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Review

Key functions in BIM-based AR platforms

Khalid Amin *, Grant Mills, Duncan Wilson

University College London, UK

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ABSTRACT

The integration of Augmented Reality and Building Information Modelling is a promising area of research; however, fragmentation in literature hinders the development of mature BIM-based AR platforms. This paper aims to minimise the fragmentation in the literature by identifying the key functions that represent the essential capabilities of BIM-AR platforms. A systematic literature review is employed to identify, categorise, and discuss the key functions. The outcome of this paper identifies six key functions: positioning (P), interaction (I), visualisation (V), collaboration (C), automation (A), and integration (T). These key functions act as the foundation for an evaluation framework that can assist practitioners, developers, and researchers with assessing the requirements of the targeted application area, and hence be better informed on the appropriate devices, software, and techniques to use. Finally, this paper emphasises the importance of industrial-academic collaboration in BIM-AR research and suggests prospects for automation through the application of artificial intelligence.

1. Introduction

Over recent decades, advancements in information technology have improved performance in construction projects [1]. A notable example is building information modelling (BIM), which is a widely accepted solution to enhance the level of digitisation in the construction sector. BIM is a digital representation of a building's physical and functional characteristics used to plan, design, construct, and manage the building throughout its lifecycle [2]. The implementation of BIM has reported clear advantages including improved collaboration, greater productivity, enhanced visualisation, and more informed decision making [2,3]. However, many argue that BIM has not yet reached its full potential [4,5]. Further development is needed to improve the representation of information among stakeholders and across project lifecycle stages [5,6]. Recent developments in immersive visualisation technologies such as augmented reality (AR) can maximise BIM's potential and improve the transferability of information across different settings [7]. Many researchers have explored the use of BIM-based AR in a range of application areas in building design, construction, and operations [8]. In doing so, they have tested out different kinds of techniques and platforms. We use the term "platform" to refer to the combination of hardware and software components that make up a BIM-AR system.

Despite the significance of BIM-AR, a thorough evaluation method to validate the effectiveness of proposed platforms is lacking. Furthermore, the literature tends to be fragmented by the diverse array of perspectives, devices, software, and techniques tested out in different stages and application areas [9–11]. The diversity of approaches can make it difficult to identify common themes or best practices. This fragmentation can be further exacerbated by the rapid pace of development in hardware and software components used in immersive visualisation technologies, which can make it challenging for studies to remain current and relevant. However, a consistent pattern of key functions can be found in BIM-AR studies irrespective of constituent components or adopted methodologies. We suggest that these key functions can be used to represent the essential capabilities of any proposed BIM-AR platform. The availability of a consistent set of key functions to describe the capabilities of different BIM-AR platforms should make it easier to assess the suitability of these platforms for the intended application. Furthermore, it contributes to minimising the fragmentation in literature by providing a holistic approach to describe BIM-AR platforms based on functionality instead of focusing on individual components. A holistic approach can reveal new opportunities for innovation that may not have been evident when examining individual parts. Hence, we adopt a systematic literature review to identify, categorise, and discuss the key functions of BIM-AR platforms. By doing so, we examine original research articles that utilise BIM-AR platforms in case studies or experiments across different lifecycle stages and application areas.

The motivation behind this paper is to minimise the fragmentation in the body of knowledge by improving our understanding of BIM-AR

* Corresponding author.
E-mail address: khalid.amin@ucl.ac.uk (K. Amin).

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platforms. Through a Systematic Literature Review (SLR), we aim to identify the key functions of BIM-AR platforms, highlight their uses and applications across different lifecycle stages, survey their techniques and challenges, and propose future directions for research. Furthermore, our work here serves as a foundation for ongoing research aimed at developing a maturity model that can be employed for consistent evaluation of various BIM-AR platforms.

2. Literature review

2.1. Augmented reality on the virtuality continuum

The "virtuality continuum" concept defines the extent of immersion generated by the visualisation technology by measuring the amount of real and virtual digital objects [12]. At one end of the spectrum is the real environment, and at the other end lies virtual reality (VR), where the user is immersed in a virtual environment. Applications that mix different levels of virtuality and reality are referred to as mixed reality (MR), with AR and augmented virtuality (AV) being two major subsets on the MR continuum. In AR, digital content is superimposed on the real environment, and most of the viewed objects come from the real environment [13]. In AV, the proportion of virtual objects and real objects is reversed [13]. Technologies on the virtuality continuum are given various collective terms in the literature, such as AR/VR, extended reality (XR) and immersive virtual environments (IVEs) [14]. VR is predominantly used in the design phase [15] while AR is more beneficial in the construction and operation phases [1,5]. See Fig. 1 for a representation of the virtuality continuum.

2.2. Relevant literature reviews

Substantial research has been done on the uses of AR in the built environment, including many reviews on the use cases, hardware, software, approaches, and future research directions. Although BIM has been consistently present in AR literature reviews, few have focused on BIM-AR as the main topic of the review. BIM-AR can be fundamentally different from general AR applications in the built environment such as training, hazard recognition, or assembly instructions. BIM-AR requires carefully designed software architecture to manage and transfer a large amount of information from BIM models to worksites and vice versa. In addition, Sophisticated localisation techniques are required to achieve the accuracy and stability necessary for the functionality of superimposed models. Table 1 shows a list of review articles on AR in the past decade, with only three out of 11 focused on BIM-AR. Sidani, et al. [5] surveyed the software and hardware components of BIM-AR platforms, the exploited BIM dimensions of AR research, and provided a framework for guided integration of BIM-AR across different lifecycle stages. Fenais, et al. [16] categorised the challenges of applying AR in underground utility construction into data collection issues, modelling alignment barriers, hardware limitations, and data management challenges. Calderon-Hernandez and Brioso [17] discussed the integration of BIM, AR, and lean construction. The mentioned reviews provide a comprehensive description of the different components and uses of BIM-AR platforms. However, none provide a holistic approach that considers the platform as a whole rather than focusing on individual components in isolation. Thus, an in-depth review of how BIM-AR platforms function in different applications and lifecycle stages is required. This paper presents a review of BIM-AR platforms from a different perspective, by identifying their key functions and the techniques that enable each function. We also provide a detailed analysis of how the key functions are used across different lifecycle stages. Finally, we discuss the building

Table 1
A comparative meta-analysis of review articles on AR in the built environment in the past decade.

Author	Title	BIM-based AR	Stages
Sidani et al. [5]	Recent tools and techniques of BIM-based augmented reality: A systematic review	Yes	All
Wang et al. [9]	Augmented reality in the built environment: Classification and implications for future research	No	All
Rankohi and Waugh [18]	Review and analysis of augmented reality literature for the construction industry	No	All
Chen and Xue [8]	The renaissance of augmented reality in construction: History, present status and future directions	No	All
Calderon-Hernandez and Brioso [17]	Lean, BIM and augmented reality applied in the design and construction phase: A literature review	Yes	Design & Construction
Song et al. [19]	Review and analysis of augmented reality (AR) literature for digital fabrication in architecture	No	Construction
Piroozfar et al. [20]	Augmented reality for urban utility infrastructure: A UK perspective	No	Construction
Xu and Moreu [11]	A review of augmented reality applications in civil infrastructure during the 4th Industrial Revolution	No	Construction & Operation
Palmarini et al. [21]	A systematic review of augmented reality applications in maintenance	No	Operation
Fernández del Amo et al. [22]	A systematic review of augmented reality content-related techniques for knowledge transfer in maintenance applications	No	Operation
Fenais et al. [16]	A meta-analysis of augmented reality challenges in the underground utility construction industry	Yes	Construction

