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Exploring the Economic Viability of Virtual Reality in Architectural, Engineering, and Construction Education

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Abstract: The role of technology in education is becoming increasingly important, and the introduction of advanced technology and AI is transforming the way we learn. Virtual reality (VR) is an effective technology that enhances student engagement and improves learning outcomes. However, the cost of implementing VR is a significant concern for educational institutions, making integrating VR technology into education challenging. To address this challenge, this study aims to explore the costs associated with integrating VR into architectural, engineering, and construction (AEC) education. The study had three objectives: to identify relevant case studies that utilized VR in AEC education, to perform keyword analysis, and to conduct a cost analysis of the selected case studies. The thematic analysis identified VR applications in various categories, including VR platforms, construction safety training, design review simulators, civil engineering labs, building information modeling (BIM) integration, architectural design, and surveying engineering. The results revealed that the cost of VR varies based on the application, indicating that it is possible to implement VR in education even on a limited budget. This research provides valuable insights and recommendations for researchers and practitioners who want to adopt VR technology in AEC education effectively.

Keywords: virtual reality; architectural, engineering, and construction; case studies; cost analysis; AEC education

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1. Introduction

Technology plays a crucial role in revolutionizing education on various fronts [1]. It enriches the learning experience by providing interactive tools, multimedia resources, and access to a vast repository of educational materials [2]. Additionally, technology expands educational access through platforms like virtual classrooms and online courses, making learning opportunities available to a broader audience. Personalized learning experiences are facilitated, tailoring education to individual student preferences and needs [3]. In today's advanced technological world, virtual reality (VR) is considered a highly influential force for change and innovation. Through immersive simulations and interactive environments, VR takes learning to new heights, captivating students' attention and fostering deep engagement with the subject matter. This technology enhances digital literacy and prepares students for the increasingly tech-driven future [4]. For educators, VR is a powerful tool to elevate teaching methods, creating dynamic and experiential learning environments [5]. Thus, within the broader spectrum of technological advancements in education, VR emerges as a cutting-edge tool with the potential to revolutionize the educational experience [2,3].

One of the primary challenges associated with implementing VR in education lies in its substantial cost [6,7]. The expense encompasses various facets, including procuring hardware, software, and ongoing maintenance. This financial investment can pose a significant hurdle for educational institutions adopting VR systems. In addition to cost, usability is also a crucial concern. VR interfaces may present challenges, potentially leading to difficulties in navigating and utilizing educational experiences [8]. Additionally, the necessity for specialized training for educators further compounds the implementation process, necessitating additional resources and time. While the potential benefits of VR in education are substantial, addressing these cost-related barriers remains a pivotal consideration for institutions looking to integrate this immersive technology into their learning environments [9].

VR adds an entirely new dimension to the learning process that traditional methods are unable to match [10]. It transports students into immersive virtual environments, turning lessons into exciting adventures. What sets VR apart is its ability to adapt to each student's unique learning style, making the educational experience more personal and effective [11]. Moreover, it encourages independent thinking, empowering students to draw their insights from their virtual experiences [12]. By not incorporating VR into education, we are overlooking a powerful tool that could revolutionize the way we learn, making it not only more enjoyable but also more impactful for every learner [13].

Addressing the cost concerns associated with VR holds the potential to unlock a new era in AEC education. Currently, the expenses related to acquiring and maintaining VR technology can be a significant barrier. Successfully navigating these financial hurdles leads to substantial benefits in AEC education [14]. VR offers the opportunity for students to immerse themselves in lifelike architectural and engineering simulations, providing hands-on experience in a controlled virtual environment [15]. This not only enhances their technical skills but also fosters a deeper understanding of complex spatial relationships and design principles [16]. By overcoming the cost challenge, educational institutions can provide a richer and more dynamic learning experience in AEC, preparing students for a future where VR technology proficiency is increasingly valuable in the industry [17].

This research aims to conduct a comprehensive analysis of the costs associated with implementing virtual reality (VR) technology in architectural, engineering, and construction (AEC) education. To reach this aim, the study had three objectives: to identify relevant case studies that utilized VR in AEC education, to perform keyword analysis, and to conduct a cost analysis of the selected case studies. This research will involve a systematic review of case studies that involve VR applications in AEC education, followed by a detailed cost analysis to determine the financial implications of integrating VR into educational practices within the AEC domain. Additionally, a word analysis will be conducted to identify and emphasize the key terms and concepts relevant to this investigation. The results of this research will provide valuable insights into the feasibility and potential benefits of adopting VR technology in AEC education.

2. Research Background

In recent years, the incorporation of VR into higher education has demonstrated remarkable potential to revolutionize the learning experience across diverse disciplines, particularly in the AEC industry [18]. While VR has been an object of exploration since the mid-20th century, its contemporary applications have engendered significant interest in academia, presenting novel opportunities for educating and training professionals within the AEC domain [19]. The immersive and interactive nature of VR has emerged as a pivotal game changer, endowing students and practitioners in the AEC industry with immersive learning opportunities. The AEC industry has already witnessed the tangible benefits of VR integration in education and training [20]. Architecture students can iterate on designs; engineering students can analyze complex structures; and construction professionals can virtually navigate through building sequences, proactively mitigating potential challenges during the actual construction phase.

Moreover, VR facilitates collaborative experiences, allowing professionals from diverse disciplines to interact and jointly address challenges within a shared virtual space, emulating real-world industry practices [14]. The advancement of VR presents considerable untapped potential for future research and innovation in the fields of architecture, engineering, and construction. The development of specialized VR tools tailored to the industry's unique exigencies will significantly enhance the learning experience and workforce readiness. Furthermore, conducting comprehensive investigations into the enduring impact of VR-based education on project outcomes, design efficiency, and industry performance will furnish valuable insights to inform the strategic incorporation of VR in the AEC landscape [21]. The study emphasizes the benefits of integrating haptic feedback devices into VR systems, demonstrating how these combined systems can facilitate realistic engagement for students in complex machine-assisted learning and experimental procedures [22]. It underscores VR's role in improving learning outcomes through immersive and interactive experiences.

