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Transforming Sustainable Architecture through Extended Reality (XR): A Cognitive and Decision-Support Framework for Sustainable Architectural Design

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Abstract

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The Architecture, Engineering, and Construction (AEC) sector significantly impacts worldwide energy consumption and greenhouse gas emissions, necessitating sustainable and data-driven design practices. Extended Reality (XR), comprising Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has surfaced as a revolutionary digital technology that enhances sustainability-focused architectural decision-making. Nonetheless, current research has mostly concentrated on visualization capabilities, offering limited empirical information concerning XR's cognitive and behavioral effect on achieving sustainability results. This research fills this gap by employing a mixed-method research strategy that combines a PRISMA-based systematic literature review with a quantitative empirical investigation utilizing structural equation modeling (SEM). A total of 214 valid replies were obtained from professionals and academics in architecture, engineering, and construction in the MENA area. The results indicate that XR usability markedly improves sustainability understanding ($\beta = 0.65, p < .001$) and user engagement ($\beta = 0.68, p < .001$), both of which positively affect decision-making efficiency. The SEM model demonstrated robust fit indices (CFI = 0.948; RMSEA = 0.052), validating the suggested conceptual framework. This study contributes conceptually by integrating experiential learning theory, embodied cognition, and human-centered decision-making into the field of XR research. The findings demonstrate XR as a cognitive and decision-support system that enhances sustainable design outputs throughout the building's lifetime.

Keywords: Extended Reality (XR); Immersive Technologies; Energy Efficiency; Sustainable Architecture; Design Innovative.

1. Introduction

Sustainable architecture has emerged as a vital worldwide priority due to climate change, fast urbanization, and escalating environmental damage. The Architecture, Engineering, and Construction (AEC) industry accounts for almost 40% of global energy consumption and around one-third of greenhouse gas emissions, making sustainability-focused digital transformation increasingly crucial. Despite advancements in Building Information Modeling (BIM), simulation systems, and sustainability assessment tools for environmental analysis, numerous architectural professionals continue to encounter difficulties in converting complex environmental data into implementable design strategies (Alizadehsalehi et al., 2020; Li et al., 2023; Casini, 2022).

In regard to these challenges, Extended Reality (XR), comprising Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has emerged as a potential technology ready to revolutionize architectural design and sustainability practices. XR provides immersive and interactive environments that allow architects and stakeholders to observe, assess, and enhance sustainability-related decisions more efficiently than traditional visualization tools. In contrast to conventional 2D and 3D tools, XR facilitates real-time engagement with environmental simulations, thereby enhancing embodied cognition, experiential learning, and collaborative design exploration (Li et al., 2023; Zhou, 2024).

Recent studies demonstrate that XR significantly boosts spatial cognition and augments users' capacity to interact with sophisticated design settings. XR enhances understanding, promotes informed decision-making, and fosters cooperation among stakeholders by converting abstract sustainability data into immersive experiences (Casini, 2022; Safikhani et al., 2022). A combination of XR with Building Information Modeling (BIM) and Digital Twin technologies enhances its functionalities via real-time data interchange, predictive analytics, and lifecycle performance assessment (Bressan et al., 2024; Yeom et al., 2024).

From a sustainability perspective, XR enhances many phases of the building lifespan. In the design and preconstruction phases, XR facilitates visualization, simulation, and crash detection, therefore minimizing design mistakes and material waste. During the operation and maintenance stages, XR combined with Digital Twins facilitates data-driven energy management and predictive maintenance, enhancing building efficiency and occupant comfort (Casini, 2022; Yeom et

al., 2024). At the urban level, XR enables participatory planning and scenario modeling, promoting sustainable city development in accordance with global sustainability frameworks like the Sustainable Development Goals (Liu et al., 2024).

Despite these benefits, the existing database of research reveals numerous major limitations. The majority of XR applications mainly concentrate on the initial design phases, showing limited adoption over the whole construction lifecycle. Moreover, empirical research assessing the long-term sustainability effects of XR such as quantifiable energy conservation and carbon reduction—remains limited (Li et al., 2023; Zhou, 2024). Challenges related to financial costs, interoperability, technical infrastructure, and user engagement continuously prevent widespread implementation (Casini, 2022; Bressan et al., 2024).

Therefore, whereas XR technologies have transformational potential for enhancing sustainable architecture, further study is necessary to quantify their effect and to create cohesive frameworks that link design, building, operation, and post-occupancy stages. Recognizing these gaps is crucial for completely actualizing the potential of XR as a catalyst for sustainable development in the built environment.

1.1. Problem statement

Limited resources and climate change make sustainable architecture a global priority. Extended Reality (XR) provides innovative methods for visualizing, simulating, and managing buildings and urban environments with enhanced efficiency and sustainability (Zhou, 2024; Li et al., 2023; Yeom et al., 2024; Casini, 2022; Mohammadrezaei et al., 2024; Shehadeh et al., 2025; Liu et al., 2024). Research covers design, building, operation, urban planning, heritage, work practices, and education; yet, evidence on the long-term sustainability impact remains in its early phases (Li et al., 2023).

Despite the existence of simulation tools and sustainability frameworks, architects frequently encounter challenges in converting complex environmental data into implementable design ideas. Current XR research predominantly concentrates on imagery and user experience, with minimal attention to the following:

- Cognitive transformation: In what manner does XR impact design thinking?
- Behavioral influence: Does XR affect sustainability choices?
- Empirical validation of environmental performance gains: Are quantifiable outcomes achievable?

