

REVIEW ARTICLE

Open Access



Augmented reality in architecture and construction education: state of the field and opportunities

Aso Hajirasouli^{1*}  and Saeed Banihashemi²

*Correspondence:

a.hajirasouli@qut.edu.au

¹ School of Architecture and Built Environment, Queensland University of Technology, Brisbane, Australia

Full list of author information is available at the end of the article

Abstract

Over the past decade, the architecture and construction (AC) industries have been evolving from traditional practices into more current, interdisciplinary and technology integrated methods. Complex and intricate digital technologies and mobile computing such as simulation, computational design and immersive technologies, have been exploited for different purposes such as reducing cost and time, improving design and enhancing overall project efficiency. Immersive technologies and augmented reality (AR), in particular, have proven to be extremely beneficial in this field. However, the application and usage of these technologies and devices in higher education teaching and learning environments are yet to be fully explored and still scarce. More importantly, there is still a significant gap in developing pedagogies and teaching methods that embrace the usage of such technologies in the AC curricula. This study, therefore, aims to critically analyse the current state-of-the-art and present the developed and improved AR approaches in teaching and learning methods of AC, addressing the identified gap in the extant literature, while developing transformational frameworks to link the gaps to their future research agenda. The conducted analysis incorporates the critical role of the AR implications on the AC students' skillsets, pedagogical philosophies in AC curricula, techno-educational aspects and content domains in the design and implementation of AR environments for AC learning. The outcomes of this comprehensive study prepare trainers, instructors, and the future generation of AC workers for the rapid advancements in this industry.

Keywords: Digital pedagogy, Immersive pedagogy, Digital technology, Emerging technology, Augmented reality, Design and architecture pedagogy, Construction pedagogy

Background

The traditional teaching and learning approaches involve lecture handouts, rote memorisation and note-taking. In this teaching environment, educators and instructors are the centres of the model (teacher-centred learning), and students passively receive information. Lord (1999) argued that learners and students in such teaching and learning environments often do not acquire the ability to apply their skills in different manners and answer questions asked in a different way to what was taught in the class. This

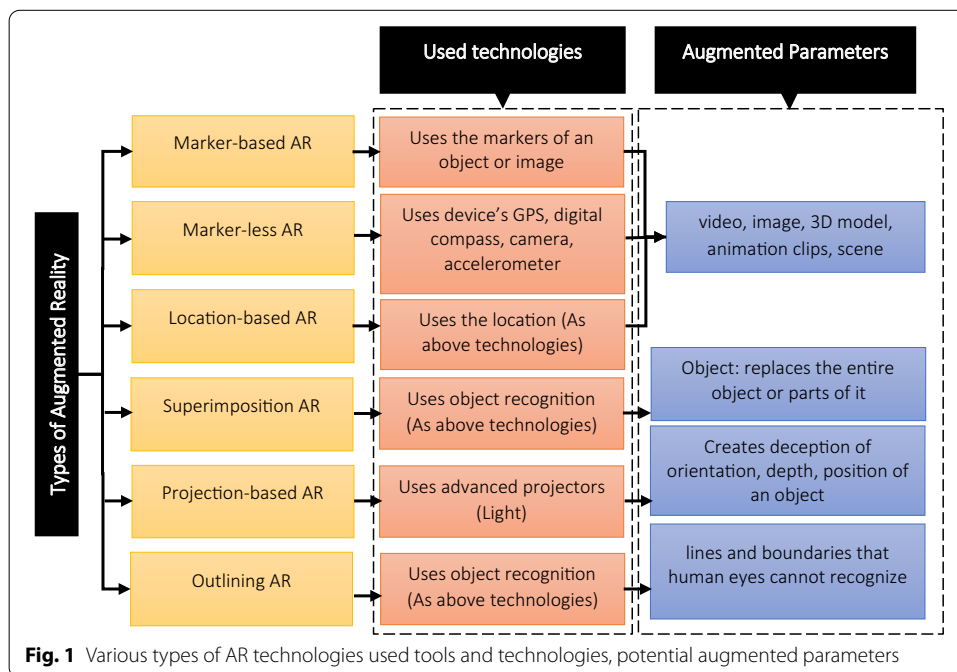
impacts student's ability to recall and retain knowledge and information learned during their education (Lord, 1999; Luo & Mojica Cabico, 2018). Similarly, Khuzaimah and Hassan (2012) and Hartless et al. (2020) argued that in architecture and construction (AC) traditional education methods, knowledge transformation happens using manuals or standard operating procedures, which is focused on the core and explicit knowledge development. This argument further alludes to the lack of hands-on and on-site experience and knowledge that students can only acquire by being exposed to the project site. "While explicit knowledge is undoubtedly important for the next generation of industry practitioners to have, tacit knowledge, which is typically developed over years of experience [...] may be especially critical as current industry members with years of experience, and tacit knowledge, retire" (Hartless et al., 2020, pp. 04,020,002–04,020,002). Although this conventional method has been proven to be inefficient and often outdated and not highly effective, it is still being practised in most institutions and schools (Shirazi & Behzadan, 2015a, 2015b).

Various research in education has emphasised the significance of learning in a blended environment where traditional and technology-based learning and teaching methods are combined (D'Souza et al., 2013). It has been suggested that the addition of technology-based supplementary pedagogical tool(s) to the conventional and traditional methods of teaching can be an ideal solution to the issues and problems involved in traditional teaching and learning for AC (Shirazi & Behzadan, 2015a, 2015b). According to Brown (2000) and Lave and Wenger (1991), digital and innovative technologies that facilitate the customised delivery of knowledge and information can significantly improve student's ability to understand and learn the provided materials (Brown et al., 1989; Lombardi, 2007). More recently, immersive technologies such as augmented reality (AR) and virtual reality (VR) have been recognised as effective and supplementary teaching tools that could address the issues and gaps of the conventional teaching methods to a great extent (Di Serio et al., 2013; Elkoubaiti & Mrabet, 2018; Sánchez et al., 2013, 2015).

VR has been extensively covered in the existing literature. Its application requires more advanced, expensive and specific tools, gadget, and devices, while AR technology can be developed and implemented using off-the-shelf and widely available and accessible tools, software and hardware. Furthermore, the review of the literature indicated that AR is still considered a relatively novel tool requiring further investigation in being practically, efficiently and appropriately embedded and implemented into the AC curriculum and its pedagogical frameworks. Besides, AC curriculum is directly connected to the real world, and establishing stronger links with industry is critical (Diao & Shih, 2019; Wang et al., 2013). The concept of AR, derived initially from VR, refers to overlaying computer-generated virtual objects and images over the real-world and physical context to produce a mixed world reality (Jiao et al., 2013). In another definition, AR is described as 'Reality – Virtuality Continuum', or a place on a continuum of interfaces, which spans from the real to virtual environment. Though, in AR, this continuum is closer to the real environment than the virtual environment, compared to VR (Milgram & Kishino, 1994). Fazel and Izadi (2018) defined AR as a line between the virtual and real-world that overlays supplementary and additional virtual information over real objects and senesces and, therefore, enhances our perception of the real world (Azuma, 2015; Fuge et al., 2012; Yang et al., 2013). In fact, the most important characteristic of AR which makes

it very suitable tool to be used in AC education is its ability to link the virtual and real worlds. Hence, students' ability in comprehending and converting information between the real and virtual world is critical in AC learning processes. The application of AR can additionally provide students with the opportunity to engage in the real world context, which supersedes the teaching methods that are confined and restricted to traditional classroom learning (Chen et al., 2011; Diao & Shih, 2019; Kamarainen et al., 2013; Milligram et al., 1995; Wang et al., 2013). Cao et al. (2018) stated that with the advantage AR-based teaching offers over the traditional teaching methods, such as informatization, visualisation, intelligence, and convenience, it can soon replace the conventional teaching methods.

Generally, there are various types of AR technologies, that are being categorised based on the complexity of the deliverable, including, marker-based AR, marker-less AR, location-based AR, superimposition AR, projection-based AR and outlining AR. Each of which uses various devices, tools and technologies for object and location recognition and augmentation process. Various parameters can be augmented into the real-world environment depending on the desired and required outcome of the AR project. The augmented parameters can be animation clips, videos, 3D models, images, scenes, addition of orientation, complete and partial objects replacement, depth and position to already existing objects and boundaries and lines that human eyes cannot recognize (Fig. 1). Mostly, developing an AR-based technology includes platforms, interfaces, and tools. Platforms can be mobile-based or station-based, PC-based, or smartphone-based, wired or wireless, or the head mounted device (HMD) or hand-held device (HHD). Utilised interfaces can include visual enhancement manipulation or hands-on and practical learning. Various tools can be used depending on the nature of the subject and the level of courses to be taught. Off-the-shelf packages or software development kits (SDK) can be utilised for customized subject learning or general knowledge and experience



delivery, which can be used for general 3D operation or enhancing fundamental course learning. “Related interfaces can be either text or with assembly, movement, or rotation made as a whole or part of a set of 3D geometries”. AR-mediaTM, ARToolKit, Junaio Layar Aumentaty Metaio Creator and String are the platforms used for this purpose. However, AR-mediaTM, ARToolKit, and Junaio have appeared to be the most commonly used platforms. AR-mediaTM has the capability of combining with a wide variety of 3D modelling software; Junaio can be used on various system platforms; and ARToolKit is one of the earliest AR open-source software (Bastug et al., 2017; Diao & Shih, 2019; Elkoubaiti & Mrabet, 2018; Farrell, 2018).

AR technology can provide an effective tool and environment for learning about contents of the materials, dangerous situations, complex spatial concepts, astronomical events, and abstract subjects (Shelton & Hedley, 2002; Turan et al., 2018). Therefore, currently, AR is being utilised extensively in every stage of education from K-12 to higher education, and in a wide range of disciplines in higher education (Akçayır & Akçayır, 2017; Turan et al., 2018). For example, AR is considered as an effective technology in geography education, as it can provide excellent opportunities for viewing and comprehending 3D terrains (Carbonell Carrera & Bermejo Asensio, 2017; Turan et al., 2018). In geology, AR technology can be invaluable in enhancing students learning, interest, and engagement by providing game-like and simulative field trips, using convenience, accessible and low-cost tools (Bursztyn et al., 2017). In transport education, it has been confirmed that the application of AR technology assists with facilitation of learning processes by providing more exciting and engaging learning and teaching environment. “Implementation of [AR in transport education] gives more information about the object being studied, information about on shapes, textures, and provide more visualization for the object” (Pranoto & Panggabean, 2019, p. 506). In urban planning studies, AR can be extremely helpful in providing an enhanced level of spatial understanding by enabling the projection of virtual 3D buildings in the real context of cities and streets (Cirulis & Brigmanis, 2013).

AR-based items can also be applied to future curriculum of AC through a number of methods, including object and element modelling, mainly utilized for visualization of drawings, books and textbooks with the application of AR. These are to form a connection between the virtual and the real world and process simulation which is utilised for the process flow simulation in real-time; training and gaming. However, the literature indicates a significant gap in the body of knowledge regarding comprehensive review and analysis on the pedagogical and technical contributions of AR towards AC teaching, training, and education.

