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Reimagining sustainable design: Leveraging 4IR and virtual reality in architectural engineering education

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Abstract

This study investigates the integration of Virtual Reality (VR), specifically the Oculus Quest 3, within architectural education to enhance sustainable design practices. Using a first-principal approach to design thinking, the research explores how immersive VR environments can improve spatial cognition, support iterative design, and encourage environmentally-conscious decision-making. The study was conducted with ten postgraduate architecture students at Nelson Mandela University, who engaged in a small house design project within a virtual design studio. Students were able to create 3D models, explore them at a 1:1 scale in VR, and receive immediate feedback to refine their designs.

Findings indicate that VR significantly enhances students' spatial awareness, allowing them to better understand proportions, relationships, and functionality within their designs. The immersive environment also supports rapid design iteration, enabling students to test multiple design options efficiently and make real-time adjustments. Moreover, VR facilitated the integration of sustainability principles, as students could visualize energy flows, natural lighting, and material impacts, leading to more environmentally-informed design decisions. Participants reported heightened engagement and satisfaction with the design process, noting that the interactive and experiential nature of VR made learning more intuitive and enjoyable.

The results suggest that VR offers transformative potential for architectural pedagogy. By incorporating immersive technologies into the design studio, educators can provide a more holistic, hands-on learning experience that develops spatial understanding, creativity, and sustainability awareness. This study highlights the importance of integrating VR into architectural curricula, preparing students to navigate the increasingly digital, collaborative, and sustainability-focused demands of contemporary design practice.

Keywords: Virtual Reality (VR); Sustainable Design; Architectural Education; Design Thinking

1. Introduction

Architectural education is undergoing a critical transformation as the demands of the profession evolve, particularly in response to pressing global challenges such as climate change, urbanization, and resource scarcity. Traditional studio-based teaching methods, while foundational in developing design skills, often fall short in equipping students with the practical tools and frameworks necessary to fully address environmental concerns, sustainable practices, and complex spatial cognition [4]. Students frequently struggle to translate theoretical knowledge of sustainability into tangible, real-world design solutions, partially due to the limitations of conventional two-dimensional drawings, physical models, and static digital representations.

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The emergence of Fourth Industrial Revolution (4IR) technologies, including Virtual Reality (VR), Augmented Reality (AR), and immersive digital tools, offers an unprecedented opportunity to reimagine architectural pedagogy. VR, in particular, enables the creation of fully immersive, interactive environments where students can explore, manipulate, and evaluate their designs at a 1:1 scale. By integrating VR into the design studio, educators can bridge the gap between abstract concepts and practical implementation, allowing students to experience the spatial, functional, and environmental implications of their design choices in real time [2] [3].

This study investigates how VR, specifically through the use of the Oculus Quest 3, can support sustainable design practices by applying a first-principle approach to design thinking. First-principle thinking encourages designers to deconstruct complex problems into their fundamental elements, promoting innovative solutions rather than relying solely on conventional methods or assumptions. Within the context of architectural education, this approach aligns naturally with VR's capacity to simulate, test, and iterate design options in a highly visual and interactive manner.

Conducted with a cohort of 10 postgraduate architecture students at Nelson Mandela University, the study focuses on a small house design project, aiming to evaluate how immersive VR environments influence students' engagement, spatial understanding, and integration of sustainable design strategies. The research seeks to understand whether VR can facilitate deeper cognitive engagement, enhance iterative design processes, and improve the practical application of sustainability principles in architectural projects. Ultimately, this study explores the potential of VR to not only transform pedagogical approaches but also to prepare future architects for the increasingly digital, collaborative, and sustainability-driven demands of the architectural profession.

2. Design/Methodology/Approach

2.1. Research Design

This study adopts a qualitative, positive case study approach to investigate how Virtual Reality (VR), specifically using the Oculus Quest 3, impacts architectural education with a focus on sustainable design principles. Case studies are particularly suitable for exploring contemporary phenomena within their real-world contexts [8], allowing for in-depth understanding of how immersive technologies influence both cognitive and practical aspects of design learning.