1.2. Research gap

Based on the synthesis of documents, the following gaps are identified:

- Lack of empirical validation using advanced statistical models (SEM)
- Fragmented research across lifecycle stages (design-dominant focus)
- Limited longitudinal evidence on energy and carbon reduction
- Underrepresentation of Mixed Reality (MR) in sustainability contexts
- Weak integration of XR with digital twins (DT) and BIM across lifecycle stages

1.3. Research objectives

This study advances current research by integrating technology adoption, cognitive understanding, and behavioral engagement into a unified empirical framework. The research contributes to the literature in four major ways:

1. It develops a human-centered XR-sustainability conceptual framework grounded in Experiential Learning Theory (Kolb, 1984) and embodied cognition theory.
2. It empirically validates the cognitive and behavioral impact of XR using Structural Equation Modeling (SEM).
3. It demonstrates that sustainability understanding mediates the relationship between XR usability and decision efficiency.
4. It extends XR research beyond visualization toward decision-support and sustainability-driven architectural practice.

1.4. Research questions

RQ0: Main Research Question: How does Extended Reality (XR) influence sustainable architectural decision-making through cognitive and behavioral mechanisms?

RQ1: XR Cognitive Impact: How does XR usability affect sustainability understanding in architectural design?

RQ2: XR Behavioral Impact: How does XR usability influence user engagement during the design process?

RQ3: Cognition for Decision-Making: To what extent does sustainability understanding improve decision efficiency in architectural design?

RQ4: Engagement for Decision-Making: How does user engagement influence decision efficiency in XR-based design environments?

RQ5: Integrated Mechanism: How do cognitive (understanding) and behavioral (engagement) factors mediate the relationship between XR usability and decision efficiency?

1.5. The research hypotheses

The study hypotheses were created directly from the research questions as shown in (Figure 1, Table 1) to empirically examine how Extended Reality (XR) influences sustainable architectural decision-making via cognitive and behavioral mechanisms. Each hypothesis assesses a unique relationship indicated in the study questions, bridging theoretical inquiry and quantitative empirical validation.

H1: XR usability positively affects sustainability understanding

H2: XR usability positively affects user engagement.

H3: Sustainability understanding positively affects decision efficiency.

H4: User engagement positively affects decision efficiency.

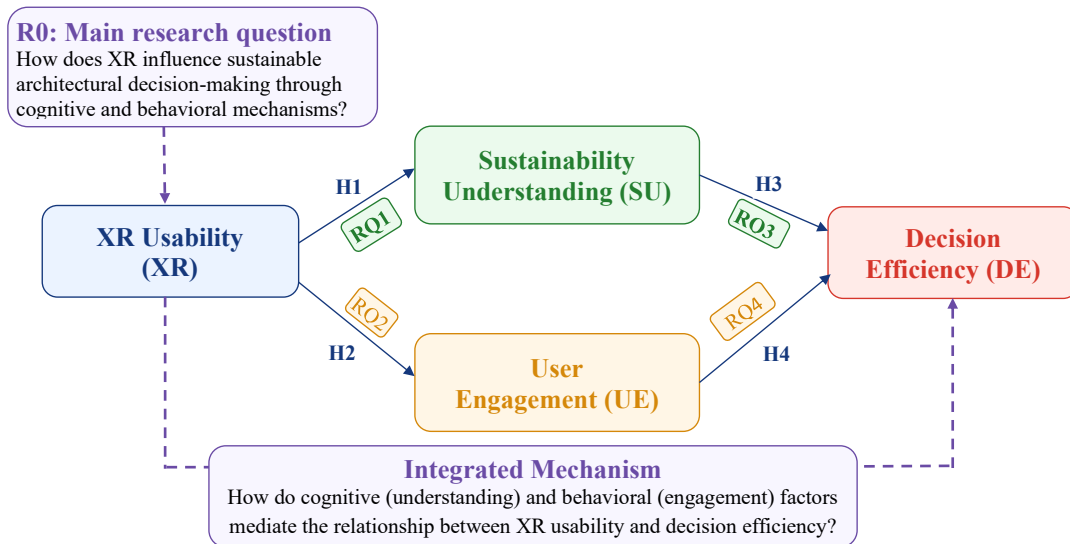


Figure 1. Conceptual framework and hypothesized structural model (Author).

Table 1: Linking research hypotheses and research questions (Author)

Hypothesis	Hypothesis statement	Questions	Research question understanding
H1	XR usability positively affects sustainability understanding	RQ1	Effect of XR usability on sustainability understanding
H2	XR usability positively affects user engagement.	RQ2	Effect of XR usability on user engagement
H3	Sustainability understanding positively affects decision efficiency.	RQ3	Effect of sustainability understanding on decision efficiency
H4	User engagement positively affects decision efficiency.	RQ4	Effect of user engagement on decision efficiency
-	Integrated mediation of cognitive and behavioural factors	RQ5	Mediating role of understanding and engagement between XR usability and decision efficiency

1.6. Research methodology

This study adopts a mixed-method research design as shown in (Figure 2), integrating a systematic literature review with a quantitative empirical investigation to provide both theoretical grounding and empirical validation.

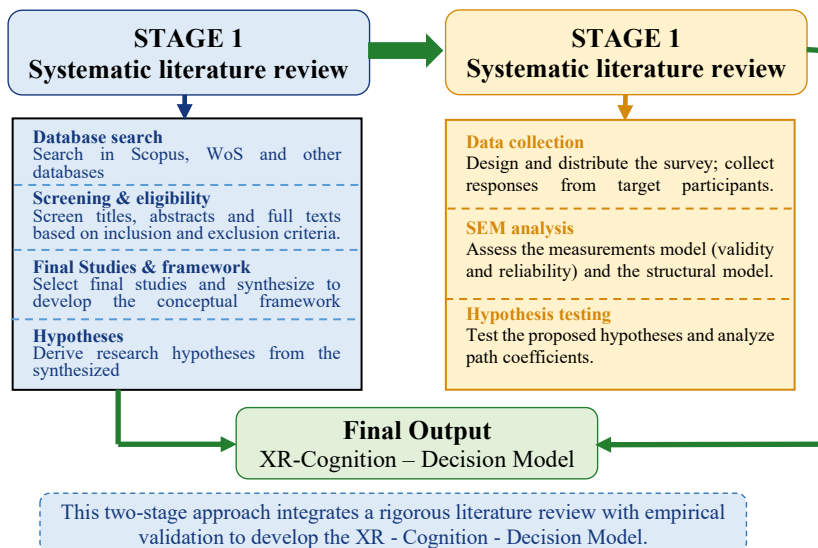


Figure 2. A graphical figure representing the research methodology (Author).