This study, therefore, aims to develop a state-of-the-art and critical review of AR practices in the teaching and learning context of AC industries and present conceptual frameworks of its application towards the future of work and education in AC implementation. It also aims to identify the gaps of the conventional methods of teaching in the field and its lack of response to the Industry 4.0 principles, and investigate the ways that AR-based technologies can mitigate these shortcomings in the context of higher education. It also highlights the most common technological processes and frameworks being used for the application and implementation of AR in the curriculum. The result of data analysis is also used to develop two principal frameworks of the AR applications

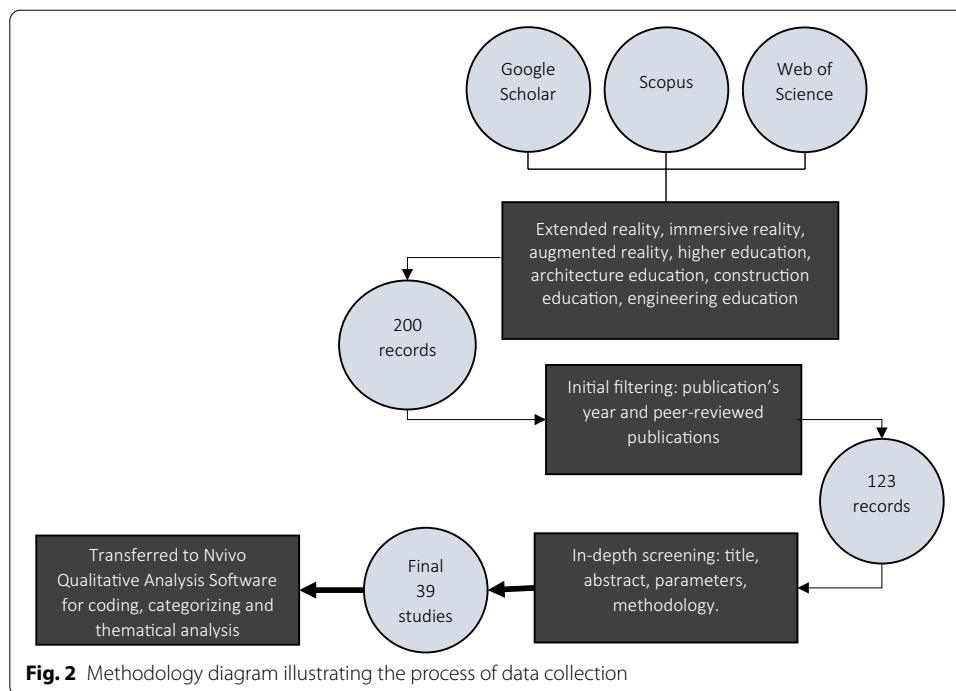
in AC higher education. It is of further intention to spark future research agenda based on the current gaps and voids in the extant literature.

Methods

This study uses a systematic literature review technique to analyse the academic publications from the first of 2010 to the mid of 2021, to investigate and present the state-of-the-art review of AR applications in the tertiary teaching and learning methods of AC industries. A search protocol was established to collect all the appropriate articles related to the topic. A thorough desktop search was performed under the “title/ abstract/ keyword” field of the, Scopus, Google Scholar, and Web of Science. This decision was mainly made due to the ‘peer review’ credibility, reliability, in addition to the comprehensiveness of the indexed platforms of these databases. To obtain the required volume of reliable and credible publications were iteratively searched utilising different search terms with similar meaning and synonyms. The terms applied for this search included extended reality, immersive reality, augmented reality, higher education, architecture education, construction education and engineering education and their combinations. Some of the boolean operators used for the search are (TITLE-ABS-KEY (augmented AND reality) AND TITLE-ABS-KEY (higher AND education) AND TITLE-ABS-KEY (architecture) AND TITLE-ABS-KEY (construction AND engineering)), (TITLE-ABS-KEY (augmented AND reality) AND TITLE-ABS-KEY (higher AND education) AND TITLE-ABS-KEY (architecture) OR TITLE-ABS-KEY (construction AND engineering)), (TITLE-ABS-KEY (augmented AND reality) AND TITLE-ABS-KEY (architecture AND higher AND education) AND TITLE-ABS-KEY (construction AND engineering AND higher AND education)). To ensure the reliability and accuracy, searching in different databases utilising equivalent terms continued until the saturation occurred after the third in-depth search. This stage of search further involved a reverse search technique, or as described by Wohlin (2014), snowballing technique. Additional sources and papers were collected from the cross-references and the citations in the selected papers.

Practical screening was then applied to explicitly select the papers that were appropriate for the scope of this work and for review, and also, to determine, which papers were eliminated without further examination (Okoli & Schabram, 2010). This round of screening involved in filtering the papers based on their titles and excluding materials that were not relevant. Afterward, the abstracts of the selected papers were carefully reviewed to identify their rigour, depth and authenticity of their research approaches. Quality appraisal was the next stage, to evaluate each paper based on a grid system (Fink, 2019). Each quality criterion has a yes or no answer, and if a paper did not meet one of the set quality criteria, then the article was excluded (Fig. 2).

Once the paper selection stage was completed, the selected 39 articles were then imported into Nvivo Qualitative Data Analysis software for data coding and analysis process. Thematic analysis was used in order to analyse the collected data of this study since it is one of the commonly accepted data analysis techniques in qualitative studies (Boyatzis, 1998; Hajirasouli & Banihashemi, 2020; Hajirasouli et al., 2021; Miles et al., 2013). It is suggested that the thematic analysis enhances the reliability and rigour of a qualitative study utilising both inductive and deductive approaches in identifying codes and themes within the data (Hajirasouli, 2015). To confirm the consistency of the



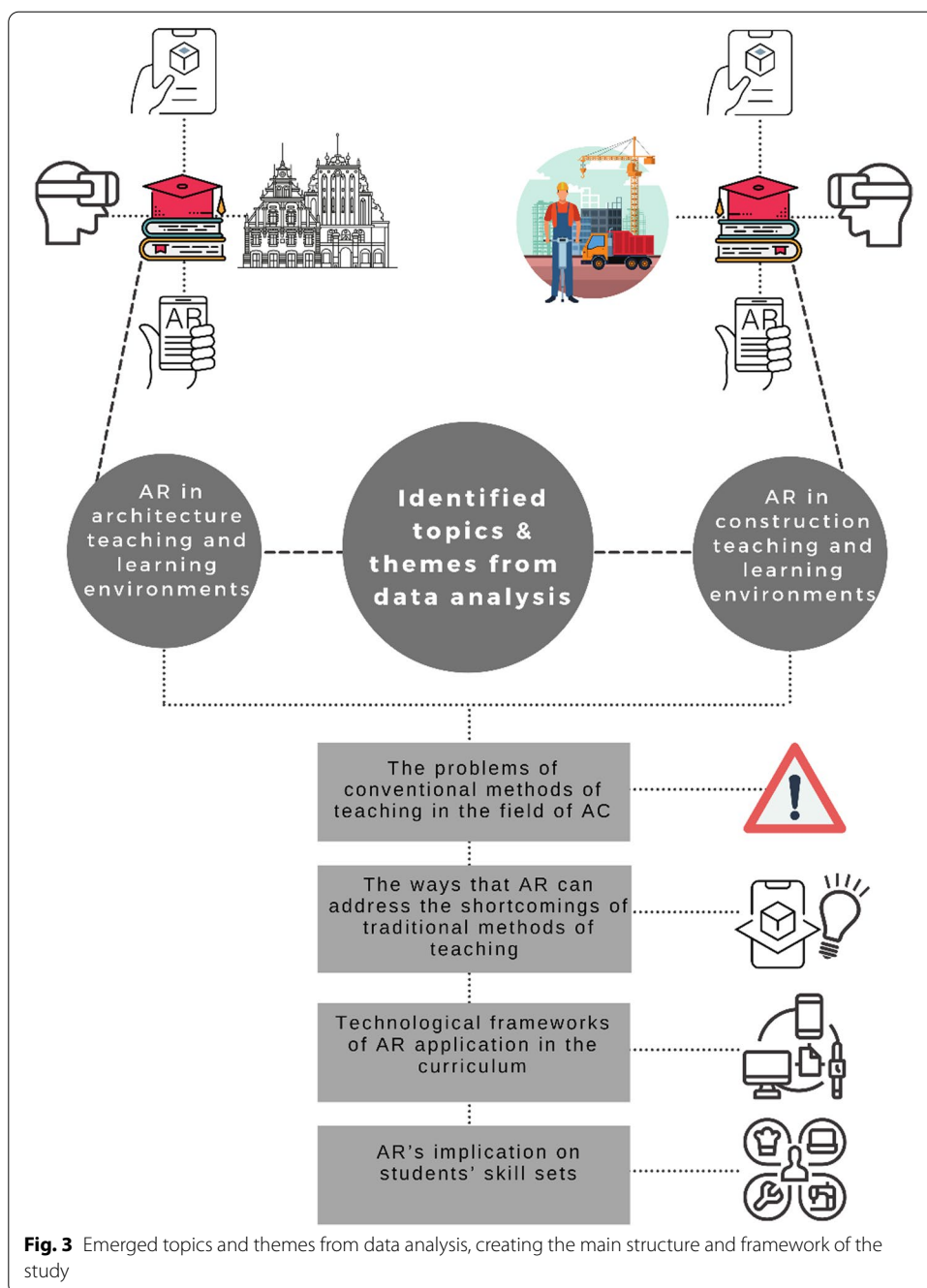
emerging codes, they were constantly compared with the data. New insights and interpretations were also recorded and subsequently coded. Three coding methods of grammatical, elemental, and exploratory were utilised (Saldaña, 2015). The emerged codes relevant to the usage of AR technology in AC higher education context were reorganised and grouped to form categories according to the similarity of their concepts and meanings and to create a comprehensive synthesis of the data (Allen, 2017; Given, 2008). The emerged categories were then regrouped to generate the prevailing themes based on their specific field of study and education. The following themes were the results of data analysis (Fig. 3):

- The problems of conventional methods of teaching in the field of AC
- The ways that AR can address the shortcomings of traditional methods of teaching in the field
- Technological frameworks of AR application in the curriculum
- AR's implication on students' skillsets

Results and discussions

Descriptive results

This section presents a comprehensive investigation of the literature, as well as the result of the thematical data analysis. The descriptive statistics of the retrieved and reviewed literature are presented in Figs. 4 and 5. Figure 4 indicates an overview of the 39 reviewed papers based on the number of publications per year. It can be seen that 2012 and 2013 have the highest number of publications related to this area. Figure 5 shows the sources of 39 selected papers. Figure 6 showing the numbers of publications per study area, and



indicating that more research has been conducted in the area of AR in construction education compared to architecture education. Finally, Table 1 shows an overview and summary of the most used AR technologies in the reviewed articles.

