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Review

The Application of Extended Reality Technology in Architectural Design Education: A Review

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Abstract: With the emergence of Architecture 4.0 and the occurrence of the COVID-19 pandemic, extended reality (XR) technology has been increasingly applied in architectural education. This study aims to systematically organize and analyze the applications and outcomes of XR technology in construction education over the past five years, provide a theoretical framework for its future widespread use, and highlight its drawbacks as well as future research directions. The paper employs content analysis to summarize and analyze the findings. The report reveals that more institutions are integrating XR technology into their architectural education programs and that it has a significant impact on teacher effectiveness, student motivation, reflection and improvement, and teacher–student communication. The study suggests that XR technology will increasingly replace conventional teaching techniques in classrooms.

Keywords: virtual reality technology; augmented reality technology; extended reality technology; mixed reality technology; architecture education

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1. Introduction

Over the past three years, online communication has replaced face-to-face interaction as the primary means of conducting work and academic study. Although the COVID-19 pandemic is coming to an end, it served as a catalyst for technological advancement [1], and more schools are implementing XR technology for distance learning [2]. Traditional teaching methods like videos, pictures, and verbal descriptions typically fall short of expected teaching effectiveness due to communication gaps between teachers and students and external challenges [3–5]. XR technology makes it possible to visualize the material being taught, lowers barriers to communication, and enables students to practice and reflect repeatedly, greatly enhancing learning outcomes and motivation, and turning students into active knowledge seekers [6–8].

The main goal of this study is to examine instances of XR technology use in construction education over the last five years, evaluate the benefits and drawbacks, and identify future research directions. The major aim of this research is to investigate the impact of extended reality technology on architecture education and learning. Specifically, this study aims to determine the role of this technology in different areas of architecture education and whether it has led to a significant shift in the teaching and learning paradigm. The results of this study indicate that XR technology improves the delivery of architectural education, motivates active learning, fosters reflection and improvement, and improves communication. This paper offers theoretical underpinnings for pedagogical applications and suggestions for incorporating XR into varied forms of educational instruction.

The literature on XR technology in the construction industry is vast. Tom Kvan et al. [9] explore various realities to improve and better understand design activities in the design lifecycle. Márcia Regina de Freitas et al. [10] discuss the potential benefits of VR and AR from early planning to conceptual building design. Xiao Lia et al. [11] mention the use of VR and AR for targeted training and knowledge-based construction risk prevention. Juan Manuel Davila Delgado et al. [12] demonstrate how VR and AR can be applied throughout the lifecycle of a building. Po-Han Chen et al. [13] show through their research that MR has a significant positive impact on the expressiveness of architectural design. This paper will review three aspects of architectural design: architectural theory, architectural practice, and architectural design.

2. Methodology

This paper utilized a content analysis research strategy. Three main databases (Science Direct, Google Scholar, and Web of Science) were used to search the English literature published between January 2017 and December 2022 in order to gather relevant research information. The search process was conducted in two phases. The keywords "VR, virtual reality, AR, augmented reality, MR, mixed reality, extended reality, and architecture education, training, or pedagogy" were searched in the initial stage. This search round resulted in 93 papers. The papers were further filtered based on the title and abstract in the second stage. The selection criteria were as follows: (1) the title and abstract address the above keywords and the main content is specific to the undergraduate architectural design program; (2) the main content addresses the knowledge of architectural theory courses; (3) study of VR/AR/MR technologies in practical architecture courses; and (4) research on the relationship between VR/AR/MR and architectural education or the inspiration of technology application to architectural education. The selection process is shown in Figure 1.

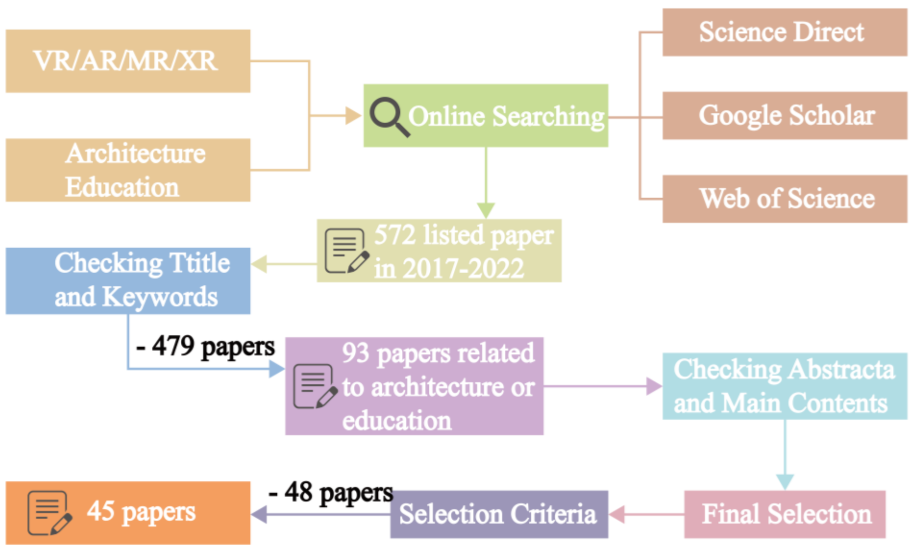

Figure 1. Flowchart of the review process.

3. Extended Reality Technologies

3.1. Concept

Rauschnabel et al. [14] provide the most recent conceptual interpretation of extended reality (XR), where X serves as a stand-in for any type of reality technology, including virtual reality (VR), augmented reality (AR), and mixed reality (MR). In this paper, we default to extended reality technologies such as VR, AR, and MR. Milgram's "reality–virtual continuum" theory [15] suggests that the degree of environment display realism corresponds to different technologies. The real environment and the virtual environment are located at opposite ends of the continuum, while augmented reality and augmented virtual reality, which are two distinct environments that do not overlap, are located in the middle. Concepts are defined as shown in Figure 2.

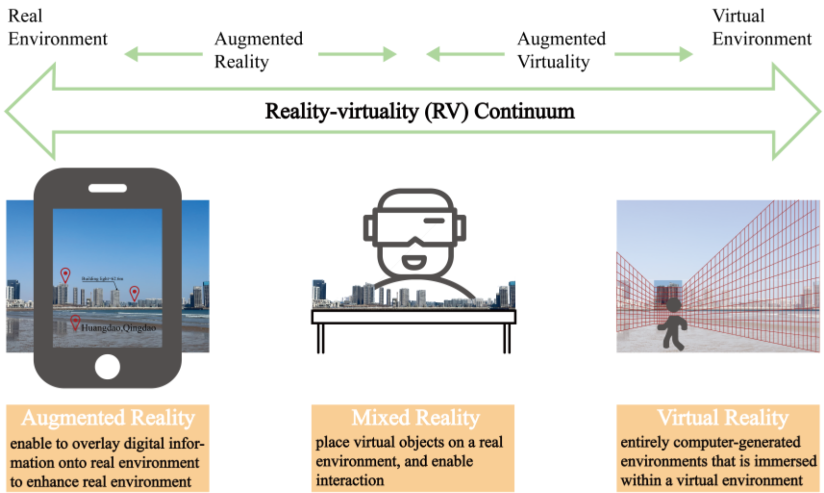

Figure 2. Concept identification.