This approach is widely recommended in emerging fields such as XR in the AEC sector, where both conceptual synthesis and data-driven analysis are required (Li et al., 2023).

- **A Systematic Literature Review** (PRISMA-Based Synthesis) is the first phase of the research to establish the theoretical foundation and identify research gaps in XR applications for sustainable architecture.
- **Quantitative Survey-Based Empirical Study** is the second phase to test the proposed conceptual model using Structural Equation Modelling (SEM).

- **The combination** of PRISMA-based review and SEM analysis provides theoretical rigor (literature synthesis) and empirical validation (quantitative testing). This mixed approach ensures a comprehensive understanding of XR's role in sustainable architectural decision-making.

1.7. Limitations of the research

Contemporary studies on XR in sustainable design face limitations due to a lack of sufficient longitudinal and empirical data regarding actual energy and carbon reductions. Additionally, the methodologies employed are often disjointed and do not take into account the entire lifespan of buildings. Furthermore, Mixed Reality (MR) is relatively underexplored in comparison to Virtual Reality (VR) and Augmented Reality (AR), despite its potential for enabling real-time, context-sensitive decision-making. Practical challenges such as higher costs, interoperability issues, inadequate facilities and training, and health and accessibility concerns further hinder the widespread adoption of XR technologies.

2. Literature review

2.1. Theoretical foundations

This study's theoretical framework is reinforced by the combination of experiential learning theory (ELT) and embodied cognition theory. Experiential learning theory clarifies how immersive experiences enhance information acquisition by exploratory activities, reflective observation, and conceptual understanding (Kolb, 1984). XR environments closely adhere to these principles by enabling users to engage directly with simulated design settings (Crogman et al., 2025; Ghanbaripour et al., 2024).

Embodied cognition posits that physical engagement and sensory participation, rather than mere abstraction, foster architectural understanding (Lee, 2025). XR technologies convert abstract sustainability indicators into interactive experiences, enhancing understanding, focus, and design cognition (Safikhani et al., 2022). Thus, XR serves both as a visualization interface and as a cognitive tool that facilitates sustainable architectural decision-making.

2.1.1. Experiential learning and Extended Reality (XR)

Experiential Learning Theory (ELT), formulated by Kolb, conceptualizes learning as a cyclical process comprising real experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 1984).

This approach is essential to architecture education and practice since design knowledge is fundamentally iterative and experimental. Extended Reality (XR) technologies are closely aligned with ELT since they offer immersive settings that facilitate active user engagement with simulated design scenarios (Crogman et al., 2025; Ghanbaripour et al., 2024). Utilizing XR, users may engage with virtual environments, evaluate design choices, and obtain real-time environmental feedback, thereby fulfilling the experiential learning cycle in a digital context (Andalib et al., 2025; Crogman et al., 2025).

Empirical research indicates that XR markedly improves information retention and engagement by converting passive learning into active experiencing processes (Crogman et al., 2025; Ghanbaripour et al., 2024). Moreover, XR enhances collaborative learning by allowing several users to engage in shared immersive settings, hence fostering communication and collective problem-solving (Paulsen et al., 2024). Consequently, XR is progressively acknowledged as a revolutionary educational instrument that connects theoretical knowledge with practical application in architecture and design education (Andalib et al., 2025; Ghanbaripour et al., 2024).

2.1.2. Designing cognitive and immersive environments

Design cognition is the cognitive process by which architects perceive, evaluate, and solve complex design challenges. Spatial thinking, visualization, issue framing, and iterative decision-making are all key aspects of architectural practice (Lee, 2025; Safikhani et al., 2022).

Traditional design tools frequently rely on abstract representations like drawings and digital models, which might impede a designer's capacity to fully comprehend spatial and environmental linkages. XR technologies overcome this constraint by offering immersive and embodied experiences that enable designers to interact directly with their design environments. This is consistent with embodied cognition theory, which holds that knowledge is produced via bodily contact and sensory engagement with the world. Studies suggest that XR improves spatial awareness and decreases cognitive load by converting abstract material into intuitive, experience-based knowledge (Lee, 2025; Safikhani et al., 2022). Furthermore, immersive environments facilitate quick iteration and exploration of design options, allowing for more effective problem-solving and decision-making processes. XR increases design quality by combining several layers of information, including geometry, materials, and environmental performance (Crolla et al., 2024).

2.1.3. XR-BIM-Digital Twin Synergy: "Technology Integration"

The integration of Extended Reality (XR) with Building Information Modeling (BIM) and Digital Twin (DT) technologies marks a significant step forward in the AEC sector's digital transformation (Alizadehsalehi et al., 2020; Yeom et al., 2024). BIM offers a full digital representation of building components, whereas digital twins allow for real-time modeling and monitoring of building performance (Casini, 2022; Yeom et al., 2024). XR functions as an interactive interface, allowing users to interact with BIM and DT data in an intuitive and immersive way (Bressan et al., 2024).

This integration promotes cooperation by allowing stakeholders to interact with shared models and make real-time choices (Alizadehsalehi et al., 2020). It also promotes lifespan sustainability by allowing for continuous performance analysis from design to operation (Yeom et al., 2024). According to empirical research, BIM-XR integration may minimize design disputes by around 37%, increasing efficiency and minimizing material waste. Furthermore, XR-enabled urban projects have shown up to a 20% decrease in greenhouse gas emissions through enhanced design optimization (Shehadeh et al.,

2025). Digital Twin-XR systems also allow for predictive maintenance and energy optimization, which contribute to long-term sustainability and operating efficiency (Casini, 2022; Yeom et al., 2024).

