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Integrating Extended Reality in Architectural Design Studio Teaching and Reviews: Implementing a Participatory Action Research Framework

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Abstract: In architectural education, the integration of Extended Reality (XR) technologies—including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—promises to revolutionise design studio teaching by offering immersive and interactive learning experiences. However, the broad adoption of XR in architectural education faces significant obstacles. These problems include a skills gap between students and educators, the challenge of establishing suitable simulation and experimental environments for specific educational needs, and the complexities of integrating these technologies into traditional curricula. This research aims to advance the pedagogical understanding of the value XR tools and techniques offer within an architectural design education context that engages students, teachers, and faculty members in a collective exploration of XR technologies. The study specifically focuses on integrating XR into the design studio's final review stage to enhance reviewer engagement and ensuing student learning outcomes, thereby transforming architectural design studio education. Utilising a Participatory Action Research (PAR) methodology, the study established an XR learning environment and created a collaborative review framework within a Master of Architecture programme. A mixed-methods strategy was employed for data collection to assess the impact of XR applications on design processes, review experiences, and learning outcomes. This strategy included creating digital prototypes of XR applications, followed by user testing to gather both qualitative feedback and quantitative performance data. In the practical implementation section, this article provides information on the applications that were developed for specific educational needs to create simulated and experimental environments. The focus is not only on the design of these applications but also on their ability to allow students to communicate with reviewers and audiences about their design projects. The findings indicate that XR technologies have the potential to enhance students' engagement by improving visualisation capabilities and bridging the gap between theoretical and practical aspects of architectural design. This study underscores the potential of XR technologies to transform architectural education, suggesting a framework for their integration into design studios. It contributes to the pedagogical discourse by providing insights into effective XR-based teaching methodologies and setting a foundation for future innovations and technology integration into architectural learning.

Keywords: extended reality integration; design studio teaching; architecture education; augmented reality (AR); virtual reality (VR)

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1. Introduction

Under the impetus of the emergence and integration of Extended Reality (XR) technologies, the field of architectural education is undergoing an unprecedented transformation [1–3]. XR, which encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), offers immersive and interactive experiences and plays an increasingly significant role in the architectural design, construction, and education [4,5].

XR has its roots in the early development of VR and AR technologies [6]. Over the years, advancements in computer graphics, hardware, and software have led to the emergence of sophisticated XR technologies that can integrate seamlessly with various design and visualisation processes [7].

In the field of architecture, XR enhances design visualisation, communication, collaboration, and decision making [8]. Key benefits of XR in architectural education include improved spatial visualisation and understanding of design concepts at an actual scale, the ability to emulate an on-site experience of designs and assess their integration with surroundings, tangible and engaging learning experiences for building systems and components, gamification and increased student engagement through serious games, and promotion of blended learning and discussion among students [9–11]. Architects can use XR to create immersive design environments, allowing clients, stakeholders, and designers to experience and interact with the proposed design in a realistic and engaging manner, all of which can lead to better-informed decision making and improved design outcomes [12]. XR has contributed to the field of architecture by enabling the exploration of complex geometries, facilitating remote collaboration, and improving the understanding of spatial relationships [13]. By utilising XR technologies, architects can create more sustainable, efficient, and user-centred designs [6].

Despite its potential, the integration of XR technologies into architectural design education faces challenges, including costs, skills gaps, complexities in curricula, and the need for effective pedagogical strategies. Their broad adoption faces considerable obstacles, including the prohibitive costs associated with Head-Mounted Displays (HMDs) and Computer-Assisted Virtual Environment (CAVE) systems, a noticeable skills gap among students and educators in utilising these technologies [14], and the intricacies involved in embedding such modern tools into the conventional curricula of architectural education [15]. Initial research endeavours primarily focused on crafting fundamental virtual environments and fostering collaborative design experiences. These initiatives often stumbled over financial, accessibility, and performance barriers [16]. However, due to this technology's rapid iteration rate, especially with the focus on certain technologies that capture the zeitgeist of the market, these barriers should be re-evaluated for feasible use in pedagogy with regular frequency [17,18]. While educational bodies globally are venturing into the realm of XR technologies, literature on their effective assimilation into the pedagogy of architectural design studios remains scarce [19,20]. The prevailing scholarly discourse tends to focus on the technological dimensions—hardware and software—leaving exploring pedagogical strategies and the educational ramifications of XR somewhat neglected [21,22].

Addressing these challenges and research lacunae, this study aims to explore how XR can be integrated into the design studio and its review culture to enhance student learning outcomes and engagement. The research objectives are as follows: establishing an immersive and interactive XR learning environment where students can engage with XR technologies through detailed demonstrations and hands-on tutorials; developing and testing digital prototypes of XR applications tailored to the specific educational needs of architectural design students; enhancing pedagogical practices by bridging the gap between theoretical concepts and practical applications through the integration of XR tools (The Oculus Quest 2 is manufactured by Meta (formerly Facebook), Menlo Park, CA, USA; The HoloLens 2 is manufactured by Microsoft, Redmond, WA, USA) into the design studio; and assessing the impact of XR technologies on student engagement, visualisation capabilities, and design project outcomes.

This study used the Participatory Action Research (PAR) methodology to establish XR learning environments in a Master of Architecture programme. Using a mixed-methods approach, including surveys, interviews, and observational studies, the research assessed the impact of XR on students' design processes and educational experiences. The research seeks to identify and implement pedagogical adjustments conducive to embedding XR technologies into the architectural curriculum and explore modifications to existing teaching workflows that can potentially leverage XR tools to close the gap between theoretical instruction and practical deployment in architectural design education.

This research contributes to the pedagogical discourse by providing insights into effective XR-based teaching methodologies. By addressing the practical challenges of XR integration and highlighting its educational benefits, the study sets a foundation for future innovations in architectural learning and practice.

2. Literature Review

2.1. The Integration of XR Technologies in Architectural Education

The integration of XR technologies in architectural education has garnered increasing attention in recent years. XR offers the potential to transform traditional teaching methodologies by bridging the gap between theoretical knowledge and practical application [23]. This section reviews the existing literature on the application of XR in architectural education, highlighting key studies, their findings, and the gaps that the current study aims to address.

Several studies have demonstrated the benefits of integrating XR technologies into architectural education, facilitating unprecedented development of teaching tools for architectural design studio instruction and enhancing architectural education in general. Schnabel et al. explored the use of VR for creating virtual design studios in 2001, enabling students to engage in collaborative design processes in a shared virtual environment [24]. This approach not only improved students' understanding of spatial relationships but also facilitated more effective communication and feedback between peers and instructors. Similarly, Vecchia et al. [25] and Kuliga et al. [26] examined the use of VR in architectural education, finding the advantages of collaborative VR in enhancing the design workflow and facilitating better communication.

The impact of XR on students' learning outcomes has also been a focal point of research. For example, Wang et al. [23] conducted a study on the effectiveness of VR in teaching architectural education. Their findings indicated that XR-based learning environments increased student engagement and retention of information compared to traditional lecture-based methods. Furthermore, Bashabsheh et al. [27] emphasised immersive VR simulations in building construction courses, and Velaora et al. [28] presented an innovative educational framework for architecture students, combining architecture and game design to enhance design skills through real-time immersive visualisation.

Recent studies further highlight the transformative potential of XR in architectural pedagogy, like in design studio crit sessions and in individual design sessions. Darwish et al. [29] present a theoretical model for integrating VR and AR into the architecture design process, emphasising its use during various design stages and activities. They concluded that XR reduces cognitive load and enhances spatial learning, making it a valuable tool in architectural education [30]. In addition, Hui et al. [31] illustrate the versatility of XR technologies in the architectural academic setting through lecture-based education, design pedagogy, project feedback delivery, and enhancement of experiential learning.

XR technology has evidently become a useful tool in architecture and design education due to its ability to immerse the audience in a one-to-one scale representation of conceptual designs [32]. VR technologies enhance students' engagement and visualisation capabilities and bridge the gap between theory and practice, promoting immersive and interactive learning experiences [22,27,33]. XR technologies address key challenges in architectural education, like the demand for practical experience, the need for deep self-reflection during the design process, and the effective integration of theoretical knowledge and technical skills [1]. With the continuous advancement of technology, including improvements in hardware performance, cost reductions, and increasingly mature software solutions, XR technologies are becoming more widespread and accessible [34].