By creating realistic simulations of various scenarios, VR captures students' attention and encourages active participation, leading to improved knowledge retention and critical thinking skills [23]. The incorporation of haptic feedback into VR systems opens up new opportunities for impactful machine-assisted learning [24]. The combination of VR and haptic feedback allows students to compete realistically in the learning process, enabling them to immerse themselves in educational content and engage with it on a deeper level [25]. By providing realistic experiences, VR empowers students to develop problem-solving and decision-making skills necessary for real-world challenges [26]. This multi-sensory environment introduces tactile sensations and force feedback, bridging the gap between the physical and virtual worlds and resulting in a deeper understanding of abstract concepts [26].

According to Kavanagh et al. [19], the systematic review of the use of VR in education identified several key findings. The analysis revealed that VR is commonly applied in specialized situations requiring realistic simulations or for training purposes [16]. However, there is a lack of solid pedagogical reasoning behind the use of VR in education [27]. Educators often rely on the novelty factor of VR technologies to motivate students, but this motivation may diminish with continual use [19]. Issues and limitations reported with VR systems include cost, training, software and hardware usability, and the lack of realism in educational VR implementations [7]. The review suggests that educators should consider design factors such as the uncanny valley hypothesis and explore alternative technologies like spherical immersive video to enhance realism. Additionally, the review highlights the potential of emerging VR technologies to overcome usability and affordability issues. However, further research is needed to fully understand the impact and effectiveness of VR in non-specialized digital education [20].

Research Gap

In the growing research on using VR technology in AEC education, a noticeable gap exists. Despite many studies that have emphasized the pedagogical advantages of VR in AEC education, a notable gap remains in comprehensively understanding the total costs associated with its implementation. This research aims to fill this gap by conducting a systematic review and cost analysis. The main aim is to show the costs of applying VR and the results of this research, which could be a crucial step in helping the practical and strategic use of VR in AEC education. The insights gained from this study can offer essential information for educators, institutions, researchers, and industry professionals. The cost analysis conducted on case studies will help academic institutions in deciding whether to adopt VR and utilize it effectively. This way, the study aims to contribute to informed decision making and the successful use of VR technologies in AEC education.

3. Methodology

The research methodology employed in this study is illustrated in Figure 1 and comprises two major sections: Data Collection and Data Analysis and Results. The Data Collection section outlines the systematic review process (SLR) used to identify relevant literature on VR applications in AEC education. This process involved an initial search using the Web of Science and Scopus databases, followed by screening and full-text review stages. The Data Analysis and Results section describes the keyword analysis and cost analysis conducted and the methodology utilized: the word analysis method for qualitative data analysis. Furthermore, a cost analysis was also conducted to determine the minimum and maximum cost range for each category of VR applications within AEC education. The details of both data collection and data analysis and results will be discussed in the following sections.

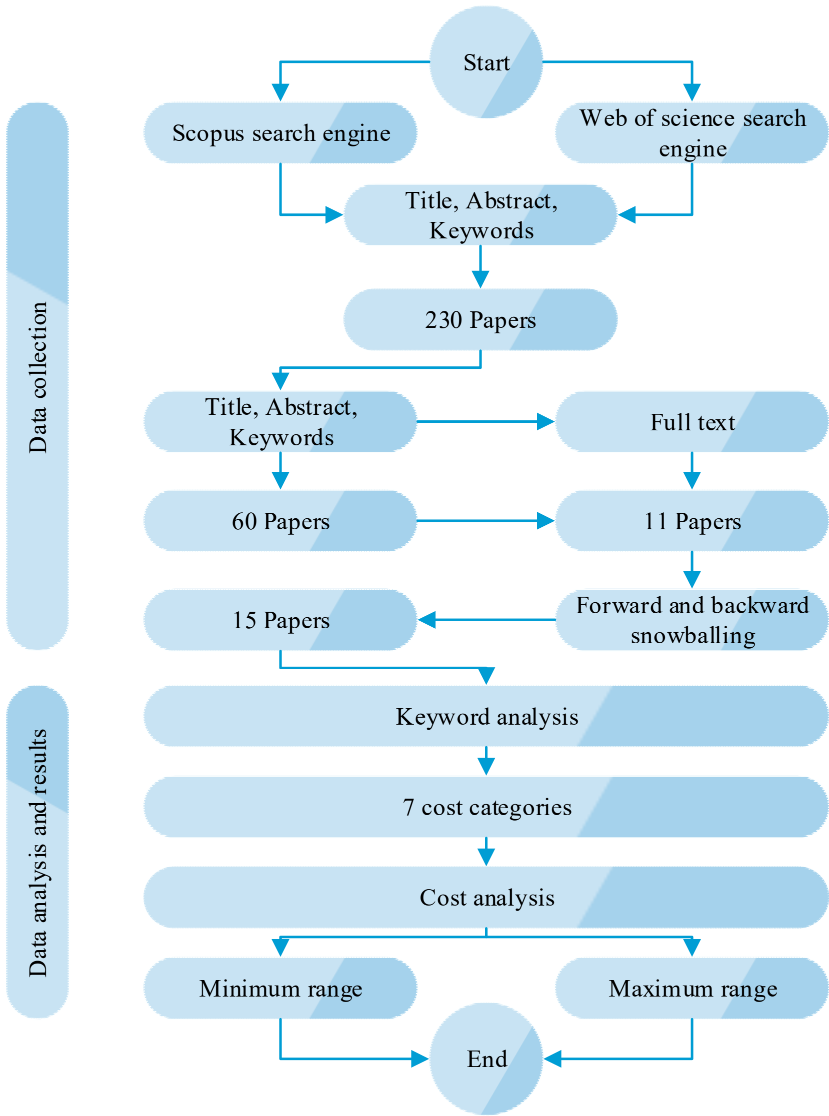


Figure 1. Research methodology.