Virtual reality (VR) is a simulation technology that creates a virtual space entirely by computer [16]. It utilizes computer technology to create multi-source information fusion, interactive 3D visual scenes, and physical behavior system simulation environments that immerse the user in the virtual environment through a head-mounted display (HMD) [17]. The system focuses on perception, user interface, backend software, and hardware to model and portray the scene in 3D using real-time computer graphics technology. VR technology is characterized by immersion, interaction, and imagination [18]. By utilizing virtual reality technology, it becomes feasible to import an architectural model at a 1:1 scale onto a display. This allows users to view the entire model through their glasses while wearing a head-mounted display (HMD). Additionally, users can even navigate inside the fully restored model environment using handle controls.

Augmented reality (AR) is a technology that overlays data and computer-generated images on models or spaces in the real environment [19] to enhance the user's perception of the surroundings. The system creates virtual models using technologies for human–computer interaction, optoelectronic displays, 3D real-time animation, computer graphics, and tracking, and then projects the models into the physical world [20]. Enhancements can be visualized with mobile devices, tablets, or head-mounted displays (HMDs). AR technology is characterized by real-time interaction between the user and the environment [21], and the blending of the physical and virtual worlds enhances human perception [22]. With augmented reality technology, users can visualize accurate spatial data, including measurements such as length, width, and height. This is achieved by overlaying the virtual data onto the real background, which serves as the base. Previously inaccessible in the real world, these data can now be seamlessly transmitted to the user's eyes through glasses, owing to this technology.

Mixed reality (MR) is a technology that allows virtual information to exist side by side with the real world and interact in real time [23], forming a new visual environment that contains both actual environmental elements and virtual objects. The system's realization is made possible through tracking, gesture recognition, 3D interaction, and language interface technologies. While augmented reality technology focuses on enhancing interactivity, mixed reality technology goes beyond simply overlaying virtual elements onto a real space. It allows users to interact with the model in various ways, not only through the visual display but also through the use of handles. This expanded functionality enables users to engage with the virtual building model in a more immersive and interactive manner.

As shown in Figure 3, the 3Rs (VR, AR, and MR) differ in terms of interaction features, with VR being one-way, AR being both one-way and two-way, and MR enabling two-way interaction between users and both virtual and physical spaces [17].

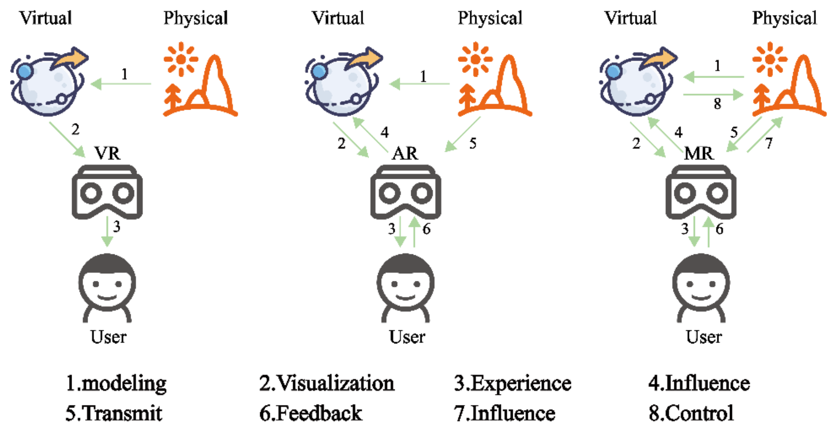

Figure 3. Technology interaction capability identification.

3.2. Development History

The concept of virtual reality was first introduced by Jaron Lanier [24]. The virtual environment is described as a 3D synthesis system that is interactive, immersive, and multi-sensory [25]. The earliest virtual reality system was developed by Ivan Sutherland [26]. The first head-mounted display (HMD) was created by Philco in 1961 [27], which marked a turning point in the history of virtual reality because it showed that it was no longer necessary to employ bulky apparatus to use VR; instead, it could be accomplished by a portable display. With the rise in popularity of the "metaverse" concept in recent years, VR has become more widely used across numerous industries [28,29].

The concept of augmented reality was first introduced by Tom Caudell and David Mizell who discussed the advantages of augmented reality as opposed to virtual reality [30]. The first AR interface was developed by Sutherland in the 1960s. The first use of AR was a training tool for airline and air force pilots in the 1990s [31].

The idea of mixed reality was first mentioned by Milgram in 1994. Early definitions of the notion were more basic; however, as technology advanced, the concept of MR became more advanced. The HoloLens gadget was released in 2016, causing MR to move from theoretical study to practical, mainstream use [32]. There are a number of other MR devices that can recognize vocal commands and user motions, such as Google Glass. However, it might be difficult to design this interaction style so that it responds in a satisfying way. Typically, for the devices to understand the gestures and spoken instructions, they must be executed and pronounced correctly, which can be challenging for regular users who have not received systematic training. Furthermore, only a small number of languages and gestures are supported. For instance, the Microsoft HoloLens, one of the most sophisticated MR systems, supports English and offers three recognized motions. Furthermore, HoloLens can provide a better viewport and free users' hands.

According to a survey, one of the top 10 strategic technologies for technology in 2018 was immersive technology (VR/AR/MR) [33]. Construction 4.0, which aims to combine the three industries of industrial production, information physical systems, and digital computing technologies—including BIM (Building Information Modeling), artificial intelligence, VR/AR, and cloud computing—has been defined by some academics in the current global context of Industry 4.0 [34–36]. As a part of Industry 4.0, Construction 4.0 represents a shift from traditional building methods to building automation. With the integration of XR technology, this change has also impacted the way building construction is taught, promoting self-directed learning. While modern technology offers numerous advantages, there are still challenges to address, such as cost and public perception.

3.3. Application Status

Architectural environment design using immersive virtual reality systems dates back to 1999, according to Dirk Donath et al. [37]. Since then, numerous studies have been conducted. In 2001, Dirk et al. [38] researched 3D design in a virtual setting. In 2006, Ross Tredinnick et al. [39] immersed virtual building concept design using SketchUp. In 2009, Aleksander Asanowicz et al. [40] investigated VR as a method for building spatial environments. In recent years, VR has been applied practically to architectural, landscape, and environmental planning. In 2013, Rolf Lakaemper et al. [41] advocated using VR to satisfy the needs of the construction sector as a visually oriented visual assistance. In 2015, M.E. Portman et al. [42] applied VR practically to architectural, landscape, and environmental planning. In 2017, Julie Milovanovic et al. [43] used a VR environment created using an HMD for a design course for second graders.

AR has also been widely applied in various fields. In 2009, Xiangyu Wang [44] proposed a solution for AR in terms of real-world modeling and technical constraints. In 2016, Süheyla Müge Halıcı et al. [45] researched the use of AR in collaborative design. In 2021, Shan Luob et al. [46] found that the use of augmented reality (AR) was significantly increasing in three areas: AR data exchange, AR human–computer interaction, and AR 3D whole-system training. In the same year, Fernando Moreu et al. studied the application of AR in civil infrastructure management and construction of buildings throughout their life cycle.

Since the 1990s, MR technology has been applied to interior design. In 2008, a fresh collaborative method for design evaluations was created using MR. In 2014, studies suggested that MR technology might be used in conjunction with other programs to visualize architectural ideas. In 2021, Po-Han Chen et al. looked into the use of MR to improve the effectiveness of architectural design expression.

As VR technology advances, the virtual environment it creates becomes more and more lifelike. However, customers also want to be able to perceive virtual objects in the actual environment, which led to the development of AR technology. The desire of consumers to engage more deeply with digital information led to the development of MR technology. However, the process of developing the 3Rs is slow. In addition to the construction industry, XR technology is widely used in a number of other sectors, including manufacturing [47], agriculture, animal husbandry and aquaculture [48], industry [49], the medical sector [50], and the entertainment sector [51]. In the future, XR technology is expected to find even wider applications in various sectors.