While existing literature provides valuable insights into the benefits and challenges of XR in education, there is a lack of practical frameworks for integrating these technologies into architectural curricula. Additionally, there is a noticeable skills gap between educators and students in effectively utilising these advanced technologies. Kluge et al. [35] highlighted the need for comprehensive training programs to equip both faculty and students with the necessary skills to integrate XR into their workflows. Furthermore, the high costs associated with XR hardware and software pose significant barriers, particularly for institutions with limited budgets. This situation underscores the necessity for research that not only explores the theoretical advantages of XR but also provides actionable guidelines for its implementation. The current study aims to address this gap by developing a framework for the effective integration of XR technologies in architectural design studios, thereby enhancing both teaching and learning experiences. This framework will not only enrich existing teaching methods in architectural education but will also provide new tools and perspectives for training future architects.

2.2. Participatory Action Research (PAR)

To address this gap, this study employs a Participatory Action Research (PAR) research method. PAR is defined as "a reflective, iterative process of problem-solving led by individuals working with others in teams or as part of a 'community of practice' to improve the way they address issues and solve problems" [36]. PAR is recognised in the literature as an effective method for integrating and evaluating XR technologies in architectural education [37]. This methodology is particularly suitable for architectural studio teaching due to its collaborative, adaptive, and reflective nature. PAR has four key characteristics that make it well-suited for architectural studio teaching:

(1) Collaborative nature: PAR's collaborative approach aligns well with architectural education, which emphasises teamwork and collaborative design processes [38]. It involves close cooperation between researchers, students, tutors, and educational institutions to develop, test, and refine teaching methods in real-world settings. This ensures continuous incorporation of insights and feedback from actual users, making the research results more relevant and actionable [39,40]. This collaborative aspect directly supports the study's objective of establishing an immersive and interactive XR learning environment where students can engage with XR technologies through detailed demonstrations and hands-on tutorials, thereby enhancing student engagement and participation.

(2) Integration with real-world environments: Building on its collaborative nature, the PAR approach supports the development of XR tools in practical, real-world environments; this involves using a "Trial and Error" strategy to iteratively refine teaching methods and technologies based on direct feedback from participants [41]. This strategy ensures that the tools and methods developed are directly applicable and beneficial to the intended users [42]. Integrating real-world feedback into the development process aligns with the objective of developing and testing digital prototypes of XR applications tailored to the specific educational needs of architectural design students. This integration aims to bridge the gap between theoretical concepts and practical applications.

(3) Reflective and adaptive learning: In addition to real-world integration, PAR fosters a learning environment where uncertainties and errors are viewed as opportunities for discovery and learning rather than obstacles [43]. This is particularly valuable in architectural education, where new, complex problems are frequently encountered and where there is often a lack of prior data. By promoting a reflective and adaptive learning environment, PAR helps to extract higher-level knowledge from experience [44]. This reflective and adaptive nature ensures that the study's methodologies can evolve based on real-time data, aligning with the objective of continuously improving XR integration. This approach supports the objective of enhancing pedagogical practices by integrating XR tools into the design studio.

(4) Real-time adjustment and feedback: To complement reflective learning, one of PAR's strengths is its ability to identify real-time challenges and opportunities, enabling researchers to iteratively adjust teaching strategies and the implementation of novel tools [45]. This facilitates a comprehensive understanding of the impact of XR tech-

nology on architectural education by considering the dynamic interactions between technology, pedagogy, and learning outcomes [46]. This ongoing evaluation and modification process supports the objective of assessing the impact of XR technologies on students' engagement, visualisation capabilities, and design project outcomes.

2.3. Literature Review Conclusion

In conclusion, the integration of XR technologies in architectural education presents significant opportunities to enhance teaching and learning experiences by bridging the gap between theoretical knowledge and practical application. The reviewed literature demonstrates the potential of XR to transform traditional educational methodologies, improve spatial understanding, and foster better communication and collaboration in design processes. However, despite these advancements, there are notable gaps, including the lack of practical frameworks for XR integration, skill deficits among educators and students, and the high costs of XR implementation. PAR emerges as a suitable methodology to address these challenges, offering a collaborative, adaptive, and reflective approach that ensures continuous improvement and real-time feedback integration. By leveraging PAR, this study aims to develop a comprehensive framework for the effective integration of XR technologies in architectural design studies, ultimately enhancing educational outcomes and preparing students for future professional practices. This literature review underscores the importance of addressing the identified gaps and provides a foundation for the subsequent research and methodologies detailed in this study.

3. Methodology

Based on the insights from the literature review, this study employs a PAR methodology to assess the integration of XR technologies within architectural education. The research hypotheses are as follows: (1) XR tools facilitate a deeper understanding of spatial relationships and design alternatives; (2) integrating XR technologies at different stages of architectural studio education (such as conceptual design, design development, and model making) significantly enhances students' understanding and application of design concepts compared to traditional teaching methods; and (3) the use of XR technology in architectural studio education improves the quality and depth of feedback in student–tutor interactions, leading to better design outcomes and higher student satisfaction.

Through PAR, the study integrates traditional design outcome media, like students' digital design model content and drawings, with cutting-edge digital tools like AR and VR applications. This approach aims to resolve and overcome challenges like technological thresholds, adaptability issues, file sharing, geometry optimisation, and multimedia communication. The study further examines the impact of these integrations through department-wide discussions, feedback surveys, and self-reflection from students and educators. This approach transcends the traditional technical integration of XR tools by promoting proactive exploration and learning, equipping students with the skills necessary for future independent integration of such technologies in their architectural practice. The cyclical nature of PAR ensures that the learning process is dynamic, responsive, and informed by comprehensive feedback and insights. As shown in Figure 1, the applied PAR methodology encompasses an "action" phase, followed by "observation" through continuous monitoring, conversations, and reviews documenting student interactions and technology engagement and, finally, a "reflection" phase to generate an in-depth understanding of these experiences. This then results in an "evaluation" phase that provides informed instructions for the consequent "modification" phase, in which trials are improved.

3.1. Action: Participant Selection and Data Generation

Participants for this study were selected from the Master of Architecture programmes at The University of Hong Kong (HKU). A total of sixteen students were chosen to participate, ensuring a diverse mix of experience levels by including students from the first and second years of the Master of Architecture programme and the second and third years of the

Master of Architecture (Design) programme. While prior experience was not mandatory, it was noted that this would be analysed as part of the study. The parameters and properties of the selected participants are shown in the Table 1.

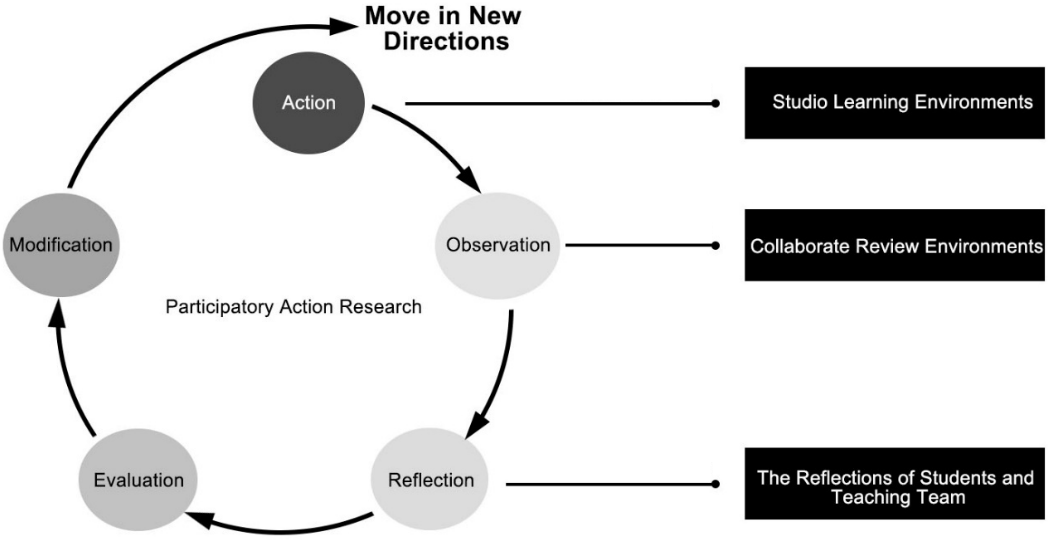

Figure 1. Diagram of PAR cycles [36,47].

Table 1. The parameters and properties of the selected participants.

Programme	Year of Study	Number of People
Master of Architecture	Year 1	6
	Year 2	8
Master of Architecture (Design)	Year 2	1
	Year 3	1

The action phase began with creating an enabling studio learning environment where students were introduced to XR technologies through detailed demonstrations and tutorials. This phase employed action tools, like hands-on workshops and interactive tutorials. Aimed at integrating XR tools into students' studio projects, this phase fostered an environment for the open-ended exploration of immersive visualisation techniques, using methods like brainstorming sessions and consensus building to generate creative ideas. The idea to develop an integrated AR and VR review application prototype stemmed from such sessions and was identified as a productive way to respond to overall research aims by establishing an interactive space for review and exhibition that encourages students to embed XR technology into their design processes.