3.1. Data Collection

A systematic review (SLR) was conducted to identify the literature on VR applications in AEC education. The search criteria for this study were determined based on the study aim, involving the identification of appropriate keywords, search engines, and databases. Both Web of Science and Scopus were utilized for the initial search, as they cover a wide range of literature and are commonly used in SLR papers [28]. A systematic review is primarily common in extracting literature and used by other research works in the AEC on different topics [29–32]. The study considered all research on VR applications in AEC education to be eligible for review. Specific keywords were selected to align the search with the study objectives. The keywords used were "VR" OR "Virtual reality" AND "AEC education". The search was restricted to the "journal" and "conference" categories, as these sources undergo a rigorous peer-review process. Additionally, the search was limited to the English language to avoid translation bias. Only case studies were included, excluding other methods to maintain focus on empirical evidence. Furthermore, only journals with more than three publications were considered to ensure the quality of the papers [33].

The search term was TITLE-ABS-KEY ("VR" OR "Virtual reality") AND ("AEC education") AND (LIMIT-TO(LANGUAGE, "English")). This initial search yielded 230 articles. The first stage of screening involved reviewing the titles and abstracts, focusing on literature involving soft costs. This process resulted in 60 articles advancing to the next stage. The second stage involved a full-text review of these articles, applying the same inclusion and exclusion criteria. This thorough review identified 13 articles that met the criteria. To enhance the comprehensiveness of the literature review, the study employed the snowballing technique. Snowballing involves reviewing the references of identified articles (backward snowballing) or exploring their citations (forward snowballing). In this research, both forward and backward methods were employed to examine citations and references across four rounds.

3.2. Data Analysis

The selected papers' abstracts and conclusions are analyzed using keyword analysis. This approach was selected due to its ability to generate reliable and impartial results [34]. The word analysis method utilized in this study is a systematic and transparent technique designed to enhance the accuracy of qualitative data analysis within the Microsoft Word environment [35]. This method stands out due to its emphasis on systematic organization and structured code analysis. By utilizing features like code counting, code hierarchy organization, and data extraction visualization, the word analysis method offers researchers a robust framework for conducting qualitative data analysis. It ensures a systematic and unbiased exploration of qualitative data, all within the familiar context of Microsoft Word, simplifying the research process [36]. The decision to employ this methodology is based on its capacity to minimize bias and improve result reliability. The systematic organization of codes and transparent analysis procedures contribute to the credibility of the research outcomes. Additionally, features like code hierarchy organization and data extraction visualization enhance the sophistication of the method, reinforcing its ability to produce dependable insights. This methodology ensures consistency in the analysis process and contributes to the overall quality and validity of the research findings. By adopting this approach, researchers can navigate the complexities of qualitative data analysis in a structured and efficient manner, leading to the production of impartial, reliable, and transparent results [37].

4. Results

4.1. SLR Results

Table 1 offers a comprehensive overview of SLR results exploring VR applications within AEC education. This table's columns consist of Paper, Aim, Method, and Category, encapsulating insights from various studies. Each entry in the table provides a succinct overview of specific research, highlighting its aims, methodologies, and categorizations across diverse VR applications. Covering seven topics, including VR platforms, construction safety, design review simulators, civil engineering, BIM, architectural design, and survey engineering, the table encompasses insights from a total of 15 papers.

Table 1. SLR results.

Paper	Aim	Method	Category
VoRtex Metaverse platform for gamified collaborative learning	The aim is to develop a high-level software architecture and design for a metaverse platform named VoRtex.	The VoRtex platform prioritizes user experience and encompasses critical elements: a web platform, access control, and a MicroLesson feature. It operates on a cloud-based and immersive architecture, offering a virtual learning environment that supports multiple users in remote teaching and collaboration.	VR Platform
Investigating hazard recognition in augmented virtuality for personalized feedback in construction safety education and training	The aim is to introduce a framework for creating and evaluating trainee data in augmented virtuality (AV).	The test involved incorporating interactive elements, scenarios, and hazards into the virtual environment. Participants were tasked with navigating through different areas, identifying hazards, and completing specific tasks using an AV controller. Their actions and interactions were monitored and recorded, including hazard recognition, interaction choices, and task completion.	Construction Safety
Assessing the impact of a construction virtual reality game on design review skills of construction students	The aim is to investigate the impact of a VR game, the design review simulator (DRS), in a classroom environment.	The study evaluated students' design review skills using DRS. Data on thinking skills and design review proficiency were collected through activity handouts and an assessment tool with multiple-choice and true-or-false questions. The study took place in a classroom equipped with various VR tools, including Oculus Rift and Lenovo Mirage headsets, as well as VR-ready desktops. Students worked in pairs, with one group using 2D drawings and the other using a VR game. Both groups received consistent design proposals for a sample building.	DRS
Virtual reality application to aid civil engineering laboratory course: A multicriteria comparative study	The aim is to develop a VR application for a civil engineering lab course and assess its potential in education.	The study included 26 civil engineering students from both undergraduate and graduate levels. They were exposed to three learning methods: VR-aided learning, instructor-aided learning, and video-aided learning. Participants used a VR application in a designated experimentation room. Participants were guided to use testing instruments with actual equipment. Lastly, participants learned independently by watching video tutorials.	Civil Engineering

Table 1. *Cont.*

Paper	Aim	Method	Category
Design and development of a virtual reality educational game for architectural and construction reviews	The aim is to design and develop an educational VR game called DRS.	The game aimed to engage students in developing a design review simulator by immersing them in a 3D model of a townhouse in San Francisco. The game was developed using Unity 3D and Oculus Rift VR headsets. The research documents the analysis, design, and development phases of the game, as well as the creation of educational assessment material for classroom implementation.	DRS
Construction safety education system based on virtual reality	The aim is to present a VR construction safety training system that allows multiple users to experience construction hazards physically, visually, and tactfully.	A VR system is developed to simulate construction hazards, allowing users to interact and explore virtual scenes. The system includes a shaking table that provides vibrations corresponding to the virtual environment. Actual terrain is created using software tools, and the VR scenes are developed with 3D modeling and the Unity game engine. The effectiveness of the system is verified through experimental testing.	Construction Safety
BIM-VR Framework for Building Information Modelling in Engineering Education	The aim is to create a student-centered learning environment that promotes active learning within simulated real-world contexts by integrating BIM and VR.	The BIM VR framework utilizes Oculus Rift VR headsets connected to a computer for immersive experiences. Autodesk Revit is employed to generate a 3D model of the existing structure, while Autodesk 3DS MAX enhances model visualization. Unity game development engine is used for scripting and VR interaction. The hardware setup includes VR headsets, tracking sensors, and touch controllers. The framework comprises three stages: integrating VR into Unity, crafting a visualization environment for both interior and exterior spaces, and modeling mechanical, electrical, and plumbing systems.	BIM