A cohort of 10 postgraduate architecture students at Nelson Mandela University participated in a six-week virtual design studio. The participants were selected based on their enrollment in advanced design modules, ensuring a comparable level of prior architectural knowledge and design experience. The study focused on the design of a small residential house, emphasizing the integration of sustainability strategies such as energy efficiency, daylight optimization, passive ventilation, water conservation, and environmentally responsible material selection.

2.2. Iterative Design Process

- The design process employed in this study was highly iterative, leveraging VR to enhance spatial cognition and sustainability integration. Figure 1 illustrates the workflow:
- Design Brief and Research: Students begin by analysing site conditions, client requirements, and sustainability guidelines. Initial sketches and conceptual ideas are developed using traditional 2D and CAD-based methods.
- 3D Modelling: Students translate their concepts into 3D digital models using CAD software (Revit, AutoCAD, or SketchUp). This step ensures a precise, manipulable representation of the project.
- VR Immersion: The 3D models are imported into Unity 3D or Escape and explored via the Oculus Quest 3 headset. VR allows students to physically navigate spaces at a 1:1 scale, facilitating an embodied understanding of spatial relationships, proportions, and circulation.
- Feedback and Reflection: During VR walkthroughs, students receive formative feedback from peers and lecturers. The immersive experience enables immediate identification of design issues, particularly those affecting functionality and sustainability.
- Model Revision and Iteration: Students revise their models based on insights gained in VR and integrate sustainable design strategies more effectively. This iterative loop—VR exploration → feedback → reflection → revision—is repeated multiple times, leading to progressively refined designs.
- Final Presentation: The studio concludes with a presentation of the final design, highlighting sustainable design interventions and demonstrating improvements achieved through iterative VR-based exploration.

This research design allows for the examination of how immersive VR can accelerate design iteration, improve spatial awareness, and support sustainability-focused decision-making. Figure 1 below illustrates the iterative steps followed by students using Oculus Quest 3, from initial design brief and 3D modeling to immersive VR walkthroughs, peer and

lecturer feedback, reflection, and final design refinement. The case study approach also provides rich qualitative data on students' perceptions, experiences, and engagement, collected through reflective journals, semi-structured interviews, and post-project surveys [2].

By integrating VR into a structured iterative workflow, the study positions technology as an enabler of both cognitive and environmental design competencies, aligning with broader 4th Industrial Revolution (4IR) educational objectives and contemporary sustainable architectural practice.

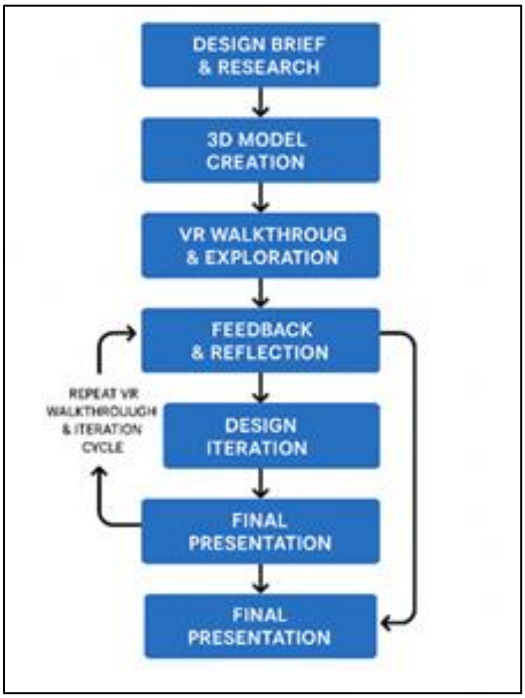

Figure 1 VR Workflow Diagram: Virtual Design Studio Process

2.3. Data Collection

To gain a comprehensive understanding of how Virtual Reality (VR) impacts architectural education and sustainability integration, the study employed triangulated qualitative data collection methods. These methods were selected to capture both the cognitive and experiential aspects of students' interactions with VR in the design process.

2.3.1. Student Feedback Surveys:

Structured surveys were administered at multiple stages of the six-week virtual design studio. These surveys included Likert-scale and open-ended questions designed to capture students' perceptions of VR usability, engagement, and its influence on sustainable design decisions. The surveys provided quantitative insights into trends in spatial comprehension, workflow efficiency, and environmental considerations within students' design thinking [1].

