

Innovative Applications of XR in Architectural Sustainability: Current Trends and Future Prospects

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Abstract: Due to the limited global resources and the threat of climate change, sustainable development has become a critical issue. This study aims to delve into the various applications of Extended Reality (XR), including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), in sustainable architectural design. Through virtual experiences, visualisation of architectural ecosystems, BIM integration, and environmental simulations, XR technology provides designers with a more comprehensive dataset and perspective. However, despite showcasing the potential of XR technology, further research and practical implementation are necessary to deepen our understanding of its role in architectural sustainability and address potential technological and application challenges. The article emphasizes the need to holistically consider multiple dimensions of data when applying XR technology in architectural design, enabling a more comprehensive evaluation of the sustainability of design solutions.

Keywords: Extended Reality (XR), Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Architectural Sustainability.

1. Introduction

The widespread application of digital and innovative technologies has profoundly transformed architecture and infrastructure design methodologies, establishing a closer interconnection between the digital and physical realms. [1] This transformation offers more energy-efficient, comfortable, and sustainable solutions for the built environment. It presents new opportunities for the architectural field to address the challenges of limited global resources and urgent climate change.

With the rapid evolution of information technology, the introduction of Extended Reality (XR) technology has injected new perspectives and choices into pursuing sustainable development in architecture. As an advanced technology, XR facilitates users' establishing a closer interaction between the digital and physical worlds, providing innovative tools and perspectives for the architectural environment. This introduces novel ideas and choices for the sustainable development of architecture and plays a crucial role at various stages of architectural design, particularly in driving sustainability checks using data (Fig. 1).

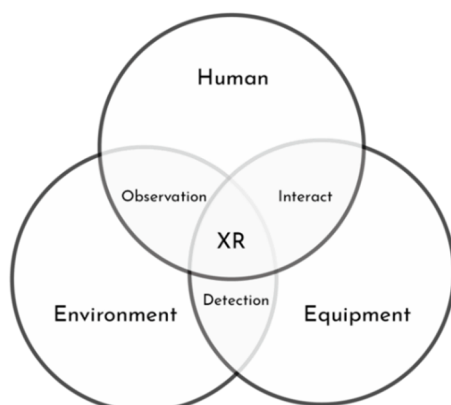


Figure 1. XR technology about the environment and equipment

Extended Reality (XR) is a comprehensive term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies, all aimed at blurring the boundaries between the real world and virtual environments. XR technology, known for its visualization and interactivity, is distinguished by its ability to overlay virtual information onto the real world. Through visual, auditory, and potential olfactory and tactile cues, XR technology achieves a fully immersive user experience.[2]

Over the past five years, the literature on applying XR technology in architecture has gradually increased. However, there still needs to be more research specifically addressing operational aspects. Recent studies have focused on applying XR in sustainable architecture, including design simulations, virtual walkthroughs, and spatial perception.[3] In design and architectural engineering cases, VR technology is a common application, with platforms like Unity3D and Unreal Engine widely used.[4] Autodesk's tools, such as Revit and AutoCAD and AR-specific tools, like Autodesk BIM 360 Layout, enable architects and engineering professionals to create detailed 3D building models, providing a rich data foundation for AR. [5]

However, the current application of XR technology is predominantly found in the creative industries such as video entertainment and gaming. The integration of XR with Building Information Modeling (BIM) is still in its early stages. [6] As the Architecture, increasingly focuses on sustainable construction, discussions around green building design, energy efficiency, and overall sustainability have gained traction. However, most XR applications in this context primarily concentrate on the pre-construction phases, with visualization and interactivity being the predominant features. [7] The current implementation of XR technology faces ongoing technical challenges. Nevertheless, XR technology holds immense potential in enhancing efficiency and productivity in the AEC domain. The widespread acceptance of XR technology in the construction industry serves as inspiration for sustainable development. [8] Future research is expected to delve deeper into applying XR

technology in sustainable construction, potentially reshaping certain work practices and disciplinary processes, and fostering more innovation and improvements.