Table 1. *Cont.*

Paper	Aim	Method	Category
CubeVR: Digital affordances for architecture undergraduate education using virtual reality	The aim is to present the current state of the CubeVR prototype, the informal impressions of users, and the use of different affordances in the virtual world.	The methodology used in CubeVR involves the development of a VR environment using Unreal Engine and HTC Vive. The program starts by transporting the user into a virtual room containing a desk with basic building materials. No physics engine is applied to the objects, allowing them to float in the air and snap together when overlapped.	VR Platform
Immersive construction detailing education: building information modeling (BIM)–based virtual reality (VR)	The aim is to create a platform for construction detailing that offers experiential learning in a zero-risk environment.	This work discusses the proposed curricular unit prototype design, implementation, and validation. The validation of the VR and BIM was conducted in three phases, namely piloting, testing (system usability and immersion), and learning gain validation.	BIM
Integration of virtual reality (VR) in architectural design education: Exploring student experience	The aim is to integrate VR environments into the architectural curriculum and establish a VR lab for architecture students at Western Kentucky University.	The study involves two architectural design projects: a hotel model created in Trimble SketchUp 2024 and a single-family house model created in Autodesk Revit. The researchers conducted empirical studies to explore the practical application of VR in architectural design education.	Architectural Design
VR-Based learning media of earthquake-resistant construction for civil engineering students	The aim is to develop a VR-based construction model that improves learning outcomes in civil engineering education.	The method described in the study involves the development of a VR-based construction tool for civil engineering education. The development process consists of three stages: pre-development, development, and post-development.	Civil Engineering
Web-based Game vs. Virtual Reality Field Surveying Labs Towards Enhancing Experiential Education	The aim is to compare web-based gaming and VR approaches in virtualizing surveying education, assessing their effectiveness, and providing insights for instructors.	The study used two distinct methods at different universities. At Penn State Wilkes-Barre, they introduced an immersive virtual tool in a surveying engineering course, conducting both physical and virtual labs on differential leveling. They gathered student feedback through questionnaires. At York University, they applied a game-based tool in a land surveying course, offering students virtual surveying tasks and the ability to save and analyze their measurements.	Surveying Engineering

Table 1. *Cont.*

Paper	Aim	Method	Category
Lessons learned from the development of immersive virtual reality-based collaborative architecture, engineering, and construction (AEC) education environment	The aim is to design and develop a collaborative VR application for construction education, allowing students to solve problems together.	The study followed the guidelines for application design and development. It consisted of three stages: design, development, and testing. The Unity game engine and Autodesk Revit were used to create the VR application. Student volunteers tested the application using the Oculus Quest 2 device and provided feedback.	Construction Safety
Virtual Reality Based Environment for Immersive, Hands-On Learning	The aim is to create a learning tool for teachers by creating a virtual environment to use in their classrooms.	The study involved designing and developing a VR learning environment. It included a virtual environment where students could assemble and disassemble models using Oculus Rift controllers. A model library was provided, and users could create their models.	VR Platform
A Pilot of Student-Guided Virtual Reality Tours	The aim is to investigate the use of VR in a construction management classroom to enhance students' BIM skills.	The pilot study involved postsecondary students in a construction technology course who created 3D site logistics models using BIM software, such as Autodesk Revit 2024.2.1 and Trimble SketchUp 2024. Two methods were used: traditional critique, where students presented their models for peer feedback using an overhead projector, and collaborative VR critique, where students curated VR tours using OculusGo® headsets.	BIM