Pedagogical review: appropriate teaching philosophies for AR implementation

With reference to the theoretical backgrounds of the emerging teaching and learning methods, Constructivism is one of the teaching methods that has been discussed in many of the existing literature as one of the most suitable pedagogies for the application

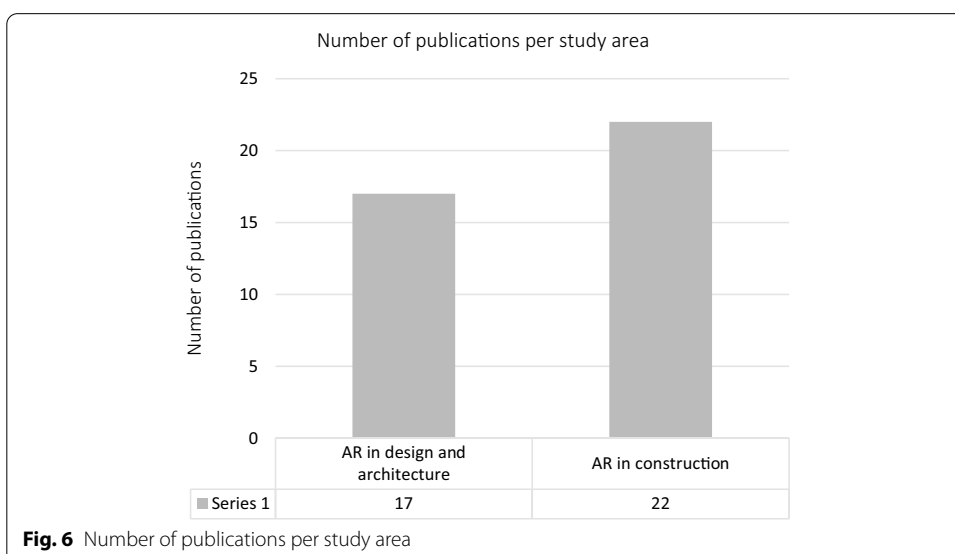
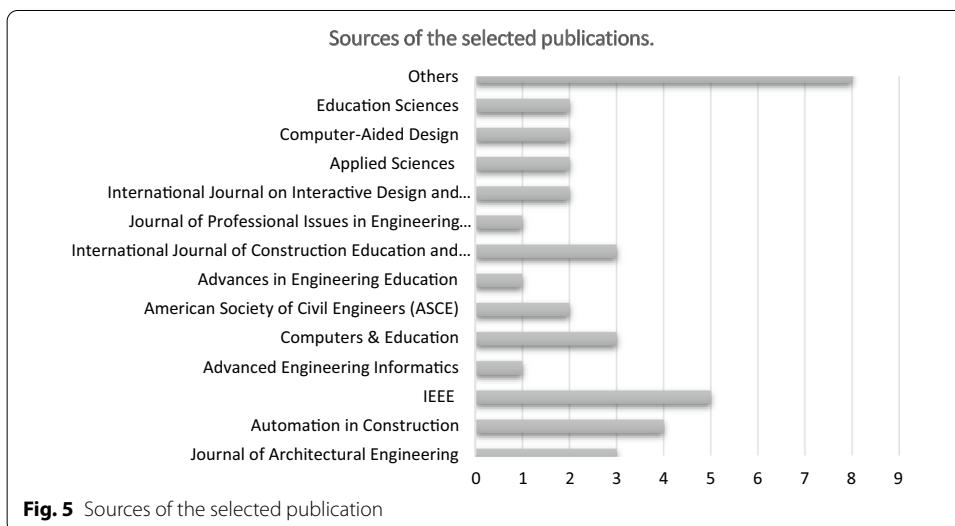
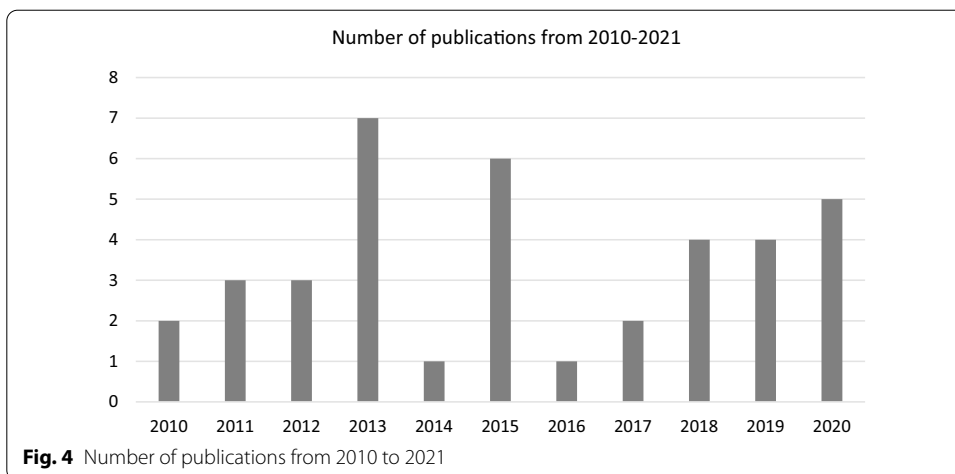


Table 1 A summary of AR applications and technologies in AC education

Title	Authors	Year	AR features-type	Building tools-software	Assets-augmented parameters	Hardware
Teaching Building Sciences in Immersive Environments: A Prototype Design, Implementation, and Assessment	Vassigh, S. Davis, D. Behzadan, A. H. Mostafavi, A. Rashid, K. Alhaffar, H. Elias, A. Gallardo, G	2020	Marker-based-AR	Unity 3D, compasses, accelerometers, and GPS	3D objects, texts, notifications (beams, columns, and the foundation with steel reinforcements and connection details; additional information such as type, size, and weight)	HHD with embedded sensors such as gyroscopes, marker
Evaluating the use of augmented reality technology to improve construction management student's spatial skills	Kim, Jeffrey Irizarry, Javier	2020	Marker-based-AR	Autodesk's 123D Design, Augment	Paper lab assignment	Marker, HHD – Apple iPad® with installed AR software, marker
A Conceptual Framework for Enriching Architectural Classroom with Mobile Augmented Reality	Hosny, Samir Sadek Abdel Mohsen, Sherif Mansour, Shireen Adel	2019	Marker-based-AR	3Ds Max 2014, Maya and Google Sketch up, and AR-media™ V2.3 plug-in and AR Media Player from Google Play on mobile device	3D learning content, annotations,	HHD- Samsung Galaxy S6 Edge cell phone equipped with 16MP camera and Android 5.0.2 Lollipop software, marker
Cross-reality environments in smart buildings to advance STEM cyberlearning	De Amicis, R. Riggio, M. Shahbaz Badr, A. Fick, J. Sanchez, C. A. Prather, E. A	2019	Marker-less-AR	BIM, CAD	Building information	HMD (Helmet), consisting of a mini projector and an iPod touch mounted on a security helmet, mouse and keyboard, 3D controllers, or multi-touch displays
Development and evaluation of an augmented reality learning tool for construction engineering education	Luo, X Mojica Cabico, C. D	2018	Marker-based-AR	AutoDesk Revit, Sketchup, Unity, Vuforia	3D objects (various bridge structure)	HHD, marker
A Novel Augmented Reality Guidance System for Future Informatization Experimental Teaching	Cao, Yanpeng Tang, Yongming Xie, Yi	2018	Marker-less-AR	Unity3D, Vuforia SDK, android platform	Image targets and 3D multi-target configurations	EPSON BT-350 AR glasses
Toward future 'mixed reality' learning spaces for STEAM education	Birt, James Cowling, Michael	2017	Marker-based-AR	Unity3d, Vuforia	3D spatial object	Samsung and a BYOD mobile phone, marker

Table 1 (continued)

Title	Authors	Year	AR features-type	Building tools-software	Assets-augmented parameters	Hardware
Augmented reality gaming in sustainable design education	Ayer, Steven K Messner, John I Anumba, Chimay J	2016	Marker-based-AR	Unknown	3D objects, exterior wall designs	HHD, marker
Augmented reality visualization: A review of civil infrastructure system applications	Behzadan, A. H Dong, S Kamat, V. R	2015	Location-based-AR	Unknown	3D objects	Attitude of the camera (Electronic Compass, Location of the world origin (RTK GPS), Lens and aspect ratio of camera (Camera), Perspective projection matrix
Geo-located teaching using handheld augmented reality: good practices to improve the motivation and qualifications of architecture students	Riera, Albert Sánchez Redondo, Ernest Fonseca, David	2015	Geo-location-based AR	SketchUp and 3dsMax, Layar	Volumetric models and texture designs	Mobile device equipped with a camera, GPS and 3G connection, Layar Viewer
Design and assessment of a mobile augmented reality-based information delivery tool for construction and civil engineering curriculum	Shirazi, A Behzadan, A. H	2015	Marker-based-AR	AREL extensible markup language (XML), AREL JavaScript, Junaio	3D) objects and other virtual multimedia (eg., sound, video, and graphs)	HHD-Android and iOS operating systems, marker
Content Delivery Using Augmented Reality to Enhance Students' Performance in a Building Design and Assembly Project	Shirazi, Arezoo Behzadan, Amir H	2015	Marker-based-AR	Augmented reality experience language (AREL), Junaio (1) the static extensible markup language (XML) to define the content and linkages, (2) the Javascript logic to define dynamic parts such as user interactions, and (3) the content itself which includes 3D objects, images, and other multimedia files	3D objects, images, and other multimedia	HHD- Mobile device, marker
Using augmented reality prototypes in design education	Chandrasekera, Tilanka	2014	Marker-based-AR	3Ds Max/Sketchup, BuildAR	3D objects, and other multimedia	HHD (with built-in webcam) and a marker

Table 1 (continued)

Title	Authors	Year	AR features-type	Building tools-software	Assets-augmented parameters	Hardware
Enabling discovery-based learning in construction using telepresent augmented reality	Behzadan, Amir H Kamat, Vineet R	2013	Marker-based-AR	Unity3D, Vuforia	3D objects, video, material	2Dmarker AR, HMD containing a GPS device + smart glove equipped with a touch sensor, marker
Impact of an augmented reality system on students' motivation for a visual art course	Di Serio, Ángela Ibáñez, María Blanca Kloos, Carlos Delgado	2013	Marker-less-AR Superimposition AR	Popcode	Digital data to images of the masterpieces Images and information	HHH (with built-in webcam)
EcoMOBILE: Integrating augmented reality and probeware with environmental education field trips	Kamrainen, Amy M Metcalfe, Shari Grotzer, Tina Browne, Allison Mazzuca, Diana Tutwiler, M Shane Dede, Chris	2013	Marker-based-AR	FreshAIR, augmented reality development platform (playfreshair.com), Vuforia	Media and information	MoGo Mobile, mobile wireless devices, marker
Augmented reality in architecture degree: new approaches in scene illumination and user evaluation	Redondo Dominguez, Ernesto, Fonseca Escudero, David Sánchez Riera, Alberto Navarro Delgado, Isidoro	2012	Marker-based-AR	Gimp, SketchUP, Autocad, 3Ds Max, Build-Ar, Mr Planet, Ar-media Inglobe Technologies, Junaio	3D models and objects	HHH, iPhone and Android Os, laptops or school notebooks, marker
A collaborative augmented reality-based modelling environment for construction engineering and management education	Behzadan, Amir H Iqbal, Asif Kamat, Vineet R	2011	Marker-based-AR	Unity3D, Vuforia	Contextual information in textual or graphical format	2Dmarker AR head-mounted display (HMD) containing a GPS device + smart glove equipped with a touch sensor, marker
Use of tangible and augmented reality models in engineering graphics courses	Chen, Y. C. Chi, H. L. Hung, W. H. Kang, S. C	2011	Marker-based-AR	ARToolkitPlus library	3D geometry, 3D objects	HHH (with built-in webcam) and a marker

of digital technologies, AR in this case. Lord (1999) argued that authentic learning happens when the newly received information is being assimilated with previously established and perceived knowledge. This philosophy and method of teaching is known as constructivism, where learning of new knowledge occurs when students build conceptual links and connections with their already existing knowledge in a topic (Behzadan et al., 2011, 2015; Biggs & Tang, 2007). In this teaching method, the emphasis has been given to students and the way they actively build and construct knowledge rather than passively receiving it (Biggs & Tang, 2007; Tynjälä, 1999). Von Glasersfeld (1995) believed that constructivist learning science is focused on two aspects of social and cultural. Bruning et al. (1999) further explained that learners and students actively and constantly build and construct their knowledge in this theory of learning. He emphasised the significance of social interactions in the process of knowledge construction. Constructivism method of teaching enables students to interact actively and collaborate with their peers, grasp and understand new knowledge and information more effectively, and resolve problems stated in different ways (Luo & Mojica Cabico, 2018). Biggs and Tang (2007) similarly argued that active learning enables the learners to become competent, independent, and lifelong learners.

