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Introduction

This document summarises the main goals, content and conclusions of 17 scientific papers from 2016 to 2024 that are centred on the **use of XR in the construction industry** and related educational fields (civil engineering, architectural engineering, construction management, etc.). It also provides a review of whether the papers touch the subjects of waste management and circular economy.

The materials have been retrieved by searching the following keywords:

- virtual augmented reality
- waste management
- extended reality building sector
- extended reality construction sector

Some references cited in the selected papers that seemed relevant to the scope of this project were further explored and included as well.
The sources used to access the literature are the following:

- IEEE (https://ieeexplore.ieee.org/)
- MDPI
- Wiley
- SID (Society Information Display)
- IOPScience

The papers are listed and summarised in chronological order below. A complete reference list is provided at the end of the document, as well as a table synthesising the main relevant aspects of each publication.

Reviews

[1] Augmented Reality Gaming in Sustainable Design Education (Mar 2016)

This paper presents the findings after the implementation of ecoCampus, a mobile application with an augmented reality–based simulation game interface designed to visualise possible building design retrofit solutions in the context of an existing space. This application, previously developed by the authors, was tested by tasking students with performing a building redesign activity in which they had to design, visualise, and assess exterior wall designs to retrofit an existing facility and improve its sustainable performance. They were not given further instructions on how to perform this task, in order to assess their approach to design. To measure student performance, 34 architectural engineering students, 47 architecture students, and 27 civil engineering students were given the same design activity using an augmented reality–based educational game called ecoCampus. The results of their work were compared with those of 65 students who completed a similar design activity using only blank sheets of paper and of another group of 23 students who used a paper-based approximation of the computerised ecoCampus. The goal was to determine how AR technology helped to reduce design fixation by stimulating the students' creativity.

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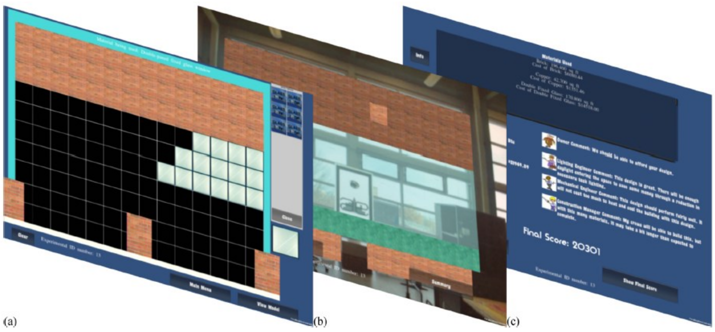
EcoCampus works in three layers: in the first one, students can define a new wall design with chosen materials in a touch based interface, in the second, students can project an AR simulation of their design over the real wall, and in the last one they receive performance feedback about the drawbacks and benefits of their design solutions. This allows them to go back and make changes in the previous stages according to this feedback.

The study evaluated results on the students' perceptions and comments (posttest survey), an assessment and comparison of their design proposals, and an analysis of the feedback provided by the application itself. The findings show that the application helped overcome design fixation, since the students considered more building concepts and materials, and that the feedback stage improved their performance significantly, since they were able to go back and reformulate their proposals, creating better solutions with further iterations.

[2] Framework for Integrating Safety into Construction Methods Education through Interactive Virtual Reality (Apr 2016)



This study proposes a virtual construction safety education system (VSES), which was tried in two prototype scenarios, presenting also the results of these trials. The main goal is to improve the acquisition of construction safety knowledge and skills by integrating it with construction materials and methods education (as opposed to the current method of isolated safety classes and workshops).

The first phase of the research is a literature review focused on the current state of construction safety training and education, and the application of visualisation technologies in it. It also includes interviews from students and educators, as well as a curricula analysis of the Construction Engineering and Management (CEM) courses in their target country (South Korea). Accident cases were also analysed. The main takeaway was to confirm the initial premise that safety training is not given the necessary attention and priority in CEM education and does not engage students enough, resulting in a lack of preparation of professionals in terms of identifying hazardous situations and preventing risks. Based on these results, the content of the proposed system was selected, also taking official national regulations and requirements into account. A prototype system was then developed to integrate VR safety scenarios into construction curricula with the hypothesis that this approach would improve learners' safety knowledge and hazard recognition ability. The system was then implemented through a series of lectures with 25 students, and evaluated through hands-on trials with questionnaires and interviews in a building construction class.

The proposed system (**VSES**) was designed with three modules:

1. **The safety and hazard lecture module (SHL)**. This is the introductory part of the course. Students acquire the basic principles and approaches to safety and improve their situational awareness by means of an interactive lecture system in which the educator proposes open-ended questions and induces critical thinking skills. This lesson is complemented by virtual

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scenarios the students can access by QR on their mobile devices. These scenarios include: ideal work methods, safe and unsafe work environments and worker actions. This module is concluded with group discussions.

2. **The hazard inspection game (HIG) module**. This is a practical module in which students can apply the knowledge of the previous module and acquire more experience in identifying, predicting and responding to hazards. It includes 2 VR activities: hazard identification and hazard response. First, students access a virtual recreation of a working environment by QR on their mobile device and interact with it by means of a graphic user interface (GUI). They can touch and click elements (workers, machinery, etc.) It allows peer interaction and teamwork. If the students do not identify all hazards, accidents occur in the simulation. This VR activity is complemented by a session in which they have to describe how they would respond to the accidents and hazards observed, and reflect on the consequences.
3. **The student evaluation and assessment module (SEA)**. This module consists of a series of tests in VR form that aim to assess whether the students retained and can apply the knowledge of the previous modules. The tests are presented as 3D simulations with 3 types of questions: multiple choice questions, in which potential answers have the form of virtual content rather than written text; site management scenario questions, in which students are required to identify hazards in a complex building site simulation with several activities taking place at once; and job safety analysis (JSA) review questions, in which students are tasked to review a JSA (a document that details the planning of construction activities and the preventive measures considered) and compared with the simulation to assess if it has been applied correctly in each case.

To create the virtual scenarios for the content of VSES, the documentation, textbooks and accident records were analysed in order to identify and classify a series of possible hazards, and matched them with their corresponding sections in the textbook. Then they elaborated 3 databases of scenarios: lecture scenarios, game scenarios and test/exam scenarios. They included a multilayered database with data manipulation system so that the educators can access, add, modify and delete scenarios as needed. Scenarios are matched to a QR placed in the corresponding section of the textbook. The prototype tested includes two virtual scenarios and a game. Scenarios are created through 3D modelling, and the game engine was also created with Blender. Virtual workers were animated and a key frame method was used to make the environment change. Scenarios were based on real-life concrete and temporary works and equipment, since they are the areas in which the most accidents occur. Animations with and without protective equipment were included.

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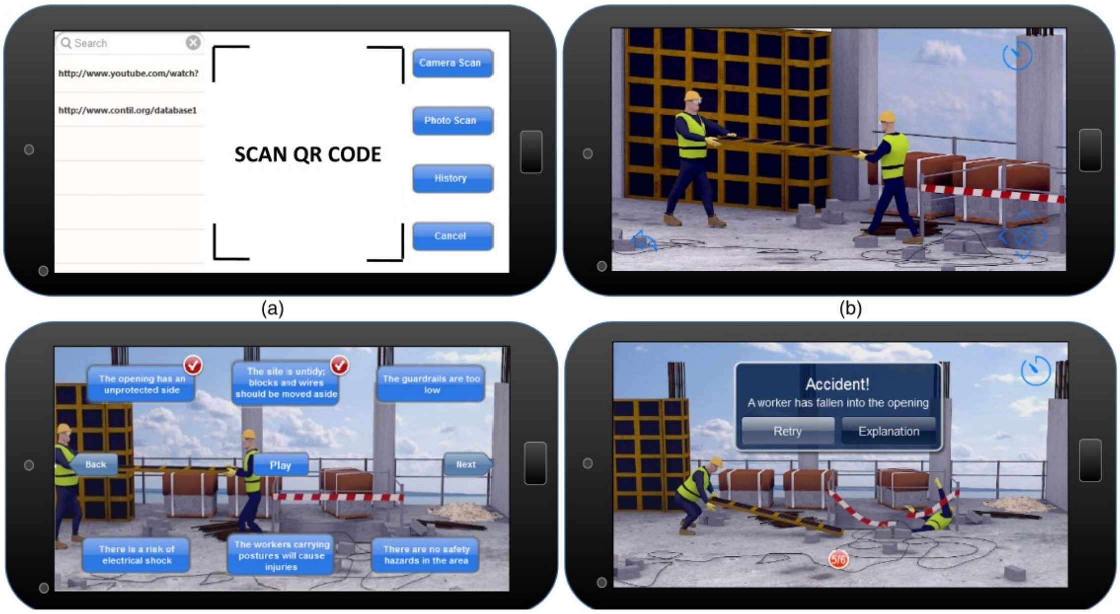

Example of the game's interfaces.

