Implementation of augmented reality in BIM-enabled construction projects: a bibliometric literature review and a case study from China

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Abstract

Purpose – In recent years, augmented reality (AR) has shown its potential to assist various construction activities. Its use commonly requires additional refinement to be integrated into the building information modeling (BIM) process. Nevertheless, few studies have investigated AR implementation in BIM-enabled projects because of numerous challenges related to its implementation. This study aims to investigate the implementation of AR in construction and identify the critical mechanisms for implementing BIM-AR successfully.

Design/methodology/approach – A mixed methodology was adopted for this study. First, this work presents a bibliometric analysis covering articles obtained from Scopus database published between 2000 and 2022. A sample size of 65 research papers pertinent to AR in construction was analyzed using VOSviewer software. Second, a participatory case study was conducted for a BIM-enabled project in China to gain insight into how BIM-AR implementation in construction is achieved.

Findings – The findings from the bibliometric analysis show an increasing interest in AR research within construction. The results indicate that AR research focuses on four clusters: real-time communication, project management, construction activities, and education. Findings from the case study provide an empirical experience of AR application scenarios in a BIM-enabled project. Concomitantly, 15 critical success factors that influence BIM-AR implementation were finally identified and demonstrated.

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Originality/value – This study provides a rich insight into the understanding and awareness of implementing AR. First, the findings are beneficial to construction practitioners and researchers because they provide a concentrated perspective of AR for emerging activities in the construction industry. Second, the results obtained from the case study could provide a useful guide for effectively implementing AR in a BIM-enabled construction project. Overall, this study may stimulate further research on AR-related studies in construction, such as BIM integration, factor analysis and construction education.

Keywords Augmented reality, Bibliometric analysis, Building information modeling, Case study, Factors, Construction industry

Paper type Research paper

1. Introduction

The architecture, engineering and construction (AEC) industry plays a fundamental role in the prosperity of nations and is predicted to reach $15.5tn in global expenditure by 2030 (PwC, 2020). The growth of the AEC industry and the increasing demands for speed and efficiency of modern building projects have given rise to challenges for project management. Generally, project management is evaluated by quality, cost and time (referred to as the PM triangle) (Atkinson, 1999). To balance the PM triangle and achieve a successful project delivery, stakeholders must generate relevant and accurate information. Over the past few years, researchers have argued that technology-enabled innovations could provide stakeholders with promising prospects to gather on-site information and deliver timely communication due to evolving technologies (Bhattacharya and Momaya, 2021; Huang et al., 2020; Wang and Guo, 2022), which can be used to balance the PM triangle of construction projects. Nevertheless, most construction projects still rely on manual procedures and conventional communication methods rather than technological advancements (Ma et al., 2020). This is partly because it always takes great efforts and risks to discover approaches for effectively adopting innovative technologies and transferring knowledge between off-site and on-site construction practitioners to warrant project success (Shouman et al., 2021).

Currently, digital technologies have resulted in a dramatic shift in information documentation and exchange; this process is also known as Construction 4.0 (C4.0) (Wang et al., 2022b). Building information modeling (BIM), one of the most significant technological advances in the era of C4.0, has driven the digital transformation of the AEC sector. BIM was proposed to unify projects with the information necessary for collaboration, which provides a paradigm change in project management by creating, using and managing digital project data throughout the project life cycle (Alizadehsalehi et al., 2020; Babatunde et al., 2020; Khosrowshahi and Arayici, 2012). With 3D modeling software, users can produce data-rich models that are parametric and object-oriented and embedded with detailed information, thus enhancing information sharing and communication. In addition to developing n-D modeling, the maturity level of BIM implementation is regarded as a process that targets daily production procedures (Edirisinghe et al., 2017; Wang et al., 2022c). However, despite BIM’s success to far, the majority of projects do not realize the full benefits of adopting BIM due to certain constraints that hinder the BIM adoption process (Alizadehsalehi et al., 2020; Garbett et al., 2021). Regarding the technology side, the most prevalent issue with BIM is that the information is not presented in such a way that construction practitioners can fully comprehend it on a real-world scale (Alizadehsalehi et al., 2020). It would be ideal if the model information could be immersed into the real-world scale, allowing for better on-site information delivery.

In this case, augmented reality (AR) may solve this problem by enabling contextually relevant communication that blurs the line between the virtual environment and the
physical world (Schranz et al., 2021). By superimposing the digital representations of objects onto the physical world, AR can generate a composite image of the virtual and reality. Such alignment of digital representations with users’ view of the physical world allows virtual and reality interpretation simultaneously (Liu et al., 2021). As a result, BIM can perform functional decision support for project management with the assistance of AR. Nevertheless, widespread adoption of the integration of AR and BIM has not been observed in real-life practices, especially in developing countries (Sidani et al., 2021). Therefore, this research is proposed to investigate AR applications in BIM-enabled projects and demonstrate the potential for their integrated implementation of reality capture and visualization in a real-life project. To be specific, the following research questions are addressed in this study:

**RQ1.** What is the current distribution of AR studies in construction globally?

**RQ2.** What has been the main focus of previous studies on AR research in construction?

**RQ3.** What are the key mechanisms for the successful implementation of BIM-AR in construction?

The remaining sections of the paper are structured as follows. First, the following section reviews the relevant literature, covering descriptions of BIM implementation in the AEC industry and the role of AR for BIM-enabled projects. In Section 3, the authors proceed to explain the research methods adopted, namely, bibliometric literature review and participatory case study. In Section 4, the results and discussion are provided to answer the three research questions and illustrate the research implications of this study. Conclusions and future directions are drawn in the final segment of the paper.

### 2. Research background

#### 2.1 Building information modeling implementation in the architecture, engineering and construction industry

The term “BIM” was first proposed in 1975 (Eastman, 1975) and has gradually gained widespread popularity. British Standards Institute (BS EN ISO 19650, 2018) defined BIM as:

> [...] the process of generating and managing information about a building during its entire life. BIM is a suite of technologies and processes that integrate to form the “system” at the heart of which is a component-based 3D representation of each building element; this supersedes traditional design tools currently in use.

BIM has enormous potential in the AEC industry and has garnered international academic attention. Notable achievements in this area include: “BIM and project management” (Merschbrock and Munkvold, 2015; Wang et al., 2022a), “BIM and design optimization” (Minagawa and Kusayanagi, 2015), “BIM and education” (Abbas et al., 2016; Wang et al., 2020), “BIM and waste minimization” (Akinade et al., 2015; Jalaei et al., 2021), “BIM and safety management” (Marefat et al., 2018; Tang et al., 2021), to name but a few examples. Its appearance has changed the traditional paper-based management mode and led to great technological innovation in the AEC industry (Jalaei et al., 2021; Keskin et al., 2020; Oraee et al., 2017).

Since BIM received significant recognition and continuously increasing attention in the mid-2000s, many significant economies have set a BIM mandate or are thinking of developing one (Arayici et al., 2011; McGraw-Hill Construction, 2014). For example, some countries have proposed their national BIM mandates for projects, including Spain, the UK, the USA, France, Finland, Sweden and Denmark, among others (Edirisinghe and London, 2015). However, the BIM diffusion among industry professionals worldwide has been lower
than expected (Babatunde et al., 2020). Lack of initiative and training, varying market readiness across geographies, the fragmented nature of the AEC business and the industry’s reluctance to change old work processes have been cited as causes for the slow progress (Siebelink et al., 2021). To implement BIM more effectively, firms require a strategy that addresses their particular demands and company values. Such needs will be more challenging for AEC companies in developing countries like China (Zhou et al., 2019). In contrast to developed countries such as the USA, Finland and Denmark, where the professional construction practice is fairly advanced, the knowledge and experience of BIM within the Chinese AEC industry is still in its early stages (Liu et al., 2017).