The experiential teaching method is another pedagogy claimed to be suitable and appropriate for AR technology application. AR technology offers various methods and ways to submerge users in educational simulations, where they can practise the acquired theoretical knowledge and concepts by interacting with the environment. Hence, it is suggested that immersive technologies can effectively support the experiential learning theory, where experimentation is the foundation of observation, abstract conceptualisation, reflection and knowledge construction (Santos et al., 2013). Kolb (1984) proposed that experiential learning happens as a cycle of actions, which contains four consequential steps, namely: concrete experience, observation and reflection on the experience, forming abstract concepts, and eventually testing the experience within new context and circumstances. Therefore, it can be suggested that experiential learning is associated with active learning, where learners and students are responsible for creating and constructing their own learning process. In this method of learning, students acquire knowledge by experiment, practice, and reflection on their actions and practise (Kolb, 1984; Santos et al., 2013). "Immersive technologies are transforming all aspects of daily life. In an educational context, augmented reality (AR) and virtual reality (VR) offer the promise of experiential learning, where the real world is enhanced with information and graphics or is completely simulated" (Vassigh et al., 2020, p. 180). Santos et al. (2013) also believed that experiential learning is the most appropriate teaching pedagogy for the application of AR in AC education, due to the experiential nature of the field. They further argued that digital technologies such as AR offers an immersive education simulation in which students and users can interact with the concepts and theories and therefore, are suitable for experiential pedagogy as well as AC education. The integration of immersive environment in traditional AC education has been highly emphasised to provide innovative and creative learning environment which fosters competencies, skills and abilities required for AC degrees. Overall, it can be argued that the application of AR in higher education and AC degrees can be effectively applied for the experiential, discovery-based and constructive pedagogies.

Technical review: AR in construction engineering education

The problems of conventional methods of teaching in construction engineering

The construction industry has not been as proactive as other industries in the adoption and application of digital and innovative technologies. However, with the rapid technological advancements brought by the fourth industrial revolution (Industry 4.0), it is crucial to incorporate skills related to these technologies into construction education (Tayeh et al., 2020). Besides, there is an increasing challenge within the construction industry to improve their productivity, quality, and sustainability while meeting the budget, schedule, and quality expectations at a time when projects are more complex than ever, and their construction processes require high level and measures of technical, spatial, digital and even social skills. The consequences of teaching these skill sets in traditional and conventional construction classes often fall short of meeting the needs of industry (Kim & Irizarry, 2020). The result of data analysis of this study has similarly indicated that there are some gaps and issues in studying construction with conventional teaching pedagogies and methods.

The first issue is the failure to draw the connection between classroom learning to real world context. It was suggested that students fail to apply their learning to the complexities and dynamics involved in a construction project (Arditi & Polat, 2010; Behzadan et al., 2015; Bowie, 2010; McCabe et al., 2000). Other academic studies have showed that the students are not satisfied with the absence of advanced problem-solving tools and digital technologies in the curriculum and course (Behzadan & Kamat, 2013; Behzadan et al., 2015). Lack of socio-technical skills in the conventional construction education has been also mentioned as another problem in this field (Behzadan et al., 2015).

Another significant skill and knowledge required for those in the field of construction in order to deal with the complexities of a construction project is the tacit knowledge. This type of knowledge is defined by the capabilities and understandings of the individuals and is developed during work experiences or when exposed to construction processes on the jobsite. Unlike traditional explicit knowledge which can be taught through manuals, textbooks and in-class examples, this type of knowledge can only be acquired through the exposure to construction process on a job site and therefore requires a more immersive method of teaching. It is suggested that the application of digital technologies can address this gap (Bademosi et al., 2019; Collins, 2010; Khuzaimah & Hassan, 2012; Pathirage et al., 2008; Patil et al., 2020; Sawhney et al., 2000; Woo et al., 2004). Mutis and Issa (2014) has also acknowledged this issue by arguing the lack of appropriate pedagogical methods and materials impacting the ability of educators and instructors to effectively bring those job experiences into the construction classrooms.

Additional identified gap in conventional and today's construction classroom was the problem of mastering the complex relationships of the interdependencies, interactions and constraints involved in complex projects. It has been argued that the understanding of such relationships is crucial for developing a problem-solving learning ability that effectively integrates the interactions and interdependencies with constraints (Mutis, 2015; Sawhney et al., 2000). Likewise, the interactive spatial relationship of construction processes was found as the gap in the conventional methods of teaching where it does not allow the educators to bring experiences of the complex and dynamic spatial relationships of the jobsites into the classrooms. Therefore, the application of more

innovative teaching methods that embraces the rapid changes brought by the Industry 4.0 through implementation of emerging and digital technologies in construction classes is essential.

Technological frameworks of AR application and implementation in construction engineering curriculum and the targeted skill sets

Numerous studies have been conducted to examine the effectiveness of AR application in resolving these challenges using various technical and technological methods, namely Aptitude Tests: Spatial Relations (DAT:SR), FBE Piling AR (PAR), Skope and others. Each of these studies has focused on a specific skill required for enhancement of students' learning experience within construction field. Aptitude Tests: Spatial Relations (AT:SR) technology has focused on student's spatial skill and perception. To implement this technology, Differential Aptitude Tests: Spatial Relations (DAT:SR), Purdue Spatial Visualization Tests: Visualization of Rotation (PSVT:R), and the Mental Rotations Test (MRT) were used. The required tools for this technology were a hand-held mobile device (HHMD – Apple iPad with installed AR software) and paper markers, which were created using a word processor editing application. Users' interaction with the HHMD happens via touch-sensitive feedback on the display of each HHMD that enables them to operate the AR software. The 3D objects of this technology were created using Autodesk's 123D Design. They were then exported to Augment for use in AR software. Augment is a "commercially available mobile software application used to scan a marker and render a 3D model on the screen of a HHMD (Kim & Irizarry, 2020, p. 106). In order to manage and upload the markers and 3D models, website interface was used and to create the correlation, three procedures were followed:

1. a 3D model was assigned to a marker image;
2. the size of the displayed 3D model was identified;
3. the location of the displayed 3D model on the marker was defined.

The effectiveness of this AR technology was then evaluated by students who participated in a study using NASA Task Load Index (NASA TLX) survey. NASA TLX is a commonly employed instrument designed to evaluate and assess workload on six categories of mental demand, physical demand, temporal demand, performance, effort, and frustration. The markers contained information about spatial skills assignment that were designed to replicated the visual assessment methods of PSVT:R, DAT:SR, and the MRT. The outcomes of this research successfully demonstrated the effectiveness of innovative tools and technologies application in constructions classrooms and lab assignments as a teaching aid. Students also confirmed the effectiveness of AR application and noted the 'ease of effort' and indicated their 'satisfaction' of using augmented reality in the curriculum to help them with their spatial skills learning. "It is essential to consider the pedagogy when a shift is made from passive to active learning, especially one that incorporates the use of technology" (Kim & Irizarry, 2020, p. 102). This study suggested the use of active learning approach toward teaching using AR technology, since it is indicated that using visual and collaborative environments can result in a more successful teaching of spatial skills (Maeda & Yoon, 2011).

FBE Piling AR (PAR) is another AR-based technology developed for implementation in construction classroom and focuses on improving students' understanding of construction processes as well as their social and team-work skills. PAR technology was developed using a commonly available augmented reality app, accessible through AppStore or Google Play. This app was then combined with content and additional information about different processes of building construction processes. The construction processes covered by PAR include site establishment, piling, especially piling methods and various types of piling defects and failures, as well as construction information of the entire structure. This technology fosters teamwork and collaboration among students by enabling up to ten people to use it simultaneously. The BIM file used for this experiment included the building's geographic information system (GIS) data, as well as information regarding light detection and ranging (lidar). Sepasgozar (2020) explained that PAR is "an interactive virtual environment that goes beyond the traditional pages of a textbook or PowerPoint and enables the foundation construction process to be explained in 4D (3D spatial models plus time)". For ease of access, PAR was developed in two versions: One version is available on Oculus headsets, and the other version can be downloaded and accessed on smart devices. The accuracy and reliability of this technology was tested in various stages. The result indicated that the application of PAR fostered and encouraged interactive, collaborative and engaging teaching and learning practises and it was perceived well and was highly valuable by both students and educators. Some of the additional benefits of PAR application can be mentioned as:

- "An ability for students to look at the 'anatomy' of the structural foundations of the selected typical 3D building model";
- Inclusion of a simple foundation construction sequence showing the different phases of a pile formation;
- The opportunity for students to interact with information hot spots positioned around the model in 3D;
- Views of the structures and typical failure modes of the foundation piles;
- Visualisation and game experience on students' mobile devices (iPhone 6 s or newer and Android S7 or newer)" Sepasgozar (2020, pp. 31–32).

Skope technology, on the other hand, was developed with a more multidisciplinary approach, while focusing on two major purposes of enhancing students' learning experience and fostering group discussions and interactions. This technology integrates an AR visualisation tool with learning modules containing interdisciplinary content. More specifically, it consists of an AR-Skope that is an AR application; core concepts learning modules, as well as a communication website. The development of this technology was divided into two sections of a user experience (frontend) and a scripting development (backend). To develop this technology embedded sensor devise such as gyroscope was used. Devises with one sensor empirically proven to be an acceptable option for the creation of augmented reality and overlying virtual object into the real contexts. This sensor together with the front-pointing camera of the devises was used to create the most accurate augmented reality. The digital content for this model was created using Unity 3D game engine libraries developed for the C# programming environment. Data related

to the BIM model was imported to an excel spreadsheet. Following this step attributes and information such as image file paths and descriptions were added to the file. An.xml file reader algorithm was then developed to embed this data into the Unity game engine. Once this technology was tested, the result indicated that its application positively impacted and enhanced students' learning experience and knowledge construction and development. The results also confirmed the positive perception and outlook toward using the technology by both educators and students.