2. Methodology

As previously discussed, Extended Reality (XR) technology presents significant potential for sustainable development in the field of architecture. The integration of XR technology into various stages of the architectural project lifecycle is crucial for advancing architectural sustainability. However, to gain a more comprehensive understanding of the practical contributions of these systems in real architectural environments, particularly in existing and ongoing projects, in-depth case analyses are necessary. Through a detailed examination of XR technology applications in different projects, we can gain clearer insights into its impact on various aspects of architectural design, including conceptualization, processes, and enhancements. These case analyses also aid in identifying challenges that may arise in practical applications, offering more specific guidance for future sustainable architectural design.

In light of the swift progression of these technologies, this paper aims to investigate the research corpus of XR technology in the sustainable development of the architectural field over the past five years. By integrating the latest developmental data and case studies in this field through literature search, screening, and summarization, the objective is to analyze specific themes and the diversity of collected works. The goal is to comprehend the recent advancements of Extended Reality technology in the architectural domain, explore relevant application cases, and examine existing research outcomes. Conducting the research trends of XR in sustainable architecture and unveiling potential gaps between research trends and actual scientific achievements. (Fig. 2)

The review theme is gathered through major online specialized repositories and search engines such as Scopus, Web of Science, and Google Scholar. Influential journals and other relevant works listed in major academic publishing companies are collected through surveys. The paper employs a set of specific keywords for website queries to ensure consistency with the paper's objectives. Using terms like "Extended Reality (XR)," "Virtual Reality (VR)," "Augmented Reality (AR)," and "Mixed Reality (MR)," and their combinations with keywords related to sustainable construction, green building, sustainable architecture, sustainable development, building information modelling (BIM), and digital innovation. The inquiry yielded 104 articles, steadily rising, signifying the increasing interest in the industry's practical implementations of these technologies.

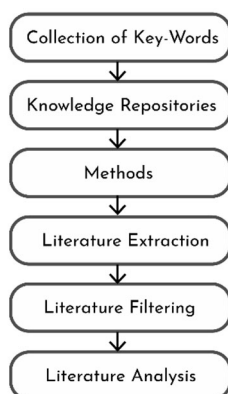


Figure 2. Literature Search Flowchart

3. Discussion: Integration and Application of XR Technology in the Early Stages of Architectural Design

This chapter explores the manifold positive impacts of XR technology in architectural design, encompassing its role in providing an intuitive design experience and early detection of sustainability issues during the conceptual phase. XR technology engages with three key aspects in the creative architectural design process: conceptualization, knowledge integration, and environmental considerations. [9] In the subsequent stages, the focus will be on how XR technology facilitates collaborative design through multi-dimensional data integration, fostering interdisciplinary data exchange, enhancing work efficiency, and aiding in considering sustainability factors. Additionally, the chapter will delve into the post-design application of XR technology, encompassing the validation and improvement of designs, promoting user engagement and education through the simulation of real-world scenarios in virtual environments, thereby elevating users' awareness of architectural sustainability. This exploration concentrates on the innovative applications of XR technology, substantiated by authentic case studies, highlighting its potential to enhance efficiency and quality in architectural design.

3.1. Conceptual Phase: Real-time Visualization and Communication

In the contemporary field of architectural design, the utilization of XR technology showcases considerable potential, fostering progress within the architecture industry towards enhanced sustainability. [10] During the initial design phase, leveraging XR technology facilitates the development of design concepts, allowing designers to creatively ideate and generate innovative design proposals within a shared augmented environment. Through the examination of design concepts and the simulation of design scenarios, XR technology assists architects in reviewing and testing various design scenarios, validating design solutions, and accessing project information in real time within an enhanced environment. The transformative potential of XR technology, with its high level of immersion and engagement, encourages a more comprehensive consideration of sustainability factors throughout the design process and aids designers in intuitively understanding design concepts. [11]

Huang and colleagues propose using VR and other technologies for real-time visualization of building performance under different conditions, facilitating better design adjustments and improving sustainability. [12] This contributes to real-time experiences and adjustments of architectural solutions, ensuring a more comprehensive consideration of sustainability factors, such as energy efficiency and environmental adaptability. This is crucial for sustainable design, as decisions regarding buildings' environmental adaptability and energy efficiency can be comprehensively considered at the early stages of design.

