Augmented reality-based knowledge transfer for facility management: A systematic review of research and applications

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Abstract: Facility management is globally recognized as a critical and knowledge-intensive field. It confronts challenges due to the increasing complexity of facilities and the vast amount of operation and maintenance information. Augmented reality (AR), emerges as a promising technology to address these challenges by enhancing knowledge transfer in facility management through immersive and interactive environments. The objective of this research is to conduct a systematic review of AR applications in facility management, and explore AR knowledge transfer capabilities in facility management. The review narrowed the literature by filtering from 618 publications to 107 papers published between 2011 and 2023. A contents analysis based on these articles could gain an insight into current facility management systems as well as AR application domains in a series of facility management activities including facility design/layout, assembly, monitoring, maintenance and renovation. Based on the above analysis, this research discussed the AR capabilities of knowledge transfer in facility management. The findings reveal that AR facilitates knowledge transfer by enabling visualization, interaction, and collaboration among stakeholders. It is influenced by factors including user interfaces and interaction types, as well as vocational training and acceptance level of stakeholders. Challenges remain in terms of tracking, registration, ergonomics, security, and management practices. Finally, this research highlighted future trends focusing on the development of knowledge-driven digital twins, trustworthy knowledge management, and collaborative platforms to further promote AR knowledge transfer in facility management. This research also contributes to deeper understanding of the role of AR within this field and provides insights for stakeholders aiming to utilize this technology.

Keywords: Augmented reality; Facility management; Operation; Knowledge transfer; AEC industry

1. Introduction

The operation and maintenance (O&M) phase is increasingly crucial in projects since this period is the longest period, accounting for over 80% of the total project costs

[1]. This phase captures worldwide attention due to its role in maintaining the initial expected asset value of a facility and enhancing the productivity of the working environment aligning with the project's primary objectives [2,3]. Facility management (FM) involves diverse tasks including inspections and maintenance by facility management staff. In order to support these tasks, facility management system (FMS) has been applied to help manage the operations and maintenance of diverse facilities effectively, ensuring a comfortable working environment. Effective facility management requires the allocation and sharing of a vast amount of information on the facility components and their related locations. Megaprojects over $10 million could contain 50 different document types and over 50,000 pages of digital contents [4]. This is compounded by the fragmented facility management tasks, including facility information from the design and construction phases, as well as historical maintenance data and the details of ongoing operations [5]. Within this context, computer aided facilities management (CAFM) systems and computerized maintenance management systems (CMMS) have been employed to digitally support facility managers. These systems support various tasks including managing from equipment procurement and supplier information in the early stages, installation drawings of facility spaces, and cost control documentation in the operation phase. They also manage equipment specifications and warranty records in the later stages of maintenance. However, these complex management systems fail to fully address the issues related to data collection data entry as well as data storage.

Building information modelling (BIM) technology has been utilized to digitally manage construction projects, facilitating the sharing of building information among different stakeholders throughout the lifecycle, overcome the information fragmentation that exists during project phases and enhancing collaboration [6,7]. BIM has also significantly reduced the updating time of the database during the O&M phase [8]. However, there is a lack of visualization tools for efficient model navigation and data retrieval in facility management. To be specific, facility managers often have to manually select and inquiry to obtain the information through electronic format files from 2D drawings, operation manuals, maintenance handbooks to carry out facility tasks. Due to scattered and non-standardized information, locating building components and 3D visualization are challenging for facility management staff in practice. For instance, building plumbing systems, often hidden behind walls or above ceilings, present challenges for maintenance work on these facilities in designated dead spots [9]. These cases lead to time-consuming search for maintenance information, and high error rates. When completing facility maintenance, another issue is the reliance on hand-written reports and manual data entry into maintenance systems. Manual data processing is error-prone, and it leads to the incomplete information report. For instance, only textual information is reported, while excluding visuals such as pictures, video and audio [10]. These delaying factors pose challenges for facility managers in staff arrangement. As a result, there are sometimes disorders in facility management, and it is urgent to enhance better facility management and operation performance with informative tools.

Augmented reality (AR) is a kind of techniques combining virtual objects with real world and achieving interaction among users, machine, and environment [11]. This technology could provide visual assistance for facility management staff. To be specific, AR techniques have outstanding potentials to enhance work efficiency [12], decrease work disorders [13], as well as promoting communication [14] and collaboration [15] among stakeholders. It could link virtual scenes with real world, and delivers multisensory information such as touch, vision, and hearing into user's environment [16]. Knowledge can be defined as information in context, as well as knowledge transfer could convey knowledge from one entity such as place, person, system or ownership to another [17]. Therefore, AR has the capability of displaying contexts and transferring information from the existing manuals, handbooks, databases and other sources to the users. AR technology has been utilized in remote assistance [18], vocational training [19], and predictive maintenance [20] in architecture, engineering and construction (AEC) industry. Previous reviews on AR techniques in AEC industry pays more attention to construction safety [21], emergency management [22], onsite construction management [23] in the construction period. There has also been some research on AR techniques in O&M phase for visualizing subsurface utilities [24], aiding facility maintenance [25] to improve maintenance procedures in building operation. While AR has demonstrated potentials in facility management, particularly in maintenance tasks, there remains a significant gap in understanding how AR can systematically address the broader range of facility management services beyond maintenance. Specifically, current research has not fully explored how AR can enhance communication and collaboration in different phases of facility management. Moreover, facility management is knowledge-intensive for O&M staff because of the complexity and diversity of facility management tasks involving various operations equipment, subsystems, and components, and the variety of standards and depth in documentation [26]. It is crucial to provide accurate and high-quality information to each stakeholder at the right time to facilitate facility management processes. AR can provide support for O&M staff to address the above knowledge-intensive challenges. While numerous studies have examined the role of AR in facility management in O&M phase focusing on technology implementation, there is still limited exploration of how AR systems can perform comprehensive knowledge management capabilities in facility management. Hence, AR-based facility management remains underexplored, particularly regarding effective knowledge transfer capability, which is crucial for improving operational efficiency, reducing errors, and promoting collaboration among stakeholders. Researchers in AEC industry can achieve a deeper understanding of the research status, and promote interdisciplinary cooperation among stakeholders. By leveraging AR technologies, facility management can address traditional data management limitations, providing real-time access to vital information, thereby enhancing decision-making processes and reducing maintenance errors. This study aims to synthesize existing AR applications within facility management, explore their knowledge transfer capabilities, and identify the challenges and future trends essential for the successful implementation of AR in this field.

Since benefits of facility management characterize managing facility resources, improving facility services and working environment, this research uniquely synthesized AR applications in different facility management processes and examined AR knowledge transfer and collaboration capabilities in facility management. It proposed the challenges and future trends of AR implementation in this domain. Therefore, this research aims to fulfill the following objectives: (1) Summarize the existing literature related to AR techniques in facility management. (2) Explore AR applications in facility management activities. (3) Review AR knowledge transfer capabilities supporting facility management in AEC field. (4) Examine the challenges and future research trends of AR knowledge transfer in facility management. By reviewing the existing literature related to AR techniques in facility management, exploring potential AR applications in facility management activities, and reviewing existing AR technologies and their knowledge transfer capabilities, this research seeks to address the challenges and propose future trends to facilitate implementation of AR with strengthened knowledge transfer capabilities in this field. This study aims to fill the critical research gap in understanding and optimizing the role of AR in facility management to enhance the operational efficiency and collaboration within facility management, which is crucial for maintaining the asset value and operational functionality of facilities. Finally, operational efficiency, stakeholder collaboration, and knowledge transfer in facility management could be enhanced within the AEC industry.

The remainder of the paper is organized as follows. Section 2 describes the methodological approach in this research. Section 3 presents the quantitative results based on the systematic review. In Section 4, this study analyzes the critical AR technologies and characteristics, and examines application procedures in facility management. Then, Section 5 reviews AR knowledge transfer mechanism and main challenges in facility management. Based on in-depth discussions, future research trends are explored in Section 6. Finally, Section 7 draws the main conclusions and proposed future research works.

2. Current status of research

2.1. AR-based facility management

FMS play a crucial role in managing service orders, inventory, procurement and assets [2]. These systems integrate different controls, have access to equipment data, operation alarms and enable the staff to monitor equipment and check system schedules effectively [27]. AR effectively integrates virtual components with the real world, creating an informative and interactive environment and linking virtual information with the real environment, captured by various human senses [26]. Hence, its ability to superimpose the reality and virtual objects within a single scene in real time enables visualization and interaction with stakeholders to promote intelligent FMS. The existing studies focus on visualization [24], indoor localization and positioning [28], and maintenance [25] in this field. Furthermore, AR has also been applied to optimize work orders and improve cooperation between onsite staff and offsite staff in a series of daily tasks [18]. AR has potentials in improving efficiency and prediction to handle complex tasks, as well as supporting decision-making of stakeholders. For instance, one study observed a significant reduction in task completion time by 55% and a 46% decrease in assembly errors, leading to less rework in laboratory experiments [29]. Considering

BIM also has potentials in visualization, communication and cooperation in AEC industry, it has been integrated with AR approach to achieve collaboration and interaction among different professionals in facility risk management and maintenance [30]. However, there are also studies doubting the benefits of AR, particularly regarding improving task performance such as increasing productivity or reducing errors, especially for simple tasks, while AR might instead expose certain cognitive load to users, potentially diminishing its advantages [31,32]. In summary, while AR has demonstrated significant potentials in facility management, the research remains inconsistent regarding its impacts on applications. Besides, there has been much research narrowly focusing on one specific process such as assembly or maintenance, and the potentials of AR techniques to facilitate facility management lifecycle should be further explored.

