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Adoption of virtual and augmented reality in the architecture, engineering, construction, and facilities management (AEC-FM): mixed method analysis of trends, gaps, and solutions

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The Architecture, Engineering, Construction, and Facilities Management (AEC-FM) industry is undergoing a transformative phase with the integration of Augmented Reality (AR) and Virtual Reality (VR) technologies. This study investigates adoption trends, challenges, and future potential of AR/VR technologies within the AEC-FM using a mixed-methods approach, including surveys of over 200 industry experts (2018, 2020, and 2023) and thematic analysis of qualitative interviews. Findings reveal initial optimism in 2018 due to technological advancements, followed by tempered expectations as limitations, costs, and implementation challenges became apparent. While adoption has been led by commercial and institutional sectors, recent growth in the industrial sector reflects AR/VR's value in large-scale, complex projects. Furthermore, perceptions about AR/VR's future are consistent across age and gender. The study also highlights the industry's growing preference for outsourcing AR/VR-related tasks and the shift toward cost-effective solutions like Virtual Design and Construction (VDC) technologies reducing the need for internal AR/VR expertise.

KEYWORDS

virtual reality, augmented reality, virtual design and construction, building information modeling, industry trend

1 Introduction

The Architecture, Engineering, Construction, and Facilities Management (AEC-FM) industry has consistently pursued strategies to decrease project costs, increase productivity and quality, and accelerate project completion. Virtual Design and Construction (VDC) emerges as a transformative approach equipped with the capacity to achieve these goals, promising significant advances in the way projects are designed, managed, and executed

(Stojanovska-Georgievska et al., 2022; Zhang et al., 2023; Herrera et al., 2021). The integration of VDC has significantly transformed the AEC-FM industry in the last decade and has revolutionized project design, construction, and management by providing a more integrated and digital approach (Almeida Del Savio et al., 2022). This digital transformation has improved collaboration among stakeholders, improved communication, and better decision-making processes throughout the project lifecycle (Elyasi et al., 2023; Lavikka et al., 2018). Simulating construction processes in a virtual environment has enabled identifying and resolving potential issues before actual construction begins, resulting in smoother processes and faster project delivery (Tariq Shafiq and Afzal, 2020; Ahmed and Nassar, 2021). This process goes beyond the initial generation of 3D models; it serves a multifaceted role by improving communication, decision-making processes, and visualization capabilities (Yih Chong et al., 2016; Noghabaei et al., 2020) and facilitates advanced planning and problem-solving capabilities throughout the life cycle of a building. Using the detection of clashes and the simulation of various construction scenarios improves decision-making efficiency, leading to a more streamlined and effective project execution (Braa et al., 2023; Juan Francisco Fernández Rodríguez, 2023). It has advanced technical capabilities, improved knowledge management processes, facilitated the standardization of practices, and enhanced diversity management within the AEC-FM industry (Ali et al., 2017) while also significantly improving collaboration, financial management, 3D design, maintenance planning, quantity estimation, material classification, and various other aspects (Moum, 2010).

Despite its considerable benefits, VDC still has inherent shortcomings, such as providing a fully immersive and interactive visualization experience to users, limitations in real-time on-site communication, and constraints in user experience provided by existing software packages (Lee et al., 2020; Otarawanna et al., 2020; Du et al., 2018a; Noghabaei et al., 2019; Kim and Park, 2018). Furthermore, professionals in the AEC-FM sectors continue to rely on human expertise when implementing these models in practical scenarios. For example, while VDC teams are skilled in creating and interpreting 3D models, inconsistencies between the content of the models and 2D drawings persist, along with a lack of comprehensive information within the models (Ying et al., 2018). There is also a lack of comprehension of the 2D drawings. However, given the nature of the AEC-FM industry, many other trades and practitioners in the AEC-FM industry rely solely on 2D drawings and lack a full understanding of the modification or interaction with 3D models (Yalcinkaya and Singh, 2019). Miscommunication between teams and other industry practitioners stems from differences in knowledge and understanding of VDC tools and processes. While VDC experts possess comprehensive skills, including advanced functionalities and customization capabilities, allowing them to tackle complex issues effectively, practitioners/users typically have a more practical grasp of these tools, focusing on their application with possibly limited knowledge of advanced features, thus relying primarily on basic functionalities (Reza Hosseini et al., 2018). In addition, they often plan ideal implementation scenarios, possibly underestimating real-world issues such as on-site constraints, staff resistance, and infrastructure limitations. In contrast, practitioners/users face the practical difficulties of applying VDC models, such as integrating with existing systems, aligning models with project timelines, and training team members, reflecting a more hands-on understanding of these challenges (Mandujano et al., 2017; Yuxi et al., 2022). This dependency increases the risk of miscalculations and blueprint interpretation errors throughout the execution of projects (Balali et al., 2022). To address some of these limitations and create new opportunities for advancement in the AEC-FM industry, researchers have proposed the integration of new technologies such as Augmented Reality (AR) and Virtual Reality (VR). AR has been recognized for augmenting physical spaces with real and virtual information simultaneously, enabling intuitive user interactions without completely replacing the real environment. In contrast, VR is acknowledged for its ability to create fully immersive virtual environments that represent physical spaces, offering users a simulated experience that can be utilized for various purposes, including design exploration and simulations of user-built environments (Seyman Guray and Kismet, 2023; Pratama et al., 2022; Valentine Angulo et al., 2023; Saglio et al., 2023; Becerik-Gerber et al., 2022; Heydarian et al., 2015).

Integrating AR/VR with VDC has been increasingly recognized for its potential to revolutionize the AEC industry. Recent studies indicate that this integration enhances education, training, and operational efficiency by improving communication, visualization, immersion, and decision-making processes (Casini, 2022; Noghabaei et al., 2020; Wang et al., 2018; Garbett et al., 2021). Integrating these technologies can help individuals unfamiliar with VDC by enhancing data visualization, thus improving usability, interoperability, visualization, interaction, and overall user experience (Hajji et al., 2022; Alizadehsalehi et al., 2021). Furthermore, studies have demonstrated the effectiveness of integrating AR with VDC to detect construction defects and improve building submission processes (Dudhee and Vukovic, 2023; Schranz et al., 2021), while VR enhances communication among architects and engineers, leading to improved design decision-making processes (Amin, 2022).

Many industries have successfully implemented AR/VR technologies to enhance their operations. For instance, the healthcare sector has utilized VR for training medical professionals and surgical simulations (Yazid Bajuri et al., 2021; Moro et al., 2021; Murali et al., 2021; Sim Khor et al., 2016). Some companies use AR to help medical professionals locate veins for blood draws and injections (Turner, 2022). Educational institutions have adopted these technologies to create immersive and interactive learning experiences for students, enhancing their engagement and facilitating hands-on learning opportunities (Kumar Tiwari et al., 2023; Noah and Das, 2021; Huang et al., 2021). For instance, a medical school adopts VR technology to create a fully immersive anatomy curriculum. By utilizing VR headsets, medical schools can offer students immersive and interactive learning experiences. Through three-dimensional virtual environments, students can engage with precise human body models, dynamically improving their comprehension of anatomy (Fox et al., 2022; Myint Kyaw et al., 2019). They also have significantly impacted the manufacturing industry by improving training, design visualization, and collaboration. These advances contribute to improved processes and efficiency in manufacturing settings (Santos et al., 2021; Berg and Vance, 2017). For example, Fraga-Lamas et al. provided a comprehensive analysis of AR systems tailored for the shipbuilding industry. Their study delved into the application of AR technology in shipyards in the context of Industry 4.0, shedding light on how AR systems can enhance manufacturing processes in shipbuilding. Furthermore, the review drew parallels between advances in AR technology within the shipyard setting and its potential impact on manufacturing processes in the automotive sector (Fraga-Lamas et al., 2018). In the automotive industry, VR has been employed for vehicle design and prototyping (Čujan et al., 2020). Moreover, the retail industry has integrated AR technology to improve customer experiences and visualize products (Dacko, 2017). For example, some companies have integrated AR technology into their mobile apps, allowing customers to visualize how furniture would look in their homes before making a purchase (McLean and Wilson, 2019). Similarly, other retail companies offer an innovative shopping experience by allowing customers to try on glasses virtually from the street, using technology to accurately position the glasses on the user's nose (Marelli et al., 2022; Bonetti et al., 2018).

Despite evidence demonstrating the high efficacy of AR/VR technologies, their adoption within the AEC-FM industry has been relatively slower compared to other sectors (Noghabaei et al., 2020; Borja García de Soto et al., 2022). One major barrier is the perception of these technologies as expensive and immature, which raises concerns about the return on investment and the feasibility of implementation (Delgado et al., 2020a). The unique nature of work of the AEC-FM industry, with its many facets and challenges, contributes to the slow adoption of these technologies (Khan et al., 2021). The lack of comprehensive feasibility studies to assess the actual cost of implementation versus the impact on profit also poses a significant barrier (Noghabaei et al., 2020). Furthermore, the shortage of AEC-FM professionals trained in technologies such as VDC and AR/VR hinders collaborative working practices in the industry (Alizadehsalehi et al., 2021). Resistance to change, technical adoption challenges, inadequate government support, and lack of training and education on these technologies also contribute to the slow adoption of AR/VR technologies in the AEC-FM industry (Ediae and Enoma, 2018).

The purpose of this study is to investigate the recent trends and future direction of AR/VR technologies in the AEC-FM industry and to predict the growth of these technologies and their integration into different project phases in the near future by analyzing practitioners' perspectives. Additionally, it outlines the barriers that affect the adoption of AR/VR technologies in the AEC-FM industry. Through the survey questions, the authors established three main hypotheses and objectives: (1) age is directly related to the adoption and utilization of AR/VR technologies; (2) commercial and institutional projects are expected to utilize AR/VR more extensively than other sectors within the AEC-FM industries; and (3) detecting the limitations of the utilization of these technologies. The authors evaluate their hypotheses through a series of comprehensive surveys. In addition, the goal of the paper is to understand the potential cost and time savings, as well as identify opportunities for AR/VR advancements. These advancements aim to enhance communication and visualization among various stakeholders.

The article contains a Review of the Literature section covering AR/VR studies and how they impact the AEC-FM industry. The Methodology and Data Collection section covers how the data was collected, lays out the main objectives, and outlines the process of formulating and distributing the questionnaire to academic and industry experts. More than 200 industry experts in the AEC-FM industry have provided their feedback and insights on the growth and utilization of AR/VR technologies within the AEC-FM industry. The questionnaire was conducted in 2018 and 2020, with the third round taking place in 2023. With this being the third round of survey distribution, the group expanded by inviting a few surveyors back for interviews to dive deeper into the topic. The 2018 survey was conducted before the COVID-19 pandemic, at a time when there were no restrictions or federal orders in place. The data from this survey serve as a baseline for understanding AR/VR adoption prior to any significant disruptions. In contrast, the 2020 survey was conducted during the initial surge of the COVID-19 pandemic. By mid-March 2020, the US federal government had declared a national emergency (FEMA, 2020), and social distancing guidelines were enforced, severely disrupting industries, including AEC-FM. The data from this survey reflect the uncertainty and operational disruptions caused by the pandemic. By 2023, most federal and state COVID-19 restrictions had been lifted, and industries were adapting to a post-pandemic environment. The US federal public health emergency for COVID-19 officially ended in May 2023 (U.S.Department of Health and Human Services, 2025). The Results and Discussion sections, which analyze the survey results, provide a detailed analysis of the survey findings, highlighting the evolving trends in the adoption and perception of AR/VR technologies within the AEC-FM industry from 2018 through 2023. They also provide insights into the industry's vision for AR/VR technologies and identify the main opportunities for the AEC-FM industry. Finally, the Conclusion section summarizes the paper and highlights limitations and future works within the study.

This study contributes to the body of knowledge in the following areas.

- Provides empirical evidence on adoption rates, perceptions, and applications of AR/VR technologies. It bridges the gap between theoretical potential and practical implementation, offering a longitudinal view of the evolution of these technologies in the AEC-FM industry.
- Identifies and discusses the main barriers hindering the widespread adoption of AR/VR technologies in the AEC-FM industry; understanding these barriers is crucial for developing strategies to overcome them and facilitate the broader integration of AR/VR technologies.
- Forecasts the growth potential of AR/VR technologies and how they might be integrated into different project phases in the near future. This foresight can guide stakeholders in strategic planning and investment decisions
- Provides insight for practitioners regarding trends in the integration of AR/VR technologies in the AEC-FM industry. These insights are instrumental in helping practitioners navigate the evolving landscape of AR/VR applications, enabling them to leverage these technologies more effectively.
- Provides a foundation for further research and development efforts aimed at harnessing the full potential of these transformative technologies in the AEC-FM industry.

2 Literature review

This section delves into the exploration of applications, recent trends, challenges, and the transformative potential of AR/VR technologies within the AEC-FM industry. In addition, it explored the significant impact of the COVID-19 pandemic on the adoption and integration of these technologies.

2.1 Applications and benefits of AR/VR in the AEC-FM industry

AR/VR technologies have the potential to bring several benefits to the AEC-FM industry due to their numerous applications and their ability to provide a realistic and reliable first-person interface (Hilfert and König, 2016). The perceptions of the stakeholders of the construction projects and the progress made toward project completion will be impacted by AR/VR technologies. Implementing these technologies will enhance the quality and effectiveness of comprehensive project design regarding scheduling, planning, and project completion (Abubakar Badamasi et al., 2022). Furthermore, VR allows the examination and simulation of designs in a three-dimensional interactive environment, aiding in understanding design intentions and project feasibility and identifying modifications before construction begins (Al-Khiami et al., 2023). According to Sacks et al., VR technology will benefit designers in understanding the impact of projects on the safety system (Sacks et al., 2015). Behzadi affirmed that the adoption of virtual technology in training could significantly enhance decision-making processes, leading to more informed, healthier, and safer outcomes (Behzadi, 2016). VR enhances design communication among professionals, allowing for the presentation of multimedia elements and improving stakeholder participation, leading to cost reductions and quality improvement in the project's lifecycle (Durmuş and Günaydın, 2023).

VR creates an environment in which people can see the building construction process and better visualize the outcome of the process while physically watching it along the way. Han et al. proposed a framework that semi-automatically identifies occluded objects (objects that are hidden behind others) in 3D construction models within a VR environment, a method particularly effective in MEPF (Mechanical, Electrical, Plumbing, and Fire) components. The study outlines a two-step solution: utilizing laser scanners for point cloud creation to make occluded objects more visible and enabling VR developers to implement real-time revealing or highlighting functions. The study demonstrated over 90% effectiveness in detecting hidden objects and a 75% accuracy rate (Han et al., 2021).