4.2. Cost Analysis

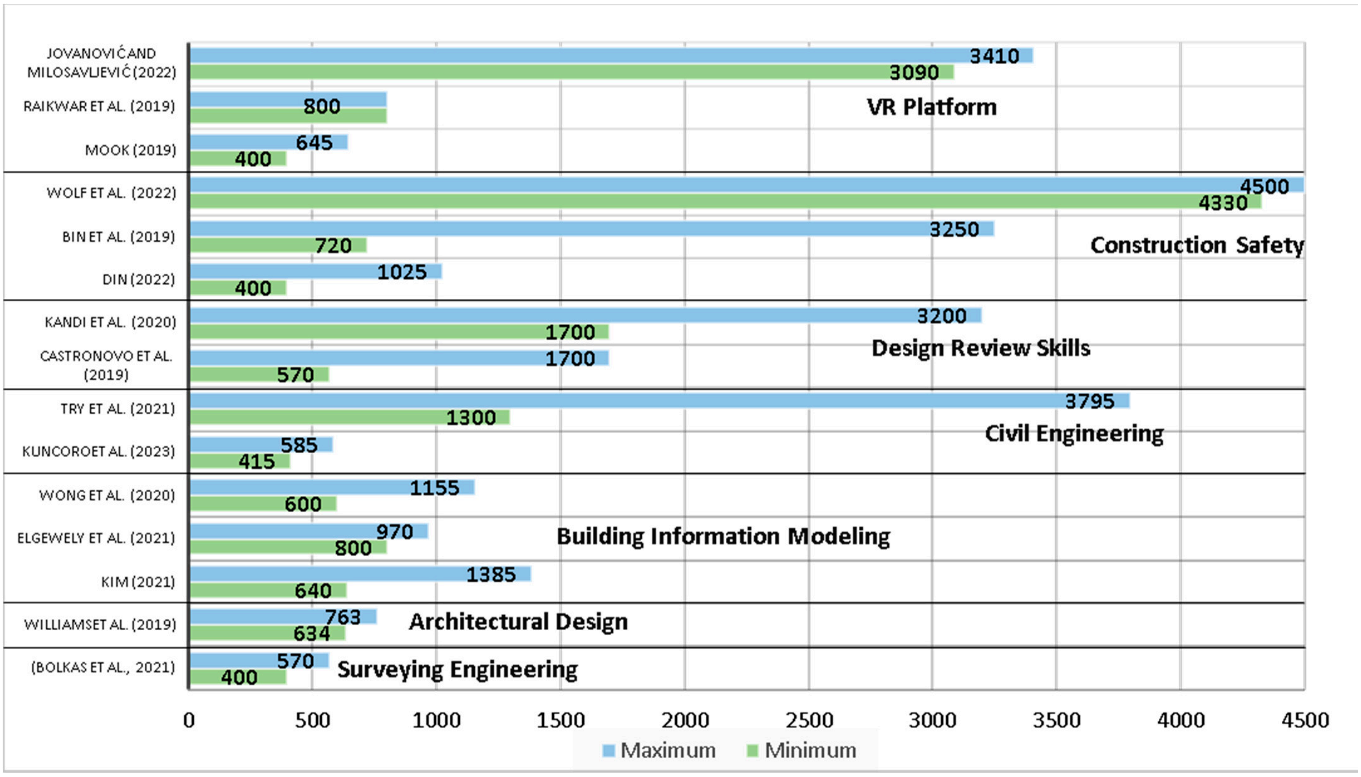
Table 2 presents the results derived from the cost analysis of software and hardware specifications in VR applications within AEC education. Each entry corresponds to unique research, elucidating specific software tools, associated costs, and requisite hardware components. From prevalent game engines like Unity to specialized applications such as Autodesk Revit (SketchUp Desktop 2024), the software column encapsulates a diverse array of tools. Simultaneously, the hardware section outlines vital components like VR headsets, cameras, and processors, with corresponding costs meticulously detailed in USD. It is important to note that the cost calculations are based on current pricing for software and hardware available online and are not influenced by any specific study area where the VR learning module was implemented. This approach ensures a standardized comparison of costs across different studies.

Table 2. Cost analysis results.

Paper	Reference	Software	Price		Hardware	Price (USD)
			Purchase	Subscription/month		
VoRtex Metaverse platform for gamified collaborative learning	[38]	Unity game engine 2024.2		Free/170	Web camera	50–200
		JavaScript ECMAScript 2024	Free		Fingerprint reader	Free
		PHP 8.3.0	Free		VR HMD	3000
		MySQL 8.0.35	Free		Input processor controls	10
		Natural Language Processing tools		30	VoRtex	Unknown
CubeVR: Digital affordances for architecture undergraduate education using virtual reality	[39]	CubeVR 1.5.2	Free		HTC Vive	800
Virtual Reality Based Environment for Immersive, Hands-On Learning	[40]	Models	Free		Oculus Rift	400
		Unity game engine 2024.2		Free/170	Oculus controller	Free/75
Investigating hazard recognition in augmented virtuality for personalized feedback in construction safety education and training	[41]	SteamVR SDK 2.7.0		Free	HTC Vive	800
		Unity game engine 2024.2		Free/170	HTC Vive Trackers	130
		Text-to-speech plugin		Free	Pupil Labs binocular add-on for HTC Vive	3000
					VR Headset	400
Construction safety education system based on virtual reality	[42]	VR virtual experience software	50–1000		Distributor	30
		EI-shayalSmart	Unknown		Stream box	200–850
		Google Earth 9.182.0.1	Free		VR Headset	400
		GlobalMapper 24.1	Free			
		WorldMachine 3.0.5	Free	120/300/2000		
Lessons learned from the development of immersive virtual reality-based collaborative architecture, engineering, and construction (AEC) education environment	[43]	Unity game engine 2024.2		Free/170	Oculus Quest 2	400/500
		Autodesk Revit 2024.2.1		Free/165/280	Oculus controller	Free/75
		OpenXR 1.0.10	Free			
		XR Interaction Toolkit 2.2.0	Free			
Assessing the impact of a construction virtual reality game on design review skills of construction students	[44]	Design review simulator	Unknown		Oculus Rift	400
					Lenovo Mirage VR headset	800
		VR Game	Unknown		VR-ready desktop computers	500–2000
Design and development of a virtual reality educational game for architectural and construction reviews	[45]	Unity game engine 2024.2		Free/170	Oculus Rift	400
		ADDIE framework	90/100			
		BIM model		Free		
Virtual reality application to aid civil engineering laboratory course: A multicriteria comparative study	[46]	Unity game engine 2024.2		Free/170	VR-compatible computer	500–2000
		Microsoft Visual Studio 2024		Free/650	HTC Vive	800
		C-Sharp (C#) 11.0		Free		
		Sketch-Up 2024				
		AutoCAD 2024		Free/120/175		
		Blender 3.6.0		Free		
VR-Based learning media of earthquake-resistant construction for civil engineering students	[47]	Unity game engine 2024.2		Free/170	Oculus Rift	400
					Google Cardboard	15
BIM-VR Framework for Building Information Modelling in Engineering Education	[48]	Autodesk Revit 2024.2.1		Free/165/280	Oculus Rift CV1	600
		Autodesk 3DS MAX 2024		Free/105		
		Unity game engine 2024.2		Free/170		
		Autodesk Forge API	Free			
Immersive construction detailing education: building information modeling (BIM)–based virtual reality (VR)	[49]	Unity game engine 2024.2		Free/170	HTC Vive	800
		SteamVR SDK 2.7.0	Free			
		VRTK 4.1.0	Free			
A Pilot of Student-Guided Virtual Reality Tours	[50]	Autodesk Revit 2024.2.1		Free/165/280	Oculus Go	200/250
		Sketchup 2024	40/55/seat	5		
		InsiteVR	400/800	8		
Integration of virtual reality (VR) in architectural design education: Exploring student experience	[51]	IrisVR Prospect 2.13.6	Free	225/350	Oculus Rift	400
		Enscape 3.6		13-Sep		
Web-based Game vs. Virtual Reality Field Surveying Labs Towards Enhancing Experiential Education	[52]	Unity game engine 2024.2		Free/170	Oculus Rift	400