Throughout this action phase, techniques like ethnographic observation and video recording were employed to document students' interactions and utilisation of XR technologies in real time. This foundational stage allowed for the observation of how students interacted with XR tools in a controlled environment, setting the stage for further exploration and development.

3.2. Observation: Group Structure and Data Acquisition

Building on the data generated in the action phase, the observation phase involved conducting architectural studio teaching. This happened through a combination of work in small groups and following individual project development, as imposed by the overarching curriculum. The common practice of teaching preferably small groups of students in architecture studios is informed by the intricate and exploratory nature of the design challenges encountered, as outlined by Kuhn [48]. Such a setting facilitated swift iterations and continuous critique of design proposals, which is essential for refining solutions. Similarly, in practice, the architect's role in providing technical guidance and the strategic application of creative constraints in design processes necessitates the formation of small, integrated teams [49].

During the first five-week-long phase of the course, the sixteen students worked together in four groups of four to carry out material research and engage in several XR tutorial workshops. This size was chosen to ensure effective interaction, personalised feedback, and manageable observation sessions. This setup facilitated our feedback mechanism: as the groups focused on the technical outcomes of different materials—timber, cross-laminated timber, earth, and rocks—they developed specific expertise in certain aspects of XR technologies. Following this, each student gained knowledge and information to individually develop a personal architectural design project throughout the remaining ten weeks of the studio. During this phase, the implemented XR tools and techniques were continually adjusted as students formed opinions and discussed their findings with the instructors. This allowed a set of complex tools to be disseminated through aptitude, appropriateness to the project, and personal interest.

Both phases employed several observational tools, including surveys and questionnaires, informed conversations, and instructors' notes, to comprehensively document student interactions. Participation in the survey was voluntary, and anonymity was maintained to encourage honest feedback. Out of the 16 students, 8 completed the survey, yielding a response rate of 50%.

Regular, structured reflection sessions with students and instructors, guided by specific open-ended questions, were crucial for generating in-depth, qualitative data. Closed questions covering engagement with specific XR tools evaluated engagement quantitatively. These sessions underscored the educational impact of XR technologies, reflecting the participatory nature of PAR. This approach not only generated insightful data but also enhanced the learning experience by involving participants in the educational discourse, demonstrating the effectiveness of PAR in data acquisition.

3.3. Reflection: Qualitative Insights

Following the observation phase, the reflection phase involved analysing data through focus groups and flowcharts to organise and provide feedback. This stage included group-based reflection on actions and observations, helping to generate insights into the effectiveness of XR tools. The reflective phase allowed the study to interpret data within the context of the learning environment, ensuring that the findings were meaningful and actionable.

3.4. Evaluation: Synthesising Feedback

Building on the reflections, the evaluation stage synthesised the data collected during the reflection stage, using qualitative methods as the main method and quantitative methods as auxiliary verification methods to comprehensively understand the impact of XR technology on student experience and architectural education.

Qualitative data from reflection sessions, ethnographic observations, and instructor notes were analysed using thematic analysis to identify key themes and patterns. Insights from focus group discussions provided a deeper understanding of student experiences and perceptions of XR technologies.

The evaluation assessed the role of technology in enhancing learning experiences, promoting collaboration, and facilitating creative problem solving. Additionally, the study evaluated the impact of XR technology on the quality of student designs, using expert reviews and peer evaluations to measure progress in design outcomes.

3.5. Modification: Iterative Implementation

The tools and method of the modification phase involved iterative cycles of planning, acting, and observing based on the evaluation results to refine and improve the integration of XR technologies in architectural education. The process of modifications was informed by the evaluation of XR technologies' impact on student experiences and design outcomes. The iterative cycles allowed for continuous adaptation of teaching strategies and technological tools, ensuring the curriculum remained innovative and effective. Feedback from students, instructors, and external experts played a crucial role in shaping these modifications, providing diverse perspectives on the integration of XR technologies.

4. Practical Implementation of the PAR Framework

The practical implementation of the PAR framework in this study was crucial for achieving the research aim: to integrate XR technologies into architectural education effectively. This section details the steps taken to create an immersive learning environment, emphasising the alignment with the research problem and methodology.

The basic process of the study outlined in the article began with establishing a studio learning environment where students were introduced to XR tools through demonstrations and tutorials, aiming to integrate these technologies into their studio work (Figure 2). The course was designed to incorporate PAR, encouraging experimentation with immersive visualisation techniques and focusing on the communicative and graphical capabilities of AR and VR [50]. A course structure was foregrounded that allowed for adaptation in response to students' experiences, with the subsequent potential to alter their design workflow while providing support for technological problems [51].

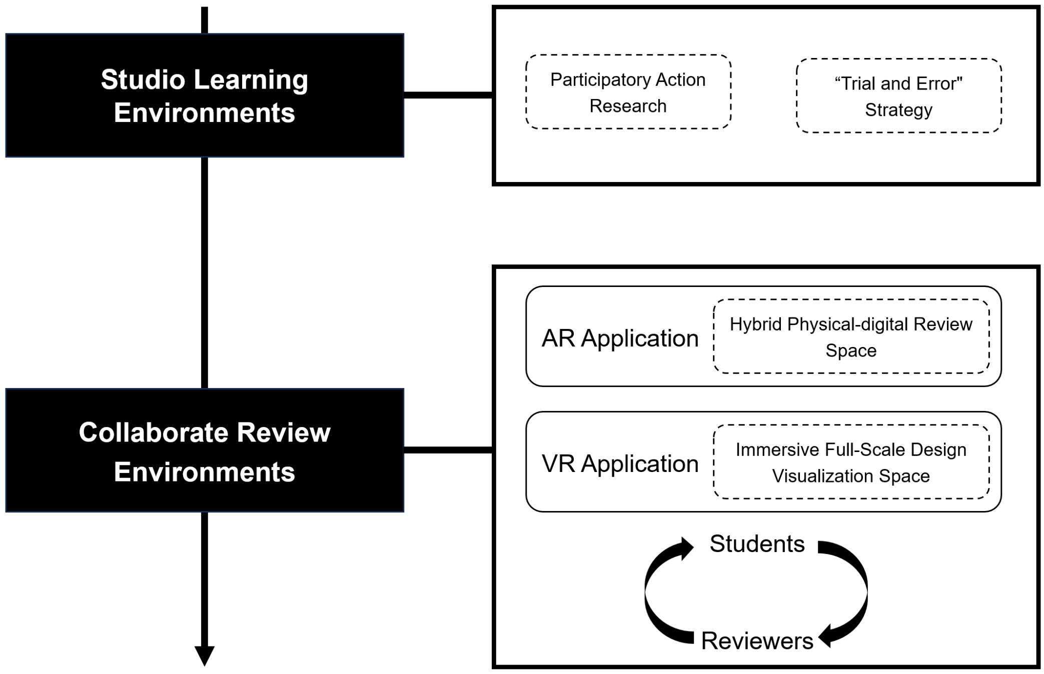

Figure 2. Workflow of implementation.

From this setup emerged the idea to develop an integrated AR and VR collaborative demonstration application that could simultaneously act as an interactive review platform and an exhibition space for the final studio review. The application was created to further allow students to easily access XR technology and integrate it into their design workflow. By collectively developing this demonstration application, students were able to request specific features within the application's unorthodox representational capabilities that they felt would strengthen their own understanding of their projects and their ability to share their designs in the final review.

This article details how this XR technology application transformed the final studio review experience by using AR and VR components to increase communication. The AR components generated three-dimensional holograms in front of a screen and on top of handheld trackers during student presentations, whereas the VR technology enabled the full-scale immersive visualisation of students' architectural design outcomes.

This application and its integration in both the studio teaching and final review spurred an in-depth discussion within the department on integrating XR tools into the curriculum, emphasising the importance of a specialised methodology for fostering students' technological innovation capabilities. The project enabled students to excel in the course requirements of developing design responses, as it facilitated proactive exploration and learning motivation. The participatory component of the methodology allowed students to gain added value from the collective communication of ideas, both within the studio and outside parties, in the final review. This allowed the focus to shift from XR as a technology that increases the quality of representation to a technology that facilitates communication and discussion on the more essential elements of architecture design studio teaching, like overarching design concepts and decisions made by each student. This resulted in an engaging and lively final review with many constructive comments from well-informed reviewers.