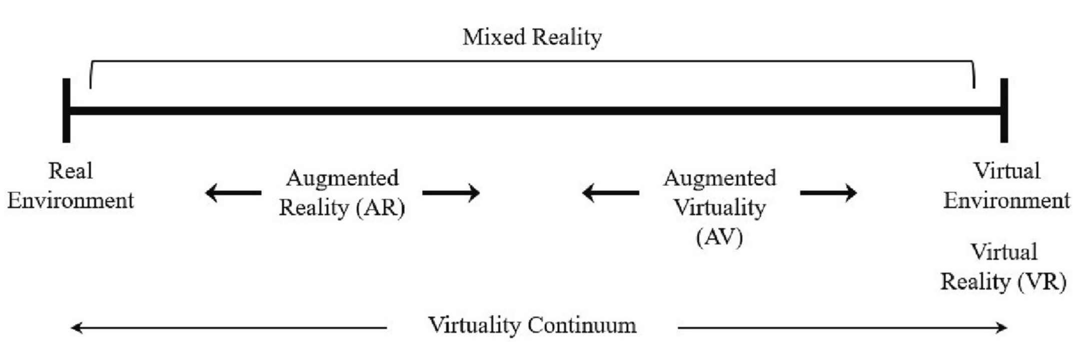

Fig. 1. Immersive technologies on the virtuality continuum [12].

blocks of BIM-AR platforms and propose a basis for developing an evaluation method based on the identified key functions, which is a knowledge gap that needs to be addressed [5,9].

3. Methodology

To achieve the aim of this research, a SLR was adopted. An SLR ensures the identification of a comprehensive body of knowledge and demonstrates transparency through an explicit and reproducible method for identifying, evaluating, and synthesising the literature [23]. Furthermore, we adopted the SALSA framework which identifies four critical steps for the review process: **S**earch, Appraisa**L**, **S**ynthesis, and **A**nalysis [23]. The selection of this methodology was inspired by other notable reviews, where different versions of the SALSA framework were used [1,21,22]. Our review comprised six phases: protocol, search, appraisal, synthesis, analysis, and report (Table 2).

In the protocol phase, we adopted the PICOC framework [23] to define the scope of the research. The PICOC framework identifies a formal structure of five elements to define the research scope, namely: **P**opulation, **I**ntervention, **C**omparison, **O**utcomes, and **C**ontext. Table 3 describes how the elements of the PICOC framework were used to define the research scope.

Based on the defined scope, relevant keywords and search databases were identified. Relevant articles were collected from peer-reviewed sources published between 2010 and 2021, a period spanning the emergence of BIM and AR technologies [1]. The last date the published papers were surveyed was the 16th of January 2023. The broad keywords selected for the search query were “augmented reality”, “mixed reality”, “BIM”, “construction”, and “built environment” (see the appendix for further details of the search strategy). The initial search resulted in a pool of 1065 articles.

The appraisal phase reduced this pool to the most relevant articles. The appraisal phase comprised two steps: screening and quality assessment. Fig. 2 shows the steps followed in the appraisal process. The appraisal process necessitated multiple iterations for ensuring coherence and consistency in selecting relevant articles.

The first iteration aimed to identify articles discussing the use of AR in the construction field by removing duplicate papers, screening titles, and excluding irrelevant articles based on criteria E1 to E4 (Table 4). The second iteration involved scanning abstracts, introductions, and conclusions, and excluding irrelevant articles based on criteria E5 to E8 (Table 4). The screening step resulted in 74 articles. The quality assessment steps involved full-text reading of the 74 articles to further assess their relevance and eligibility for the analysis phase. This was based on inclusion criterion I1 (Table 4) and quality criteria Q1 to Q3 (Table 5). The final sample consisted of 55 articles.

The synthesis phase involved extracting and classifying relevant data from the selected articles based on the research scope. Among other methods, thematic synthesis was used [23] to identify the range of BIM-AR key functions across multiple articles and organise them into principal themes.

Table 2
The SALSA framework: includes research phases, the methods and outcomes used in each phase.

SLR Phase	Method	Outcome
Protocol	PICOC Framework	Scope Definition
Search	Search String	Studies Pool
Appraisal	Inclusion & Exclusion Criteria	Selected Studies
	Quality Criteria	
Synthesis	Data Extraction	Main themes
	Thematic Categorisation	Main Categories
Analysis	Thematic Analysis	Results
	Comparison	Discussion
	Gap Identification	Conclusion
Report	Written Report	PRISMA

Table 3
Defining the research scope using the PICOC framework.

Research scope/ phases	Description
Population	Problem situation of articles discussing different uses of AR applications through the design, construction, and operation stages in a building lifecycle.
Intervention	Use cases, hardware, software, challenges, and applications of AR platforms used by human participants, e.g., superimposing the model or interacting with virtual model elements.
Comparison	Contrast between intervention techniques, e.g., the contrast between uses, development requirements, challenges, and utilisation levels in different lifecycle stages.
Outcomes	Key functional BIM-based AR categories frequently used in construction projects.
Context	BIM-based AR setting.

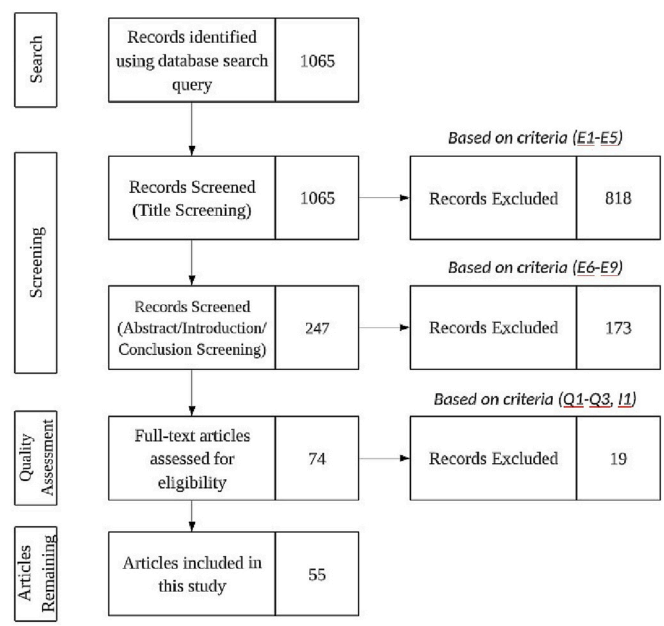

Fig. 2. Systematic literature review appraisal steps.

Table 4
Inclusion/exclusion criteria.

Type	ID	Statement
Inclusion	I1	Primary research representing the use of BIM-based AR to improve the performance of onsite activities in construction projects through case studies or lab-based experiments
Exclusion	E1	Duplicate papers
Exclusion	E2	Review articles
Exclusion	E3	Articles discussing the use of VR or both AR and VR
Exclusion	E4	Articles not related to construction, such as manufacturing, optics, sensors, etc.
Exclusion	E5	Non-BIM-based AR, such as using AR with robotics
Exclusion	E6	Articles discussing the use of AR for training and education
Exclusion	E7	Articles relating to people’s acceptance, behaviour, or perceptions of AR

Table 5
Quality criteria.