2.3.2. Semi-Structured Interviews:

Follow-up semi-structured interviews were conducted with each student to obtain in-depth qualitative insights. Questions explored how VR supported iterative design, enhanced spatial awareness, and encouraged experimentation with sustainable design strategies. These interviews enabled students to articulate personal experiences and challenges with the Oculus Quest 3 VR environment, highlighting the practical and cognitive benefits of immersive technology [2].

2.3.3. Reflective Journaling:

Students maintained reflective journals throughout the project, documenting design decisions, iterative changes, and sustainable strategies considered during the VR walkthroughs. Journaling provided rich, first-person narratives that revealed how immersive VR environments influenced creativity, critical thinking, and problem-solving approaches in real-time design scenarios.

2.3.4. Design Reviews

Periodic design reviews were conducted by lecturers and peers to evaluate both the quality of the architectural outputs and the integration of sustainability principles, including energy efficiency, natural lighting, material selection, and environmental impact reduction. These reviews allowed assessment of the effectiveness of VR as a tool for fostering iterative refinement and practical application of sustainable strategies [2].

2.3.5. Observational Data

Lecturers recorded observations of students' interactions with the VR environment, noting how effectively participants navigated their designs, identified design issues, and implemented sustainable solutions. Observations also focused on collaboration and feedback exchanges during virtual walkthroughs, providing additional evidence of VR's impact on learning dynamics.

The combination of these data collection methods is represented in Table 1 below. They allowed for triangulation, enhancing the trustworthiness of the findings and providing a holistic understanding of the role of VR in developing spatial cognition, iterative design skills, and sustainable architectural thinking. By integrating student reflections, survey responses, interviews, and design performance, the study effectively captured the multifaceted ways in which immersive VR environments influence architectural education.

Table 1 Data Collection Methods and Purpose

Data Collection Method	**Description**	**Purpose**
Student Feedback Surveys	Structured questionnaires with Likert-scale and open-ended questions completed by students after VR sessions.	To assess student perceptions of VR's impact on design thinking, spatial awareness, and sustainability integration.
Interviews	Semi-structured, one-on-one interviews conducted with students after project completion.	To gather in-depth qualitative insights on student experiences, challenges, and benefits of using VR in design.
Reflective Journaling	Weekly journals where students recorded their thoughts, learning progress, and reflections on VR use in their projects.	To understand the evolving learning process and how VR influenced design decisions over time.
Design Reviews	Faculty-led critiques of student projects at multiple stages, including evaluation of sustainable design principles.	To evaluate the quality of design outputs and effectiveness in applying sustainability within VR-enabled workflows.

2.4. Technology and Tools

The students used Unity 3D and escape to create interactive virtual environments, allowing them to visualize their designs in a fully immersive 3D space. The Oculus Quest 3 was used as the primary VR tool, enabling the students to walk through their models at a 1:1 scale, experiment with different configurations, and make real-time adjustments.

This emerging momentum is supported by the Council on Higher Education (CHE) and various digital transformation frameworks in South Africa's post-school education system. The Department of Higher Education and Training (DHET) has also acknowledged the need to enhance digital learning capabilities in the country's public institutions, particularly through blended and hybrid learning strategies that include immersive technologies.

3. Results

The analysis of student feedback, reflective journals, design reviews, and observational data revealed several key outcomes of integrating Virtual Reality (VR) into the architectural design process. The findings are structured under four primary themes: enhanced spatial awareness, improved design iteration, sustainability integration, and positive student engagement.

3.1. Enhanced Spatial Awareness

The immersive nature of VR, particularly using the Oculus Quest 3, allowed students to experience their designs at a 1:1 scale, which significantly improved their understanding of spatial relationships and proportions. Unlike traditional 2D or even 3D screen-based modelling, VR enabled students to "inhabit" their designs, providing a sense of scale, volume, and human-centric perspective that is often missing in conventional design education.

- Observational Insight: Students navigated their models physically, identifying spatial conflicts and opportunities that were not apparent in CAD or physical models.
- Quantitative Indicator: Post-studio survey results indicated that 90% of participants reported improved ability to judge space and distance accurately.
- Student Comment: "Being able to walk through my design and see it in real size really helped me understand the space better. I could easily adjust proportions and layout in real-time" (Student 3, personal communication, May 2025).