4.1. Establishment of Studio Learning Environments

This study used a HKU Master of Architecture design studio as a case study. This course used the previously mentioned characteristics of PAR combined with architectural studio teaching to integrate reflective and cyclical problem-solving strategies as its method. This deliberately created an environment where uncertainty and mistakes were not seen as obstacles but as valuable opportunities to explore new ideas and innovative solutions. The overarching curriculum setup permitted 16 students from the first and second years of the Master of Architecture programme and the second and third years of the Master of Architecture (Design) programme to join the course. Under the guidance of two course coordinators and two technical experts, the brief required students to explore the integration of traditional and modern technologies in architectural design. For this, they were requested to use traditional materials, like wood, stone, or earth, in conjunction with cutting-edge digital design tools, like the Rhinoceros modelling platform, its graphical programming language Grasshopper, and its AR plugin Fologram, as well as VR technology and 3D scanning tools (https://3dscannerapp.com/) in Unity.

The XR tools introduced in the course transcended traditional visualisation methods, aiming to transform the comprehensive learning experience to become more immersive. Tutorials covered various topics, from Fologram applications (https://fologram.com/) on the HoloLens 2 (https://www.microsoft.com/en-us/hololens) AR Head-Mounted Display (ARHMD) to VR representation techniques in Unity for use on the Oculus Quest 2 (https://www.meta.com/quest/products/quest-2/) VR Head-Mounted Display (VRHMD). The tutorials catered to multiple skill sets, progressing in complexity to foster engagement with more technical methods in the later stages. To ensure an accurate assessment of the use and support needed for XR tools, the students' use of these tools was documented in detail in teaching notes and consistently discussed among the course teachers.

The students' final design projects demonstrated the practical outcomes of integrating traditional and modern technologies in architectural design. Their feedback underscored the effectiveness of the teaching strategy in facilitating the cross-pollination of technology and creativity, thus producing new possibilities for architectural education. In addition, positive feedback was received on how challenges encountered during the course, like technological thresholds and student adaptability issues, implications of new tools, and changes to workflow, were resolved through continuous instructional adjustments and technical guidance.

4.2. Establishment of Collaborate Review Environments

Studio courses in architectural education often lack quantitative assessments and compensate for this by organising a "final review" that convenes both internal and external experts. During this phase, students are required to present their design process, discoveries, and solutions through thematic reports and group discussions. Effective expression and communication skills are crucial in this process, as students need to convey their ideas clearly and compellingly through visual and verbal means. Establishing a collaborative review environment in architectural education allows us to further incorporate the subjectivity of art and the principle of self-interpretation [39]. By making the establishment of review environments collaborative, traditional review processes can be transformed into even more dynamic, interactive sessions where students, instructors, and external experts can more easily engage in constructive dialogue and collaborative critique.

Considering this, the decision was made to utilise XR tools in the final review to showcase the collective experimental outcomes of the studio, aiming to stimulate broader discussions about the academic potential of XR through enhanced visual presentation modes. This decision was based on observations of the challenges students faced when integrating AR or VR technology into their design processes. Despite tutorials intended to cultivate application skills, students found it difficult to dedicate time to mastering these technologies under the pressure of meeting the course's typical core requirements. Therefore, the XR portion of the final review was designed under the close guidance of the technical experts to practically expand the typically available presentation tools and media. These are usually primarily based on multimedia slide presentations on TVs or projection screens, supported by scale models and printed drawings. To add new elements to this, the decision was made to have all reviewers wear a HoloLens 2 ARHMD during the review, allowing them to see the traditional media in physical space with holographic digital projections overlaid on top (Figure 3). Separately, a station with VRHMDs was created where full immersion in the designs was possible (Figure 4).

Figure 3. Reviewers wearing ARHMDs during a student's final review presentation.

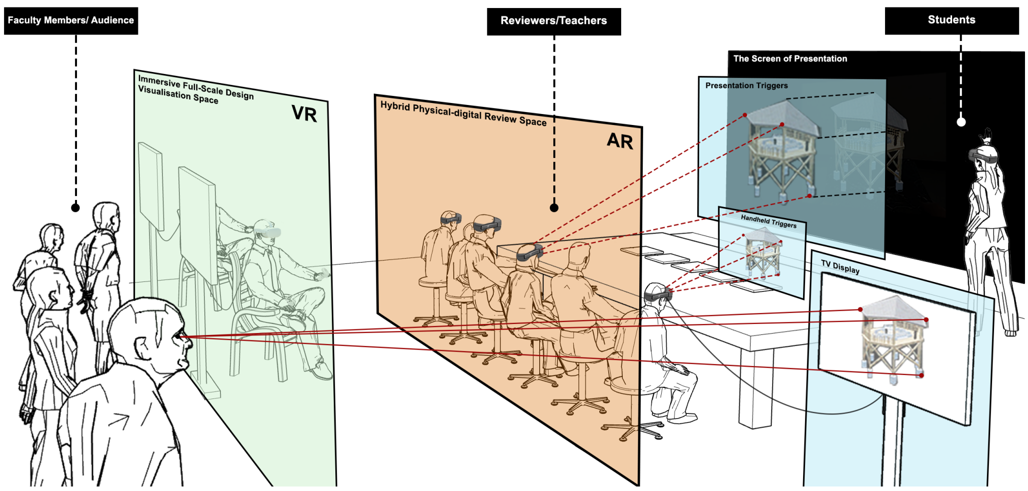

Figure 4. Example of live streaming from both the ARHMD and VRHMD to TVs.

For the live student presentations, a "hybrid physical–digital review space" was set up, creating a zone between the projection screen and the reviewers in which holographic content was displayed in synchronisation with the students' slide presentations. The holographic view seen by one of the reviewers through a HoloLens 2 was displayed on a television monitor to allow other attendees to share the immersive experience. This setup meant that even those not wearing the HoloLens could still appreciate the holographically enhanced, three-dimensional aspects of the designs being reviewed. This method leveraged the capabilities of extended reality to extend the immersive experience to a larger audience, enhancing collaborative feedback and interaction during the review sessions.

The final review of the XR demonstration application resulted from two weeks of intensive collaboration between students and assisting technical experts, who led the development of its components in close communication with students, constantly incorporating their feedback. Team members were given distinct roles, including developers, asset designers, motion designers, and testers. All team members jointly developed and tested the AR and VR assets, ensuring the smooth operation of the applications.

Students presented their work in groups through personalised XR presentations that utilised 2D drawings, 3D models, 4D animations, and dynamic graphics. Brief impromptu tutorials were provided in preparation for this, covering topics like AR and VR asset production, file management, motion graphics creation, XR interaction methodologies, and custom XR software development to help students overcome communicative barriers and fully exploit the potential of their digital content. This made the final review not just a showcase of design outcomes but also a platform for exploration, learning, and discussion on the discovered potential of XR technologies. Collaborate review environments carried out in this manner leverage modern technologies to enhance visualisation and understanding of complex concepts and designs. By doing so, they allow students to explore the full potential of their designs in an immersive and interactive manner.

4.2.1. AR Component: Hybrid Physical–Digital Review Space

Developing the AR component of the final review application became an essential component of the research aims to explore the integration of XR technologies within architectural education. This application enabled students to enhance their slide presentations with holographic content, providing a more interactive and collaborative learning experience during the review process by triggering holographic content—like 4D animations, 3D models, and 2D-exploded drawings and annotations—projected into the room's centre upon the detection of specific presentation triggers (Figure 5). This holographic content would become visible through ARHMDs that project localised digital content onto a transparent liftable visor, allowing users to modulate at will between normal viewing and overlaying digital content. This allowed reviewers to more easily follow along with the presentations, giving them control over comfort and thus extending feasible ARHMD use time to the length of a traditional review.

The use of individual presentation triggers allowed custom content, specific to the presenter, to be loaded in front of the main presentation projection but also on top of small, hand-held printed markers, printed on 20 cm × 20 cm foam boards, that could be passed around and discussed as the student related their presentation. This interactive component allowed for real-time sharing among all review participants, who could collectively navigate, point at, and discuss both physical and digital presentation artefacts.

The XR application was developed using Unity, a robust and versatile game engine widely used for creating various interactive experiences [52], in tandem with a wide library of third-party plugins and open-source documentation that supports many hardware platforms, especially HMD for XR/VR to AR.