Item	Description
Q1	Clarity of research methodology and coherence between methodology and implementation
Q2	Illustration of devices, technologies, and knowledge involved in the development of the AR application
Q3	Clarity of the targeted construction area

The analysis phase consisted of three steps: thematic analysis, discussion of results, and drawing conclusions. The thematic analysis involved assessing the constructed categories [24] to demonstrate their application across lifecycle stages. Finally, the reporting phase involved presenting and discussing the results. The structure of this paper and the description of its main elements are based on the PRISMA checklist for literature reviews [25]. PRISMA stands for **P**referred **R**eporting **I**tems for **S**ystematic reviews and **M**eta-**A**nalysis, and aims to increase the usefulness of literature reviews by following a standard structure for reporting the findings [25].

4. Results

4.1. Descriptive analysis

The selected articles included journal papers (67%) and articles published in conference proceedings (33%). From the total sample of 55 papers, 11 were drawn from *Automation in Construction*, five from the *International Symposium on Automation and Robotics in Construction (ISARC)*, four from *Applied Sciences,* and the rest from other sources (Fig. 3). Forty percent of the articles involve lab-based experiments and case studies, while the remaining 60% are conducted onsite. The research on BIM-AR has seen an increase in the number of publications since 2010 (Fig. 4). This reflects the increase in the capability of AR devices and software [26] and the growing BIM adoption [27]. It is noted that the majority of the articles are focused on the construction stage totalling 62%. This can be attributed to the potential of AR to expand the scope of BIM to be used in construction sites [5]. The facilities management and design stages account for 22% and 16% of the selected articles respectively (Fig. 4).

In each stage, BIM-AR has been used to support the improvement of a range of activities. In the construction stage, the explored activities fall under four application areas: inspection, progress tracking, construction planning, and site assistance. In the facilities management stage, activities can be grouped under maintenance and operation. In the design stage, the focus is on investigating the practicality of BIM-AR in collaborative review sessions. Inspection, progress tracking and design review are the most discussed in the selected articles. On the other hand, using BIM-AR to operate buildings is the least discussed topic. Table 6 groups articles based on stage and application area, and summarises the activities explored in each group.

4.2. BIM dimensions

The use of BIM relies heavily on the efficient management of data throughout the project lifecycle. It allows all stakeholders to have access to a centralised, reliable source of information [82]. A 3D BIM model serves as a database of smart building objects with attributes and relationships, fostering an environment where information can be extracted for different applications [82,83]. Time is considered a fourth

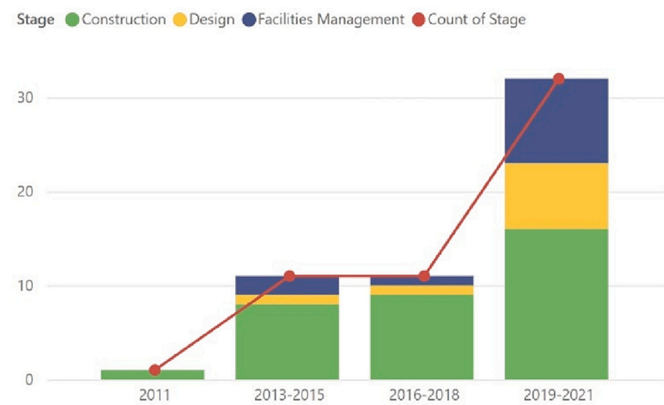

Fig. 4. The number of BIM-AR publications since 2010 and the addressed lifecycle stage.

dimension added to 3D BIM models i.e., 4D BIM models. The concept of modelling additional attributes in BIM models is referred to as *nD modelling*, where *n* stands for numbers bigger than three. Although there is a consensus that 4D stands for time and 5D stands for cost, the following dimensions are defined differently among practitioners [82]. Therefore, this paper is in line with articles conducted by Kamardeen [84] and Charef, et al. [83]. As such, this paper considers BIM dimensions as 3D: size and shape, 4D: time, 5D: cost, 6D: sustainability, 7D: facilities management (including as-built data), and 8D: safety.

Throughout the selected articles, the most exploited dimension is 3D (Fig. 5). Indeed, the use of a 3D model is an intuitive step to integrate other dimensions, however, 55% of the articles rely solely on 3D BIM. Surprisingly, 7D BIM is the second most addressed dimension in the context of BIM-AR. All articles in facilities management have used BIM-AR to improve access to operation and maintenance information stored in BIM models i.e., 7D models. In third place comes 4D BIM with 16% of articles on progress tracking and assisting tower cranes in the construction stage. Other dimensions are underrepresented with either single or no occurrences. Interestingly, Degani, et al. [48] use projective AR to superimpose full-scale 2D construction layouts onsite. These results demonstrate a shortcoming in examining various BIM dimensions, thereby resulting in an unutilised potential for important research topics.

4.3. Identifying the key functions in BIM-AR platforms

Identifying the key functions required several iterations of analysis on the selected articles. In the first run, we identified three main themes representing the key functions, namely visualisation, interaction, and integration. However, for the key functions to form a basis for an evaluation framework, each key function should reflect its unique enabling technologies, development methods, and challenges. This was not

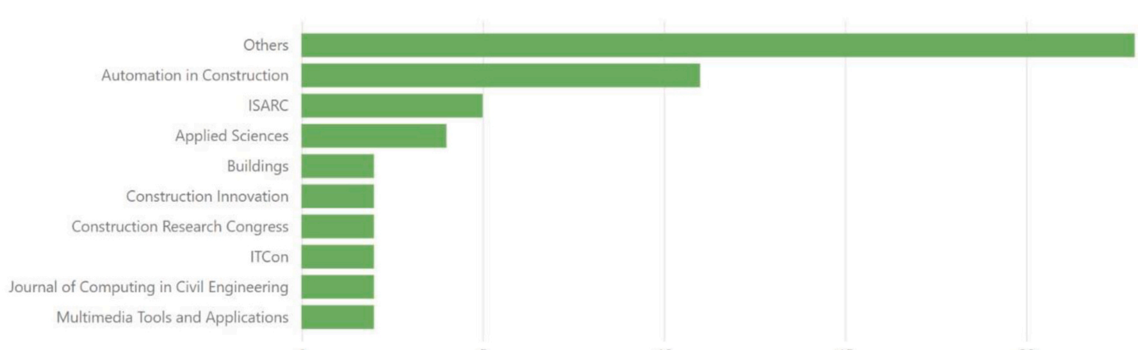

Fig. 3. Sources of the 54 articles.

Table 6
Distribution of lifecycle stages, application areas, and activities in the selected articles.