According to NBS (2022), China’s National Bureau of Statistics reported that the total output value of the AEC industry was ¥29,307bn in 2021. It denotes an increase of 11.0% from the previous year, a relatively high growth rate, accounting for 7.0% of the gross domestic product. The performance shows that the AEC industry has sustained essential support for Chinese social and economic development. As the giant AEC market worldwide, the characteristics and dynamics research of BIM in China are important. The implementation of BIM is emerging in China but showing some progress in recent years. According to Jin et al. (2015), China’s BIM policy movement has taken significant advances since 2011 and has become more unified with the publication of the first BIM standard in 2012. In 2013, the strategic objectives for BIM adoption were established. In 2014, the BIM application across the entire project life cycle was presented, and a National BIM Standard was issued in 2017.

Regarding the research contributions, many researchers have explored ways to promote BIM adoption in China from different perspectives. For example, Zhou et al. (2019) gave proposals for fostering the development of BIM based on the lessons learned from the experiences of other countries. Based on the technology—organization—environment framework, Chen et al. (2019) investigated the factors that influence the adoption of BIM in the Chinese AEC industry. Ma et al. (2020) identified 10 critical strategies for enhancing BIM implementation within the Chinese AEC project context through a questionnaire survey. Also, Chen et al. (2021) proposed a profile-oriented collaboration strategy selection framework for BIM-enabled construction projects. Despite the accomplishments of the BIM movement in terms of both policy development and scientific research, studies about how BIM might transcend design to real-time on-site construction have rarely been investigated in China.

Many Chinese BIM-enabled projects use BIM simply as a representation and simulation tool (Liu et al., 2017). The ineffective use of BIM on the construction site has been hampered by difficulties in managing vast amounts of data and a lack of situational understanding regarding its accessibility. In other words, the current contribution of BIM to fieldwork is limited due to the lack of interaction between the virtual and physical worlds (Meža et al., 2014; Schranz et al., 2021; Sidani et al., 2021). The majority of current BIM delivery is based on tools that lack sensory components, resulting in limited model–environment interaction. Therefore, it is worthwhile to integrate another digital technology, such as AR, into the existing BIM to overcome such problems and to connect the BIM model with the physical environment.

2.2 Application of augmented reality in building information modeling-enabled projects

AR is a layer of computer-generated content in the real world that can interact with the environment visually in real time. Fundamentally, it is an environment in which computer-generated data is superimposed on the user’s view of a real-world scene (Machado and Vilela, 2020). AR enables a person to operate in a real-world environment while visually receiving additional computer-generated or modeled data to complement the current task.
Current AR technologies allow a mixed world to be formed when users view surroundings through specially designed head-mounted equipment or a portable device (Harikrishnan et al., 2021). The display of the head-mounted equipment should be made of transparent material so that the user can observe the real-world environment while viewing the display. In the case of a portable device, the virtual object is displayed alongside the real-time image captured by the device’s camera, establishing a composite environment. The user can then compare and distinguish between the real and virtual worlds.

AR is a feasible option for digitally displaying BIM information, as the information on BIM given on the desktop in the office is insufficient for some management purposes (Chai et al., 2019). The combination of BIM and AR expands the possibilities for architectural visualization, navigation and interaction well beyond the usual static navigation and interaction in front of a computer screen. Therefore, studies to investigate the integration of BIM and AR are necessary for better project management. In previous studies, Meža et al. (2014) analyzed the AR potential and developed an architecture of the software system to implement a BIM-based AR system for construction. Chu et al. (2018) adopted a design science research approach to test and evaluate a mobile BIM-AR system with cloud-based storage capabilities based on a portable desktop experiment. Dang and Shim (2020) proposed a BIM-based innovative bridge maintenance system and used AR devices to conduct an automated inspection. In the study of Chalhoub et al. (2021), the performance advantages and disadvantages of using AR were investigated to verify deviations between the model and the built environment among mechanical, electrical and plumbing (MEP) systems. Also, Sidani et al. (2021) conducted a review study and collected 24 papers to examine the previous findings of AR in construction in terms of AR techniques, BIM-based AR implementation, main target groups and limitations. Throughout the past decade, despite the advances of AR from the technical perspective, the extent of literature remains very short of empirical studies of AR implementation in BIM-enabled projects, especially for real-life practices. Also, the investigation of effective methods for the promotion of successful BIM-AR adoption remains a challenging research issue (Machado and Vilela, 2020; Schranz et al., 2021).

Accordingly, this paper presents an exploration of the research trend and main topics of AR in the construction and implementation of AR in a BIM-enabled project. To achieve this, a review study was conducted in the first stage to quantitatively and qualitatively analyze the AR research in construction. In the second stage, the authors aimed to provide key insights into the workflow and critical success factors (CSFs) that facilitate the effective implementation of BIM-AR based on a real-life construction project. This research gap was also highlighted by Arowoiya et al. (2021), who indicate that developing countries require more studies on CSFs of AR implementation to support the adoption and implementation of AR.

3. Methods: bibliometric exploration and case study
Mixed methods combine both quantitative and qualitative research approaches. In this study, the exploratory sequential design of methods was adopted for the purposes of exploring and generalizing the findings. First, this research relies on a bibliometric analysis to investigate the research trend and focus of AR in construction. Then, a detailed, in-depth case study of implementing BIM-AR was conducted, which enabled the comprehensive exploration of AR in a real-life project. The research flow of this study is described in Figure 1.
3.1 Bibliographic literature review

The bibliographic literature review was conducted to address RQ1 and RQ2. A bibliometric technique was used to identify and map knowledge domains through the identification of research patterns. The bibliometric approach was employed because it allows one to derive the essence of a research domain from a large amount of literature, thereby facilitating the investigation of information structure, the development of research areas and the identification of the interdisciplinary research subject. It has been widely applied to detect emerging research domains and technologies in construction management research (Oraee et al., 2017; Wang and Guo, 2022). The development of the literature review is based on a clearly defined procedure for selecting target articles and reporting findings from prior research. This literature review had a dual objective. First providing a quantitative analysis
and data visualization of the collected papers to comprehend the key aspects of AR research within the AEC field. Second, using the text-mining tool to explore the research map of AR themes in construction and perform a rigorous content analysis of the selected articles to summarize the contributions of thematic areas from the research map and investigate the integrated applications of AR and BIM.

### 3.1.1 Identifying primary studies

Stage 1 comprises research using Scopus database as a search engine to retrieve primary studies that satisfy the review criteria. A myriad of researchers has widely used Scopus within the construction management field because of its extensive coverage of primarily journal articles (Oraee et al., 2017). The innate capacity of Scopus to interrogate literature ensures that current developments and implementations of emerging technologies are adequately documented. The systematic data collection followed in this research relies on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) (Moher et al., 2009). Figure 2 presents the overall view of the systematic process.