2.2 Integration of AR/VR with building information modeling (BIM)

In recent years, AR/VR technologies have demonstrated high levels of performance and quality in terms of their assistance with construction activities. AR/VR technologies significantly enhance Building Information Modeling (BIM) in the AEC-FM industry by offering immersive visualization and simulation of BIM data. These technologies foster collaboration through 3D virtual environments, improving decision-making and coordination among stakeholders. They also provide vital tools for on-site monitoring, safety training, and risk prevention, thus increasing site safety. Integrating AR and VR with BIM enhances project management efficiency and facilitates better building operation and maintenance, while also serving as innovative educational tools for training and skill development (Schiavi et al., 2022). Rework is a common result of changes in design and construction, which typically has a high impact on the performance of a project (Love and Smith, 2018). Panya et al. examined the integration of BIM with AR/VR technologies to reduce rework in design and construction. They identified the limitations of BIM in change management and proposed an innovative methodology that combines BIM with VR and AR technologies to improve project performance by mitigating rework. The process of re-designing, maintaining the flow of information, and delivery is critical to allowing re-design to happen effectively (Stephen Panya et al., 2023).

Modular buildings are becoming increasingly popular due to government policies and international incentives, allowing more automation and productivity (Agenda, 2016). The transition to modular design significantly impacts the factors of indoor comfort in volumetric modules, including humidity, temperature, natural ventilation, and air pollutant transport, which have a major effect on human health and wellbeing. Gan et al. explored the integration of BIM and Computational Fluid Dynamics (CFD) with VR for modular construction. This combination addresses indoor comfort by visualizing airflow and the wind environment, improving design, operation, and maintenance efficiency. The study demonstrated how the versatility of BIM and the simulation capabilities of CFD, when combined with VR, can enhance the understanding of non-professional stakeholders of complex data, leading to better aerodynamic design and thermal comfort in modular buildings (Gan et al., 2022).

Natephra et al. focused on integrating BIM and VR to enhance indoor lighting design in construction. By leveraging gaming engine technologies, their novel approach allows for the creation of 3D environments to experiment with various lighting designs, addressing the critical role of lighting in both aesthetics and functionality. The study revealed that the Building Lighting Design Framework (BLDF) enhances the ability of design stakeholders to accurately assess and improve lighting conditions, resulting in greater satisfaction in lighting design and energy efficiency for future occupants (Natephra et al., 2017). Davidson et al. demonstrated a proof of concept for integrating VR with BIM to streamline the creation of bill of quantities during the design phase. This integration addresses challenges such as document complexity and the decline in the traditional bill of quantities usage due to modern procurement systems. By incorporating VR and BIM, this approach allows the participation of the client in design decisions, potentially offering time and cost savings while reinvigorating the role of the bill of quantities in construction projects (Davidson et al., 2020).

The AEC-FM industry leverages BIM for design and the Internet of Things (IoT) for operation and maintenance, enhancing cost-effectiveness, productivity, and safety while ensuring timely project delivery. The integration of VDC and digital twin with AR/VR technologies offers the unique benefit of real-time monitoring of the current status and predicting the future of any physical structure at any level of work. This results in substantial cost savings in the AEC-FM industry, particularly in the design, construction, operation, and maintenance phases (Nabizadeh Rafsanjani and Nabizadeh, 2023). Kwiateka et al. evaluated the impacts and applications of AR in construction, particularly focusing on assembly tasks. The study showed how AR improves construction productivity, reduces rework, and improves the communication of design intent, using modular construction and 3D BIM applications. The study noted that the implementation of 3D BIM can lead to increases in productivity of up to 30% by fostering collaboration and reducing requests for information and change orders (Kwiatek et al., 2019).

Delays and cost overruns are major challenges in the construction industry that can be controlled through effective risk management. Properly managing risks before project completion helps to control these issues, ensuring projects are delivered on time and within budget (Willems and Vanhoucke, 2015). The study conducted by Alirezaei et al. presented an example in which the use of BIM and AR significantly increased project efficiency and early risk detection, demonstrating the potential of these technologies to advance construction project management (Alirezaei et al., 2022). Du et al. introduced the BIM-VR Real-time Synchronization (BVRS) system, a novel protocol designed to address the significant challenges of integrating VR within the AEC-FM industry. The study identified key issues, time-consuming conversion processes, lack of real-time data synchronization, and maintenance of data integrity, and proposed BVRS as a solution. Utilizing BIM metadata and a cloud-based workflow, BVRS ensures real-time updates and synchronization of design changes in VR environments, offering zero latency and enhancing informed decision-making among stakeholders (Du et al., 2018b).

2.3 Safety and risk management using AR/VR technologies

Construction safety has become a significant topic due to an increasing number of injuries and casualties each year (Salinas et al., 2022). Worldwide, construction-related fatalities amount to 60,000 annually, averaging one death every 9 minutes (Lingard, 2013). Although there has been a 37% reduction since 2006, the construction industry continues to have the highest fatality rate among all industries in the United States. This sector is responsible for more than 20% occupational deaths nationwide (Jeelani et al., 2020). These injuries have tremendously increased workers' compensation, company lawsuits, and disability rates. Safe and efficient training is created through the utilization of VR technology for training, which enables workers to experience hazardous situations without suffering any form of injury (Khan et al., 2021; Xu and Zheng, 2020). Jeelani et al. focused on the critical need for enhanced safety training within the construction industry to reduce injuries and fatalities. Traditional training methods have proven to be insufficient due to a lack of personalization and realism. They proposed the adoption of VR-based safety training, which offers realistic and immersive experiences tailored to specific trades, significantly improving hazard recognition, engagement, and skill development. The findings demonstrated a notable enhancement in safety performance, with hazard recognition improved by 39% and hazard management performance increasing by 44% (Jeelani et al., 2020). Rokooei et al. focused on the use of VR for enhancing safety training in the construction industry, addressing the persistent issue of high injury and fatality rates. Through the study, VR training programs, specifically designed for roof workers, were developed using an agile methodology, allowing for adaptable and iterative improvements. The results of the study showed that VR training positively impacts worker safety, with the potential to significantly lower the rates of injury and death if implemented on a larger scale (Rokooei et al., 2023).

Salinas et al. analyzed the evaluation methods of Extended Reality (XR), which encompasses VR, AR, and Mixed Reality (MR) technologies, in construction safety. The study indicated the role of XR in creating virtual interactive environments for hazard identification and safety training, enhancing risk management in construction projects. By reviewing both quantitative and qualitative studies, the paper highlights XR's contribution to immersive training environments, proper equipment use, and effective safety planning. The utilization of VR, AR, and MR technologies not only engages users emotionally but also offers innovative solutions to improve safety and streamline project timelines in the construction industry (Salinas et al., 2022). Zhao et al. emphasized XR's contribution to reducing fatalities and delays through improved safety practices and effective management. Implementing XR in real-time visualization and interaction within training programs shows promise for progress planning, quality control, hazard identification, and safety education (Zhao et al., 2023). According to Alizadehsalehi et al., the integration of BIM and XR significantly enhances decision-making throughout a project's lifecycle in the AEC-FM industry. Having a virtual environment allows users to create scenarios in which they are not limited to large risk factors, including injuries, machinery, and deaths. XR allows the BIM platform to become more realistic considering the logistics of scaling, movement, and physics when conducting the data (Alizadehsalehi et al., 2020).

Dobrucali et al. evaluated the impact of emerging technologies like AR, VR, and Artificial Intelligence (AI) on construction safety performance. Their study investigated how these technologies, including wearable devices and machine learning, influence safety through enhanced planning, training, and risk management. BIM, robotics and automation, AI, and wearable devices were detected as the most significant technologies in enhancing safety performance (Dobrucali et al., 2022). By leveraging BIM models within AR and VR environments, amos-Hurtado et al. illustrated how these technologies can facilitate intuitive and cost-effective safety inspections, thereby potentially reducing accidents on construction sites. The study concluded that AR significantly benefits construction safety by facilitating more efficient and reliable inspection processes, thus contributing to the goal of zero accidents on construction sites (Ramos-Hurtado et al., 2022).

Communication plays an important role in identifying hazards in the construction workforce. The current state of communication, with methods such as speaking on the phone, video chatting, and waiting to speak to someone in person, lack access to urgent information (Issa, 2015). Dai et al. examined the potential of MR to enhance safety communication on construction sites. The study presented an assessment of the feasibility of MR through trial-and-error and industry feedback, highlighting MR's benefits, such as improved collaboration and safety awareness. MR combines real and virtual environments, allowing for the coexistence and interaction of physical and digital objects, which could significantly improve workplace safety and prevent accidents. The analysis results showed that MR's application in construction could lead to better risk communication and reduce fatalities, marking a novel exploration of MR in the workforce (Dai et al., 2021).

2.4 Educational uses of AR/VR in the AEC-FM industry

Tan et al. reviewed different studies on using AR and VR in education and training within the AEC-FM industry. Their study identifies how AR/VR can make learning more engaging, but also acknowledges the contradictory findings of the studies and the limitations of current AR/VR systems in educational contexts. Using meta-analysis and Review Manager 5.4 for data synthesis, the study concludes that AR/VR has not yet significantly impacted education and training in the AEC-FM industry, but has potential for future advancements (Tan et al., 2022). The integration of BIM and VR technologies can enhance workflow efficiency and foster a shared understanding, equipping students in architecture and engineering programs with the skills to lead in the AEC-FM industry. Alizadehsalehi et al. showed the significance of BIM-to-VR technology in facilitating better communication and comprehension of complex projects by analyzing learning characteristics such as learnability, interoperability, visualization, real-world interaction, creativity, motivation, and comfort (Alizadehsalehi et al., 2021). In another study, Alizadehsalehi et al. explored the use of VR as an educational tool in the design and construction disciplines within the AEC-FM sectors. The study emphasized the ability of VR to enhance student learning by offering immersive and interactive experiences that allow a deeper understanding of spatial relationships, construction processes, and design complexities (Alizadehsalehi et al., 2019).

2.5 Challenges and barriers to AR/VR adoption in the AEC-FM industry

Several research studies have identified the drivers of AR/VR in the construction industry. These drivers include improved project knowledge, reduced overall project costs, low-cost and realistic training scenarios, reduced damage and development costs, enhanced user experience, improved communication and collaboration, enhanced project performance, risk identification, digitalization, safety planning, and improved hazard identification skills (Abubakar Badamasi et al., 2022; Emmanuel Oke et al., 2023; Maqsoom et al., 2023). Alongside the identified drivers of AR/VR, many researchers have also discovered the various barriers to VR adoption in the construction industry. These barriers include the high cost of initial investment, lack of knowledge, skills and expertise, lack of training on VR application, limited demand, resistance to change, and risks to work safety (Al-Khiami et al., 2023; Maqsoom et al., 2023; Mastrolembo Ventura et al., 2022; Olushola Afolabi et al., 2022). Cultural factors also significantly influence the adoption of AR/VR in the AEC-FM sector. The conservative nature of the industry and the existing adversarial culture can create resistance to change, making it difficult for organizations to embrace innovative technologies (Borja García de Soto et al., 2022). Moreover, the lack of training and familiarity with AR/VR tools among professionals can hinder their willingness to adopt these technologies (Tan et al., 2022) Davila Delgado et al. investigated the research gaps of AR and VR in the AEC-FM industry. After involving 54 qualified operatives from industry and academia organizations, their research identified six main applications for AR and VR: design support, design review, stakeholder engagement, operations and management support, construction support, and training. Despite a high participation rate among participants, with a significant portion advanced in the use of AR and VR, the study concluded that these technologies are not yet fully ready for widespread adoption in the construction industry (Delgado et al., 2020b).

2.6 Advanced applications of AR/VR in specialized fields

Tarek and Marzouk emphasized AR's potential in overlaying virtual objects onto the real world, using technologies like Microsoft HoloLens to improve visualization and address pipeline location accuracy. By integrating AR with BIM and cloud computing, the study proposed a novel approach to automate asset tracking of the infrastructure, improve information retrieval, and bridge the gap between the digital and real world, suggesting a mobile application for efficient facility management (Tarek and Mohamed, 2022). Blanco-Novoa et al. examined the implementation of Industry 4.0 principles in shipbuilding, focusing on Industrial Augmented Reality (IAR) technology. IAR is utilized to enhance efficiency and performance in complex shipbuilding processes through interactive and informative interfaces. These interfaces assist shipyard operators by providing task-related information and interaction with their environment, highlighting the importance of AR in automating and optimizing shipbuilding operations in line with Industry 4.0 standards. They explored the modernization of shipyards using IAR, evaluating the performance of various IAR devices (smartphones, tablets, and smart eyewear) and AR software tools (ARToolKit and Vuforia). The study, conducted at Navantia Shipyards, assessed the effectiveness of IAR in shipbuilding and smart manufacturing, highlighting the potential of IAR in Industry 4.0 shipyards but noting the need for improvements, particularly in low-light situations and market-based solutions (Blanco-Novoa et al., 2018).

Carbonari et al. proposed a mixed reality-based platform called ODAVS (On-site Design Analysis and Verification Service) for on-site assessment and renovation of existing residential building stock. By integrating BIM with MR, ODAVS enhances sustainable construction management by enabling clear visualization of renovations, improving team understanding of every project stage, and timely conflict identification. The service offers a virtual interface for on-site workers to visualize projects, record audio feedback, and solve problems efficiently, such as geometric clashes and component misplacement. Despite initial challenges with worker adaptation to MR technology, training improved efficiency, communication, and project management in renovation processes (Carbonari et al., 2022). Vermandere et al. presented a study on a two-step process for aligning MR devices with existing building data, aiming to enhance the efficiency and precision of architectural and construction applications. The initial phase involves coarse alignment to establish a fundamental spatial relationship between the MR device and the building data. The subsequent refined alignment process ensures a precise overlay of virtual and physical elements. This methodology significantly improves the integration of digital and physical information, facilitating better decision-making in design, construction, and maintenance by leveraging accurate MR overlays (Vermandere et al., 2022). Han and Leite introduced a Generic Extended Reality (GenXR) model to streamline the BIM-to-Extended Reality development process in the AEC-FM industry. This model aims to reduce repetitive tasks in traditional BIM-to-XR conversions, saving significant development time. By developing and validating six XR prototypes in two case studies, the research demonstrates the efficacy of the GenXR model in supporting typical XR functionalities and significantly decreasing the development time from 63. 8% to 66. 7% (Han and Leite, 2022).

