Integration of AI and XR in Optimizing Human-Centered Architectural Spaces: A Scoping Review

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Abstract:- Background. With the rapid advancement of technology in architectural design, the integration of Artificial Intelligence (AI) and Extended Reality (XR) presents a transformative approach to optimizing architectural spaces. This scoping review aims to synthesize current research on the integration of AI and XR technologies in architectural design, with a specific focus on human-centered design principles.

Methods. An extensive scoping review was conducted, adhering to the PRISMA-ScR guidelines. A total of 1159 records were initially identified from various academic databases, leading to the inclusion of 16 highly relevant studies after a rigorous screening and selection process.

Results. The review revealed significant advancements in AI-driven design tools and XR applications in architecture. Key themes identified include the automation and personalization of design processes through AI, the enhancement of user interaction and experience with XR, and the integration of human-centered design principles. However, a notable gap was identified in comprehensive research focusing on the optimization of existing architectural spaces using an integrated AI and XR approach.

Discussion. The findings indicate a promising trajectory of AI and XR technologies in revolutionizing architectural design, highlighting their potential to create more efficient, personalized, and emotionally resonant spaces. The review also underscores the need for future research to explore comprehensive methodologies that leverage AI and XR for the evaluation and enhancement of existing architectural spaces, emphasizing human-centered design.

Conclusion. This scoping review provides valuable insights into the current state of AI and XR integration in architectural design. It underscores the transformative potential of these technologies in fostering innovative, user-centric design approaches, while also identifying critical areas for further research. The integration of AI and XR technologies in architecture promises a new era of design, characterized by enhanced user experience, sustainability, and adaptability to human needs.

***Keywords**:* Artificial Intelligence (AI), Extended Reality (XR), Human-Centered Design, Architectural Optimization, Spatial Analysis.

1. Introduction

1.1 Background and Rationale

In the evolving realm of architectural design, the emphasis on human-centric approaches has gained significant traction, recognizing that architectural spaces are more than mere physical constructs. These spaces serve as vital influencers of human behavior, well-being, and overall experience [1], [2], [3], [4]. When designed with a profound understanding of human psychology and needs, architectural environments can greatly enhance comfort, productivity, and overall quality of life [5]. Traditional methods for evaluating and optimizing architectural spaces, though foundational, often fail to capture the dynamic intricacies of human interaction and response [6].

These conventional approaches, while valuable, can be time-consuming, subjective, and susceptible to inherent biases, thereby limiting their scope and adaptability [7]. In contrast, the digital age introduces promising potentials with Artificial Intelligence (AI) and Extended Reality (XR) — encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These cutting-edge technologies offer faster, more accurate, and comprehensive evaluations, significantly reducing biases [8]. AI and XR, through data-driven insights and immersive simulations, ensure objective evaluations, democratizing design by providing quality design services accessible to a broader audience, regardless of location. This forward-thinking perspective has the potential to reshape the dynamics of the design industry, ensuring that spaces meet diverse needs without discrimination. The immersive nature of XR further narrows the gap between design conception and the lived reality, enhancing the user's experience and understanding [9], [10]. However, while the individual impacts of AI and XR in architecture have been independently explored, a comprehensive understanding of their integrated potential in creating human-centered architectural spaces remains largely uncharted. This research aims to explore the integration of AI and XR within architectural design, with a specific focus on enhancing human-centered spaces. The study conducts a scoping review to meticulously uncover the interconnected methods of applying AI and XR in the domain of human-centered architectural environments. The significance of this endeavor extends beyond academic contributions, holding the potential to shape future architectural practices. By providing architects, designers, and technologists with insights into the symbiotic relationship between AI, XR, and human-centered design, this research aspires to pave the way for spaces that resonate deeply with their inhabitants, fostering well-being, harmony, and unbiased inclusivity.

1.2 Objectives of the Scoping Review

Our scoping review, aimed at thoroughly exploring the intersection of Artificial Intelligence (AI) and Extended Reality (XR) in architectural design, is guided by several key objectives. The first objective is to gain a comprehensive understanding of the current applications of AI and XR in architecture. This involves delving into the specific tools, methodologies, and practices currently in use where AI and XR are making a significant impact in the field. Additionally, the review focuses on examining the role of AI and XR in enhancing user experiences within architectural spaces. This includes assessing how these technologies contribute to creating spaces that are more interactive, responsive, and engaging, ultimately leading to a more immersive experience for users. Another crucial objective is exploring the potential of AI and XR in optimizing existing architectural spaces. This aspect looks at how these technologies can make spaces more efficient, sustainable, and aligned with human needs, thereby contributing to the overall betterment of architectural design. Lastly, the review aims to identify gaps in the current body of research, especially those pertaining to the integration of AI and XR from a human-centered design perspective. This involves pinpointing areas that have not been comprehensively studied and highlighting opportunities for further research in these domains. Overall, these objectives shape the scope of our review, ensuring a focused yet comprehensive exploration of AI and XR technologies in the context of modern architectural practices.

1.3 Research Questions

Our scoping review is steered by several research questions, each aiming to unravel the complexities and potentials of Artificial Intelligence (AI) and Extended Reality (XR) in architectural design. The first question seeks to understand the current applications of AI and XR technologies in architectural design, delving into their roles in optimizing architectural spaces. This includes exploring the methodologies, tools, and techniques where AI and XR are employed to enhance the functionality and aesthetics of architectural projects. Another central question of the review revolves around the impact of AI and XR on user experience and interaction within these architectural spaces. This involves investigating how these technologies contribute to making spaces more immersive, intuitive, and engaging for users, thereby transforming the way people interact with and perceive their built environment. Finally, the review aims to identify and analyze the gaps in the current literature regarding the integration of AI and XR in architectural design, with a specific focus on human-centered design. This question addresses the need to explore areas where existing research may be lacking or where further study could provide deeper insights into the effective combination of AI and XR in architecture, particularly in terms of design that prioritizes human experience and interaction. Collectively, these questions guide the direction of our review, ensuring a comprehensive and insightful examination of the interplay between AI, XR, and architectural design.

1.4 Scope and Significance

This review targets studies published between 2014 and 2024, reflecting recent advancements in AI and XR technologies and their applications in architecture. The time frame ensures that the review captures cutting-edge developments and contemporary practices in the field. The significance of this review lies in its potential to inform architects, designers, and researchers about the current trends, challenges, and opportunities in integrating AI and XR into architectural design. Moreover, by identifying gaps and unexplored areas, this review sets the stage for future research that could lead to innovative design practices and methodologies, ultimately contributing to the creation of spaces that are more in tune with human needs and experiences in the built environment.

2. Methodology

To explore the integration of Artificial Intelligence (AI) and Extended Reality (XR) in enhancing human-centered architectural spaces, we conducted a comprehensive Scoping Review. This review adheres to the PRISMA-ScR guidelines to ensure rigorous and transparent research practices. Our systematic search spanned several key databases, including Avery Index to Architectural Periodicals, Scopus, Web of Science, IEEE Xplore, JSTOR, and Google Scholar. We utilized meticulously crafted search strings and Boolean operators to identify relevant studies.

Eligibility criteria for studies included a focus on the applicability of AI and XR within architectural spaces, an emphasis on human-centered design principles, and publication in peer-reviewed journals within the past decade. Each researcher independently assessed the studies, and any discrepancies resolved through collective discussion and consensus. The data extraction process involved charting key information from each study and synthesizing it to identify prevalent methodologies, metrics, and discernible gaps in the literature. This process aimed to provide a comprehensive overview of the current state of AI and XR in human-centered architectural design, offering insights for future interdisciplinary research.

2.1 Data Collection

In our quest for a comprehensive review, the data collection for our study extended to a wide array of sources, ensuring a well-rounded and thorough compilation of relevant information. Our primary focus was on scholarly databases, known for their extensive coverage in fields pertinent to our study. We conducted rigorous searches in databases such as Avery Index to Architectural Periodicals, Scopus, Web of Science, IEEE Xplore, JSTOR, and Google Scholar. These platforms were chosen for their rich repository of literature in technology, architecture, and interdisciplinary studies, providing a wealth of academic articles and papers that are essential to our research. To complement this, we also delved into gray literature sources. This included a careful review of dissertations, theses, and books. The rationale behind including these sources was to capture insights, theories, and developments that might not be available in traditional academic journals. These non-conventional sources often offer a different perspective and can include valuable research findings and discussions that provide a more rounded and comprehensive view on the topics of Artificial Intelligence (AI), Extended Reality (XR), and their applications in architectural design. Together, these diverse sources of data formed the foundation of our comprehensive review, ensuring that we gathered a broad spectrum of information and viewpoints, which are crucial for a holistic understanding of the current state and future potential of AI and XR in architectural design.

2.2 Eligibility Criteria

In our effort to ensure the relevance and quality of the literature reviewed, we carefully established a set of eligibility criteria for inclusion. These criteria are crucial in guiding our selection of studies and ensuring that our review is both comprehensive and current.

Firstly, topical relevance is a key criterion. We specifically looked for studies that explicitly focus on the application of Artificial Intelligence (AI) and Extended Reality (XR) technologies in optimizing architectural spaces. This criterion ensures that the selected literature directly contributes to our understanding of how these advanced technologies are being used to enhance and transform architectural design.