2.2. AR-based knowledge transfer

AR can contextualize information by linking with the physical world and enhancing learning and communication through visualization and interactivity. This technology can display information in an intuitive way, thereby helping users to better understand and retain the information. These advantages make AR a promising solution to support knowledge sharing. Currently, AR has been applied to aid knowledge transfer in various industries. For instance, internal structure of equipment or complex surgical steps can be displayed via AR devices [33]. Such visual aids can help surgeons to operate accurately during surgery through instant skills acquisition and transfer. In education sector, AR technology can reduce the external cognitive load of learners and promote generative processing, thereby supporting the acquisition of conceptual knowledge, and hands-on experimental learning [34]. AR has advantages in presenting abstract concepts and invisible phenomena through three-dimensional models and dynamic interactions. Studies have shown that students using AR multimedia contents have higher knowledge retention rates, leading to improved enthusiasm and interests in learning [35,36]. However, AR is not universally superior to traditional learning methods. For example, a study found that text-based instruction performed better than AR methods in terms of conceptual knowledge of human digestive system [37]. This highlights the needs for careful consideration of the learning context and contents in AR applications. In facility management field, AR is applied to visualize the internal structure and maintenance steps to O&M staff, providing intuitive guidance for complex tasks [4,38]. They focus on single utilizing AR to complete specified tasks through transferring explicit knowledge from documents and diagrams such as handbooks. Recently, AR multi-user collaborative communication to promote tacit knowledge transfer has begun to be explored in this field. For instance, experienced off-site personnel or experts can impart skills and experience through AR remote guidance [5,14]. This not only improves task performance through knowledge sharing, but also promotes collaboration among stakeholders.

To conclude, AR knowledge transfer has applied in specific application scenarios, influenced by content types and interface designs. As a knowledge-intensive field, facility management requires AR to help knowledge transfer, but the knowledge transfer ability of AR in this field is not well explored, and the transfer mechanism is still unclear. The potentials of AR techniques to facilitate knowledge transfer in facility management process need more investigation. Within this context, the objective of this research is to conduct a systematic review of AR applications in facility management, and further explore AR knowledge transfer capabilities in this field.

3. Methodology

This study adopted a combination approach of bibliometric analysis and a systematic literature review (SLR) [39]. SLR method could systematically and comprehensively allocate existing knowledge with transparency and repeatability. Based on previous studies [11,39], this review implemented the SLR methodology through three consecutive steps: identifying review research objective, clarifying conceptual boundaries, and executing inclusion and exclusion criteria.

3.1. Identifying review objectives

The purpose of this literature review is to comprehensively examine the existing research on AR applications in facility management. This research aims to synthesize current knowledge and insights into AR technologies in facility management and their role in executing bi-directional knowledge transfer capability among various stakeholders in facility management. Specifically, the existing techniques and stakeholders of AR applications in facility management was examined, as well as the factors influencing AR knowledge transfer mechanism were then further investigated. This research helps identify key challenges and future opportunities for advancing AR-driven knowledge management for facilities. By reviewing the state-of-the-art in this field, this research seeks to establish a conceptual foundation which will guide further research and facilitate AR applications in promoting knowledge transfer and management in complex facility management workflows.

3.2. Clarifying research concepts

Facilities management has been adopted in numerous vectors including energy, utilities, entertainment, medical facilities, tourism, etc. Therefore, to determine the scope of this review, it is necessary to restrict the conceptual boundaries of facility management in the AEC industry. This research focuses on typical facility management in AEC industry which consist of facility layout, facility assembly, facility monitoring, facility maintenance, and facility renovation activities [4]. AR could enhance user perception and interaction by superimposing virtual information on the real world in real time. Knowledge transfer involves shifting knowledge, experience, skills, information, and insight from one person, organization, or field to another, applying it to new contexts, solving problems, supporting innovation and facilitating learning [17,26]. AR significantly supports this process through visualization, instruction, interaction, and immersive experiences, translating knowledge into an intuitive, real-time and actionable form. This can facilitate understanding and application, and the efficiency of knowledge transfer. The process of knowledge transfer typically involves defining the goals and users' needs, then gathering required key knowledge, integrating and encoding the knowledge into presentation forms. Based on the integrated and encoded knowledge, specific applications or tools can be developed and users can manipulate and provide feedback on knowledge contents, based on which tools can be adjusted to improve knowledge transfer. Finally, the assessment can be conducted to ensure knowledge transfer objectives and optimized process. Through clarifying conceptual boundaries of AR applications in facility management, this research can better execute searching criteria and conduct a critical review.

3.3. Executing inclusion and exclusion criteria

The literature search and filtering process are demonstrated in the following sections. The significant keywords of the research were selected based on the four research objectives, and the literature was filtered for topic-based relevance. The literature was bibliographically consistent with research methods and critically reviewed for applications of AR in FM. The 'Preferred Reporting Items for Systematic Reviews and Meta Analyses' (PRISMA) method was performed to select and determine the final literature since it can enhance the accuracy of the systematic review [40]. The review process can be categorized into four stages: identification phase, screening phase, eligibility phase, and included phase.

The 'keywords' approach is widely employed in systematic literature review. In the identification phase, this research identified the most relevant keywords to augmented reality and facility management. 'augmented reality', as well as terms related to facility management [41], including 'facility' or 'facilities' or 'facility management' or 'facilities management' or 'FM' or "operation and maintenance" or "asset management", were the search keywords. In this research, two search engines, Web of Science and Scopus were selected as databases for collecting the relevant literature. Besides, the type of literature was restricted to peer-reviewed journal articles, and the language of articles was restricted to English. As of March 2023, 305 and 313 documents were found in Web of Science and Scopus, respectively, totaling 618 articles.

In the screening phase, 219 duplicate articles were removed as well as 399 articles remained for further review. During this stage, titles, keywords, and abstracts of the remained literature were carefully examined, and the removal of four critical criteria were as follows. (1) The theme of literature was not related to AR and FM. For instance, keywords related to AR and FM only emerge in the abstract while the main contents were out of the research scope and concepts. (2) studies focusing on other technologies such as virtual reality (VR), wireless communications were excluded in this study. (3) articles relevant to applications of AR in FM were limited in the engineering field, with the education, tourism, medical fields excluded. In this step, 133 articles remained with 266 articles excluded.

In the eligibility phase, this research reviewed full texts of articles and 56 papers were excluded. The inclusion and exclusion criteria to find the most relevant articles are as follows. (1) The articles without available full texts were excluded. (2) Research must apply AR techniques to one or more FM processes such as layout design, assembly, monitoring, maintenance and management, disassembly, etc. Hence, research on only describing AR application situations without practical implementation was excluded.

(3) Research which only proposed a conceptual framework without making contributions to practically implementing AR techniques in facility management were also excluded. After the eligibility evaluation of 133 articles, there were 107 papers remained for further study with 26 articles excluded.

In the included phase, 107 articles were determined for literature review ultimately, which were then quantitatively analyzed regarding bibliometrics and research contents. In this study, VOSviewer, a research visualization software developed by researchers at Leiden University in the Netherland was adopted for establishing and visualizing bibliometric networks. This powerful software can generate interactive maps or graphs and provide analytical tools for bibliometric networks, integrating with diverse external data sources such as Web of Science, Scopus [42]. The quantitative analysis facilitated a detailed content analysis of the literature to help address the research questions. Finally, the future applications of AR capabilities for facility management were summarized. The entire review screening procedure is demonstrated in Fig. 1.

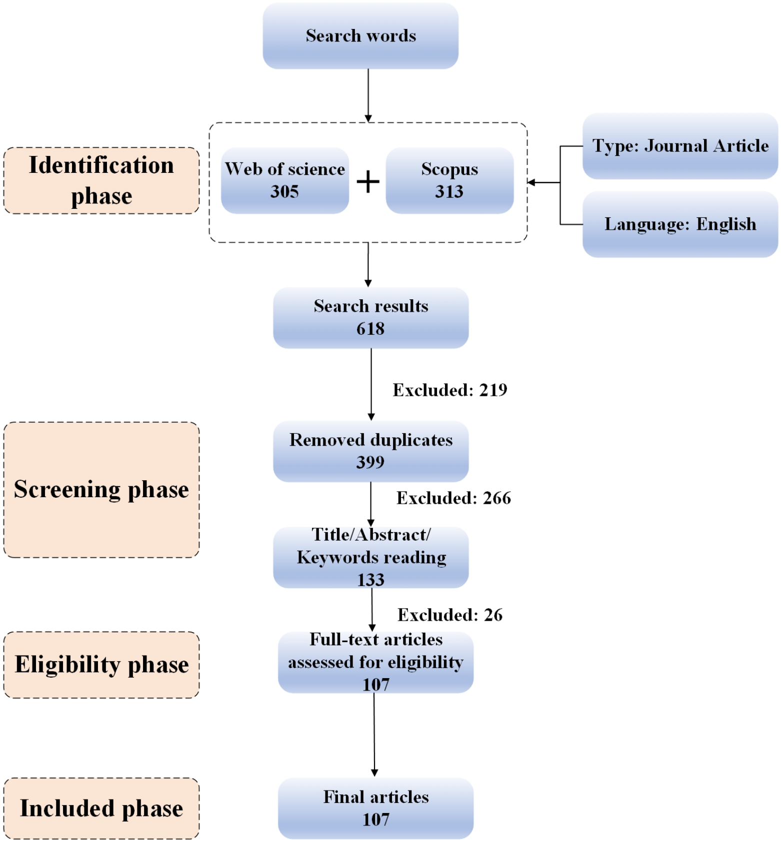


Fig. 1. Overview of the systematic review screening procedure.

4. Quantitative analysis

This section provides a quantitative analysis and an overview of AR technology development and publication trends. Research question 1 was addressed through analyzing a total of 107 selected research articles.

4.1. Tendency of publications

The annual trend of publications related to this scope is shown in Fig. 2. In 2011, AR in O&M for equipment support was examined to help fieldwork efficiency [38]. The publications rocketed by 8 articles in 2013, followed by fluctuations between 2014 and 2018. A notable surge occurred in 2019 with totally 14 publications, and continued to increase in 2020. By 2021 and 2022, the number reached 18 articles, with 8 articles until March 2023. The total number of publications in the last four years has doubled compared to the first eight years. Hence, the publications tendency has witnessed an increasing trend in recent four years, indicating the rapid growth of research opportunities alongside the increasingly development of BIM techniques. However, this expansion also reserves multiple challenges for future research to address.