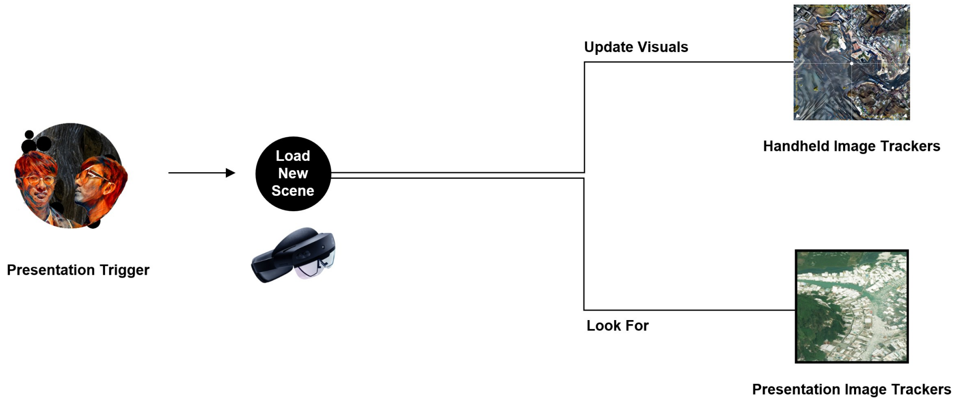

Figure 5. AR interaction logic.

The AR component of the review application used the third-party application Vuforia for image detection, which corresponded to presentation triggers, as shown in Figure 6 [53]. These triggers were assigned individually to each presenting student. On activation, as shown in Figure 7, the application loaded content from the student's presentation slides, the associated augmented content, and the augmented content assigned to the hand-held trackers, as seen in (Figure 8). Designing the trackers required visually distinctive imagery with distinct features to ensure the computer vision component of the application could robustly identify each tracker. This was achieved using student portraits or other images, like key project drawings or aerial photographs of Hong Kong. These images were processed through a Generative Adversarial Network (GAN) algorithm to enhance visual complexity, facilitating the system's recognition of individual trackers (Figures 6 and 8). To further this individualisation, each presentation trigger was also given unique styling in order to further distinguish them from each other.

Figure 6. Example of presentation triggers.

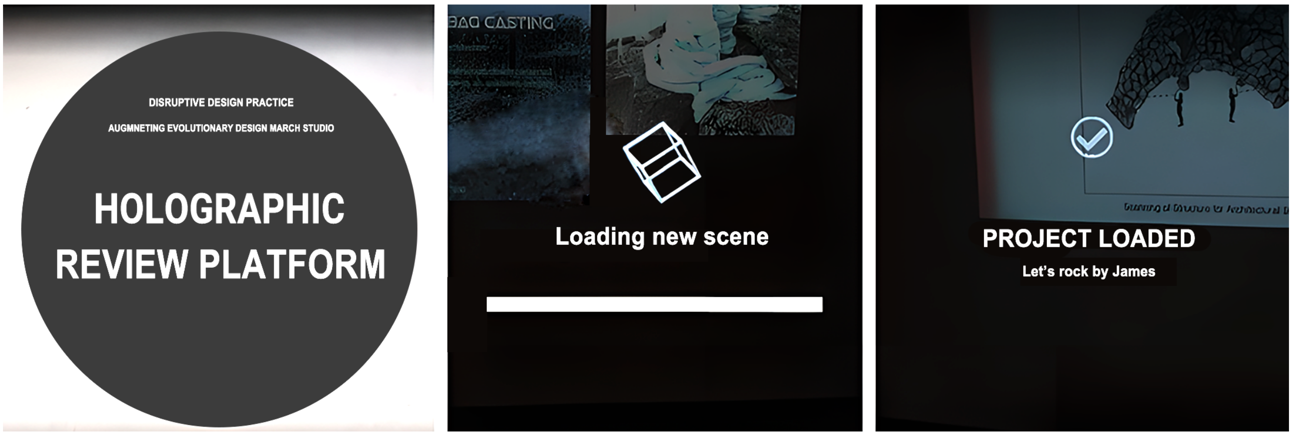

Figure 7. Launching the application and loading a new scene from a presentation trigger.

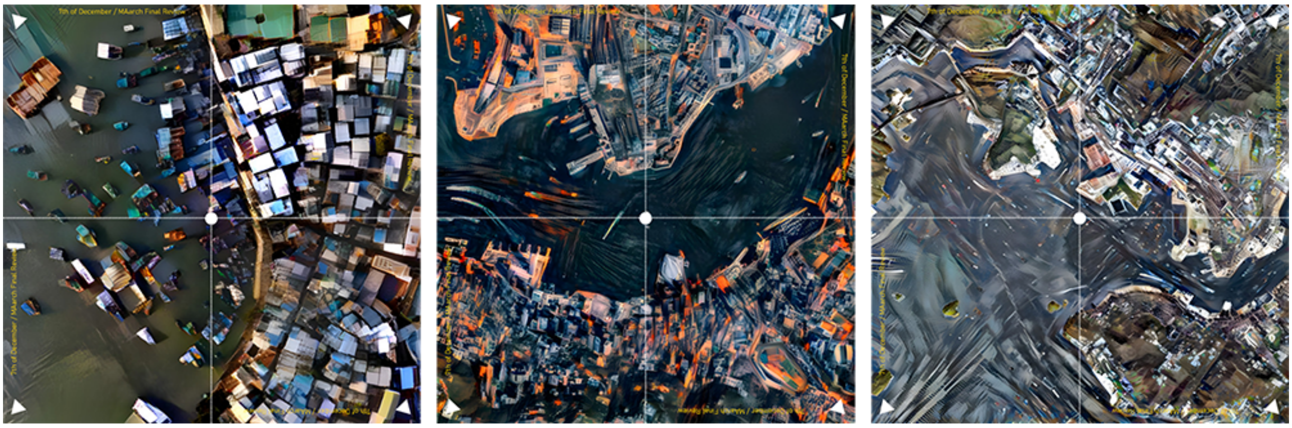

Figure 8. Example of 20 × 20 cm printed trackers mounted on foam boards.

The visibility of a tracker to the ARHMD's camera dictated the duration of its associated interactions. A student's augmented content on a projected presentation slide remained active until the detection of a new presentation trigger, at which point the assets from the preceding slide were cleared, and the succeeding slide content was introduced. With this setup, presenting students could proceed at their own pace and even go back to reiterate information, as the application automatically switched between content on a new tracked image entering the reviewer's field of view. This process ensured a seamless transition between the augmented content of each slide in any chronology and in collaboration with the presentation triggers of each presentation.

As reviewers kept their focus on the presentation screen, the ARHMD's camera would detect trackers on the presentation screen, giving a sizeable distance to place large content within the ARHMD's display that fell in line with the reviewers' field of view (Figure 9). On looking down, reviewers' entire field of view could be occupied by a much closer hand-held tracker, allowing them to view smaller-scale but more detailed pieces of technical models (Figure 10). Consequently, students could showcase compact holographic 3D models and animations for in-depth examination by viewers (Figure 11). This interaction between experts and students, with a holistic overview of their project at multiple scales and resolutions, along with the inclusion of 4D data in animations, streamlined conversations and allowed reviewers to have more complex reference points to make informed comments (Figure 12).

Figure 9. Reviewers inspecting handheld holographic models.

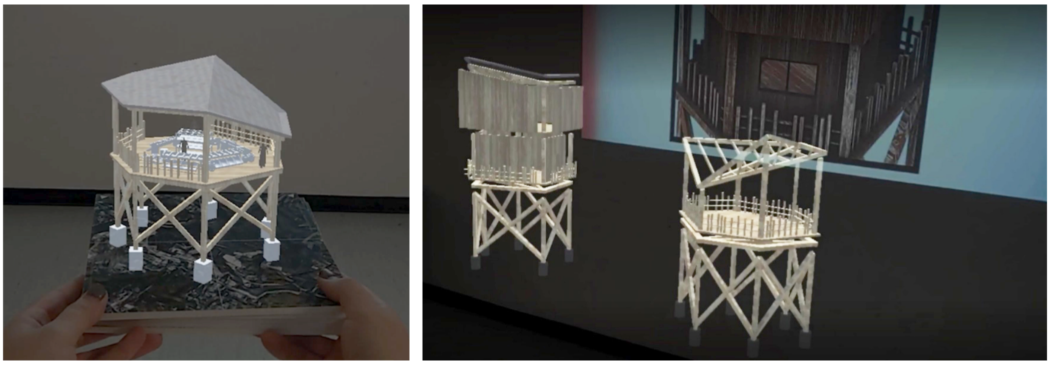

Figure 10. Architectural example of presentation tracker and thin-air triggered hologram.