Virtual Reality (VR) has not only transformed the approach to architectural design but has also presented opportunities for optimizing the design of green buildings. The need for physical prototypes in visual design has been reduced by employing real-time rendering and VR technology, thereby minimizing material waste. Architects engage in virtual experiments, such as observing sunlight exposure, experimenting with different light cycles, and adjusting

building orientations to reduce energy costs or optimize solar energy systems. [13] This offers significant opportunities for users to engage deeply in virtual environments, and interactivity aids in enhancing users' practical understanding of the impacts of climate change, creating a robust experiential basis for fostering sustainable behaviours and awareness. The application of VR technology in architectural design underscores its potential to create immersive design experiences, extending beyond flat drawings and models. Through real-time rendering of architectural designs in VR, designers gain a more intuitive understanding of the relationship between buildings and their surrounding environments. [14]

3.2. Design proposal phase: multidimensional data integration and synergy

In architecture, XR technology has been successfully integrated into multidisciplinary design systems, fostering collaboration among professionals from different fields. Building Information Modeling (BIM) integrates multidimensional data into the design process, encompassing energy usage, material selection, structure, and greenery.[15] Designers can acquire a holistic comprehension by utilizing visualization tools, aiding in making more balanced and sustainable decisions to optimize architectural designs and meet diverse sustainability requirements.

The experiential focus of XR technology's application on construction sites is particularly prominent, especially concerning materials and equipment.[16] In modern architectural design, interdisciplinary collaboration and collaborative design are crucial, and applying XR technology opens up new possibilities for integrating multidimensional data and team collaboration. David Gillespie's XR platform, Glaucon, extends beyond visualization, allowing experiences in fully immersive, collaborative virtual environments. This platform aims to directly present the experiential aspects of architectural projects to on-site environments, providing a deeper understanding of the experience within that space, compatible with a wide range of XR hardware systems.[17] Team members can enter a shared virtual space through VR headsets, enabling real-time collaboration and design evaluation. This innovative platform supports real-time model interaction and editing and facilitates more efficient communication and feedback through remote client presentations and design discussions within the virtual environment.

Several studies observed applying data extracted from Building Information Models (BIM) to the context of Digital Twins. Take the EASEE project in Italy as an example. BIM technology is utilized to design prefabricated insulation board systems precisely, creating information-rich models by embedding physical and material information. Integrating information from various data sources enhances the efficiency of design and installation. [18]

In conclusion, XR technology demonstrates significant potential in multidimensional data integration, collaborative design, and interdisciplinary collaboration. This presents a promising avenue for achieving more sustainable designs and developments in architecture through further research and innovative applications of these technologies.

3.3. Verification of the improved design phase: User Involvement and Education

The XR technology in the field of architecture provides

users with opportunities to interact with buildings; they are progressively gaining ground in user participation and education within architectural design, offering multifaceted benefits to the design process.

Augmented Reality (AR) technology holds significant potential in 3D and 2D information. [19] Research conducted by Saeed et al. introduces mobile Augmented Reality (AR) technology, fostering deeper public engagement in the planning and design processes. Implementing an Augmented Reality Participatory Platform (ARPP), [20] particularly in resource-deprived communities, has opened new avenues for improving the design of community walkways. The platform consists of a mobile AR application, a cloud database and a real-time mapping service that facilitates two-way communication between community residents and decision makers. The ARPP holds promise in promoting sustainable architectural design and implementation, supporting a sustainable circular economy with easily disassembled and recycled designs. This tool has the potential for positive impacts on sustainability and public engagement in community planning.

One notable tool in this domain is XREmul, developed by researchers like Jaewon Choi, [21] serving as a Unity3D development environment plugin. The tool's design objective is to abstract input streams from complex data sources, providing applications with a unified input acceptance channel and efficiently supporting the recording and playback of user input activities. Research also suggests that integrating XR technology can significantly reduce teaching time, minimize waste from manual model creation, and provide students with modifications for design convenience, aiding in a better understanding of damaged building characteristics and structures. [22]

In conclusion, XR technology injects new perspectives and means into the sustainability of architectural design by providing powerful design tools, enhancing collaboration, and promoting user engagement.

4. Limitations and Perspectives: The Road to XR Technology in Building Sustainability

XR technology presents rich possibilities for sustainability in architectural design. Through virtual experiences, visualization of architectural ecosystems, BIM integration, and precise environmental simulations, designers can access comprehensive data and perspectives, potentially steering the architecture industry towards greater sustainability. Despite existing cases showcasing the potential of XR technology, further research and practical applications are needed to deepen our understanding of its role in architectural sustainability and address associated challenges.