4. Traditional Architecture Education

4.1. The Significance of Modifying Conventional Teaching Techniques

The old system of education has numerous flaws, and as society has advanced, it has become crucial to alter the manner in which education is delivered. A comprehensive education for sustainable development has been attained through the creation of innovative teaching tools and educational philosophies. Kristin Børte et al. [52] discovered, however, that a lot of instruction still relies heavily on conventional methods and instructors and ignores the value of supportive infrastructure and collaborative development. Extensive reality technology can serve as a good substitute for instructional infrastructure, which is another factor that influences students' eagerness to learn and their eagerness to participate in class. Numerous academics have developed novel approaches to teaching and learning. For example, Torsten Masseck [53] used experiments to show the value of living laboratories as a cutting-edge infrastructure for higher education. Easy, a sustainable energy simulation tool, was utilized by Camille de Gaulmyn et al. [54] to test a novel approach to teaching and learning in a building program. Technology and tools should advance alongside teaching methods [55].

4.2. Traditional Architecture Learning Theory

Several theories, including experiential learning theory (ELT) [56,57], adaptive learning theory [58], behaviorist theory, social cognitive theory, information processing theory, constructivism, cognitive learning process theory [59], and learning style theory [60] have been used to explain architectural instruction, as shown in Table 1. The principles of experiential learning and cognitive learning processes are often applied in the teaching of architectural design.

Table 1. Learning theory.

Theory	Proposer	Time	Theory Content
Experiential learning theory	Kolb	1984	1. Concrete experience (CE), reflective observation (RO), abstract conceptualization (AC), and active experimentation (AE) are the four steps of the process of transforming experiential knowledge. 2. Four learning styles—convergent, divergent, assimilative, and adaptive—are distinguished among students.
Adaptive learning theory	Newland	1987	Investigating learning preferences, stereotypes, and cultural prejudices in light of Kolb's theory led to the identification of four learning preferences for teaching: general knowledge learning, dynamic learning, contemplative learning, and joyful learning.
Behaviorist theory	Watson	1916	Based on Pavlov's conditioning model, which explains learning from the standpoint of environmental events rather than processing behavior
Social cognitive theory	Bandura	1986	1. People can pick up new behaviors by seeing how others behave; learning does not require performing the new behaviors nor does learning require reinforcement. 2. After adopting personal standards, it gives the person the ability to function as a self-regulator. The gap between performance and the measure prompts a self-evaluative reaction, which affects subsequent behavior.
Information processing theory	Shuell	1986	A focus on how individuals interact with environmental events, how they learn new information, how they relate it to prior knowledge, how they store new information in memory, and how they retrieve it when necessary. Throughout the process, people are the information processors.
Constructivism	Hyslop-Margison and Strobel	2008	Constructivism is not a theory but an epistemology, a philosophical explanation of the nature of learning, and a method for students to build their own learning. It does not suggest the presence and ongoing discovery and testing of learning principles.
Cognitive learning process theory	VanLehn	1996	One learns from experts in a field of knowledge if they desire to learn more about it. Experts spend more time at the outset of a problem's analysis, have a larger domain knowledge, are better at grasping what they do not know, and solve problems more quickly and precisely. Although this method of learning necessitates a learner's long-term study and takes a lot of time, it produces valuable outcomes.
Learning style theory	FeldereSoloman	1991	The study of learning style preferences can assist in developing teaching strategies to enhance information acquisition by identifying learning styles using models like the MBTI and K-LSI and then providing learning guidance for various styles.

Experiential learning has been applied in various professional educational contexts, such as management, computer science, and education. Thomas Kvan et al. used comparative experiments to demonstrate that the basic design approach of architects is adaptive. Chinese architecture schools provide students with a wider range of learning styles and more opportunities for experimentation with theory due to the longer design courses and numerous opportunities for communication and peer learning.

4.3. Traditional Architecture Education Issues

Pedagogy was defined by Mortimer [61] in 1999 as "a conscious activity undertaken by one person to enhance the learning of another person". Educational technology makes rational use of technology to support and enhance learning [62]. Information technology and education are interdependent. The discipline of architectural education is based on ongoing involvement in architectural design and advancement, and spatial imagination is crucial to teaching. According to Wang T-J [63], students can become more imaginative through the examination and study of excellent design works. Imagination cannot be taught like rational thought. Traditional architectural design education often emphasizes teacher-centered learning, where the teacher transmits knowledge and the students passively accept it, relying on the depiction of two-dimensional drawings [64]. Rich spatial shapes are challenging to communicate verbally and visually alone [65]. Spatial imagination and spatial comprehension are the most challenging areas for modern students to master, and they are also the focus of traditional architecture education that has been searching for a breakthrough, as noted in numerous studies [66].

Architectural education has experimented with various methods, including computer modeling [67], hand models, and additional courses like color and construction to improve students' abilities and learning, but these strategies still involve teaching in 2D form. Students find it difficult to accurately experience and master the 3D spatial perception of architectural design because they cannot personally experience the 1:1 field space [68]. A critical ability for students to participate in practical projects after graduation is to mix information with design, which is lacking in contemporary architectural design education. One study identified five key issues with today's architecture education [69]: (1) design and theory do not go together; (2) lack of understanding of how color and scale feel in the real world; (3) lack of design reflection; (4) ineffective design process guidance; and (5) lack of opportunities for students to address real-world design issues.

The limitations of traditional architectural teaching methods can be overcome by incorporating extended reality technology (XR). XR technology allows for a 1:1 restoration experience, addressing challenges related to experiencing and perceiving architectural spaces. In the past decade, there has been a shift in education, with a focus on exploring new learning models suitable for architecture students [70]. The COVID-19 pandemic disrupted face-to-face teaching and learning, confining people to their homes. However, XR technology has bridged the gap by enabling remote communication and immersive experiences. The adoption of XR technology in education is rapidly accelerating, both domestically and internationally, facilitating flexible teaching and learning approaches.

5. Results

A total of 45 articles survived the second round of screening, and additional analysis was conducted to extract data such as title, author, date of publication, published journal, category, keywords, technical tools, research area, main research content, key findings, importance of the paper, and thesis or practical restrictions. It was found that the advent of XR technology is changing the teaching approach from "teacher-centered" to "student-centered". This paradigm shift indicates that an active teaching approach is starting to replace the conventional passive teaching strategy. Students will actively use the resources to conduct academic study rather than passively accepting the indoctrination of knowledge; this change will inspire students' enthusiasm and ambition to learn. A keyword co-occurrence analysis was performed on the papers, and the level of correlation between the chosen articles is depicted in Figure 4. VR and AR are currently the most popular applications, while MR is slowly generating new ones. Moreover, there is a robust correlation among the 3Rs, as evidenced by the thick connecting lines that link them. The research direction of this paper is supported by data from the education field, which is also a growing area of study. It is apparent that scholars are increasingly focusing on the field of education where the implementation of the 3Rs takes place. The articles are grouped into three categories based on the research topic: architectural design, architectural theory, and architectural practice. The grouping criteria are as follows: architectural design refers to articles created specifically for the purpose of design, such as those on designing architectural spaces, architectural expressions, architectural monoliths, etc.; architectural theory refers to courses that introduce theoretical knowledge, such as the technical theory of architecture, theory of building structures, history of architecture, etc.; and architectural practice refers to courses that teach technology-based practices, such as building construction practice courses and construction safety management practice courses. In order to apply XR to architectural design, an architectural student's model is typically imported into the device. From there, the user can walk into a space that they have designed and enjoy the amazing sensation of overlapping, interlacing, and dislocating space through practical experience. In addition, the user has the ability to instantly receive a fresh design area by altering the model whenever they see fit based on their personal experiences. When XR is used in architectural theory, users can enter the space to view the actual building, comprehend its structure, volume, and space, and make up for the drawbacks of the 2D photos' flat portrayal. This usually happens after importing the architectural model 1:1. An example of a forward teaching style is that when XR is used in architectural practice, it is typically possible to simulate the architectural practice activities beforehand. By practicing beforehand, users can become familiar with a wide range of scenarios that could arise in the real world and devise strategies for handling them when they do.