Step 1	1.1 Concept Evaluation	
	Focus group discussions Unstructured Feedback sessions	
	1.2 Interface Evaluation	
	Prototype System Trials Questionnaires and Interviews	
Step 2	Effectiveness Evaluation	
	Prototype System Trials Questionnaires and Interviews Focus group discussions	
Step 3	Performance Based Comparison	
	Test Group 1, 2	Test Group 3
	Conventional & no safety course	VSES
	Immediate knowledge retention	
	6 months knowledge retention	
	Questionnaire and T-test	

The VSES was implemented in a third year Building Construction Class, in conjunction with the concrete works chapter being taught at the time. The system was applied to integrate safety knowledge with construction methods and materials knowledge pertaining to concrete works. Their evaluation method is summarised into the table on the right (step 3 is out of the scope of the paper). Preliminary results show that for both students and educators, the proposed system was superior in terms of clarity and engagement. Main challenge is reducing costs. Future research is also directed towards exploring further how the framework proposed (safety training integrated into construction methods content) is proven to be more effective than the traditional, isolated approach.

[3] Development of Virtual Reality Game-Based Interfaces for Civil Engineering Education (Apr 2017)

This study discusses the development of VR applications in civil engineering education with a focus on the students' acceptance. It analyses the data from three case studies. This is in the context of the Educational Laboratory - Big Machine (ELBigMAC) project. In these case studies, they tested VR hardware with Natural User Interfaces (NUI) on pre-university students, with the ultimate goal of

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evaluating its usefulness in engaging their interest and helping them to familiarise with the field of Civil Engineering.

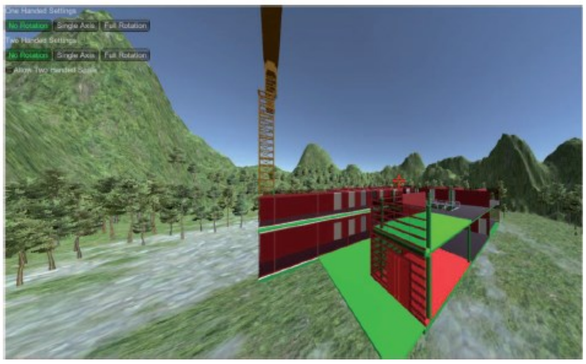
First case study: Building models using a VR interface

In this case, they used Unity3D to create a beginner-friendly, virtual approach to BIM (Building Information Modelling), in which the users could edit a previously designed model using a head-mounted display. It was tested on 30 participants. The idea was that users unfamiliar with BIM software could easily get started. For that reason, they included a short tutorial stage in which users could familiarise with all the commands before having to complete a task, which consisted on placing certain elements in the right position within a building. They were surveyed about the intuitiveness and usability of the platform. Overall, results show that participants mostly considered the platform completely intuitive or with little training required.

Second case study: Exploring a Building Solution

The test was performed on 42 students on a campus visit. They used a head-mounted display and a gamepad for this platform. In it, users were able to identify the different components of building systems based on real buildings around the campus, extract them and assemble them on a virtual model. They were later surveyed about their previous knowledge of building systems and experience with VR, and assess whether their ability to identify the elements of the building systems around them was improved. Most participants had no previous experience, and a vast majority of them considered that the test helped them to identify components of the building system, as opposed to before.

Third case study: Discovering the main disciplines involved in a Civil Engineering project



This consisted of a VR workshop and exhibition on a career fair with the aim to motivate and clarify the scope of intervention of a Civil Engineer. The goal was that the participants could understand the various disciplines involved in civil engineering projects. They were first asked to give their ideas of what CE works is, to assess their perception of the field. As expected, none of the 18 participants associated it with innovation or technological advances. Through a head-mounted display and gamepad, participants were then exposed to a virtual environment in which a virtual model of a building was placed. They could interact with a series of buttons assigned to each CE specialty, and the model would reveal the corresponding elements on the model (for example, hydraulic elements would turn blue, structural elements green, etc). Then they used a leap motion sensor to move objects of the model around and experience how VR interfaces could serve to build and design house structures. They were lastly surveyed about the effectiveness and relevance of VR in understanding the concepts of the exhibition. Although the sample was too reduced, the data still shows a tendency towards considering VR relevant or necessary to understand the concepts.

The general conclusion of this study is that VR is useful for Civil Engineering education, and that the NUI resulted in a practical and user-friendly experience for most participants.

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[4] An immersive Virtual Reality interface for Civil Engineering dissemination amongst pre-university students (July 2017)

This paper is by the same authors of the previous one. It centres around the same topic: VR for education in the CE field in the context of the ELBigMAC project, but in this case the focus is on the aspect of importing BIM into a game engine. It explains further on the process of the second case study addressed in the previously reviewed article. Students from Informatics in Construction classes created a BIM model of one of the campus buildings, which was later imported to Unity game engine in order to create the interactive virtual environment. It also specifies they used a HMD (head mounted device) and controllers for the VR simulation, and C# programming scripts to allow navigation and interaction with the layers of the construction model, selecting the visibility of the desired structures. They provided two alternatives for moving the elements: a virtual laser pointer and a conventional gamepad.

[5] Virtual Reality for Design and Construction Education Environment (Apr 2019)

This paper is a literature review of the uses of VR in the AEC (Architecture, Engineering and Construction) industry, with a particular emphasis in education. It also includes interviews from students in a master of project management (MPM) program. The goal is to provide a reference for future implementation.

The studies included in the literature review of VR applied to construction industry are summarised into the following table:

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Table 1. VR in Different Areas of Design and Construction

N	Authors	Years	Application Scenario/ Explanation	Phase	Using alongside BIM	Tested in project
1	Du et al.	2018	Collaborative decision making	Design and Construction	Yes	Yes
2	Shi et al.	2018	Utilized a multi-user virtual reality (MVR) system with motion tracking function to simulate hazardous scenarios to study how social influence affects construction workers' safety behaviors.	Construction	No	Yes
3	Du et al.	2017	Introduced a cloud-based multiuser VR headset system (CoVR) which was able to facilitate interpersonal project communication.	Design and Construction	Yes	Yes
4	Paes and Irizarry	2017	Described a systematic study aimed to investigate the implications and usability issues of an immersive VR system in design review.	Design	Yes	Yes
5	Natephra et al.	2017	Developed a BIM-based lighting design feedback (BLDF) prototype system for realistic visualization of lighting condition and the calculation of energy consumption.	Design	Yes	Yes
6	Liu et al.	2014	Examined the use of a VR media and display system in the design process of an energy retrofit project.	Design	Yes	Yes
7	Fang et al.	2014	Presented and implemented a virtual training system for crane operators by simulating the as-built work scenarios.	Construction	Yes	Yes
8	Hollermann and Bargstädt	2014	Linked product model with a time schedule to a 4D construction model and visualized in a stereoscopic multi-user system to support the process of planning of the construction site.	Design and Construction	Yes	Yes
9	Koutsabasis et al.	2012	Make a combined use of established principles in design and computer-mediated communication studies to provide an account of their value for collaborative design.	Design	No	Yes
10	Woksepp and Olofsson	2008	Explore the way VR models are apprehended and used by AEC professionals in their everyday work.	Design and Construction	No	Yes

The literature on VR applied to AEC education at the time was scarce. Studies highlighted its potential to improve students' engagement and motivation, as well as its usefulness for visualising concepts that are complex, or situations that are risky to experience in real life. The benefits and results of the studies reviewed are summarised in the following table:

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Table 2. Characteristics of VR in Design and Construction Education Environment

References	Characteristics							
	Learnability	Interoperability	Visualization	Real World	Interaction	Creativity	Motivating	Comfort
(Wang et al., 2018a)	√	√	√	√		√		
(Fogarty et al., 2017)	√		√	√	√	√	√	
(Paes et al., 2017)	√		√	√				
(Pedro et al., 2015)	√		√	√	√			
(Fogarty et al., 2015)	√		√	√	√			
Frequency	5	1	5	5	3	2	1	0

Note: Learnability (easy to learn); Interoperability (easy to convert and enable the VR feature from native 3D models); Visualization (ability to visualize); Real World (provides a similarity to the real world); Interaction (perceived interaction with instructor and classmates); Creativity (improve students creativity); Motivating (provides students with a motive for learning); Comfort (ease of use as a level of motion sickness).

The next phase of the study is analysing the experience of the students participating in the course "Integrating VR/AR/MR with Design and Construction", as part of their MPM studies. They tested 5 different VR headsets. Feedback from students was categorised as the same parameters from the table above. Results showed that VR technologies generally ranked the highest in motivating, learnability, creativity and similarity to the real world, while ranking the least in comfort (for certain headsets specially) and interoperability. The results from the different headsets were also compared.