Stage	Application Area	Activities	Articles
Construction	Inspection	Superimposing BIM models over built items for quality management, defects detection, and remote collaboration	[28–38]
	Progress Tracking	Superimposing 4D BIM models over built items to measure progress	[39–47]
	Construction Planning	Projecting 3D models and 2D layouts onsite to guide installations and building activities	[48–54]
	Site Assistance	Using superimposed models to view building instructions, retrieve information, and visualise crane lifting paths to assist with tower crane operation	[55–61]
Design	Design Review	Using superimposed models in collaborative design review sessions	[51,62–69]
Facilities Management	Maintenance	Superimposing maintenance and operation instructions in the form of text, 3D models, or animations.	[70–76]
	Operation		[77–81]

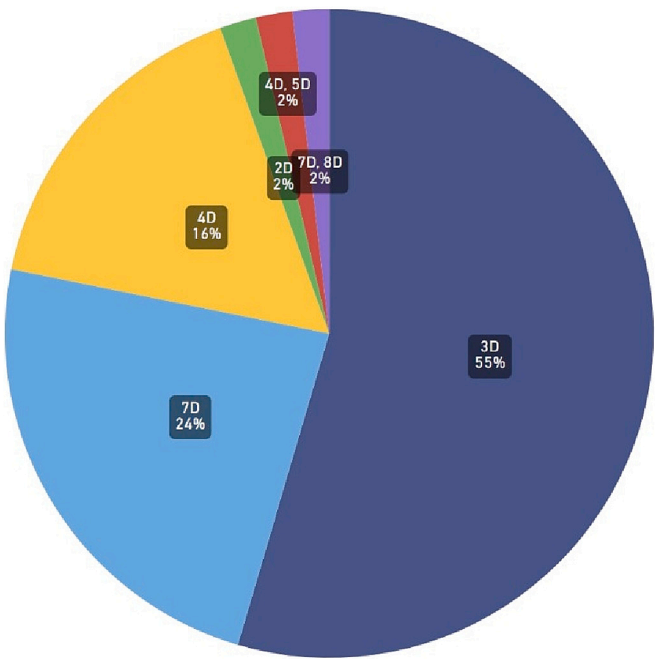

Fig. 5. Occurrences of different BIM dimensions.

achieved in the three identified themes. The “visualise” term is used in literature to refer to localising AR models in the physical environment, as well as to describe graphical fidelity and visibility customisation options, such as showing or hiding digital elements. Model registration and model visibility customisation are two distinct functions. Controlling the visibility of superimposed models relies mainly on programming techniques, the type of display (optical see-through, video see-through, projector) and the graphical processing power of the system. On the other hand, localising AR models requires sophisticated techniques and depends on the use of sensors and computer vision. The “interact” term is used in literature to refer to user-to-user communication as well as users’ interactions with digital elements. User-to-user interaction can include using a business communication platform, providing shared storage for captured data, or utilising cloud-based document management systems. In contrast, interacting with digital elements happens through a different User Interface (UI), and depends on programming techniques for selection, modification, and measurements. The “Integrate” term refers to the utilisation of other services and technologies to facilitate or automate particular functions, such as integration with UAVs or Computer Vision. However, we saw that integrating technologies with the aim of automation should be separate from the integration aimed for other purposes, considering that automation in the context of AR is still considered to be in the very early stages. Eventually, we identified six key functions representing the essential capabilities of BIM-AR, namely: positioning, interaction, visualisation, collaboration, automation, and integration. We define each key function as:

- ***Positioning (P)***: refers to the system’s ability to accurately localise and track the BIM model with the proper alignment, orientation, and elevation
- ***Interaction (I):*** refers to the functions provided to users to enable them to interact with both digital and physical objects through the system’s User Interface (UI)
- ***Visualisation (V):*** refers to the system’s visibility control capabilities and the achievable level of graphical fidelity
- ***Collaboration (C):*** refers to the functions provided to users to communicate and share information with other users
- ***Automation (A):*** refers to the system’s ability to carry out and finish a task with no or minimal intervention from the user
- ***Integration (T):*** refers to the system’s ability to utilise external technologies and services to extend the system’s functionality

The identified key functions are not in total isolation from each other, but rather the performance of one function can be impacted by another. For example, integration can be made with a business communication platform to include real-time collaboration functionality, or the stability of visualisation can be impacted by the adopted positioning technique. However, the categorisation into PIVCAT helps understand the interdependency between the functions and their uses in different applications.

Table 7 demonstrates the various ways in which the key functions were addressed in the selected articles. Each row represents a single article and provides information about the lifecycle stage and application area that have been the focus of this article. Checkmarks denote the key functions addressed by each article.

On the level of key functions, a total of 123 occurrences in 55 articles are demonstrated. Fig. 6 shows the research trends based on the key functions in the past decade. The research on positioning has been consistently present in BIM-AR research since 2010 till date, mainly aiming at evaluating the suitability of different techniques in a construction site. It is not until around 2014 that researchers started to investigate using other functions besides positioning. The duration between 2019 and 2021 witnessed a noticeable increase in articles discussing positioning techniques. Automation is the least addressed function accounting for around 1% of the selected articles (four publications).

Although all the articles discuss positioning, 15 articles focus exclusively on this function. Interaction is addressed in 22 articles, visualisation in 16 articles, collaboration in 15 articles, automation in 3 articles, and integration in 10 articles. Nineteen articles utilise dual-function platforms, discussing positioning with another single function (PI = 8, PV = 5, PT = 4, PC = 3, and PA = 1). Multi-functions (three or more) are covered in 18 articles (PIC = 6, PIV = 3, PIT = 1, PAT = 1, PCT = 1, PIVC = 3, PVCT = 1, PIVAT = 1, PICT = 1, and PIVCT = 1). None of the selected articles covered the six key functions. We can see that there is no consensus among researchers on the functions that are deemed necessary for a certain application area. For instance, among 10 articles discussing inspection, nine combinations of key functions have been used (P, PI, PIV, PIC, PIT, PVCT, PIVC, P, PT). To further analyse this phenomenon, the heatmap in Fig. 7 provides information on which

Table 7
Key functions of BIM-based AR platforms identified in the literature (newest to oldest, 2021–2010), with a truth table denoting Positioning (P), Interaction (I), Visualisation (V), Collaboration (C), Automation (A), and Integration (T).