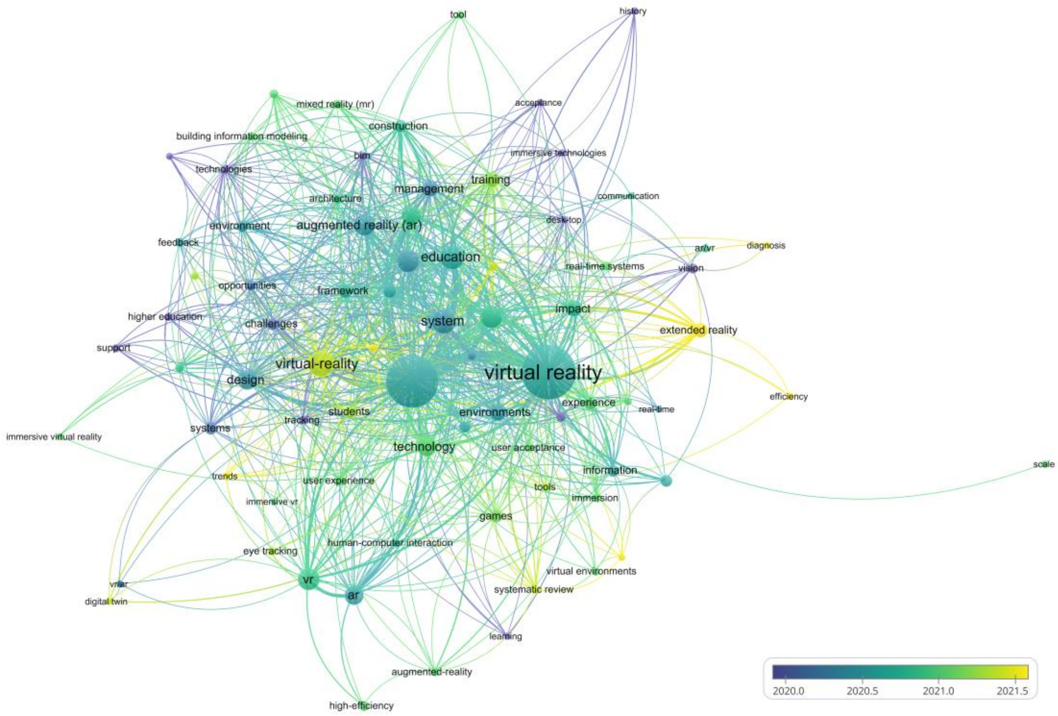

Figure 4. Network of keywords based on VOSviewer.

5.1. Paper Publication Time

As shown in Figure 5, the increasing trend in the literature on the use of VR, AR, and MR technologies in architecture from 2017 to 2020 showed no discernible growth in 2018 or 2019 and a more discernible increase in 2020. Furthermore, XR technology in architecture education has seen a significant increase between 2019 and 2022, especially since the COVID-19 pandemic (2019–2022) forced most people to work and study from home, replacing face-to-face communication with online chat tools like ZOOM, Hangouts, Skype, Tencent Meetings, etc. [71]. Architecture is a profession that demands both communication and experience. However, online chat tools can only offer users a two-dimensional graphic representation of a building plan, leaving the user to rely on their imagination to understand spatial relationships, structural elements, materials, and other building-related issues. Unfortunately, users cannot physically interact with the design or experience it in three dimensions. Instruction researchers are also investigating the potential for XR technology to be used in architectural design instruction as more and more aspects of architecture are effectively enhanced by it [72,73].

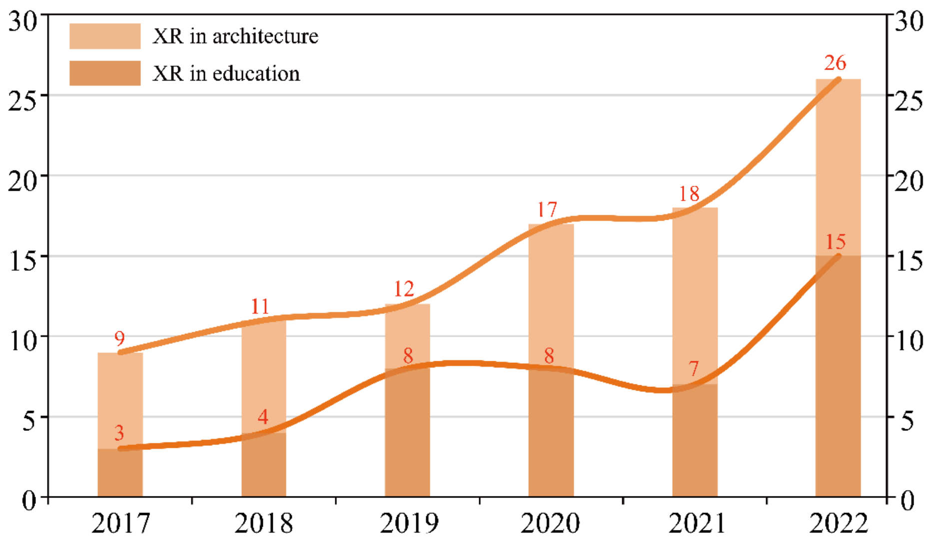

Figure 5. Frequency of literature on the use of XR technology in architecture and education after 2017.

5.2. Country of Publication

As shown in Figure 6, the quantity of articles published in various nations reflects the significance of XR technology in that nation, specifically examining how XR technology is being used in building and education. The United States has the most research papers from the past five years, accounting for around 22.6% of the total. With a combined 35.5% of the total, China is in second place behind the United States, followed by the United Kingdom and Australia. Technology has been developed in other nations as a result of research conducted in advanced nations, and the future trend for XR in architecture and architectural education is a result of research emerging in each nation.

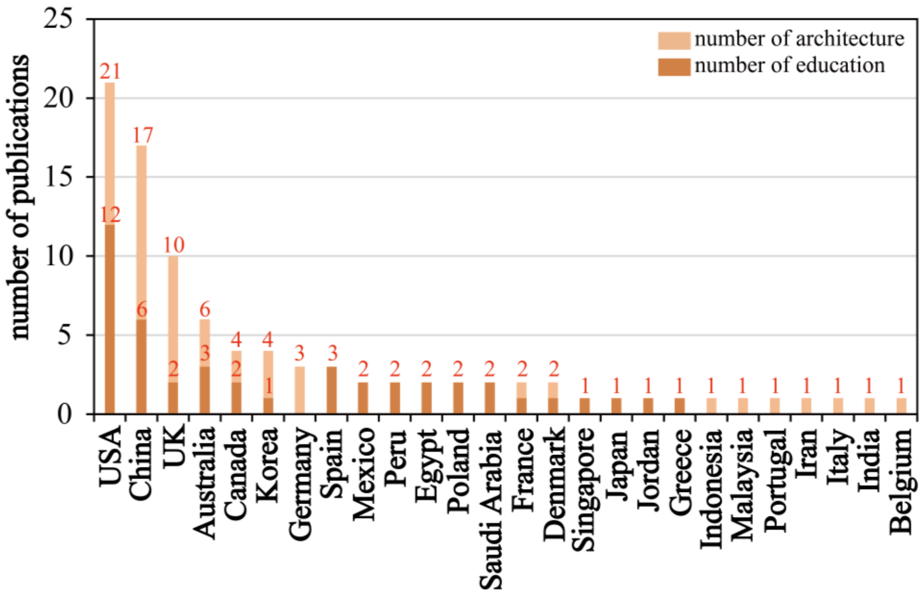

Figure 6. Frequency of literature on the use of XR technology in architecture and architecture education based on country.