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**Figure 2.** PRISMA systematic records selection flow
To determine the scope of research conducted in the field of AR within the AEC industry, keywords were used to search for relevant publications. These keywords are either found in the title, abstract or keywords of articles. The search was restricted to academic journal articles published between 2000 and 2022 in English. The complete search code is provided below.

TITLE-ABS-KEY (“AR” OR “augmented reality” OR “immersive technology” OR “interactive technology”) AND TITLE-ABS-KEY (“construction industry” OR “construction sector” OR “built environment” OR “civil engineering”) AND DOCTYPE (ar) AND (LIMITED-TO [LANGUAGE, “English”]).

This round of searching yielded 193 related articles (the data were obtained on May 7, 2022).

3.1.2 Selecting target papers. At this stage, articles were selected based on their eligibility for further examination. The titles and abstracts of the 193 studies retrieved in Stage 1 were assessed first. After a visual assessment, 97 papers were eliminated because their research findings were unrelated to the topic of this investigation. Second, the full text of the rest articles was read by the authors to remove the papers that were not related to research areas of AR. Finally, a total of 65 publications were selected for further analysis.

3.1.3 Analyzing target papers. The selected papers were subjected to content analysis and keyword co-occurrence analysis to determine the research trends and AR-related issues in the AEC field. With text mining algorithms applied in reviews, findings are free from the subjectivity characterized by conclusions provided in narrative and systematic reviews. Several text-mining applications, such as BibExcel, Gephi, CiteSpace and VOSviewer, have been created for the mapping of scientific literature. This study adopted VOSviewer because it provides basic functionalities in viewing scientometric networks (Hussein and Zayed, 2021). Using the clustering feature of VOSviewer, researchers can use the network of keywords to uncover the relationships between the study subjects and the research procedures used by earlier publications and comprehend the research area’s dominant themes (Hussein and Zayed, 2021).

The bibliometric data of the included articles were exported to VOSviewer so that the interconnection between keywords could be presented as nodes and linkages. In all scientometric networks generated by VOSviewer, the circular nodes are color-coded to reflect different groupings, the node sizes represent the frequency of occurrence of the various keywords, the arcs denote co-occurrence associations and the line thickness represents the strength of each link.

3.2 Case study
Following the literature review, a participatory case study was undertaken to empirically explore the key mechanisms for the successful implementation of AR in a real-life BIM-enabled project to answer RQ3. Participatory case study is a research strategy for addressing problematic circumstances in which local actors collaborate with researchers to interactively make sense of perceived problems and seek suitable contextual solutions in noncontrolled contexts (Reilly, 2010). This approach “focuses on research in action, rather than research about action”; hence, unlike other research methodologies, it stresses the collaboration of insiders (i.e. practitioners) and outside facilitators (i.e. researchers) in addressing a real-world issue (i.e. AR implementation). For the purposes of this study, a single case was chosen because it is suitable for exploratory research and provides sufficient scope for in-depth observations (Voss et al., 2002; Yin, 2013).

3.2.1 Case selection and background. The studied case is one of the largest and most important infrastructure developments to take place in the south-eastern Jiangsu Province in
China. The project is designed to provide the production of hydrogen fuel cells for new energy transformation. It is 108,000-ft² and was built at the cost of $5.4m over 13 months. The design and construction of a hydrogen cell facility are highly complicated and involve various infrastructures, including buildings, industrial facilities, power generators, fuel stations, storage facilities, car parks and roads. Construction was finished by the end of December 2020, and the facility has been in service since March 2021. Company X funded the project, which is a Germany-based leading global engineering and technology company founded in the 1880s. Company Y is a Chinese engineering company and was involved as the main actor in the design and construction. Company Z was established in the 2010s with the aim of developing AR technology and providing the BIM full life cycle intelligent implementation tool for the AEC industry, which has gained much experience in the implementation of AR in construction, accounting for about 95% of the AR market in the Chinese AEC industry. The main reasons for selecting this case are as follows:

- It is one of the rare cases that demonstrates the phenomenon of AR implementation in a BIM-enabled project, thus, representing a case involving “unique circumstances.”
- Company X has a considerable magnitude, which makes its invested project worth devoting attention to. Also, Company Z has a great experience in AR implementation in construction.
- It was purposefully selected because authors had easy access to a rich set of data. Based on these reasons, the case provided a wealth of data for research, and it is anticipated that the lessons acquired in this project would aid in the implementation of AR in future projects.

3.2.2 Data collection and analysis. In this case study, the authors performed three roles:

1. consultant for providing AR assistance to the managers and workers of the project;
2. owner project manager for managing the available resources for the construction project; and
3. observers on the AR implementation without any intervention from managers and workers’ daily operations.

The case study was designed with multiple methods of data collection (i.e. project document review, meetings, observations, field notes and interview) to enable triangulation and increase validity. The data collection points and outputs are explained below:

- Regular project meetings with key stakeholders to check the work progress of the project.
- Published files containing reports, notes and correspondence relating to the project from its inception to the time were collected from Company X and Company Z. The documents were reviewed to identify background information, such as the history and operations of the project, which is particularly useful in identifying the issues of AR implementation during the project.
- Observations of the AR implementation process on-site by authors to investigate the key mechanism of successful AR implementation.
- To yield additional observations and tales of AR implementation, a semi-structured interview with the vice president of Company Z was conducted after project completion. In addition to being in charge of the company’s AR business, he has extensive expertise as a software engineer and project manager. The interview
lasted for one and a half hours and was recorded with permission to avoid misunderstanding of explanation.

To identify the key mechanism of AR implementation and its related CSFs, an innovation framework (see Figure 3) proposed by Ozorhon (2013) was used to analyze the factors that influence the implementation of AR. The framework has been established to analyze the construction innovation process at the project level, which has been used to study technology innovation in previous literature (Keskin et al., 2020; Koseoglu et al., 2019; Wang and Guo, 2022). The innovation process is depicted as a system with several interconnected factors, including drivers, inputs, innovations (i.e. AR technology), barriers, enablers and outputs.

4. Results and discussion
In this section, the research results from different sources (i.e. academic literature, project documents, meetings, field observations and interview) during the study are presented. The results are furtherly analyzed and discussed based on the proposed research questions.

4.1 RQ1: the current distribution of augmented reality studies in construction globally
4.1.1 Publication year. Figure 4 depicts a time series of annual publication frequency from 2000 to 2022. The time series shows an increasing tendency in publishing, with a particularly sharp increase from 2019 to 2021. Among the 65 primary studies, 7 papers were published in 2019, 8 in 2020 and 19 in 2021. The significance of AR in the AEC industry has grown in recent years, as seen by this expanding trend in publications.