Author(s)	Article Title	Stage	Application Area	P	I	V	C	A	T
Garbett et al. [68]	A multi-user collaborative BIM-AR system to support design and construction	Design	Design Review	✓	✓	✓	✓		
Sangiorgio et al. [62]	Augmented reality based decision making (AR-DM) to support multi-criteria analysis in constructions	Design	Design Review	✓					
Chalhoub et al. [28]	Augmented reality to enable users to identify deviations for model reconciliation	Construction	Inspection	✓	✓				
Choi and Park [56]	Development of augmented reality system for productivity enhancement in offshore plant construction	Construction	Site Operation	✓		✓	✓		
Liu et al. [33]	Integrating building information model and augmented reality for drone-based building inspection	Construction	Inspection	✓	✓				✓
Schranz et al. [69]	Potentials of augmented reality in a BIM based building submission process	Design	Design Review	✓		✓	✓		
Shan et al. [60]	Real time localization method research with monoslam and BIM Model	Construction	Site Operation	✓					
Chung et al. [75]	Smart facility management system based on open BIM and augmented reality technology	Facilities Management	Maintenance	✓	✓				
Lin et al. [55]	4D-BIM based real time augmented reality navigation system for tower crane operation	Construction	Site Operation	✓				✓	✓
García-Pereira et al. [31]	A collaborative augmented reality annotation tool for the inspection of prefabricated buildings	Construction	Inspection	✓	✓	✓			
Wang and Chen [41]	A construction progress on-site monitoring and presentation system based on the integration of augmented reality and BIM	Construction	Progress Tracking	✓	✓	✓			
Liu et al. [80]	System development of an augmented reality on-site BIM viewer based on the integration of SLAM and BLE indoor positioning	Facilities Management	Operation	✓					✓
Lin et al. [47]	A real-time 4D augmented reality system for modular construction progress monitoring	Construction	Progress Tracking	✓		✓			
Mirshokraei et al. [32]	A web-based BIM-AR quality management system for structural elements	Construction	Inspection	✓		✓	✓		✓
Degani et al. [48]	An automated system for projection of interior construction layouts	Construction	Construction Planning	✓					
Khalek et al. [63]	Augmented reality for identifying maintainability concerns during design	Design	Design Review	✓	✓				
Sydora and Stroulia [65]	Augmented reality on building information models	Design	Design Review	✓		✓			
Baek et al. [70]	Augmented reality system for facility management using image-based indoor localization	Facilities Management	Maintenance	✓					
Ratajczak et al. [34]	BIM-based and AR applications combined with location-based management system for the improvement of the construction performance	Construction	Inspection	✓	✓	✓	✓		
Diao and Shih [71]	BIM-based AR maintenance system (BARMS) as an intelligent instruction platform for complex plumbing facilities	Facilities Management	Maintenance	✓	✓	✓			
Wang and Piao [72]	Development of BIM-AR-based facility risk assessment and maintenance system	Facilities Management	Maintenance	✓					
Bahri et al. [66]	Efficient use of mixed reality for BIM system using Microsoft HoloLens	Design	Design Review	✓	✓				
Chalhoub and Ayer [49]	Exploring the performance of an augmented reality application for construction layout tasks	Construction	Construction Planning	✓		✓			
Herbers and König [50]	Indoor localization for augmented reality devices using BIM, point clouds, and template matching	Construction	Construction Planning	✓					
Natephra and Motamedi [79]	Live data visualisation of IoT sensors using augmented reality (AR) and BIM	Facilities Management	Operation	✓					✓
Alsafouri and Ayer [67]	Mobile augmented reality to influence design and constructability review sessions	Design	Design Review	✓			✓		
Golparvar-Fard et al. [45]	Model-based detection of progress using D4AR models generated by daily site photologs and building information models	Construction	Progress Tracking	✓				✓	
Gomez-Jauregui et al. [46]	Quantitative evaluation of overlaying discrepancies in mobile augmented reality applications for AEC/FM	Construction	Progress Tracking	✓					
El Ammari and Hammad [74]	Remote interactive collaboration in facilities management using BIM-based mixed reality	Facilities Management	Maintenance	✓	✓	✓	✓		
Fazel and Izadi [52]	An interactive augmented reality tool for constructing free-form modular surfaces	Construction	Construction Planning	✓					
Kim et al. [43]	Improvement of realism of 4D objects using augmented reality objects and actual images of a construction site	Construction	Progress Tracking	✓	✓				
Riexinger et al. [59]	Mixed reality for on-site self-instruction and self-inspection with building information models	Construction	Site Operation	✓	✓				
Zaher et al. [44]	Mobile augmented reality applications for construction projects	Construction	Progress Tracking	✓					
Fenais et al. [61]	Using augmented reality in horizontal directional drilling to reduce the risk of utility damages	Construction	Site Operation	✓					
Chalhoub and Ayer [54]	Using mixed reality for electrical construction design communication	Construction	Construction Planning	✓					
Zhou et al. [30]	Implementation of augmented reality for segment displacement inspection during tunneling construction	Construction	Inspection	✓	✓				
Yokoi et al. [78]	Integrating BIM, CFD and AR for thermal assessment of indoor greenery	Facilities Management	Operation	✓					✓
Lee et al. [64]	Augmented reality for ndimensional building information modelling: Contextualization, customization and curation	Design	Design Review	✓		✓			
Gheisari et al. [57]	Integrating BIM and Panorama to create a semi-augmented-reality experience of a construction site	Construction	Site Operation	✓			✓		
Lin et al. [53]		Construction		✓	✓		✓		

(continued on next page)

Table 7 (*continued*)

Author(s)	Article Title	Stage	Application Area	P	I	V	C	A	T
	Using augmented reality in a multiscreen environment for construction discussion		Construction Planning						
Kwon et al. [29]	A defect management system for reinforced concrete work utilising BIM, image-matching and augmented reality	Construction	Defects Detection	✓	✓		✓		
Wen and Kang [36]	Augmented reality and unmanned aerial vehicle assist in construction management	Construction	Inspection	✓					✓
Zollmann et al. [39]	Augmented reality for construction site monitoring and documentation	Construction	Progress Tracking	✓	✓	✓		✓	✓
Han and Golparvar-Fard [40]	Automated monitoring of operation-level construction progress using 4D BIM and daily site photologs	Construction	Progress Tracking	✓					
Williams et al. [77]	BIM2MAR: An efficient BIM translation to mobile augmented reality applications	Facilities Management	Operation	✓		✓			
Wang et al. [85]	Integrating augmented reality with building information modelling: Onsite construction process controlling for liquefied natural gas industry	Construction	Inspection, Progress Tracking	✓	✓	✓	✓		✓
Wang et al. [51]	Integrating BIM and augmented reality for interactive architectural visualisation	Design	Design Review	✓	✓		✓		
Chen and Chang [58]	Integration of augmented reality and indoor positioning technologies for on-site viewing of BIM information	Construction	Site Operation	✓	✓		✓		
Koch et al. [73]	Natural markers for augmented reality-based indoor navigation and facility maintenance	Facilities Management	Maintenance	✓					
Bae et al. [42]	High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications	Construction	Progress Tracking	✓					
Siu and Lu [35]	Augmented-reality visualizations of bored pile construction	Construction	Inspection	✓					
Chen et al. [76]	A BIM-based location aware AR collaborative framework for facility maintenance management	Facilities Management	Maintenance	✓	✓		✓	✓	
Portalés et al. [37]	From the Paper to the Tablet: On the Design of an AR-Based Tool for the Inspection of Pre-Fab Buildings. Preliminary Results of the SIRAE Project	Construction	Inspection	✓			✓		
Chernick et al. [38]	On-Site BIM-Enabled Augmented Reality for Construction	Construction	Construction Planning	✓	✓				
Chen, et al. [86]	BIM-based augmented reality inspection and maintenance of fire safety equipment	Facilities Management	Operation	✓			✓		✓

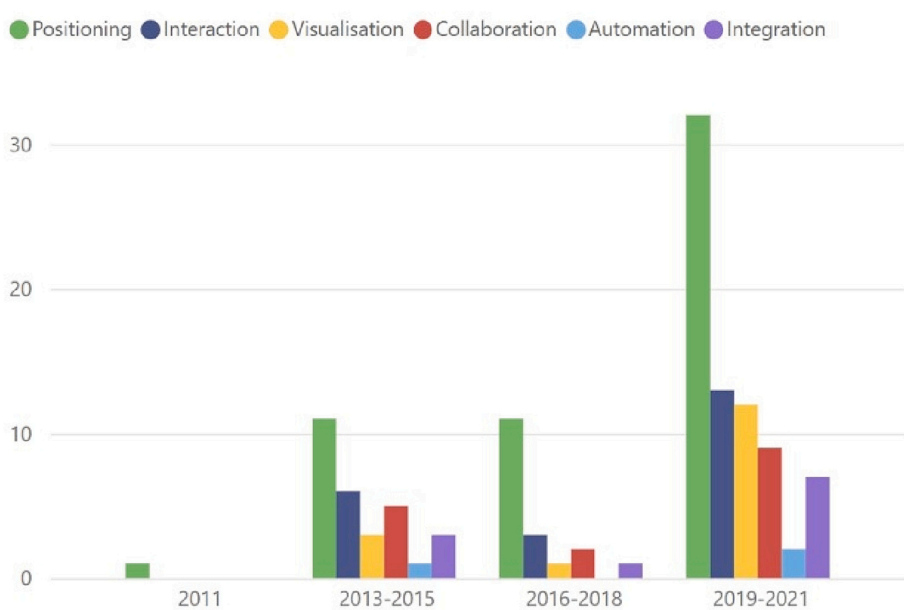

Fig. 6. Research trends based on key functions from 2010 to 2021.

key functions received the most attention in each application area. Each row represents a key function, and the columns are the application areas. Each cell has a colour representing the number of articles that have addressed each key function in each application area, with the lightest being the lowest and the darkest being the highest. The heatmap shows that specific key functions are used more frequently in specific application areas. For instance, the focus of articles discussing design review is on PIVC, but there are no attempts to automate certain tasks or integrate other technologies. Design review has the highest number of articles addressing collaboration. Another example would be the lack of focus on collaboration in progress tracking and focusing on PIVA instead. Automation is only investigated for progress tracking and site assistance in the construction stage.

