento, V.N. Okorie, O.W. Oyewo, Construction 4.0 technologies in a developing economy: awareness, adoption readiness and challenges, Front. Eng. Built Environ. 3 (2023) 108–121, https://doi.org/10.1108/FEBE-08-2022-0037.
[61] A. Ghaffarianhoseini, J. Tookey, A. Ghaffarianhoseini, N. Naismith, S. Azhar, O. Efimova, K. Raahemifar, Building Information Modelling (BIM) uptake: clear benefits, understanding its implementation, risks and challenges, Renew. Sust. Energ. Rev. 75 (2017) 1046–1053, https://doi.org/10.1016/j.rser.2016.11.083.
[62] M.A. Rojas-Sánchez, P.R. Palos-Sánchez, J.A. Folgado-Fernández, Systematic literature review and bibliometric analysis on virtual reality and education, Educ. Inf. Technol. 28 (2023) 155–192, https://doi.org/10.1007/s10639-022-11167-5.
[63] A.Z. Sampaio, D.P. Rosário, A.R. Gomes, J.P. Santos, Virtual reality applied on civil engineering education: construction activity supported on interactive models, Int. J. Eng. Educ. 29 (2013) 1331–1347. http://www.ijee.ie/latestissues/Vol29-6/04_ijee2767ns.pdf.
[64] F. Osti, R. de Amicis, C.A. Sanchez, A.B. Tilt, E. Prather, A. Liverani, A VR training system for learning and skills development for construction workers, Virtual Reality 25 (2021) 523–538, https://doi.org/10.1007/s10055-020-00470-6.
[65] P. Wang, P. Wu, J. Wang, H.-L. Chi, X. Wang, A critical review of the use of virtual reality in construction engineering education and training, Int. J. Environ. Res. Public Health 15 (2018) 1204, https://doi.org/10.3390/ijerph15061204.
[66] M. Ilbeigi, D. Bairaktarova, A. Morteza, Gamification in construction engineering education: a scoping review, J. Civil Eng. Educ. 149 (2023) 04022012, https://doi.org/10.1061/(ASCE)EI.2643-9115.0000077.
[67] Z. Feng, Y. Gao, T. Zhang, Gamification for visualization application in the construction industry, in: M. Bolpagni, R. Gavina, D. Ribeiro (Eds.), Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills, Springer International Publishing, Cham, 2022, pp. 495–514 (ISBN: 978-3-030-82429-7).
[68] E. Halmetoja, The role of digital twins and their application for the built environment, in: M. Bolpagni, R. Gavina, D. Ribeiro (Eds.), Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills, Springer International Publishing, Cham, 2022, pp. 415–442 (ISBN: 978-3-030-82429-7).
[69] J.O. De-Graft, S. Perera, R. Osei-Kyei, M. Rashidi, Digital twin application in the construction industry: a literature review, J. Build. Eng. 40 (2021), 102726, https://doi.org/10.1016/j.jobe.2021.102726.
[70] M. Xu, X. Nie, H. Li, J.C. Cheng, Z. Mei, Smart construction sites: a promising approach to improving on-site HSE management performance, J. Build. Eng. 49 (2022), 104007, https://doi.org/10.1016/j.jobe.2022.104007.
[71] H. Liu, J. Song, G. Wang, A Scientometric review of smart construction site in construction engineering and management: analysis and visualization, Sustainability 13 (2021) 8860, https://doi.org/10.3390/su13168860.
[72] J.C. Huang, From building information modeling to extended reality, in: M. Bolpagni, R. Gavina, D. Ribeiro (Eds.), Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills, Springer International Publishing, Cham, 2022, ISBN 978-3-030-82429-7, pp. 471–493, doi: 10.1007/978-3-030-82430-3_20.
[73] F. Al-Turjman, Information-centric framework for the Internet of Things (IoT): Traffic modeling & optimization, Future Generation Computer Systems 80 (2018) 63–75, https://doi.org/10.1016/j.future.2017.08.018.
[74] G.F. Huseien, K.W. Shah, A review on 5G technology for smart energy management and smart buildings in Singapore, Energy AI 7 (2022), 100116, https://doi.org/10.1016/j.egyai.2021.100116.
[75] J.M. Nwaogu, Y. Yang, A.P. Chan, H.-L. Chi, Application of drones in the architecture, engineering, and construction (AEC) industry, Autom. Constr. 150 (2023), 104827, https://doi.org/10.1016/j.autcon.2023.104827.
[76] J. Howard, V. Murashov, C.M. Branche, Unmanned aerial vehicles in construction and worker safety, Am. J. Ind. Med. 61 (2018) 3–10, https://doi.org/10.1002/ajim.22782.
[77] Marwan Gharbia, Alice Chang-Richards, Lu Yuqian, Ray Y. Zhong, Heng Li, Robotic technologies for on-site building construction: a systematic review, J. Build. Eng. 32 (2020), 101584, https://doi.org/10.1016/j.jobe.2020.101584.
[78] OpenAI, Introducing ChatGPT. https://openai.com/blog/chatgpt, 2023 (accessed 10 July 2023).
[79] OpenAI, GPT-4. https://openai.com/research/gpt-4, 2023 (accessed 10 July 2023).
[80] European Commission, Key Enabling Technologies Policy. https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/key-enabling-technologies_en#kets (accessed 12 July 2023).
[81] R. Kurzweil, The Law of Accelerating Returns. http://www.baxtek.com/products/wireless/files/law-of-accelerating-returns.pdf, 2001. (Accessed 9 October 2023).
[82] M. Buchanan, The law of accelerating returns, Nat. Phys. 4 (2008) 507, https://doi.org/10.1038/nphys1010.
[83] Y.K. Cho, Y. Jang, K. Kim, F. Leite, S. Ayer, Understanding Different Views on Emerging Technology Acceptance between Academia and the AEC/FM Industry, in: Y.K. Cho, F. Leite, A. Behzadan, C. Wang (Eds.), Computing in Civil Engineering 2019, American Society of Civil Engineers, Reston, VA, 2019, pp. 614–621. ISBN: 9780784482438.
[84] H. Piwowar, J. Priem, V. Larivière, J.P. Alperin, L. Matthias, B. Norlander, A. Farley, J. West, S. Haustein, The state of OA: a large-scale analysis of the prevalence and impact of open access articles, PeerJ 6 (2018), e4375, https://doi.org/10.7717/peerj.4375.
[85] M. Norris, C. Oppenheim, F. Rowland, The citation advantage of open-access articles, J. Am. Soc. Inf. Sci. Technol. 59 (2008) 1963–1972, https://doi.org/10.1002/asi.20898.
[86] A. Booth, A. Sutton, M. Clowes, M. Martyn-St James, Systematic Approaches to a Successful Literature Review, Third ed., SAGE Publications Ltd, London, 2021. ISBN: 9781529759648.