2.2. XR in sustainable architecture, PRISMA review:

The role of Extended Reality (XR) in sustainable architecture has been thoroughly examined through systematic reviews, bibliometric analyses, and empirical case studies, indicating the growing maturity of this interdisciplinary research area. A systematic literature review was performed in accordance with PRISMA guidelines to analyze XR applications in sustainable architecture from 2018 to 2025 as shown in (Table 2, Figure 3), utilizing databases such as Scopus, Web of Science, and IEEE.

Table 2 : PRISMA screening process (XR in Sustainable Architecture), (2018 – 2025) (Author).

Database	Identification	Screening	Eligibility	Included
Scopus	220	160	55	35
Web of science	160	120	35	25
IEEE Explore	100	70	20	15
Total (n)	480	350	110	75

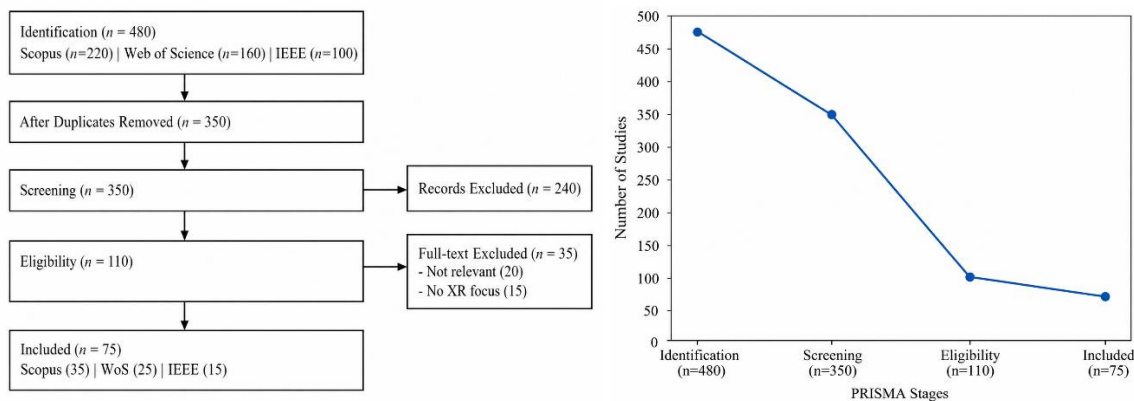


Figure 3. PRISMA flow diagrams for screening process (XR in Sustainable Architecture), (2018 – 2025) (Author).

2.3. XR Applications by lifecycle domain:

As shown in (Table 3), the distribution of the 35 full text excluded from PRISMA flow diagram, the XR technologies are employed across various domains within sustainable architecture, including sustainable construction, smart lighting systems, environmental sustainability. According to the literature, XR technologies are used in various areas of sustainable architecture, such as sustainable construction, smart lighting systems, environmental sustainability, urban planning, and architectural education (Cosio et al., 2023; Agbobli & Mo, 2024; Liu et al., 2024). This varied set of applications demonstrates XR's adaptability as a digital interface that can integrate environmental data, human interaction, and spatial simulation into a coherent design environment (Li et al., 2023).

Table 3: Distribution of 35 studies across main domains (XR in Sustainable Architecture) (Author).

Domain	Number of studies	Percentage (%)	Interpretation
Design and Preconstruction	14	40%	Dominant use for visualization, simulation, sustainability evaluation
Construction & Project Management	7	20%	Clash detection, safety, workflow optimization
Operation and Maintenance (DT-XR)	5	14%	Energy monitoring, predictive maintenance
Urban Planning and Smart Cities	4	11%	Scenario simulation, SDG 11 applications
Education and Training	3	9%	Experiential learning, sustainability education
Environmental Awareness and Behavior	2	6%	User engagement, climate awareness
Total	35	100%	--

The distribution of XR applications in sustainable architecture shown in (Figure 4) reveals a significant focus on the design and preconstruction phase (40%), followed by construction (20%) and operation and maintenance (14%). In contrast, urban planning (11%), education (9%), and behavioral applications (6%) are comparatively limited. This trend indicates that XR is primarily utilized as a visualization and simulation tool during the initial design stages, with notably less application in lifecycle-oriented and user-centered contexts. These observations align with previous systematic studies, which have identified a predominance of design-focused XR implementations, while operational and behavioral sectors remain underrepresented.

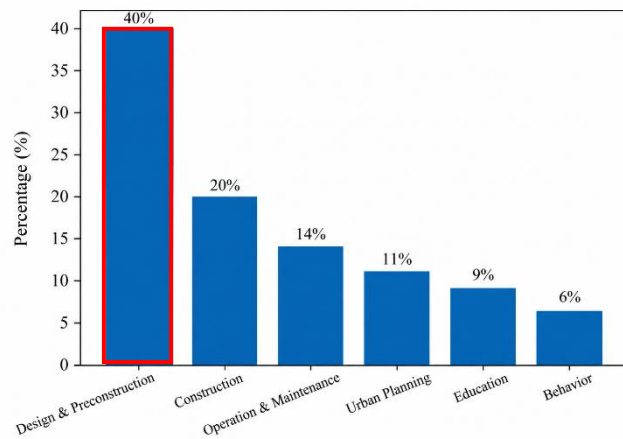


Figure 4. XR Applications by domain in sustainable architecture (Author).