4.1.2 Publication’s country of origin. Regarding the number of studies by the nation of origin, the findings indicated that several papers are affiliated with more than one country; accordingly, there exists some overlap. Figure 5 illustrates the publications classified by the 24 countries between 2000 and 2022. This diversity in various geographic distributions suggests a global interest in AR technology in the AEC industry. Articles from the USA \(n = 23\) are at the forefront of this field, accounting for 35.3% of all publications. Next comes South Korea, with 10 publications, and these are followed by Australia \(n = 9\), China \(n = 8\), the UK \(n = 6\) and Nigeria \(n = 4\).
4.1.3 Publication channel. The public perception of a journal is influenced by its credibility. This mapping review reveals that Automation in Construction (n = 12) is the most prominent publication venue among those under review. The other prominent journals covered in the primary studies include the Journal of Information Technology in Construction (n = 5), Advanced Engineering Informatics (n = 4), Engineering, Construction and Architecture Management (n = 2), Computer-Aided Civil and Infrastructure Engineering (n = 2) and many others, as shown in Figure 6. From a scientific standpoint, publications in these journals highlight the importance of AR and its applications in construction. Also, the
interdisciplinary nature of AR applications is shown by the number of papers in these diverse and well-reputed journals.

4.1.4 Research methods. The methodology used in AR research was investigated in the primary studies. Figure 7 indicates that the majority of primary studies used conceptual and literature review approaches \( (n = 21) \), followed by experiments \( (n = 14) \), surveys \( (n = 11) \), simulations \( (n = 10) \), mixed methods \( (n = 7) \) and archival and other designs \( (n = 2) \). Mixed-method studies combine quantitative and qualitative research methods. The results predominantly demonstrate that archival and other designs were in the minority in the publication, such as case study research, which should be adopted more in future studies.

4.2 RQ2: the focus of previous studies on augmented reality research in construction

4.2.1 Research status analyzed by keyword co-occurrence analysis. Figure 8 shows the strong connections of AR with other keywords, such as education, visualization, project management, collaboration, BIM and underground utilities. Based on the keyword co-occurrence analysis, the classification of keywords into the topics was generated according to similar research areas. With the help of VOSviewer, keywords from similar or interrelated research areas are illustrated closer to each other. The keywords that have similar meanings are merged, and the keywords that are the same in meaning but different in spelling are also combined. For instance, “AR” and “augmented reality” are unified as “augmented reality,” while “BIM” and “building information modeling” are named “building information modelling.” The co-occurrence analysis was performed on keywords with more than five occurrences. The visual word co-occurrence network is presented in Figure 8.

Figure 6. Top 10 journals in terms of number of AR publications

Figure 7. Research methods used in primary studies
As shown in Figure 8, the results of the analysis have been presented according to the frequency of keywords and intersections of clusters which are classified into four research domains:

1. team collaboration;
2. project management;
3. construction work; and
4. construction education.

These indicate the practical application areas of AR in the AEC sector, which will be discussed further in the content analysis.

4.2.2 Content analysis

4.2.2.1 Key research topics of AR in construction. The co-occurrence of keyword analysis has indicated the research trend of AR in construction, and the content analysis was conducted to comprehend the topics of each research domain. Content analysis is a key stage in methodically analyzing the research progress of numerous relevant areas (Boyack and Klavans, 2010). To synthesize the corpus of knowledge, four research domains were identified based on bibliographic coupling. Table 1 lists the research areas, together with their focus, specifics and supporting references.

Team collaboration is essential to the success of construction projects, which encourages project participants’ knowledge and information sharing. AR applications can benefit from collaboration between humans and computational intelligence in an AR environment (Baroroh et al., 2021). Three research topics of AR consist of team collaboration: wearable and mobile devices, collaborative design and real-time communication. Zaher et al. (2018) developed a method that enables improved face-to-face communication and project control by directly visualizing construction progress on-site via AR and portable mobile devices. In the study of Fukuda et al. (2019), an integration system of AR and computational fluid dynamics was developed to facilitate a
collaborative design environment across stakeholders. The system was implemented to enable visualizing results of thermal simulations to support retrofitting for indoor design. To tackle collaboration issues, Harikrishnan et al. (2021) suggested AR communication scenarios as a viable alternative to in-person meetings. They found that using AR can result in more meaningful engagement of the project team and efficient leveraging of experienced staff skills.

Project management areas include safety management, stakeholder engagement, integration with digital tools, design monitoring and modification, information management, facility management and project productivity analysis. For safety concerns, construction practitioners must have a thorough understanding of the real objects and hazards that surround them. For this purpose, AR efficiently assists users in gaining a clear understanding through visualization (Li et al., 2018; Schranz et al., 2021; Shouman et al., 2021). AR in walkthroughs provides better seamless immersive experiences in construction management tasks. Mutis and Ambekar (2020) developed an AR system to improve the accuracy of walkthroughs and help stakeholders conveniently visit an area of interest in the job site. To achieve the full potential of AR, it is also integrated with other technologies such as BIM (Chen et al., 2020), geographic information system (GIS) (Shekargoftar et al., 2022), Internet of Things (Rashid et al., 2017) and virtual reality (Delgado et al., 2020). For example, in the study of Machado and Vilela (2020), they found a great potential for using integrated AR and BIM to assist in operations inspection, installation assemblies, infrastructure and building maintenance.

In addition, Shouman et al. (2021) stated that AR shows a positive impact on design interaction among project practitioners to easily manipulate and generate design solutions in the design process. For more convenient information management, Garbett et al. (2021) demonstrated that information could be added to the AR environment and stored in an online database that any of the users could access instantaneously. In another study focused on facility management, Chung et al. (2021) presented a system that configures data categories and defines the functions required to apply AR to facility management tasks. Wang et al. (2022a, 2022b, 2022c) proposed an automated vision-based technique for the productivity analysis of cable crane transportation using a novel synthetic image methodology based on AR.

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<th>CI</th>
<th>AR application domains</th>
<th>Main topics</th>
<th>Examples</th>
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<tr>
<td>Team collaboration</td>
<td>Wearable and mobile devices</td>
<td>Zahe et al. (2018)</td>
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<td>Collaborative design</td>
<td>Fukuda et al. (2019)</td>
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<td>Real-time communication</td>
<td>Harikrishnan et al. (2021)</td>
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<td>Project management</td>
<td>Safety/emergency management</td>
<td>Li et al. (2018)</td>
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<td>Stakeholder engagement</td>
<td>Mutis and Ambekar (2020)</td>
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<td>Integration with digital tools</td>
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<td>Design monitoring and modification</td>
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<td>Underground utilities construction</td>
<td>Fenais et al. (2019)</td>
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AR has been implemented in three main areas in addressing the construction activities:

1. underground utility construction;
2. on-site construction inspection; and
3. monitoring, and construction operation and maintenance.

*Fenais et al. (2019)* proposed an AR-GIS system to improve mapping inputs for utility lines and real-time utility registration. The system has been assessed as an effective underground construction safety information and communication management system. *May et al. (2022)* presented an AR system for detecting construction flaws during on-site inspection and operation. The system was evaluated to achieve up to 1 cm accuracy. An AR field application was presented by *Tarek and Marzouk (2022)* to help maintenance and operation engineers imagine infrastructure networks by graphically portraying infrastructure networks enhanced with facility data, such as manufacturer, maintenance history and facility management organization.

Regarding construction education, AR has been demonstrated to improve the performance of personnel performing various construction activities, and it is also being investigated as a learning assistance for students and technicians alike (*Kim and Irizarry, 2021*). For instance, *Guray and Kismet (2021)* developed a digitalization model to improve learning efficiency for students to obtain the necessary skills using AR and BIM tools. The digitalization model enables instant access to simulations and 3D representations by scanning the QR code, which provides a dynamic digital design environment for architecture education. For job training, with the assistance of AR, *Chalhoub et al. (2021)* conducted an experiment to compare the performance of untrained and trained persons in construction-related tasks to that of well-trained professionals. The findings offer empirical evidence of performance similarities and variations that may exist across untrained and trained persons while using AR.