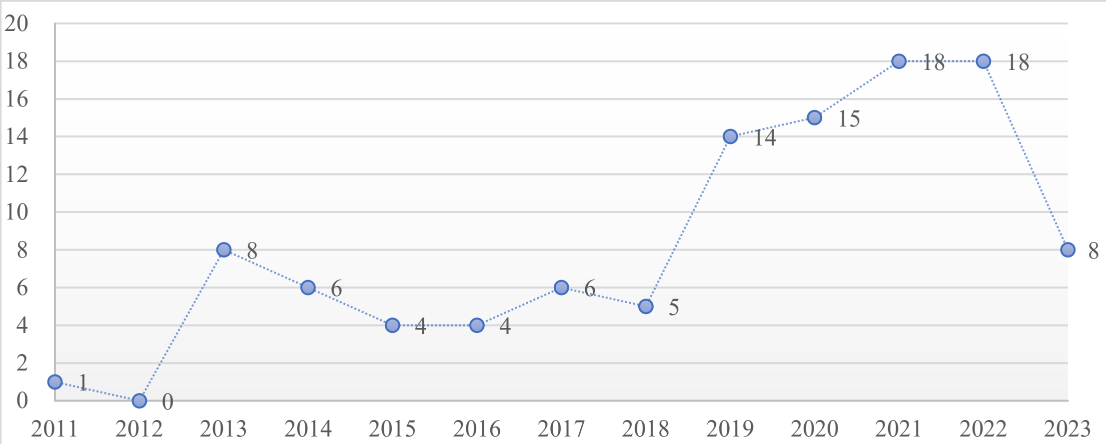


Fig. 2. The number of publications tendency.

4.2. Geographic sources of publications

Fig. 3 shows the distribution of publications by the first author's country/region. A total of 32 countries and regions have published articles in this field in the last 12 years. *South Korea* was the most active contributing to the most papers (14 papers), followed by *mainland, China* (13 papers) and *USA* (13 papers), respectively. *Italy* ranked next with 11 papers. Besides, *UK* and *Spain* both contribute 9 papers in this field, followed by *Germany* (6 papers) and *Greece* (6 papers). These countries/regions accounted for nearly 80% of the total papers in this field.

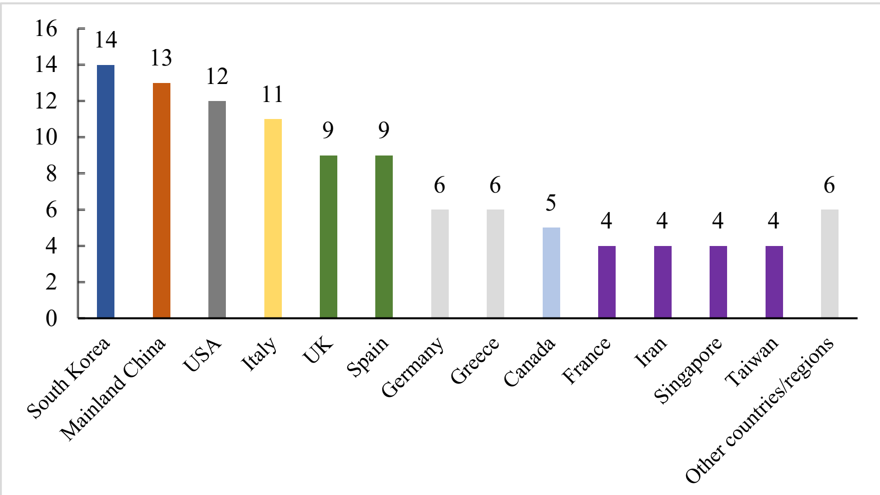


Fig. 3. Total publications by country/region.

4.3. Academic sources of publications

Fig. 4 illustrates the contributions of the publication sources. It is notable that *Automation in Construction* and *Applied Sciences*, both of which contributed 12.1% of the total papers, indicating that their prominence in this field. Furthermore, *IEEE Access*, *International of Advanced Manufacturing Technology*, *Sustainability* were also main sources which contributed 11.1 % of the total papers. Journals focused on facility management such as *Facilities* (2.8%), *Engineering, Construction and Architectural Management* (2.8%) as well as those related to advanced computing methods and digital technologies in engineering such as *Advanced Engineering Informatics* (2.8%) and *Computers in Industry* (2.8%) made contributions to promoting the implementation of AR applications in facility management.

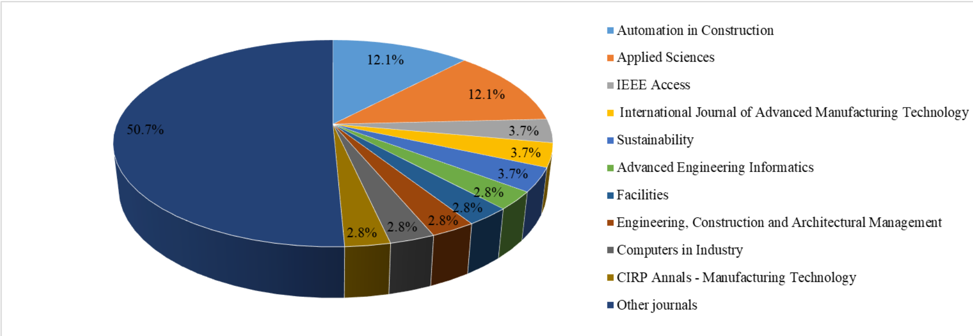


Fig. 4. Contributions of publication sources.

4.4. Co-occurring keywords of publications

Vosviewer software was performed to analyze the co-occurring subject categories, a Java tool for visualizing research trends and clustering. According to Fig. 5, each keyword is linked with other keywords. Specifically, the circle size of the keywords and the relationship of the keywords are illustrated based on two features, including occurrence frequency and centrality among keywords. The more frequent of the keyword occurrence and central for a cluster is, the larger circle of this keyword with apparent connections is. It was found that *augmented reality*, appears as the most frequently used keywords in the analyzed papers, as well as some other keywords surrounded by the largest blue circle. One significant keyword is *system* linked with *natural markers* and *management* as well as *industry* which is also connected with *facility layout* and *guidance*. According to the blue clusters, *augmented reality* is closely related to *facility management*, when *design*, *maintenance* is the most common consideration during the process of facility management. Note that *BIM techniques* are also linked with *AR* to help O&M of facilities based on the connections of the blue circles. *Visualization*, especially *data visualization* is one of the most important issues when combining *BIM* and *AR* techniques. Based on the keywords analysis, the in-depth content analysis of AR applications was conducted in Section 5.

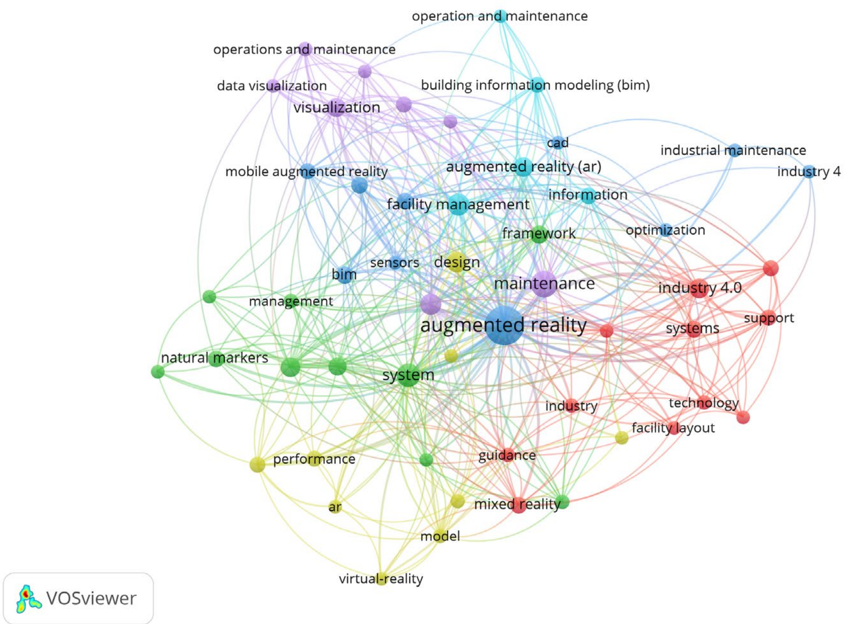


Fig. 5. Keyword clustering of the publications.

5. Contents analysis

This section examined the contents of the reviewed literature, providing a quantitative analysis of AR technologies and facilities discussed in related publications and application procedures associated with facility management.

5.1. AR technologies associated with facility management

5.1.1. AR functions

AR technology, firstly introduced in the 1960's has evolved, supported notably by multiple devices with different features and benefits. This study reviewed six different functions of AR in this field.

Authoring and visualization: Authoring is to create augmented contents and properly display them in the real world [43]. AR can guide facility inspection and maintenance based on physical markers (i.e. images, words, animation) on a graphical user interface (GUI), as well as by visualizing 3D models can be visualized to make comparisons with the real objects.

Interaction: AR enables human-machine interaction between user and augmented contents, which can provide relevant feedback on facility management [44]. This interaction can observe 3D models, touch the operation menu, or follow speech instructions with the authored augmented contents to complete facility maintenance tasks.

Context aware: AR can sense and understand facility management staff’s environment, detect and recognize facilities or related markers in the actual operating scene sensing and understanding facility management staff's environment, and display virtual contents based on the features of the environment and facility management staff’s requirements [45].

Tracking and registration: By means of sensors (e.g. cameras, gyroscopes, accelerometers, etc.), AR could track the position and orientation of devices and register augmented contents with working environments to ensure geometric and visual consistency [46].

Navigation: AR could provide real-time location navigation and guidance, guiding operators to maintenance task destinations in an operational environment. This enables precise facility location by displaying navigation markers or indicators [47].

Inquiry and storage: Facility management staff could inquiry facility data and information on the AR screen [48] as well as transmit operation facility information from AR devices to databases. This allows both onsite and offsite staff to access the operation status of facilities [49].

Communication and collaboration: AR supports communication among facility management staff by allowing them to view the scene live from AR devices [50]. Multiple staff could collaborate by creating and sharing AR markers on the screen, and discussing repair solutions [51].

5.1.2. AR hardware and software

This study reviewed three tools, including handheld devices, wearable devices and projection-based displays commonly performed to implement AR in facility management.

Handheld devices (HHDs): HHDs including smartphones and tablets, are flexible and mobile in facility management since they are commonly lightweight, less expensive and requires less complex hardware. While hand assistance may reduce dexterity when encountering complex repairs. HHDs with built-in sensors and cameras enable sense the user's orientation and environment. HHDs could provide 3D facility models in facility management [52,53], real-time dynamic information [54,55], record and send onsite reports [56,57], interactive tracking and markers [58-60] which finally help facility managers decision-making.