The suitability of the key functions to the intended application area is determined by analysing the techniques used to enable them. In the next section, we look at the different techniques used to enable the key functions through the selected articles.

Fig. 7. The frequency of PIVCAT across different application areas.

4.4. *Surveying the techniques used to enable the key functions*

A wide range of techniques is used to execute each key function. The diversity of these techniques produces different types of platforms based on the corresponding application scenario. Table 8 provides a comprehensive overview of the state-of-the-art techniques used in the selected articles, grouped based on PIVCAT, as well as the associated advantages and disadvantages.

The selection of the technique is usually based on the nature of the application area and the objective of the study. In the following section, we use the information in Table 8 to analyse how the key functions and their corresponding techniques are used in different stages and application areas.

4.5. *Techniques of key functions across lifecycle stages*

Positioning is a fundamental aspect of BIM-AR. The accurate placement of BIM models using AR remains a major challenge across all stages and application areas [8,46,57,99]. To superimpose the digital models accurately, the system must map the environment and track the user's pose in six degrees of freedom (6DOF). To do so, it draws information from different sensors, so environmental effects such as lighting, network coverage, occlusion, and materials may cause distortion or interference [90,94]. To overcome such challenges, different positioning techniques can be used according to the prevailing environmental conditions, each with its own advantages and limitations. For instance, marker-based AR may be a good option for construction sites in offshore plants [56] but may not be suitable for other types of construction sites, as it may easily be obscured by other objects [65,77]. As a result, most articles utilise hybrid positioning techniques (76%) which involve using multiple methods to overcome multiple challenges. In the selected articles, hybrid systems use IMUs to estimate the local position of the device and use artificial markers and natural feature techniques to initialise the model and map the surroundings. Ten percent of articles use 3D image reconstruction systems in which Structure from Motion (SfM) techniques are used. One article adopts a sensor-based approach by using LiDAR to localise 2D layouts of construction drawings [48]. Manual mapping is used in the remaining articles (Fig. 8).

In addition to positioning, interaction is another crucial aspect of BIM-AR. AR is an interactive medium with mutual influences between users and digital and physical objects through the UI [93]. Designing AR interaction systems is challenging because it is developed in 6DOF, making the design process more complex than the conventional desktop UI. Although tangible interfaces provide optimum usability in AR settings [88], none of the selected articles use tangible UI types such as pointing wands or tracking gloves. The majority of articles (75%) use mobile devices; virtual UI is the most used interaction technique in BIM-AR research. In studies using the HoloLens, a couple of studies use the headset's voice command capabilities in design review sessions [28,63], while other articles use hand gestures. Interaction functions used in the articles can be grouped under selection, modification, and annotations. Selection enables users to retrieve elements' information. Modification enables them to add or remove attributes and modify elements' spatial properties, such as moving, rotating, and resizing. Annotations include the ability to add comments, revision clouds, and other 2D representations to captured media.

Visualisation is a core function of BIM-AR platforms. Visualisation functionality includes visibility customisation options and graphical fidelity of positioned models. Fig. 9 shows that mobile devices (video see-through) are the dominant display device (75%), while 18% use optical see-through HMDs, mainly Microsoft's HoloLens. Few studies utilise multiple monitors and mobile devices, and a projector is used in a single study. Visualisation functions include hiding and showing model elements (single elements, systems, and categories), changing their colour, texture, and transparency, playing animations, and controlling the BIM model's overall appearance (wireframe, shaded, edges, etc.). Achieving photorealistic visualisation is particularly challenging due to the limited processing power of mobile devices and HMDs [5,90].

BIM-AR enables new means of collaboration between both onsite and offsite users [79]. However, some argue that AR research focuses largely on standalone applications, despite the sector's need for improved collaboration practices [26,68]. Similarly, our analysis shows that only

Table 8
Techniques used to enable the key functions of BIM-AR platforms.

Key Functions	Techniques
Positioning (P)	*Sensor-based techniques* combine information from different sensors. Sensors may be optical (LiDAR, infrared), inertial (gyroscopes, accelerometers), wireless network (GPS, wi-fi, radio, Bluetooth), acoustic or magnetic [77,87]. They may be faster and more accurate in device positioning [88]. Inertial measurement units (IMU) determine the local pose for all six degrees of freedom by fusing information from an integrated gyroscope, accelerometer, and magnetometer [89], and are used in modern mobile devices and HMDs. However, sensors are susceptible to network coverage, temperature, humidity, and noise [77] and require continuous calibration [90]. *Vision-based techniques* combine frames captured by cameras to create a reference map of the surroundings. The cameras may be monocular and/or stereo (binocular) and may use visible or invisible light (e.g., infrared). Vision-based methods can be grouped under two main categories: feature-based and model-based [77]. Feature-based systems cover two techniques, fiducial marker, and natural feature. Fiducial marker techniques are usually referred to as marker-based AR, while natural feature and model-based techniques are considered markerless approaches [8,77]. Another vision-based technique that has been used in the selected articles is Structure from Motion (SfM). SfM techniques are used to create a 3D model of the environment by using the camera poses from sequentially ordered or unordered image sets [91,92]. Vision-based techniques are superior for environment mapping but are inaccurate in determining the local pose of the device. They are also very dependent on the complexity of the scene. *Hybrid techniques* use sensor-based techniques for local pose estimation, and vision-based techniques for initialising the application, mapping the surroundings, and dynamically correcting the errors of sensor-based techniques. Mobile devices (e.g., smartphones) and modern AR headsets generally employ cameras and IMU sensors for AR positioning. Hybrid systems can be employed as marker-based, model-based, or feature-based systems. This can be seen in new powerful tablets such as the iPad Pro, which fuses LiDAR, inertial sensors, and vision information to provide more stable tracking. Hybrid techniques provide better results than solely vision-based or sensor-based techniques [8,77,88]. *Manual mapping techniques* employ a stationary camera to capture live footage of the construction site and adopted a calculative approach using matrices to transfer the coordinates of the physical objects into screen space. By knowing the position and orientation of the camera, the mapped coordinates system is used to overlay digital objects on physical objects on the screen [33,35,46,47,55]. Another manual mapping technique involves specifying a fixed location within a space and mapping it to a corresponding location in the BIM model. The user then stands in the physical location and initialises the BIM-AR application [77]. Manual mapping techniques do not provide a dynamic experience and are used in very specific applications.
Interaction (I)	*Tangible User Interface* employs physical objects such as tracking gloves or pointing wands to interact with objects through the system's display. These may be unidirectional, when there is no user-feedback functionality, or bidirectional, employing haptic feedback to inform users that their commands have been executed. Tangible UIs are the most usable compared to other types because physical objects have familiar properties, making them more actionable and easier to use [88]. *Virtual User Interface* is the use of touch gestures such as taps, drags, and multi-touch on handheld devices to interact with objects through the screen display. It employs cameras and computer vision techniques to understand hand gestures and/or eye gaze and translate these into actions. *Visual User Interface* depends on computer vision techniques to understand the user's hand gestures and/or gaze and translate them into actions. This type is used mainly in head-mounted displays (HMDs). The disadvantage of this type is that it is only usable in HMDs and that it takes users some time to match the required gestures [93]. *Auditory User Interface (aural UI)* uses microphones for voice commands. This type can be impractical in noisy situations at work sites. *Hybrid interaction systems* employ multiple techniques [88,93,94].
Visualisation (V)	*Video see-through* uses video captured from cameras as a background for overlayed digital objects. It is used mainly in mobile devices and some HMDs. Disadvantages include parallax, lag, inconsistent field of view, and refresh rate [5,94]. *Optical see-through* uses holograms to overlay digital objects over the real environment. This is used mainly in HMDs and is disadvantageous for outdoor use [88]. Challenges include the narrow field of view and occlusion [6]. *Projective* techniques display digital information onto a physical object using single or multiple projectors. They may be head-worn or stationary [88]. and may display 2D images using conventional projectors, or 3D objects using holographic projectors [6]. Projective techniques do not provide an immersive 3D experience.
Collaboration (C)	Collaboration can be defined in terms of time as synchronous (same time) and asynchronous (different time), and in terms of space as co-located (at the same place) and remote (at different places) [95,96]. Disadvantages include concerns over data security and the privacy of onsite users [96]. Technological limitations are mainly related to reliance on advanced technology which may not always be available or reliable, and latency which can reduce the quality of the experience [93].
Automation (A)	Automation in the context of AR relies on Artificial Intelligence, in particular, Computer Vision. Computer Vision deals with the development of algorithms and techniques to enable machines to interpret and understand visual information from the world, such as images and videos [97]. Automation using BIM-AR is considered to be in the very early stages, so there is little about the techniques that have been effectively used in a real project setting. However, the rapid developments in the AI field promise great potential for BIM-AR.
Integration (T)	Integration can be made on the level of software such as CFD applications [78,79], hardware such as UAVs [33,36,39] (UAV), or complete technology platforms such as IoT [78], RFID [85], and cloud computing [32]. The integration with other technologies and services may intensify interoperability issues, which is already a major challenge in the built environment [98]. Integration can also raise security concerns as information needs to be sent to external services.