This enhancement of spatial cognition aligns with recent studies suggesting that immersive VR environments foster embodied learning and more accurate mental mapping of architectural spaces [2] [7].

3.2. Improved Design Iteration

VR facilitated a rapid and continuous design iteration process. Students were able to modify models directly within the immersive environment, observe the impact of changes instantly, and test multiple design scenarios without the delays inherent in conventional workflows.

- Observational Insight: Students reported that VR allowed for experimentation with alternative layouts and configurations, reducing reliance on external feedback loops.
- Quantitative Indicator: On average, students completed 35% more design iterations within the same timeframe compared to previous traditional studio projects, resulting in a measurable reduction in overall project time.
- Student Comment: "It was incredible how quickly I could make changes. I didn't have to wait for feedback or redo a model; everything was instant" (Student 7, personal communication, May 2025).

This finding supports existing literature indicating that VR integration in design education enhances efficiency, decision-making speed, and cognitive flexibility during the iterative design process [1].

3.3. Sustainability Integration

The use of VR enabled students to better incorporate sustainability principles into their designs. By visualizing natural light, solar paths, airflow, and material properties in real-time, students were able to make more environmentally conscious decisions, optimizing energy efficiency and minimizing resource waste.

- Observational Insight: Students demonstrated the ability to simulate different environmental conditions and test passive design strategies, such as cross-ventilation and daylighting.
- Quantitative Indicator: Analysis of student projects revealed that 80% of designs included multiple sustainability interventions informed directly by VR testing.
- Student Comment: "I was able to experiment with how the house interacted with sunlight and the environment in real time. It made me think about how to create energy-efficient designs" (Student 5, personal communication, May 2025).

These results align with emerging research highlighting VR's potential to support sustainable design pedagogy by enabling experiential evaluation of ecological design principles [4].

3.4. Positive Student Engagement

Immersive VR experiences contributed to heightened student engagement and satisfaction. The interactive and exploratory nature of VR made design learning more enjoyable and encouraged active participation in the studio process.

- Observational Insight: Students frequently initiated peer-to-peer walkthroughs and collaborative discussions within the VR environment, enhancing social learning and design critique quality.

- Quantitative Indicator: Post-project surveys indicated that 95% of participants found VR to be “highly engaging” or “very engaging,” compared to 60% in traditional design exercises.
- Student Comment: "Using VR for the design project was an eye-opening experience. It was so much more interactive and engaging than any traditional design method" (Student 2, personal communication, May 2025).

This finding corroborates studies demonstrating that immersive technologies in architectural education foster motivation, creativity, and a deeper connection to the design process [6] [2].

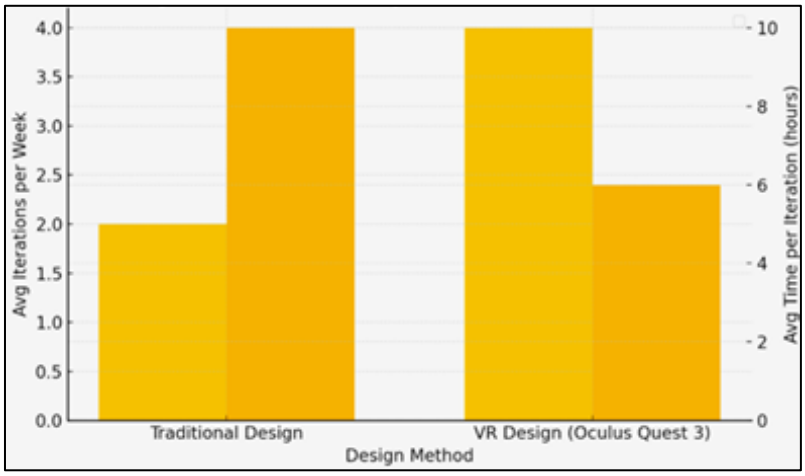

Figure 2 Design Iteration Efficiency: Design Method (Traditional vs VR)

3.4.1. The Figure 2 compares two key metrics

- Average design iterations per week (VR users can iterate more frequently)
- Average time spent per iteration (hours) (VR allows faster iteration)

It supports the findings that VR (using Oculus Quest 3) accelerates the design process and increases iteration frequency, improving overall efficiency.