Wearable devices: Wearable devices like helmets, glasses, and wrist watches regarded as optical flat screen displays, superimposed computer-generated contents in front of the facility management staff's eyes. For instance, HoloLens, a head-mounted type of AR glasses developed by Microsoft, is equipped with the cameras in AR glasses functioned as 3D tracking and positioning, fixing facility components to specific locations through spatial anchor settings [61]. This is conducive to identifying and accessing facilities components for maintenance staff [62]. These devices facilitate visual guidance characterized as text or pictures, and remote communication or cooperation [63,64]. Wrist devices can enhance human-machine interaction through vibration, helping staff to determine rotation locations and time for facility components [65,66]. Note that wearable devices are more expensive with greater endurance for long periods of maintenance work teams.

Projection-based displays: Projectors can superimpose 2D maintenance contents such as images and videos directly onto the physical world or guide lights into the environment without intermediary [67,68]. This kind of device usually requires outreach device or configuration of sensors. Since projector is not equipped with inertial measurement unit (IMU) sensors, external sensors can be used to enable multi-interactions and tracking systems [69]. Due to the ability to turn object surface into screen, uneven surfaces or complex parts of the real environment may not be covered by augmented contents in complex facility maintenance environments.

Table1 AR implementation tools with features

AR device	Features	Visualization	Interaction	Context-aware	Tracking/ registration	Navigation	Inquiry and storage	Communication and collaboration
Handheld Devices	Mobility Low-cost Convenient use	√	√	√	√	√	√	√
Wearable devices	Multi-interaction More freedom More immersed	√	√	√	√	√	√	√
Projection-based displays	Large-scale view Self-adaptive	√	√					

AR-enabled hardware and software is concluded in Fig. 6. AR technology integrates authoring capabilities utilizing platforms such as Unity/Unreal Engine platform, linked with AR related Software Development Kits (SDKs) and BIM related software [54]. There are multiple senses such as vision, touch, and hearing to achieve human-machine-environmental interaction and help make decisions. They could click buttons on the screen to acquire further instruction with their gestures, and follow speech instructions to better understand further steps. Operation information can be inputted onto computers linked with database, facilitating real-time decision-making [70,71]. Once processed, the operation information can be updated in BIM and sent back to the AR device [72,73], forming am information flow of AR-enabled facility management.

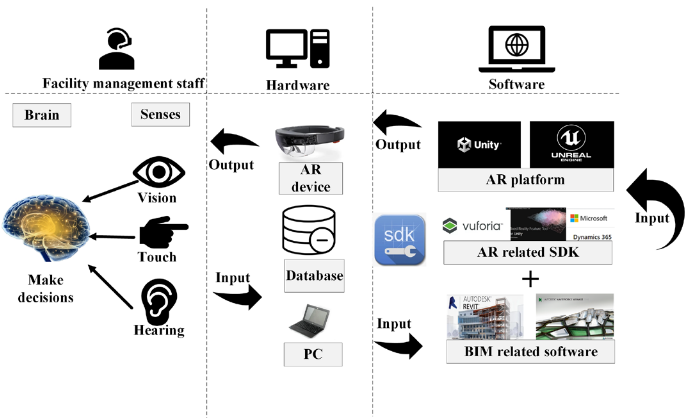


Fig. 6. AR-enabled hardware and software

5.2 Facility characteristics associated with facility management

Based on Fig. 7, the majority of studies in this field focus on *complex facilities* (32 papers) and *mechanical facilities* (30 papers), followed by *plumbing facilities* (19 papers). Besides, *electrical facilities* (13 papers) as well as *other facilities* (7 papers) were also examined by the existing studies.

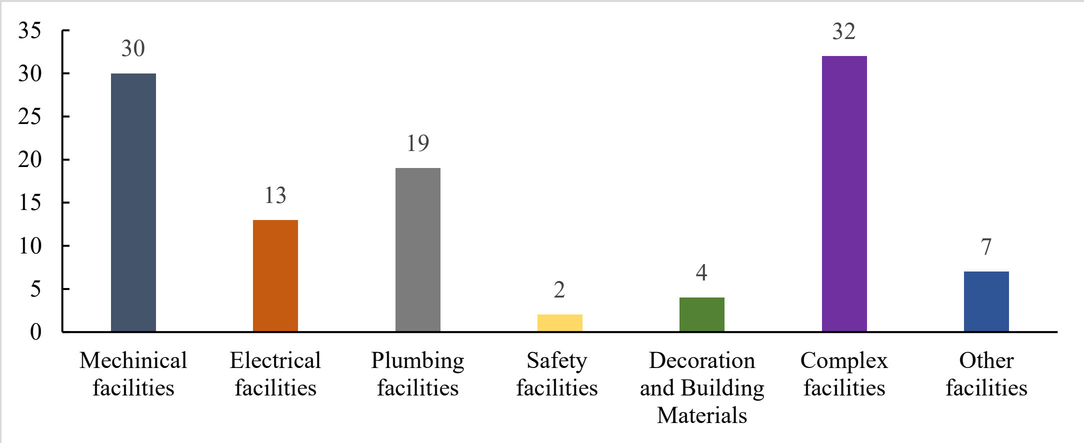


Fig. 7. Classification of facilities categories

5.2.1 Mechanical facilities

During the operation period, mechanical facilities are critical for building maintenance and management. Note that 30 papers focused on mechanical facilities in this area, including building water pumps [8,74] or oil pumps [64,75], followed by air conditioning [70,76], other HVAC equipment [38,77] and mechanical machines for building operation [52,67], etc. The complexity in assembly and disassembly of the these systems as well as the needs for regular inspection and predictive maintenance, makes AR useful. This technology can integrate 3D models designed to promote high-level communication through digital and virtual contents, provide visual guidance and monitoring, facilitate preventive maintenance [78].

5.2.2 Plumbing facilities

Plumbing is mainly concerned with water supply, drainage, heating and ventilation systems in buildings. This field also witnessed important AR applications. These studies mainly focus on gas pipes [54,55] ventilation ducts [60,79], underground water pipes [80-82] in buildings. Considering some pipes' physical attributes, hidden within the ceiling or the wall poses difficulties to view and inspect directly. AR visualization capabilities can highlight the targeted object and identify the locations of the pipes in buildings.

5.2.3. Electrical facilities

13 papers focused on building's electrical installations such as cables and lifts. These studies mainly examined the overall layout of electrical equipment installations and maintenance [66,30,83,84]. AR visualization techniques could install electrical equipment to prevent overlap or collision. The visual inspection system also enables

staff to locate and repair faulty assets when carrying out maintenance tasks, and different stakeholders' information can be created, shared, exchanged and managed during O&M phase of buildings [8]. Meanwhile, integrating GPS information and AR could present information maps of electrical cables, providing additional information when corresponding areas via the map service are selected [85].

5.2.4. Decoration and building materials

Decorative and construction materials include a wide range of materials and products for building beautification and reinforcement. There also exist 4 papers that examine the decoration and building materials such as the placement of interior doors [86,87] and windows [2], and door/chair assembly [62]. AR technology assists in visualizing the placement and assembly processes, enhancing accuracy and aesthetic outcomes.

5.2.5. Complex facilities

32 papers focused on complex facilities consisting of different types of facilities. The majority of studies examined the complex underground facilities systems [88-90], as well as focusing on overall MEP system of buildings [91-92] for implementation and tracking services in complex systems.

5.2.6. Other Facilities

Seven papers have explored additional facility types, such as the layout of building landscapes and greenery [93]. For example, an AR application has been developed to superimpose realistic designs onto paper markers, enabling users to select colors and textures for cultural landscape installations and to create and modify building materials.

5.3. Application procedures associated with facility management

The typical applications of AR-based facility management consist of facility design/layout, facility assembly, facility monitoring, facility maintenance, and facility renovation [4,94]. According to AR technology characteristics in Section 4.1, AR features in these activities are shown in Fig. 8.

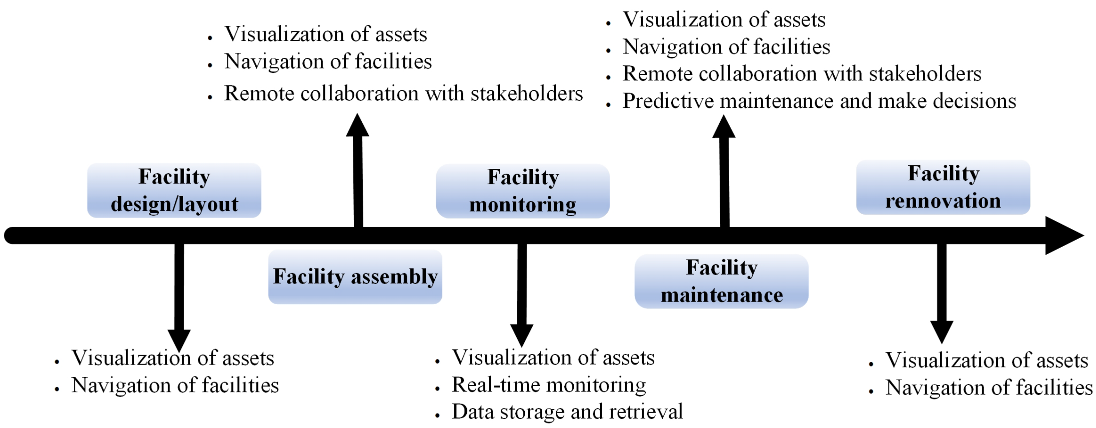
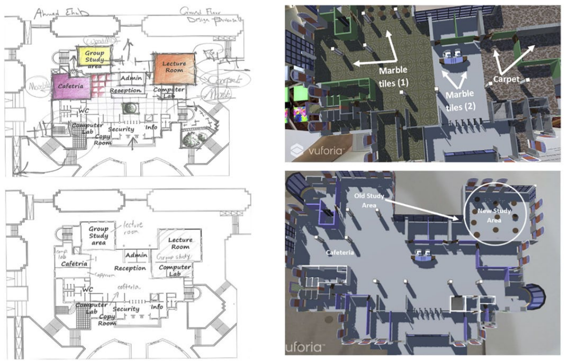


Fig. 8. AR features in application procedures

5.3.1. Facility design and layout

The integration of AR technology in facility design overlays virtual equipment onto existing equipment in a real environment, where the real equipment remains fixed while the position and size of the virtual equipment can be adjusted through the interface. This is crucial in examining the spatial relationships with different facilities in single working scenario, helping facility managers decision-making by adjusting important layout parameters [63]. In addition, AR can superimpose realistic facility design solutions onto drawings or paper markers, achieving flexible facility positioning. AR visualization interface allows users to create and modify the shape of the facility and the materials required for the facility, facilitating free architectural design and collaboration between property owners and architects [93].