XR applications in sustainable architecture are primarily concentrated in the design and preconstruction phases, where immersive visualization and simulation support performance evaluation while reducing errors and material waste (Li et al., 2023; Zhou, 2024). This dominance underlines the vital importance of early-stage decision-making for sustainable results, and it is reinforced by integration with BIM, which promotes cooperation and informed design processes (Alizadehsalehi et al., 2020; Bressan et al., 2024). Despite the promise for real-time monitoring and energy optimization provided by Digital Twin-XR systems (Yeom et al., 2024; Casini, 2022), operation and maintenance applications remain relatively restricted. Additional applications include urban planning, where XR facilitates participatory and scenario-based decision-making (Liu et al., 2024; Allam & Jones, 2021; Lee, 2022), and education and behavioral domains, where immersive environments improve sustainability awareness and learning outcomes (Cosio et al., 2023; Agbobli & Mo, 2024; Zhang & Huang, 2024). Overall, the distribution shows a strong bias toward early design applications, with relatively low uptake in lifespan, behavioral, and post-occupancy settings, highlighting the need for more integrated and longitudinal methods.

3. Materials and methods

The methods section has been updated to increase transparency and scientific rigor. The questionnaire was sent online throughout professional AEC networks and universities. Research groups, LinkedIn professional communities, and institutional email lists in the MENA area. The geographical emphasis was chosen due to increased urbanization, smart-city efforts, and growing investment in sustainable digital transformation in nations such as Saudi Arabia, Egypt, and the United Arab Emirates.

The research used a mixed-method approach, integrating:

The first stage involves doing a PRISMA-based systematic literature review. It enables:

- Identifying major XR application domains.
- Recognize methodological shortcomings, such as lack of empirical validation.
- Developed the conceptual framework and theories.

The second stage involves a quantitative SEM-based empirical inquiry. It included quantitative empirical research to evaluate the suggested conceptual model using Structural Equation Modeling (SEM). Following data cleaning and validation, 214 valid replies remained. The reliability and validity evaluations revealed good concept consistency (Cronbach's $\alpha > 0.87$; AVE > 0.50). The SEM model had satisfactory goodness-of-fit indices (CFI = 0.948; RMSEA = 0.052), which confirmed the conceptual framework's resilience.

3.1. Conceptual framework

The conceptual framework shown in (Figure 5) serves as the foundation for this study. It outlines the hypothesized relationships among four key constructs:

- XR Usability (independent variable)
- Sustainability Understanding (mediator)
- User Engagement (mediator)
- Decision Efficiency (dependent variable)

The approach hypothesizes that XR usability improves sustainability understanding and user engagement, resulting in better decision making. This dual-path mediation captures both cognitive and behavioral processes by which immersive technologies impact architectural decision-making.

The model proposes that XR influences decision-making both directly (via engagement) and indirectly (via understanding).

- Indirect pathway (cognitive route): XR \rightarrow Sustainability Understanding \rightarrow Decision Efficiency
- Direct pathway (behavioral route): XR \rightarrow User Engagement \rightarrow Decision Efficiency

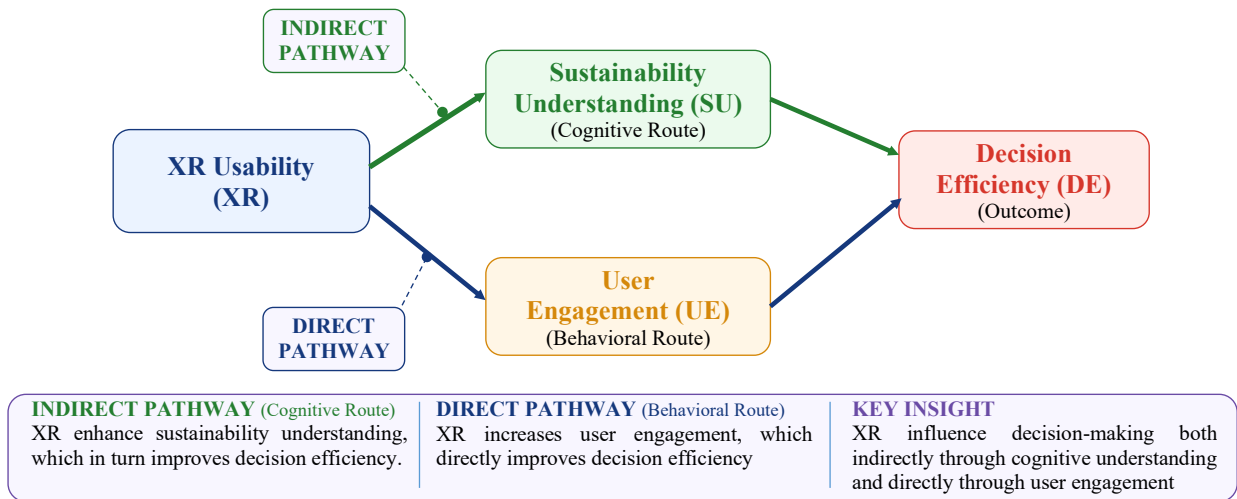


Figure 5. The XR-Sustainability Conceptual Framework (Author).

3.2. Data collection

The quantitative section of this research utilized a structured questionnaire to experimentally investigate the correlations between XR usability, sustainability understanding, user engagement, and decision-making efficiency. The questionnaire was designed using verified components from previous studies in XR, BIM, and design cognition research.

3.2.1. Survey design

The quantitative survey instrument included 24 measurement questions (Table 4) that were methodically organized among four latent constructs as shown in (Table 5), each represented by six indicators to guarantee balanced measurement and construct reliability. All items were assessed using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), which is a commonly used method in Structural Equation Modelling (SEM) investigations to examine perceptual and behavioral components.

Table 4 : Measurement Items for Latent Constructs (Author).