Gomez-Jauregui et al. proposed a novel approach to quantitatively evaluate the discrepancies between virtual and real objects in Mobile Augmented Reality (MAR) applications, focusing on the AEC-FM industry. The method addresses the challenge of accurately overlaying virtual models onto real-world images, identifying key sources of error in tracking and image projection. The study presented the Drift-Vibration-Threshold (DVT) function as a new approach to improve the precision of virtual overlays. Through a series of tests and analyzes, they demonstrated the effectiveness of this methodology in reducing overlay discrepancies, contributing significantly to the advancement of MAR applications in the AEC-FM industry (Gomez-Jauregui et al., 2019). Boton explored the use of Immersive Virtual Reality (IVR) to support constructability analysis meetings in construction projects through collaborative BIM and 4D simulation. The study demonstrated how IVR can enhance the understanding and communication of complex construction sequences and potential issues among project stakeholders. By integrating BIM data with IVR, the research found that project teams can more effectively visualize, analyze, and discuss construct-ability issues in a collaborative setting, leading to improved decision-making and project outcomes (Boton, 2018).

Advanced AR-based safety solutions represent another area where augmented reality is increasingly being utilized in the broader construction industry. The capabilities of AR technology to overlay digital information within users' field of view have created opportunities for it to function as a real-time safety system. This feature allows for the delivery of multimodal warnings to workers through AR interfaces that can enhance workers' reaction times and situational awareness (Sabeti et al., 2024a). For instance, Sabeti et al. proposed an AI-enabled AR technology designed to deliver predictive multimodal warnings to highway construction workers (Sabeti et al., 2021). This technology utilizes AI in its backend to predict vehicle intrusions in the work zone ahead of time, and deliver multimodal warnings to workers through the customized AR user interface. The authors investigated the performance and usability of the real-time communication of the system and concluded that the technology has the potential to improve workers' safety in highway construction zones (Sabeti et al., 2022; Sabeti et al., 2024b).

2.7 AR/VR in facility management

Facility management focuses on the maintenance, improvement, and adaptation to ensure the optimal performance of buildings. It involves a wide range of multidisciplinary activities to preserve the built environment's functionality. Sampaio et al. demonstrated how integrating BIM, IoT, and AI significantly boosts facility management efficiency, especially in places like medical buildings that see constant operation. This integration enhances real-time data accessibility, predictive maintenance, and intelligent management, promising improved operational effectiveness in facility management (Pedral Sampaio et al., 2023).

Facility managers face challenges in managing the complex systems associated with larger buildings, as these systems are intricate and require detailed control. Alijani Mamaghani and Noorzaei proposed a framework to enhance the operation and maintenance of mechanical facilities in large buildings and proposed a two-phase method for implementing BIM and AR. Phase one involves collecting data during the preconstruction of a commercial building and integrating mechanical facility documents into a server for facility managers. Phase two then leverages the AR platform to provide comprehensive operational and maintenance oversight. With this approach, Mamaghani and Noorzaei demonstrated a significant reduction in machinery repair times, demonstrating the effectiveness of the approach and advocating for BIM and AR as new standards in facility management (Alijani Mam et al., 2023).

El Ammari et al. evaluated the application of MR to enhance facility management by improving collaboration and efficiency in field and office operations. They proposed their own framework that integrates multisource facility information, BIM models, and feature-based tracking within a mixed reality. The approach allows field workers to use AR applications for on-site work while managers utilize Immersive Augmented Virtuality (IAV) to supervise sites remotely. Their framework significantly improves data collection, visualization, and remote collaboration, leading to an 85% reduction in time and a 62% decrease in errors (El Ammari and Amin, 2019).

2.8 Impact of COVID-19 pandemic

The COVID-19 pandemic has in fact significantly impacted the AEC-FM industry, leading to both challenges and opportunities in the adoption of AR/VR technologies, accelerating the adoption and integration of advanced technologies such as AR/VR and MR (Juan et al., 2022). This acceleration is a direct consequence of the digital transformation required by the pandemic-induced restrictions on physical interactions, thereby fostering the maturation of these technologies within the AEC-FM industry. The shift towards digital platforms and tools has been vital in maintaining operations, facilitating remote work, and ensuring the continuity of essential services, highlighting the critical role of AR and VR in navigating the challenges posed by the pandemic (Dhar et al., 2021; Piyathanavong et al., 2022). With the pandemic, it is predicted that the use of AR/VR technologies within businesses worldwide will experience a significant increase, expanding from \$829 million in 2018 to an estimated \$4.26 billion by 2023. This remarkable growth in the AR/VR market is largely driven by a higher preference for social distancing measures and the need to accommodate remote work practices (Balali et al., 2022). Although the pandemic has had short and mid-term negative impacts on the AEC-FM industry, it has also created long-term opportunities for development and transformation (Bouhmoud et al., 2022). The surge in demand for essential healthcare equipment and advanced information technologies due to the pandemic has further emphasized the importance of technologies such as AR and VR in various industries, including AEC-FM (Javaid et al., 2020). Furthermore, the pandemic has led to the adoption of innovative strategies to mitigate disruptions in the supply chain, highlighting the importance of technologies such as AR and VR in ensuring operational continuity (Syed Abdul Rehman Khan et al., 2022). In addition, the pandemic has led to a shift towards e-learning and remote education, with AR and VR technologies emerging as key enablers of this transition (Raihan Manzoor et al., 2021). These technologies have been instrumental in enhancing learner motivation and engagement by providing immersive and interactive learning experiences, even in fields as critical as medical education, where AR has been identified as a valuable tool for improving learning outcomes in the absence of face-to-face interactions (Dhar et al., 2021).

3 Methodology and data collection

This study leveraged a mixed-methods approach to examine the adoption and utilization of AR/VR technologies within the AEC-FM industry. Through a fusion of quantitative (surveys) and qualitative (interviews) data, our goal was to capture trends, patterns, and insights of technology adoption in the AEC-FM industry. This statistical approach allowed us to establish a solid foundation of empirical evidence on the subject. Furthermore, by conducting qualitative interviews, we delved deeper into the personal experiences, motivations, challenges, and perceptions that underlie their decisions to adopt or resist new technologies. This mixed-methods approach enriched our research, giving us a more holistic understanding of the dynamics at play in the process of technology integration and acceptance.

The authors designed the questionnaire in a way to analyze the growth of AR/VR technologies by collecting responses at different time periods. The survey results allowed the authors to identify industry trends from 2018 to 2023, provide insights into the industry's vision for AR/VR technologies, and identify the main opportunities of the AEC-FM industry.

3.1 Quantitative methodology

The quantitative surveys included a total of 30 questions designed to target a variety of AEC-FM professionals, including architects, engineers, general contractors, subcontractors, construction managers, owners, consultants, public agencies, and academics. The survey questions were categorized into five main categories, including (1) Demographic background, (2) Company profile, (3) VDC knowledge and experience, (4) AR/VR and Mixed reality knowledge and experience, and (5) Vision for AR/VR adoption within the AEC-FM industry. The details of the data collected and the objectives of each category are shown in Table 1.

Before distribution, the questionnaire was reviewed by three industry VDC specialists and three researchers in the field of construction engineering and management, ensuring that the questions were clear and not misleading. The review resulted in an improvement in the form and choices provided to the participants on several questions. It is important to note that the categories and question types remained consistent across different years of data collection, allowing us to conduct a trend analysis.

The surveys were administered using the Qualtrics survey tool, which also included the consent form followed by the survey questions. Incomplete surveys were excluded since these responses could not be reliably credited with achieving research objectives.

The first category of the survey aims to gather general information about the respondents, including age, gender, geographic location, occupation, and professional experience. The second category requires respondents to answer a series of questions regarding their companies, focusing on aspects such as company size and types and sizes of projects (for example, residential, commercial, institutional, etc.). The third category examines how respondents with different levels of VDC knowledge perceive the future of AR/VR in their field. In the next two categories, the survey results assess the utilization of AR/VR in the AEC-FM industry and explore future opportunities for AR/VR applications. First, the survey asked about the types of AR/VR devices used by respondents and the number of AR/VR experts employed in their companies. These questions enabled the authors to assess the respondents' familiarity with AR/VR tools and their company's efforts to integrate these technologies into current and future projects. This category also assesses visions for cost and time savings through the integration of AR/VR technologies in their projects. In the last category, respondents were asked to share their insights regarding the future integration of AR/VR technologies within the AEC-FM industry. The design of these questions aims to highlight the potential of AR/VR for future development. For instance, respondents were asked to identify sectors (such as education and healthcare facilities) and project sizes that can best leverage AR/VR technologies.

3.2 Participants

The surveys were distributed directly to professionals within the AEC-FM industry and also through the Construction Management Association of America (CMAA). The CMAA was selected for its diverse membership, comprising 16,000 members in the AEC-FM industry from the public and private sectors across the United States. CMAA includes a wide range of stakeholders in the AEC-FM industry, such as owners, architects, designers, general contractors, and construction managers, providing a broad perspective on industry challenges and trends. To assess the survey's effective significance, the total number of respondents across different surveys is provided: 72 in 2018, 139 in 2020, and 75 in 2023. Table 2 represents the distribution of respondents from industry and academic participants. The data is categorized into industry and academic, given the study's main focus of examining trends in the adoption of AR/VR technologies within the AEC-FM industry. The insights of academic participants are also employed to support and strengthen our findings and to understand the vision of these technologies in the future.

TABLE 1 Description of survey categories, collected data, and objectives.

Category name	Collected data	Objectives
Demographic background	Age, gender, location, occupation, and professional experience	- Determine how respondents in different positions foresee the future of AR/VR
		- Determine if Participants' age is related to the AR/VR adoption
Company profile	Companies size, project types, project sizes, and years of experience	- Assess how companies with different sizes envision the future of AR/VR
		- Assess which sectors adopt and benefit the most from such technologies
VDC knowledge and experience	VDC experience and used VDC tools	- Evaluate how respondents with different VDC knowledge envision the future of AR/VR
AR/VR/Mixed reality knowledge & experience	AR/VR experience and used AR/VR tools	- Identify the current industry trends
		- Assess the companies' effort to integrate such technologies in ongoing and future projects
		- Evaluate savings in project's cost and time that can be achieved based on the practitioners' experiences
Vision for AR/VR adoption	Trends for the future adoption in the AEC-FM industry	- Utilization of AR/VR technologies in the AEC-FM industry

TABLE 2 Distribution of respondents across surveys.

Category	2018	2020	2023
Total	72	139	75
Industry	52	118	66
Academic	20	21	9

The initial phase of our research involved compiling a list of companies and industries, drawing from databases established in previous surveys. In an effort to enrich the participant pool, additional individuals were identified and added. Subsequently, we reached out to participants through email and LinkedIn messages as our main channels of communication. Initially, our approach was to distribute the surveys on a global scale, aiming to gather information from participants in various countries and regions. This worldwide distribution was motivated by the intention to capture a diverse range of perspectives and experiences within the industry. However, as the data collection process progressed, we found that the response rate of participants outside of the United States was significantly lower than anticipated. Therefore, we decided to limit the focus of our survey exclusively to North America. By focusing our efforts on North American participants, we aimed to ensure a more focused and representative sample that could inform our research objectives effectively. To protect the privacy of the participants, the surveys did not ask for personal information such as name or company name.

To detect whether respondents participated in previous rounds of this survey, distributed in 2018 and 2020, the authors added a question asking participants if they had participated previously. The study did not include participants from the same company or institution.

3.3 Qualitative methodology

In this study, our goal for conducting qualitative data collection was to obtain a deeper and more comprehensive understanding of the factors and strategies that are used within the AEC-FM industry in integrating AR/VR technologies and solutions across different project sizes and phases—such as design, construction, and operations. We aim to supplement the quantitative survey findings with direct, practical, and hands-on information that is collected from industry experts. For this reason, we created a group of eight experienced professionals and developed an interview-focused approach to collect qualitative data.

Participants in this study were selected based on their experience and expertise in the AEC-FM industry. We prioritized representatives from medium and large-scale organizations, as they are more likely to offer AR/VR solutions in their portfolios. The roles considered for participation included VDC Directors, VDC Engineers, and Product Managers. Our aim in including these diverse roles was to gather perspectives on the limitations, incentives, and practicality of AR/VR solutions and technologies across the AEC-FM business ecosystem from different points of view.

To develop the qualitative approach, we first designed the interview protocol and the questions. Our aim in formulating these questions was to explore the integration challenges and strategic visions of AR/VR technology across different phases and stages of

TABLE 3 Distribution of respondents across interviews.

#	Topic	Summary of questions/Topics
1	Professional role and daily activities	- Description of the interviewee's role and how their typical day involves AR/VR technology
2	Project-Specific AR/VR integration	- Walk-through of specific projects where AR/VR has been implemented
3	Evolution of AR/VR in the organization	- How the application of AR/VR technology has progressed within the company
4	Maturity of AR vs. VR	- Evaluating the developmental stages and integration levels of AR compared to VR
5	Vision on AR/VR	- Colleagues' perspectives on the future of AR/VR technology
6	Client demographics	- Differences in AR/VR usage and challenges faced when working with federal vs. private sector clients
7	Client perception and adoption	- How clients view and are inclined to adopt AR/VR technologies
8	Financial dynamics of AR/VR projects	- Discussion about funding aspects such as company overhead, R&D budgets and client investment
9	Demand and applications	- Types of AR/VR applications clients want and the demand for including AR/VR in projects
10	Development process	- Structure of development for AR/VR and the related challenges
11	Business Impact	- Impact of AR/VR on business processes, particularly in presentations and pitches
12	Previous project challenges	- Issues and challenges encountered in previous AR/VR projects
13	Future opportunities and trends	- Potential future opportunities and the direction of AR/VR in the industry
14	Company vision for AR/VR	- The company's vision and strategy for the future use and expansion of AR/VR
15	Ideal usage of AR/VR	- A vision of the ideal utilization of AR/VR within the company

the AEC-FM industry. We focus on current assimilation strategies, technological challenges, future potentials, and the overall vision for the adoption and implementation of technology in the industry from the perspectives of selected experts. In addition, the development of the interview protocol was informed by the responses to the survey conducted. We strategically identified areas that were underexplored in the survey and strategies questions that can augment the collected quantitative survey findings. Table 3 provides an overview of the questions and topics explored during the interviews.