[6] Mixed Reality Multimedia Learning To Facilitate Learning Outcomes From Project Based Learning (Apr 2020)

This paper reviews literature on Project Based Learning (PBL) and multimedia learning to identify six learning gains that could be facilitated using Augmented Reality & Virtual Reality technologies. The authors of this paper propose using these learning gains as targets to specifically design implementation studies. The focus of this study is on the importance of tacit knowledge (usually expressed as points of view that the individuals develop during their career experiences) as opposed to explicit knowledge (typically conveyed through textbooks, manuals and detailed in-class examples) in the field of AEC and how these new methods could be beneficial for the acquisition of said tacit knowledge before any actual working experience. That is the main goal of the Project Based (or Problem Based) Learning strategies: to provide real world context to students. These strategies could be defined as projects involving practical design and construction experiences that help generate comprehensive tacit and explicit knowledge.

The literature shows that physical experiences that have a physical building component (such as competitions) are proven to be really effective, providing students with a rare opportunity of building and designing full-scale. However, these experiences are not always available due to the resource requirements. PBL is a teaching strategy that leverages from real world projects but does not require students to physically build, making it more accessible. Immersive virtual environments have a potential benefit over real, physical competitions due to their cost-effective nature and the ease of repurposing them for other projects.

The following table summarises learning gains from PBL and physical experiences and also from MR applications. Considering that, for the same learning gains, MR has a smaller cost and a longer lifespan, its advantages are evident.

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Learnings Reported	**Physical/PBL**	**Mixed Reality**
Sequencing Construction Activities	(Matulka, 2013) (Glick et al., 2012) (Sampaio & Martins, 2014)	(Ku & Mahabaleshwarkar, 2011)
Autonomous Decision making	(Craft, Click, & Marshall, 2004)	(Alsafouri et al., 2017)
Students reported higher motivation for activities	(Holt, 2012)	(Martín-Gutiérrez, 2017), (Radu, 2014)
Increased communication with team members and other stakeholders	(Thomas, 2000)	(Le et al., 2015),
Ability to solve problems without teacher-instruction	(Thomas, 2000)	(Okamura, 2004)
Increased student engagement during activities	(Thomas, 2000)	(Enyedy, Danish, & DeLiema, 2015)

Another table includes learning gains that have been reported using either immersive virtual or physical and applied learning environments, but not in both. This is aimed to be used as a guide for future research.

Learnings Reported	**Physical/PBL**	**Mixed Reality**
Empathy for team members	(Matulka, 2013)	
Increased Interdisciplinary Negotiation skills	(Holt, 2012)	
Access to multiple visual perspectives		(Teizer, Cheng, & Fang, 2013)
Long-Term Memory retention		(Radu, 2014)
Collaborative Learning		(Martín-Gutiérrez et al., 2015)

[7] Digital Twin and Web-Based Virtual Gaming Technologies for Online Education: A Case of Construction Management and Engineering (July 2020)

This is a very extensive study in which the authors designed and developed a series of digital modules using different types of digital twin and mixed reality technology and tested them in an Infrastructure and Industrial Construction course, further interviewing the students in order to analyse the feedback and provide a more in-depth insight of how these technologies can be useful for AEC training.

One of these modules was an **Interactive Construction Tour**, presented as a 360° video projected to the students in an interactive and immersive chamber. This chamber consisted of a cylindrical canvas and five projectors with stereo sound.

Students were able to interact with the 3d visualisation by means of motion tracking systems and hotspots added to the video, which triggered additional information in the shape of more detailed photos or videos of the different construction processes, as well as interviews with professionals. It

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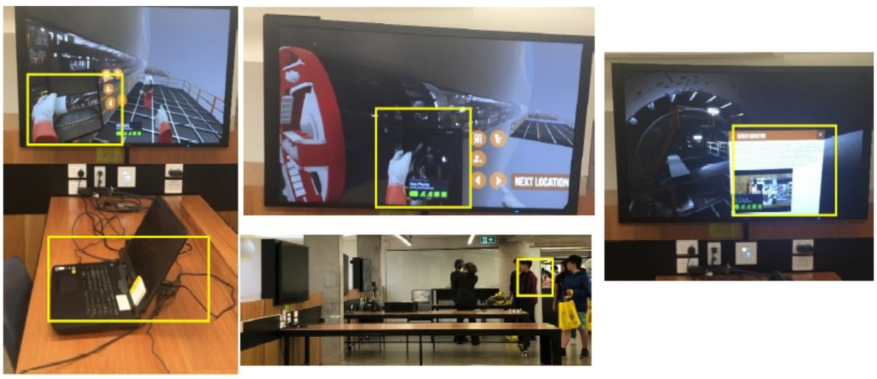
also allowed the educators to control the simulation through a tablet. A browser-accessible version of the experience was later uploaded to YouTube in the form of an interactive video with the possibility of zooming in and out.

This experience made it possible for the students to experience and see the activities of real construction work (filmed with 360° cameras) in areas that usually are not easily accessible to them (excavation works) or pose a serious safety risk in case of a real visit.

Another module is a **Virtual Tunnel Boring Machine**, a game-based virtual environment to which several students can connect at once and interact with each other's avatars. This virtual environment is based on a 3D model of a tunnel, and there are various virtual tools, machines and equipment the students can interact with to complete tasks. The "game" can be accessed from a laptop or a headset, both remotely and in the classroom. Additionally, Discord servers were provided for the students to communicate simultaneously.



Another module is a **Piling AR experience** that can be accessed via mobile device or headset. This includes a 3D model of the process of constructing piling foundations step by step. Students can see all the sections in 3D and interact with several hotspots around the model, triggering additional augmented information. A multi-user version is also possible, where students can have avatars and interact with each other to share knowledge and engage in the learning experience. Sessions can be saved and downloaded as video for further study.

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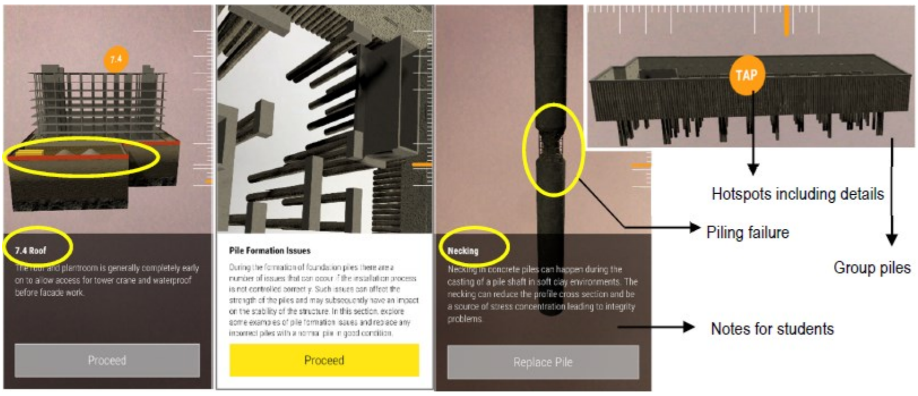

Lastly, they also created an **excavator Digital Twin**, that is connected to a real excavator, allowing students to practise moving an excavator. An entirely virtual simulator version is also available for when off-campus. A promotional video can be seen in this link:

https://youtu.be/rxaf8J6Lyp8?feature=shared

The study then contains an extensive data analysis of the students' interviews and the study results. To summarise, students' satisfaction was significant, and overall, the trial was deemed a "successful integration of theoretical concepts into practical experience in an authentic learning environment". In general, the tools designed have been proven to be useful and valuable to enhance learning. "Compared with a textbook or a lecture, students understand the practicalities and concepts more rapidly and with greater clarity". The authors emphasise the need for analysing the perceptions of the educators after the implementation of these modules in further research. Another relevant aspect of this study's discussion is that the content designed, although innovative and highly interactive, was not dependent on expensive hardware, as they were able to implement these modules with a high number of students. Another interesting factor is the novelty of applying digital twin technology in AEC education, which, as opposed to VR or AR, is not often documented. This paper is presented as the first step in further research aimed to create a fully immersive construction learning experience.

[8] Remote Indoor Construction Progress Monitoring Using Extended Reality (Feb 2021)

This paper proposes a construction work inspection system called iVR. The goal is to make the process of construction monitoring more efficient and closer to real time, as opposed to the traditional method of visiting the job-site, collecting data, and waiting for it to be processed before making an assessment. It proposes a communication platform that improves the process of quality and progress assessment and decision-making.

Visual manual inspections require professionals to travel to the construction sites, personally evaluate dimensional errors and surface defects, collect and store data. This requires a lot of energy, manpower and time. Remote monitoring is a more sustainable alternative, since it reduces the impact of travelling, is faster and requires a fewer number of inspectors. It also reduces interaction, which was a key aspect of safety in the context of the development of the study, during the COVID-19 pandemic.