5.3. Thesis Analysis

According to the classification criteria, the papers were categorized and examined. Table 2 lists some representative papers that qualified for selection. The primary focus of this literature is on how XR technology can be used to improve students' architectural learning by creating new platforms, displacing antiquated teaching methods, and sharpening spatial skills.

Table 2. Excerpts from representative literature.

No.	Technology	Author	Research Content	Research Results
1	AR	URBAN H. et al.	Creation of a new augmented reality teaching platform for classroom assessment.	The program is well liked and might be applied to education in the future.
2	VR/AR	MOREAU G. et al.	Proposes VR alternative system CORAULIS to support teaching and learning.	Although the technique is successful in raising design quality, it does not support building size design.
3	XR	HUI V. et al.	Examines the benefits of XR for the performance of architecture teaching.	Examines the various meanings and applications of XR in architectural education.
4	VR [74]	RYHERD E. et al.	Investigates the pedagogical use of VADER's learning modules.	Module improves first graders' self-efficacy.
5	VR [75]	VELAORA M. et al.	Investigates how the use of VR in education affects the capacity for architectural design.	Realizing in a virtual reality environment the experience of dynamic spatial ideas.
6	VR/AR/MR [76]	CABERO-ALMENARA J. et al.	Examines the potential use of VR, AR, and MR in higher education.	Multiple instructional modes can be applied to XR technology.
7	VR/MR [77]	WU W. et al.	Investigates VR/MR Interventions for Education and Workforce Development in the Construction Industry.	The development of expertise and the acquisition of tacit knowledge can be facilitated using VR/MR.
8	VR [78]	SHINOZAKI M. et al.	Uses research review techniques and eco-psychological ideas.	Establishes a VR-based cognitive design assessment process for architectural design.
9	VR/AR [79]	AYER S. K. et al.	Uses technology to teach by simulating events that one would encounter in one's career.	Supports VR/AR in AEC education to encourage the development of tacit knowledge.
10	AR [80]	KIM J. et al.	Uses augmented reality in the classroom and for lab work.	AR enhances students' spatial abilities.
11	VR [81]	CARDONA-REYES H. et al.	Develops innovative interactive teaching strategies based on virtual reality settings.	Proposes a process for creating virtual learning environments.

5.3.1. Architectural Design

Architectural Space Design

The creation of architectural space through design requires mature thought [82]. Developing the ability to design architectural spaces is one of the most important skills for architects to acquire during their careers [83], and it is the result of several interconnected elements [84,85]. Nora Argelia Aguilera González [86] introduced interactive design in a descriptive geometry course to help her students better comprehend space, master the principles of spatial projection, and hone their spatial skills. It was found that VR/AR can more effectively teach pictorial geometry and evaluate different student characteristics, enhancing their learning experience. However, enhancing architectural design education by relying solely on VR/AR is not ideal. Integrating technology with conventional teaching methods and finding ways for professors to interact with students can help students learn more effectively. Jorge Martin-Gutierrez et al. [87] asked senior students to assess their visual–spatial perception by acquiring a sense of space in a virtual environment, while first-year architecture students were asked to sketch architectural spaces in physical size to improve their spatial skills. The experiment included six building blocks, which were categorized into three difficulty levels for analysis and observation once the space had been drawn. In the second portion of the experiment, students virtually wandered each architectural room to note perceptions and sensations, employing the same six architectural spaces but with the inclusion of various materials, textures, colors, and natural sunlight. The study found that training considerably enhanced spatial orientation, rotation, and vision. Additionally, it was discovered that immersive virtual reality environments could convey the intended emotions of the designer. However, for tactile simulation of materials, VR technology is currently not advanced enough and requires further development.

Instructive experiments on architectural space design have also made use of controlled experiments. Jeffrey Kim et al. sought to engage students, enhance their spatial skills, and reduce their cognitive load by introducing augmented reality technology, as they found that students prefer active participation in the classroom to passive lectures and textbooks. The study involved 254 randomly assigned students who participated in a post-observation experiment on the visualization lecture, a NASA TLX, and a post hoc survey regarding the intervention. The findings indicated that while AR enhanced assessment scores, it had no effect on students' acquisition of spatial abilities, but it did increase their motivation to study. Mohamed Darwish et al. [88] conducted controlled investigations using pre- and post-project examinations of spatial aptitude. The study compared two groups of architecture department students at Ain Shams University and found no discernible variation in spatial competence levels between them. The experimental group used VR for 3D sketching and modeling and AR as an assessment tool for self-feedback throughout a three-week entrance door design project, while the control group employed conventional tools. The findings revealed an improvement in the group employing XR technology's overall level of spatial ability, suggesting that XR technology may enhance architectural design education by strengthening students' spatial skills and lowering their cognitive load. However, learning the technology itself might be challenging and requires improvement for efficient tool learning.

Additionally, new systems have been created for use in the architectural space design process. Ziad Ashour et al. [89] developed a new educational platform called BIMxAR (BIM software combined with AR) that utilizes a physical–virtual overlay feature. The study first discussed the system's performance and technical features before conducting a three-stage experiment in a pilot user study to gauge participants' learning gains and mental cognitive load while using the system. The study found that the system model offers an accurate solution, with only minor inaccuracies that can be applied to AEC AR applications. Additionally, the system provides an innovative augmented reality representation that allows users to interact with it and access BIM metadata. The system enables a sliced perspective of the area behind the actual objects, helping users better understand spatial relationships in the building. The approach reduces the additional cognitive strain placed on students and enhances their learning. With its integrated learning capabilities and visuals, BIMxAR is a straightforward and practical learning solution for construction education. Hadas Sopher et al. [90] conducted a case study at the Israel Institute of Technology where participants alternated between immersive and non-immersive media each week to evaluate a structure. The study gathered each participant's ideas through the FOs network to represent their perspectives on the design space. The results suggest that IVR (immersive VR) has the potential to increase student interest in design criticism while also reducing carbon emissions, providing evidence for sustainable development in teaching. However, to improve the use of IVR as a teaching tool, the study needs to be more specific in terms of how IVR can improve design criticism communication.

Traditional architectural design prioritizes form and function [91,92]. Research academics began to recognize the significance of technology for teaching architectural design after the COVID-19 pandemic outbreak [93,94]. According to C. Lorenzo et al. [95], immersive technologies are a new tool that will be necessary for future architectural careers and should be learned during undergraduate years. At Madrid's CEU University Digital Lab, students are taught to use VR and AR to interpret architectural projects, analyze inaccessible buildings in depth, visualize and analyze architectural design projects, and allow for iterative trial and error and summary reflection during the design process. The study found that the use of technology significantly affects the learning outcomes of students. Chun-Heng Lin et al. [96] developed a multi-user system integration framework integrating 3D modeling, process modeling, and VR platforms based on procedural modeling and immersive VR to assist architectural design education based on design scenario development. However, a research limitation is the potential contradiction between the design parameters built in the process modeling platform and the direct object manipulation provided in the virtual reality environment, which necessitates the creation of a solution.