In this study, we used thematic analysis to interpret the qualitative data collected from the interviews. This method is widely used in qualitative research in different domains and is valued for its versatility and ability to extract in-depth insights from qualitative information (Pinti et al., 2022; Samad et al., 2018). Thematic analysis usually begins by generating codes to organize key aspects of the data. Each code is designed in such a way that it represents key semantic information of the communicated content. The codes are then grouped into broader themes. These themes are essential to uncover important patterns related to the research questions. After the initial themes are generated, they often undergo a review and refinement process with the aim of ensuring an accurate reflection of the research questions in the adopted themes (Castleberry and Nolen, 2018; Kiger and Varpio, 2020).

To implement the thematic analysis strategy adopted in this study, we first reviewed the interview transcripts from our Zoom sessions with the participants, which were transcribed using the Rev software transcription service. After an initial review, we identified and highlighted the content of the transcripts that are relevant to our research objectives and assigned different codes to these sections. Each code was designed to capture the primary semantic context of the highlighted phrases as they relate to the study objectives.

Once we compiled a comprehensive inventory of pertinent content and generated codes, the research team collaboratively reached a consensus on the final codes and created a homogeneous inventory of all codes. Based on the generated codes, we developed higher-level themes that encapsulated one or more of the codes. After extracting the initial codes from the interviews, the team reviewed each transcript again to ensure that the newly developed themes effectively supported the coded content, highlighting where the identified codes appeared in the discussions. We paid close attention to the context in which each code was generated, as well as to the detailed narratives provided by the interviewees.

3.4 Statistical methods

The main software used to perform the statistical analyzes were Minitab and Microsoft Excel. Data from survey responses were analyzed utilizing descriptive statistics and the cross-tabulation method. We also adopted the unpaired t-test based on a null hypothesis that there were no statistically significant differences in mean values among the groups to analyze the differences between the results of three surveys or subgroups of AEC-FM professionals.

In our analysis, we have chosen a significance level of $\alpha = 0.05$ to reject the null hypothesis. This decision takes into account the sensitivity of the significance level to variations in sample size. If the p-value is less than $\alpha = 0.05$, the difference in means is considered statistically significant.

Several key considerations drove the choice of the unpaired t-test to analyze differences among the results of three survey rounds or subgroups of AEC-FM professionals. The unpaired t-test is particularly well suited for comparing the means of two independent groups, making it an appropriate statistical tool for our analysis. This test assumes that the data from each group are independent, normally distributed, and have similar variances (homoscedasticity). While slight deviations from the homogeneity of variance assumption may occur, the t-test is known to be robust to moderate violations. Additionally, we assessed the equality of variances using Levene's test and found that the variance differences were within an acceptable range. Therefore, we can justify using a standard unpaired t-test because the assumption of equal variances is met. In addition, the unpaired t-test is widely recognized and accepted in academic research, which enhances the credibility and acceptance of our findings. By adopting a standard and well-regarded statistical method, we ensure that our results can be easily interpreted and compared with other studies in the field.

4 Results

This section provides an overview of the survey results. The first part focuses on the quantitative data, examining the current adoption levels, usage patterns, and the perceived benefits of AR/VR technologies within the AEC-FM industry. It highlights the trends over time, as well as the barriers that continue to impact broader implementation. The second part delves into the qualitative insights, capturing the key themes, challenges, and opportunities revealed through in-depth interviews with industry experts. By integrating surveys and interviews, we captured quantitative data and gained a deeper understanding through qualitative interviews on the aspects of AR/VR technology adoption, offering a more comprehensive view of the industry's evolving landscape.

4.1 Quantitative results

The primary focus of the study was to understand the trends in the AEC-FM industry in the adoption of AR/VR technologies and to identify the vision to integrate such technologies within different phases and sizes of projects. Therefore, in this section, the responses to industry surveys are analyzed to (1) investigate the current use and comprehension of AR/VR technologies in the AEC-FM industry, (2) study the future trends in the application of these technologies, and discern their potential integration into various project phases in the near future, and (3) outline the barriers that affect the adoption of AR/VR technologies in the AEC-FM industry. To ensure the replicability of this study, the full survey questionnaire is publicly available at https://doi.org/10.6084/m9.figshare.28600778.v1.

4.1.1 General information

The analysis included feedback from 66 industry experts to evaluate the current state, projected growth, and potential cost-saving applications of AR/VR technologies within the AEC-FM industry. Overall, in this survey, 85% of the respondents were male, 14% were female, and 2% preferred not to specify their gender. Approximately 75% of the respondents were under the age of 45 years, as shown in Figure 1. Most of the respondents represented companies located in North America (92%).

The respondents were also asked about their roles in the AEC-FM industry. Of the 66 respondents, 73% were in construction, 30% were in engineering/consulting, 12% were in architecture and design, 8% were in facility management, 8% were in information technology (solution management) and 5% were in public agency.

The project engineer and project manager make up the largest individual categories, each accounting for 11% of the respondents. This is closely followed by Project Executive (9%) and senior-level positions, including BIM Specialist, Sr. VDC Engineer, and VDC Engineer, along with roles such as VDC Manager and VDC Director, each making up 8% of the total. The roles in operation positions such as Senior Project Engineer and Senior Field Engineer constitute 4%. Meanwhile, various support services functions such as Estimator, Senior Estimator, Scheduler, Quality Control, and Safety occupy the lowest rate, each accounting for 1%–2%.

In 2023, 55% of the respondents reported having more than 10 years of professional experience within the AEC-FM industry, while in 2020 and 2018, the percentages were 38% and 21%, respectively. Table 4 shows the number of years that the respondents have spent in their current companies or organizations, as well as their total years of experience in the AEC-FM industry across three surveys. The majority of the participants had 1–5 years of experience in their current company throughout all years.

4.1.2 Company-related information

The number of employees, as shown in Table 5, serves as an indicator of a company's size. These metrics can provide insight into how companies of different sizes perceive the future of AR/VR technologies.

Participants working in the AEC-FM industry were asked to identify the value of the project(s) they were involved in (e.g., over $100 million, between $10 million and $50 million, etc.) and instructed to select all applicable options. Approximately 70% of the respondents indicated their involvement in projects valued at more than $10 million, while 20% reported working on projects valued at less than $5 million.

When asked about the sectors of the AEC-FM industry in which their projects were involved, the responses were divided into five different sectors, as shown in Figure 2. It shows that the commercial sector consistently held the largest share of projects across all years, and the institutional sector remained relatively stable, accounting for around a quarter of the projects each year.

4.1.3 Virtual design and construction knowledge and experience

When asked about the current VDC approach in the companies of the respondents and instructed to select all the options that apply, 75% of the respondents reported employing BIM techniques, utilizing software such as Revit, Navisworks, Synchro

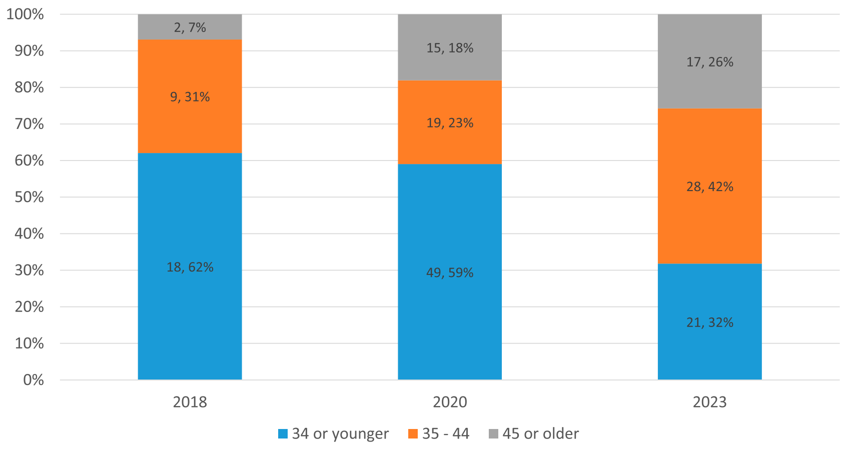

FIGURE 1
Age groups of industry participants.

TABLE 4 Industry participants' experience in their current company or organization and in the AEC-FM industry.

Option	Organization or company			AEC-FM industry		
	2018	2020	2023	2018	2020	2023
Less than a year	29%	13%	15%	6%	2%	3%
1–5 years	59%	63%	53%	47%	31%	17%
6–10 years	6%	16%	12%	26%	29%	25%
More than 10 years	6%	9%	20%	21%	38%	55%

and Bentley. A slightly higher proportion, 82%, indicated their reliance on Conventional Blueprint methods, mainly facilitated by Bluebeam software. Meanwhile, 71% of the respondents indicated using Reality Capture technologies, including Point Clouds, Laser Scanning, and Equipped Drones. Finally, 45% of the respondents were using an integration of BIM with AR/VR technologies in their companies.

When queried about the frequency of VDC tool usage, half of the respondents reported using VDC tools daily. However, it's noteworthy that 29% of respondents do not use VDC tools at all. This includes 12% who work in firms without a dedicated VDC team and 17% who do not utilize these tools despite having access to a VDC team in their firm. Table 6 shows the VDC usage rate for the respondents. The data reveal that there is an increase in daily use and a decrease in the proportion of those who never used VDC tools in 2023 compared to 2020. This trend likely indicates a deeper integration of VDC tools into routine workflows, paralleled by substantial improvements in the tools themselves, making them more indispensable to users.

When respondents were asked about the primary VDC applications and instructed to select all applicable options, as shown in Table 6, clash detection, visualization and trade coordination, and model validation were consistently ranked as the top three applications across all survey years, with their usage increasing in 2023 compared to 2018. Using VDC for 4D simulation, transportation and logistics, cost estimation, facility management, safety and training, energy simulations, and lighting analysis were the least chosen options by the respondents. Please note that the option "Safety and training" was added in 2020 and therefore no data are available for 2018.

Finally, when respondents were asked about their experience with VDC tools in their companies, the majority (57%) in 2023 reported having more than 6 years of experience, marking a significant increase compared to previous years. Table 6 presents the experience of the respondents with VDC tools.

4.1.4 AR/VR/mixed reality knowledge and experience

This section assesses the adoption and utilization of AR/VR and mixed reality technologies in the AEC-FM industry, with a focus on (1) usage rates, (2) team expertise, (3) respondents' experience, (4) the improvement communication between stakeholders to enhance end-user satisfaction through AR/VR integration, (5) key purposes for adopting AR/VR, (6) parties that benefit the most, (7) perceptions of potential time and cost savings compared to VDC technologies, and (11) the limitations and challenges associated with AR/VR adoption.

When asked about the usage of AR/VR technologies, as shown in Table 7, in 2023, 44% of the respondents reported using AR/VR technologies, reflecting a decline in usage compared to 2020 and 2018, alongside a slight increase in the number of non-users.

Similarly, when asked about the number of experts with AR/VR skills in the AEC-FM industry, as shown in Table 7, the 2023 results indicate a slight decrease compared to previous surveys. It also shows that although there may be some interest or even investment in AR/VR technologies, expertise remains concentrated within a small segment of team members.

TABLE 5 Companies-related information.

Section	Option	2018	2020	2023
Company sizes	Mega companies (>5,000 employees)	26%	25%	17%
	Large companies (1,000–5,000 employees)	26%	12%	27%
	Medium companies (200–1,000 employees)	16%	32%	38%
	Small companies (<200 employees)	32%	32%	18%

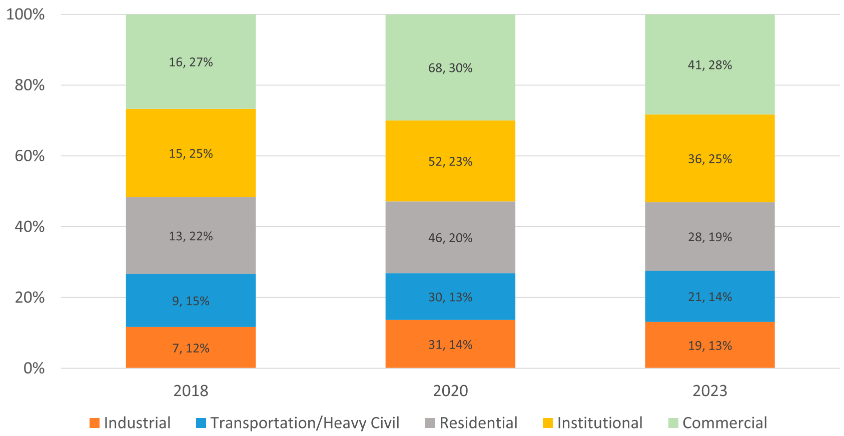

FIGURE 2
AEC-FM sectors that industry respondents' companies get involved with.

Respondents were also asked to indicate their level of agreement with the statement that integrating AR/VR technologies could lead to an increase in end-user satisfaction (e.g., owners, customers, occupants). As shown in Table 7, while there was a slight decrease in the proportion of respondents who "Strongly agree" and a corresponding slight increase in those who "Agree," these changes do not represent a statistically significant difference.

When asked about the purpose of using AR/VR technologies in their companies and instructed to select all applicable options, as shown in Table 8, the majority of the respondents consistently identified design visualization and evaluation as the primary use throughout all survey years. This technology allows different project parties to virtually experience a design before its actual construction, providing an intuitive grasp of spaces, dimensions, materials, and aesthetics. Following closely, respondents reported the use of AR/VR for enhancing communication between different stakeholders, such as clients and design teams, as well as for preconstruction services like clash detection throughout all survey years. In particular, in 2023, 55% of the respondents reported using AR/VR technologies for construction safety, reflecting a significant increase in this purpose compared to 2020 and 2018. Please note that the option "AR/VR for training (safety, welding, pre-manufacturing/modular)" was added in 2020, so no data are available for 2018. Additionally, the option "Augmented reality inspections and quality control (measurements, object detection, deviations, etc.)" was added in 2023.

The respondents were queried regarding their views on which parties benefit the most from AR/VR technologies in the AEC-FM industry, as shown in Table 9. They were instructed to rank seven options in descending order of benefit, with "1″ being the most benefited party and "7″ the least. Architecture design companies are consistently viewed as the top beneficiaries, followed by owners in all survey years.