5. Discussion

The summary of the cost analysis performed on the identified case studies is presented in Figure 2. Figure 2 displays the cost distribution for various papers across disciplines related to the VR Platform. The vertical axis represents the cost range in USD, while the horizontal axis corresponds to different papers categorized under specific disciplines. In the VR Platform category, "Paper [38]" ranges from $3090 to $3410, "Paper [39]" incurs a fixed cost of $800, and "Paper [40]" varies from $400 to $645. Within Construction Safety, "Paper [41]" ranges from $4330 to $4500, "Paper [42]" spans from $720 to $3250, and "Paper [43]" ranges from $400 to $1025. For DRS, "Paper [44] ranges from $1700 to $3200, while "Paper [45]" ranges from $570 to $1700. In Civil Engineering, "Paper [46]" varies from $1300 to $3795, and "Paper [47]" ranges from $415 to $585. BIM papers include "Paper [48]" with a range of $600 to $1155, "Paper [49]" from $800 to $970, and "Paper [50]" from $640 to $1385. Architectural Design's "Paper [51]" ranges from $634 to $763. Finally, in Surveying Engineering, "Paper [52]" ranges from $400 to $570.



[38]: (Jovanović and Milosavljević, 2022), [39]: (Raikwar et al., 2019), [40]:(Mook, 2019), [41]:(Wolf et al., 2022), [42]: (Bin et al., 2019), [43]: (Din, 2022), [44]: (Kandi et al., 2020), [45]: (Castronovo et al., 2019), [46]: (Try et al., 2021), [47]: (Kuncoro et al., 2023), [48]: (Wong et al., 2020), [49]: (Elgewely et al., 2021), [50]: (Kim, 2021), [51]: (Williams et al., 2019), [52]: (Bolkas et al., 2021)

Figure 2. Cost analysis summarized results.

5.1. VR Platform

The keyword "VR Platform" emerges as a significant term in the keyword analysis, appearing multiple times in the cost analysis represented in Table 2. Upon comparing the cost analyses of the VR platforms presented in papers [38–40], distinct patterns emerge regarding the financial considerations associated with developing immersive environments. Paper [38] focuses on the VoRtex metaverse platform, with total costs ranging from $3090 to $3410. This platform utilizes a combination of free and paid software, including the Unity game engine 2024.2, JavaScript ECMAScript 2024, PHP 8.3.0, MySQL 8.0.35, and Natural Language Processing tools. On the hardware side, components such as web cameras, fingerprint readers, input processor controls, and the VR HMD contribute to the overall expenditure. The objective of this paper is to develop a high-level software architecture and design for VoRtex, emphasizing user experience in a cloud-based, immersive virtual learning environment. Paper [39] highlights the CubeVR 1.5.2 prototype, presenting a more streamlined VR platform with a total cost of $800. This prototype employs the Unreal Engine at no cost, making it a cost-effective choice. The HTC Vive, priced at $800, is the main hardware component driving the immersive experience. The objective of this paper is to showcase the current state of the CubeVR 1.5.2 prototype, emphasizing informal user impressions and the use of various affordances in the virtual world.

Paper [40], centered on creating a VR learning tool for construction education, incurs a total cost ranging from $400 to $645. This platform utilizes free software components, such as the Unity game engine 2024.2 and Models software. The Oculus Rift, priced at $400, serves as the primary VR HMD, accompanied by the Oculus controller. The aim of this paper is to design an intuitive VR learning environment where students can assemble and disassemble models using Oculus Rift controllers. In summary, each paper addresses unique aspects of VR platform development with varying cost structures, software choices, and hardware components. Paper [38] focuses on a comprehensive metaverse platform, whereas papers [39,40] present more specific use cases, with paper [40] emphasizing educational applications. Understanding the financial implications and objectives of these VR platforms provides valuable insights into the diverse landscape of VR development.

5.2. Construction Safety

The second keyword identified from the keyword analysis is "Construction Safety", which is reflected in the cost analyses of the VR platforms presented in papers [41–43]. Nuanced insights emerge regarding the financial considerations associated with developing immersive environments. Paper [41] introduces a framework for creating and evaluating trainee data in augmented virtuality, with total costs ranging from $4330 to $4500. This encompasses various software components, such as the SteamVR SDK 2.7.0, Unity game engine 2024.2, text-to-speech plugin, and Pupil Labs binocular add-on for HTC Vive. On the hardware side, expenses include the HTC Vive, HTC Vive Trackers, and a VR headset, contributing to the comprehensive cost structure.

Paper [42] delves into presenting a VR construction safety training system, with total costs ranging from $720 to $3250. The software components include VR virtual experience software, EI-shayalSmart, Google Earth 9.182.0.1, GlobalMapper 24.1, and WorldMachine 3.0.5. Notably, the hardware elements encompass a distributor, stream box, and VR headset. This paper focuses on a specialized application for construction safety training, emphasizing practical and immersive solutions. Paper [43] aims to design a collaborative VR application for construction education, incurring total costs ranging from $400 to $1025. The software components involve the use of Unity game engine 2024.2, Autodesk Revit 2024.2.1, OpenXR 1.0.10, and XR Interaction Toolkit 2.2.0. On the hardware side, expenses include the Oculus Quest 2 and Oculus controller. The paper emphasizes collaborative problem solving in construction education, with ongoing improvements based on student feedback.