Additionally, a strong design focus is essential. The studies must exhibit a clear approach to human-centered design principles. This criterion is crucial as it aligns with our intent to explore how AI and XR can be integrated into architectural design in a way that prioritizes human experience and interaction.

Table I: Keyword list for the literature search. The search term was constructed by putting an OR operator between each phrase within a set and an AND operator between the two keyword sets.

AI Key Words	XR Key Words	Human-Centered Design Key Words	Optimization Key Words	Architectural Space Key Words
AI, Artificial Intelligence, Machine Learning, Deep Learning	VR, Virtual Reality, AR, Augmented Reality, MR, Mixed Reality, XR, Extended Reality	HCD, Human-Centered Design, User-Centered Design	Optimization, Optimization Strategies, Evaluation, Evaluation Techniques	Architectural Spaces, Interior Spaces, Built Environment, Interior Design, Architecture Design

Lastly, we set strict publication criteria. Only studies published in peer-reviewed journals within the past decade were considered. This parameter is set to ensure that the studies included in our review are not only rigorously vetted for academic rigor but also offer contemporary relevance. This helps us stay abreast of the latest trends, innovations, and methodologies in the rapidly evolving fields of AI, XR, and architectural design.

By adhering to these carefully crafted eligibility criteria, we aim to curate a body of literature that is highly relevant, academically sound, and reflective of the latest advancements in the intersection of AI, XR, and architectural design.

2.3 Search Strategy

In our endeavor to conduct a comprehensive review of the literature, we implemented a meticulous search strategy that involved several key steps:

The first step was the identification of key concepts critical to our study. We focused on four main areas: Artificial Intelligence (AI), Extended Reality (XR), Human-Centered Design, and Architectural Spaces. This initial step was crucial in defining the scope and direction of our literature search. To ensure an exhaustive search, we expanded our focus with synonym expansion for each key concept. This involved compiling a list of synonyms and related terms for each concept to broaden the search scope. As in Table I, for example, under AI, terms like 'Machine Learning' and 'Computational Design' were included, while XR was expanded to include terms such as 'Virtual Reality', 'Augmented Reality', and 'Mixed Reality'. This step was essential in capturing the full breadth of relevant literature across these concepts.

Finally, we employed Boolean operators (AND, OR) in constructing our search strings. As shown in Fig.1, this methodological use of Boolean operators was instrumental in combining these terms effectively, ensuring that our search was not only comprehensive but also targeted. This approach facilitated a thorough retrieval of relevant studies from various academic databases, thereby enhancing the quality and relevance of our literature review.

Through these strategic steps, we ensured that our literature search was systematic, exhaustive, and tailored to capture the most pertinent and up-to-date research in the fields of AI, XR, Human-Centered Design, and Architectural Spaces.

2.4 Selection Process

Initial Identification and Pre-screening Phase. Our extensive scoping review began with an initial identification of 1151 records, sourced from a variety of academic databases, marking the start of our journey into the integration of AI and XR in architectural design. The pre-screening phase saw the removal of 32 duplicate records, streamlining our collection for relevance and uniqueness. Additionally, 787 records were marked as ineligible by our automated tools, ensuring that the remaining pool was highly pertinent to our research focus, as shown in Fig. 2.

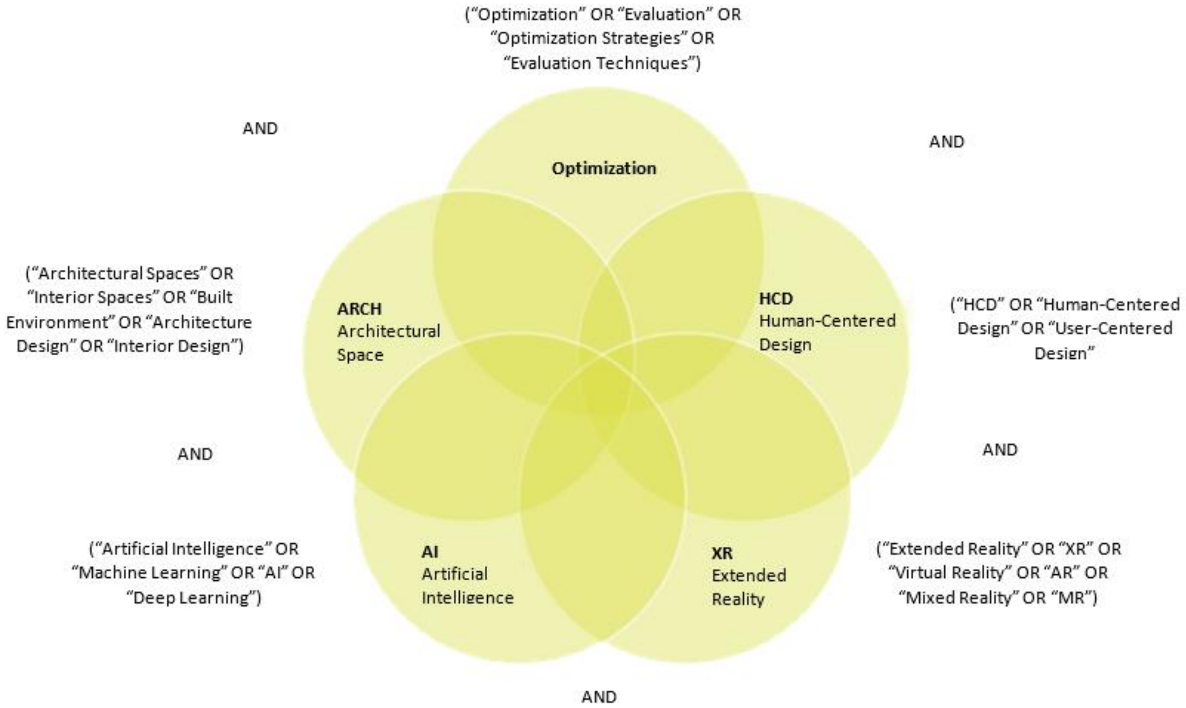

Fig. 1. Search String of keywords with a list of synonyms and related terms, using Boolean operators (AND, OR)

Screening and Selection Process. The subsequent screening phase was rigorous and detailed. We closely examined 332 records based on their titles and abstracts, a process that led to the exclusion of 243 records. This scrutiny was essential to ensure that each study closely aligned with our research objectives.

Retrieval and Eligibility Assessment. During the retrieval phase, we sought to assess 89 reports for a more in-depth assessment. However, 49 reports were excluded due to the reasons listed in Table II, leading us to assess the eligibility of the remaining 40 reports. This step was crucial in determining the most relevant and impactful studies for our review.

Criteria-Based Exclusion. In our final step, we adopted a rigorous yet flexible approach to selecting studies. Initially,

24 reports were excluded due to not fully meeting our criteria, primarily due to the absence of one or more key components of our study's focus. Upon closer examination, 6 of these were found to satisfy all our requirements and were selected for detailed analysis. Recognizing the evolving nature of AI and XR research, we also included 10 additional studies that did not completely align with our criteria, especially in terms of AI and XR integration. This decision was made to capture a broader range of insights despite some limitations. Ultimately, our final selection comprised 16 studies (See Table V in the Appendix for the Selected Articles): 6 meeting all criteria and 10 included with a level of flexibility. This approach ensured a balance between strict academic rigor and the

inclusion of diverse, albeit less aligned, research, providing a comprehensive overview of the current landscape and potential future directions in AI and XR integration.