AR-assisted facility layout planning programs have been developed which could detect the location of AR markers, equipment and personnel using a real-time positioning system [95]. One key ability of this technology is to identify the surroundings and zoning, delineate safety zones and facility placement areas to avoid collisions. Through repositioning and reorienting different facility layouts, such as straight line, W-shaped, or U-shaped layout, the optimal layout can be identified determining the shortest path between facility management staff and their destinations by combining relevant path planning algorithms. For automatic facility layout optimization, an optimization scheme based on hierarchical analysis-genetic algorithm (AHP-GA) can be employed. This can aid visualization of both automatic layout process and manual facility layout planning, ensuring heuristic fast modelling by the users in combination with experience and personal preferences [96].



Note: Designing with coloured pencils in 2D drawings and on-screen interaction in augmented environments for facility design.

Fig. 9. The implementation of AR in facility design [93]

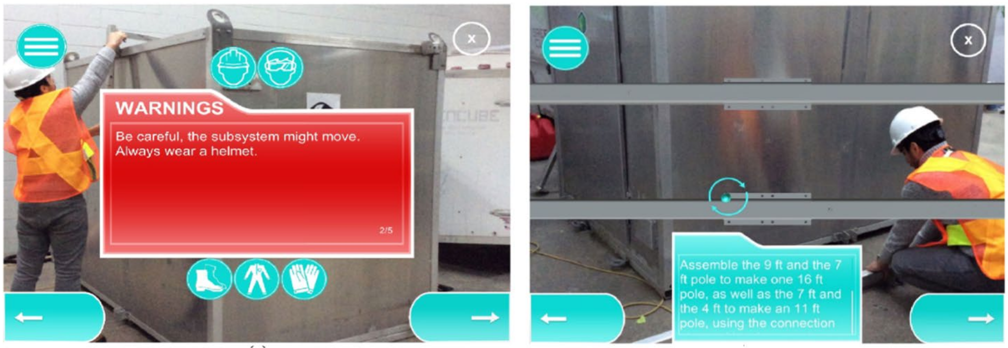
Note: The facility manager is creating augmented scenarios and changing facility layouts and production parameters, while the operator performs facility layout operations and places products in correct storage racks.

Fig. 10. The implementation of AR in facility layout [63]

5.3.2. Facility assembly

Facility assembly operators perform three main tasks including identifying parts, aligning them in assembly position and fastening. Auxiliary tasks include adjustment and inspection. AR-enabled facility assembly requires aforementioned tasks information to aid in the assembly process. The manual effort in traditional facility assembly can be characterized by mental and physical efforts [97]. Studies have shown that AR technology exhibited remarkable advantages particularly in difficult assembly steps [98]. In the context of building facilities in section 4.2, AR can demonstrate highly beneficial in complex mechanical, plumbing and electrical equipment systems, particularly in large-scale underground complexes. The notable advantages include the visual representation of micro-geometry details of assembled objects, and organizational process information [99,100].

AR can be performed to train new employees enabling quickly understand the assembly operations through the transfer of assembly knowledge. This could facilitate creating AR contents and transferring assembly knowledge from experts or experienced staff to non-experts or inexperienced technicians. A study has shown that AR-based in-situ augmentation notably reduces learning time by approximately 50% compared to traditional methods such as paper manuals, videos, or virtual instructions on screen [101]. This facilitates operators to master assembly skills and the contents in assembly manuals within a constrained timeframe. Furthermore, abstract virtual metaphors and virtual human avatars have been explored [62], where operators could gain an immersive experience through AR devices and gain assembly support in augmented environment. This results in narrowing the gap in maintenance time between experts and non-experts. Note that as more parts and tools need to be handled, the complexity of assembly task increases [98]. When visual features and specific interfaces are characterized in an augmented environment, 3D visual features such as BIM models can be utilized in simpler assembly tasks. Conversely, 2D visual features and interfaces such as 2D drawings and animations should be performed for more difficult tasks to help operators better recognize complex assembly contents. Adaptive assembly deserves attention to understand assembly contents. For example, adaptive display methods based on CAD feature bounding boxes [102] can be combined with optimal viewpoint selection algorithms and adaptive visual aids (AVA) linking contextual information to specific machine parts [103]. These methods not only enable the display of position-related information but also present information for specific tasks or components, reducing misplaced information and alleviating difficulties associated with complex assemblies. Additionally, besides visual and audio interactions, haptics can be involved in guiding assembly work utilizing vibrotactile feedback such as rotational or translational motion cues. The adaptive creation-based platform decreases the resources required for AR development, enabling both experts and non-experts to create and develop contents. This platform facilitates assembly data management and enhances operator efficiency [104].



Note: The assembly procedures of the facility are guided by AR and assembly precautions are issued when necessary.

Fig. 11. The implementation of AR in facility assembly [105]

5.3.3. Facility monitoring

The installation or dismantling of facility components as well as the operational status are in the scope of facility monitoring through AR technology. AR devices linked to remote control centers or databases can guide facility management staff to identify, retrieve and visualize historical maintenance records during onsite installation, operation and maintenance [105,106]. Data are generally sourced from monitoring sensors during the monitoring period. With the adoption of mobile augmented reality (MAR) and Brillouin fibre optic sensors (BFOS), the structural stress state of underground pipelines can be assessed. Real-time monitoring data based on dynamically modelling the evolution of the pipeline structure can gain insights into the structural safety assessments [54]. The combination of AR and cloud-based technologies allows for visualization of underground pipe networks, integrating static and dynamic data from multiple sources, enhancing inspection and further condition assessment of facility components. In addition to pipeline facilities, AR also extends to be applied in managing rail assets. AR and IoT-based connectivity facilitate communication between on-site maintenance operators and remote experts or supervisors with digital means, which helps understand the conditions of rail assets, monitor degradation and digitize failure modes for predictive maintenance process [107]. Critical commercial complexes also witness AR applications where sensors transfer data online to BIM, integrated with AR platforms to operate and maintain mechanical facilities within limited time [52]. Furthermore, AR technology, combined with machine learning algorithms, has potentials in identifying facility anomalies, alerting facility managers to initial operation issues [108], and exchanging facility system data using JavaScript object notation (JSON) data format, transmission control protocol/internet protocol (TCP/IP), open platform communications unified architecture (OCP UA) or other communication protocols [28,64,83].

Note: The visualisation of underground pipelines and the results of monitoring data and stress analysis allow data interrogation in an AR environment for operational assessment and decision making on pipelines.

Fig. 12. The implementation of AR in facility monitoring [109]

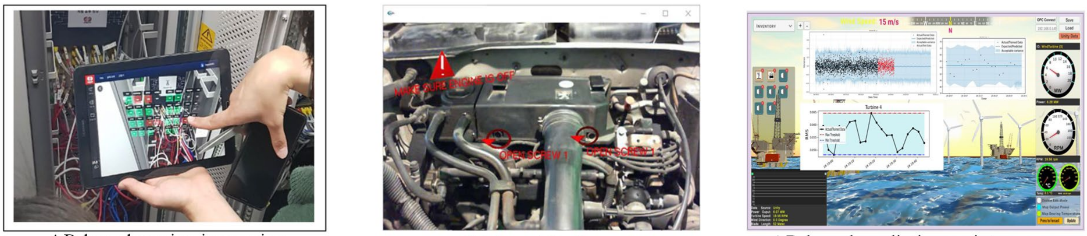
5.3.4. Facility maintenance

The maintenance of facilities mainly consists of routine inspection, repair of failures and predictive maintenance. They are based on the principles of typical equipment failure statistics, the principles of reactive measures and preventive measures respectively [110]. In O&M phase, it is essential to develop facility risk assessment and maintenance system to help select maintenance strategies and prioritize the maintenance of equipment components [30]. The system has vast amount of facility information as well as maintenance, resources and support. The required data can be defined through the construction operations building information exchange (COBie), mapped from BIM attributes information to AR-enabled visualization for users [2]. The large amount of data is pre-processed and updated on servers. This enables the quick identification of faulty components in real space and improves the efficiency of information retrieval [75].

Routine inspections: AR technology can conduct routine inspections for facilities by means of displaying virtual information onto real equipment, providing an intuitive understanding of the equipment's condition and improve the efficiency of facility inspections. To be specific, AR-enabled adaptive maintenance system supports daily equipment maintenance through data exchange and efficient communication between facility technicians and the engineering department [111]. After completing inspection tasks, AR devices assist in reporting the contents, including tracked and collected verbal comments, pictures, audio tracks and video clips, which are then integrated into online maintenance forms [10].

Fault repair: AR-based training is conducted before actual maintenance tasks, combining traditional repair manuals with virtual components overlaid onto the real environment. During this process, AR devices can provide warnings for dangerous and challenging maintenance procedures to ensure safety and accuracy. This technology facilitates the sharing of experienced knowledge and assists maintenance personnel in performing operations correctly [112]. Building information modelling-based augmented reality maintenance system (BARMS) enables maintenance routes and viewpoints locate in the form of animated guides [59] and natural marker-based AR framework provides digital support for navigation [113]. Note that the accuracy of visual information is particularly important, which depends on the object alignment and tracking quality [110]. Estimating the camera's point of view (POV) pose is accomplished by capturing video images through the mobile camera. By utilizing computer vision techniques, feature point-based maps are created to identify repair locations by means of simultaneous localization and mapping (SLAM) techniques [114]. On-site troubleshooting of faulty parts through AR enables viewing model numbers and maintenance history by pointing at the affected components. This capability significantly reduces repair cycles from two months to two weeks [115]. In the event of complicated maintenance, technical documentation can be accessed for assistance by integrating video and depth cameras for capturing user gestures, webcams for marker-based tracking and a see-through head-mounted display system for digital information overlay [116]. When onsite maintenance is not feasible, AR-based remote maintenance and repair operations provide significant benefits, as the platform is connected to cloud databases for mutual information exchange. This allows expert engineers to create tools online with a graphical user interface (GUI), or search algorithms that automatically generate recommendations [50]. After maintenance, an integrated AR and social media solution supports the sharing of contextual knowledge for future maintenance visits [117].