Numerous other academics have used a variety of different approaches for their study of teaching and learning. Fauzan Alfi Agirachman et al. examined the application of the VRDR system in a visibility-based design review process in a third-year architectural design studio course in conjunction with eco-psychological ideas. The study found that a virtual reality, which is based on a cognitive-based design review approach, can aid students in developing their design work. However, the study was only conducted in an educational setting. Further research and modification are needed to determine whether cognitive-based design review methodologies are appropriate for use by professional architects. Julie Milovanovic et al. examined specific VR/AR research projects to support collaborative design in teaching and learning environments and enhance student design quality. The study identified the advantages and disadvantages of VR/AR devices and suggested an alternative system, CORAULIS, that incorporates VR and SAR technologies. CORAULIS offers multiple augmented viewpoints of design objects as well as seamless navigation and interaction in all representation spaces. However, the study did not assess the impact of utilizing the CORAULIS application, which is a drawback. Tane Moleta compared real-time virtual engines (RTVEs) with several well-known frameworks for architectural design education to investigate the level to which RTVEs are used in architectural design studios. The study suggests developing the use of technology in architectural design from the viewpoint of the students. However, a limitation of the study is its inability to thoroughly examine students' experiences using RTVEs in architectural design studios.

While useful, immersive interaction design for architecture has many drawbacks. Hugo C et al. [97] conducted a study in which first-year architectural design students developed recreational buildings using vertical elements, horizontal elements, light, color, degree of closure, and materials. The effectiveness of IVR in the four design phases was evaluated through a questionnaire. The findings suggest that IVR has several benefits, including the ability to perceive spatial design at a real scale, create visualizations in a virtual space, experiment and interact with the space from a first-person perspective inside the building, and experiment with various forms of design in the virtual environment. The study also found that the short length of IVR use and the challenge of adopting it in remote and underdeveloped locations were significant challenges for teachers.

Numerous academics have studied how to acquire and learn implicit knowledge. Justin F. Hartless et al. examined the use of VR/AR to simulate scenarios that might occur in students' careers by asking students to evaluate architectural designs and make decisions on how to adapt them to serve VR/AR wheelchair users. This inspired students to utilize implicit knowledge. The findings demonstrated that both VR and AR simulations allowed wheelchair users to complete the assignment, and comments indicating tacit knowledge eventually came to light. However, students preferred the VR experience. The experiment provides empirical evidence that the use and development of tacit knowledge helpful to AEC decision making is encouraged by VR/AR. Wei Wu et al. suggested a similar VR/MR technology to help with the acquisition of implicit knowledge and the development of expertise by simulating a small house accessibility design assessment and investigating the potential technological interventions in construction education and workforce development to close the current skills gap between novices and specialists. The study found evidence to support VR/MR's ability to close the experience gap and help with college students' expertise.

Urban Design

A unique type of architectural design known as "urban design" takes the structure's surroundings into account [98]. David Fonseca et al. developed virtual games for teaching architecture and urban design. Examples of educational technology include a PBL-based teaching model, enhancements to the virtual navigation system based on data from earlier user studies, and hybrid research of user perception enhancement based on both educational and professional use. The study found that teaching tactics can be chosen with the student's adaptation and area of competence after identifying the limitations of the system and the essential distinctions and requirements of the user profile functions. Workflow efficiency and building project sustainability are both enhanced by technology. The effect of age and gender has to be evaluated in the future. Maria Velaora et al. combined a self-learning educational experience based on a digital reality model with methodology and design evaluation to show the effectiveness of urban design solutions for improving architectural design abilities. They combined play space with architecture. The study found that urban virtual environments are free from static nature by dematerializing and replicating the location coordinates and geographic restrictions of the redesigned elements. Additionally, in a virtual reality setting, dynamic spatial ideas can be observed and evaluated.

Architectural Expression

Architectural expression is a form of expression of architectural design and concept [99]. Tatiana Estrina et al. developed a collection of case studies on pedagogy and curriculum in the construction industry. Using extended reality cases that are taught in lecture courses, influenced by architectural design, and learned experientially, we can discuss various immersive technologies in various environments. This enables us to trace the evolution of immersive media across diverse instances of architectural expression, from solely interactive technology to mixed reality and interactive. The students in the case studies all received high marks for their architecture course work and evaluations.

5.3.2. Architectural Theory

Architectural History Theory

Architectural history is the study of the positioning of architectural works in history [100]. It is frequently important to expand on the study of architectural history to learn architectural design from earlier works. Agnieszka Gębczyńska-Janowicz [101] asserted that virtual buildings created with VR can replace actual ones. Virtual reality can assist students in learning new abilities for future careers by fusing the past and present and reconstructing nonexistent architecture in classes on monument conservation or designing monumental architecture. Chiu-Shui Chan et al. [102] created a virtual pantheon scenario using images, sketches, and textures to provide students with a rich architectural learning experience. The IVR environment combined high-resolution photographs and audio narration of historical items, enabling students to precisely measure, recognize, and understand the 3D characteristics, size, and scale of the virtual space. The study found that VR technology facilitated a better comprehension of the dimensions and scale of space, and the recreation of historical facts in the IVR environment enhanced students' understanding of the past. Similarly, Eliyahu Keller et al. [103] analyzed the joint archaeological Lifta of the MIT Department of Architecture and Ben-Gurion University, recognizing the limitations of VR in creating objects and time. The study highlights the importance of exploring how students learn and using progressive educational methods to enhance learning outcomes. Mohammed A. Bahobail et al. [104] incorporated architectural history into virtual technology and turned real-world projects into three-dimensional movies to substitute conventional lectures. The study found that VR technology has the potential to improve architecture education, but further research is needed, along with financial support from schools. One of the study's limitations is its narrow focus on teaching architecture courses at King Saud University's Faculty of Architecture and Planning, highlighting the need for a more comprehensive pedagogical study.

Architectural Structure Theory

Building structures are crucial to the form, style, and sustainability of architecture [105]. Building Structure enhances construction design [106]. Yelda Turkan et al. introduced an AR program available for iPads and used interactive 3D visualization technology to teach a structural analysis course for civil and architectural engineering students at Iowa State University. They conducted pre-tests, post-tests, and surveys to assess the accuracy of the program. The study found that traditional teaching methods overemphasize the analysis of individual structural members and fall short of providing a holistic approach to analyzing complex structures with numerous interrelated elements. AR technology fills this gap, benefits students' structural learning, and is a tool that students prefer. The study's shortcoming is that, even after quantitative analysis of the data, not enough students made up the sample size, which prevented the results from being statistically significant.

Architectural Technology Theory

Architectural technology, which is based on the philosophy of knowledge of science, engineering, and technology [107], is the art of building construction [108]. WOOD, C.F. et al. [109] created a questionnaire to gather information on the indicators of virtual reality approaches in the UK and explain how to effectively set up the system in the classroom. The study highlights the benefits of virtual reality for students and clarifies any software concerns, demonstrating that students understand the need for beneficial aspects of technology that they would encounter in their profession. The findings offer a solid theoretical foundation for the introduction of virtual reality technology in education, emphasizing the need for teachers to change the way they educate to enable pupils to master technology at a young age. In another study by Julio Cabero-Almenara et al. at the University of Seville Chapel, 44 students from a basic construction mathematics course participated, and their acceptance of MR technology was consistently high. The study suggests that MR technology can be adopted in various teaching modes, including face-to-face and non-face-to-face teaching, highlighting the need to support university instructors who advocate for MR in the classroom.