Identification of studies via databases and registers

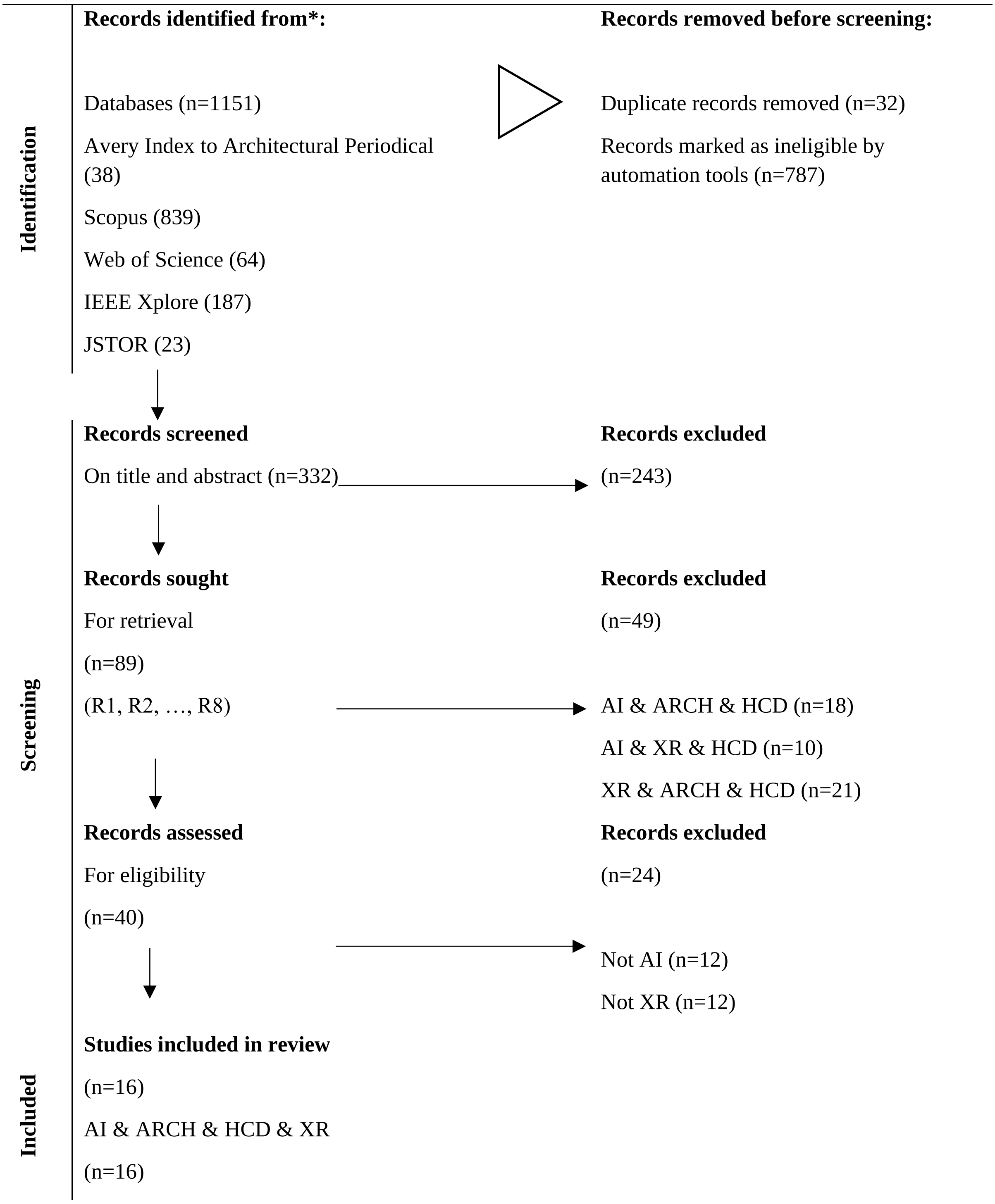

Fig. 2. PRISMA flow diagram *Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372: n71. doi: 10.1136/bmj. n 71

Table II: Reasons for Exclusion

	Reasons	Number of Articles
R1	Reports are not part of the main proceedings, such as adjunct publications or short papers.	2
R2	Surveys or literature reviews, which did not provide original research data.	1
R3	Publications outside our designated time frame of 2015 – 2024.	1
R4	The absence of specific terms related to XR or AI is crucial to our research.	11
R5	Instances where terms were used in contexts not relevant to our study.	24
R6	Reports where XR and AI were merely mentioned as examples without substantive application.	5
R7	Usage of XR in the context of training or testing AI, rather than in actual deployment.	3
R8	Lack of sufficient details for accurate coding and analysis.	2

2.5 Data Analysis

In our scoping review, we utilized NVivo, a qualitative data analysis software, to organize and analyze the collected data. This tool was crucial in systematically interpreting the extensive information gathered from our literature search. To enhance this process, we developed a comprehensive codebook as shown in Table III, which was instrumental in our data analysis. This codebook facilitated a structured thematic analysis, identifying key themes like AI-Driven Design Tools and XR Applications in Architecture. Employing this methodical approach, we effectively compared methodologies, identified research gaps, and critically evaluated the studies. This thorough analysis was vital in achieving a nuanced understanding of the integration of AI and XR in human-centered architectural design.

3. Results

Our scoping review explored the integration of Artificial Intelligence (AI) and Extended Reality (XR) in optimizing architectural spaces from a human-centered design perspective.

Source Overview: The review included a total of sixteen articles, primarily journal articles, six of which focused in some way on the integration of AI and XR in architectural design. We meticulously analyzed these scholarly articles, each offering unique insights into the intersection of these cutting-edge technologies within the architectural domain. These articles represent a rich tapestry of research, spanning various methodologies, themes, and applications, all converging on the innovative use of AI and XR in architectural design.

Table III: Summary of the codes used for data extraction. See Table V in the Appendix for the code book including a description for each code.

AI & XR Technologies	Human-Centered Design	Optimization Strategies	Future Directions
Integration Strategies of AI/XR in Design	Ergonomic Considerations in Design	Sustainable Design Adaptations	AI/XR in Disaster Resilience and Emergency Planning
User Interface Adaptations in AI/XR	Psychological Impact on Users	User Adaptability and Flexibility	Predictive Analytics in Design Evolution
Role of AI/XR in Collaborative Design	Accessibility and Inclusivity Factors	Cost-Effectiveness and Resource Efficiency	Interdisciplinary Collaborations Opportunities

Evaluation Techniques	Challenges and Limitations	Case Studies / Practical Applications	Ethical and Privacy Considerations
User Feedback Mechanisms	Integration Challenges with Existing Infrastructure	Impact Analysis of Implemented Solutions	Bias and Fairness in AI Algorithms
Environmental Impact Assessment	User Acceptance and Adaptability	Comparative Studies of before and after Scenarios	Long-term Societal Impacts
Long-term Performance Tracking	Scalability Issues of AI/XR Solutions	Longitudinal Studies of AI/XR Implementation	User Consent and Transparency Protocols

Nature of Publications: All sources are academic journal articles, indicating peer-reviewed and scholarly contributions to the field.

Geographical Distribution: The reviewed studies present a diverse geographical perspective, with contributions from various countries and regions, as shown in Fig. 3, indicating widespread interest in the application of AI and XR technologies in architecture. This global perspective underscores the universal relevance and applicability of these technologies in addressing architectural challenges worldwide.

Focus of the Studies: The studies included in this research project offer a comprehensive view into the diverse

applications of AI and XR in architectural design, each contributing unique insights into the field's evolving nature. Kán et al. (2023) delve into the realm of interior design, exploring how AI can automate and personalize interior design processes, while Morris, Guan, and Azhar (2023) investigate the integration of XR in visualizing complex architectural data through their study on an XRI Mixed-Reality Internet-of-Things Architectural Framework. Elwageeh et al. (Year) contribute by examining AI's role in optimizing building layouts, focusing on efficient space utilization and energy conservation. Wu (2022) provides a

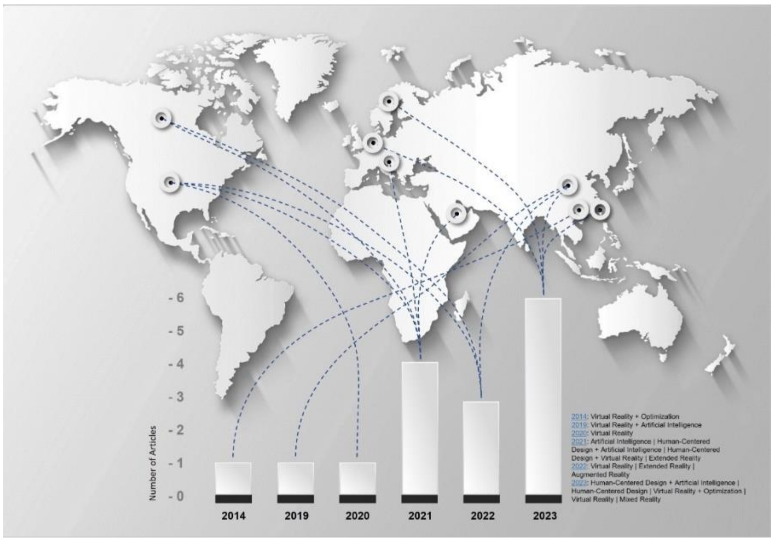

Fig. 3. Geographical Distribution and Year Distribution of Articles

perspective on enhancing architectural modeling through AI, showcasing streamlined design processes enabled by machine learning techniques. The integration of AI in environmental control systems within architectural designs, as explored by Hu and Roberts (2020), emphasizes AI’s capacity to create responsive and adaptive building environments. Zhao et al. (2023) extend the application of AI to urban planning, using AI-driven tools to analyze demographic data for informed city-scale architectural decisions. Lang and Zhuang (2023) examine AI's utility in facade design, demonstrating how AI aids in crafting both functional and aesthetically pleasing building exteriors. Huang (2022) takes a unique approach by focusing on XR applications in heritage

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conservation, illustrating how AR and VR can be instrumental in restoration efforts and engaging the public. In construction management, Han and Leite (2022) investigate the use of Mixed Reality for on-site decision-making, enhancing collaboration and real-time problem-solving. Sundstedt et al. (2022) explore XR's role in client-architect interactions, enabling immersive experiences that allow clients to visualize and interact with design proposals. He (2023) centers on the application of AI algorithms for structural analysis, contributing to the development of safer and more efficient architectural designs. Zhang et al. (2022) delve into AI's potential in optimizing architectural acoustics, particularly in public spaces, while Wang et al. (2023) focus on XR's utility for virtual site visits, facilitating remote assessment of construction progress.

Finally, Zhou et al. (2019) discuss AI in landscape architecture, particularly in the context of designing sustainable and aesthetically pleasing outdoor spaces.

This rich tapestry of studies underscores the broad and multifaceted nature of AI and XR applications in architecture. From enhancing design processes and optimizing structural elements to enriching user experiences and conserving heritage, these technologies are steadily reshaping architectural practices, heralding a new era of innovation and user-centric design.

3.1 Main Themes

The thematic analysis of AI and XR in architectural design highlights a range of innovative approaches and applications, as reflected in the studies reviewed, see Table IV in the Appendix for the Themes including a literature and a quotation for each theme:

AI-Driven Design Tools. A key theme identified is the development of AI algorithms for automating design processes in augmented reality (AR) environments. This aspect of the research highlights how AI is being used to enhance the efficiency and personalization of interior design, demonstrating a significant shift towards more sophisticated and user-tailored design methodologies.