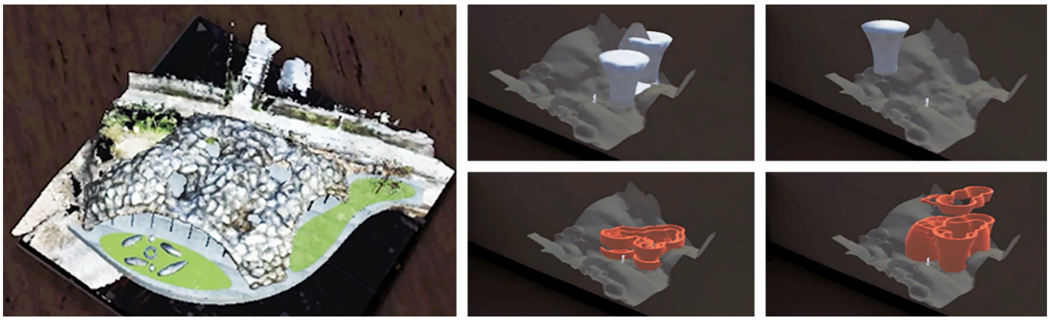

Figure 11. Landscape example of holographic 3D models and animations.

Figure 12. Example of image trackers in the students' presentations.

4.2.2. VR Component: Immersive Full-Scale Design Visualisation Space

The development of the VR component of the review application played a crucial role in this project. The criteria for judging design variants introduced by VR include scale and realism, interaction and navigation, lighting and context, technical proficiency, user interface effectiveness, holodeck setup, and overall experiential impact. The VR component, built for the Oculus Quest 2 VRHMD, facilitated the full-scale visualisation of textured models within a Unity scene [54], referred to as the studio's "Holodeck" (Figures 13 and 14). Its elements consisted of student content, navigation controls, a control panel interface, and assets. The elements of the VR application for student content were customised to facilitate ease of use, collaboration, and impact.

The VR component not only displayed students' projects in VR but also employed them in the development process to inform students of all aspects related to a VR environment's development [55,56]. Students were tasked with preparing and optimising their files for VR display using Rhinoceros 3D (version 7) (https://www.rhino3d.com/7/) in one-to-one sessions, with the assisting technical expert overseeing the process. They then exported the files into Motion Builder (.FBX) format, which automatically transferred materials, animations, and layer structure into Unity. To add realism and context, iPad LiDAR scans (3D Scanner) (https://3dscannerapp.com/) and 360-degree high-dynamic-range image (HDRI) recordings of project sites were incorporated. This enabled students to directly add to a representation of their real-world scene with compatible tools and customise their design with assets from the site.

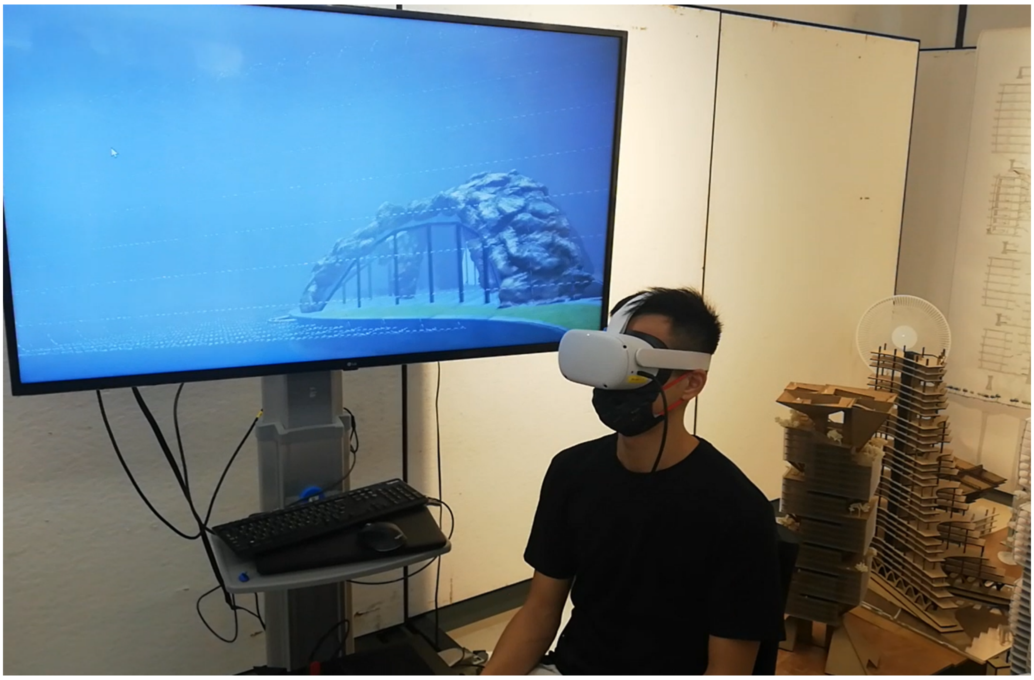

Figure 13. Example of a VR scene inside the Holodeck.

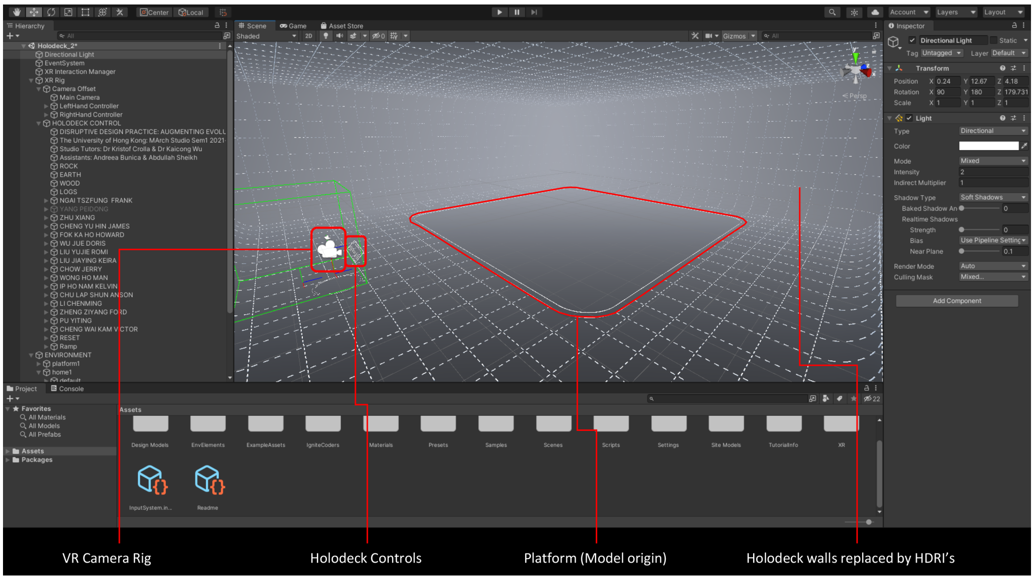

Figure 14. Holodeck setup inside Unity.

A navigation control system was developed to enable users to traverse the Holodeck freely. This system consisted of a game object, a Unity data structure containing all the elements, a player controller with an input system, a physics collider, and a VR camera rig. Through different iterations, different input systems were trialled, finally settling on a continuous movement locomotion system through the XR interaction toolkit chosen for its intuitive controls. These included the left thumb stick of the Oculus Quest 2's touch controller, which mapped to the movement of the player controller in the XY plane, and the right thumb stick, which was mapped to the rotation of the player controller in the same plane. Once the character was moved, the physics collider would apply a simulacrum of the effects of gravity with every movement. The geometry of the Holodeck floor provided support to the capsule, or, if the student added a collision-compatible terrain, a simplified version of their site geometry exported from Rhino 3D, the player would traverse it and experience level changes and a higher sense of realism. To reinforce the realism of the experience, the VR camera rig was offset in height from the floor at the average height of a person, which emphasised the experience one would have when facing projects at a 1:1 scale.

The control panel functioned as a controlling interface, listing all the students' names, divided into sections based on materiality and architectural tectonic system, as well as a reset function and a trigger to add a viewing ramp (Figure 15). The control panel was locked both in rotation and location to the player at a desk height suitable for standing and seated positions and inclined gently to help with visibility. To interact with the control panel, the player could use their controllers, visible in the Holodeck through tracked digital twins, and "point and shoot" at the buttons with the trigger of the controller to activate an option.

Figure 15. Control panel inside the Holodeck.