30% of the selected articles discuss collaboration using BIM-AR platforms. We adopted the Time-Space Matrix (Table 9) from Ens, et al. [95] to describe the different modes of collaboration in the selected articles. The Time-Space Matrix depends on four quadrants to describe different modes of collaboration [95]. Results show that 10 articles use remote asynchronous collaboration. The onsite user captures information and stores them in a local or cloud storage for later use by remote users. Three articles use remote-synchronous collaboration through video live streaming to an offsite user. The remaining three articles adopted a co-located synchronous approach. Remote collaboration relies mainly on internet connectivity, which is not always available on construction sites. Therefore, BIM-AR platforms should offer the ability to switch between offline and online modes while onsite.

Automation is the least discussed subject in the selected articles, all in the construction stage. Two articles address automating progress tracking using 3D reconstruction techniques [39,45], and one article uses A* algorithms to automate the generation of lifting paths for tower cranes [45].

Integration is represented in 15% of articles, and all of them discuss the construction and facilities management stages. Integration improves other functions by utilising external services, technologies, or datasets. Several studies use UAVs to improve inspection activities [33,36,39], and others integrate their AR systems with IoT to obtain numerical environmental data, such as temperature and humidity [79,80]. Two studies integrate databases to facilitate accessing managed asset information in maintenance [76,86]. Another study integrates Computational Fluid Dynamics (CFD) applications to visualise heat maps of temperature and humidity [78].

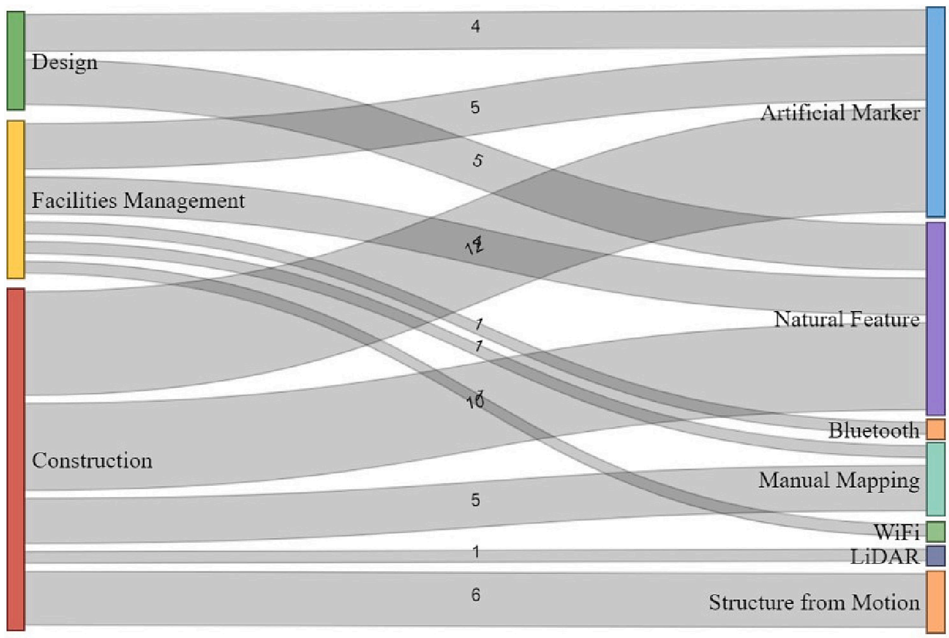

Fig. 8. Positioning techniques across lifecycle stages.

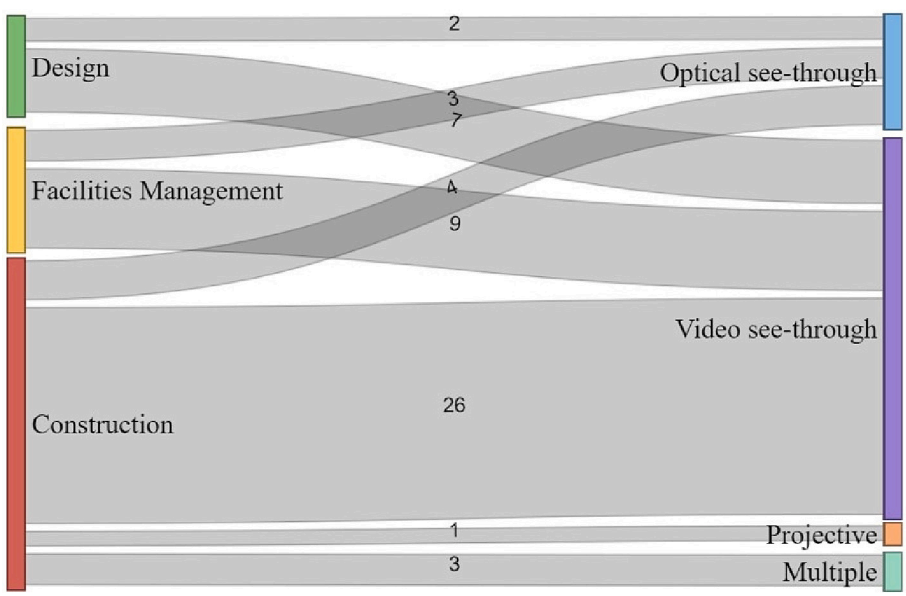

Fig. 9. Visualisation techniques across lifecycle stages.