Construct	Code	Measurement Item
XR Usability	XRU1	The XR system is easy to use in architectural design tasks.
	XRU2	The XR environment provides intuitive interaction with design elements.
	XRU3	XR allows clear visualization of building components and spatial relationships.
	XRU4	The XR system enhances my ability to explore design alternatives.
	XRU5	XR provides real-time feedback on design performance.
	XRU6	Overall, the XR system is effective for supporting design activities.
Sustainability Understanding	SU1	XR helps me better understand energy performance in buildings.
	SU2	XR improves my understanding of environmental impacts of design decisions.
	SU3	XR enhances my awareness of sustainable materials and resources.
	SU4	XR enables me to evaluate sustainability trade-offs effectively.
	SU5	XR helps me understand lifecycle performance of buildings.
	SU6	XR improves my overall knowledge of sustainable architectural design.
User Engagement	UE1	I feel highly engaged when using XR for design tasks.
	UE2	XR increases my interest in the design process.
	UE3	XR encourages active participation in design exploration.
	UE4	I spend more time interacting with designs in XR environments.
	UE5	XR enhances my focus and attention during design activities.
	UE6	XR creates an immersive experience that keeps me involved in the task.
Decision Efficiency	DE1	XR helps me make faster design decisions.
	DE2	XR improves the accuracy of my design decisions.
	DE3	XR reduces errors in design evaluation.
	DE4	XR increases my confidence in design decisions.
	DE5	XR helps me compare design alternatives more effectively.
	DE6	XR improves the overall efficiency of the design process.

Table 5: Measurement Constructs (Author)

Construct	Items	Focus
XR Usability	6	assessing ease of use, interactivity, immersion, and system quality
Sustainability Understanding	6	capturing participants' comprehension of environmental performance, energy efficiency, and sustainability concepts
User Engagement	6	measuring levels of interaction, attention, and involvement in XR-based design environments
Decision Efficiency	6	evaluating the speed, accuracy, confidence, and overall effectiveness of design decision-making

3.2.2. Survey administration and response validation

The survey was conducted online utilizing a standardized questionnaire for professionals and academics in the Architecture, Engineering, and Construction (AEC) sector. A total of 214 responses were received. A multistep validation procedure was used to assure data quality, which included removing incomplete replies, duplicate entries, and inconsistent answers. Cronbach's alpha reliability study confirmed satisfactory internal consistency for all constructs ($\alpha > 0.70$), meeting accepted standards in behavioral research.

3.2.3. Participants' demographics and geographical distribution

3.2.3.1. Participants' roles

Participants in the study originated from various professional backgrounds within the AEC industry, including architects, engineers, urban planners, and university researchers. Participants covered a wide range of experience levels, from early-career professionals to senior specialists, ensuring a thorough understanding of XR adoption and its influence on sustainable design decisions. This variety strengthens the conclusions since it includes both practical and theoretical insights regarding XR usability, engagement, and sustainability awareness.

The sample is dominated by **architects (40%)**, followed by **engineers (30%)**, with smaller representation from **academics (20%)** and **urban planners (10%)**, ensuring a balanced perspective across design, technical, and research domains as shown in (Figure 6).

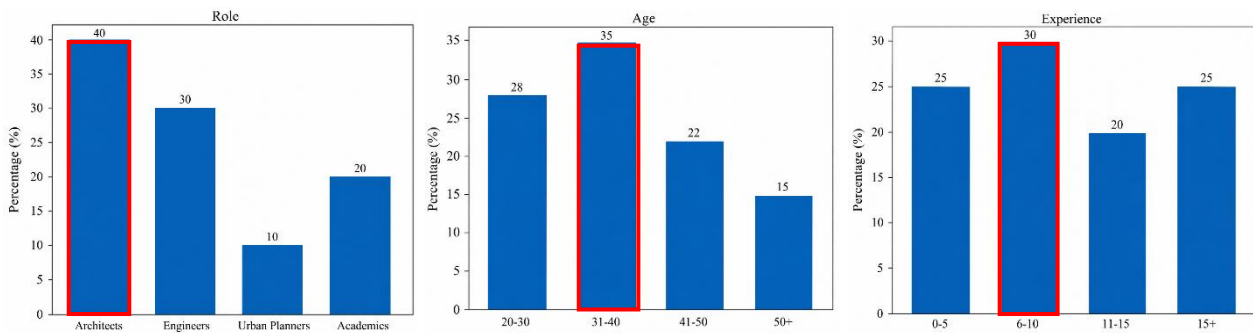


Figure 6. Combined distribution of participants' role, age and years of experience (Author).

3.2.3.2. Geographic distribution (MENA Region)

The majority of participants were from the Middle East and North Africa (MENA) area, including Saudi Arabia, Egypt, the United Arab Emirates, and other regional settings as shown in (Figure 7). Focusing on the MENA area is especially important because:

- Rapid urbanization and extensive building activity.
- The focus is on sustainable development and visionary ideas.
- Digital technologies are increasingly being used in the AEC industry.

This regional emphasis provides useful insights on XR deployment in emerging and fast-rising markets, but it may restrict the results' generalizability to other global settings.

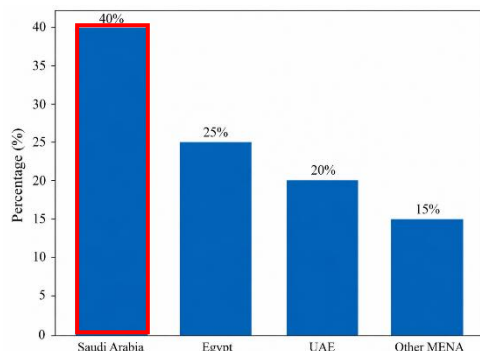


Figure 7. Geographical distribution of survey participants across the MENA region (Author).

3.2.4. Ethical considerations and methodological limitations

Participation in the study was entirely voluntary and anonymous. No personally identifiable information was gathered, and informed consent was obtained prior to survey completion. The ethical principles governing social science research were followed throughout the data collection process.