5.3.3. Architectural Practice

Safety Management Practice

As construction is a high-risk industry, safety management is a top concern for construction organizations, making it crucial for students to understand safety management [110]. To create an authentic learning framework, Fan Yang et al. [111] used nine authentic learning principles to design instructional materials and develop an immersive VR/MR simulation of an actual tunnel collapse occurrence. The study found that while VR/MR simulations are more motivating than video courses, they can also be uncomfortable and disrupt learning, and the virtual environment is not entirely realistic, making it difficult for students to gauge the simulation's accuracy. This highlights a need for future improvement in this area. According to research, utilizing both 3D and 2D media can result in the most efficient authentic learning environment.

Building Construction Practice

Building construction and construction industries are constantly refining work methods to produce the finest possible construction results [112–114]. As more construction units are using extended reality technology [115,116], it is essential to include technology in construction courses at the undergraduate level. Samad M. E. Sepasgozar [117] discusses the use of digital twins and mixed reality in the construction industry to extend the body of knowledge on building construction, showcase the capabilities of virtual technology for education, and provide educators with a set of simple to complex technological tools. The study implemented digital teaching of tunnel excavators, allowing students to learn the procedure of operating an excavator to plan excavations at a construction site. Morgan Mcarthur [118] engaged students in an architectural engineering teaching module using the VADER testing platform. The VADER was utilized as an add-on to enhance the curriculum being taught, and the study found that VADER improves students' comprehension of disciplines linked to architectural design and construction while addressing the challenges and ambiguities associated with selecting interests and career aspirations. Ece Erdogmus et al. invited 89 students to participate in the VADERs module, which allowed them to experience a virtual rotation of architectural engineering and its sub-disciplines, solve computational tasks, and investigate the effects of design decisions on the sub-disciplines. The study found that students were more engaged and conscious of diversity, more confident in their subject knowledge, and very interested in and supportive of the use of technology. Future empirical studies are needed to assess each module utilizing more participant-friendly virtual apps and the methods described in the text.

Hajirasouli A. et al. analyzed the most cutting-edge AR technology and integrated it into teaching and learning methods for building construction to give students a more practical and realistic learning experience. The study found that using augmented reality to educate building processes enhances students' overall performance and capacity for both short- and long-term learning, as well as their knowledge of complicated assembly processes. The utilization of the students' courses as experimental research constituted the experimental constraint, but the cycle was insufficiently long. Longer cycles should be used in future experimental experiments to show that AR applications can be made to be sustainable for both the short- and long-term.

Many scholars have reviewed XR's applications and directions for development in order to confirm that the technology is currently being used in building construction practice. Peng Wang et al. [119] analyzed the development and future directions of virtual reality technologies and applications, from desktop-based VR to immersive VR to 3D game-based VR and BIM-based VR, in the CEET field. The study found that education has benefited from the shift from teacher-centered to student-centered learning and the trend toward establishing integrated teaching and learning. However, the research is limited to the technology in the CEET field and has not been tested in emerging engineering education models, nor has the applicability of the technology to other educational tools been tested. Yi Tan et al. [120] reviewed the current state, constraints, difficulties, and potential directions of VR/AR educational applications in the architectural, engineering, and construction sectors. The study separated educational applications into four categories: "immersive AR/VR learning", "AR/VR structural analysis", "visual aid design tools", and "AR/VR-based teaching aids", and educational training into two categories: "AR/VR virtual operation guide" and "safety training". The findings demonstrated that VR/AR provides the AEC sector with the chance to change education and enhance current teaching methodologies in a more diverse educational environment.

Reviews of the state of AR applications today have been compiled by a number of academics. Pei-Huang Diao et al. [121] reviewed the use of AR in construction engineering education courses and proposed that AR courses be preferred over those with objective grading criteria to examine students' learning outcomes, thereby improving classroom quality. The study examined fundamental knowledge, application areas, development tools, system types, teaching devices, teaching methods, and learning strategies. However, the application of research methodologies, learning strategies, and teaching techniques, as well as the choice of equipment and type of AR system, continue to provide challenges. Aso Hajirasouli et al. proposed the usefulness of AR in the educational environment of building construction using qualitative methodologies and thematic data analysis. The study found that while little research had been conducted on other skills, educational research in the field of architecture had largely concentrated on performance, communication, and spatial skills. However, there is a lack of appropriate pedagogical approaches to applying technology to architecture and specialized training in technology. Nonetheless, the introduction of technology has led to more sustained learning, improved learning experiences, and enhanced learning in both the short and long terms, according to educational research in the field of architecture.

Additionally, certain scholars have invented new teaching paradigms and expanded upon existing educational platforms. Harald Urban et al. created a new "AR-enabled teaching" platform to test the usefulness of the AR Editor and AR Viewer applications in building construction and engineering classes. The study found that the AR editor can be used in the classroom to help students and teachers build AR teaching situations without having any programming experience. Students expressed satisfaction with the app and a desire to continue using the technology in the future. However, there is a need to further expand the common 3D format in the future because the "AR-supported teaching platform" can only be used in the IFC file discipline at this time. In the framework of a sports design competition, Karan R. Patil et al. [122] presented technology using PBL as a new teaching methodology. PBL does not demand investment in projects, but rather leverages real-world projects to conceptually frame the learning process, providing students with hands-on building design and construction experience during the competition. The study found that projects incorporating actual design and construction experience can help students learn certain skills that help them develop broad tacit and explicit knowledge.

A number of academics and researchers have opened up their campuses to students so they might participate in practical construction learning. Fopefoluwa Bademosi et al. [123] assessed undergraduate students in the University of Florida's lower and middle education buildings in randomized groups. The study combined AR and visualization layers, simulating exterior masonry systems, roofing, and steel assembly system environments based on BIM model elements and diagrams overlaid on real-time live video, and transforming the site into a virtual scene introduced into the teaching classroom for interactive student experience. Pre-testing and post-learning tests were used to reinforce key technological and buildability concepts. When compared with modeling using AR alone, it was found that BIM's robust and comprehensive database makes it possible for AR to obtain model information for educational buildings more quickly and precisely, which significantly reduces labor time. The findings demonstrated that students who had taken the AR course were better able to recognize components of steel, masonry, and roofing structures, qualifying them for future employment. Ahmad K. Bashabsheh et al. employed a questionnaire research and software test to simulate a building construction course and chose consulting office modeling with Jordan University of Science and Technology construction students as their experimental subjects. The study found that students learn more while utilizing VR technology, develop tri-axial competences more effectively than when receiving traditional education, and find technology use to be more enjoyable.

6. Discussion

According to studies, XR technology used in architectural instruction is a current trend [124], especially in an era where VR/AR predominates and MR is still in the research phase. XR technology application advantages are shown in Figure 7.

6.1. Advantages of XR Applications

One of the main advantages of virtual reality (VR) in education is its ability to provide an immersive experience that replicates reality. By entering a virtual environment, students can explore and analyze various design elements from a first-person perspective, which can enhance their spatial cognitive abilities. Additionally, visualization in VR can help students understand complex problems and foster their learning efficacy through frequent manipulation and repetition [125]. The immersive experience of VR can also increase students' motivation and engagement in learning.