Predictive maintenance: Integrating BIM software such as Autodesk Revit, Navisworks and Unity software, as well as multiple sources from building, structural and facility data through sensors mounted on Arduino boards and smartphone or AR goggle tools, enables facility managers to access information and monitor possible failures through data prediction [52]. Predictive algorithms are crucial for enhancing the outcomes of predictive maintenance. Furthermore, the adoption of AR technology aids preventative maintenance by providing an intuitive navigation system through information and communication technology (ICT) to overlay information such as operating instructions and manuals required for on-site operations [115].



AR-based routine inspection　AR-based fault repair　AR-based predictive maintenance

Fig. 13. The implementation of AR in facility maintenance [106,114,118]

5.3.5. Facility renovation

Before refurbishment, the original facility requires dismantling. During this process, AR is applied to the designed model, leading to the development of a new aided maintenance system (ARAMS) for maintenance activities. This system enables context-aware information, and supports presenting virtual information. ARAMS also facilitates experts in creating and delivering AR-based remote collaboration and allows the creation of dynamic AR maintenance content both offline and in the field, ensuring bidirectional communication. [119].

Collaboration among stakeholders is crucial in the retrofit design process to facilitate the decision-making process during facility renovations. AR techniques have the capability to display facility candidates, including appearance, materials, colors, and more. This allows for the alignment of virtual models with real buildings, enabling direct comparison between the renovated virtual model and the current state of real buildings [120]. By leveraging AR technology, detailed information about the facility's history, current condition, and renovation options can be available, aiding facility managers and maintenance staff in making effective decisions. AR also facilitates the layout and planning of facility spaces during the selection process, allowing for realistic visualization and operation within the augmented environment. This capability further supports adjustments and optimizations during the redesign of facility spaces.

Note: Assessment of ducting in ceilings as well as external wall coatings and window renovations in an augmented environment.

Fig. 14. The implementation of AR in facility renovation [120]

6. Critical review of AR-based knowledge transfer in facility management

Based on the contents analysis, AR facilitates multi-directional knowledge flows among humans, machine, and the physical environment [26]. This technique acts as an immersive bridge embedding knowledge into real-world throughout the facility lifecycle including design, layout, assembly, monitor, maintenance and renovation for more efficient and effective facility management. Knowledge contents are created using AR authoring platforms such as Unity 3D and Unreal Engine. The implementation of AR technology involves selecting appropriate software and hardware. The authored knowledge is then overlayed onto the facility environment, integrating with BIM, FMS or CMMS. Then AR can facilitate real-time communication and collaboration among stakeholders including on-site facility staff and off-site experts to ensure knowledge can be shared bidirectionally through AR interfaces. AR not only enables knowledge transfer between experts and non-experts, but also between on-site facility staff and off-site staff providing immersive experiences that facilitate training and upskilling. Finally, AR collects and analyzes facility operational data to identify patterns and predict maintenance needs. It also allocates feedback from users to promote knowledge transfer process. As facility management practices evolve, new knowledge contents can be expanded to cover broader aspects through updated knowledge processes and procedures [43]. In this section, this research further discussed AR related techniques and stakeholders in this mechanism, and further examined the influencing factors and potential challenges associated with AR knowledge transfer in this field.

6.1. Techniques combined with AR knowledge transfer in facility management

There are a series of advanced techniques integrated with AR in facility management (see Table2). BIM has been regarded as an effective approach to managing and analyzing building information in 3D digital settings [6]. BIM could also provide virtual objects and scenes with appropriate scales to enhance facility management in practice [121]. Considering these advantages, research has focused on integrating BIM and AR approaches to capture FM information, conduct space management, identify facility components, and display operation procedures. Geographic information systems (GIS) have also been integrated into BIM-AR systems to help position the large-scale assets such as underground city facilities [55]. Furthermore, artificial intelligence (AI) techniques have been proved advantageous in automation and intelligent decision-making, as well as continuous learning and environmental adaptation to identify and anticipate [122]. With the combination of AR and AI techniques, facility failures can be identified efficiently during operation and maintenance decisions can be effectively determined by facility managers. To be specific, computer vision techniques can position facility components by means of identifying visual features or markings on equipment as well as registering images/information. The involvement of semantic techniques is conducive to context-aware authoring of information. Through rules reasoning, facility managers can make decisions on inspections, maintenance, and proactive measures. Furthermore, deep learning methods provide guidance for modelling facility operations as well as help classification of facilities and decision-making for facility maintenance.

Facility monitoring requires various sensors to collect operation data. Internet of Things (IoT) and AR techniques can collect facility operation data, and visualizing the operations through images and live data streams. Cloud computing can be involved in uploading and synchronizing on-site facility information to provide decision support for maintenance. The monitoring data collected from AR and IoT are typically managed through cloud platforms. Considering that facility management related activities have requirements for extensive data and information, information and communications technology (ICT) technology can play a vital role in this process. The combination of ICT and AR provide opportunities for remote assistance in facility maintenance to ensure high-quality communication and facilitate facility information transmission with the assistance of 5G techniques.

Table 2 Supportive tools in FM

Supportive tools	Main functions	Results
	Capture of FM information [2,5,8,49,55,58,60,73,79,82,83,123,124]	Integration of FM data in BIM models, visualization of FM information by overlaying models and data into the real environment.
	Space management [28,56,114]	By placing a model of the facility, users can view the virtual layout and space usage of the facility in realistic environment.
AR+BIM	Identification of facility components [53,59,77]	By disassembling the model components of the facility, the composition of the facility can be viewed to assist in the assembly, disassembly and maintenance of the facility.

	Displaying of management procedures [72]	Facility management steps can be simulated via the AR side through GUI creation.
AR+Computer vision	Positioning of facility components [38,76,125]	Positioning of facility components based on computer vision, with improved and complementary marker detection techniques.
	Registration of images/information [45,114,126]	Creating AR markers and using AR sensors to perform the correct identification of images/information.
	Splitting text codes and reading characters [127]	Reading screen-aligned text, segmentation and text codes using optical character recognition (OCR) technology.
AR+IoT sensors	Identification of facility failure [128]	Assessing facility situations and helping failure early-warning.
	Visualizing facility monitoring data [65,107]	Visualizing real-time facility monitoring data collected by IoT sensors as virtual objects or charts.
AR+Semantic techniques	Context aware [106,117]	Context-aware facility management AR interface through methods such as ontology modelling, recommending information based on users' preferences and location.
	Authoring facility information [43,50]	Dynamic creation of facility diagnostics based on facility maintenance data.
	Reasoning for facility management and decisions [106]	Selecting the right set of actions for the facility management task steps to be performed by rule-based reasoning.
AR+Deep learning	Decision-making support for facility maintenance [129]	Collection and processing of facility faults to support decision making systems.
	Monitoring and categorizing of facilities [114,130,131]	Real-time classification of facilities through real-time deep learning.
	Algorithms support for facility management platform [28]	Using deep learning algorithms to identify facility operation situations.
AR+Cloud computing	Decision-making support for facility maintenance [57,58]	Meeting users' needs for decision support through cloud-based facility maintenance data.
	Uploading and synchronizing on-site facility information [53]	Using cloud services to upload and synchronize information contained in live AR devices
AR+ICT	Remote assistance for facility maintenance [132]	Combining diagnostic data with real-time in-situ acquisition and sharing with remote experts.

Facility information transmission [115]	Accessing messages in the field, improving accuracy of messaging and preventive maintenance.

6.2. Relations of stakeholders in AR-based knowledge transfer in facility management

There are multiple related stakeholders involved in facility management. Facility owners, as the owners of the facility, are concerned about the operation status of the facilities, and are responsible for providing resources and control for facility management activities. Facility managers are responsible for supervising regular inspection and maintenance to satisfy the needs of occupants or users. Manufacturers and maintenance company are engaged to provide facility services including facility repair, cleaning, and security. Field workers, assigned by manufacturers or specialized maintenance company perform onsite inspection and maintenance. Facility assessment can be performed to analyze the operation status by facility managers, manufacturers, and facility owners. The operation status can be categorized as normal and abnormal. To be specific, in normal operational conditions,, field workers conduct regular facility inspection and then the inspection reports are automatically uploaded to a cloud database. In cases of abnormal conditions, stakeholders discuss the operation issues and make decisions on the deployment of filed workers. When the failure is determined, field workers conduct onsite facility maintenance in collaboration with facility managers or other staff in the office.

Within this context, AR-based multi-stakeholder collaboration framework is illustrated in Fig. 15. Field workers equipped with AR tools can work with facility managers, and cloud server is available for data inquiries. Communication among facility management staff is supported by AR tools integrated with Dynamics 365 [18]. Offsite staff can view live scenes from the onsite staff's perspective and provide remote guidance. Furthermore, facility management staff can collaboratively create and share AR markers on their screens to discuss repair solutions [2]. All inspection and maintenance records are generated through AR device and transmitted to cloud platforms for further inquiry and analysis by stakeholders.

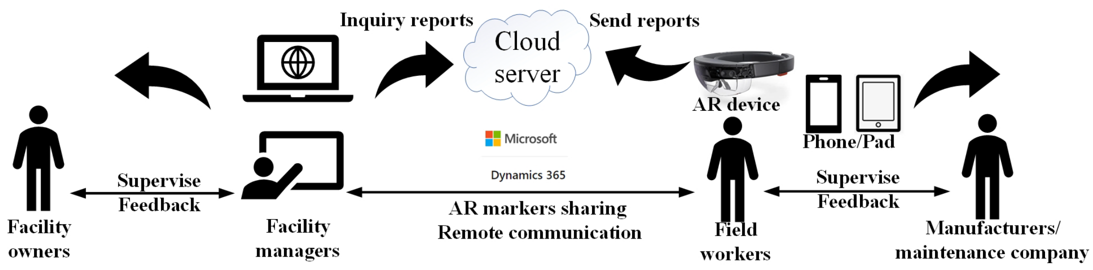


Fig. 15. AR-enabled FM stakeholder collaboration framework

6.3. Knowledge types transferred by AR-based facility management

6.3.1. Facility operation

According to Section 5.2, various stakeholders have different responsibilities involved in facility management possess. Their different knowledge reserves, and prior experience have an impact on AR technology in knowledge transfer during facility operations. For complex failure issues that arise during facility operations, AR technology facilitates the sharing of expertise among stakeholders by creating markers and comments on the live images. This enables the knowledge effortlessly accessible, helping to handle challenging issues during facility operations within constrained time. The knowledge gap between original equipment manufacturers and maintenance operators is bridged by a mobile augmented reality maintenance assistant (MARMA), providing detailed instructions for equipment operation [76]. Further improvements include enhancing the building platform with integrated facility operations information and introducing BIM into AR environment. This integration enables the utilization of data extracted from BIM as well as three-dimensional (3D) geometric information. Through the transfer of knowledge representation models, facility managers can better understand the operational status of the facility and assign tasks to onsite staff [8,124].