AR has already been used in combination with BIM technology for construction management, but the problem is that BIM models cannot be synchronised with the job site since they require to be stored on separate servers. This causes a delay between the job-site and the management office, which can be critical and result in reworks or slowdown. In this context, the authors' proposed platform aims to

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close that gap between the construction site and the office by creating a system that transfers data in real-time. It captures point cloud data from the construction activity with laser scanning, converts it into 3D models, allows managers at the office to do the remote monitoring through VR, and then presents their feedback and reports to the workers on-site in AR. It was tested in two cases of study successfully, although limited to indoor activities so far.

First step is creating an inspection checklist of all the elements that need to be inspected and the degree of accuracy. This is based on the project specifications. Then, the iVR system can be used to perform the inspection remotely, in communication with the on-site engineers.

The iVR system consists of 5 modules:

- **iVR-location finder:** optimises laser scanner device location in the physical model. It helps the inspector to control the location of the scanning camera. The inspector can choose options of scanner type and date of activity, and the system then provides the most optimal field of view location.
- **iVR-scan**: captures point cloud data with 3D laser scanners. This requires a monitoring camera placed on the job site, and managed according to the parameters of the previous module.
- **iVR-prepare:** Converts the point cloud data into a 3D mesh geometry. It receives the data from iVR-scan with a 100 ms time-lapse. In this step, the inspector can select particular target objects by determining the desired boundaries, and the system then ignores everything outside the chosen region, optimising the data processing.
- **iVR-inspect**: allows the inspector to generate a quality assessment report using VR. It aligns the 3D mesh from the previous step with the BIM model, and by means of a VR headset allows the inspector to trace workflow, compare the progress with blueprints, measure and highlight objects and add text or design notes to the 3D model.
- **iVR-feedback:** visualises inspection feedback in AR on the construction site. It synchronises the BIM model from the construction office (in the iVR-inspect module) with the worker smartphone, presenting the report data in AR form.

The process of the two test case studies is summarised in the following diagrams:

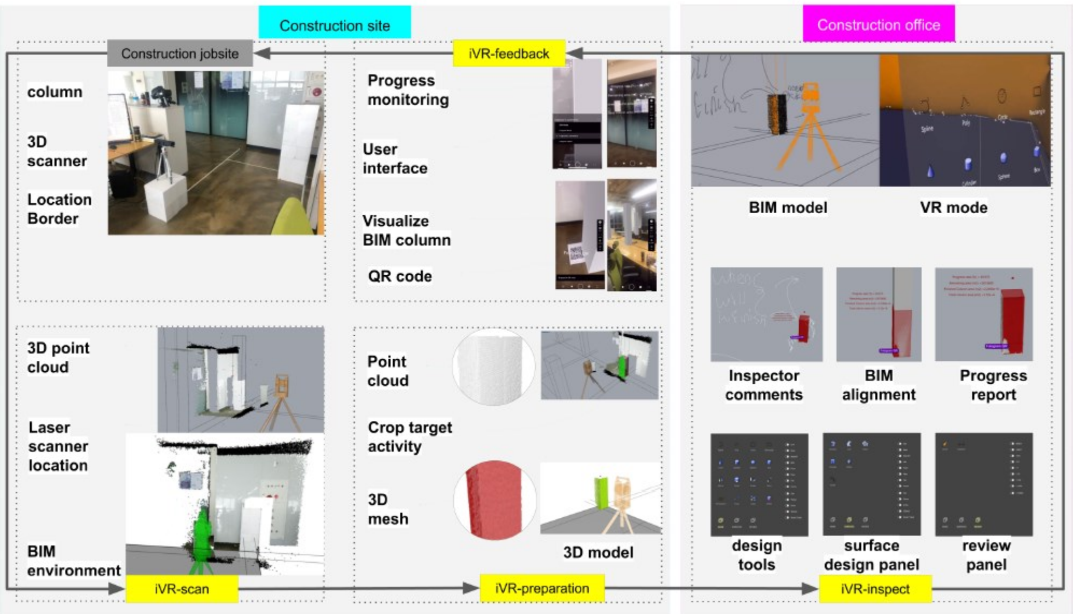

Figure 10. Column lab test case study for work inspection using the iVR system all phases.

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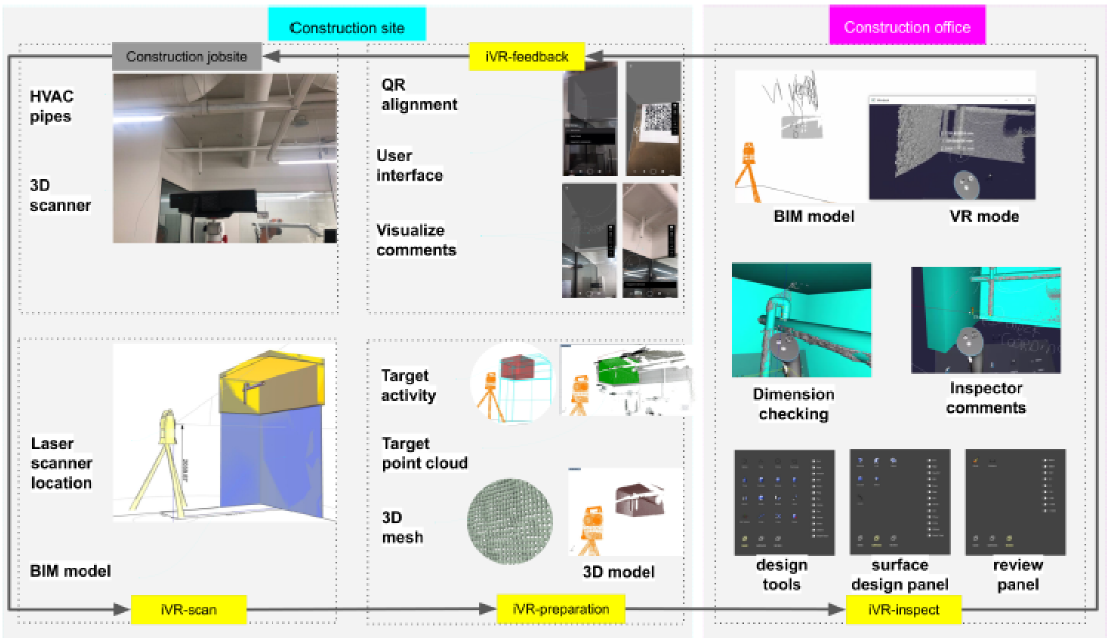

Figure 12. case study for HVAC pipe work inspection using the iVR system all phases.

The results indicate that the developed tool helps bridge the gap between the construction office and job-site. Immersive virtual and AR helps the inspector and workers to visualise the activity from different angles, which cannot be achieved via conventional methods, and provides the necessary tools for drawing, commenting, attaching data, and communicating faster. Using iVR, inspectors can monitor various activities quickly without physically leaving the construction office.

[9] Use of Virtual Reality to Improve Engagement and Self-Efficacy in Architectural Engineering Disciplines (Oct 2021)

This paper presents the results of the pilot test of VADERs (Virtual/Augmented-Reality-Based Discipline Exploration Rotations). This is a program consisting of a series of modules that aims to offer a virtual experience of an engineering discipline and its sub-disciplines. The purpose of this program is to offer first-year engineering students a connection with the actual impact of their future work, thus improving retention and helping the students maintain motivation and commitment with their studies. Traditionally, the most effective way to create that connection between the curricula and the real-world problems, which are what motivates students to choose those majors, is by means of internships or similar programs. However, the problem with those is that they are required to be offered at the last years of the curriculum, since the students need to acquire the foundational knowledge before working at a real company. The VADERs program aims to serve as a virtual alternative for the earlier stages of the degrees, "immersing students in an exploration of the sub-disciplines and their integration through an authentic work-like experience".