### 4.2.2.2 Current practices of integration of AR and BIM

Furthermore, as BIM becomes the mainstream process for building projects, new technical working methods enable practitioners in the project team to collaborate more effectively. As noted previously, BIM is not just about 3D models or confined to visualizations; it is defined as the collaborative effort of stakeholders throughout a building’s life cycle to embed, update, extract or manage data in a model (*Garbett et al., 2021*). AR is a tool in which the real environment is “augmented” by means of virtual objects. In the AEC sector, AR has been explored for a variety of applications to improve the quality of communication between various stakeholders. With a simple access interface, AR has the potential to transform the way construction professionals associate and retrieve sophisticated specialized data in BIM.

Several studies have concentrated on the integration of BIM and AR. *Chen et al. (2020)* proposed a fire safety equipment (FSE) inspection and maintenance system combining AR and BIM environments. The viability of the system was validated by a case study and demonstrated that the system effectively displayed information for FSE inspections and maintenance in a rapid, visible and convenient manner. *Liu et al. (2021)* presented an AR solution by integrating BIM and the unmanned aerial vehicle inspection workflow to expedite the visual inspection of buildings. The integration allows for the simple extraction of important information from BIM to help better understand the risk issues identified from the aerial video. In addition, *Schranz et al. (2021)* merged AR and BIM in the submission plan verification process, allowing for a more intelligible depiction of content for persons unfamiliar with the work. The result confirmed that an AR-supported plan checking substantially enhances the presentation of technical knowledge and
promotes practitioners’ understanding of the interaction of the planned project with the physical environment.

Moreover, to reduce the risk of damaging buried utilities, Shekargoftar et al. (2022) proposed a system based on BIM, AR and GIS to transform traditional maintenance information into a virtualized 3D work containing rich information. This integration can support visual information, information retrieval and utility model modifications. In the study of May et al. (2022), a three-stage research project to assess an on-site BIM-based AR defect management system was conducted, which included identification, development and evaluation stages. The findings revealed that the AR and BIM systems significantly outperformed traditional analog drawings in terms of inspection task performance, completion time, mental workload, building element location, user support and defect inspection.

According to the review analysis, despite the desire for AR, not many applications of AR have been seen in real-life construction practices. While researchers agree on the potential of AR to support BIM-enabled projects, most published work reports the use of AR in a controlled environment, and most have not been deployed to actual project sites for construction professionals. There are several probable explanations. For instance, stakeholders may not have been completely aware of the potential applications of AR in construction. Various financial, technological or environmental obstacles may also limit the widespread AR adoption in the AEC industry. These encourage the authors to explore the key mechanism for successful BIM-AR implementation in the AEC industry. Accordingly, case study research is needed to show how AR technology was implemented in a BIM-enabled project.

4.3 RQ3: the key mechanisms to the successful implementation of building information modeling–augmented reality in construction

The literature review confirms the growing interest in AR within the AEC industry as a disruptive technology trend that may significantly improve project performance. Given the research background of AR, the question remains as to how to successfully implement AR in real-life projects. With this question raised by the preceding analysis, the study now focuses on a case study, which is an example of the successful implementation of AR in a BIM-enabled project.

4.3.1 Building information modeling-to-augmented reality implementation scenarios. In the case study, BIM-AR implementation denotes “the arrangement of BIM-AR activities that helps project participants move forward with clear roles and expectations.” The implementation framework for adopting BIM-AR in the project is proposed in Figure 9 and validated in the case study. The framework identifies and defines the most critical process and activities that project participants should consider in implementing BIM-AR. The framework also explains how AR can be integrated into the process of a BIM-enabled project in terms of objectives (i.e. motivation) and activities (i.e. task flow).

In this project, the AR technology provided real-time visualization and status information at critical points and locations across the design and construction stages, as illustrated in Figure 9. With the input of the BIM model in AR, the correspondence between the virtual model coordinate system and the real space coordinate system can be constructed, then the virtual model is embedded into the real world and can be used to guide construction tasks. Several hardware and software components have been integrated to achieve the above purpose (e.g. Revit, Navisworks, sensors, Bluetooth beacons, Bluetooth gateways, tablets, smartphones and a cloud-hosted data processing platform). Figure 10 shows a visual depiction of the hardware and software devices used in this project, which is summarized into four phases, according to Chi et al. (2013). The components of the BIM-AR ecosystem include the data phase, computing phase, tangible
Figure 9. Implementation protocol of BIM-AR application process

Figure 10. A visual depiction of the BIM-AR ecosystem
phase and presentation phase. The main technologies and tools used in each phase are described below.

4.3.1.1 Data phase. The cloud computing environment is used to access information in the data phase. Cloud-based collaboration tools, Autodesk Revit and Navisworks have been chosen to transfer digital BIM data from office to site because of their interoperability with mainstream design tools. The service-oriented architecture in cloud servers avoids the multiple copies of the data and allows data to reside in one application, which can be easily accessed and modified by other applications. The time for data interaction between BIM and AR was about 3 min. In addition, software as a service and offline support was provided by the AR platform, enhancing project execution by reducing overhead expenses and increasing productivity.

4.3.1.2 Computing phase. The localization technologies applied in the computing phase significantly impact the future development of AR applications (Baek et al., 2019). Through adopting indoor and outdoor high-precision data acquisition methods (e.g. radio frequency identification (RFID), Bluetooth, real-time kinematic and simultaneous localization and mapping), the continuous coordinate system of the mobile device can be quickly constructed. Then the coordinates of the virtual model can be quickly mapped and updated via the intermediate and reference layers of the coordinate system. On the basis of the virtual coordinate system, its relative relationship with the real-world coordinate system can be calculated to form a stable coordinate system and achieve centimeter-level positioning accuracy, which is based on two-point positioning and QR code positioning, both of which are realized by establishing a spatial coordinate system to achieve the 1-to-1 scale restoration of a virtual model in real space.

4.3.1.3 Tangible and presentation phases. The technologies related to tangible and presentation phases are portable mobile devices and natural user interfaces. After the relative position relationship is fixed, AR enables the visualization of virtual models of specific locations in real space on the screen by showing BIM information at coordinate positions in the real-world and mapping them to the platform screen for visualization and interaction. By adjusting the transparency, it is easy to check whether the construction is consistent with the design. The inconsistent part is recorded by photo screenshot and marked in the platform for follow-up correction.

In this project, AR was used in various scenarios, with examples shown in Figure 11. While BIM provided a platform for all professionals to communicate, it was important to extend these efforts beyond the office to the construction site to achieve the full benefits of BIM. The applications of AR and BIM together have offered multidisciplinary collaboration during the design and construction phases of the project. An improvement in design visualization, reduction in unnecessary rework, and cost and time savings have been achieved through BIM and AR. Particularly, six application scenarios were identified in the case study, as summarized in Table 2 and further described below:

1. **Design (project) visualization at full scale on-site.** The development of AR makes it possible to generate 3D models on the 2D plane. Using BIM-AR, project participants can produce detailed interactive building project models and present them to customers at the beginning of the project, allowing customers to fully understand the project results and make any required changes before construction begins. Involving customers early in the process helps prevent costly changes later in the construction phase.