In summary, each paper contributes uniquely to the landscape of VR platform development, addressing specific aims and objectives. Paper [41] focuses on augmented virtuality and trainee data evaluation; Paper [42] specializes in construction safety training; and Paper [43] emphasizes collaborative problem solving in construction education. The systematic comparison of their cost structures, software choices, and hardware components provides valuable insights into the diverse applications and financial considerations associated with VR technology in different contexts.

5.3. Design Review Simulator

The third keyword identified from the keyword analysis is "Design Review Simulator (DRS)", which is reflected in the cost analyses of the VR platforms presented in papers [44,45], both centered around the DRS; distinct patterns emerge regarding the financial considerations, aims, and methodologies. Paper [44] investigates the impact of the DRS in a classroom environment, utilizing Oculus Rift, Lenovo Mirage headsets, and VR-ready desktops. The aim is to assess students' design review capabilities by comparing two groups: one using 2D drawings and the other using the VR game. While specific software costs are unspecified, the total cost encompasses hardware expenses, including Oculus Rift, Lenovo Mirage VR headset, and VR-ready desktop computers, ranging from $1700 to $3200. On the other hand, Paper [45] aims to design and develop an educational VR game called DRS, engaging students in a design review process through a 3D model of a San Francisco townhouse. The methodology involves using Unity 3D and Oculus Rift VR headsets for game development. The total cost of implementing the DRS game in this paper ranges from $570 to $1700, considering specified prices for the Unity game engine 2024.2, Oculus Rift, and the ADDIE framework. Additionally, the BIM model is listed as free.

Comparatively, while both papers revolve around the DRS, Paper [44] focuses on evaluating its impact in a classroom setting, incorporating varied VR tools, and assessing the design review process. In contrast, Paper [45] emphasizes the design and development of the educational VR game DRS, explicitly using Unity 3D and Oculus Rift VR headsets. The total cost for Paper [44] includes hardware expenses with unspecified software costs, while Paper [45] itemizes costs for the Unity game engine 2024.2, Oculus Rift, and the ADDIE framework. This comparative analysis sheds light on the distinct approaches, applications, and financial considerations in utilizing the DRS in educational contexts.

5.4. Civil Engineering

The fourth keyword identified from the keyword analysis is "Civil Engineering", which is reflected in the cost analyses of the VR platforms presented in Papers [46,47], both concentrating on VR applications in civil engineering education; notable distinctions arise concerning the financial considerations, aims, and methodologies. Paper [46] sets out to develop a VR application for a civil engineering lab course, targeting 26 students with the objective of assessing the application's educational potential. The study employs VR-aided learning, instructor-aided learning, and video-aided learning methods, involving participants using VR tools such as VR-compatible computers and HTC Vive in a designated experimentation room. The total cost ranges from $1300 to $3795, encompassing the Unity game engine 2024.2, Microsoft Visual Studio 2024, C-Sharp (C#) 11.0, Sketch-Up 2024, AutoCAD 2024, Blender 3.6.0, and various hardware components. In contrast, Paper [47] focuses on crafting a VR-based construction model to enhance learning outcomes in civil engineering education. The method involves a three-stage development process: pre-development, development, and post-development. Utilizing the Unity game engine 2024.2, Oculus Rift, and Google Cardboard, the total cost ranges from $415 to $585.

While both papers share the overarching goal of leveraging VR for civil engineering education, Paper [46] engages in a broader exploration of VR applications with a higher cost range, emphasizing the development of a versatile VR application for educational assessment. Conversely, Paper [47] concentrates on a specific VR-based construction model with a more concise set of tools and a lower total cost, emphasizing efficiency in creating an immersive learning experience. This comparative analysis underscores the diverse approaches within the realm of VR applications for civil engineering education, shedding light on the nuanced considerations in terms of scope, tools, and financial investments.

5.5. BIM

The fifth keyword identified from the keyword analysis is "Building Information Modeling" (BIM), which is the focus of the cost analyses in Papers [48–50]; distinctive patterns emerge regarding their cost analyses, aims, and methodologies. Paper [48] aims to create a student-centered learning environment through BIM and VR integration, utilizing Oculus Rift, Autodesk Revit 2024.2.1, Autodesk 3DS MAX 2024, and the Unity game engine 2024.2. The total cost ranges from $600 to $1155, covering both software and hardware components. In contrast, Paper [49] proposes a VR platform for construction detailing, employing the Unity game engine 2024.2, HTC Vive, SteamVR 2.7.0, and VRTK 4.1.0, with a total cost ranging from $800 to $970. This study emphasizes the practical application of VR in construction detailing, focusing on precision and validation processes. Meanwhile, Paper [50] explores collaborative VR for enhancing BIM skills in a construction management classroom, conducting a pilot study with Autodesk Revit 2024.2.1, SketchUp 2024, InsiteVR, and Oculus Go. The total cost of this setup ranges from $640 to $1385, incorporating a blend of software and hardware tools to facilitate collaborative learning.

Comparing the total costs, Paper [48] features the lowest range, while Paper [50] exhibits the widest range. Each paper contributes uniquely to the intersection of BIM and VR in education. Paper [48] focuses on creating a comprehensive BIM VR framework for student-centered learning, emphasizing the integration of BIM with VR tools to enhance the educational experience. Paper [49] proposes a VR platform for construction detailing, utilizing a three-phase validation process to ensure accuracy and effectiveness. Paper [50] investigates collaborative VR for enhancing BIM skills in a construction management classroom, employing a pilot study and two critique methods to evaluate its efficacy. This comparative analysis provides nuanced insights into the financial investments, scope, and methodologies within the BIM framework, highlighting the diverse applications and educational benefits of integrating VR with BIM technologies.