The survey also asked about respondents' perceptions, based on their knowledge and experience, of the potential time and cost savings achievable through the integration of AR/VR technologies compared to VDC technology during the design and construction phases (e.g., change orders and design revisions during the construction phase and communication among design teams) and the operational and maintenance phases (e.g., energy consumption and end-user interaction with building system). The options provided to the respondents for this question were based on the percentage of project cost savings. In response to this question on cost and time savings, 32%, 22% and 13% of the respondents in 2023, 2020, and 2018, respectively, indicated no opinion during the design and construction phases. Similarly, 37%, 25%, and 17% of the respondents in 2023, 2020, and 2018, respectively, expressed no opinion during the operational and maintenance phases. However, among those who had an opinion, Table 10 represents that the percentage of respondents who perceived AR/VR as "noticeably effective (1%–3% in savings)" during the operational and maintenance phase decreased significantly in 2023 compared

TABLE 6 Respondent insights on VDC tool usage frequency, primary applications, and duration of experience.

Section	Option	2018	2020	2023
Frequency of VDC tool	Never use any VDC tools	18%	46%	29%
	Monthly basis	18%	30%	14%
	Weekly basis	18%	20%	9%
	Daily basis	45%	5%	48%
VDC applications	Clash detection	59%	74%	76%
	Visualization and trade coordination (e.g., MEP with structural)	66%	83%	67%
	Model validation	59%	83%	60%
	4D simulation (3D + schedule)	47%	60%	43%
	Model-based cost estimation	44%	50%	38%
	Transportation and logistics	44%	32%	36%
	Facility management purposes	13%	32%	28%
	Safety and training	-	28%	14%
	Energy simulations and lighting analysis	6%	21%	9%
	Others	3%	11%	3%
Familiarity with VDC tools	More than 6 years	25%	18%	57%
	4–6 years	6%	26%	26%
	1–3 years	44%	31%	16%
	Less than a year	9%	25%	2%
	Never used them before	16%	0%	0%

to 2018. Furthermore, the proportion of respondents who found AR/VR to be "more effective (greater than 5% in savings)" during the design and construction phases decreased from 23% in 2018 to 16% in 2023.

Finally, when respondents were asked to identify the limitations and challenges they faced when using AR/VR and were instructed to select all the options that apply, as shown in Table 11, the "Time-consuming translation process and optimizing the resultant (the VR model takes several hours and even days)" consistently ranked as the top challenge in all survey years, with an increase in reports in 2023 compared to 2020. One participant highlighted the challenge of complexity and setup time, stating:

"It is not super simple to set up. It takes some time and effort, and there is a cost component related to it. I find that project teams are less likely to use things, especially out in the field, if it is not easy to use. It has to be very simple for them. Even right now, it is not that simple. There is a lot of setup time, getting the models to align correctly."

Additionally, concerns over "Interoperability of multiple software platforms" increased, reflecting the growing prominence of challenges in ensuring seamless communication between various software tools as AR/VR technologies are more deeply integrated into workflows. This may be due to the increasing complexity of technology ecosystems within organizations, where different tools need to efficiently exchange data to optimize AR/VR applications. Conversely, issues related to "Integration with legacy systems" showed a decline, suggesting that companies have made progress in modernizing their infrastructure or developing solutions that better accommodate older systems, thereby reducing the perceived challenges in this area. Please note that there are no data available for 2018 since this question was first added in the 2020 survey.

In addition to technical challenges, user experience issues are also a concern, as one participant shared.

"If you are not used to it, and especially after the age of 30, AR/VR can make you feel dizzy. I myself feel dizzy after using it for a long time."

Another participant further elaborated on the usability of current AR/VR hardware, particularly headsets.

"The headsets are another challenge. I do not know if you have tried it, but it is incredibly hot, like having a microwave on your

TABLE 7 Survey responses on the adoption and utilization of AR/VR technologies in the AEC-FM industry, including usage rates, team expertise, respondents' experience, and their improvement on stakeholder communication to enhance end-user satisfaction rate.

Section	Option	2018	2020	2023
Usage of AR/VR	Yes	56%	65%	44%
	No, but I have seen demos and videos	28%	18%	35%
	No, not at all	16%	17%	21%
Number of AR/VR experts in the company	None	15%	14%	29%
	1–3 people	42%	24%	42%
	4–6 people	15%	14%	8%
	7–10 people	19%	18%	13%
	11–25 people	4%	16%	4%
	More than 25 people	4%	15%	4%
Respondents experience in using AR/VR	More than 6 years	30%	18%	8%
	5–6 years		26%	14%
	3–4 years	7%	0%	20%
	1–2 years	52%	31%	16%
	Less than a year	11%	25%	42%
	Strongly agree	60%	65%	38%
Increase in end-users satisfaction rate by integrating AR/VR	Agree	37%	22%	48%
	Neutral	3%	6%	12%
	Disagree	0%	0%	0%
	Strongly disagree	0%	7%	2%

TABLE 8 The purposes of using AR/VR technologies in the AEC-FM industry.

Option	2018	2020	2023
Design visualization and evaluation	74%	81%	77%
Communication among different parties (e.g., clients, design team, etc.)	48%	48%	55%
Construction safety	37%	20%	55%
Pre-construction services (e.g., clash Detection)	56%	38%	41%
Construction sequencing and operations	33%	26%	34%
Augmented reality inspections and quality control (measurements, object detection, deviations, etc.)	-	-	27%
Facility management (e.g., visualization of sensor data, and building system operations)	11%	14%	14%
AR/VR for training (safety, Welding, Pre-manufacturing/Modular)	-	22%	14%
Real-time lighting and energy simulation	11%	13%	2%
Others	11%	15%	7%

TABLE 9 Ranking of industry respondents' perspectives on which parties benefit the most from AR/VR technologies in the AEC-FM industry and emerging domains for the extensive use of AR/VR in the near future.

Section	Option	2018	2020	2023
Ranking of industry respondents' perspectives on which parties benefit the most from AR/VR technologies in the AEC-FM industry	Architecture design companies	1	1	1
	Owners	2	2	2
	Engineering/Consulting	-	3	3
	Contractors	3	4	4
	Construction management	4	5	5
Ranking of emerging domains for the extensive use of AR/VR in the near future	Facility manager	6	6	6
	Occupants or end-users	5	7	7
	Design and construction coordination	2	2	1
	Design evaluations	1	1	2
	Change orders and cost management	6	7	3
	Space management (operation phase)	4	4	4
	Real estate	3	3	5
	Inspection	-	6	6
	Retrofitting	5	5	7
	Others	8	8	8

TABLE 10 Cost and time savings by integrating AR/VR compared to VDC technology during the design and construction, and operational and maintenance phases.

<table>
<tr><th rowspan="2">Option</th><th colspan="3">Design and construction</th><th colspan="3">Operational and maintenance</th></tr>
<tr><th>2018</th><th>2020</th><th>2023</th><th>2018</th><th>2020</th><th>2023</th></tr>
<tr><td>Not effective at all</td><td>0%</td><td>1%</td><td>2%</td><td>0%</td><td>1%</td><td>0%</td></tr>
<tr><td>Not much (<0.5% in saving)</td><td>4%</td><td>20%</td><td>12%</td><td>12%</td><td>19%</td><td>29%</td></tr>
<tr><td>Slightly effective (0.5%–1% saving)</td><td>35%</td><td>46%</td><td>30%</td><td>20%</td><td>39%</td><td>34%</td></tr>
<tr><td>Noticeably effective (1%–3% saving)</td><td rowspan="2">38%</td><td rowspan="2">20%</td><td rowspan="2">40%</td><td rowspan="2">56%</td><td rowspan="2">33%</td><td rowspan="2">24%</td></tr>
<tr><td>More effective than VDC technologies</td></tr>
<tr><td>(>5% in savings)</td><td>23%</td><td>12%</td><td>16%</td><td>12%</td><td>7%</td><td>13%</td></tr>
</table>

head. I do not think that is practical. Then you have other devices, like Magic Leap, which you cannot wear with a hard hat on site. So again, it is about being fit for purpose. Indoors, it might be fine, but outdoors or on a construction site, it is just not feasible."

4.1.5 Vision for the future of virtual/augmented reality

This section aims to explore the potential applications and opportunities of AR/VR technologies within the AEC-FM industry.

In the first question, respondents were asked to identify the reasons for the limited adoption of AR/VR technologies in their organizations. They were provided with seven options and asked to rank them in significance order, with 1 being the most significant factor and 7 the least. As shown in Table 12, in 2023, the most significant factors were "Lack of champions in organizations to push for the integration of new technologies" and "Benefits offered by this technology and if it meets the company's internal need". Interestingly, in 2020 "Lack of funds" and "Lack of training" were

TABLE 11 Industry respondents' perspectives on limitations and difficulties of using AR/VR technologies.

Rank	Option	2020	2023
1	Time-consuming translation process and optimizing the resultant (Virtual Reality model takes several hours and even days)	45%	61%
2	Jobsite usability issues (e.g., poor lighting)	44%	43%
3	Tools and options available for model creation in Virtual Reality are not as sophisticated as the CAD tools	35%	36%
4	Interoperability of the multiple software	21%	32%
5	Hardware-software compatibility	31%	32%
6	Low rendering quality	38%	30%
7	High latency of the models	21%	21%
8	Integration with legacy systems	39%	21%

TABLE 12 Ranking of the main factors preventing the integration of AR/VR technologies in companies.

Option	2020	2023
Lack of champions in organizations to push for the integration of new technologies	—	1
Benefits that are offered by this technology and if it meets the company's internal needs	6	2
Lack of management support	4	3
Lack of funds	1	4
Lack of training	2	5
Skill level of the project team	5	6
Business competition and employing the most up-to-date technology	3	7

identified as the most significant barriers, but they no longer ranked as top concerns in 2023. Additionally, "business competition and employing the most up-to-date technology", which ranked third in 2020, fell to the lowest rank in 2023. This shift can be due to two key factors: (1) current technologies have become more affordable and accessible compared to previous years, and (2) in recent years, business competition has not been as heavily reliant on AR/VR technologies, reducing their perceived value as a competitive advantage. Please note that the option "Lack of champions in organizations to push for the integration of new technologies" was added in 2023, and therefore no data are available for 2020.

When asked to identify the most effective method to highlight the benefits of AR/VR technology and persuade companies to adopt it, most of the respondents consistently pointed to a 'cost-benefit analysis study' as the most persuasive approach, with 48% selecting it in 2023 and 57% in 2020 and only a small fraction (less than 5%) remained doubtful about the benefits of AR/VR. Although a 'Successful pilot study' was one of the main methods cited in 2020, its significance decreased in 2023. Please note that there are no data available for 2018 since this question was first added to the 2020 survey.

Table 13 presents the projections of the respondents for AR/VR utilization in more than 90% of projects in the AEC-FM industry over the next 5–10 years. Throughout the survey years, there has been a noticeable decline in "Strong agreement" and "Agreement," with fewer respondents in 2023 expressing confidence in the widespread adoption of AR/VR. Conversely, the proportion of those who "Disagree" and "Strongly disagree" with the statement has increased.

As shown in Table 13, when respondents were asked about the future adoption of AR/VR technologies in different sectors of the AEC-FM industry over the next 10 years and instructed to select multiple sectors that apply, a decline in adoption rates for 'Healthcare' and 'Education' facilities was observed in 2023 compared to previous surveys. In contrast, the adoption rate for "Commercial buildings" exhibited a slight increase, reflecting consistent growth. Approximately 6% of the respondents in 2023 responded "Others," which includes the "Applied Science," "Industrial," and "Mining and Environmental" market sectors.

When asked about the optimal project size to maximize the benefits of AR/VR technologies and instructed to select all the options that apply, as shown in Table 13, the perceived benefit for large-size projects has remained consistently high throughout the survey years, although it experienced a slight decrease from 90% in 2018 to 83% in 2023. In contrast, the perceived benefit for mega-projects has shown a steady increase, increasing from 55% in 2018 to 68% in 2023.

Finally, respondents were asked to identify potential areas where AR/VR might experience significant usage in the near future. They were instructed to rank eight provided options, with 1 indicating the most likely and 8 the least likely. As shown in Table 9, "Design and construction coordination" ranked highly, showing an increasing trend over time. In particular, "Change orders and cost management" emerged as a notable area of potential AR/VR application in 2023, despite not being a focus in previous surveys. Some of the top repeated in the "Others" category can be listed as "Value engineering," "Building data management," "Field verification of underground," "Owner validation", and "Safety management". Please note that the option "Inspection" was added in 2020, so no data are available for 2018.

4.2 Qualitative results

In this section, we summarize the results of the thematic analysis conducted in the interviews. Our analysis of the qualitative data revealed three main themes that are central to understanding the challenges of adopting and integrating AR/VR solutions in the AEC-FM industry. These themes provide critical insights into (i)the key barriers to implementing AR/VR solutions in everyday practices of the AEC-FM industry, (ii) the most prevalent existing AR/VR applications, and (iii) the major technical challenges that hinder further expansion and growth of

TABLE 13 Respondents' projections on AR/VR adoption, future use in different sectors of the AEC-FM industry, and perceived benefits by project size.

Section	Option	2018	2020	2023
Respondents agreement with the following statement Within the next 5–10 years AR/VR will be used in more than 90% of your projects	Strongly agree	39%	33%	20%
	Agree	42%	44%	39%
	Neutral	19%	15%	21%
	Disagree	0%	7%	17%
	Strongly disagree	0%	1%	3%
Future adoption of AR/VR in different sectors of the AEC-FM industry within the next 10 years	Commercial buildings	68%	72%	72%
	Healthcare facilities	84%	73%	69%
	Education facilities	61%	48%	45%
	Residential buildings	45%	42%	40%
	Real estate	48%	58%	38%
	Transportation/Heavy civil	32%	33%	29%
	Others	0%	5%	6%
Optimal projects size for maximum AR/VR benefits	Mega projects (e.g., nuclear plants, heavy civil)	55%	64%	68%
	Large size projects	90%	81%	83%
	Medium size projects (e.g., a few stories building)	48%	58%	37%
	Small projects (e.g., single-family housing)	19%	36%	17%
	I am not sure	6%	4%	8%

TABLE 14 Summary of the qualitative methodology results.