Finally, the Holodecks contained assets like a central platform, a player platform, walls, and a grid (Figure 14). These were rendered in neutral black materials to provide a neutral background but also served as a placeholder for student-generated content. When a student project was chosen, the walls would 'fall away' and be replaced by a 360 HDRI generated by the student. This HDRI affected lighting, changing it to accurately represent lighting conditions found on-site. A centralised platform with the origin of the application was set up to simplify the mass importing of student models at appropriate scope in a 1:1 scale. The platform was encircled by an invisible two-storey viewing ramp that could be activated to walk on for those students who did not provide terrain, allowing users to ascend and gain differing perspectives of the design.

To spatially centralise and ground the VR experience in one location, all Holodeck assets were accompanied by white highlight elements that stayed present when all black elements were gone. This included a floating outline on platforms and the bounding box grid. These were added to remind users of the location of elements once a project was chosen so that the user would not navigate outside the application's main space. These assets, when imported into Rhino, served as great tools to communicate to students the technicalities of the application in its native software, providing a reference of scale and experience.

Users initiated their journey from the player platform of the Holodeck, engaging with the control panel to choose their environment and with controllers for navigation. The user was introduced to 3D-textured models at a 1:1 scale that, at times, incorporated 4D animations in the form of particle systems, accurate site lighting through HDRIs, as well as LIDAR site scans to provide an accurate experience of the site's terrain and landmarks (Figure 13).

In conclusion, the primary goal of the development of the AR and VR components of the XR review application was to ensure ease of use and to provide a comfortable experience for non-technical users, thereby fostering interaction with the application and the technology. The application was developed iteratively with a focus on experiential impact and ease of access, which allowed students to increasingly gain an understanding of the impact of their design decisions at full scale. Reported issues, like software compatibility problems and bugs, were corrected, and feedback was incorporated to improve the comfort of the application, enabling longer reviews and bringing more insights at a greater resolution each time. The iterative development and user-centric design of the VR application contributed significantly to the student's learning experiences, demonstrating the potential of XR technologies in enhancing architectural education and aligning with the research aim of the study.

5. Results and Analysis

This section aims to understand the impact of XR tools on students' learning experiences by discussing feedback data acquired through a survey questioning the establishment of the XR studio learning environments and collaborative XR review environments. The purpose of this survey was twofold: to complete the reflection and evaluation stages of the PAR methodology and to qualitatively analyse the influence of XR technologies on students' experiences before, during, and after their studio learning experience.

5.1. Student Reflections

The survey was distributed to all of the 16 students who were enrolled in the design studio course, all of whom actively participated in the course and engaged with the XR tools introduced during the semester. Participation was voluntary, and the survey was conducted anonymously to encourage honest feedback. Out of 16 students, 8 completed the survey, providing a response rate of 50%. The main questions of the survey are presented in Table 2.

Table 2. The main questions of the survey.

Code	Questions
Question 1	Have you had any experience with AR/VR tools before this course?
Question 2	How much has the integration of AR and VR technologies influenced your design processes when comparing before and after participating in the course?
Question 3	Did the final review setup, which integrated XR technology, inspire you to explore more possibilities of combining XR technology with architecture in the future, and if so, how?
Question 4	What could be the future role of architecture and architects when XR technology is applied in the field of architecture?

In this survey, all students reported an increased understanding of advanced architectural tools, including XR and its related technologies, throughout the course. As shown in the results for Question 1, 25% of the students had prior experience with AR/VR tools, while for the remaining 75%, this was their first time delving into the technical aspects of the technology (Figure 16a).

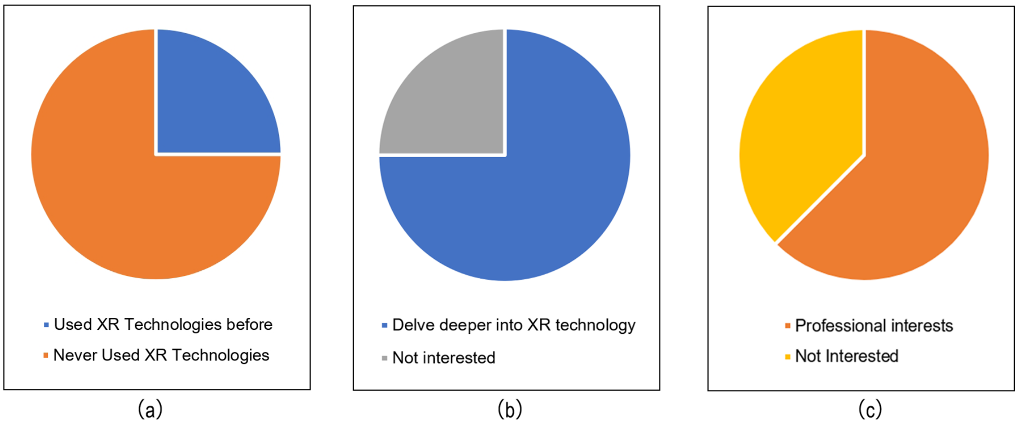

Figure 16. (**a**) Experience with XR technologies. (**b**) Interest in XR integration. (**c**) Interest in professional applications.

The histogram in Figure 17 shows the results of Question 2, graded on a Likert scale, comparing the overall scores before and after the study, with the x-axis representing the eight samples and the y-axis representing scores. Question 2 was formulated as an open-ended question, requesting a more detailed response from the participants to help assess the impact of AR/VR technologies on the participants' design processes and to help identify any specific changes or improvements they experienced. A score of 5 indicates a high impact of the integration of XR, 3 represents a moderate impact, and 0 indicates no impact. The light blue bars represent the extent to which students self-assessed their integration of XR into their design process before the study. The results show that four out of eight students originally scored below 3, with an average score of 2.625. This suggests that the application of AR/VR in students' work was originally mainly focused on visualisation and rendering rather than exploring XR as an integrated design tool. The dark blue bars represent the tool's influence on the students' work after having partaken in the course. Now, only three out of eight students scored below 3, with an overall average score of 3.375. This suggests that the establishment of the XR studio environment and final review, on average, led students to change their design processes to incorporate the new tools.

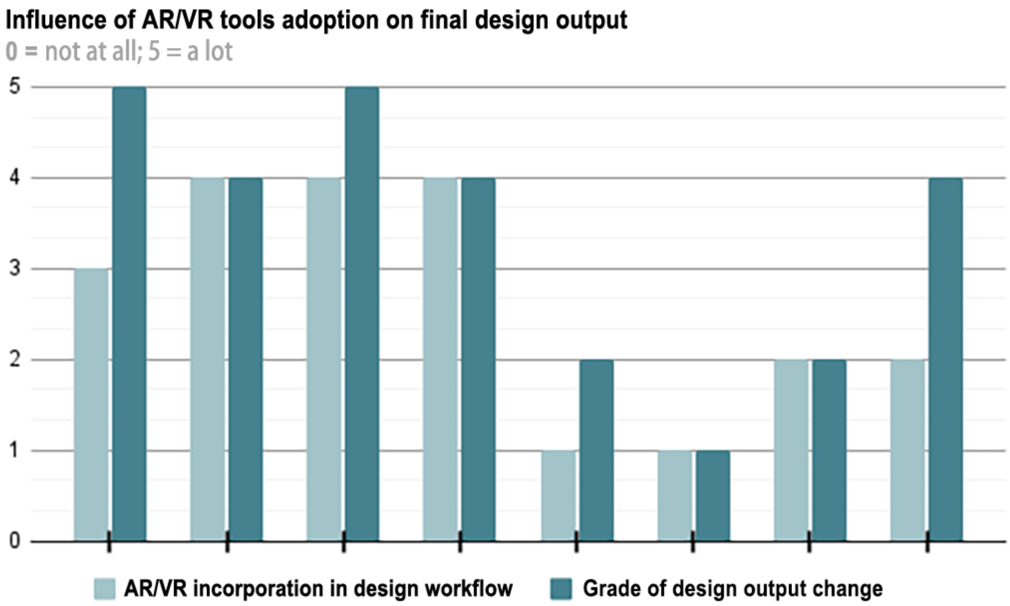

Figure 17. Comparison of the integration of AR and VR technologies influencing the design process before and after learning.

Question 3 explored whether the final review integrating XR technology inspired students to explore further the possibilities of combining XR technology with architecture, and if so, how. This question combines a close-ended first part and an open-ended part at the end. Such a question can help evaluate the participants' interest in further exploring XR technologies in their future architectural work and identify specific areas where they see potential. Through the solicited long-text feedback, 75% of the respondents expressed a desire to delve deeper into computing, programming, and XR technology (Figure 16b). Notably, two students specifically indicated their interest in developing design applications to optimise the design process.