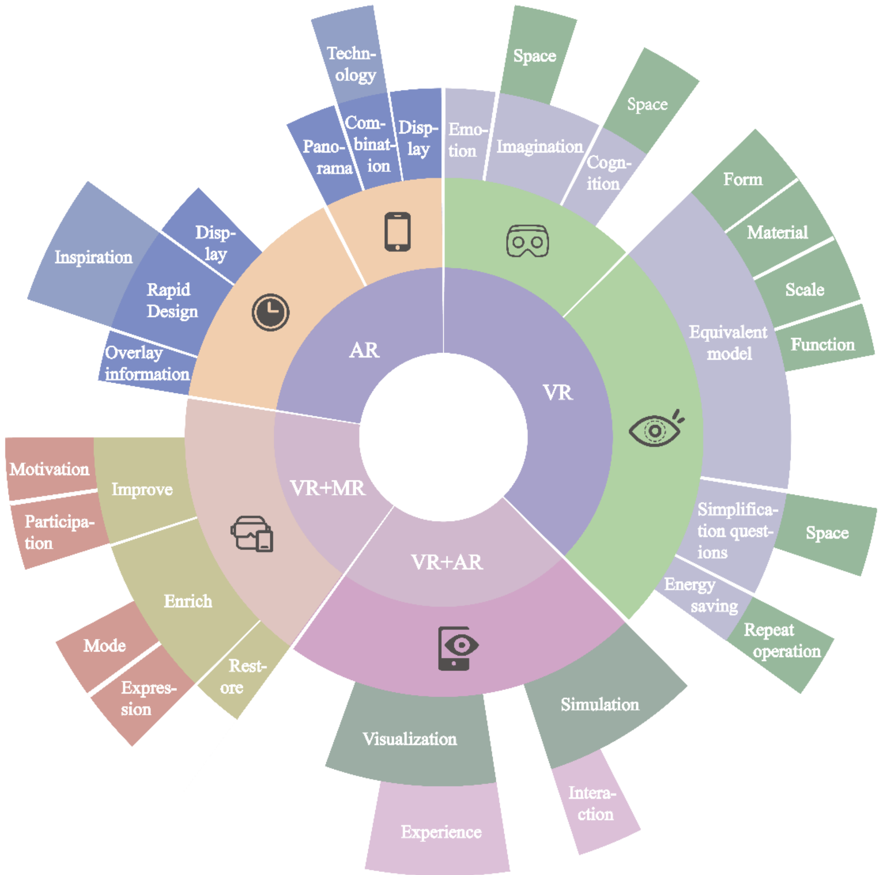

Figure 7. XR technology application advantages.

On the other hand, augmented reality (AR) offers the benefits of convenience and real-time operation. With AR, students can overlay digital information on reality in real time, allowing for quick design iterations, ongoing improvement, and immediate information distribution. AR devices are also easy to use with mobile devices and provide a panoramic view. With AR technology, students no longer have to rely on their spatial imagination to fantasize about data and information when utilizing them. It also helps to lessen the cognitive burden on pupils and compensate for the challenges posed by limited ability.

The use of VR and AR technologies in education has revolutionized the traditional teaching model by providing a multisensory learning experience that outperforms conventional two-dimensional forms of training. By combining VR and mixed reality (MR) technologies, students' learning preferences and modes of expression are enhanced, and teachers' modes of instruction are elevated, leading to improved learning outcomes.

In architectural design education, the use of XR technology has brought about significant changes. The traditional "teacher-centered" teaching model has been replaced with a "student-centered" approach, where students can learn independently and shift from being passive to active learners. XR technology has also bridged the communication gap between teachers and students [126] by visualizing and enabling real-time operation and modifications, restoring the 1:1 design space for students, and promoting interaction and communication. Moreover, XR technology reduces teaching costs by allowing students to iteratively revise their designs in real time, reducing the need for physical models. The creation of a virtual environment also permits repeated usage by numerous sessions of students without the limitations of regional restrictions [127], resulting in significant time and cost savings.

6.2. Limitations and Challenges of XR Applications

While using XR technology has many benefits, there are also some drawbacks and difficulties that need to be considered. Regarding the technology itself, there are technical limitations. Although VR technology has made significant advancements, users still struggle to experience the same level of touch sensitivity in the virtual environment as they would in the real world. When the technology is first introduced to educators, it might be challenging to quickly become up to speed and put it to use due to a lack of systematic technical training for using it and the expertise required to create virtual environments quickly. Adapting existing educational materials for usage in XR environments can also be time consuming and require extensive training. Users should be aware that wearing head-mounted displays for extended periods of time can cause vertigo. Students who wear displays also find it challenging to communicate with teachers outside of the classroom for demonstrations, and teachers find it challenging to assess students' states in the virtual environment. These issues will impact the classroom process and will need to be resolved in the future when XR technology is applied to teaching.

6.3. Inspiration

While considering the application of extended reality technology, practitioners will select a scene based on the benefits and drawbacks of the technology. For instance, the use of virtual reality technology in VR scenes allows buyers to view the house before they commit to renovating it; many businesspeople also directly utilize augmented and virtual reality technology for the tourism industry. When tourists are traveling, they can use augmented reality technology to view historical scenes, introduce themselves to the locals, and more. If they are feeling particularly tired, tourists can use a virtual device to virtually visit the next attraction, which allows them to satiate their curiosity without physically travelling to the site. These are only a few of the numerous uses for extended reality technologies, which inspire educators even more. Since different talented students require different amounts of time and energy to cultivate a spatial sense of the time and results obtained, there is variation in the degree of difficulty associated with teaching architectural spatial design. However, immersive three-dimensional spaces can be a good way to address students' inadequate spatial imagination by allowing them to enter the virtual space and experience it firsthand. Simultaneously, historical sites that many people cannot see in person can be restored through technology, allowing students to visit and learn from them. Extended reality technology can also help reduce the cost and time spent on teaching since it lets students make changes to their own designs repeatedly, shows real-time results of those changes, eliminates the need for students to redo models, allows for the drawing of plans and other materials, and is generally a very efficient way for both teachers and students to consume less teaching resources. However, the price of buying it and the technical support for using it should be considered before utilizing extended reality. Thus, obtaining financial support from the school and technical training is the first step toward receiving technical support at the start of the teaching session. Further advancements in extended reality technology are still needed; the technology is far from flawless.

7. Conclusions

XR technologies are increasingly being utilized in architecture education due to technological advancements. This article categorized and evaluated the applications of VR/AR/MR in architectural education over the last five years and found that XR technology can be used as a teaching tool in "architectural design", "architectural theory", and "architectural practice". The following findings are presented in the paper: (1) VR/AR/MR has become increasingly adept at satisfying user demands, and the technology is developing steadily; (2) the application of XR technology can boost professional skill development, raise academic achievement, and improve teacher–student communication; (3) the use of XR technology in architectural design education can minimize instructional time, lessen the waste of handcrafted models, and enable users to modify their own designs at any moment;

(4) the use of XR technology in architectural theory can address heritage structures and aid students in comprehending the features and structure of damaged buildings; (5) the use of XR technology in architectural practice can replicate conditions that may arise in the practice beforehand, allowing users to avoid or promptly identify solutions for unforeseen situations in real practice; and (6) a thorough analysis of the use of XR technology in architectural space design is absent from this research. Future studies should concentrate on the application of XR technology in architectural space design. Overall, this paper serves as a guide for the adoption of XR technology in architectural education.

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