Other AR-based technologies focus on enhancing students' cognitive skills. In one of these technologies, construction sites and job sites were simulated into the classroom utilising AR technology, integrated with a layer of computer-generated visualizations, physical context and spatio-temporal constraints of various construction projects and assemblies. The novelty of this approach lies in the usage of real-time data and videos from the site that were amalgamated and superimposed by BIM-based model elements and images. Using this method, the construction sites become "interactive experience subjected to digital manipulation which reinforces and highlights key technique and constructability based concepts" (Bademosi et al., 2019, p. 58). Images and videos were collected during the site visits and were checked for smooth camera positioning and quality. Eventually, the selected videos and images were combined with meticulously chosen augmentation using a video-editing software. Once the augmentation process was completed the content was securely kept on a server. Students who participated in this study were granted the access to these contents. The outcome of this study and experiment indicated that students who used AR technology were more competent in identifying the tasks and elements relating to various structural parts and systems in a building. It also indicated that the application of this technology enhances students' overall cognitive skills. This study further confirmed that integration of state-of-the-art with typical classroom instructions benefits the educators as it provides them "with an advantage as they strive to prepare their students for successful careers in construction" p. 58.

The other AR-based technology that focused on the cognitive workload had a similar approach in developing the technology and consisted of a device with camera, a computer with ARToolkit software, and a paper marker. The virtual model required for this experiment was developed using Revit Structure and 3D Max. Consequently, the ARToolKit connected the virtual model to the marker, and enabled the viewers to view the object from various angles by rotating the marker. This technique is novel in terms of implementation. To implement and test this technology, eye-tracking data was used to assess a developed AR-based learning technology. Cognitive theory of multimedia learning (CTML) was also utilised to quantitatively assess this developed technology. Learner's visual behaviours were tracked, compared, and summarized in a physical model- (PM-) based, a text-graph- (TG-) based, and an AR-based learning environment. During a cognitive testing process, participants' answers and answering times was recorded and compared among three groups. Through this process, participants' eye movements were retracked and recorded utilizing an eye tracker (SMI iView XTM HED at 50 Hz) and Begaze (iView software). The result of this study indicated that both PM-based and AR-based tools foster and promote generative processing, resulting in better learning performance. However, the TG-based group failed to provide the same results. No

significant differences between AR-based and PM-based learning environments could be witnessed, further clarifying the benefits and advantages of AR-based learning environment in construction classroom.

AR's implication/areas of effectiveness on construction engineering students' skillsets

Although various technologies and studies have focused on different skill sets required for a successful engagement in construction education and industry, the big majority of the reviewed papers argued the usefulness of implementing AR-based technologies within the construction teaching and learning environments. The coded and analysed data confirmed that the application of AR technology provides engaging and motivating teaching and learning using immersive contents. Having immersive and interactive contents, it further promotes active students' participation, as well as, creating more effective and entertaining teaching and learning environment. The interactive contents of AR environment further benefits students by isolating them from the distractions of the physical environment. It is also enhancing students' social skills through improving communication channels, engaging them in teamwork and discussion and encouraging collaboration through interaction.

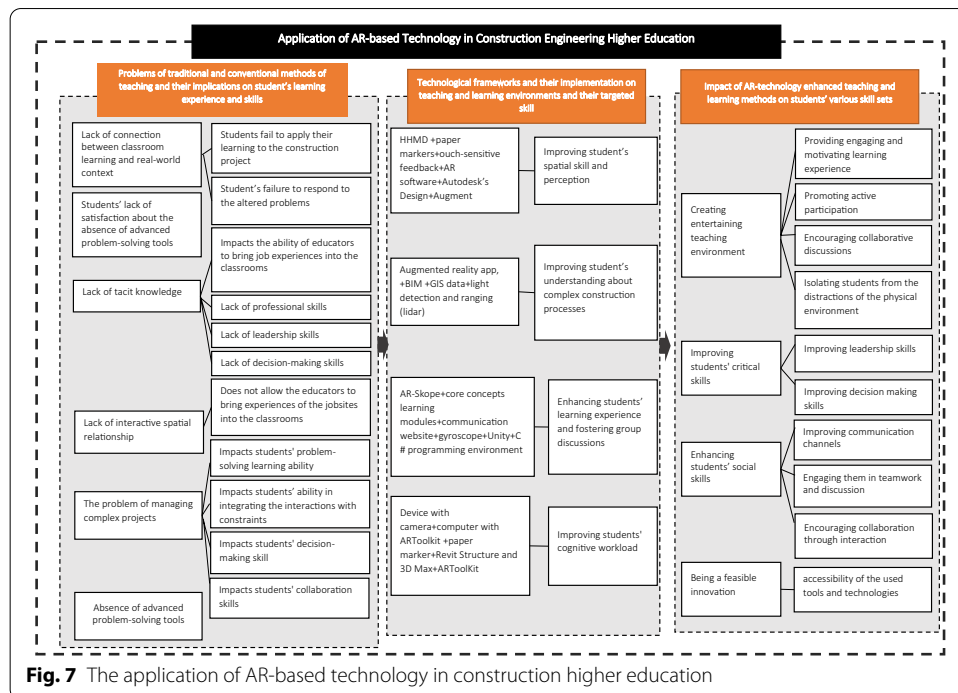
Furthermore, AR technology was identified as a feasible innovation, since it can be accessed through hand-held devices, mobile phones, tablets and other frequently used devices. The users and learners who experienced the AR technology-enhanced teaching and learning environments indicated their satisfaction and perceived this technology well within the higher education context. It also improves student's overall performance by positively impacts on learning both in short-term and long-term. Learning in technology-enhanced environments assist students to learn more persistent through the insertion of three-dimensional virtual contents and to gain more in-depth and long-lasting knowledge (Fig. 7).

Technical review: AR in architecture education

The problems of conventional methods of teaching in architecture

Architectural education has been traditionally focused on paper-based and content-related explicit knowledge in the classroom. However, the architecture industry is rapidly advancing to address the new demand in the building industry, such as new standards and codes, requirements for buildings to be more maintainable, sustainable, resilient, accessible, and responsive to the users' needs. The traditional and conventional teaching and learning methods have been criticised for falling short in responding to the rapidly changing needs and demands of industry. The data analysis outcome indicated the following themes to be the most prominent issues with traditional architectural teaching methods.

One of the most significant problems is the absence of an integrated learning experience. Limited access to the working site, hazards involved in the site visits for students, and scheduling difficulties result in this issue. This insufficiency results into students' inability to apply their classroom knowledge to real-world contexts. Studies that were conducted in this area confirmed that if the matters, problems and questions were altered from their original forms and the ones taught in the classrooms, the majority of students would fail to properly respond and solve them. Lack of a comprehensive spatial



perception and visualisation was identified as another flaw of the traditional teaching and learning of architecture.

It is also suggested that the traditional method of design presentation and communication, which involves model making and photomontages, can be utterly time-consuming, and not capable of real-time checking strategies, not accurate in terms of scale, and not interactive. The conventional methods do not exploit and take advantage of new interaction, interconnection and information sharing possibilities between participants and users on a project.

Other issues involved in traditional architecture teaching and learning, particularly in design-related units, is students' lack of engagement and motivation. Lack of teaching methods that foster students' social skills can be mentioned as another gap in conventional engineering pedagogies. This impacts learners' and students' critical thinking, leadership skills, decision making, and collaboration skills. Behzadan et al. (2015) emphasised the significance of these skillsets and argued that having them are in demand more than ever, because of the rapid advancement of the digital era and its impact on building industry. The absence and lack of attractive teaching methods were also identified as another issue in the current teaching practices (Behzadan et al., 2015; Birt & Cowling, 2017; González, 2018; Hartless et al., 2020; Katzis et al., 2018; Sánchez et al., 2014; Sullivan & Rosin, 2008). Therefore, due to this industry's rapidly changing nature, it is crucial to prepare a new generation of professionals who are ready to meet these needs and adapt to the swift changes in an effective manner (De Amicis et al., 2019).

Technological frameworks of AR application and implementation in architecture curriculum and the targeted skill sets

Various studies have examined the usage and implementation of AR-based technologies in architectural teaching and learning environments. It was suggested that the application of AR technologies in the process of architectural design can assist with creating time-spatial models and simulation as well as providing a tool for analytical and evaluation purposes. Focused on the AR technology, the results of data analysis for this study indicated that by creating technology-enhanced teaching and learning environments, improvement can be seen in various skill sets of architectural students.

Several technologies have been developed and dedicated to enhancing students' spatial and visual perception, since a comprehensive awareness of spatial qualities is an essential skill for architecture students. A big majority of the developed AR-based technologies that were applied in architectural courses utilised widely accessible and off-the-shelf software and hardware. One of these developed technologies, which focused on increasing spatial skills, used 3D printed objects and models utilising a MakerBot Replicator. This model was then placed into an AR simulation environment using Oculus Rift, Unity3d, Vuforia and Samsung via a BYOD mobile phone to create interactive representation. This technology enabled exploration and interaction with the object by manipulating and navigating these AR visualisations. The result indicated the engagement of both high and low spatial learners for conceptualising the object and translating the 3D spatial objects in their head. This technology proved to create "learner centered active engagement through physical and virtual interaction with the visualisation technologies" (Birt & Cowling, 2017; Birt et al., 2017).

Another AR technology that was developed to increase and improve spatial skills and constructive visual representation, focused on the accessibility and affordability aspects of this technology. SketchUp and 3ds Max V-Ray were mainly used in the development of it. In the first step, Sketchup was used due to its relative accuracy in representing quality of 2D lines, coordinates, dimensions and managing various scale 3D objects. The designed objects and elements were then transferred to AR simulation environment. Hand-held mobile device (HHMD) accessible via Apple iPad and Google Play Store with installed AR software were used to scan the paper markers. The markers were created utilising using a word processor editing application. After implementing this model on a first-year architecture course, the outcome confirmed that using this technology resulted in enhancement in students' spatial perception and understanding as well as improvement in their constructive visual representation (González, 2018; González et al., 2020). Other AR technologies have been developed using similar methods and techniques and confirming the same results (Navarro Delgado & Fonseca Escudero, 2017; Riera et al., 2015).

Sánchez et al. (2014) similarly investigated the impacts of implementing AR technology in a spatial design education and teaching context using different mobile devices. The aim of their study was to assess the system usability and evaluate the academic performance improvement. Complex model processes were augmented into real context to validate this developed model. A synergy between conventional methods of education and AR-based models were used to develop and visualise hybrid construction processes, which proved to be effective.

Improving spatial and graphical skills and competencies was once again the aim of the development of another didactic AR-based technology. Very similar to the other AR frameworks, this technology used accessible software and hardware such as personal laptops equipped with webcam as well as additional webcams of Logitech C200, physical markers, and 3D models created by Google SketchUp exported to AR and using media Inglobe as a free plug-in technology. This technology was tested by evaluating students' level of satisfaction of the framework, and their degree of engagement with architectural design using this technology. To examine the effectiveness of this framework and the user's satisfaction, the state of the art related to the usage of surveys was reviewed. The perception of the application of such technologies in the design and architectural educational frameworks and the degree of implementation was also evaluated. The results indicated substantial improvement in students' spatial awareness in a short span of time as well as overall improvement in their academic performance. Students indicated the high degree of satisfaction and acceptance toward this technology (Redondo Domínguez et al., 2012).