The VADERs modules combine several VR/AR techniques with engineering tasks, focused on connecting the content of the course to real-life problems and situations. They are not designed to be used singularly as instructional tools nor to replace lessons or technical content of the course, but as a complement. Content includes: virtual rooms with spatial and audio interaction, and possibility of communication by life-like avatars, interactive building environments, interactive exercises with embedded audio and video to visualise the impact of the design decisions. The program is inspired by real-life training rotations and internships. 3 levels were designed, the first one, VADER-1, was tested by 89 students in two Introduction to Architectural Engineering courses. At this level, students took

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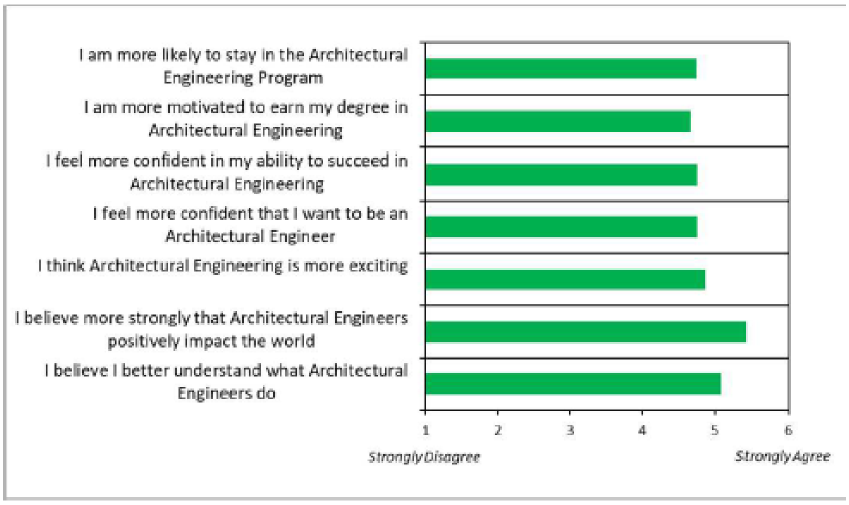
the roles of interns working on the design of a clinic, and were able to rotate through different positions to explore several sub-disciplines of their studies. The experience was complemented by introduction videos to prepare before accomplishing a series of tasks and missions in the virtual environment. The students also had to fill out a pre-survey before the program which aimed to determine their perception on self-efficacy, motivation, engagement, and expectations towards the module. After completing the tasks and missions of the module independently, the students had to provide a presentation with their personal observations and final design decisions (including choosing a design team), to prove the knowledge acquired. They were also asked to complete a post-survey. The main goal of collecting this data was to determine the students' confidence in the selection of AEC as their discipline and in the selection of any sub-discipline chosen, as well as their level of engagement during the test.

Results show that the majority of students felt immersed in the activity and that most of them felt more confident of their top sub-discipline choice compared to before the test. A portion of them also decided to change their top choice after the test. Overall self-confidence and retention were improved, as shown in the responses:



Students were also asked to explain what they learned through the experience, revealing a wide range of themes from equations and technical content to broader aspects such as the importance of decision-making and the complexity of AE projects. These results evidence that students became more familiarised with the real implications of their future area of expertise through this program. General enjoyment of the activity was also reported. In summary "the added benefits of the authenticity of the learning environment supported by the VR/AR technologies are evident", and the program proved to be effective as a way to improve retention and self-efficacy in first-year students by gaining acquaintance with the real complexity of their work but in a low-stakes environment.

[10] Comparing 360° Virtual Reality Learning Configurations for Construction Education (Feb 2022)

This study aimed to analyse the effectiveness of a 360° VR site visit as an alternative or supplement to a real-life site visit for construction students. In order to determine the best way to implement VR as a learning tool, the study compares the feedback and learning experiences of students exposed to a 360° photography of a construction site versus students exposed to the same photography but with

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annotations. The expectation was that the second group would report a better learning experience than the first.

The study design included 81 students from a 4-year construction management program, of different ages and background knowledge. They were sorted into the control (17 students) and test groups (64 students). Both groups visualised the same 360° photography by means of a mounted VR set with controllers. The annotations for the test group consisted of text pop-ups with additional information, videos with audio track and quizzes that had automatic scoring. After the exercise, students from both groups were asked to rate their learning experience in 9 items: quality of experience, effectiveness for communication, overall ranking, improved skills, improved CM skills, rate of the learning element, quality of colour and texture and technology interfering. Students from the test group scored higher in all items except for Q8 (quality of colour and texture). This might be due to the fact that they rated the quality of the annotations, since the resolution of the 360° was the same in both cases. Lastly, the study was then complemented by an eye-tracking analysis of the students in the control group to determine the areas that attracted their attention when asked to explore the VR environment.

The conclusions from this study are that the annotated exercise provided a better perceived learning experience, and that eye-tracking and head-motion tracking can be useful to determine where are the best areas to include annotations and content when designing a VR learning exercise. Since the annotations were proven to be significant, the emphasis of this type of interventions should be on the content of the VR exercises. Overall, the authors propose VR site visits not as a replacement to real visits but as a complement, and consider that more research is needed in order to determine how much this technology can improve learning.

[11] Group-based VR Training to Improve Hazard Recognition, Evaluation, and Control for Highway Construction Workers (Mar 2022)

The goal of this paper is to present a VR training platform for highway construction workers. Given that construction workers fail to recognise about 40% of workplace hazards, and that among all construction subdisciplines, highway workers suffer the most injuries, the idea is to introduce VR as an alternative to individual, lecture-based safety training, in order to increase its effectiveness and introduce the benefits of collective engagement.

This platform is centred on evidence-based and experiential learning. To help instructors with a high number of students in class, they chose a group-based, interactive VR setting consisting of 360° projections instead of a more traditional, HMD individual approach. They provide fully immersive scenarios based on real highway construction sites, complemented with spatialized audio, that can be adjusted to fit the level of knowledge of the students. It includes several elements of risk and environmental conditions that can be customised, such as time of day, weather, different worker roles, equipment, etc. It allows an instructor to create and modify work zone scenarios and share them with the entire class, either by large projection screens or mobile devices. The platform gives the instructors freedom to propose different activities, like asking them to identify what is wrong in the scene or what hazards are being ignored, for example. This helps to expose the students to realistic, hazardous situations in a safe virtual environment, enabling collective learning.

They tested the proposed platform on a 360° projection environment, complemented with motion capture and spatial audio systems, to involve groups of multiple people at once. It was evaluated by an experienced safety training instructor, with positive results.

[12] Virtual Reality in Construction Design (May 2022)

This paper revolves around the use of VR technology for visualising construction designs in 3D. The simulation created uses Unity 3D engine and C# scripts to create realistic virtual environments that can be explored with a VR headset. They used Unity *progrid* and *probuilder* functions to create 3D structures and surfaces that translate the information from the plans, as well as to design interiors that include all the clients' particular requirements and preferences. The goal is to assess the client satisfaction in understanding the construction design in comparison to traditional 2D construction plans. It highlights how VR can enhance communication between builders and clients by allowing clients to experience their planned construction virtually before building it. This method aims to reduce errors and dissatisfaction in the final construction.

[13] Virtual and Augmented Reality Infused in AEC Ir 4.0 (Nov 2022)

This paper discusses various applications of XR (referred to as VAR) in the AEC industry and how they relate to the context of the 4th Industrial Revolution (Ir 4.0), with a particular focus on XR technology for BIM. The goal is to propose a classification of all the possible areas of application, based on the previous research on the subject, to serve as a guide for further research.

After a brief introductory timeline of the evolution of VR and AR technologies, the paper includes a quick overview of previous work related to the use of XR in the AEC industry, in the frame of Ir 4.0, which includes: studies that explore VR's benefits in stakeholder engagement and interaction productivity, meta-analysis of the usefulness of XR for BIM, a survey on the barriers and success factors of industrial AR deployment or a proposed method for converting traditional written documentation and manuals into AR.

In the next section, the authors propose a classification of different use-cases of XR in the AEC industry, as well as their challenges, and summarise it into the following diagram:

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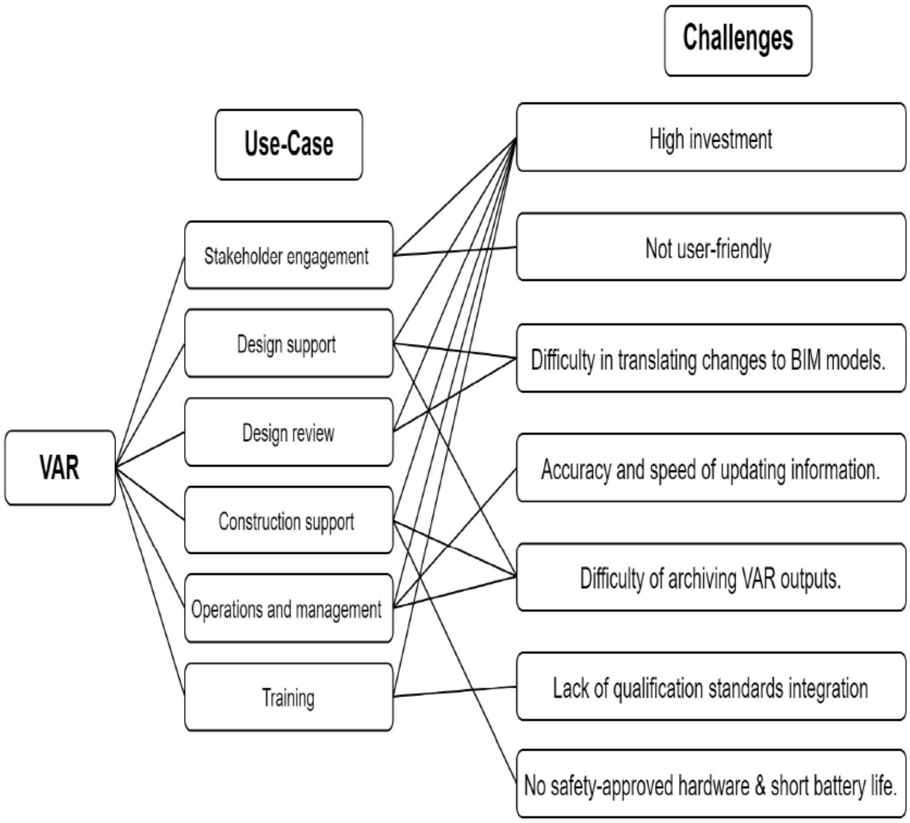

The use-case of construction support contemplates different applications: construction planning, progress monitoring, construction safety and operative support. Operations and management also include building maintenance. In the category of training, the authors state that XR can help participants to build expertise by imitating real life actions, reducing the training expenses of costly equipment and travels as well as minimising risks by simulating hazardous conditions.