XR Applications in Architecture. The diverse applications of XR technologies in architecture from another

Table IV: General Characteristics of the Included Literature Organized in Descriptive Themes

Themes	Literature	Ouotations from Literature
Al-Driven Approaches in Architectural Design	(Sundstedt, et el., 2023). Hints. • Human- Centered Intelligent Realities.	'The "Human-centered Intelligent Realities" (HINTS) profile project will develop concepts, principles, methods, algorithms, and tools for human-centered IRS.' 'The systems will be equipped with cognitive features based on Al and ML'
Extended Reality (XR) Applications in Architecture	(Elwageeh, et el., 2021). A Framework of Integrating VR and IOT Technology to Test Users' Preferences of Artificial Lighting Variations in Hotel Guest Room.	'Virtual reality (VR) and augmented reality (AR) technology helped in digitalizing the physical environment, adding enormous interaction capabilities.'
	(Morris, et el., 2021). An XRI Mixed-Reality Internet-of-Things Architectural Framework toward Immersive and Adaptive Smart Environments.	'Another approach is Virtual Environment of Things (VEoT), to integrate real-world smart things and virtual world avatars in a computer-generated virtual environment so that entities in either worlds can interact with one another in a real-time manner. '
	(Kån, et el., 2021). Automatic Interior Design in Augmented Reality Based on Hierarchical Tree of Procedural Rules.	'Mixed Reality (MR) refers to a "subclass of Virtual Reality (VR) related

	(Hu, et el., 2020). Built Environment Evaluation in Virtual Reality Environments—a Cognitive Neuroscience Approach. (Lang, et el., 2023). Design of Interactive Virtual System of Architectural Space Based on Mult Objective Optimization Algorithm. (Huang, et el., 2021). From Building Information Modeling to Extended Reality.	technologies that involve the merging of real and virtual worlds", and applications make use of multiple kinds of display devices.' 'VR technology is virtual reality technology, which enables real people to experience the same things and things as the real world in the virtual information world created by computers.' 'Based on digital terrain, all models are built on it, and a complete 3D virtual architecture space model is constructed according to its position, angle and proportion. ' 'Through virtual reality technology and architectural animation technology, buildings can give people the truest feelings in the virtual environment.' 'Mixed reality (MR), sometimes referred to as hybrid reality, is the merging of real and virtual worlds to produce new environments and visualizations where physical and digital objects co-exist and interact in real time. '
Human-Centered Perspectives in Spatial Design	(Wu, et el., 2022). Architectural Interior Design and Space Layout Optimization Method Based on VR and 5G Technology. (Sundstedt, et el., 2023). Hints: Human-Centered Intelligent Realities. (Chatterjee, et el., 2023). Human-Centered and Ai Driven Generation of 6-DOF Extended Reality,	'Architectural style and spatial layout are related to people's quality of life, safety, health, comfort, and other issues.' 'It has been proposed to open new opportunities for creating an enhanced human-centered digital world. ' 'The whole system is aided by a human-computer interaction (HCI) component. '
Al and XR for Enhanced User Experience	(Morris, et el., 2021). An XRI Mixed-Reality Internet-of-Things Architectural Framework toward Immersive and Adaptive Smart Environments. (Han, et el., 2022), Generic Extended Reality and Integrated Development for Visualization Applications in Architecture, Engineering, and Construction.	'The levels of design related to mixed reality remain to be fully explored, as the XRI system potential spans the conventional reality-virtuality continuum [27] from real world physical use cases, into augmented reality use cases, augmented virtuality uses cases, and even virtual use-cases. ' 'Model-related functions, such as overlapping virtual models with the real world and modifying 3D objects based on semantic information, were developed to an application level.'

significant theme. This research area showcases how XR is transforming visualization and user interaction in architectural spaces, adding new dimensions, and enriching the overall architectural experience.

Human-Centered Design Approaches. Another prominent theme revolves around the integration of human-centered design principles in architecture. This involves the use of virtual reality (VR) and biometric sensing to align architectural designs more closely with user needs and experiences, emphasizing a shift towards more responsive and empathetic design strategies.

AI and XR for Enhanced User Experience. The combination of AI and XR in creating immersive and interactive user experiences in architectural spaces is also a key theme. This area of study illustrates the synergistic potential of these technologies in pushing the boundaries of conventional design, offering novel ways to engage with and experience architectural spaces.

These themes collectively indicate a significant evolution in architectural design practices, driven by the integration of AI and XR technologies, and highlight the field's ongoing shift towards more immersive, user-centered, and technologically advanced approaches.

4. Finding

This scoping review delves into the dynamic intersection of Artificial Intelligence (AI) and Extended Reality (XR) within the realm of human-centered architectural spaces, highlighting the pivotal role of these technologies in revolutionizing architectural design. The selected studies present a varied landscape of approaches and applications, demonstrating how AI and XR are reshaping architectural practices to be more attuned to human needs and behaviors. Central to this exploration is the role of AI and XR, both independently and jointly, in creating spaces that are not only functionally efficient but also emotionally resonant and user-friendly. The review underscores a significant shift towards user-centered design approaches in architecture, propelled by technological advancements. Studies like those of Kán et al. (2023) and Morris, Guan, and Azhar (2023) emphasize the development of AI-driven design tools and XR applications in architectural modeling, enhancing visualization and user interaction. Recent advancements in these technologies have led to novel opportunities and challenges, as evidenced by diverse applications ranging from automated interior design to the assessment of emotional responses within architectural spaces. Elwageeh and Karoui (2020) and Wu (2022) exemplify personalized design solutions using VR and IoT, while Hu and Roberts (2020) and Zhao et al. (2023) explore the integration of VR and cognitive neuroscience in evaluating built environments. The research by Lang and Zhuang (2023) on virtual architectural spaces and Huang (2022) on BIM and XR integration demonstrates the evolving landscape of architectural design. Han and Leite’s (2022) GenXR model, Sundstedt et al.'s (2022) HINTS project, and He is (2023) study on machine vision in indoor VR design further illustrate the integration of AI and XR in creating intelligent, human-centered realities. Moreover, Zhang et al. (2022), Wang et al. (2023), and Zhou et al. (2022) showcase the diverse applications of these technologies in predicting restorative experiences, enhancing workplace safety, and developing WebVR frameworks for indoor layout design. These studies collectively represent a paradigm shift where AI and XR technologies are employed to create more efficient, personalized, and emotionally resonant architectural spaces. This overview highlights the convergence of AI and XR technologies as a beacon for the future of architectural design. It points towards a future where design is deeply intertwined with digital innovation, emphasizing human-centric principles and advanced technological integration. The synthesis of these advancements provides insights into their practical applications, challenges, and potential future directions in the context of human-centered architectural design.

4.1 AI-Driven Approaches in Architectural Design

The integration of Artificial Intelligence (AI) in architectural design has brought about a profound transformation in the field, marked by increased efficiency, enhanced user experience, and personalization. AI's role in architectural design is multifaceted, ranging from environmental control to advanced design tools and streamlined processes.

The integration of IoT, closely related to AI, in environmental control systems such as lighting, exemplified in Elwageeh and Karoui's study (2020), marks a significant advancement in personalized environmental control. This is complemented by Wu's (2022) exploration of 5G technology in interior design, hinting at the potential for

AI to enhance real-time data processing and spatial optimization. Hu and Roberts (2020) have demonstrated a novel application of AI

in evaluating built environments using EEG data and VR, providing insights into human responses to architectural designs. This is further extended by Zhao et al. (2023), who implemented 3D virtual vision to create interactive and realistic design models, showcasing AI's complementary role in interior design. Lang and Zhuang (2023) have developed an interactive virtual space system using multi-objective optimization algorithms, optimizing user interaction and design processes. Huang (2022) discussed the potential of AI in enhancing the integration of Building Information Modeling (BIM) and XR, indicating pathways for automated and efficient design processes.

The GenXR model by Han and Leite (2022) streamlines the BIM-to-XR model transfer, enhancing design efficiency, while Sundstedt et al. (2022)'s HINTS project highlights AI's role in creating intelligent, interactive digital systems. He (2023) explored machine vision in indoor VR design, demonstrating AI's precision in interior design. Moreover, Kán, Kurtic, Radwan, and Rodríguez (2023) have contributed significantly with their study on automated interior design in AR environments, presenting an AI-based algorithm that automates furniture arrangement, integrating user preferences and spatial constraints. This advancement reflects a leap in personalized interior design. The work of Han and Leite (2023) on the GenXR model illustrates the efficient integration of BIM with XR technologies, showcasing substantial timesaving in XR application development. Chatterjee and Vega (2023) further explored AI in XR applications, generating dynamic and immersive 3D environments, enhancing realism and interactivity in virtual spaces. These studies collectively illustrate the transformative impact of AI in architectural design, from automating complex tasks and enhancing user experiences to streamlining integrations and optimizing design processes. They reflect a paradigm shift towards more efficient, user-centered, and technologically advanced architectural practices, signifying a major advancement in resource efficiency and design methodology within the industry.