#	Themes	Codes	Frequency (%)
1	What are the major barriers to adopting AR/VR into the everyday practice of the construction industry?	Cost	18.24%
		Hesitation/Apprehension	18.24%
		Rules/Regulations	16.35%
		Company Attitude/Culture	3.14%
		Safety/Safety Training	1.89%
2	What are the most frequent applications of AR/VR in the construction industry?	Project Visualization	18.24%
		Remote Access	3.14%
3	What are the major technical challenges hindering the implementation of AR/VR in the construction industry?	Skillset	5.66%
		Limitations of Technology	15.09%

AR/VR-based solutions in the industry. These outcomes are all summarized in Table 14. This table cross-references the extracted themes with the generated codes and outlines the frequency of each code's occurrence in each individual interview. In the following, we will explain the synthesized results of each theme in more detail:

4.2.1 Major barriers toward adoption of AR/VR in AEC-FM industry

Our results indicate that financial aspects (coded as "Cost" in Table 14) and hesitation toward new technologies (coded as "Hesitation/Apprehension" in Table 14) are the primary barriers outlined by the interviewees regarding the adoption of AR/VR in the AEC-FM industry, with each cited by 18. 24% of the participants when discussing the challenges of implementing AR/VR technologies. Furthermore, overcoming the rules and regulatory environment (coded as "Rules/Regulations" in Table 14) was highlighted as another significant barrier, mentioned in 16.35% of the interviews.

Our interviewees mentioned the financial implications of AR/VR investments in several ways, including inadequate development budgets, restricted access to capital to purchase the necessary hardware, and client or company disapproval of investments stemming from a limited understanding of the potential return on investment. However, hesitation towards the adoption of new technology is not an isolated attitude; it has been identified as a significant barrier to the adoption of AR/VR in multiple domains, including construction (Zhang Qingyu et al., 2024; Van Tam et al., 2024). In addition, several interviewees pointed out the complexity of integrating new technologies within the existing regulatory framework. Differences between client requirements in the public and private sectors, regulations concerning budget adjustments, and internal ruling issues within larger companies in terms of investments were cited as significant challenges related to regulations and rules that hinder the growth of AR/VR in the AEC-FM industry.

Our analysis also uncovered other factors that were less frequently mentioned as potential blockers. The results summarized in Table 14 indicate that the company culture and attitudes toward new technologies (coded as "Company Attitude/Culture") accounted for 3.14%, while safety implications (coded as "Safety/Safety Training") represented 1.89% of the challenges related to adopting AR/VR. Company culture has been identified as a significant factor in the adoption of new technologies in several domains, particularly in digital technologies such as Building Information Modeling (Roberts et al., 2021; Nwabueze Mogbo et al., 2023). In contrast, safety is a diminishing concern factor toward adoption that is more relevant to AR than VR. With advances in technology, AR is increasingly being used in built environments and is, in fact, being implemented as a safety system in certain industrial applications, such as manufacturing (Zhang Xiaoli et al., 2024; Fang et al., 2023).

4.2.2 Most frequent applications of AR/VR technologies

While AR/VR applications have been growing exponentially in similar industries, particularly manufacturing, our results indicate that in the AEC-FM industry, the primary applications of AR/VR are visualization-focused use cases (coded as "Project Visualization" in Table 14) and remote access and monitoring of project status (coded as "Remote Access" in Table 14).

Providing visual understanding at different stages of construction projects, including bidding, design, and stakeholder presentations, was outlined by our interviewees as the primary use case for AR/VR in the AEC-FM industry. The immersive visualization capabilities of VR were emphasized as a pivotal factor in presentations and engagement, especially during the early phases of projects when effective communication with stakeholders is vital. Other related activities mentioned by our interviewees included requesting approvals through rapid design processes and facilitating public engagement for community outreach through virtual reality. Additionally, the ability to remotely access 3D models and designs was highlighted as another important use case to support remote collaboration on 3D designs, design reviews, and presentations.

4.2.3 Major technical challenges in AR/VR implementation

Similarly to other major disruptive technologies, participants in this study highlighted several areas where significant technological challenges hinder the expansion of AR/VR technologies in the AEC-FM industry. Limitations in existing AR/VR hardware and software technologies (coded as "Limitations of Technology" in Table 14) were cited by 15. 09% of the participants, while a lack of adequately trained staff (coded as "Skillset" in Table 14) was mentioned by 5.66% of the interviewees as major hurdles in the adoption of AR/VR. Although there have been significant advances in AR/VR technology over the past few years, several challenges still have not been fully addressed. For example, model drift, which has traditionally been recognized as a major obstacle in leveraging AR/VR in the field in the AEC-FM industry, was also cited by our interviewees as a current challenge they face (Zhang Xiaoli et al., 2024).

The lack of a specialized workforce with the programming skills and technical knowledge necessary for the effective deployment of AR/VR solutions was also called a significant barrier by our participants. As the AEC-FM industry undergoes a rigorous transition from traditional practices to a digital landscape, the demand for skilled professionals who can navigate this shift becomes increasingly critical and has been highlighted in similar research works in the past (Irfan et al., 2024; Longo et al., 2023). Therefore, building a workforce equipped with the right technical skills is for successfully integrating AR/VR solutions in the AEC-FM industry future.

5 Discussion and analysis of survey findings

This section provides a detailed discussion of the survey results and identifies recent AR/VR adoption trends to explore potential future directions for their implementation.

5.1 Trends in AR/VR adoption

To evaluate the change in the confidence level of the respondents about the future of AR/VR technology adoption between the survey rounds, the unpaired t-test was performed to analyze the participants' level of agreement with the statement that AR/VR technologies will be utilized in more than 90% of their projects in the next 5–10 years. For the analysis of the responses, scores were assigned to each answer choice (strongly disagree = 0, disagree = 1, neutral = 2, agree = 3, strongly agree = 4). The results,

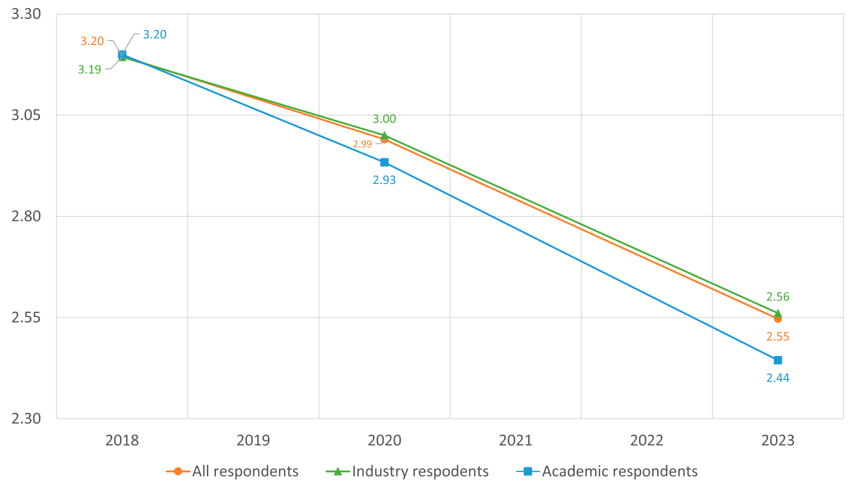

FIGURE 3
Trends in AR/VR adoption expectations in more than 90% of projects within the next 5–10 years.

as shown in Figure 3, indicate that the confidence level of the respondents in the future of AR/VR technologies was highest in 2018 (M = 3.20, SD = 0.75). However, this confidence shows a decreasing trend in the next round of surveys, in 2020 (M = 2.99, SD = 0.94) and 2023 (M = 2.55, SD = 1.06). The results of the unpaired t-test also showed a significant difference in the mean scores of the responses between 2018 and 2023 (p-value = 0.001) and between 2020 and 2023 (p-value = 0.004). This trend indicates that, while there was initial optimism regarding the adoption of AR/VR technologies in the AEC-FM industry, fewer participants have been optimistic about utilizing AR/VR in recent years. From 2018 to 2021, several significant events contributed to the initial change in optimism surrounding AR/VR technologies. Facebook rebranded as Meta, signaling a major shift in focus towards the metaverse and immersive technologies (Meta, 2025). Furthermore, HTC released the HTC Vive Pro, an upgraded version of its VR headset (VIVE, 2018), and Microsoft launched HoloLens 2, offering enhanced field of view and hand-tracking capabilities, along with advanced eye-tracking features, which was notably adopted by the U.S. military. It was integrated into the military's Integrated Visual Augmentation System (IVAS), making it a key tool for improving situational awareness on the battlefield (Author anonymous, 2025). This change in optimism among participants may be due to the hype surrounding AR/VR technology during 2018 and a lack of clear understanding of the capabilities, time, and cost benefits that these technologies can bring to different sizes/types of projects in different sectors of the AEC-FM industry. As a result, investments in AR/VR technologies might be viewed as non-essential. This decline in confidence levels was observed among both industry and academic participants, with significant differences between 2018 and 2023 (p-values of 0.004 and 0.039, respectively), reflecting a change in the views of all participants on the practicality of AR/VR implementation. Detailed descriptive statistics can be found in Supplementary Appendix Table SA1.

To measure the adoption of AR/VR technologies in the AEC-FM industry, the number of people in the teams of respondents with AR/VR experience and skills was analyzed, as shown in Figure 4. For the analysis of the responses, scores were assigned to each answer choice (none = 0, not sure = 1, one to three people = 2, 4-6 people = 3, 7–10 people = 4, 11–25 people = 5, more than 25 people = 6). Performing an unpaired t-test revealed that while there was a statistically significant increase in the number of employees with AR/VR skills from 2018 (M = 2.20, SD = 1.68) to 2020 (M = 2.88, SD = 1.87); p-value = 0.039, a significant decrease was observed from 2020 to 2023 (M = 1.77, SD = 1.49); p-value = 0.001. The increase in the number of employees with AR/VR expertise between 2018 and 2020 could reflect the industry's increased investment in these technologies in response to the hype of AR/VR, as well as remote working during the COVID-19 pandemic. However, after the removal of lockdown restrictions (May 2023 (Page freezer, 2024)), as companies began to re-evaluate their operational strategies and focus on VDC for practical solutions, AR/VR technologies might not be seen as a practical and cost-effective solution for the AEC-FM industry's needs. As mentioned in the Introduction, the 2018 survey reflects the pre-COVID, providing a baseline for AR/VR adoption trends before the pandemic. The 2020 survey captures industry responses during the pandemic, marked by disruptions and the shift to remote working, while the 2023 survey represents post-COVID responses, reflecting how the industry adapted to new operational strategies after lockdowns were lifted. The impact of COVID-19 and post-COVID will be evaluated in future surveys to gain a clearer understanding of how the pandemic has influenced the adoption of AR/VR technology. These future evaluations will allow us to make more concrete judgments and insights for our study.

The significant decline in the number of employees' familiarity with AR/VR technologies observed in 2023 may be due to some key factors. One potential reason may be the reduction in the need for specialized VR expertise due to advances in hardware and software packages. As AR/VR systems become more user-friendly and automated, many of the complex and specialized steps required for integration have been eliminated. This is further supported by the observation that the challenge of "Integration with legacy systems" ranked lower in 2023 compared to 2020 (as shown in Table 11), indicating that newer systems are more

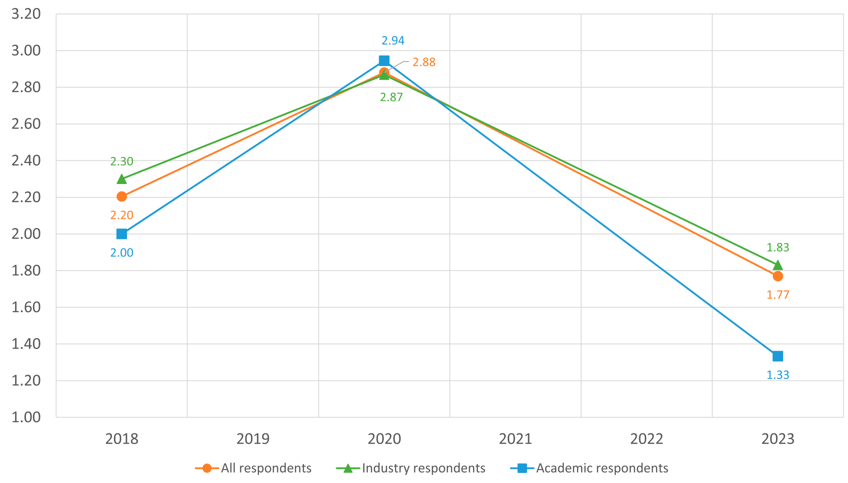

FIGURE 4
Number of respondents' team members with AR/VR experience and skills.

easily integrated into existing workflows, reducing the need for extensive technical expertise. Furthermore, the rise of specialized subconsultants with VDC expertise has contributed to the decline in the need for internal AR/VR skills. Many companies are now outsourcing these specialized tasks to subconsultants with expertise in VDC, allowing companies to access cutting-edge technologies without investing heavily in internal training or resources. This change in outsourcing tasks to VDC consultants reduces the need for a large number of in-house AR/VR experts. Furthermore, outsourcing AR/VR work to international markets, particularly to some Asian and European countries with lower labor costs, such as the Philippines, India, and Ukraine, has become a growing trend (Time Doctor, 2021). These countries offer skilled labor at competitive rates, making them attractive options for companies looking to reduce operational costs while maintaining technological capabilities. This outsourcing strategy allows companies to leverage external expertise without the need to develop extensive in-house AR/VR capabilities, contributing to the observed decrease in employee familiarity with these technologies in 2023. It should be noted that, despite the advancements in these technologies, the need for specialized VR expertise has not decreased, suggesting that while hardware and software packages may have improved, they still require a workforce with a specific skill set to operate and integrate these technologies effectively within organizations. Moreover, many of the improvements, such as hardware and software advancements, were focused on VR technology rather than AR technology. Similar trends are also observed in industry and academic groups, strengthening the findings. Detailed descriptive statistics can be found in Supplementary Appendix Table SA2.

5.2 Impact of age and gender on perception of industry on AR/VR utilization within 5–10 years

To evaluate and compare the confidence levels of younger (younger than 45 years) and older (45 or older) generations about the future of the adoption of AR/VR technologies, an unpaired t-test was performed for the last survey. The results do not indicate significant differences in scores between the older generations (M = 2.35, SD = 1.27) and the younger generation (M = 2.63, SD = 1.01); p-value = 0.363. This implies that age does not seem to significantly impact how industry experts perceive the future of AR/VR technologies, and such a finding invalidates the research's first hypothesis. However, this is not aligned with the general expectation that owners and top management of the AEC-FM industry, typically belonging to the older generation group, would be hesitant to adopt AR/VR technologies. This hesitation is often rooted in resistance to change, coupled with limited understanding and familiarity with these new technologies. Our findings reflect that positive perceptions of the potential and benefits of AR/VR technologies are not limited to any particular age group. Both young and old seem to see the value the AR/VR technologies can bring to various industries, ranging from healthcare to education.