3.3 Data analysis and measurement model:

Reliability analysis: Cronbach’s $\alpha > 0.87$

Validity test: AVE > 0.50

Analysis: Correlation, Regression, and Structural Equation Modeling (SEM)

3.3.1 Confirmatory Factor Analysis (CFA) measurement model for validity:

The CFA model shown in (Figure 8) confirms the validity of the measurement structure, where all observed indicators (e.g., XR1, XR2...) load onto their respective latent constructs (XR, Understanding, Engagement). This demonstrates adequate construct reliability and convergent validity, supporting the robustness of the measurement model prior to structural analysis.

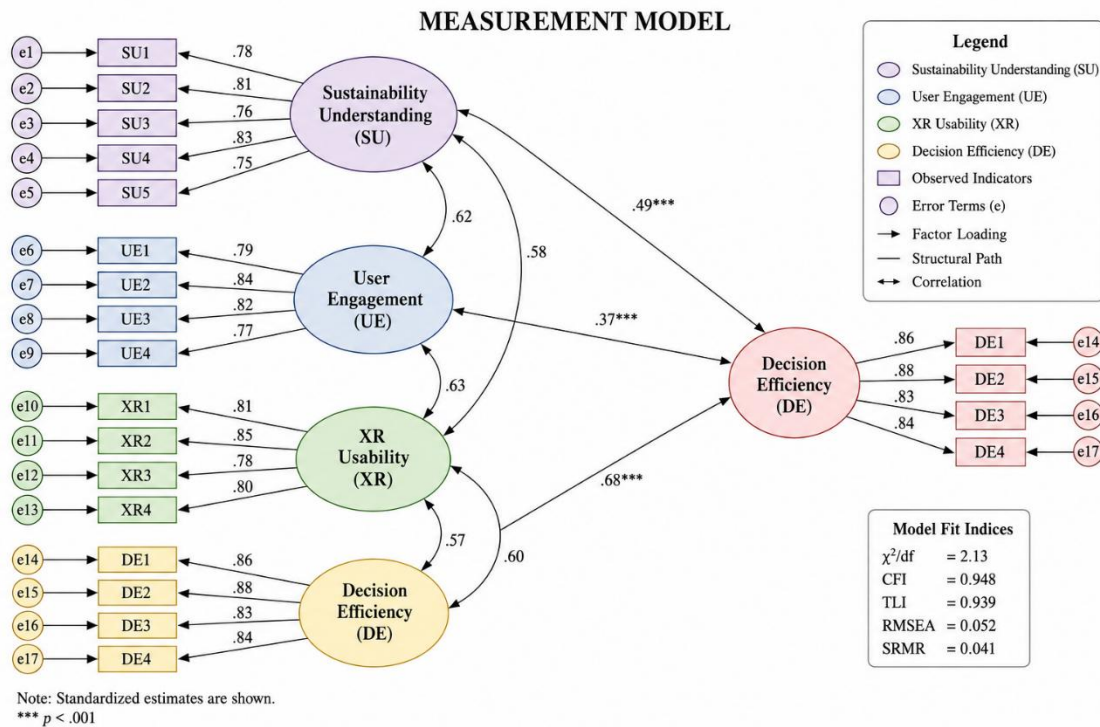


Figure 8. Confirmatory Factor Analysis (CFA) Measurement Model (Author).

The model fit indices shown in (Table 6) demonstrate that the proposed SEM model achieves a strong fit with the observed data, with a Comparative Fit Index (CFI) of 0.95 and a Root Mean Square Error of Approximation (RMSEA) of 0.058, both within acceptable thresholds. This confirms the adequacy and robustness of the structural model.

Table 6: Shows goodness-of-fit indicators of SEM model (Author).

Indicator	Value	Acceptable Threshold	
CFI	0.948	> 0.90	excellent fit
RMSEA	0.052	< 0.08	acceptable/good fit

3.3.2 Structural Equation Model results (SEM)

The tested Structural Equation Model SEM model as shown in (Figure 9), including the following:

- Standardized path coefficients (β values)
- Directional relationships between variables
- Error terms (e1, e2, e3) representing unexplained variance (Not all variation in outcomes is explained by the model, and other external factors (e.g., experience, tools, context) may influence results)

The structural equation model findings are displayed in (Table 7), which indicate statistically significant correlations between all constructs. XR usability significantly improves sustainability understanding ($\beta = 0.65, p < 0.001$) and user engagement ($\beta = 0.68, p < 0.001$). Sustainability understanding ($\beta = 0.49$) and user engagement ($\beta = 0.37$) improve decision efficiency. The presence of error terms represents unexplained variation, implying that other contextual variables may potentially influence decision-making outcomes.