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The next section is focused on the applications of XR in BIM, which can fall into three categories: education and training, design and data exchange, and project management and collaboration. These applications are organised into the following table:

Category	Application	Description
Education and Training	Safety Training	Building an intuitive virtual simulation to instruct workers on several areas of AEC projects' safety [28]
	Design Training	Leveraging immersive VAR to educate students and specialists to enhance their knowledge of AEC projects and their productivity in true scenarios [29]
Design and Data Exchange	Decision Making	Addressing real-world difficulties in a virtual setting ensures better decision-making in real-world AEC projects [30]
	Interactive Visualization	Improving the productivity of the design process utilizing immersive VAR interactions [31]
	Data Exchange	Transforming and exporting BIM data across different tools is simplified [32]
	MEP (Minimum Energy Path) Structures	Allowing for the visualization and design of concealed facilities in AEC projects, such as MEP structures [33]
Project Management and Collaboration	On-Site Implementation	Using an on-site VR system to experience the benefits of a virtual space, such as real-time project management and coordination [34]
	Disaster Management	Simulating crisis situations and designing safety solutions with extensive BIM visualization [35]
	Workspace Planning	Envisioning execution techniques to help employees and engineers truly understand building operations [36]
	Building Maintenance	Enhance resource visibility and ensure that they are sustainable beforehand [37]

The paper concludes by emphasising the need to provide with more data on the subject, to help operators determine which methods to apply. This calls out for further research on benefits versus drawbacks, compatibility with previous methods, ease of testing and the magnitude to which findings can be monitored. The authors also draw attention to the fact that the use of XR in AEC seems to be lacking as compared to other industries, and relate it to its possible restrictions and challenges.

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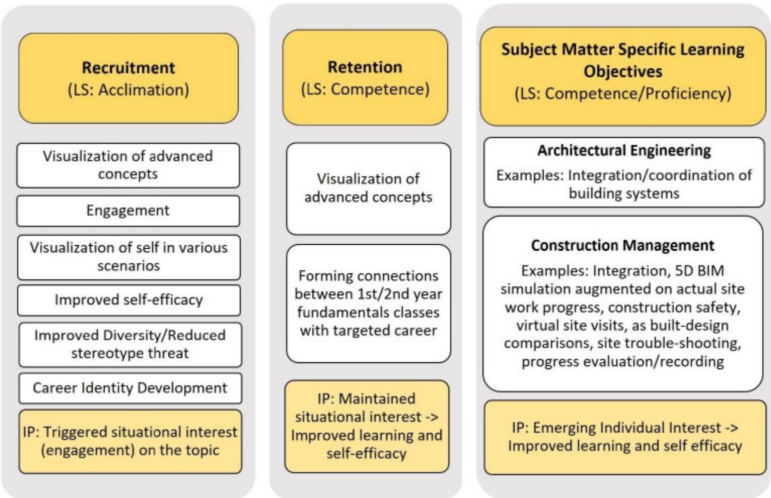
[14] Framework for the Use of Extended Reality Modalities in AEC Education (Dec 2022)

The ultimate goal of this paper is to propose a decision-making framework that would serve as a guide for educators in the field of Architectural Engineering and Construction (AE/C) to choose the best modality of Extended Reality (XR) depending on their learning goals and the priorities of the activity.

In order to ground the proposal of their framework, the authors performed an extensive literature review in two phases:

- First, literature was analysed in order to establish a consistent definition of the terms Virtual Reality, Augmented Reality and Mixed Reality.
- Second, a series of case studies were reviewed to evaluate the feedback and general effectiveness of the implementation of XR interventions for educational purposes in AEC education.

The case studies were classified based on their primary educational objectives. The three categories, based on the Model of Domain Learning, are the following:



- **Recruitment**: used in precollege, to generate interest in AE/C domains by presenting career options and helping students visualise themselves in these careers. These interventions are motivated by the hypothesis that misconceptions about the field and career options of A/EC studies are the main reason why teenage students do not pursue a major in this field. A general increase of the interest in the field was reported.
- **Retention**: the main goal in these cases is to maintain the students' interest in their classes by providing interactive and immersive learning experiences as an alternative to the predominant lecture-based, theoretical approach of most courses, which lacks the necessary connection of the students with the highly visual and tangible nature of their careers. This was reported to be effective in increasing the students general motivation to learn, as they report to be more likely to continue their studies and also feel more confident in their abilities to succeed.
- **Subject Matter-Specific Learning Objectives**: the studies on this last category focus not on the increasing of engagement or interest, but on the potential benefits of XR for learning particular higher level subject matters that are either too difficult to explain/understand without a 3d visualisation or too risky to experiment in real-life situations. Some of the areas in which interventions with XR have been tested are:

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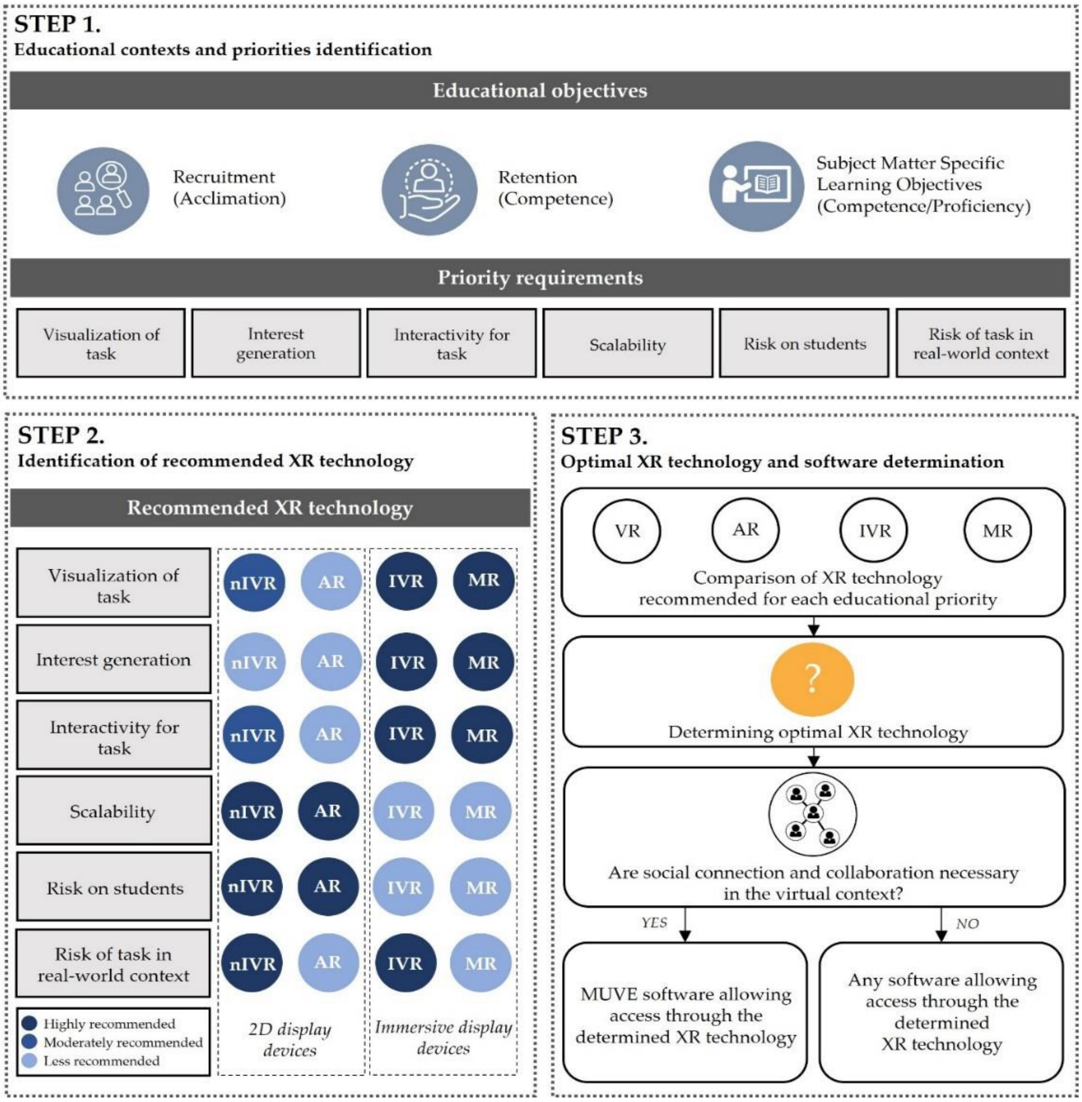
- Construction safety training. In these cases, XR experiences helped students to identify safety hazards without enduring any actual physical risk.
- Virtual site visits. In this case, XR serves as a solution to the logistical challenges of arranging real-life construction site visits for the students, as well as to make the visits accessible to students with disabilities without the physical barriers of the real site.
- Other case studies: identifying design mistakes in VR vs 2d plans, AR to improve the comprehension of the construction process of pad foundations, virtual rotations (a project in which students experienced a virtual simulation of a real working situation as interns).