4.2 Extended Reality (XR) Applications in Architecture

The application of Extended Reality (XR) technologies in architecture has brought significant advancements in enhancing user experience, design visualization, and interaction within architectural spaces. Studies spanning various aspects of XR applications reflect the technology's transformative impact on the field. Elwageeh and Karoui (2020) have explored the role of XR in simulating real-world environments for user preference analysis in hotel room lighting, highlighting XR's potential in personalized environmental control. Complementing this, Wu (2022) demonstrates XR's capabilities in real-time, high-fidelity spatial visualization, integrating VR and 5G technology in interior design. The immersive capabilities of XR, as shown in Hu and Roberts (2020)'s application of VR with EEG for built environment evaluation, provides novel insights into human emotional responses to architectural spaces. This approach is further advanced by Zhao et al. (2023), who discuss the use of 3D virtual vision in interior design, enhancing realism and interactivity. Lang and Zhuang (2023) developed an interactive virtual system leveraging XR technology, illustrating enhanced user interaction and spatial planning capabilities. Huang (2022) discusses the effective integration of BIM and XR in the AECO industry, showing how XR bridges digital models with real-world applications. Han and Leite (2022) emphasize XR's role in streamlining the transfer of BIM data to immersive XR applications, while Sundstedt et al. (2022)'s HINTS project explores XR's potential in creating intelligent, immersive environments, enhancing cognitive interactions. He (2023) demonstrates XR's precision and customization in indoor VR design, and Zhang et al. (2022)'s study on non-immersive VR highlights XR's application in user-centric design processes. Wang et al. (2023) showcase the practical applications of XR in educational settings, particularly in occupational safety training in clinical workplaces. Zhou et al. (2022) illustrate the synergy of XR and AI in enhancing architectural design processes through the development of a WebVR framework for indoor layout design. Moreover, Morris, Guan, and Azhar (2023) introduce an architectural framework integrating XR and IoT, termed XRI, aimed at creating immersive and adaptive smart environments. This framework revolutionizes architectural visualization and interaction, offering comprehensive insights into the spatial and functional aspects of design. Huang (2023) bridges the gap between BIM and XR, highlighting the potential of XR to enhance the utility of BIM by providing immersive and interactive experiences. This integration aids in overcoming traditional BIM limitations, particularly in scale representation and user immersion. Dias et al. (2014) emphasize the importance of user-centric design approaches, with VR and biometric sensing providing valuable insights into users' emotional responses to architectural spaces. This approach aligns architectural design with human-centric principles, emphasizing emotionally resonant spaces. The incorporation of XR in architecture marks a significant shift towards interactive, immersive, and user-focused design processes. These advancements facilitate enhanced visualization, offer more empathetic design practices, and indicate a growing trend in adopting XR technologies in architectural design, reflecting their potential to significantly alter the landscape of architectural practices.

4.3 Human-Centered Perspectives in Spatial Design

The evolving landscape of architectural design increasingly emphasizes human-centered perspectives, focusing on enhancing user experience, comfort, and emotional well-being. This shift, particularly evident through the application of AI and XR technologies, underscores the importance of designing spaces that fulfill both functional needs and positively influence users' emotions and behaviors. The research by Dias et al. (2013), "Virtual Reality and Biometric Sensing as Tools to Evaluate Space Use," exemplifies this trend. By employing VR and biometric sensing, their innovative method assesses users' emotional responses to different architectural spaces. This approach highlights the significance of creating environments that resonate emotionally with users. In the realm of interior design, the move towards personalization is clearly seen in the work of Kán et al. (2023), "Automatic Interior Design in Augmented Reality." Their AI-driven algorithm customizes furniture arrangements based on user preferences, reflecting advancements in creating spaces that align with individual tastes and needs. Similarly, Elwageeh and Karoui (2020) have showcased the importance of tailoring environmental conditions to human preferences in their research on lighting preferences in hotel rooms using VR and IoT technologies. Wu (2022)’s exploration in VR and 5G in interior design emphasizes the need for designs that resonate with user interactions. The integration of AI in creating user-centric environments is further highlighted in Chatterjee and Vega (2023)'s "Human-Centered and AI-driven Generation of 6-DoF Extended Reality." Their work on generating dynamic 3D environments enhances user presence in XR spaces, prioritizing user experience in the design process. Other studies like those by Hu and Roberts (2020), Zhao et al. (2023), and Lang and Zhuang (2023) focus on using EEG data in VR environments, 3D virtual vision, and virtual architectural space systems, respectively, each aligning with the goal of creating spaces optimized for human use and experience. Huang (2022) discusses the integration of BIM and XR in the AECO industry, emphasizing the creation of spaces aligned with human needs. Han and Leite (2022) focus on streamlining the process of creating immersive XR applications, and Sundstedt et al. (2022)'s HINTS project develops intelligent digital systems responsive to human behavior. He (2023)'s study on machine vision in indoor VR design and Zhang et al. (2022)'s approach to using machine learning in residential architecture underscore the significance of personalizing spaces based on user preferences and well-being. Wang et al. (2023) and Zhou et al. (2022) further illustrate the importance of considering human factors in safety training and layout design. These diverse studies collectively underscore the paradigm shift towards human-centered design in architecture. This approach not only considers aesthetic and functional aspects but also prioritizes emotional, psychological, and physical well-being, reflecting a holistic approach to architectural design that is deeply intertwined with technological advancements.

4.4 AI and XR for Enhanced User Experience

The fusion of Artificial Intelligence (AI) and Extended Reality (XR) technologies in architectural design has significantly enhanced user experiences, ushering in a new era of interactive, immersive, and intelligent environments. This integration is evident in various studies that showcase how AI and XR collaborate to create more personalized, emotionally resonant, and immersive experiences in architectural spaces. The research by Chatterjee and Vega (2023) in "Human-Centered and AI-driven Generation of 6-DoF Extended Reality" exemplifies this integration. They leverage AI to generate dynamic 3D environments from 2D images, enriching the depth and realism in XR spaces. This seamless integration not only enriches the sensory experience but also allows for nuanced interaction with virtual architectural models. Similarly, the work of Elwageeh and Karoui (2020) demonstrates how AI and XR can personalize environmental conditions, such as lighting in hotel rooms, enhancing user comfort and experience. Wu (2022)'s exploration of VR and 5G in interior design further emphasizes the potential of XR technologies in providing real-time, high-fidelity spatial experiences, a domain ripe for AI optimization. Personalization is a key theme in AI-driven XR environments, as shown in Kán et al.

(2023)'s "Automatic Interior Design in Augmented Reality." Their AI algorithms automate interior design in AR, tailoring designs to individual user preferences and room data. This approach highlights AI's transformative role in traditional design processes. Emotional connectivity through XR is explored by Dias et al. (2023) in "Virtual Reality and Biometric Sensing as Tools to Evaluate Space Use." By integrating VR with biometric sensing, they capture real-time emotional responses of users, providing valuable insights into how different designs evoke varying emotional reactions. Morris, Guan, and Azhar (2023) in "An XRI Mixed-Reality Internet-of-Things Architectural Framework Toward Immersive and Adaptive Smart Environments" present a framework where XR interfaces visualize IoT data, facilitating enhanced decision-making and interaction with intelligent environments. The studies by Hu and Roberts (2020), Zhao et al. (2023), and Lang and Zhuang (2023) further illustrate the combination of AI and XR in enhancing user interaction, design realism, and optimizing virtual architectural space systems. The GenXR model by Han and Leite (2022), Sundstedt et al. (2022)'s HINTS project, He's (2023) study on indoor VR design, and Zhang et al. (2022)'s application of machine learning in residential design highlight how AI enhances the efficacy and engagement of XR applications. Finally, Zhou et al. (2022)'s development of a WebVR framework for indoor layout design, integrating AI techniques such as CNN and deep Q-learning, demonstrates the powerful combination of AI and XR in creating intuitive and user-friendly design tools. These studies collectively illustrate the transformative impact of AI and XR in architecture. They offer novel ways to enhance user experience through interactive, intelligent, and immersive design solutions, signifying a major leap forward in creating user-centric, efficient, and emotionally engaging architectural spaces.

4.5 Challenges and Opportunities

The integration of Artificial Intelligence (AI) and Extended Reality (XR) in architectural design, while offering immense possibilities, also brings considerable challenges alongside significant opportunities. The complexity of developing and implementing these advanced technologies and the adaptability required by users are key concerns that emerge from the recent studies. The technical complexities are evident in the work of Kán et al. (2023) and Morris, Guan, and Azhar (2023), where the creation of sophisticated AI algorithms and the integration of IoT data with XR environments pose substantial challenges. Similarly, Elwageeh and Karoui (2020) face challenges in merging IoT and VR for lighting preferences in hotel rooms, including technological compatibility and user adaptability. Wu (2022)'s exploration of VR and 5G technology reveals issues related to data bandwidth and real-time processing. User adaptability and the learning curve associated with these technologies are highlighted in studies by Dias et al. (2023) and Chatterjee and Vega (2023). The need for intuitive and user-friendly interfaces is crucial for successful technology implementation in architectural design. Furthermore, the GenXR model by Han and Leite (2022), Sundstedt et al. (2022)'s HINTS project, He is (2023) study on machine vision, Zhang et al. (2022)'s use of machine learning, Wang et al. (2023)'s application of HAI, and Zhou et al. (2022)'s development of a WebVR framework all identify challenges ranging from creating standardized models to achieving precise sketch recognition. These hurdles suggest a need for more robust and flexible systems, more accurate predictive models, and more intuitive AI algorithms.