2. **Visualization of underground utilities (i.e. pipeline).** The construction process of the embedded pipeline needs to go through marking, excavation, installation, acceptance and backfilling. For the acceptance work of large quantities, wide distribution and complicated details of the embedded casing, the visible BIM models are used to make the branch pipe, steering and exposed ground position. Before backfill, the design model is compared with the actual constructed pipeline;
thus, the differences between the site and the model are clearly presented. In total, 49 question points were identified in this scenario.

(3) **Steel structure integrity check.** Steel structure installation verification mainly includes an installation review of prefabricated components, a review of collar size and installation direction, as well as review of auxiliary reinforcement of structural installation integrity. Through BIM-AR, the missing steel structures and wrongly installed steel structures in the project can be checked. Timely detection of problem avoids the omission and mis-installation of steel components, ensuring the integrity of steel structure installation, reducing the cost of rework that may be increased by later calibration and rediscovery, as well as reducing the safety hazards of the building. During the project, 12 question points were identified in this scenario.

(4) **Civil and structural part acceptance.** BIM and AR can be used for review and acceptance of the reserved holes of the wall and column to ensure the consistency of the number, location and size of the reserved holes and avoid the rework later due to the mismatch of the reserved holes. BIM-AR not only saves costs but also shortens the construction period. One problem was detected in this scenario.

(5) **MEP installation guidance.** The MEP installation project includes support hanger positioning scribing, spacing review, multilayer pipe layering installation guidance, predrilled hole positioning guidance, concealed pipeline scribing, slotyping
and review. Before the installation of MEP, project managers can use BIM-AR to give workers an intuitive construction briefing so that construction workers can easily understand the location and installation requirements of each professional pipeline layout.

(6) **MEP installation checks and acceptance.** The use of BIM-AR acceptance in the installation project of MEP can visually check the deviation between the model and site, mark the problems and discuss the solutions on the cloud, as shown in Plate 1. The design can be implemented more comprehensively at the construction site and even optimized to maintain the consistency of design and construction. Totally, 68 irregularities in construction were checked out.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Features</th>
<th>Question points</th>
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<tbody>
<tr>
<td>Design (project) visualization at full scale on-site</td>
<td>• Visualize BIM models on-site</td>
<td>/</td>
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<tr>
<td></td>
<td>• Give stakeholders and visitors a clear description of the project design in the early project execution stage</td>
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<tr>
<td>Visualisation of underground utilities (i.e. pipeline)</td>
<td>• Check before embedding and backfilling</td>
<td>49</td>
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<tr>
<td></td>
<td>• Compare and check the installation, including position, direction, pipe diameter, accessories, etc.</td>
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<tr>
<td></td>
<td>• Guide the adjustment of the as-built model</td>
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<tr>
<td></td>
<td>• Check steel size, orientation and installation integrity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Review the prefabricated components about the picking size and installation direction</td>
<td></td>
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<tr>
<td></td>
<td>• Review the installation integrity of the auxiliary reinforcement structure</td>
<td></td>
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<tr>
<td>Steel structure integrity check</td>
<td>• Check structure reserved hole</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>• Check the size, dimension, location and quantity of embedded casting and reserved openings</td>
<td></td>
</tr>
<tr>
<td>Civil and structural part acceptance</td>
<td>• Multiprofessional cross construction pipeline installation disclosure</td>
<td>/</td>
</tr>
<tr>
<td>MEP installation guidance</td>
<td>• Check the location of pipeline installation</td>
<td></td>
</tr>
<tr>
<td>MEP installation check and accept</td>
<td>• Review support and hanger positioning marking and spacing</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>• Review multilayer pipe layered installation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Guide and review reserve hole positioning</td>
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Plate 1.
Site team is using tablets for inspection

Source: Authors
4.3.2 Critical success factor for a successful implementation of augmented reality in building information modeling-enabled projects. This section discusses the CSFs to implement BIM-AR within the AEC industry. A systematic methodology was applied to derive the CSFs by using an innovation framework. Rockart and the Sloan School of Management established the concept of CSFs, with the term first appearing in the context of information systems and project management (Rockart, 1982). CSFs, according to Rowlinson (1999), are the basic concerns intrinsic to the project that should be addressed for efficient and successful collaboration, requiring day-to-day attention and operating throughout the life cycle of the project. Based on the results from the content of documents and observations on site, the authors conclude 15 CSFs for successful implementation of AR in the case study, as shown in Table 3. The CSFs were further validated by the vice president of Company Z via a semistructured interview, which is described below:

4.3.2.1 Drivers. Drivers represent the primary reasons and sources of motivation to initiate AR implementation in the case project (i.e. the need or main reasons for innovation).

4.3.2.1.1 Clear owner requirements. Changes during the execution of construction projects are often undesirable, as they could lead to a great increase in overall time and cost. However, if owners or clients recognize change as an opportunity to enhance project management, the objective is simpler to attain. In this case study, the owner provided specific AR implementation requirements:

- improve the design efficiency and design quality;
- promote team communication and cooperation;
- reduce rework, errors and omissions; and
- produce a faster review and improve the overall work efficiency.

The interviewee explained the owner’s motivation for using BIM-AR:

Considered from the top management, the reason for owners using BIM-AR is because they need a visible and controllable project management method. Since owners do not have much time on the project site, they generally focus on results. BIM-AR platform can realize visible and controllable project management and find problems in time during the project so that the owner can see some deviations and problems of the project.

4.3.2.1.2 Project with high complexity and risk. As construction projects involve various stakeholders and types of construction tasks, it contains high complexity in both administrative and technical aspects. The increasing complexity of construction projects has led to a need for new project management methods. The case study included specialized building systems and an accelerated schedule, which contained high complexity and risk. Accordingly, AR was investigated and used as a new project management tool. The interviewee also noted that:

This project is quite intensive and difficult, with a strict deadline. During construction, it is easy to cause a high error rate and inconsistency between BIM design and actual construction, increasing the pressure for later acceptance. The project manager agreed to employ AR technology to optimize restoration of design solutions in this project in order to improve the efficiency of construction delivery and review and acceptance to assure the consistency of the BIM model and construction site.

4.3.2.1.3 Need for project management improvement. It has been suggested that implementing a compatible information platform (i.e. BIM and AR) for project teams is an effective strategy for enhancing project management (Huang et al., 2020). In this case study, AR technology was used to improve collaboration and information sharing among project
teams, thus improving project management efficiency. Also, the interviewee emphasized that:

Following the incorporation of BIM-AR into the existing workflow, the entire management paradigm has been changed from paper-based management to a model-based management strategy, with the goal of utilizing and integrating data at the application level to help and improve project management throughout the project life cycle.