Based on this literature review, the authors propose the following decision-making framework in three steps:



This is meant to serve as a guide for educators to select the right type of XR modality and hardware based on their educational objective, but also on a ranking of possible six priorities: interactivity, interest generation, scalability (which could mean accessibility in terms of disability but also cost effectiveness and the possibility to include larger groups of students), risk on students (in terms of avoiding cybersickness but also other health risks related to the students sharing equipment) and lastly, risk of the task in the real-world context. Once priorities are established, a certain type of XR is recommended. The framework also takes into consideration MUVE (Multi-user virtual environments)

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as a way to provide a collaborative space for students. Lastly, the study also includes a pilot validation of the framework on two different projects, one to increase retention in first-year Architectural Engineering students, and the other to generate interest in precollege students attending a Tech summer camp.

The conclusions of the paper are:

- The use of XR as an umbrella term as the best alternative when various modalities are employed, as well as the need to put an emphasis on the differentiation between immersive and non-immersive XR.
- The case studies show evidence that XR increases student interest and engagement in AEC education, while its contribution to improved learning needs to be measured and tested further.
- The effectiveness of the proposed framework in simplifying the process of decision-making is validated by the pilot case studies.

The authors suggest that the goal of XR interventions should not be to replace conventional methods of learning but rather to complement and support them.

[15] SWOT Analysis of Extended Reality in Architecture Engineering and Construction Organizations (Oct 2023)

The paper proposes SWOT (Strengths, Weaknesses, Opportunities, Threats) based criteria to evaluate the usefulness of XR in AEC organisations. In order to do so, a systematic review of literature from 2018 to 2022 is performed. By means of a spreadsheet matrix and thematic analysis, the authors developed a total of 22 criteria that aim to serve as a guide for AEC organisations in the implementation of XR technologies.

As a base, the authors establish the procedure for carrying out SWOT analysis of XR technologies:

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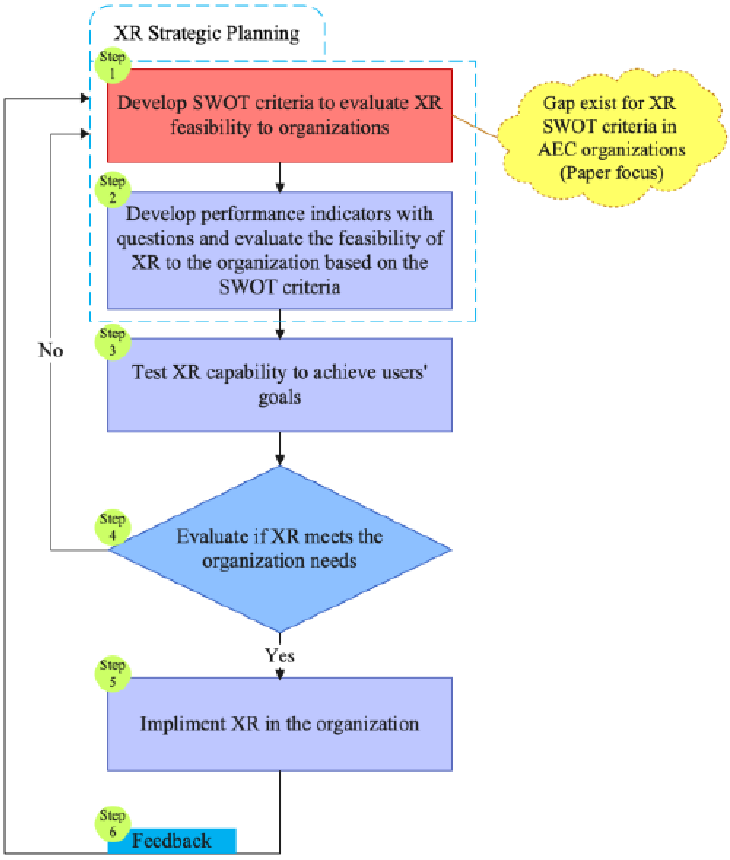

The definitions and corresponding keywords established for the analysis are the following:

- **Strengths**: internal criteria that ensure success (keywords include advantage, benefit, improve, enhance)
- **Weaknesses**: internal criteria that hinder success (disadvantage, shortcoming, limitation)
- **Opportunities**: external environment criteria that help to achieve success (potential, future, recommend)
- **Threats**: external environment criteria that hinder the achievement of success (challenge, barrier, obstacle, risk)

Then, the 22 criteria are listed and defined, and later summarised into the following diagram:

As shown, personnel training and learning and development are listed as opportunities of XR in AEC organisations. Personnel training refers to education on the subject matters of construction by means of XR as a learning tool while learning and development refers to the capability of organisations of applying the knowledge from previous XR use cases and how it benefits their goals.

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The paper ends by calling a need for further research in developing and testing performance indicators to evaluate XR technologies and validate them by industry experts.

[16] Extended Reality (XR) – A Magic Box of Digitalization in Driving Sustainable Development of the Construction Industry: A critical review (Nov 2023)

This paper reviews the impact of XR for the construction sector to aim towards sustainable development. The main goal of the study is to systematically summarise how VR, AR, and MR technologies can be applied to Sustainable Construction (SC) throughout the entire lifecycle, in order to help stakeholders understand the advantages and possibilities of XR technologies for particular sustainable goals.

It starts with an overview of the situation of the construction industry within the context of climate change, providing data on how this sector's methods and materials are heavily impactful on the environment with high resource consumption and pollution emissions. This helps to shift focus on SC as a matter of high interest in research and development, relating it to the UN 17 Sustainable Development Goals. Analysing the state of the matter in research (a total of 44 publications from 2001 to 2023), it emphasises the gap among the different stages of the construction process, since the design phase of the pre-construction stage is the most explored area of application in XR studies, with a particular interest in its association with modelling and design systems.

The paper examines XR's role in various stages of building projects, from planning and design to construction and operation. The applications examined are:

- Pre-construction stage: apart from interactive and multi-integration design, applications in this stage also include engineering education tools. This section evidences that the literature centred on XR applied to construction training, in the topic of SC in particular, is still not extensive and highly theoretical.
- Construction stage: operation analysis, pre rehearsals and simulations, communication of operations and zoning locations, among others.
- Post-construction stage: very few studies propose XR in this stage, mainly in facility management (information transfer, condition assessment, simulations).
- Smart cities for sustainability: VR can be used in developing and planning smart cities for a more sustainable urban environment.

The review also discusses the challenges of XR in SC, such as tackling the problem of motion sickness caused by immersive XR (kinetosis), improving the balance between costs and benefits, solve the problems of interdevice compatibility and information security, and a general approach to universality of these technologies and applications (since they are mainly always designed for particular cases). Other lines of future research include exploring more multiuser and multifunctional applications of XR support systems, improving immersion and experience, and a more even distribution across the building lifecycle phases (more research on the construction and specially the post-construction stage applications).

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[17] Extended Reality as a Catalyst for Circular Economy Transition in the Built Environment (Jan 2024)

This article aims to analyse the potential of XR in the transition of the built environment towards circular economy.