Question 4 inquired about the potential future of architecture and the role of architects within the context of XR technology application (Figure 16c). This is an open-ended question, as it requires participants to provide their opinions and perspectives on the potential impact of XR technologies on the field of architecture. This question can help gather insights into the participants' vision for the future of architecture with XR technologies and identify possible opportunities and challenges they foresee. Students demonstrated a strong interest in exploring technologies that could automate architectural tasks. In total, 62.5% of the respondents indicated their interest in professional practice applications, like investigating the role of XR in "design–manufacture–construction" processes and how interdisciplinary technologies like this could be used to alter the industry by potentially altering standardisation or by creating more innovative, enhanced communication systems. This indicates that students have begun to form a conceptual understanding of the potential of the tools they were introduced to and are contemplating how these tools could be applied in practice.

The results from the survey highlight several key findings: (1) Students' understanding and integration of XR technologies improved significantly after participating in the course; (2) the XR studio environment and final review setup inspired further exploration and application of XR in architectural design; and (3) there is a strong interest among students in the professional application of XR technologies, particularly in automating architectural tasks and enhancing design–manufacture–construction processes.

5.2. Teaching Team's Self-Reflection

Self-reflection is a crucial aspect of pedagogical innovation, particularly when introducing new technologies like XR in architectural education. In the context of the research aim, the teaching team's self-reflection provided valuable insights into the challenges and successes encountered during the integration of XR technologies, informing future improvements and developments in this area. When introducing new tools, the teaching team faced the dual challenge of ensuring that students had both sufficient creative freedom and the ability to effectively utilise the technologies in their design process and presentation. Differing student skills and time constraints curtailed the exploration of diverse applications, hindering the development of a robust technical knowledge base and exchange among students. Despite these challenges, the initiative to integrate XR and advanced architectural tools sparked considerable interest. Feedback from students and faculty alike revealed that the use of holographic and virtual imagery to augment the final studio review ignited imaginations about the broader potential of XR technology. The subsequent review discussions and debates highlighted opportunities for innovation within the architectural curriculum and its review methodologies. This experiment, as a result, laid the groundwork for further incorporation of XR-related content in the curriculum, as well as any other new tools or technologies that may have technical limitations.

In summary, the teaching team's self-reflection highlights the challenges and opportunities associated with integrating XR technologies in architectural education. Despite the obstacles, the positive feedback and interest sparked using XR tools indicate the potential for further innovation in this area. The insights gained from this self-reflection will inform future research and practice, as well as the continued development and incorporation of XR technologies and other advanced tools in architectural education.

6. Discussion

Based on the insights gained from the study, this section discusses the key observations that emerged and offers several recommendations and strategies for researchers aiming to integrate XR technology into architectural design studies. The findings underscore the importance of evolving XR applications beyond simple visualisation to include comprehensive design workflows, adapting studio requirements to facilitate the incorporation of advanced technologies, and fostering critical technological thinking among students.

6.1. Strategies for Integrating XR Technology into Architectural Design Studies

6.1.1. Evolve XR Beyond Visualisation

The study found that relying solely on visualisation limits the range of discussions and speculations about the potential of XR tools for innovation and optimisation in the architectural profession. To address this, it is suggested that semester-long projects involving students in technological development at various design stages should be implemented. This approach encourages the exploration of XR tools for tasks like design optimisation and innovative problem solving.

6.1.2. Adjust Studio Requirements to Enable Advanced Tool Integration

The challenge of teaching advanced tools in a studio setting was also highlighted. Students focused primarily on producing required architectural outputs, leaving little time for experimenting with novel technological skills based on interest rather than utility. To overcome this, design studio requirements should be adapted to provide more time for establishing advanced workflows. Introducing electives and workshops focused on the integration of technology and architecture can create a comprehensive catalogue of methodological practices that can then be more easily and readily applied in a design studio setting.

6.1.3. Foster Critical Technological Thinking

The importance of fostering deep critical technological thinking within the studio context was observed. Shorter exercises that challenge students to consider XR applications beyond obvious uses, like concept design, sketching, collaborative design, and fabrication, were more effective. This approach helps students quickly familiarise themselves with XR technologies and achieve functional proficiency.

6.1.4. Enhance In-Studio Knowledge Sharing

Enhancing in-studio knowledge sharing and promoting independence in research and technological knowledge acquisition were identified as crucial needs. Assigning specific roles within each group and encouraging peer teaching can broaden the range of topics covered and deepen knowledge. This strategy ensures that students become experts in particular aspects of complex workflows and lead development in those areas.

6.1.5. Develop Technologically Informed Workflows

The final review demonstration prompted discussions among students and faculty about the future of XR in architectural academia and industry. It set a precedent for integrating experimental tools into the pedagogical process while preserving the student experience. This initiative laid the groundwork for further incorporation of XR-related content in the curriculum, as well as any other new tools or technologies that may have technical limitations.

6.2. Research Contributions and Significance

This study makes several unique contributions to the field of architectural education and the integration of XR technologies. By employing a PAR methodology, we established a collaborative and adaptive learning environment that effectively integrated XR tools into the architectural design studio. Our findings demonstrate that XR technologies can significantly enhance student engagement and learning outcomes and provide valuable insights for educators looking to incorporate these technologies into their curricula.

The significance of this study lies in its practical application and potential to transform traditional architectural education methodologies. The integration of XR technologies bridges the gap between theoretical knowledge and practical application, fostering a more immersive and interactive learning experience. This research underscores the importance of evolving educational frameworks to fully leverage the capabilities of XR tools.

6.3. Scope and Limitations

While the study provides valuable insights, it is important to acknowledge its limitations. The sample size was limited to 16 students from a single academic institution, which may affect the generalizability of the findings. Additionally, implementing XR technologies faced challenges related to technical proficiency and resource availability. Future research should aim to include more diverse groups and a larger sample size and explore the integration of XR tools in different educational settings.

6.4. Potential Impact and Way Forward

The broader implications of our findings suggest that XR technologies can revolutionise architectural education by enhancing visualisation capabilities, improving design communication, and facilitating a deeper understanding of spatial relationships. These technologies offer new opportunities for students to engage with complex design concepts and for educators to develop innovative teaching strategies.

Future research should prioritise developing robust frameworks and methodologies for integrating XR technologies into architectural education. This encompasses exploring various applications of XR tools across different stages of the design process, from conceptualisation to final presentation. For instance, VR can serve as a visualisation tool and an adaptive design instrument. VR could also be combined with innovative techniques that integrate human factor data to address human-centred design [57,58]. This could, for example, be made possible through Electrocardiograms (ECG), Galvanic Skin Response (GSR) measuring devices, Electroencephalograms (EEG), or emotional expression detectors [59,60]. Such an approach will not only enhance user experience but also ensure that design solutions can be more attuned to the needs and well-being of users. By incorporating these elements, VR can transcend its role as a static visualisation medium and become a dynamic component of the design process, offering real-time feedback and enabling more nuanced and personalised design solutions.

As the field of architectural education and the technology industry continue to evolve rapidly, it is crucial to maintain an ongoing dialogue and collaboration between educators, researchers, and industry professionals. This collaboration will ensure that the integration of XR technologies in architectural education remains up-to-date, relevant, and responsive to the changing needs of students, educators, and the profession.

7. Conclusions

This study's exploration into the integration of XR technologies within architectural education has sparked a meaningful dialogue among students and faculty regarding the future role of XR in architectural contexts. The interactive final review demonstration and subsequent discussions underscored the transformative potential of XR technologies while also highlighting challenges and opportunities for innovation in pedagogical practices.

Feedback from students, as evidenced by the questionnaire survey results, combined with insights gathered through the final critique, revealed a critical need to evolve the educational framework to fully leverage the capabilities of XR technologies. This includes moving beyond mere visualisation to develop technologically informed design workflows that rigorously integrate XR at various stages of the architectural design process. The study found that XR tools significantly enhance students' visualisation capabilities, deepen their understanding of spatial relationships, and improve design outcomes.

The PAR methodology proved effective in fostering a collaborative and adaptive learning environment. By involving students, educators, and technical experts in iterative cycles of action, observation, reflection, and modification, we were able to refine our approach continuously and address integration challenges.

In conclusion, XR technologies represent a valuable addition to architectural education, offering new ways to engage students and enrich their learning experiences. This study has laid a foundational understanding and set a precedent for integrating XR technologies to enhance the infrastructure for future architectural education and practice. As the field evolves, the insights gained from this study will inform future efforts to integrate advanced technologies into architectural curricula, ultimately preparing students for the complexities of modern architectural practice.

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