In the next step, a series of unpaired t-tests were performed to determine if there were statistically significant differences between the means of the confidence level of industry respondents on the future of AR/VR in the AEC-FM industry in different age groups over different survey years. The significant decrease in mean scores for the "34 or younger" age group from 2018 (M = 3.16, SD = 0.78) to 2023 (M = 2.42, SD = 1.08); p-value = 0.021, and also from 2020 (M = 3.06, SD = 0.87) to 2023; p-value = 0.012, suggests that respondents in this age group have become less confident regarding the prospective integration of AR/VR technologies during the years mentioned. This downward trend was observed in all age groups in all survey years, as shown in Figure 5, indicating that it is not specifically related to age. The observed decrease in confidence level may be due to increased awareness and understanding of AR/VR technologies over time, which potentially led to a more realistic assessment of their limitations and challenges. Furthermore, by 2023, respondents had developed a more comprehensive view of the practical applications and capabilities of AR/VR technologies. This contrasts to 2018, a period marked by significant hype around AR/VR, driven by early innovations and

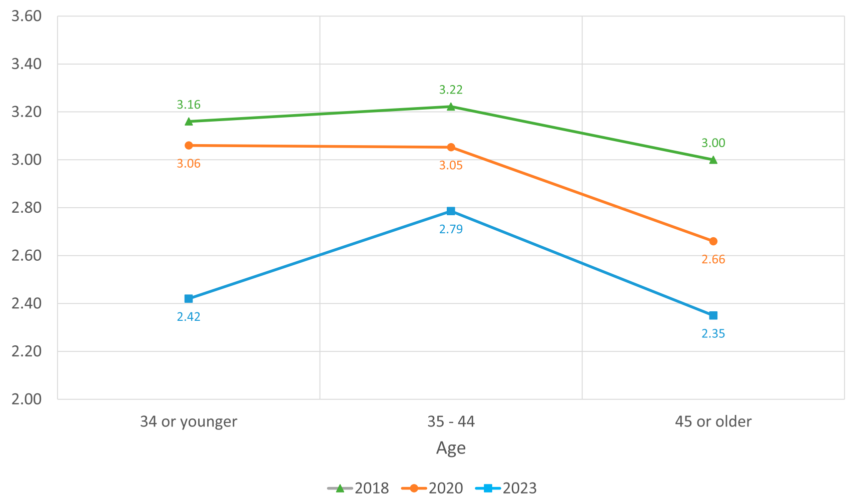

FIGURE 5
Confidence level of industry respondents about the future of AR/VR technologies by age group.

expectations of widespread adoption. Detailed descriptive statistics can be found in Supplementary Appendix Table SA3.

Furthermore, the responses of industry participants on the use of AR/VR technologies were analyzed based on their age. Figure 6 demonstrates a change in the industry approach, as it shows a decrease in the percentage of respondents aged 34 years or younger using AR/VR technologies compared to previous survey years. This decrease aligns with the trend for new hires to gain experience in project management and operations before transitioning to VDC roles. In the VDC industry, new hires are now required to start as project engineers to gain essential project management and operational training. This step is a deliberate strategy designed to immerse these individuals in the core aspects of project management and operational practices. By starting in this role, new hires are exposed to the daily realities of construction projects, where they develop a deep understanding of the complexities involved in coordinating various trades, managing timelines, and ensuring project milestones are met. This experience is invaluable, as it equips them with practical knowledge of construction processes, site operations, and the critical thinking skills required to navigate challenges that arise in the field. Moreover, it provides them with a comprehensive view of how different project components integrate, which is essential for their future responsibilities in VDC. Furthermore, as indicated in Table 6, the majority of respondents (57%) in 2023 have more than 6 years of experience with VDC tools, indicating a change in the industry approach that newly hired engineers are now expected to undergo project management and project engineering training first, and only after a few years transition to VDC roles. This trend reflects an evolving recruitment strategy and career path within the VDC industry.

Furthermore, the unpaired t-test was performed to evaluate the confidence level of respondents about the future of AR/VR technologies based on their gender. The results indicate that while there is a visible difference in confidence levels between males and females, as shown in Figure 7, with males reporting higher confidence levels in general, this difference does not appear to be statistically significant in the years 2018 (p-value = 0.176), 2020 (p-value = 0.306) and 2023 (p-value = 0.590). The lack of statistical significance suggests that gender may not be a strong determinant of confidence levels about the future of AR/VR technology adoption. Detailed descriptive statistics can be found in Supplementary Appendix Table SA4.

5.3 Trends in the number of AR/VR experts by company size

This study analyzed the number of AR/VR experts based on company sizes, as shown in Figure 8. By dividing the company size into four categories, represented in Table 5, mega-companies experienced a significant downturn over the 5-year period from 2018 (M = 4.00, SD = 1.29) to 2023 (M = 2.20, SD = 1.93), with a p-value of 0.046. One potential reason may be the advancement in AR/VR hardware and software packages. As these technologies have evolved, they have become more user-friendly and automated, reducing the complexity of integration (Wang et al., 2024). The removal of certain technical steps has probably led to a decreased need for employees with specialized AR/VR skills. Additionally, this trend may indicate a strategic shift within mega-companies, where they are reevaluating their operational priorities. Mega-companies might be focusing more on VDC as a viable and efficient solution and may be gradually moving away from AR/VR technologies, viewing them as less critical to their long-term operational goals. This shift can indicate a growing perception that AR/VR technologies do not offer practical and cost-effective solutions to meet the demands of the AEC-FM industry. However, analysis of AR/VR expert employment rates in large companies, utilizing unpaired t-tests, reveals a statistically significant increase between 2018 (M = 1.75, SD = 1.58) and 2020 (M = 3.91, SD = 1.45), as indicated by a p-value of 0.007. This upward trend is then followed by a significant decline from 2020 to 2023 (M = 2.06, SD = 1.47), with a p-value of 0.003. Detailed descriptive statistics can be found in Supplementary Appendix Table SA5.

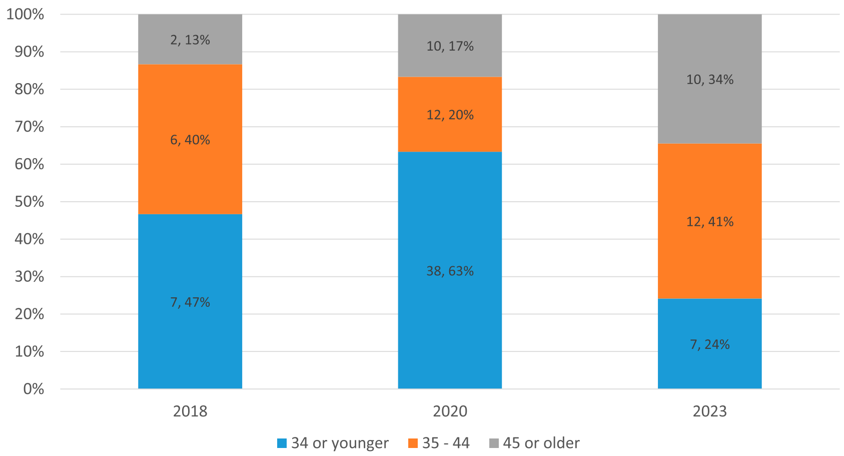

FIGURE 6
Industry participants' usage of any AR/VR technologies by their age.

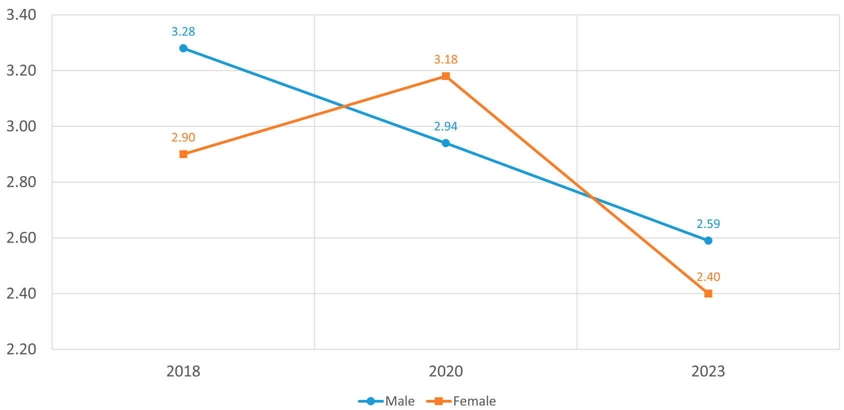

FIGURE 7
The confidence level of respondents about the future of AR/VR technologies based on gender.

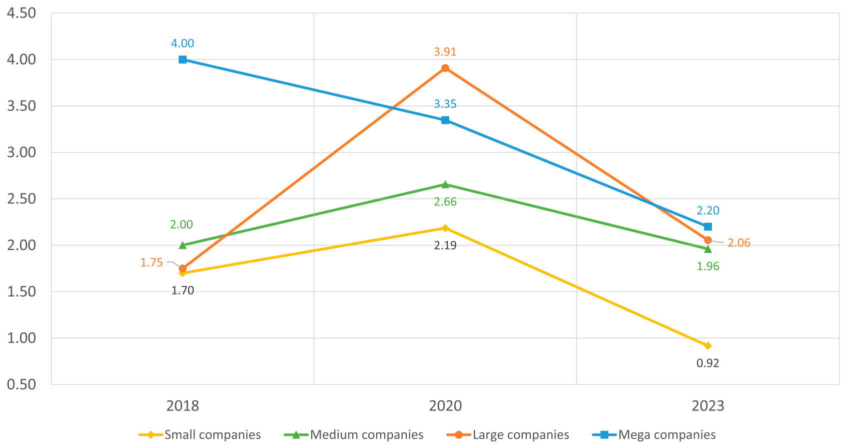

FIGURE 8
Number of industry respondents with AR/VR experience and skills across different company sizes.

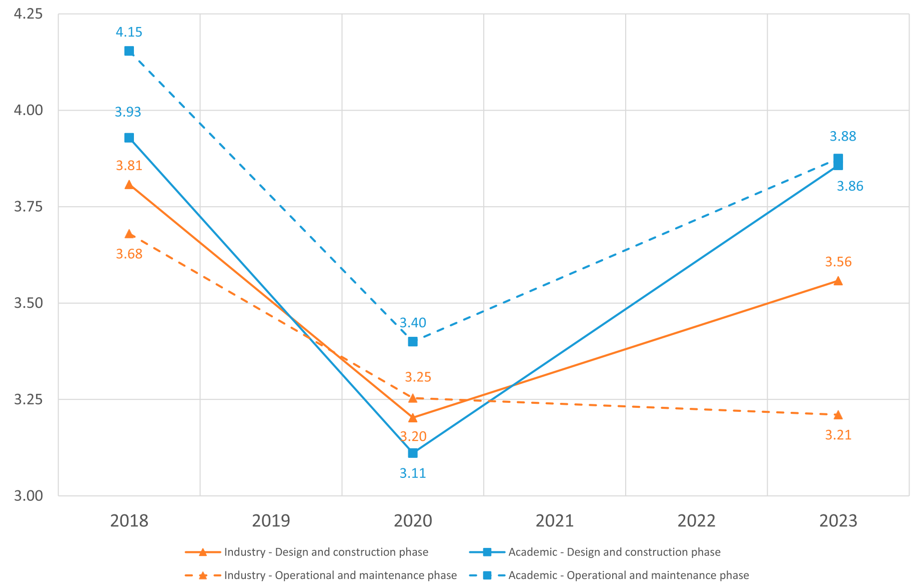

FIGURE 9
Potential time and cost savings by integrating AR/VR technologies during the project life cycle (design, construction phase, and operational and maintenance phase).

5.4 Perceptions on time and cost saving potential of AR/VR

To evaluate the predictions of AEC-FM experts on possible time and cost savings (percentage of the total value of the project) in the design, construction, and operational and maintenance phases using AR/VR technologies, as shown in Figure 9, a series of unpaired t-tests were performed on the results of the survey questions. For the analysis of the responses, scores were assigned to each answer choice (not effective at all = 1, not much (< 0.5% in saving) = 2, slightly effective (0.5%–1% saving) = 3, noticeably effective (1%–3% saving) = 4, more effective than VDC Technologies (> 5% in savings) = 5).

The predictions of the AEC-FM experts observed a statistically significant decrease in the potential time and cost savings of AR/VR from 2018 to 2020 during both the design and construction phase (p-value = 0.005) and the operational and maintenance phase (p-value = 0.045). However, despite the improvements in perceptions in 2023, the statistical analysis did not indicate a significant change from 2020 to 2023 in the design and construction phase (p-value = 0.060) and in the operational and maintenance phase (p-value = 0.823). These results suggest that while initial experts' initial predictions of the benefits of AR/VR technologies in 2018 were high, the increased practical applications and growing experiences with AR/VR technologies have tempered these expectations and became more conservative over time by 2023.

Furthermore, the analysis of the predictions of the academic respondents did not show significant changes in the design and construction phase between 2018 and 2020 (p-value = 0.062) and between 2020 and 2023 (p-value = 0.157). Similarly, no significant changes were observed in the operational and maintenance phase from 2018 to 2020 (p-value = 0.109) and 2020 to 2023 (p-value = 0.398). However, academic respondents generally predicted higher time and cost savings by using AR/VR technologies throughout the project life cycle compared to industry respondents. It is worth considering that academic experts might have a different perspective from industry professionals due to their focus on theoretical potential versus practical application. This trend may also stem from a bias towards technological optimism, where AR/VR capabilities were perceived in an idealistic manner. As these technologies were integrated into applications, their limitations and the challenges of implementing them in existing workflows became more evident, leading to a more conservative assessment of their benefits. Detailed descriptive statistics can be found in Supplementary Appendix Table SA6.

It is important to note that all respondents were asked to answer these questions regardless of whether they had VDC experience or not. Therefore, once more, the unpaired t-test was conducted to analyze the time and cost savings predictions among VDC tool users. As shown in Figure 10, the results indicate a statistically significant decrease in the perception of time and cost savings using AR/VR technologies from 2018 to 2020 during both the design and construction phase (p-value = 0.004) and the operational and maintenance phase (p-value = 0.049). The results also show a statistically significant increase in perceptions of time and cost savings from 2020 to 2023 during the design and construction phases (p-value = 0.001), whereas no significant increase was observed in the operational and maintenance phases (p-value = 0.680). It indicates that the experiences of users of VDC tools with AR/VR technologies reflect a shift in perceptions of their benefits over time.