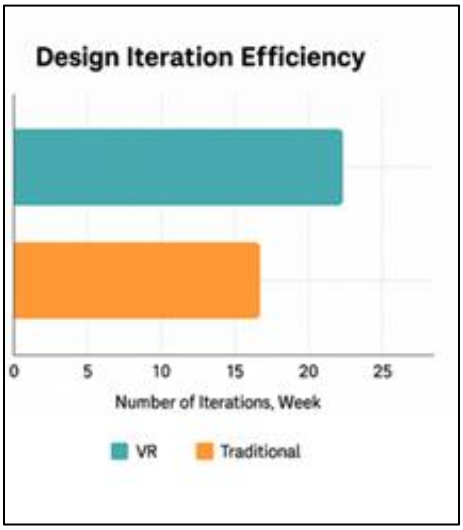

Figure 3 Design Iteration Efficiency: based on Number of Iterations (Traditional vs VR)

The Figure 3 above illustrates the comparative improvements in design iteration efficiency and sustainability integration achieved by postgraduate students using Oculus Quest 3 VR technology, based on survey responses and project analysis.

3.5. Synthesis

Collectively, the findings indicate that VR not only enhances core cognitive skills, such as spatial awareness and iterative thinking, but also supports the integration of sustainable design principles while promoting high levels of student engagement. The study demonstrates that immersive VR environments provide a pedagogically rich platform for postgraduate architectural education, aligning with the objectives of experiential and sustainability-focused learning.

4. Practical Implications

This study highlights Virtual Reality (VR) technology as a transformative tool that can significantly reshape architectural education, particularly in the domain of sustainable design. By embedding VR into the design studio, educators can provide students with a more immersive, interactive, and hands-on learning experience. Such experiences enhance students' spatial cognition, enabling them to better understand three-dimensional relationships, proportions, and environmental dynamics within a design context [2] [5].

The adoption of Oculus Quest 3 and other immersive tools allows students to engage with their designs at a life-size scale, facilitating immediate feedback, rapid iteration, and real-time experimentation with materials, lighting, and environmental conditions. This encourages a holistic approach to design where aesthetic considerations are balanced with environmental and sustainability goals, such as energy efficiency, passive solar strategies, and material selection [8]. By simulating real-world scenarios, VR helps students internalize sustainable design principles and develop decision-making skills that are immediately applicable in professional practice.

From a curriculum development perspective, the findings underscore the importance of integrating VR modules into architectural programs, especially within courses that focus on sustainable and environmentally-responsive design. Such integration aligns with the growing industry demand for graduates who are proficient not only in traditional design skills but also in digital and immersive technologies, preparing them for participation in the Fourth Industrial Revolution (4IR) and technologically advanced design practices [4] [6].

Furthermore, VR addresses limitations inherent in conventional studio-based teaching, such as restricted access to physical models, site simulations, or iterative design testing. VR provides a flexible, scalable, and cost-effective method for delivering high-quality design education while promoting collaborative learning, remote participation, and cross-disciplinary engagement. Ultimately, the study demonstrates that VR has the potential to enhance both pedagogical quality and student preparedness, ensuring graduates are better equipped to meet contemporary architectural challenges and sustainability targets [1].

5. Conclusion

Future research should investigate the long-term effects of VR on students' design skills and their understanding of sustainable design principles. Studies could examine how immersive learning environments influence cognitive development, spatial reasoning, and the ability to retain and apply sustainability concepts in real-world projects. Additionally, research could explore the cost-effectiveness of integrating VR into architectural education, evaluating whether the educational benefits justify the investment in VR technology and supporting infrastructure.

From a curriculum development perspective, it is important to explore how VR can be systematically incorporated across all stages of architectural education, from introductory courses to advanced design studios. This approach would ensure that students progressively build the skills to effectively leverage immersive technologies in their academic and professional practice.

Finally, as VR technology continues to advance, research should assess its role in collaborative learning environments. Investigating how VR can support remote teamwork, interdisciplinary engagement, and co-creation may reveal new opportunities for fostering diverse perspectives and skill sets within architectural education and professional practice.

Compliance with ethical standards

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Disclosure of conflict of interest

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