4.3.2.2 Inputs. Inputs denote the resources sacrificed to integrate AR technology into the construction process.

4.3.2.2.1 Group meetings. Project meetings promote team commitment, assist leaders in identifying issues, and develop technical abilities (i.e. AR learning) for project teams. Using AR, on-site issues were identified and resolved through regular meetings (see Plate 2). The interviewee stated that:

In the presence of disputed issues on the construction site, communication using 2D drawings may result in information asymmetry between office and site workers. The building crew can

| Table 3. Summary of CSFs for BIM-AR implementation |
|---------------------------------|---------------------------------|
| **Innovation framework**        | **Variables**                   |
| Drivers                         | (1) Clear owner requirements    |
|                                 | (2) Project with high complexity and risk |
|                                 | (3) Need for project management improvement |
| Inputs                          | (1) Group meetings              |
|                                 | (2) Experience of the project team |
|                                 | (3) Consultancy and training of team members |
| Enablers                        | (1) Continuous involvement of the client |
|                                 | (2) Collaborative partnering of contractor and other stakeholders |
|                                 | (3) Minimal documentation and simple solutions |
| Barriers                        | (1) Individual resistance to technology adoption |
|                                 | (2) Accuracy of imported BIM model accuracy |
|                                 | (3) Hardware of AR technology   |
|                                 | (4) Investment in technologies  |
|                                 | (5) Project management method and workflows |
|                                 | (6) Government policy support   |

Plate 2. Regular project meetings

Notes: Left: AR operation training; right: establish a feedback method for project system application problems

Source: Authors
record and upload the disputed issues to the cloud using the AR platform, and the staff from each department will discuss solutions in regular meetings.

4.3.2.2.2 Experience of the project team. The project team was comprised of T-shaped rather than I-shaped members. People with a T-shape can solve transdisciplinary difficulties and make accurate judgments. The interviewee explained that:

The construction sector is currently undergoing a digital transformation, and new jobs such as industrial Internet engineering technicians, virtual reality engineering technicians, and industrial vision system operators and maintainers have emerged on the market. The industry is in urgent need of professional digital talents; however, the original IT talent training system is becoming increasingly difficult to meet, resulting in a scarcity and flaw of digital skills, as well as a significant mismatch between supply and demand. In such circumstances, we must cultivate more abilities through holistic training. T-shaped talents, for example, are persons with extensive knowledge and professional expertise. Of course, this type of skill demand does not occur overnight, and it also requires strong communication and collaboration between industry and universities.

4.3.2.2.3 Consultancy and training of team members. Initially, Company Z facilitated a training and coaching section for personnel to learn how to use AR technology in various settings. By actively participating in the training tutorials on AR utilization, project members made more sense of and became more confident about AR, as reflected by the interviewee:

Following the introduction of AR in this project, the owner requested that the management business employ AR to support project management. The management firm requested that the AR vendor train the project workers from each department on-site on how to use AR at each stage. For example, the technical staff would assist the construction staff with some preliminary work, such as model uploading and positioning the layout of the QR code, and then guide some problems found on site and regularly discuss how to solve the problems found during the construction process.

4.3.2.3 Enablers. Enablers facilitate the integration of AR into a BIM-enabled project.

4.3.2.3.1 Continuous involvement of the client. It is important to ensure that project progress is aligned with the client (i.e. owner project manager in this project) at the project development stage. By using AR technology, clients could know the effect and layout of the project design. The interviewee reflected that:

The owner cares about the results, and he wants to know the progress of the project completion. In this project, the owner provided AR to the contractor because the owner wanted to be involved in the project acceptance by visualizing the project and its systems through AR. AR as a tool can provide long-term value, such as the improvement of efficiency and the improvement of management capability. For example, a better construction unit may have a pass rate of 90% or even 95%. However, for some projects, it may only be 70% or even less. For this project, the construction process is standardized based on BIM, and then AR is used to guide the construction on site. The final result was that the pass rate of the whole project reached more than 98%, which means that a lot of rework caused by errors and omissions had been avoided.

4.3.2.3.2 Collaborative environment. A collaborative environment can help remove interfaces between project members and foster trust, leading to improved project management. AR can enhance the collaboration among key project stakeholders to overcome challenges encountered in building construction, as the interviewee stated:

While in the field, we can zoom in on the model so that it is presented on a one-to-one scale. Roaming in the model, you can immerse yourself in the perception and experience of the spatial scale relationship of the model. In the model layer management, through the operation of hiding layer
opacity adjustment, you can view the model of each subspecialty and also click on any component of
the model to view its BIM attribute information. By doing so, you can use the visualized model for
construction guidance in the field and facilitates communication among various professions.

4.3.2.3.3 Minimal documentation and simple solutions. Reporting based on documents is
time-consuming and costly. Implementation of digital tools such as AR and BIM can
increase efficiency and simplify the construction process. The interviewee stated that:

In a general construction site, the construction workers look at various drawings to determine the
construction of the structure and the installation process of the components. In this project, when I
use AR technology, I can project and zoom out some components, such as piping information, to
see some details of its structure. For example, for some very small parts, a QR code can be
generated on the drawing, and then I may not be clear about the specific direction or location of
the part when I am on site, so I can just scan the QR code, and a projection will appear, showing
the part location, size, and direction. At the same time, it saves a lot of paper-based drawings
in the whole process.

4.3.2.4 Barriers. The main factors that impede AR implementation are known as barriers.
4.3.2.4.1 Individual resistance to technology adoption. The AEC sector has been
criticized for its slow adoption of new management practices and technology, where some
individuals are unwilling to change old ways of working and thinking due to various
reasons. The interviewee further explained that:

I think some people are resisting the use of new technologies. AR brings the BIM model to the
construction site for guidance. If the model is accurate, it is the responsibility of the construction
personnel if the construction goes wrong. In this project, the owner has very high requirements
for consistency between the model and the site. However, some workers resist using AR because
it improves acceptance accuracy, which can lead to increased rework for them. Also, some project
staff may not want to spend time learning new technologies.

4.3.2.4.2 Accuracy of imported BIM model. The model information is stored in the cloud
server and transferred to the AR platform. The quality of AR applications is influenced by
the accuracy of the imported BIM model. The interviewee resonated that:

BIM models and data must be reliable, and data must be provided in a timely manner. Project
models should be available prior to construction. However, in many domestic projects, the model
is not provided in a timely manner, and the accuracy rate is not very high. Because the model
information of AR is provided by BIM, inaccurate model information will lead to a decrease in the
accuracy of AR. If we want AR to be successfully implemented, we must need a model with high
accuracy that is recognized by all parties. In this way, when we use AR in various scenarios, the
results will be accurate.

4.3.2.4.3 The hardware of AR. The functionality of hardware components (e.g. RFID,
global positioning system, accelerometers and sensors) significantly impacts the
performance of AR applications. The attitude of the interviewee was supportive:

I think the future development of AR depends on the upgrade and iteration of hardware. In terms
of positioning capability, the role of the algorithm is limited, and the improvement of hardware
has a qualitative change in positioning capability. For example, the current market products, such
as Microsoft HoloLens 2, have significantly improved positioning and computing capabilities.
Also, the global technology company Apple is focusing on their AR product ‘Apple Glasses,’
which will likely bring AR to the next-level exploration.

4.3.2.4.4 Investment in AR. Lack of financial investment is a key obstacle to technology
innovation. Regarding market size, the cost of AR is still substantial. Capital investment is
needed for investing in AR and software, and companies must have sufficient turnover to raise the required investment. Also, the interviewee mentioned:

Many private companies have closed down and gone bankrupt in the past few years because of the COVID-19 pandemic. More importantly, their project management capability and the ability to invest in digital innovations have not kept pace with technological developments. Some leading companies have clarified their digital development direction and improved their information management capability and production efficiency.