5.6. Architectural Design

The sixth keyword identified from the keyword analysis is "Architectural Engineering", which is the focus of the cost analysis in Paper [51]. This paper aims to integrate VR environments into the architectural curriculum at Western Kentucky University and establish a VR lab for architecture students. The methodology involves conducting empirical studies using two architectural design projects: a hotel model created in Trimble SketchUp 2024 and a single-family house model created in Autodesk Revit 2024.2.1. This empirical approach aims to explore the practical application of VR in architectural design education. By leveraging cost-effective VR tools and incorporating them into the educational curriculum, the paper contributes to enhancing the learning experience for architecture students and fostering a deeper understanding of VR's practical applications in the field. The total cost for this paper ranges from $634 to $763, considering both software and hardware expenses. The software components include IrisVR Prospect 2.13.6, which is free, and Enscape 3.6, which has a subscription cost ranging from $9 to $13 per month. On the hardware side, Oculus Rift is utilized, incurring a purchase cost of $400 and an additional cost of $225–$350.

5.7. Surveying Engineering

The seventh keyword identified from the keyword analysis is "Surveying Engineering", which is the focus of the cost analysis in Paper [52]. This paper aims to conduct a comparative analysis between web-based gaming and VR approaches in virtualizing surveying education. The overarching goal is to assess the effectiveness of these methods and provide valuable insights for instructors. The methodology involves implementing two distinct approaches at different universities. At Penn State Wilkes-Barre, an immersive virtual tool is introduced in a surveying engineering course, incorporating both physical and virtual labs on differential leveling. Student feedback is gathered through questionnaires. At York University, a game-based tool is applied in a land surveying course, offering students virtual surveying tasks with the ability to save and analyze their measurements. The total cost for this paper ranges from $400 to $570. The study leverages the Unity game engine 2024.2 which its price ranges from 0$ till 170 $ and the Oculus Rift hardware, with a total cost ranges from f $400 to $570. This combination ensures accessibility while delivering a practical and immersive learning experience for students in the field of surveying engineering.

6. Research Outcome

6.1. Research Implications

The research findings on the integration of VR within AEC education have significant implications that can shape the future of this field. One of the primary considerations that the research highlights is the need to scrutinize the factors that influence the costs of VR platforms in AEC education. This scrutiny aims to identify opportunities for making these platforms more affordable while maintaining the quality of education delivery. Another critical aspect that the research emphasizes is the evaluation of the educational impact of VR within AEC contexts. Specifically, it is vital to assess how VR platforms influence learning outcomes and student engagement, especially when compared to traditional teaching methods. This assessment can provide valuable insights for educators and institutions seeking to leverage VR to optimize the educational experience for students.

Furthermore, the seamless integration of VR into existing educational systems is a pivotal point of discussion. The exploration of effective methods for embedding VR within established frameworks for AEC disciplines while accounting for instructor training and curriculum standards becomes essential. This exploration promises practical insights into the incorporation of VR, ensuring alignment with the prevailing educational norms. Overall, the research findings suggest that careful consideration of the cost, educational impact, and integration of VR within AEC education can lead to a more effective and engaging learning experience for students.

6.2. Research Limitations

The discussion provides a highly informative and insightful analysis of the use of VR in AEC education. However, it is essential to note that the study does have some limitations that need to be acknowledged. Firstly, the sample size of the case studies analyzed is relatively small, comprising only fifteen studies. While these case studies offer valuable insights into the use of VR in AEC education, the limited number of studies analyzed may not fully represent the diverse range of practices in this field. Therefore, it is advised to exercise caution in generalizing the findings, as the study's scope may not encompass all VR applications in AEC education.

Another noteworthy limitation of the study is its exclusive reliance on word analysis for topic generation. While the study's focus on identifying topics through word analysis is valid, it may unintentionally exclude relevant dimensions of VR applications in AEC education that are not captured by this method of analysis. This may result in certain aspects of the field remaining unexplored, indicating a potential gap in the study's coverage. Thus, it is crucial to conduct further research to expand the dataset, explore alternative methodologies for topic identification, and offer a more comprehensive understanding of the diverse landscape of VR applications in AEC education. Recognizing and addressing these limitations will further enhance the depth and breadth of insights derived from research in this rapidly evolving field.

6.3. Research Recommendations

Based on the research findings, there are several suggestions to improve the use of VR in AEC education. Firstly, it is recommended that developers prioritize creating a user-friendly VR interface that makes the VR experience easy and enjoyable for users. By incorporating user-centered design principles, developers can significantly improve satisfaction and engagement, which positively impacts the educational benefits of these platforms. Another critical recommendation is to consider the long-term sustainability of VR initiatives. Institutions and educators are advised to evaluate the long-term viability of adopting specific VR platforms, considering factors such as budget constraints and educational objectives. It is essential to ensure that the chosen technologies remain relevant and well-supported over time.

Moreover, the research suggests that institutions and development teams should actively seek interdisciplinary collaboration in the development of VR applications for AEC education. Bringing together the expertise of educators, technologists, and industry professionals can lead to a more holistic and practical approach. This collaborative effort has the potential to yield versatile and impactful educational tools that cater to the unique needs of AEC learners, ultimately enriching the overall educational experience.

6.4. Research Conclusions

This research aimed to explore the costs associated with integrating VR into AEC education. To achieve this aim, the study had three objectives: to identify relevant case studies that utilized VR in AEC education, to perform keyword analysis, and to conduct a cost analysis of the selected case studies. The research involved a comprehensive and systematic review of relevant case studies, focusing on investigating the implications of using VR in AEC education. Furthermore, a thorough word analysis was conducted to identify the key terms and concepts that are relevant to this investigation. The research methodology involved applying inclusion and exclusion criteria during the systematic review of established databases, such as Scopus and Web of Science. This was done to ensure that the literature examined was relevant to the study. Keyword analysis was then performed using specialized software to obtain consistent and unbiased results. The study identified 15 case studies that were thoroughly examined to shed light on the diverse cost structures, software choices, and hardware components involved in VR applications across various domains in AEC education. These domains included VR platforms, construction safety training, design review simulators, civil engineering labs, building information modeling (BIM) integration, architectural design, and surveying engineering. The findings of this study suggest that user-friendly VR experiences are of great significance. Moreover, the research highlights the long-term viability of VR initiatives, as well as the importance of interdisciplinary collaboration in VR development. The study provides valuable insights and recommendations for the effective adoption of VR technology in AEC education, guiding researchers and practitioners in the field.

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