Improving spatial skills, developing critical judgement and self-evaluation of architectural students were also the targets of Geo-location-based AR application. This technology, which was developed based on a GPS, intended to create a user friendly and easy to access 3D multimedia content that is accessible through mobile devices and is adaptable to various types of content. To visualise 3D models and objects on mobile and hand-held devices, Layer platform was used. The 3D objects were connected to the virtual information channels utilising a database and geo-located in the actual position. The initial step in implementation of this technology is based on "planimetric" images and documents provided by project managers. Students and users were asked to carry mobile devices such as tablets or phones that contained a camera and was equipped with GPS and 3G connection. They were also asked to download the free browser Laya Viewer. A Geo-location-based AR application that employs compass, GPS, and other sensors in mobile devices was used to visualise the final models that were created using SketchUp and 3dsMax. Testing of this technology on architectural students proved that it can assist with more in-depth task realisation by heterogeneous learning techniques that meet high expectations. The result of the usability analysis also demonstrated the effectiveness and feasibility of this technology. Furthermore, this technique of content visualisation proved to assist students in evaluating and judging their architectural proposal which led to improvement in their spatial skills. The interaction and relation between educators and students was also enhanced through more effective feedback processes (Riera et al., 2015).

Another AR-based technology developed for this purpose aimed to augment AADIE with an additional layer by using instruction design (ID) for architecture teaching and learning purposes, rather than creating an entirely new ID. In this framework ID model was implemented on Mobile Augmented Reality (MAR) using AR-media™. A Sub User Interface was adapted on desktop from AR-Media™ plug-in. The developed ADDIE model was used as a basic model to combine the instructional design for architecture. Amongst the three most used augmenting applications in architectural education namely "AR-media™", "Aurasma" and "Augment", AR-media™ was selected for this application. AR-media™ is suggested to be more prevailing in terms of system features,

usability, multimedia creation, cost and ease of use. Other software used were 3Ds Max 2014, AR-media™ V2.3 plug-in and AR Media Player from Google Play on mobile device. The hardware utilised included Samsung Galaxy S6 Edge cell phone equipped with 16MP camera as well as Android 5.0.2 Lollipop software. Choosing Samsung Galaxy was mainly due to its suitability to use with applications on multiple platforms such PC, MAC, Android and IOS' since it is compatible and capable of accepting exported models from various architectural modelling software such as SketchUp, Maya and 3DMax. This developed AR technology proved to be effective in a number of ways including:

- being a constructive approach and enabling students to build knowledge during their learning experiences;
- enhancing experiential learning by adopting and improving student centered approach;
- adaptive to social and personal modes by supporting diverse modes of communication and collaboration;
- being flexible to integrate with other technologies such as AR based BIM (Building Information Modelling), Intelligent Augmented Reality systems (IARs), systems and Cloud computing;
- increasing student's learning motivation;
- "Edutainment: provides potential for memorizing knowledge, as it provides enjoyment while learning through deep inquiry and social engagement with real problem situations" and
- Immediacy ability and being capable of providing immediate information delivery and feedback; and being user friendly (Hosny et al., 2019; M Yilmaz et al., 2015; Pimmer & Pachler, 2014; Saidin et al., 2016).

Most of the AR-based technologies used in the field of architecture higher education have followed very similar procedures and frameworks (Ayer et al., 2016; Chandrasekera, 2014; Kerr & Lawson, 2020; Shirazi & Behzadan, 2015a, 2015b; Vassigh et al., 2020). They all have also confirmed the effectiveness of AR-based technology-enhanced teaching and learning environment in Architecture. It was suggested that by augmenting parameters such as 3D models and objects, sculptural elements, complex urban models, systems of units, scales or coordinates such as length, width and thickness, shape, volume into teaching practises, more interactive and engaging content can be made.

AR's implication/areas of effectiveness on architecture students' skillsets

Overall, the result of data analysis of this study confirmed that application of AR technology is effective through the followings: enhancement in students' overall academic performance and learning processes, considered to be effective and efficient, improved critical skills and social skills, creating more entertaining and more engaging learning environments. These were the main themes identified and emerged during the coding and analysis process.

The application of AR technology proved to be effective in improving students' spatial and graphical skills at undergraduate and graduate levels. It is suggested that AR application in architectural pedagogy can assist the development and evolution of students'

graphic competencies and spatial skills as defined by Gonzales (2018), "visual perception and spatial expression, under systems of parallel and conical projection in the construction of objects and spaces" p. 133. It further assists students' spatial perception, projection and skills in a shorter span of time and learning periods. This quality, positively, impacts students' ability on their design presentation and communication. Consequently, it provides them with a better, more in-depth and comprehensive understanding of their design proposals and its application within the actual context.

With respect to the teaching efficacy, by applying this technology, most of the students could complete the given tasks during the course, within the required time or even earlier. However, this did not negatively impact the accuracy and precision of the tasks performed. On the other hand, AR resulted in an increased accuracy and integrity level which is related to the efficiency of the task undertaken by properly assigning resources and the expenditure of time and effort for solving the proposed exercise.

Data analysis results indicated that the implementation of AR within the curriculum can improve students' critical skills. It was revealed that using AR technology in architecture course provides an effective evaluation tool for students and educators to assess design proposals, and evaluate its practicality and feasibility prior to any intervention. It also enhances the overall understanding of the built forms by diminishing the problems and issues of lighting, scaling, and texturing (Sánchez et al., 2014). The process of decision making for formal and functional qualities are fostered in light of its ability in allowing physical exploration and interaction with the context (Hartless et al., 2020). AR also encourages participation and engagement amongst the learners. Likewise, social skills, engagement and collaborative discussions are encouraged which, in turn, create a self-formative process (Fig. 8).

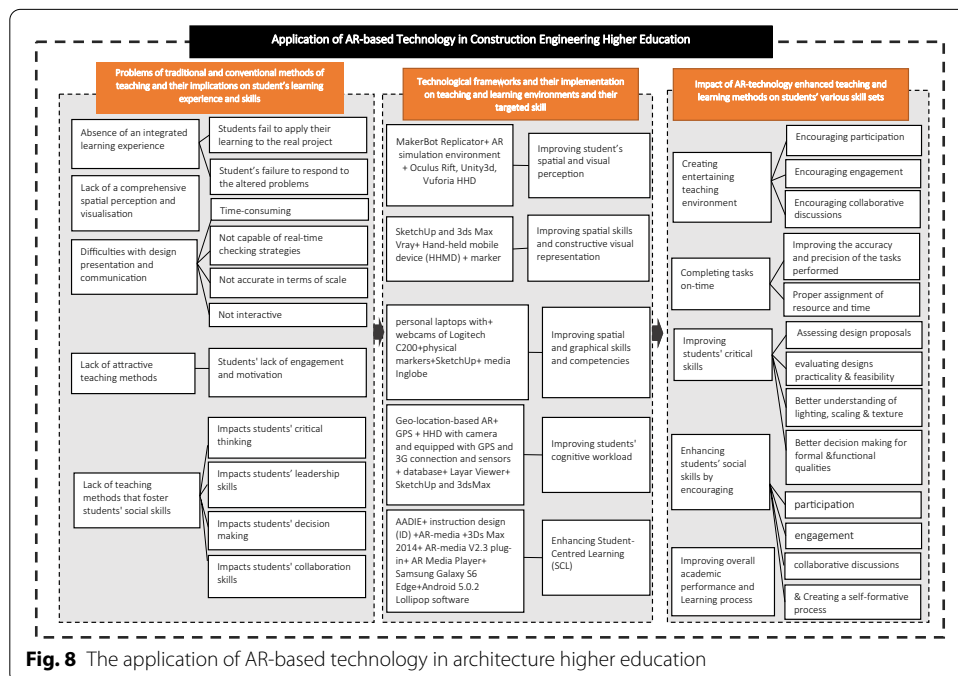


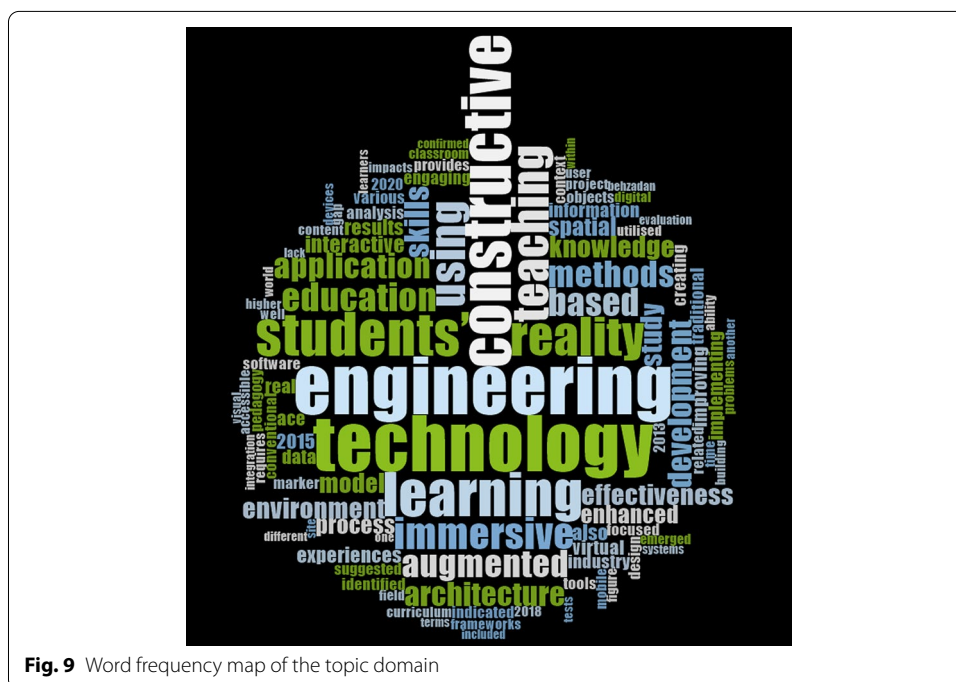
Fig. 8 The application of AR-based technology in architecture higher education

Gap analysis and future research agenda

The result of data analysis of this study revealed various gaps in the body of knowledge which can be addressed through further research. A large portion of the existing literature is focused on the application of AR-based technologies in primary and secondary education. The gamifying aspects of this technology has attracted the attention of these levels of education. However, it is suggested that the benefits and abilities of such technologies reach far beyond their attractiveness, interactive and engaging nature, making them appropriate for higher levels of education as well. Furthermore, the review of literature indicated that amongst the studies conducted in the topic, architecture is the least researched field. The sheer volume of current literature is focused on the construction engineering higher education (Fig. 9). Besides, most of the studies in the field of architecture have focused on, representation, communication and spatial skills and abilities, leaving other skills required for this profession less researched and to some extent overlooked and scarce.