Despite these challenges, there are significant opportunities for interdisciplinary collaboration, as evidenced by the diverse authorship and approaches in the reviewed literature. The integration of AI and XR in architectural spaces opens doors for collaboration between architects, computer scientists, engineers, and psychologists. Hu and Roberts (2020), Zhao et al. (2023), Lang and Zhuang (2023), and Huang (2022) discuss various challenges, including accurately capturing neurological responses, implementing 3D virtual vision, developing multi-objective optimization algorithms, and achieving interoperability between software systems. These challenges present opportunities for more refined methods in user experience evaluation and the development of more sophisticated AI models. Addressing these challenges and capitalizing on the opportunities will be key to fully realizing the potential of AI and XR in transforming architectural design and user experience.

The integration of these technologies in architectural design presents a landscape filled with both challenges and opportunities. Overcoming technical hurdles and enhancing user adaptability could lead to more efficient, user-friendly, and intelligent architectural designs.

Table V: Summary of Reviewed Studies

	Sources	Focus	Methodology	Finding	Goal	Participants	Country	Peer-reviewed
Databased								
1	(Elwageeh, et el., 2021). A Framework of Integrating VR and IOT Technology to Test Users' Preferences of Artificial Lighting Variations in Hotel Guest Room.	The focus of the research is developing a theoretical framework for integrating Virtual Reality (VR) and Internet of Things (LOT) technologies in the interior design process.	The research methodology primarily involved a systematic review of existing literature related to the applications of both VR and 10T in the interior design process.	The research identifies a gap in integrating VR and IOT in the interior design process and proposes a theoretical framework to address this.	The goal is to create a framework that can be used by interior designers to determine the appropriate intensity of artificial light in hotel guest rooms, enhancing guest satisfaction.	2	Bahrain	✓
2	(Morris, et el., 2021). An XRI Mixed- Reality Internet-of-Things Architectural Framework toward Immersive and Adaptive Smart Environments.	Integration of Mixed Reality (MR) and Internet- of-Things (TOT) technologies.	Development of a multi-dimensional methodology and an architectural framework.	Prototyping demonstrating the feasibility and potential of the XRI framework.	To create immersive and adaptive smart environments.	3	Toronto	✓
3	(Wu, et el., 2022). Architectural Interior Design and Space Layout Optimization Method Based on VR and 5G Technology.	This research article focuses on the automatic design and optimization of interior space layout. It proposes a method for automatically generating layout plans for indoor spaces based on design	The methodology involves proposing an optimization method based on design constraints.	The study highlights the inefficiency and labor-intensive nature of traditional layout design methods.	The goal is to automate the interior space layout design process, making it more efficient and accessible.	1	China	✓

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		constraints, utilizing VR (Virtual Reality) and 5G technology.						
4	(Kån, et el., 2021). Automatic Interior Design in Augmented Reality based on Hierarchical Tree of Procedural Rules.	Automating furniture arrangement using a hierarchical tree of procedural rules. Methodologies: Al-based algorithm for interior design in RA.	Al-based algorithm for interior design in AR.	High probability of generating sensible furniture layouts.	To enhance interior design through AR and automation.	4	Austr ia	✓
5	(Hu, et el., 2020). Built Environment Evaluation in Virtual Reality Environments—a Cognitive Neuroscience Approach.	The primary focus of this research is to develop, test, and validate a data-driven approach for evaluating the quality of the built environment.	The study uses cognitive neuroscienc e methods, particularly EEG, to measure brain activity related to specific stimuli in the built environment .	The study found that the post-Purple Line (post-PL) developmen t scenario received higher scores than the Pre Purple-Line (Pre-PL) scenario in all four built environment characters.	The goal is to offer a new method for assessing the built environment that goes beyond traditional post-occupancy surveys (POS).	2	USA	✓

Continued of Table V

	Sources	Focus	Methodolog y	Finding	Goal	Parti cipan ts	Count ry	Peer-review ed
Databas ed								
6	(Zhao, et el., 2023). Construction of Interior Design Platform Based on 3D Virtual	The focus of this study is the construction of a new interior design	The study involved constructing an interactive interior	The research concluded that the new interior design platform	The goal of this research was to create an advanced interior design	4	China	✓

	Vision and Wireless Network.	platform based on 3D virtual vision and wireless network.	design platform using 3D virtual vision technology.	based on 3D virtual vision is superior to traditional design methods, achieving high user satisfaction and ease of use.	platform that enhances the design process using 3D virtual reality.			
7	(Lang, et el., 2023). Design of Interactive Virtual System of Architectural Space Based on Multi- Objective Optimization Algorithm.	The study focuses on designing a new interactive virtual system for architectural space.	The study employs 3D visual modeling of building space, using virtual reality (VR) technology and architectural animation.	The interactive virtual system designed in this study shows superior user experience scores compared to traditional systems, with average scores above 90 points versus around 84 points for traditional systems.	The goal is to create a virtual architectural scene design system that is oriented towards architectural design, urban planning, and layout of the surrounding environment.	2	China	✓
8	(Huang, et el., 2021). From Building Information Modeling to Extended Reality.	Integration of Building Information Modeling (BIM) with XR technologies.	Review of XR technologies , BIM-to-XR workflows, and software applications.	XR enhances the utility of BIM for design and construction projects.	To bridge the gap between BIM and XR.	1	USA	✓
9	(Han, et el., 2022). Generic ExtendedReality and Integrated Development for Visualization Applications in Architecture, Engineering, and Construction.	Developing a generic Extended Reality (GenXR) model for BIM-to-XR model transfer.	Creation of a workflow and algorithm for efficient model transfer.	Significant reductions in development time using the GenXR model.	To streamline BIM- to-XR processes in the AEC industry.	2	USA	✓

10	(Sundstedt, et el., 2023). Hints: Human-Centered Intel ligent Realities.	Developing concepts and tools for human-centered Intelligent Realities (IRS).	Novel experience assessment methodologies,visual analytics, adaptive Al.	Development Of novel interaction techniques and efficient networking solutions for IRs.	To enhance user experience in intelligent digital systems.	16	Sweden	✓
11	(Chatterjee, et el., 2023). Human-Centered and Ai-Driven Generation of 6-DOF Extended Reality.	Generating dynamic, photorealistic 3D environments using Deep Generative Networks.	Combination of computer vision methods and deep learning approaches.	Capability of generating panoramic scenes and 3D environments from single images.	To enhance user presence in XR environments.	2	Belgium	✓

Continued of Table V

	Sources	Focus	Methodology	Finding	Goal	Participants	Country	Peer-reviewed
Databased								
12	(He, et el., 2023). Intelligent Innovative Design of Indoor VR Based on Machine Vision.	This paper focuses on the intelligent innovative design of indoor VR, utilizing machine vision technology.	The study employs machine vision technology for indoor positioning and tracking and uses virtual reality technology for the design and modeling of interior spaces.	The paper demonstrates that the use of machine vision and VR technology in interior design can lead to a more efficient and user centric design process.	The goal of this research is to integrate machine vision with VR technology to revolutionize interior design, making it more interactive, personalized, and efficient.	1	China	✓
13	(Zhang, et el., 2022). Prediction of Human Restorative Experience for Human-Centered Residential Architecture Design: A Non-Immersive VR-DOE-Based	The article focuses on exploring the feasibility of machine learning in capturing the restorative quality of design alternatives in	The study employs non-immersive Virtual Reality (VR) and Design of Experiments (DOE) methods integrated with machine	The paper's primary objective is to develop data-driven prediction models to evaluate the restorative quality of design alternatives.	The goal is to improve the efficiency of design selection and iteration processes in human-centered architectural design.	4	Canada	✓

	Machine Learning Method.	built environments.	learning techniques.					
14	(Dias, et el., 2014). Designing Better spaces for People.	Evaluating space use and users' emotional responses using virtual reality (VR) and biometric sensing.	Use of biometric sensors (EDA, EMG) in a VR environment to assess emotional arousal.	Different architectural spaces evoke varying emotional responses, measured through biometric data.	To understand how different designs influence users' emotions in architectural spaces.	1 0	Hong Kong	✓
15	(Wang, et el., 2023). Feasibility and accessibility of Human-Centered AI-based Simulation system for improving the occupational Safety of Clinical workplace — Doaj.	The study focuses on the development and implementation of a Human-centered Artificial Intelligence (HAT) based training system for improving occupational safety in clinical settings.	The research utilizes HAI technology to create an occupational safety training system.	The study found hat the HAI-based training system significantly improved learning performance, decreased anxiety, and increased mastery level of clinical work safety knowledge and skills among its users.	The goal of the study is to enhance occupational safety training for medical personnel using a technologically advanced, cost-effective, and user- friendly method.	1 1	Taiwan	✓
16	(Zhou, et el., 2019). Web-VR Human- Centered Indoor Layout Design Framework Using a Convolutional Neural Network and Deep Q-Learning.	The study focuses on enhancing Web Virtual Reality (Web-VR) indoor scenario design. It proposes a novel framework for automatic furniture layout and interactive virtual scenarios using Web-VR.	The methodology involves two main components: - A CNN-based method. -An approach using deep Q-learning	The research demonstrates the feasibility of the proposed framework through experiments.	The goal of the study is to enhance Web-VR technology's capabilities in indoor scenario design.	4	China	✓