Furthermore, the analysis of the predictions of the academic respondents did not show significant changes in the design and construction phase between 2018 and 2020 (p-value = 0.0621) and between 2020 and 2023 (p-value = 0.857). Similarly, no significant changes were observed in the operational and maintenance phase

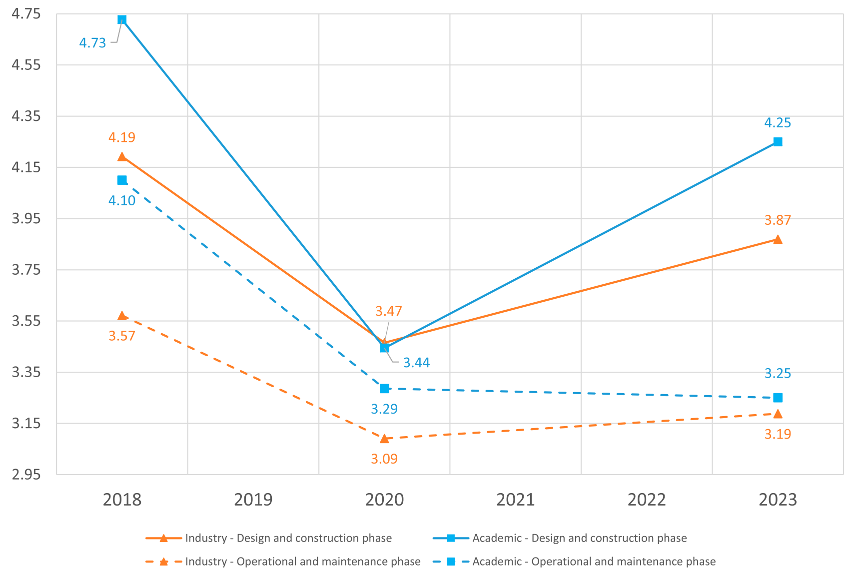

FIGURE 10
Potential time and cost savings by integrating AR/VR technologies during the project life cycle (design and construction phase and operation phase): insights from VDC tool users.

from 2018 to 2020 (p-value = 0.156) and 2020 to 2023 (p-value = 0.962).

Generally, the respondents' predictions of time and cost savings using AR/VR technologies were lower in the operation phase compared to the design and construction phase. The possible reason is that the built-in BIM models provided for operational and maintenance purposes do not have the granularity of the level of development (LOD) and Construction Operations Building Information exchange (COBie) data required for facility managers to use these models effectively (Lavy and Jawadekar, 2014). In addition, most projects do not require the LOD 500 which includes the highest level of detail information and geometry. Therefore, the models used during the operation phase may not provide the comprehensive information needed to fully leverage AR/VR technologies for time and cost savings. Figure 10 shows the predictions of the respondents who use VDC tools in terms of potential time and cost savings by adopting AR/VR technologies throughout the project life cycle. Detailed descriptive statistics can be found in Supplementary Appendix Table SA7.

5.5 Different sectors in the AEC-FM industry

The responses on the adoption rate of AR/VR technologies across different project types were analyzed, as shown in Figure 11. The results indicate that the commercial and institutional sectors have utilized AR/VR more extensively than other sectors within the AEC-FM industry in recent years. This finding confirms the second hypothesis of the research. One participant also shared their perspective on this topic, stating:

"I think the institutional sector would be one of the areas that can benefit the most because the complexity of these projects is much greater compared to high-rise residential copy-paste projects. I also think the next step would be in the commercial sector. So, in these two areas, I believe that there are good grounds for improvement in AR/VR."

However, it should be noted that the commercial sector experienced the most significant decline compared to all other sectors, with a 20% reduction in adoption between 2018 and 2023. As the initial enthusiasm and hype surrounding AR/VR technologies fade, the limitations and challenges of these technologies may become more apparent, leading to a reassessment of their practical value in commercial projects. The high costs associated with implementing AR/VR solutions and uncertainty about the return on investment could be other possible reasons for this result over time. In contrast, the industrial sector experienced the most significant increase in the adoption of AR/VR technology, with a remarkable 75% growth between 2018 and 2023. The industrial sector, often at the forefront of adopting new technologies to enhance efficiency and safety, may have driven this increased integration of AR/VR. The complexity and scale of industrial projects also provide an ideal situation for these technologies to improve visualization and control processes. The institutional sector, which encompasses educational, healthcare, and government buildings, has shown a relatively stable adoption of AR/VR technologies, as evidenced by the slight fluctuation in adoption rates between 2018 and 2023. In educational and healthcare institutions, AR/VR technologies have been particularly useful for visualizing spatial layouts and simulating real-world environments, which can lead to more informed decision-making and increased satisfaction among end users such as students and patients. These findings also align well with the sectors predicted by the project stakeholders to adopt AR/VR technologies extensively over the next 10 years, as shown in Table 13.

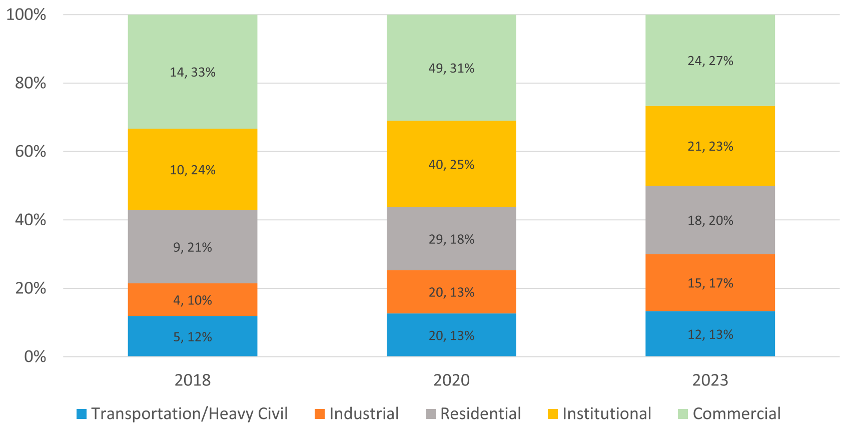

FIGURE 11
AR/VR technology adoption across different project types.

5.6 Expanding AR/VR applications in VDC and project collaboration

Although the survey results, as shown in 6, indicate that VDC applications such as clash detection and model validation are top priorities for companies, there remains significant potential for expanding AR/VR's role in the AEC-FM industry. By integrating AR/VR into community engagement efforts, project stakeholders can experience immersive 3D visualizations of projects, allowing a better understanding of design intent and spatial configurations before construction begins. This level of involvement can help address concerns early in the project cycle and foster more informed feedback. As one participant mentioned:

"It is much easier for clients to see and understand, that is what you are talking about. In some cases, when they see it in a model or in a rendering, it just looks pretty. But when they see it in VR and actually enter the space, they might say, 'Oh, this is too tight. I did not expect the furniture to be so close.' So, they give us feedback like, 'Let's make more space.'

Additionally, AR/VR can support value engineering by providing an interactive platform to explore multiple design and system configurations in real time. Engineers and designers can test various scenarios to identify cost-saving opportunities while maintaining the desired performance, reducing rework, and improving efficiency. These expanded applications of AR/VR could help address gaps in VDC, such as facility management and safety training, where immersive, experiential tools can deliver substantial value.

6 Conclusions and future vision

More than 200 experts in the AEC-FM industry provided valuable insights into trends in the adoption of AR/VR technologies within the AEC-FM industry through surveys conducted in 2018, 2020, and 2023, highlighting both the opportunities and challenges these technologies present. The 2018 survey serves as a pre-pandemic baseline, capturing AR/VR adoption trends without the disruptions caused by COVID-19. In contrast, the 2020 survey was conducted during the early stages of the COVID-19 pandemic, reflecting the uncertainty and operational challenges that the industry faced under strict social distancing guidelines. By 2023, with most federal and state COVID-19 restrictions lifted, the data revealed how the industry adapted to the post-pandemic environment. These three rounds of surveys provided a comprehensive view of how external disruptions and evolving industry conditions have impacted the adoption of AR/VR technologies in the AEC-FM industry over time.

While early survey results in 2018 showed strong optimism regarding AR/VR technologies in AEC-FM, our most recent findings suggest a decline in enthusiasm among industry professionals. This shift may be attributed to the initial hype surrounding AR/VR in 2018, which led to inflated expectations, followed by a realization of the challenges associated with implementation. Specifically, our data indicate that uncertainty regarding the cost-benefit ratio, a lack of clear understanding of AR/VR's tangible advantages across different project types, and integration complexities have contributed to tempered expectations. As a result, AR/VR investments may increasingly be perceived as non-essential by AEC-FM firms, especially those prioritizing cost-effective solutions. In addition to the quantitative data collected through surveys, we conducted qualitative interviews that provided deeper insights into the complexities of AR/VR adoption in the AEC-FM industry. A thematic analysis of the interviews revealed three major themes that are central to understanding the barriers and applications of AR/VR technologies in practice. These themes provide valuable insights into (i) key barriers to implementing AR/VR solutions, (ii) the most frequent AR/VR applications, and (iii) major technical challenges that hinder the growth and integration of AR/VR in everyday operations within the industry.

Through comprehensive quantitative surveys and qualitative interviews, we explored the potential applications of AR/VR technologies, focusing on their impact on project phases such as design, construction, and operations. Our findings reveal that while initial optimism surrounding AR/VR technologies was high, particularly in 2018, the confidence level of respondents about the future of AR/VR technology adoption has decreased over time. This change in optimism can be attributed to a more practical understanding of the limitations, time, and costs associated with AR/VR integration. Furthermore, the industry's preference for outsourcing AR/VR-related tasks, combined with advancements in VDC technologies, has contributed to a reduction in the need for in-house AR/VR expertise.

The survey results revealed a decrease in the number of employees with AR/VR expertise from 2020 to 2023, reflecting a shift toward outsourcing specialized tasks or focusing more on cost-effective solutions like VDC. Advancements in AR/VR hardware and software packages have made these systems more user-friendly, reducing the need for extensive technical expertise. Furthermore, the rise of specialized VDC subconsultants and the outsourcing of AR/VR tasks to international markets, particularly in countries with lower labor costs, has further decreased the need for in-house AR/VR experts. Mega-companies also experienced a significant reduction in the number of AR/VR experts across survey years, indicating a strategic shift toward VDC technologies, which they perceive as more viable and cost-efficient to achieve their long-term operational objectives.

Age and gender did not significantly influence perceptions about the future adoption of AR/VR technologies. Our findings reveal that both younger generations (younger than 45 years) and older generations (45 or older), as well as both male and female respondents, shared similar levels of confidence about the future of AR/VR technology adoption, contradicting the expectation that owners and top management of the AEC-FM industry, typically belonging to the older generation group, would be more resistant to adopting AR/VR technologies. Furthermore, industry trends indicate a shift in onboarding strategies, where younger professionals first gain project management experience before transitioning to VDC roles. This approach underscores a strategic focus on building practical hands-on expertise before introducing advanced digital tools such as AR/VR.

Predictions of AR/VR's time and cost-saving potential have also become more conservative over time. Although initial predictions in 2018 were optimistic, the data suggest that as AR/VR technologies were integrated into projects, increased practical applications and growing experiences with AR/VR technologies have tempered these expectations by 2023, leading to more conservative assessments of their benefits.

The analysis of AR/VR adoption rates across different project types reveals that the commercial and institutional sectors have utilized these technologies more extensively than other sectors within the AEC-FM industry in recent years. However, the commercial sector has experienced the most significant decline in adoption rate from 2018 to 2023, probably due to high implementation costs and uncertainties about return on investment. In contrast, the industrial sector saw an increase in AR/VR adoption during the same period, driven by the need for enhanced visualization and control in complex large-scale projects. The institutional sector, including educational, healthcare and government buildings, maintained relatively stable adoption rates, with AR/VR proving particularly valuable for visualizing spatial layouts and simulating real-world environments to improve decision-making and user satisfaction. For AR/VR adoption to expand further, it will be crucial to overcome barriers such as a lack of organizational champions to push for the integration of new technologies and to ensure that the benefits offered by this technology align with a company's internal needs.

Moving forward, expanding the applications of AR/VR in areas such as community engagement, value engineering, and safety training can unlock further potential for these technologies. Integrating AR/VR into community engagement efforts can provide stakeholders with immersive 3D visualizations, offering a clearer understanding of design intent and spatial configurations before construction begins, thus addressing concerns early in the project cycle and fostering better feedback. In addition, AR/VR can improve value engineering by enabling real-time exploration of multiple design and system configurations, helping engineers and designers identify cost-saving opportunities, reduce rework, and improve efficiency.

Despite our efforts to engage a representative cross-section of the industry, we acknowledge certain limitations in our sampling process. First, our primary distribution methods—email and LinkedIn—may have excluded professionals who are less active on LinkedIn. This could lead to the underrepresentation of field-based construction professionals who may not frequently participate in online professional networks. Second, while our survey targeted professionals across North America, it did not employ randomized or stratified sampling techniques to ensure proportional representation of all industry subgroups. To mitigate these uncertainties in future research, a more structured sampling approach could be implemented. Although this study provides a comprehensive analysis of the trends in AR/VR adoption between 2018 and 2023, some areas remain to be explored in future research. Although the 2023 survey captures post-COVID responses, it does not fully reflect the late impact of the pandemic on AR/VR adoption. In the next rounds of surveys, we plan to evaluate the longer-term effects of COVID-19 and the post-pandemic recovery on the AR/VR adoption rate of the AEC-FM industry, providing insight into how these shifts have shaped the industry's digital transformation strategies. Another key area for future work is to focus on specialized subconsultants with VDC expertise. Future work should explore the role of these subconsultants in the AEC-FM industry, including how their expertise shapes AR/VR implementation and the potential benefits and risks of relying on external consultants. Moreover, advancements in hardware and software, such as those made by companies like Autodesk, have contributed to making AR/VR systems more user-friendly and automated. Future research should investigate the role of these technology providers in simplifying AR/VR integration and examine how their innovations are reshaping the broader AR/VR landscape in the AEC-FM industry. By analyzing the contributions of key hardware and software providers, we can better understand the trends and technological developments that influence the future of AR/VR adoption.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SF: Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing. SS: Formal Analysis, Methodology, Writing – original draft, Writing – review and editing. OS: Conceptualization, Formal Analysis, Methodology, Validation, Writing – original draft, Writing – review and editing. AH: Conceptualization, Formal Analysis, Methodology, Validation, Writing – original draft, Writing – review and editing. VB: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2025.1580639/full#supplementary-material

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