At the technical level, challenges in real-time processing, accuracy, and hardware compatibility may arise during the design phase. [23] The high cost and technical requirements of XR technology could limit its widespread adoption. [24] Additionally, the perceptual differences within virtual environments demand attention. The multidimensional integration of data involves challenges related to data standards and sharing among professionals in different fields. [25] Furthermore, different users' varying perceptions and experiences in virtual environments may impact the effectiveness of design assessments and shared conceptualizations. Ensuring seamless integration of various

data sources to comprehensively understand the sustainability impacts of design proposals remains a significant challenge. Hence, conducting thorough investigations into the diversity of user experiences and engagement becomes imperative to enhance the implementation of XR technology during the design phase. While existing cases predominantly focus on the physical conditions and characteristics of construction sites in XR applications, future research should delve deeper into how multiple data dimensions can be synthetically considered in virtual environments to evaluate design sustainability comprehensively.

Prospects include advancing the integration of BIM and XR technologies to address challenges in multidimensional data integration. Intelligent design-assistive tools and more sophisticated collaborative platforms are anticipated to be pivotal in the development of the design phase. Simultaneously, ongoing upgrades in virtual reality technology's hardware and software are expected to provide smoother, more realistic user experiences. In summary, these developments offer new horizons for the sustainability of architectural design.

5. Conclusions

The widespread application of XR technology in architectural design presents a significant potential for enhancing sustainability across various stages. From real-time visualization in the conceptual phase to integrating multidimensional data and collaboration in the design stage and designing and improving designs through user engagement and education, XR technologies offer novel perspectives and methodologies for advancing architectural sustainability. Nevertheless, it is crucial to acknowledge the array of challenges and limitations accompanying this technological wave. Issues such as cost, learning curves, the complexity of data integration, and divergent user experiences necessitate in-depth research and innovative solutions. Addressing these challenges requires interdisciplinary efforts to facilitate the broader adoption of XR technology in the field of architecture.

Looking ahead, with continuous technological evolution and deeper application penetration, XR technology is poised to play a more pivotal role in architectural design, emerging as a central driving force for digital transformation and sustainable development. Ongoing efforts are imperative to overcome technical, cost-related, and user experience challenges, ensuring the full realization of XR technology's potential in enhancing architectural sustainability. In summary, XR technology not only introduces new perspectives for sustainable design and development but also steers the architectural realm towards the shared goals of digitization and sustainability.