6.3.2. Facility management procedures

Knowledge can be transferred from experts to non-expert technicians in facility management operations (e.g. layout, assembly, maintenance, disassembly, refurbishment) through AR technology [100]. For instance, in the case of maintenance for a MEP system pipeline that requires specialized electromechanical engineering knowledge, on-site operators can seek assistance through AR from experienced experts or facility managers. Furthermore, when confronting unfamiliar issues, predefined procedures are employed to present relevant knowledge in the AR system, generating contents based on the acquired knowledge for subsequent inquiries [133]. Note that AR-based annotations and labeled visualizations can prevent risks and reduce human errors due to inexperience in dissemination [112]. In addition to seeking facility managers and experts for assistance, AR-based social media knowledge-sharing solutions can facilitate the exchange of learning ideas and experiences among facility maintenance staff [117]. Experienced field workers holding a wealth of tacit knowledge, including tricks and hands-on experience, in addition to their understanding of maintenance operations and work reporting greatly benefit from these platforms. This solution provides an opportunity for the transfer of tacit knowledge through knowledge sharing among stakeholders.

6.3.3. Vocational training and education

Acquiring knowledge from expert operators allows novice operators to leverage their experience effectively for problem-solving. [133]. By gathering both general and domain-specific knowledge, incremental learning can be provided for vocational training and staff education in this field. This can be achieved by implementing specific strategies including offering visual checklists prior to commencing facility maintenance, providing virtual experiences from maintenance manuals, and utilizing AR immersive learning experiences which replicate the effectiveness of previous learning. Knowledge capture and re-use can facilitate novice operators to acquire specialized maintenance knowledge [43]. In addition to AR training based on maintenance manuals and checklists, knowledge transfer can also be facilitated by allowing remote operators to locate training facility components. New operators can then access visual instructions through virtual animations or view 3D models and icons, enhancing effective knowledge transfer [62]. The scope of knowledge consists of static information on facility failure causes and maintenance routines, periodic facility operation warnings and procedures, and dynamic facility operation data and statistical reporting [107]. After completing vocational training, it is indispensable to acquire expert knowledge on the performance of maintenance tasks. This involves mimicking the decision-making processes of experienced operators based on their experience, thereby developing a rational approach to new situations, and supporting incremental learning for modeling purposes [87].

6.4. Influencing factors in AR-based knowledge transfer in facility management

Knowledge transfer involves a fluid and circular process including the stages of knowledge creation, acquisition, transfer, understanding and feedback.

6.4.1. Knowledge source

The first step in the facilities management process is to identify and capture relevant knowledge. The source of this knowledge is an important factor in in the efficacy of transfer. The main sources of knowledge currently transferred through AR technology in the process of facility management include existing maintenance manuals or checklists [112,134], experienced operators or experts [50,87], maintenance websites or social platforms [117]. Knowledge transfer from maintenance manuals usually extracts key steps and information usually representing official knowledge which lacks of tacit knowledge and updates from recent experiences. Knowledge transfer based on experienced operators or experts, usually involving AR remote guidance and r the real-time creation of markers by these experienced staff, allows for the sharing of tacit knowledge and experience. However, the applicability and correctness of some knowledge may need require verification. Knowledge transfer through maintenance websites or social platforms usually requires on-site operators to access expertise and relevant experience, which offers more autonomy than the first two sources but may have knowledge misconceptions or inaccuracies.

6.4.2. Advanced training

The application of AR technology in facility management requires targeted training and education for staff. This training could familiarize them with AR tools, understanding the AR interface and deepen their knowledge of AR human-computer interactions. Furthermore, the repeated presentation of the presented knowledge can help facility management staff to deepen their impressions and improve knowledge retention. Through advanced training, the frequency of human errors during the maintenance of the execution facilities can be reduced increasing the operational efficiency of facilities.

6.4.3. Visualization interface

The design of the AR interface is crucial in the process of knowledge transfer in this field. A complex interface , for example, characterized by challenging-to-comprehend guidance markers or massive textual information, can be more problematic and time-consuming for facility operators to read and grasp the necessary knowledge. On the contrary, interfaces with easy-to-understand standardized markers or visual animations can capture facility operators' attention and deepen their understanding. Note that the importance of colour information, as consistent use of color maintains attention and focus on tasks without distraction [100]. The integration of 3D models through the BIM-AR system can further enrich the knowledge of facility components and operational procedures. A self-responding context-aware interface can adjust information and data based on the location and preferences of the operator, as well as creative authoring which can positively contribute to knowledge transfer.

6.4.4. Human-machine interaction types

The usability of AR devices plays a crucial role in knowledge transfer. According to section 4.1, it is necessary to select the appropriate AR tool for specific scenarios considering the variability in tool features, as well as the flexibility of operators during maintenance, environmental conditions, and the design of the visualization interface and other factors, playing a positive role in accurate information delivery and knowledge transfer. In addition, AR tools provide various human-computer interactions, and the integration of visual and audio interactions as well as haptic feedback may enhance human-machine-environment interaction, thus facilitating knowledge transfer [66]. It should be notable that multiple forms of interaction may pose maintenance difficulties in practice. Hence, human-machine interaction types need to be informed based on outcomes from advance training and feedback from the staff.

6.4.5. Users' acceptance level

AEC industry, as a traditional and slightly conservative industry, is usually cautious about incorporating innovative technologies [135,136]. The application of AR in facilities management requires assessment of the acceptance level among various stakeholders. Resistance towards the involvement of AR technology can impede knowledge transfer and even result in worse management outcomes. It is therefore important to analyze the psychological, physical and temporal demands, as well as their performance, effort and potential frustration of facility managers towards adoption of AR in facility management [137]. On this basis, innovative solutions for AR facility management need to be further evaluated, mainly in terms of staff's real attitudes towards technological changes and their actual usage of the developed solutions, as well as staff feedback for improving the solutions [65].

6.5. Challenges in AR knowledge transfer in facility management

6.5.1. Tracking issues

It is customary to employ AR technology to identify and locate facility components during facility management processes, especially assembly and disassembly, where precise alignment is critical. However, the accuracy of AR-based facility alignment still needs to be improved, remaining issues including overlapping deviation between actual and virtual images. This is attributed to two main factors: the necessary accuracy of AR device's internal sensors, and the impacts of the external environment, including drift resulting from facility management staff's rapid movement with the AR device. This drift can lead to misalignment of facility components as well as incorrect information during the knowledge transfer process. These issues needs to be handled by better reliable alignment and positioning accuracy.

6.5.2. Registration issues

AR technology supports the registration of models and icons in the augmented environment. Current AR-based registration faces accuracy and latency challenges [138] that can adversely impact knowledge transfer. Accuracy issues are caused by the accuracy of the sensing device, sensor placement and the tracking process itself which can cause registration errors such as misplacing augmented information. Latency refers to the delay between facility management staff reaching a new location and the AR system updating this change. Factors such as the network speed, staff movement speed, and operational speed can contribute to delays in registration. To enable precise spatial registration needed for effective knowledge transfer, it is crucial to enhance both tracking and rendering speeds.

6.5.3. Ergonomics issues

The prolonged use of HMD devices can cause eyewear fatigue and physical discomfort to the operator particularly when used for long periods. In addition, the devices' limited battery capacity and the requirements for continuous network support can impose difficulties such as the absence of some functions in long periods of complex activities in environments like underground pipelines. HMD devices such as HoloLens also place specific requirements for the surroundings. The presence of reflective media or bright surfaces in the environment can cause failure in identifying facility components. For example, dark environments impose difficulties in identifying facility components. In addition, while brighter projectors may provide better legibility, but also raise concerns regarding potential eye damage or dizziness when directly exposed to high-intensity projectors in maintenance [68,139].

6.5.4. Security issues

AR-enabled FMS collect and process large amounts of data and information, and maintaining cybersecurity issues is critical for users, as data breaches and unauthorized access threaten user privacy and facility security. In addition, personal and company sensitive information needs to be protected when multiple users access shared knowledge. The reliability of these systems is essential for the execution of key facility management tasks. Currently, there are relatively few studies on the redundancy design of AR-enabled FMS. It is urgent to ensure continuous knowledge transfer even when some system components fail, and further discuss on strategies to reduce potential downtime and related risks, ensure rapid recovery of data and system functions in emergency situations, and maintain the continuity of facility management.

6.5.5. Management issues

There exist vast amounts of data in facilities management, currently predominantly transferred through explicit knowledge from maintenance manuals or checklists. This suffers from delays in updates and error correction. In addition, current research on AR-enabled facility management usually selects isolated scenarios such as assembly and maintenance, or a singular facility for experimentation, neglecting the extension of AR technology to multi-facility management in complex facilities with multiple scenarios. It is important to develop effective knowledge management mechanisms in comprehensive FMS, that address data privacy and information accessibility issues in the knowledge sharing process considering the multiple stakeholders involved in facility management.

In summary, previous studies reviewed AR performance in terms of visualization, positioning, and maintenance within facility management [24,25,140,141]. This study provides a more comprehensive overview of AR applications throughout the entire lifecycle of facility management, including design and layout, assembly, monitoring, maintenance, and renovation. It has been found that AR is primarily applied in complex facilities as well as mechanical, plumbing, and electrical systems in this field. The benefits of AR seem evident in knowledge-intensive and spatially complex operational environments, consistent with the perspectives in [26]. This study reveals that AR knowledge transfer is closely related to knowledge sources, visualization interfaces, and interaction types. Hence, it is necessary to develop appropriate visualization interfaces and interaction modalities to enhance user immersion and facilitate effective knowledge transfer through AR. This is supported by research in the education sector [34-36]. The study also identified user acceptance and vocational training as factors influencing the effectiveness of AR knowledge transfer in this field. Challenges remain in current practices, as the study found that organizational leaders are hesitant to bear the costs on AR hardware and employee training [140]. Furthermore, previous reviews have explored AR potentials for knowledge sharing in industrial maintenance applications [20,26,142], but there is lack of related research on facility management. Compared to the above studies, this research analyzed AR knowledge transfer processes in this field from the stakeholders' perspective, facilitating multi-directional knowledge flows among humans, machines, and environments in facility management. This can serve as an immersive bridge for deepening the understanding of AR in facility management not only as a visualization tool but also as a dynamic method for knowledge management. Finally, besides ergonomics and technical difficulties such as tracking, registration confronted in industrial environments which also exist in this field, there are some other challenges in information security and management in this field. This study emphasized collaboration among stakeholders while establishing mechanisms to ensure user information security, enhancing the understanding of AR's role in this field, and gaining a new perspective on implementing knowledge-driven digital twins in the AEC industry.