Another gap is the lack of appropriate teaching methods, pedagogies and philosophies which could embrace and cater for the application of emerging and immersive technologies within the curriculum. Also, the lack of specified training for students' immersion in such technology-enhanced teaching and learning environment is identified. Improvement in AR-related Educational Kits is suggested in order to improve the degree of interaction and immersion in the virtual environment. It is further recommended that design and development of appropriate pedagogies and teaching methods in the field of AC, which has been tailored for the integration with immersive technologies, and supports both students and educators, can be immensely beneficial.

Moreover, the existing body of knowledge has been focused on the benefits and areas of effectiveness of AR in teaching and learning environments. Very few, if any, studies have elaborately identified the pitfalls and shortcomings of using AR in teaching and



learning practices. The challenges involved in the implementation of this technology must be identified and addressed to optimise the outcomes and impacts on the learning processes. Finally, the existing studies and experiments have focused on the examination and experimentation of AR implementation in classrooms, which have been conducted over a short period of time. Longitudinal studies that monitor and examine the long-term effects of AR and technology-enhanced teaching and learning environment on students' academic and professional performances are missing. So, longitudinal studies that can examine the evolution of the students' knowledge, performance and skillsets over a period of time would bridge this gap.

A limitation of this study is its focus on the topics of architecture and construction engineering, while other study areas such as geography, geology, transportation, real estate, urban planning, environmental studies, and others, can also use the benefits of AR application.

Conclusion

The systematic literature review presented in this study utilized the qualitative methodology and thematic data analysis method to identify the effects and implications of using AR in technology-enhanced teaching and learning environments. This study presented two principal frameworks in which the followings were identified:

- The gaps and short fallings of the traditional methods of teaching in the field of AC, and its lack of response to the industry 4.0 principles;
- The ways that AR-based technologies can alleviate these deficiencies in the context of higher education;
- The most common technological frameworks used for the application of AR in the technology-enhanced teaching and learning environments;
- And, the impacts of AR-based technology enhanced teaching methods on students' various skillsets

It was identified that using immersive 3D virtual contents results in the more persistent learning, in-depth and long-lasting knowledge for students, as well as, creating a more fluid learning, improving students' experience and knowledge-acquisition process, and developing in-depth perception and spatial representation. Integrating AR in curriculum can provide students with more realistic and practical learning experience, adaptable to real and physical jobsite. AR allows students to adapt their design to the real scale of construction, within the site. It also provides with unlimited access, to otherwise limited opportunities, to participate in jobsite experiences. It was also confirmed that in teaching construction processes, the application of AR assists with enhancing the participants' understanding of complex assembly procedures. Overall, it can be concluded that the application of AR results in the overall enhancement of students' academic performance and learning, both in short-term and long-term.

Acknowledgements

Not applicable.

Authors' contributions

This is the outcomes of our own research as a review paper which has neither previously nor simultaneously in whole or in part been published anywhere else. All the authors have contributed to, read and approved the final manuscript.

Funding

Not applicable.

Declarations**Competing interests**

The authors acknowledge that there is no conflict of interest for this publication.

Author details

¹School of Architecture and Built Environment, Queensland University of Technology, Brisbane, Australia. ²Design and Built Environment School, University of Canberra, Canberra, Australia.

Received: 13 January 2022 Accepted: 14 March 2022

Published online: 19 July 2022

References

- Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, 20, 1–11.
- Allen, M. (2017). *The SAGE encyclopedia of communication research methods*. SAGE Publications, Inc. <https://doi.org/10.4135/9781483381411>.
- Arditi, D., & Polat, G. (2010). Graduate education in construction management. *Journal of Professional Issues in Engineering Education and Practice*, 136(3), 175–179.
- Ayer, S. K., Messner, J. I., & Anumba, C. J. (2016). Augmented reality gaming in sustainable design education. *Journal of Architectural Engineering*, 22(1), 04015012.
- Azuma, R. T. (2015). Location-based mixed and augmented reality storytelling. In W. Barfield (Ed.), *Fundamentals of wearable computers and augmented reality* (2nd ed., pp. 259–276). Boca Raton, FL: CRC Press.
- Bademosi, F., Blinn, N., & Issa, R. R. (2019). Use of augmented reality technology to enhance comprehension of construction assemblies. *Itcon*, 24, 58–79.
- Bastug, E., Bennis, M., Médard, M., & Debbah, M. (2017). Toward interconnected virtual reality: Opportunities, challenges, and enablers. *IEEE Communications Magazine*, 55(6), 110–117.
- Behzadan, A. H., Iqbal, A., & Kamat, V. R. (2011). A collaborative augmented reality based modeling environment for construction engineering and management education. In *Proceedings of the 2011 winter simulation conference (WSC)* (pp. 3568–3576). IEEE.
- Behzadan, A. H., Dong, S., & Kamat, V. R. (2015). Augmented reality visualization: A review of civil infrastructure system applications. *Advanced Engineering Informatics*, 29(2), 252–267. <https://doi.org/10.1016/j.aei.2015.03.005>
- Behzadan, A. H., & Kamat, V. R. (2013). Enabling discovery-based learning in construction using telepresent augmented reality. *Automation in Construction*, 33, 3–10. <https://doi.org/10.1016/j.autcon.2012.09.003>
- Biggs, J., & Tang, C. (2007). *Teaching for quality learning at University Maidenhead*. McGraw-Hill Education.
- Birt, J., & Cowling, M. (2017). Toward future 'mixed reality' learning spaces for STEAM education. *International Journal of Innovation in Science and Mathematics Education*, 25(4).
- Birt, J. R., Manyuru, P., & Nelson, J. (2017). Using virtual and augmented reality to study architectural lighting. In H. Partidge, K. Davis, & J. Thomas (Eds.), *Me, Us, IT! Proceedings ASCILITE 2017: 34th International conference on innovation, practice and research in the use of educational technologies in tertiary education* (pp. 17–21). ASCILITE. <http://2017conference.ascilite.org/wp-content/uploads/2017/11/Concise-BIRT.pdf>.
- Boyatzis, R. E. (1998). *Transforming qualitative information: Thematic analysis and code development*. Sage.
- Bowie, J. (2010). Enhancing classroom instruction with collaborative technologies [online]. Available at: <http://www.eschoolnews.com/2010/12/20/enhancing-classroom-instruction-withcollaborative-technologies/>.
- Brown, J. S. (2000). Growing up: Digital: How the web changes work, education, and the ways people learn. *Change: the Magazine of Higher Learning*, 32(2), 11–20.
- Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher*, 18(1), 32–42.
- Bruning, R. H., Schraw, G. J., & Ronning, R. R. (1999). *Cognitive psychology and instruction*. ERIC.
- Bursztyn, N., Walker, A., Shelton, B., & Pederson, J. (2017). Increasing undergraduate interest to learn geoscience with GPS-based augmented reality field trips on students' own smartphones. *GSA Today*, 27(5), 4–11.
- Cao, Y., Tang, Y., & Xie, Y. (2018). A novel augmented reality guidance system for future informatization experimental teaching. In *2018 IEEE international conference on teaching, assessment, and learning for engineering (TALE)* (pp. 900–905). IEEE.
- Carbonell Carrera, C., & Bermejo Asensio, L. A. (2017). Landscape interpretation with augmented reality and maps to improve spatial orientation skill. *Journal of Geography in Higher Education*, 41(1), 119–133.
- Chandrasekera, T. (2014). Using augmented reality prototypes in design education. *Design and Technology Education: an International Journal*, 19(3). <https://ojs.lboro.ac.uk/DATE/article/view/1971>.

- Chen, Y. C., Chi, H. L., Hung, W. H., & Kang, S. C. (2011). Use of tangible and augmented reality models in engineering graphics courses. *Journal of Professional Issues in Engineering Education and Practice*, 137(4), 267–276. [https://doi.org/10.1061/\(ASCE\)EI.1943-5541.0000078](https://doi.org/10.1061/(ASCE)EI.1943-5541.0000078)
- Cirulis, A., & Brigmanis, K. B. (2013). 3D outdoor augmented reality for architecture and urban planning. *Procedia Computer Science*, 25, 71–79.
- Collins, H. (2010). *Tacit and explicit knowledge*. University of Chicago Press.
- De Amicis, R., Rigglo, M., Shahbaz Badr, A., Fick, J., Sanchez, C. A., & Prather, E. A. (2019). Cross-reality environments in smart buildings to advance STEM cyberlearning. *International Journal on Interactive Design and Manufacturing*, 13(1), 331–348. <https://doi.org/10.1007/s12008-019-00546-x>
- Di Serio, Á., Ibáñez, M. B., & Kloos, C. D. (2013). Impact of an augmented reality system on students' motivation for a visual art course. *Computers & Education*, 68, 586–596.
- Diao, P. H., & Shih, N. J. (2019). Trends and research issues of augmented reality studies in architectural and civil engineering education—A review of academic journal publications. *Applied Sciences (switzerland)*, 9(9), 1840. <https://doi.org/10.3390/app9091840>
- D'Souza, D., Singh, U., Sharma, D., & Ranjan, P. (2013). *Educational technology in teaching and learning: Prospects and challenges*. Patna Women's College Publication.
- Elkoubaiti, H., & Mrabet, R. (2018). Key elements of educational augmented and virtual reality applications. In *Conference Europe Middle East & North Africa information systems and technologies to support learning* (pp. 100–105). Springer, Cham.
- Farrell, W. A. (2018). Learning becomes doing: Applying augmented and virtual reality to improve performance. *Performance Improvement*, 57(4), 19–28.
- Fazel, A., & Izadi, A. (2018). An interactive augmented reality tool for constructing free-form modular surfaces. *Automation in Construction*, 85, 135–145. <https://doi.org/10.1016/j.autcon.2017.10.015>
- Fink, A. (2019). *Conducting research literature reviews: From the internet to paper*. Sage Publications.
- Fuge, M., Yumer, M. E., Orbay, G., & Kara, L. B. (2012). Conceptual design and modification of freeform surfaces using dual shape representations in augmented reality environments. *Computer-Aided Design*, 44(10), 1020–1032.
- Given, L. (2008). *The SAGE encyclopedia of qualitative research methods*. SAGE Publications, Inc. <https://doi.org/10.4135/9781412963909>.
- González, N. A. A., Suarez-Warden, F., Milian, H. N. Q., & Hosseini, S. (2020). Interactive design and architecture by using virtual reality, augmented reality and 3D printing. *International Journal of Simulation and Process Modelling*, 15(6), 535–545.
- González, N. A. A. (2018). Development of spatial skills with virtual reality and augmented reality. *International Journal on Interactive Design and Manufacturing*, 12(1), 133–144. <https://doi.org/10.1007/s12008-017-0388-x>
- Hajirasouli, A. (2015). An investigation of influential factors in the long-term survival of vernacular architecture in the form of cone-shaped dwelling: Case studies of Kandovan and Goreme (Cappadocia). *Journal of Engineering and Architecture*, 3(1), 89–98.
- Hajirasouli, A., & Banihashemi, S. (2020). The unfolding tragedy of Kandovan: The loss of the last inhabited cone-shaped settlement in the world. *Habitat International*, 102, 102211.
- Hajirasouli, A., Banihashemi, S., Kumarasuriyar, A., Talebi, S., & Tabadkani, A. (2021). Virtual reality-based digitisation for endangered heritage sites: Theoretical framework and application. *Journal of Cultural Heritage*. <https://doi.org/10.1016/j.culher.2021.02.005>
- Hartless, J. F., Ayer, S. K., London, J. S., & Wu, W. (2020). Comparison of building design assessment behaviors of novices in augmented-and virtual-reality environments. *Journal of Architectural Engineering*, 26(2), 04020002. [https://doi.org/10.1061/\(ASCE\)AE.1943-5568.0000396](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000396)
- Hosny, S. S., Abdel Mohsen, S., & Mansour, S. A. (2019). A conceptual framework for enriching architectural classroom with mobile augmented reality. *Journal of Al-Azhar University Engineering Sector*, 14(50), 158–175.
- Jiao, Y., Zhang, S., Li, Y., Wang, Y., & Yang, B. (2013). Towards cloud augmented reality for construction application by BIM and SNS integration. *Automation in Construction*, 33, 37–47. <https://doi.org/10.1016/j.autcon.2012.09.018>
- Kamarainen, A. M., Metcalf, S., Grotzer, T., Browne, A., Mazzuca, D., Tutwiler, M. S., & Dedde, C. (2013). EcoMOBILE: Integrating augmented reality and probeware with environmental education field trips. *Computers & Education*, 68, 545–556.
- Katzis, K., Dimopoulos, C., Meletiου-Mavrotheris, M., & Lasica, I. E. (2018). Engineering attractiveness in the european educational environment: Can distance education approaches make a difference? *Education Sciences*, 8(1), 16. <https://doi.org/10.3390/educsci8010016>
- Kerr, J., & Lawson, G. (2020). Augmented reality in design education: Landscape architecture studies as AR experience. *International Journal of Art & Design Education*, 39(1), 6–21.
- Khuzaimah, K. H. M., & Hassan, F. (2012). Uncovering tacit knowledge in construction industry: Communities of practice approach. *Procedia-Social and Behavioral Sciences*, 50, 343–349.
- Kim, J., & Irizarry, J. (2020). Evaluating the use of augmented reality technology to improve construction management student's spatial skills. *International Journal of Construction Education and Research*, 17(2), 99–116.
- Kolb, D. A. (1984). *Experience as the source of learning and development*. Prentice Hall.
- Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press.
- Lombardi, M. M. (2007). Authentic learning for the 21st century: An overview. *Educause Learning Initiative*, 1(2007), 1–12.
- Lord, T. R. (1999). A comparison between traditional and constructivist teaching in environmental science. *The Journal of Environmental Education*, 30(3), 22–27.
- Luo, X., & Mojica Cabico, C. D. (2018). Development and evaluation of an augmented reality learning tool for construction engineering education. In *Construction Research Congress 2018* (pp. 149–159).
- Maeda, Y., & Yoon, S. Y. (2011). Scaling the Revised PSVT-R: Characteristics of the first-year engineering students' spatial ability. In *2011 ASEE Annual Conference & Exposition* (pp. 22–1273).
- McCabe, B., Ching, K. S., & Rodrigues, S. (2000). STRATEGY: A construction simulation environment. In *Construction Congress VI: Building Together for a Better Tomorrow in an Increasingly Complex World* (pp. 115–120).
- Miles, M. B., Huberman, A. M., & Saldana, J. (2013). *Qualitative data analysis*. Sage.

- Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995). Augmented reality: A class of displays on the reality-virtuality continuum. In *Telem manipulator and telepresence technologies* (Vol. 2351, pp. 282–292). International Society for Optics and Photonics.
- Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, 77(12), 1321–1329.
- Mutis, I., & Issa, R. R. (2014). Enhancing spatial and temporal cognitive ability in construction education through augmented reality and artificial visualizations. In *Computing in Civil and Building Engineering (2014)* (pp. 2079–2086).
- Navarro Delgado, I., & Fonseca Escudero, D. (2017). New visualization technologies to improve the representation of architecture in education. *Architecture, City and Environment*, 12(34), 219–238. <https://doi.org/10.5821/ace.12.34.5290>
- Okoli, C., & Schabram, K. (2010). A guide to conducting a systematic literature review of information systems research. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.1954824>
- Pathirage, C., Amaratunga, D., & Haigh, R. (2008). The role of tacit knowledge in the construction industry: Towards a definition. In: *CIB W89 International Conference on Building Education and research (BEAR)*, 11–15th February 2008, Sri Lanka
- Patil, K. R., Ayer, S. K., Wu, W., & London, J. (2020). Mixed reality multimedia learning to facilitate learning outcomes from project based learning. In *Construction Research Congress 2020: Computer Applications* (pp. 153–161).
- Pimmer, C., & Pachler, N. (2014). Mobile learning in the workplace: Unlocking the value of mobile technology for work-based education. In M. A. A. Tsinakos (Ed.), *Increasing access through mobile learning*. Vancouver: Commonwealth of Learning and Athabasca University.
- Pranoto, H., & Panggabean, F. M. (2019). Increase the interest in learning by implementing augmented reality: Case studies studying rail transportation. *Procedia Computer Science*, 157, 506–513.
- Redondo Domínguez, E., Fonseca Escudero, D., Sánchez Riera, A., & Navarro Delgado, I. (2012). Augmented reality in architecture degree: New approaches in scene illumination and user evaluation. *Journal of Information Technology and Application in Education (JITAE)*, 1(1), 19–27.
- Riera, A. S., Redondo, E., & Fonseca, D. (2015). Geo-located teaching using handheld augmented reality: Good practices to improve the motivation and qualifications of architecture students. *Universal Access in the Information Society*, 14(3), 363–374.
- Saidin, N. F., Halim, N. D. A., & Yahaya, N. (2016). Designing mobile augmented reality (MAR) for learning chemical bonds. In S. Z. Abidin, R. Legino, H. M. Noor, V. V. Vermol, R. Anwar, & M. F. Kamaruzaman (Eds.), *Proceedings of the 2nd international colloquium of art and design education research (i-CADER 2015)*. Springer Singapore. https://doi.org/10.1007/978-981-10-0237-3_37
- Saldaña, J. (2015). *The coding manual for qualitative researchers*. Sage.
- Sánchez, A., Redondo, E., Fonseca, D., & Navarro, I. (2013). Hand-held augmented reality: Usability and academic performance assessment in educational environments. Case study of an engineering degree course. *Information (Japan)*, 16(12 B), 8621–8634. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84898725791&partnerID=40&md5=3c2753a6d2cece630d1092ff959acef>
- Sánchez, A., Redondo, E., Fonseca, D., & Navarro, I. (2014). Academic performance assessment using Augmented Reality in engineering degree course. In *2014 IEEE Frontiers in Education Conference (FIE) Proceedings* (pp. 1–7). IEEE.
- Santos, L., Escudeiro, P., & De Carvalho, C. V. (2013). Evaluating virtual experiential learning in engineering. In *2013 International Conference on Interactive Collaborative Learning (ICL)* (pp. 42–48). IEEE.
- Sawhney, A., Marble, J., Mund, A., & Vamadevan, A. (2000). Internet based interactive construction management learning system. In *Construction Congress VI: Building Together for a Better Tomorrow in an Increasingly Complex World* (pp. 280–288).
- Sepasgozar, S. M. E. (2020). Digital twin and web-based virtual gaming technologies for online education: A case of construction management and engineering. *Applied Sciences (switzerland)*, 10(13), 4678. <https://doi.org/10.3390/app10134678>
- Shelton, B. E., & Hedley, N. R. (2002). Using augmented reality for teaching earth-sun relationships to undergraduate geography students. In *The First IEEE International Workshop Augmented Reality Toolkit* (pp. 8). IEEE.
- Shirazi, A., & Behzadan, A. H. (2015a). Content delivery using augmented reality to enhance students' performance in a building design and assembly project. *Advances in Engineering Education*, 4(3), n3.
- Shirazi, A., & Behzadan, A. H. (2015b). Design and assessment of a mobile augmented reality-based information delivery tool for construction and civil engineering curriculum. *Journal of Professional Issues in Engineering Education and Practice*, 141(3), 4014012. [https://doi.org/10.1061/\(ASCE\)EI.1943-5541.0000229](https://doi.org/10.1061/(ASCE)EI.1943-5541.0000229)
- Sullivan, W. M., & Rosin, M. S. (2008). *A new agenda for higher education: Shaping a life of the mind for practice* (Vol. 14). Wiley.
- Tayeh, R., Bademosi, F., & Issa, R. R. A. (2020). Information systems curriculum for construction management education. In *Construction Research Congress 2020: Safety, Workforce, and Education* (pp. 800–809). Reston, VA: American Society of Civil Engineers.
- Turan, Z., Meral, E., & Sahin, I. F. (2018). The impact of mobile augmented reality in geography education: Achievements, cognitive loads and views of university students. *Journal of Geography in Higher Education*, 42(3), 427–441.
- Tynjälä, P. (1999). Towards expert knowledge? A comparison between a constructivist and a traditional learning environment in the university. *International Journal of Educational Research*, 31(5), 357–442.
- Vassigh, S., Davis, D., Behzadan, A. H., Mostafavi, A., Rashid, K., Alhaffar, H., Elias, A., & Gallardo, G. (2020). Teaching building sciences in immersive environments: A prototype design, implementation, and assessment. *International Journal of Construction Education and Research*, 16(3), 180–196. <https://doi.org/10.1080/15578771.2018.1525445>
- Von Glasersfeld, E. R. N. S. T. (1995). Aspekte einer konstruktivistischen Didaktik. Regional Institute for school and secondary education (Hrsg.), *Lehren und Lernen als konstruktive Tätigkeit*, Soest.
- Wang, X., Kim, M. J., Love, P. E., & Kang, S.-C. (2013). Augmented reality in built environment: Classification and implications for future research. *Automation in Construction*, 32, 1–13.
- Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. In *Proceedings of the 18th international conference on evaluation and assessment in software engineering* (pp. 1–10).

- Woo, J.-H., Clayton, M. J., Johnson, R. E., Flores, B. E., & Ellis, C. (2004). Dynamic knowledge map: Reusing experts' tacit knowledge in the AEC industry. *Automation in Construction*, 13(2), 203–207.
- Yang, M.-D., Chao, C.-F., Huang, K.-S., Lu, L.-Y., & Chen, Y.-P. (2013). Image-based 3D scene reconstruction and exploration in augmented reality. *Automation in Construction*, 33, 48–60.
- Yilmaz, M. R., Reisoglu, I., Topu, F. B., Karakus, T., & Goktas, Y. (2015). The development of a criteria list for the selection of 3d virtual worlds to design an educational environment. *Croatian Journal of Education: Hrvatski Časopis Za Odgoji Obrazovanje*, 17(4), 1037–1069.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- ▶ Convenient online submission
- ▶ Rigorous peer review
- ▶ Open access: articles freely available online
- ▶ High visibility within the field
- ▶ Retaining the copyright to your article

Submit your next manuscript at ▶ [springeropen.com](https://www.springeropen.com)