5. Discussion

The findings from our comprehensive scoping review and analysis of recent studies reveal a significant application of Artificial Intelligence (AI) and Extended Reality (XR) technologies in architectural design. This integration resonates with emerging trends in the field and marks a notable shift from traditional design methodologies, placing a stronger emphasis on personalization [26], user interaction [27], and efficiency [21]. As illustrated by the diverse range of studies, [28], [29], [30], [31], [32], [33], [34], [35], [36], AI algorithms have been successfully applied to automate design processes and enhance user experiences in XR environments, reflecting a paradigm shift towards more human-centric, efficient, and innovative architectural practices [8].The successful integration of AI and XR, as evident in these studies, aligns with current trends observed in the broader field, highlighting the versatility and growing importance of AI and XR integration across various sectors. A systematic review emphasizes that the combination of AI and XR is emerging as a powerful tool not only in architecture but also in fields such as autonomous cars, robotics, military, medical training, and entertainment [37]. This underlines the versatility and growing importance of AI and XR integration in multiple fields, reflecting the relevance of our findings in a wider context. This discussion synthesizes the multifaceted implications, challenges, and prospects of integrating AI and XR in architectural design. It aims to contextualize emergent trends and technological synergies, critically examining their impact on the field of architecture [30]. The insights drawn from these diverse studies provide a basis for a deeper understanding of the current state and future potential of AI and XR in shaping the field of architecture, illustrating their transformative effect in creating more user-centric, efficient, and innovative practices.

5.1 Interpretation of Results in the Context of Other Evidence

The application of Artificial Intelligence (AI) and Extended Reality (XR) in architectural design, as our research findings demonstrate, aligns with, and expands upon the existing body of evidence in this rapidly evolving field. Our interpretation of these results places them within the broader context of architectural innovation and the integration of cutting-edge technologies. The findings from various studies, such as those by Elwageeh and Karoui (2020) and Wu (2022), resonate with the current trends in digital architecture, emphasizing the growing importance of immersive technology in enhancing user experiences [38]. This trend is in line with a broader emphasis on user interaction and personalization in architectural spaces [39], [40], as evidenced by studies like those of Hu and Roberts (2020) and Zhao et al. (2023). These studies provide insights into leveraging XR for empathetic and human-centric design approaches, echoing the current shift towards more holistic architectural practices.

Moreover, the application of advanced AI techniques in architectural design, as seen in works by Lang and Zhuang (2023) and He (2023), mirrors a broader industry push towards automation and optimization in design processes. This trend of integrating AI to enhance efficiency and precision in design is supported by other studies as well. The convergence of AI and XR technologies in architecture, exemplified by the GenXR model [18], and the HINTS project [19], represents a significant development that aligns with the ongoing narrative in the architectural field. This synergy is viewed as a key driver in creating more adaptive, intelligent, and responsive architectural environments. The practical applications of these technologies in specific architectural contexts, as demonstrated by Zhang et al. (2022) and Wang et al. (2023), support the broader evidence of AI and XR's versatile applications in various aspects of architecture, from residential design to occupational safety.

Adding to this discourse is the theme of AI and XR synergy, which is fundamentally reshaping the landscape of architectural design. This transformation, characterized by enhanced personalization, improved interaction, and the creation of immersive experiences [41], represents a shift away from traditional design methodologies towards more intelligent, interactive, and user-focused practices [42]. Studies such as "Human-Centered and AI-driven Generation of 6-DoF Extended Reality" by Chatterjee and Vega (2023), and "Automatic Interior Design in Augmented Reality" by Kán et al. (2023), illustrate this synergy in action. Chatterjee and Vega's work on AI in creating dynamic 3D environments enhances the realism and interactivity of XR spaces, while Kán et al.'s AI-driven algorithm automates the interior design process in AR, streamlining the design process with unprecedented precision and personalization.

Further illustrating this synergy, studies by Elwageeh and Karoui (2020), Wu (2022), Hu and Roberts (2020), Zhao et al. (2023), Lang and Zhuang (2023), Huang (2022), Han and Leite (2022), Sundstedt et al. (2022), He (2023), Zhang et al. (2022), Wang et al. (2023), and Zhou et al. (2022) collectively demonstrate the revolutionary impact of AI and XR in architectural design. From enhancing user experience to providing innovative solutions for complex architectural challenges, the fusion of AI and XR technologies is forging new frontiers in design. The capabilities of AI in data processing, analysis, and predictive modeling complement XR's immersive experiences, as seen in He's (2023) use of machine vision for interior design and Zhang et al.'s (2022) predictive modeling of human experiences. Zhou et al.'s (2022) showcase of AI integration with WebVR for layout optimization demonstrates AI's potential to enhance XR's interactive capabilities. The integration of IoT and VR in Elwageeh and Karoui's study (2020) and the use of EEG data in VR environments by Hu and Roberts (2020) reveal the depth of user experience enhancement achievable through AI and XR. These technologies work together to create environments that are not only technologically advanced but also deeply responsive to human needs and behaviors. Lang and Zhuang (2023) and Huang (2022) emphasize AI and XR's transformative potential in optimizing design processes. The GenXR model by Han and Leite (2022) and the AI/ML approaches in Sundstedt et al.'s (2022) HINTS project, along with Wang et al.'s (2023) application of HAI in occupational safety training, further illustrate the practical applications of this synergy in diverse architectural scenarios. While the combination of AI and XR offers unparalleled opportunities for advancing architectural design, it also presents challenges such as technological compatibility, complexity of algorithms, and the need for user-friendly interfaces. Addressing these challenges is crucial for fully harnessing the potential of AI and XR in creating more efficient, personalized, and interactive solutions that align with user needs and preferences [43].

In summary, our research findings offer a comprehensive application of how AI and XR technologies are reshaping the field of architectural design. The results align with existing evidence in the domain, contributing new insights and perspectives that underscore the transformative potential of these technologies. They not only validate the current trends in digital architecture but also extend the discourse by showcasing novel applications and methodologies.

5.2 Implications of Results for Practice and Policy

The recent studies examining the integration of Artificial Intelligence (AI) and Extended Reality (XR) in architectural design highlight transformative implications for both professional practice and policy formulation in the field.

In the realm of professional practice, the inclusion of AI and XR is seen as a revolutionary force. Wu (2022) and Zhao et al. (2023) illustrate how these technologies enhance design processes, making them more efficient and accurate, which in turn facilitates better decision-making and nurtures creativity. Furthermore, Hu and Roberts (2020) and He (2023) have shown the potential of AI and XR in creating user-centric designs, indicating a significant shift towards more personalized and interactive architectural experiences that prioritize user comfort and satisfaction.

On the policy front, the advancements in AI and XR technologies, as demonstrated by Lang and Zhuang (2023) and Han and Leite (2022), underline the need for new policies and standards. These should focus on the ethical use of these technologies, ensuring data privacy, and standardizing AI and XR applications in architectural design. Additionally, the impact of AI and XR on architectural education, highlighted by Wang et al. (2023) and Zhou et al. (2022), calls for a revamp of educational curricula and training programs. It is essential that policies support this integration, equipping future architects with the skills needed for a technologically advanced practice [44], [45].

In conclusion, the integration of AI and XR in architecture as gleaned from this comprehensive review carries significant consequences for practice and policy. Proactively addressing these implications is key to advancing the field and ensuring the responsible integration of these cutting-edge technologies in architecture.

5.3 Identification of Research Gaps

The ongoing exploration into the use of Artificial Intelligence (AI) and Extended Reality (XR) in architectural design has marked significant progress but also unveiled several critical research gaps that need to be addressed to further advance the field.

One of the primary gaps identified is the need for deeper AI integration with XR technologies. While initial studies have begun this exploration, there is a vast potential yet to be tapped into, especially concerning deep learning and advanced AI algorithms in XR environments. This area has significant promise for enhancing architectural simulation and user interaction. Another crucial area is the holistic integration of AI and XR for optimizing the entire architectural process. Current literature demonstrates advancements in design creation and visualization, but a comprehensive approach that encompasses assessment, evaluation, redesign, and enhancement of spaces through AI and XR is still lacking. Long-term studies focusing on user adaptation to AI and XR augmented spaces are also vital. Understanding how users interact with and adapt to these environments over extended periods is crucial for designing user-centric spaces. Furthermore, there is a need for more focused application of human-centered design principles in AI and XR technologies, incorporating aspects like environmental psychology, ergonomics, and user-centric methodologies. The adaptability of AI and XR technologies to different cultural and environmental contexts is another area requiring more research. This includes understanding how these technologies can be tailored to various architectural styles and regional needs. Economic aspects, such as the feasibility and scalability of AI and XR applications in architecture, are also areas that warrant further investigation to determine their viability across different project scales. With the increasing implementation of AI and XR, ethical and privacy challenges are emerging as critical concerns. Comprehensive research focusing on data security and ethical implications is essential. The capability of AI for real-time data processing within XR environments is another gap that needs exploration. This is crucial for developing dynamic and responsive architectural designs. Moreover, there is a noticeable lack of interdisciplinary research approaches. Integrating architectural design with fields like psychology, sociology, and environmental science is essential for creating holistic design solutions. Lastly, the current research often lacks diversity in application and contextual relevance, especially in terms of sustainability, urban development, accessibility, and inclusivity.