References

- [1] Han, B., & Leite, F. (2022). Generic extended reality and integrated development for visualization applications in architecture, engineering, and construction. *Automation in Construction*, 140, 104329. <https://doi.org/10.1016/j.autcon.2022.104329>
- [2] Çöltekin, A., Lochhead, I., Madden, M., Christophe, S., Devaux, A., Pettit, C., Lock, O., Shukla, S., Herman, L., Stachoň, Z., Kubíček, P., Snopková, D., Bernardes, S., & Hedley, N. (2020). Extended Reality in Spatial Sciences: A Review of Research Challenges and Future Directions. *ISPRS International Journal of Geo-Information*, 9(7), Article 7.
- [3] Li, H., Fang, S., Chen, L., Menadue, V., & Martin, S. (2023). Extended reality (XR)—A magic box of digitalization in driving sustainable development of the construction industry: A critical review. *Sustainable Development*. Scopus.
- [4] Bressan, N. M., Scarpa, M., & Peron, F. (2024). Case studies of eXtended reality combined with Building Information Modeling: A literature review. *Journal of Building Engineering*, 84, 108575.
- [5] Potseluyko, L., Pour Rahimian, F., Dawood, N., Elghaish, F., & Hajirasouli, A. (2022). Game-like interactive environment using BIM-based virtual reality for the timber frame self-build housing sector. *Automation in Construction*, 142, 104496.
- [6] Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*, 116, 103254.
- [7] Balzani, R., Barzaghi, S., Bitelli, G., et al. (2024). Saving temporary exhibitions in virtual environments: The Digital Renaissance of Ulisse Aldrovandi – Acquisition and digitisation of cultural heritage objects. *Digital Applications in Archaeology and Cultural Heritage*, 32, e00309.
- [8] Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*, 116, 103254.
- [9] Abhari, M., Abhari, K., Drinkwine, M., & Sloan, J. (2021). Extended Reality (XR) Applications in Architectural Practice: Towards a Development Framework. *HCI International 2021 - Late Breaking Papers: Multimodality, eXtended Reality, and Artificial Intelligence*, 185–196.
- [10] Li, H., Fang, S., Chen, L., Menadue, V., & Martin, S. (2023). Extended reality (XR)—A magic box of digitalization in driving sustainable development of the construction industry: A critical review. *Sustainable Development*. Scopus.
- [11] Stanney, K. M., Nye, H., Haddad, S., et al. (2021). Extended Reality (xr) Environments. In *HANDBOOK OF HUMAN FACTORS AND ERGONOMICS* (pp. 782–815). John Wiley & Sons, Ltd.
- [12] Huang, J., Lucash, M. S., Scheller, R. M., & Klippel, A. (2019, March). Visualizing ecological data in virtual reality. In 2019 IEEE conference on virtual reality and 3D user interfaces (VR) (pp. 1311-1312). IEEE.
- [13] Suryawinata, B., & Mariana, Y. (2022). The Role of Virtual Reality in Green Building Design. *IOP Conference Series: Earth and Environmental Science*, 998, 012037.
- [14] AlQallaf, N., Bhatti, S., Suett, R., Aly, S. G., Khalil, A. S. G., & Ghannam, R. (2022). Visualising Climate Change using Extended Reality: A Review. 2022 29th IEEE International Conference on Electronics, Circuits and Systems (ICECS), 1–4.
- [15] Chen, L., & Wang, J. (2020). Application Research of Virtual Reality Technology in Green Building Design. 2020 5th International Conference on Smart Grid and Electrical Automation (ICSGEA), 249–253.
- [16] Muñoz-La Rivera, F., Mora-Serrano, J., & Oñate, E. (2024). A Critical Review of How EXTENDED REALITY (XR) HAS ADDRESSED KEY FACTORS INFLUENCING SAFETY ON CONSTRUCTION PROJECTS (fSCPs). *Archives of Computational Methods in Engineering*, 1–34.
- [17] Gillespie, D., Qin, Z., & Tsigkari, M. (2023). Augmenting Design: Extending Experience of the Design Process with Glaucon, An Experiential Collaborative XR Toolset. *Towards Radical Regeneration*, 332–342.
- [18] Banfi, F., Brumana, R., Salvalai, G., & Previtali, M. (2022). Digital Twin and Cloud BIM-XR Platform Development: From Scan-to-BIM-to-DT Process to a 4D Multi-User Live App to

- Improve Building Comfort, Efficiency and Costs. *Energies*, 15(12), Article 12.
- [19] Raybourn, E. M., Stubblefield, W. A., Trumbo, M., et al. (2019). Information Design for XR Immersive Environments: Challenges and Opportunities. In J. Y. C. Chen & G. Fragomeni (Eds.), *Virtual, Augmented and Mixed Reality. Multimodal Interaction* (pp. 153–164). Springer International Publishing.
- [20] Ahmadi Oloonabadi, S., & Baran, P. (2023). Augmented reality participatory platform: A novel digital participatory planning tool to engage under-resourced communities in improving neighborhood walkability. *Cities*, 141, 104441.
- [21] Choi, J., Jeong, S., & Ko, J. (2022). Emulating Your eXtended World: An Emulation Environment for XR App Development. 2022 IEEE 19th International Conference on Mobile Ad Hoc and Smart Systems (MASS), 131–139.
- [22] Wang, J., Ma, Q., & Wei, X. (2023). The Application of Extended Reality Technology in Architectural Design Education: A Review. *Buildings*, 13(12). Scopus.
- [23] Akyildiz, I., & Guo, H. (2022). Wireless communication research challenges for Extended Reality (XR). 3, *ITU Journal on Future and Evolving Technologies (ITU J-FET)*.
- [24] Stals, A., & Caldas, L. (2022). State of XR research in architecture with focus on professional practice – a systematic literature review. *Architectural Science Review*, 65(2), 138–146.
- [25] Theodoropoulos, T., Makris, A., Boudi, A., et al. (2022). Cloud-based XR Services: A Survey on Relevant Challenges and Enabling Technologies. *Journal of Networking and Network Applications*, 2, 1–22.