Table 9
Modes of collaboration using the Time-Space Matrix [95].

	Synchronous	Asynchronous
Co-located	Face-to-face interactions	Continuous task
Remote	Remote interactions	Communication and coordination

5. Discussion

5.1. *The building blocks of BIM-AR platforms*

In this paper, we have identified the key functions of BIM-AR platforms, PIVCAT, across different application areas. We consider PIVCAT as the building blocks of BIM-AR platforms. Positioning is fundamental because the accuracy and stability of positioned models will impact other functions. Visualisation and interaction can be added to positioning to make up the core functions of BIM-AR platforms. These key functions represent the core functions for single users. Collaboration, integration, and automation extend the functionality of the platform beyond core functions to include multiple users and technologies. And so, as the building blocks of BIM-AR platforms, PIVCAT can be utilised from both a practitioner and developer perspective. We have seen in Fig. 7 that different application areas necessitate using specific key functions. Hence, practitioners can utilise PIVCAT to compare and evaluate various BIM-AR platforms based on their functionality and suitability for the intended application area, without the need for an in-depth understanding of the underlying technology. On the other hand, developers can gain a more defined scope of the functions required for the intended application area, and thus be better informed on which devices, software, and approach would be most appropriate. However, this approach requires further experiments and case studies on BIM-AR to enrich the body of knowledge, as well as and more reviews that adopt PIVCAT to collect and categorise utilised functions and report additional ones when found.

5.2. Designing BIM-AR platforms

The challenge in designing BIM-AR platforms stems from the fact that the platform must continuously gather information from its surroundings, making it susceptible to environmental conditions. In the construction stage, the dynamic nature of work sites adds further complexity to the design process. Based on the surveyed articles, we have seen that a single device or technique cannot achieve the same level of usability in all site conditions and application areas. For site conditions, optical see-through HMDs may be effective indoors, but may not perform well in outdoor environments due to the increased transparency of holographic objects caused by bright light. As for application areas, the techniques used in construction planning activities can be impractical if used for progress tracking or site assistance activities. Construction planning activities rely on marker-based and feature-based techniques to provide a dynamic viewing experience to users in certain spaces using their mobile devices or HMDs. On the other hand, progress tracking activities rely on using SfM techniques or a stationary camera to provide a static viewing experience for the whole construction site. And so, based on the current approaches in BIM-AR research, a main contractor seeking to adopt BIM-AR for different applications would need to purchase a different platform for each application, which would undermine the scalability and usability of the technology. Therefore, we recommend that developers should give more attention towards developing multi-functional platforms that incorporate a variety of devices and techniques instead of focusing on a single device or single approach.

5.3. Evaluating BIM-AR platforms

Comparing BIM-AR platforms based on their constituent components has proved to be a challenging task due to the diversity in the shapes, sizes, and functions of these components. Furthermore, the rapid advancements in these components can make the comparison criteria obsolete. PIVCAT can serve as a basis for evaluating BIM-AR platforms. In future research, we aim to define maturity levels for each key function, each level represents a benchmark against which the key function can be assessed. By determining the maturity levels for each key function, the resulting model can be used to identify the functional requirements of the intended application area, and subsequently, assessing the suitability of a proposed platform. However, in industry settings, other non-functional evaluation factors such as price, scalability, deployment effort, and speed of onsite installation should also be considered.

5.4. Suggestions for future research

The application of AI in the construction industry has the potential to greatly improve automation in various tasks such as site planning, management, and cost prediction. In the context of BIM-AR, automation is mainly related to tasks that include visual inspection of physical objects against specific criteria and is typically achieved through the use of computer vision techniques. Many computer vision techniques are being investigated by researchers including SfM, photogrammetry, image stitching, and object recognition. Such techniques can enable the development of context aware BIM-AR platforms, allowing for more informed decision making and more accurate predictions. Encouraging more research in this direction can have significant improvements in application areas related to safety, progress tracking, and quality management. However, with many articles already demonstrating proof of concept for BIM-AR, it is crucial to contextualise the findings in real project settings by involving more practitioners.

It is important to critically examine current practices and identify the necessary changes to facilitate AR adoption. Hence, there is a need to give attention to BIM-AR use cases and explore the underlying BIM workflows. In addition, no research has yet examined the hierarchical information structures of the superimposed BIM-AR models so that each user can see the information that is relevant to his role. In other words, the research on better performing BIM-AR platforms coincides with the research on processes, roles, and information structures. This should help practitioners identify opportunities and pinpoint the areas where AR can add value and improve efficiency.

Finally, extracting the keywords that inferred the key functions has been an exhausting process. Many articles do not state which features are included in their experiments. In addition, there is no standard structure for BIM-based AR experiments or case studies. This makes it more difficult to identify the main capabilities of the proposed platform. We propose using PIVCAT as sections or sub-sections in future BIM-based AR research. Under each section, the author would describe the techniques used, the features available, and the challenges faced, which would facilitate future literature reviews and enable more guided research.

6. Conclusion

Augmented reality is a visualisation technology with great potential for maximising the benefits of BIM in the design, construction, and operation stages. A means of assessing BIM-AR platforms holistically is lacking in the literature owing to the wide variety of constituent components and techniques. We propose a basis for developing an evaluation method by identifying key functions of BIM-AR platforms from relevant literature. Through a systematic literature review, we selected 54 articles from an initial total of 889. Our descriptive analysis identified seven main application areas for BIM-AR. In the construction stage, BIM-AR is used in the activities of inspection, progress tracking, construction planning, and site assistance. In the design stage, it is used for design review, and in the facilities management stage for maintenance and operation activities. Through thematic analysis, we identified six key functions: positioning, interaction, visualisation, collaboration, integration, and automation. Positioning functions are the bedrock of any AR-BIM platform and impact the quality of all other functions. Interaction and visualisation are also core functions of AR-BIM platforms. Collaboration enables multi-user communication. Automation offers great potential for progress tracking and site assistance but is still at an early stage of development and requires extensive further research. Integration expands the capabilities of the platform by utilising external services and technologies.

Having discussed the enabling techniques and potential challenges of each function, we have correlated the key functions with lifecycle stages and application areas. Different applications require different devices and techniques. No single device or technique can be used in all applications and under all conditions. We propose a scalable, multifunctional platform to encourage industry adoption, using PIVCAT as a basis for an evaluation framework in future research. We also suggest that PIVCAT should be used as a standard structure for BIM-AR research to facilitate future literature coordination.

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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.

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Data availability

Data will be made available on request.

Appendix A. Appendix

Search strategy

Search Keywords	Augmented Reality, Mixed Reality, Construction, Built Environment, BIM
Subject Area	Engineering
Databases	Scopus, ScienceDirect, Google Scholar, Web of Science, and CumInCAD
Timespan	2010–2021
Document Category	Conference papers, articles
Language	English
Search Query	TITLE-ABS-KEY(augmented reality) OR TITLE-ABS-KEY(mixed reality) AND TITLE-ABS-KEY(construction) OR TITLE-ABS-KEY(BIM) OR TITLE-ABS-KEY(built environment) AND (LIMIT-TO (SUBJAREA,"ENGI")) AND (LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012) OR LIMIT-TO (PUBYEAR,2011)) AND (LIMIT-TO (DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English"))

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