The article starts first by reviewing how XR is already implemented in the different stages of the Built Environment:

1. **Design phase:** the stage in which XR is most often used. 3D interactive visualisation using XR has been more effective in increasing the users' accuracy, perception, and memory in understanding the designs, as compared to 2D visualisation. XR provides a realistic, safe and fully manipulable testing environment. It has been used to leverage user feedback, assess risk situations and safety of workers, as well as for collaborative and participatory design.
2. **Construction Phase:** XR has been used for communication, like a cloud-based multi-user XR communication platform. Even if face-to-face communication outperforms it in many cases, studies show that XR could help problem-finding and improve communication efficiency among stakeholders in a joint walk-through. AR is also widely used during the construction phase to visualise the design of a building or infrastructure before it is built on the site. This can be used both as a planning tool and as a learning environment. There are also several applications of AR for guidance on site, to avoid mistakes and risks, as well as for quality control.
3. **Operations and End-of-Life:** XR is not used as much for this stage unlike the previous two. However, AR has been explored for maintenance and operations. One example is remote maintenance, in which colleagues can assist the operator remotely by sending overlaid AR information along with voice instructions. It has also been used to preview renovations and retrofit interventions by projecting a "digital window" that overlays the BIM model of an object. There are also AR applications to provide measurements of a real object, as well as to project fluid or thermal simulations over the real environment. It can also be used as guidance for disassembling and material recovery processes.

The next section of the article is a literature review that analyses studies about applications of XR that can be useful for one of the four circular economy strategies: regenerate, narrow, slow and close.

1. **Regenerate**: regenerate strategies focus on creating sustainable systems that restore or enhance the environment. In this category there are several examples of XR used for urban planning and design. One example that can be useful for regenerating strategies is to offer realistic simulations in VR of environmental changes, to induce visceral reactions and build stakeholder empathy. It can also help illustrate the debate about alternative design options.
2. **Narrow**: these strategies focus on optimising a process or design in order to maximise resource efficiency and building performance. XR is useful for this process by providing a clearer visualisation of otherwise data-intensive simulations, simplifying stakeholders' understanding and decision-making. AR applications have been used to scan the environment and measure and identify materials, making it easier to reuse and reintegrate pre-existing components. Displaying models of alternative scenarios over the real building can also optimise the renovation processes.
3. **Slow**: in this case, the goal is to improve the lifetime of an asset by accounting for reversibility, adaptability and reconfigurability in its design. XR combined with other technologies like deep learning, can optimise data retrieval to provide automated status reports of the assets or

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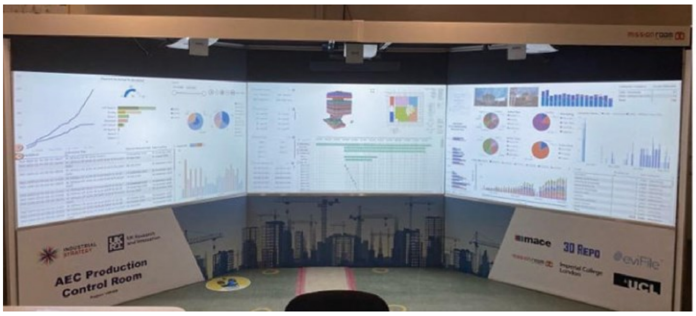
buildings. The applications of AR in facility management include intelligent fault diagnosis, visualised operation guidance, situational aware-ness, and building performance monitoring. It can also help visualise and plan for reconfigurable systems by visualising several alternative configurations at once.

4. **Close**: these strategies revolve around recycling, reusing and minimising waste. XR has been effective for training people to identify waste and how to dispose of it correctly. AR has also been used in construction to help repurpose waste for new projects, like designing a structure based on existing scraps of material. XR can help track resources over the life cycle of a building, creating a database of materials that can be reused. It is also useful for urban mining, helping visualise the material stock within a studied building.

Lastly, the article provides a section of examples of programs or commercial applications that involve XR in construction practice, and that have useful benefits for circular transition:

1. **Collaborative Visualisation of Design:** As explained above, XR has been implemented successfully to improve communication between the experts and partners involved in the construction process, within an immersive environment. An example is 3DMOVE (in picture), a collaborative tool for multiple users to interact with and explore full-scale 3D models and built environments. Additionally, there are also commercial offerings that provide collaborative design visualisation by means of semi-immersive hardware solutions (Mission Room, Fulcro Fullmax).

2. **Construction Production Control Rooms:** these are collaborative digital interfaces that offer real-time project information and efficient construction management. They provide real-time project information leading to efficient use of resources, helping to minimise waste and maximise the value of materials. An example of this is the AEC Production Control Room (in picture).



3. **Construction AR**: technologies that allow professionals to interact with digital models and information overlaid onto the physical environment. As seen before, these can be useful in all three stages of construction, as well as for all four circular strategies. There are many AR solutions for construction, a significant example mentioned is XYZ Reality Atom (in picture), that combines a construction safety headset with AR displays and laser-based tracking

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technology to offer millimetre accuracy in placing the 3D models and holograms within real construction structures.

As a further discussion, the article ends with acknowledging some limitations for applying XR that need to be addressed, namely: the slow building of digital twins, which are crucial for a successful implementation of XR in the built environment; the potential misuse of technology, which can lead to misleading or ineffective designs; and technical and logistical challenges and barriers derived from the need for specialised hardware, software and training.

Table summary

Study/ Paper /project	Technology used: AR/VR/MR, other	Topic within the construction sector	Environmental topics addressed
[1] ecoCampus	AR combined with a touch-based game interface (on a mobile device)	Building redesign, AEC Education	Sustainable design (the context is redesigning renovations on pre-existing facilities with sustainability as a goal)
[2] VSES	VR (on mobile device), GUI, 3D modelling, Blender game engine, key frame animation	AEC Education (safety training)	None
[3] ELBigMAC	VR and NUI (Natural user interface)	AEC Education, BIM, Design	None
[4] ELBigMAC	VR and NUI	AEC Education, BIM, Design	None
[5] Virtual Reality for Design and Construction Education Environment	Different modalities of VR (literature review)	AEC Education	None
[6] Mixed Reality Multimedia Learning To Facilitate Learning Outcomes From Project Based	Different modalities of XR (theoretical approach/literature review)	AEC Education	None

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Learning			
[7] Digital Twin and Web-Based Virtual Gaming Technologies for Online Education	Digital Twin, VR, AR, 3D modelling, 360° video (immersion chamber, mobile devices and browser-based VR/AR)	AEC Education (excavation, construction site visits)	None
[8] iVR system	VR (on headset), AR (on mobile devices), Cloud point, 3D modelling, laser scanner.	Quality Assessment, Construction Inspection and Management	The technology aims to reduce the direct environmental impact of traditional construction inspection by making it remote.
[9] VADERs	VR and AR. Multi-user interfaces, spatial audio, 360° video and 3d modelling	AEC Education	None
[10] Comparing 360° Virtual Reality Learning Configurations for Construction Education	VR, 360° photography, eye and head motion tracking	AEC Education (construction site visits)	None
[11] Group-based VR Training	VR, 3D modelling, immersion chamber, multi-user interface, spatial audio, motion tracking	Safety training for highway construction	None
[12] Virtual Reality in Construction	Unity, 3D modelling, VR (on headset)	Design and BIM	None
[13] Virtual and Augmented Reality Infused in AEC Ir 4.0	Different modalities of XR (theoretical approach/literature review)	All, particular focus on BIM	None
[14] Framework for the Use of Extended Reality Modalities in AEC Education	Different modalities of XR (theoretical approach/literature review)	AEC Education	None
[15] SWOT Analysis of Extended Reality in Architecture	Different modalities of XR (theoretical approach/literature review)	All	None

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Engineering and Construction Organizations			
[16] Extended Reality (XR) – A Magic Box of Digitalization in Driving Sustainable Development of the Construction Industry: A critical review	Different modalities of XR (theoretical approach/literature review)	All	Sustainable Construction, Sustainable Development goals (in general)
[17] Extended Reality as a Catalyst for Circular Economy Transition in the Built Environment	Different modalities of XR (theoretical approach/literature review)	All	Circular Strategies (regenerate, close, narrow, and slow). Includes recycling, waste management and reduction, efficient planning, etc.

Conclusions

Regarding the papers and studies reviewed in this document, the main takeaway is that XR, in different modalities, has been widely used and explored in the context of its application to the AEC industry, particularly in the first two stages of the construction process (design, planning, construction management, etc.). However, when it comes to education and training, their applications are less widespread. Most study cases are tailor-made prototypes, and according to the literature reviews and framework proposals, the implementation of XR technologies in AEC education and construction training is far from established. Main explored areas are safety training, design, construction simulations and virtual site visits, while the main learning goals are engagement and visualisation. Topics of environmental issues are not specifically addressed and, as very recent studies like [16] and [17] evidence, the application of XR technologies towards particular sustainability goals or circular strategies is a fresh and new area of research that has only begun to be approached, and its relevance and urgency is emphasised.

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