Addressing these gaps is essential for the advancement of architectural design, especially in the context of rapidly evolving AI and XR technologies. Bridging these gaps will not only deepen theoretical understanding but also enhance practical applications, leading to more innovative, efficient, and human-centric architectural solutions.

5.4 Suggesting Future Research Directions

The comprehensive analysis of current studies in the realm of Artificial Intelligence (AI) and Extended Reality (XR) in architecture has led to the proposition of several key future research directions that aim to further explore and expand the field.

There is a significant opportunity to delve into the integration of advanced AI techniques, like deep learning and neural networks, within XR environments. Such exploration could substantially improve the realism and interactivity of XR applications in architecture, offering more immersive and effective design solutions. In terms of comprehensive integration, there is a need for research that develops methodologies for the full-scale integration of AI and XR.

Table VI: Code Book

Name	Description	Files	References
Al and XR Technologies		13	107
Integration Strategies of Al/XR in design	Techniques and methodologies for embedding Al and Extended Reality (XR) in the design process.	7	22

User Interface adaptations in Al/XR	Modifications and enhancements of interfaces facilitated by Al and XR technologists.	1	2
Role of Al/ XR in collaborative design	Contributions and impact of Al and XR in facilitating collaborative design processes.	12	83
Case Studies or Practical Applications		12	82
Impact analysis of Implemented Solutions	Evaluation and assessment of the effects resulting from the implementation of AI and XR solutions.	12	82
Comparative studies of before and after scenarios	Comparative analysis conducted to examine conditions before and after the application of Al/XR solutions.	2	4
Longitudinal studies of AL/XR implementation	Comprehensive studies tracking the implementation and evolution of Al and XR solutions over extended periods.	1	2
Challenges and Limitations		8	55
Integration challenges with existing infrastructure	Obstacles and complexities encountered when incorporating Al and XR into pre-existing systems.	5	22
User acceptance and adaptability	Understanding how users perceive and adapt to Al/XR technologies.	6	33
Scalability issues of Al/XR solutions	Considerations regarding the ability of Al/XR solutions to scale effectively.	5	12
Ethical and Privacy Considerations		1	1
Bias and fairness in Al algorithms	Examination of partiality and equity issues arising from Al algorithms.	1	1
Long-term societal impacts	The enduring effects of Al and XR on society over extended periods.	7	16
User consent and transparency protocols	Protocols and guidelines ensuring transparency and obtaining user consent in ALXR systems.	3	10
Evaluation Techniques		7	23
User feedback mechanisms	Mechanisms and systems established to collect and process user feedback.	5	14
Environmental impact assessment	Evaluation of the ecological effects resulting from the application of AI/XR.	6	12
Long-term performance tracking	Ongoing monitoring and evaluation of Al/XR systems' performance over time.	3	9
Future Directions		12	96

Al/XR in disaster resilience and emergency planning	Application of Al/XR in enhancing resilience and planning for emergency situations.	7	48
Predictive analytics in design evolution	Use of predictive analytics to foresee and influence the evolution of design.	6	48
Interdisciplinary collaborations opportunities	Opportunities for collaborative efforts between various disciplines facilitated by AI/XR.	7	52
Human-Centered Design		3	8
Ergonomic considerations in design	Considerations and adjustments ensuring comfort and usability in Al/XR-based designs.	3	7
Psychological impacts on users	Exploration of psychological effects and influences of Al/XR on users.	8	22
Accessibility and Inclusivity factors	Factors ensuring that Al/XR systems are accessible and inclusive for all users.	1	1
Optimization Strategies		12	96
Sustainable design adaptations	Modifications in design aimed at environmental sustainability, aided by Al/XR.	7	48
User adaptability and flexibility	Assessment of users' ability to adapt and be flexible in utilizing AILXR technologies.	6	48
Cost-effectiveness and resource efficiency.	Analysis of cost-effectiveness and efficient resource utilization in Al/XR implementations.	7	52

This would involve evaluating, redesigning, and enhancing existing architectural spaces, tackling the challenges of technological integration and its applicability in diverse architectural scenarios. Another important area is the focus on user-centered design in long-term applications. Investigating how users adapt to and interact with AI and XR-enhanced environments over time, with particular attention to user behavior, comfort, and satisfaction, is essential for creating spaces that truly meet user needs. The research should also extend to AI and XR applications in varied cultural and environmental contexts. This involves exploring how these technologies can be adapted to different cultural sensibilities and environmental constraints, ensuring their relevance and effectiveness across a broad spectrum of settings. Economic analysis and scalability are also crucial areas for future research. This includes examining the cost-effectiveness, economic viability, and scalability of AI and XR applications in architecture, crucial for their widespread adoption. Addressing ethical considerations and data privacy is increasingly important as AI and XR technologies become more integrated into architectural design. Future research needs to explore issues of data security, user consent, and the broader ethical implications of these technologies.

The potential of real-time data processing and integration in architectural design using AI and XR is another promising area. This could lead to more responsive and adaptable designs, capable of evolving in real time according to changing data inputs. Interdisciplinary methodologies in architectural design, incorporating insights from psychology, sociology, and environmental sciences, are needed to create holistic and sustainable design solutions. This approach can lead to more comprehensive and multi-faceted architectural strategies. Broadening the scope of AI and XR applications in architecture to include sustainable urban planning, emergency response, historical preservation, and adaptive reuse projects can also provide new insights and applications for these technologies. Lastly, understanding the impact of AI and XR on architectural education and professional training is crucial. This includes how these technologies are shaping the skills and perspectives of future architects, and their role in the evolving landscape of architectural design and practice.

In summary, these suggested directions for future research underscore the vast potential and the need for continued exploration in the integration of AI and XR in architecture, promising to advance the field in diverse and impactful ways.

5.5 Limitations of the Study

In conducting our research on the integration of Artificial Intelligence (AI) and Extended Reality (XR) in architectural design, we encountered several limitations that are important to acknowledge for a comprehensive understanding of our findings.

Firstly, the scope of the literature reviewed, while providing valuable insights, only covers a segment of the extensive and rapidly evolving research in AI and XR applied to architectural design. This limitation means that not all pertinent developments or viewpoints in this field may have been fully captured. Additionally, the process of article selection, governed by specific criteria, might have inadvertently introduced biases. This could favor certain types of studies while potentially overlooking emergent research areas, leading to a potentially skewed portrayal of AI and XR integration in architectural design. The generalizability of our findings is another concern. The studies we reviewed are context-specific and may not be universally applicable across different architectural practices or geographical locations. Variations in access to AI and XR technologies across regions and architectural firms further complicate this issue. The rapid evolution of AI and XR technologies also poses a challenge. Keeping our review current and relevant is difficult given the swift pace of advancements in these fields. Technological constraints and data accuracy are significant hurdles as well. Challenges such as integrating the Internet of Things (IoT) with Virtual Reality (VR), ensuring the seamless operation of 5G technology, and rendering high-fidelity VR environments are substantial. Furthermore, the accuracy of data interpretation, like EEG data in VR environments, critically impacts the effectiveness of design solutions. The complexity of AI algorithms and their practical application in diverse architectural contexts is another notable concern. This includes developing and implementing sophisticated optimization algorithms and machine vision systems. Economic aspects like scalability and cost-effectiveness have not been thoroughly investigated in the existing literature. This gap highlights the need for more comprehensive economic analyses of AI and XR applications in architecture. Ethical considerations and data privacy in AI and XR integration in architectural design also require more in-depth exploration to address emerging concerns effectively. The review process itself presents limitations. Variability in study design and methods, geographical and contextual constraints, rapidly evolving technologies, and potential biases in primary studies create challenges in drawing uniform conclusions and ensuring the long-term relevance of our findings. Lastly, capturing the interplay between technological, architectural, and human factors is complex. There may be limitations in fully integrating these multidisciplinary perspectives, which is crucial for a holistic understanding of AI and XR applications in architecture.

In summary, while our research provides valuable insights into the integration of AI and XR in architectural design, these limitations highlight the need for continued exploration and adaptation in this dynamic field.

6. Conclusion

This research, incorporating insights from key studies in AI and XR in architecture, highlights the transformative role these technologies play in modern architectural design. AI and XR are not just technological advancements but represent a paradigm shift towards dynamic, responsive architectural spaces that cater to human needs and environmental changes.

The integration of AI and XR brings innovative approaches to design, enhancing user experience and interaction. However, challenges such as the complexities of integration, the need for sophisticated algorithms, and addressing ethical concerns around data privacy remain. There are also gaps in long-term user adaptation, cross-cultural applications, and economic feasibility. The future of architectural design, as indicated by this research, points towards spaces that are more adaptive, personalized, and attuned to emotional and psychological needs. This requires a careful balance between technological advancement and ethical considerations. Future research should focus on developing holistic methodologies that synergize AI and XR, emphasizing human-centered design. In summary, AI and XR in architecture promise a new era of design aligning technological innovation with human-centric principles. While challenges exist, the potential for revolutionizing architectural practices is immense, opening new avenues for exploration and innovation in creating responsive and sustainable architectural spaces.

7. Funding

In accordance with the PRISMA-ScR guidelines, specifically ITEM 22 on funding, it is pertinent to disclose that our scoping review was conducted without any external financial support. This research, including all phases from conception to analysis and reporting, was self-funded and carried out independently. The absence of external funding ensures that there were no influencing factors from funders, thus maintaining the independence and unbiased nature of the research. The transparency in this aspect underscores our commitment to academic and ethical research standards.

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