7. Future trends of AR-based knowledge transfer in facility management

Based on the critical review, the potential research trends and future directions are demonstrated in this section, gaining further insights into AR research in the development and applications in facility management.

7.1. Advancing AR-enabled tracking and registration

Advanced AR devices can improve immerse experience for facility management staff track human senses by high-precision tracking and registration. In addition, high-precision tracking and registration are the basis for ensuring virtual-real fusion and information alignment in AR scenes. This not only reduces visual fatigue due to technical problems, but also ensures that information is accurately aligned and displayed in the real-world environment. Reducing tracking delays can also facilitate real-time AR-based knowledge transfer in facility management. To resolve the alignment issues in AR-enabled facility management, computer vision, and point cloud technology, can be further combined with AR techniques to demonstrate marker-based or natural feature and model-based tracking. Ultra-wideband (UWB) can be adopted in the process of facility management to improve accuracy. Vision-based tracking can address drift issues and improve positioning accuracy by improving automatic orientation through the calibration of mobile device sensors. Furthermore, through automatic tracking technologies such as the internet of IoT and radio frequency identification (RFID) to dynamically update the positions of facility management staff. Pose estimation and overlap can be further improved by extracting homogeneous points from depth images and minimizing spatial distance through a combination of AR, computer vision, and machine learning techniques. to improve accuracy of tracking and registering.

7.2. knowledge-driven digital twins of facility management

The integration of BIM and AR is transforming facility management by harnessing the power of knowledge-driven digital twins. The combination in this field enables the visualization of models, interaction with operational data from BIM models via AR interfaces. Due to the increasing complexity of building facilities, the construction operations building information exchange (COBie) can transform open-source BIM data into AR data reducing manual data entry. COBie datasets can contain different types of information such as facility attributes, location, maintenance history, operational status, and stakeholders, further increasing the usability of BIM data.

BIM serves as a dynamic knowledge repository, combined with AI tools analyzing the integrated data, provide predictive maintenance and operational insights. This realizes dynamic synchronization, providing more intelligent decision support. The knowledge-driven digital twin of facility management evolves into a cyber-physical system (CPS) where real-time data flow between BIM and AR enables continuous updates and learning, forming a cycle of improvement for the knowledge base.

7.3. Normative and user-centric visualization interfaces

AR visualization interfaces are crucial in facility management, as a well-designed AR interface can improve the quality of the visualization and provide a better user experience. To facilitate comprehension and represent design intent, more normative language needs to be utilized. Future exploration is needed to develop specifications or guidelines for building facility management markup, such as standardized terminology in simplified English and universally recognized icons. This helps staff easily understand the knowledge transmitted to facilitate knowledge transfer. Ergonomics is a critical factor in AR-enabled facility management. AR applications need to be integrated with the cognitive abilities of facility management staff to determine appropriate forms of interaction. Designing interfaces based on ergonomic principles can reduce the cognitive load of the staff allowing them to focus more on learning and internalizing knowledge. There is also a need to consider the design of animation and touch interactions within the interface, such as the duration of animations [143]. In view of large numbers of steps involved in managing complex facilities, the window management of in AR interfaces should be further enhanced. For example, designing the windows to be touch-proof and creating different windows for different maintenance tasks, can increase the efficiency of facility operators and reduce operational errors. Undoubtedly, a human-centered approach is crucial when developing AR applications. The design and operation of AR should be optimized to maximize the user experience and meet comfort requirements. Inappropriate interactions and design of the user interface (UI) may result in neglected user experience and diminish the benefits of AR [144]. It is necessary to consider AR interaction modes to enhance the intuitiveness and engagement of knowledge transfer. Therefore, the ability of the interface to respond to changes in user scenarios and needs and realize adaptive knowledge transfer can improve the efficiency of learning and applications.

7.4. Trustworthy knowledge transfer in facility management

According to Section 4.3, the application of AR in facility management involves facility design and layout, assembly, monitoring, maintenance, and renovation, involving a large amount of explicit and implicit knowledge. A knowledge graph can be constructed to represent the entities and their relationships in the facility management process to create a standardized knowledge framework. Semantic tools such as ontology modeling can be integrated with AR creation platforms such as Unity and Unreal Engine, so that AR devices can access this knowledge graph and recommend related maintenance processes, precautions and other contents based on the specific operational environment and needs, achieving self-responsive knowledge services.

To ensure the credibility of knowledge, blockchain technology can be applied to the tracking and testing to promote trustworthy knowledge transfer in facility management. The application of AI technologies such as large language model ensures AR more powerful knowledge management and learning abilities. These technologies analyze the text information across the whole life cycle of facility management, and the structured historical knowledge to handle new problems. To ensure reliable AR knowledge transfer in facility management, it is crucial to implement authentication mechanisms allowing facility management staff to perform AR operations. This is conducive to alleviating security issues on inadequate or incorrect execution of facility management [108]. In addition, regarding security concerns, encryption measures should be performed in AR knowledge transfer procedures, and redundancy mechanisms should also be incorporated into AR systems so that critical knowledge transfer tasks can continue seamlessly in the event of system failures, thereby reducing potential downtime and associated risks, and ensuring rapid recovery of data and system functions in case of emergency.

7.5. Stakeholder collaborative knowledge management

AR technology can play a crucial role in facilities management by integrating knowledge during the lifecycle of facility operations. This enriches the amount of information in AR programs and facilitates communication, knowledge sharing and staff training among stakeholders [145]. This can be achieved through a combination of BIM, AR and cloud technologies, using cloud services to upload and synchronize the data from on-site AR devices providing decision support for maintenance operations through complex algorithms in the cloud. As facility structural design changes occur during the operational phase, the corresponding facility maintenance knowledge needs to be updated, and the AR-based cloud service system can facilitate these updates. Through establishing a sound authority management system, the data security and privacy of all stakeholders in the knowledge management process can be guaranteed. In order to better support the collaboration among cross-departmental stakeholders, standardized data interfaces and sharing protocols should be developed to enable stakeholders from different professional backgrounds to work together effectively, improving the coordination and overall efficiency of the facility management process. Finally, by means of regular training and knowledge updating, stakeholders can have access to operational skills and knowledge.. This helps ensure that all stakeholders can meet the evolving demands of facility management.

8. Contributions and implications

8.1. Theoretical contributions

From a theoretical perspective, this review synthesizes the fragmented knowledge and provides a comprehensive framework for understanding the potential of AR in different FM activities during the facility management lifecycle. This review extends knowledge transfer theory through exploring the transfer mechanism for facility management. This facilitates knowledge flows in complex facility management environments. Through reviewing AR technologies, relations of stakeholders, and influencing factors in knowledge transfer mechanisms, this research lays the foundation for future research to gain new insights into AR-enabled capture, share, and receive knowledge in complex environments. Another theoretical contribution is to extend the conceptual boundaries related research beyond the current focus on AR visualization and interaction technology development as a component of AR-enabled knowledge management strategies in the AEC industry. Finally, this study has proposed trends for future research including advanced AR tracking and registration, knowledge-driven digital twins, user-centric interfaces, trustworthy knowledge transfer, and collaborative knowledge management, which can deepen the understanding of leveraging AR to optimize knowledge flows, improve facility management outcomes, and advance the adoption of digital technologies in AEC industry.

8.2. Practical contributions

Practically, the main findings could gain valuable insights for stakeholders of facility management including facility managers, manufacturers, and policymakers to harness the potential of AR and collaborate in establishing knowledge management mechanism in FMS. The proposed challenges can facilitate decision-making on AR investment, development, and implementation in this field. Furthermore, the future trends drawn in this study provide guidelines for the sustainable facility management practice. Regarding policy implications, this research highlights the needs for standards and guidelines to support trustworthy knowledge transfer in facility management. Policies that promote advanced AR technologies and related training and education for facility management professionals can help bridge current skills gap and accelerate the adoption of these technologies in this field. Furthermore, standardized interoperability standards could be developed for AR in FM to facilitate in-depth integration with BIM and FMS, and this could further enhance knowledge-driven digital twins of facility management. Finally, security policies could be developed to clarify sharing permissions and ensure data privacy for AR applications protecting facility information and stakeholder data during the knowledge transfer process.

To conclude, by means of a comprehensive review of AR applications in facility management and highlighting the critical role of knowledge transfer, this study contributes to extending knowledge transfer theory in facility management, enriching research on AR applications in this field, and improving facility management processes and outcomes in the AEC industry.

9. Conclusions

This systematic literature review examined AR applications in facility management based on 107 documents. It has demonstrated that AR technology has made contributions to facility management over the past decade. This research conducted a comprehensive analysis of AR technology characteristics and its potential applications in various facility management activities. This research investigated the great potentials of AR-enabled knowledge transfer in facility management. Building upon the knowledge transfer mechanisms facilitated by AR, the related digital technologies, stakeholders as well as influencing factors in AR-enabled knowledge transfer in facility management have been examined in this research to expand the benefits of AR in this field.

Based on the findings of this review, it is suggested that researchers continue to explore and address the challenges related to technical, ergonomics, security and management to optimize the adoption of AR in facility management since it seems evident that AR technology with strengthened knowledge transfer capabilities have a promising future in the facility management field, which is conducive to the AEC industry. The outcomes of this review also demonstrate the opportunities for AR-enabled knowledge transfer and highlight the need for future research to address the existing challenges. By harnessing the power of AR in collaborative knowledge management and integrating it with knowledge-driven digital twin technologies, smart facility management can generate new possibilities and drive advancements in the AEC industry. Considering the rapid advancement in AR technology in this field, recent articles published beyond the selected publication sources and timeframe might not be covered in this research. In the future, this study would expand the literature selection to include more recent publications and utilize a more interdisciplinary approach to studying AR applications in facility management.

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Declaration of Competing Interest

This manuscript has not been published or presented elsewhere in part or entirety, and it not under consideration by another journal. There are no conflicts of interest to declare.