4.3.2.4.5 Project management methods and workflows. With the adoption of digital tools such as AR and BIM, the project team is responsible for implementing senior leadership’s vision and deploying the project’s digital capability rather than the traditional two-dimensional process; however, the existing project management system still needs to be further adapted to better use and manage the digital data resulting from the adoption of these digital tools:

When applying new technology such as AR, people will pay attention to the application scenarios of this technology in construction projects. The difficulty of adopting the new technology to real-life projects lies in integrating it into the current workflows and data fusion with other applications. This is a change in the entire management model, requiring data utilization and data access at various application levels.

4.3.2.4.6 Government policy support. Government support for AR implementation in the construction project is considered an important factor. The interviewee emphasized that the government has not applied any interventions to stimulate AR adoption in the AEC sector, which may cause the low adoption of AR. The interviewee said:

In recent years, the Chinese government has issued some policies to support BIM diffusion in the AEC sector, but there is no policy dividend on AR.

4.3.2.5 Benefits. Major outcomes accomplished at the end of the project as a result of the use of AR are referred to as project benefits. Based on document analysis, three major benefits were achieved by using AR in this BIM-enabled project, including reduced construction period, improved project quality and cost savings.

4.3.2.5.1 Reduction of project schedule. During construction, handover and acceptance efficiencies were enhanced. The time period between handover and acceptance was cut in half, according to the final project report.

4.3.2.5.2 Improvement of project efficiency and quality. The communication and coordination for multitasking had been improved. The effectiveness of MEP installation was increased by 30%. In general, better design insights and better project quality have been achieved through the implementation of AR.

4.3.2.5.3 Reduction of the project cost. Implementation of AR could improve accuracy and reduce rework. Regarding this project, rework-related costs were reduced by 80%.

By addressing these CSFs, project teams can design and carry out more effective AR implementation strategies to make AR suitable for their respective contexts. The case study also verified that the successful implementation of AR is determined by various factors. AR applications may still fail without the support of skillful staff, project stakeholders, software and hardware, and other facilitators.

4.4 Research implications
Concerning the papers’ practical/managerial implications, the significance of the study was sought to explore the application scenarios and workflow of BIM-AR, as well as to identify the CSFs for the successful implementation of BIM-AR in a real-life construction project in
China. The bibliometric study contributes to the body of AR knowledge by offering a focused view on the evolution of AR research in construction. Key study areas were identified, applications of various scenarios were studied, and the integration of AR and BIM was researched.

The findings and recommendations from this study might benefit policymakers, researchers and other stakeholders to start looking beyond AR technology applications in the AEC industry. Industry professionals might benefit from the identified detailed CSFs and the measures to devise and implement their mechanisms regarding successful AR technology applications in the Chinese built environment. The study outlines the responsibility of industry leaders and senior managers to invest in AR technology and recognize the need for, support existing, and nurture a new generation of construction staff with digital skills as a core component of their lifelong learning. Because AR technology is one of the main drivers of C4.0-related technologies (Wang and Guo, 2022), future researchers might contribute from this paper to propose a systematic investigation into the applications of digital technologies to enhance project performance and productivity. Also, the results of this study can potentially serve as guidance for other companies to implement AR in their construction projects with the necessary modification.

This study also provides theoretical implications. First, it highlighted how a study field with a large number of scientific papers might be reviewed more efficiently by extending the bibliometric analysis to a discussion in depth. Second, it benefits industry professionals by providing them the emerging practices in AR applications in construction, such as team collaboration and construction education. Third, the research findings may provide a strong basis for the formulation of hypotheses for future empirical investigations on the development of an index of assessment criteria for AR adoption. Lastly, the list of CSFs would inform legislators and governments of the most important and growing standards and incentives to consider when developing AR technology for the AEC industry. This may enable the AEC industry to be adequately prepared for any future diffusion of AR technology, even for digital transformation.

5. Conclusions
5.1 Conclusion remarks
AR is an emerging technology within the AEC industry. This digital innovation is advantageous for project planning and presentation, real-time communication and information visualization. Despite its great potential, AR has been less explored in construction. In this context, this study focused on the research question of what is the current distribution and focus of previous studies on AR research in construction and what are the key mechanisms to the successful adoption of AR in construction. To achieve this, this study began with a bibliometric survey and analyzed 65 publications published between 2000 and 2022 to illustrate the research trend and areas of AR in the AEC industry. According to the literature study results, the AEC industry is currently underrepresented in AR research. Four research areas of AR were identified from the emerging body of research. In terms of technology innovation, BIM is regarded as the core technology in the Construction 4.0 era. With the assistance of AR, it is possible to achieve a better performance of BIM in design and construction in terms of model visualization and construction inspection. Subsequently, a participatory case study investigation of BIM-AR was explored to empirically investigate the workflow and factors that affect its implementation. The study results demonstrate, among other findings, the following:
This study was able to demonstrate the research trend of AR in construction. The number of research publications on AR has increased, particularly during the last four years (i.e. 2019–2022). The USA has led the number of publications for countries, followed by South Korea, Australia and China. Most AR articles were published in *Automation in Construction, Journal of Information Technology in Construction* and *Advanced Engineering Informatics*. In addition, a significant portion of studies used conceptual and literature review approaches, and fewer studies adopted archival and other designs for AR investigation.

- The VOSviewer visualization map revealed four clusters in AR topics: team collaboration, project management, construction activities and learning. It is observed that AR presents great potential in enhancing project performance via real-time communication, model visualization, information retrieval and training.
- The study depicted the workflow of BIM-AR proposed in the case project. The project revealed six application scenarios of the BIM-AR system and gave insights into the AR functions in the construction project. Several benefits were achieved in the case study; for example, reduction of the project schedule (saving 50% of construction time), improvement of project efficiency and quality (30% increase in MEP installation efficiency) and reduction of the project cost (80% savings in rework costs).
- Successful AR implementation depends on multiple factors. Based on the construction innovation framework, 15 CSFs (i.e. drivers, inputs, barriers, enablers and outputs) were identified to demonstrate what variables impact AR implementation in construction at the project level.

This study contributes to the body of knowledge by identifying areas where research is focused on problems relating to AR within AEC fields. Its findings have mapped out research areas of AR and application scenarios and CSFs for the successful implementation of BIM-AR in the AEC industry.

5.2 Limitations of the research and future directions
First, research on AR in the AEC industry is constantly evolving; therefore, the bibliometric analysis is not exhaustive as it is based on a limited sample of literature published in the Scopus database and only includes articles in English. It may omit some recent research in other languages. Therefore, future work on the in-depth development of AR in construction can be further explored based on multiple sources.

Second, this exploratory study used a single case study to demonstrate the process of implementing AR in a BIM-enabled project. Although a single case is considered appropriate for exploratory investigations and provides a great opportunity for in-depth observations, the authors recommend that further empirical research can be conducted to determine with greater certainty how BIM-AR can be more effectively implemented in the current construction practices.

Finally, CSFs were explored based on a case study and validated from the perspective of the vice president of AR company, thus might be biased toward the role of the vendor. This limitation necessitates more research involving the validation of the CSFs in other contexts and using larger samples representing other types of organizations and professionals. Exploring the CSFs by incorporating the perspectives of a wider variety of construction stakeholders might add value to the results and provide fertile ground for future research.
References


Further reading

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