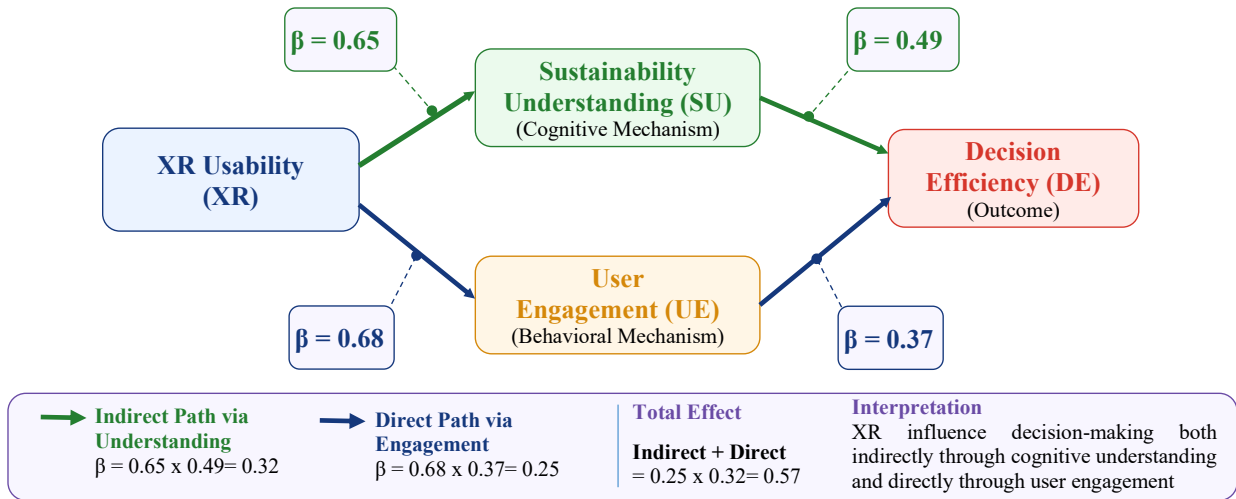


Figure 9. Structural Equation Model Results (SEM) path diagram (Author).

Table 7: Shows the structural relationships between XR, Understanding, Engagement, and Decision Efficiency (Author).

Path	β Value	Significance		
XR affects sustainability Understanding	0.65	$p < 0.001$	Strong positive effect	XR significantly improves users' comprehension of sustainability concepts
XR affects user Engagement	0.68	$p < 0.001$	Strongest relationship	XR substantially enhances user immersion and interaction
Understanding influence Decision	0.49	$p < 0.001$	Moderate effect	Better understanding leads to more informed decisions
Engagement influence Decision	0.37	$p < 0.001$	Moderate but weaker than cognition	Engagement contributes, but less than understanding

The standardized path coefficients (β values) shown in (Figure 10) highlights the relative strength of relationships across all paths within the SEM model. The results indicate that XR usability has the strongest influence on user engagement ($\beta = 0.68$) and sustainability understanding ($\beta = 0.65$). However, sustainability understanding exerts a greater impact on decision efficiency ($\beta = 0.49$) compared to user engagement ($\beta = 0.37$), suggesting that cognitive comprehension plays a more critical role than behavioral engagement in enhancing sustainable design decisions.

Key insight are following;

- The strongest driver is XR \rightarrow Engagement ($\beta = 0.68$)
- However, decision-making is more influenced by understanding ($\beta = 0.49$) than engagement
- XR is effective not just because it is engaging, but because it improves cognitive comprehension of sustainability.

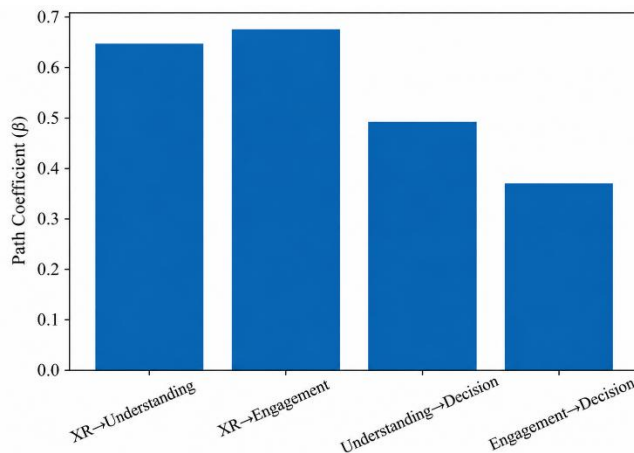


Figure 10. SEM Path Coefficients Chart (Graph Representation of SEM Relationships) (Author).

3.3.3. Integrated quantitative and literature findings

The empirical results obtained from the quantitative SEM analysis is synthesized and compared with the findings reported in previous literature as shown in (Table 8) to validate the study's outcomes, demonstrate consistency with existing

research, and provide a comprehensive understanding of how XR contributes to sustainable architectural design and decision-making across different application domains.

Table 8: Combination between the study’s empirical SEM results with findings synthesized from previous literature.

Indicator	Empirical Result	Literature Support
Cognitive improvement	High ($\beta = 0.65$)	XR enhances learning
Engagement	High ($\beta = 0.68$)	XR increases immersion
Decision efficiency	Moderate–High	BIM–XR improves decisions

3.3.3.1. Design and preconstruction

XR enables environmental simulations, ecosystem visualization, and BIM-based assessment of sustainable design solutions (Zhou, 2024; Li et al., 2023; Shehadeh et al., 2025). Integrating BIM-VR decreases design disputes and iterations (37%), as well as reduces greenhouse gas emissions by around 20% in urban projects. XR-BIM combinations promote communication and decision-making throughout the AEC process (Bressan et al., 2024; Alizadehsalehi et al., 2020).

3.3.3.2. Energy, operation, and maintenance

Digital Twins and XR work together to enhance energy consumption management, indoor environmental quality, and facility management by allowing human-building interaction and metaverse-type control interfaces. XR for smart O&M improves comprehension and management of energy efficiency, comfort, and safety, as well as predictive operations; however, cost-benefit data remains limited (Casini, 2022; Banfi et al., 2022).

3.3.3.3. Urban scale, heritage, and civic participation

In smart and sustainable cities, XR and digital twins are positioned as critical instruments in the 5G-6G development, in line with SDG 11 (Barberis et al., 2025; Liu et al., 2024). XR systems for participatory planning empower residents via 3D immersive visualization of future possibilities (Lee, 2022), while also supporting bottom-up restoration choices in historic neighborhoods, enhancing cultural preservation, and lowering paper consumption (Li & Li, 2024). In heritage settings, XR, photogrammetry, and 3D printing reduce display costs while enabling sustainable maintenance and exposure of lesser-known places (Barberis et al., 2025).

3.3.3.4. Work practice and mobility

The "Phygital workspace" idea employs XR to combine physical and digital work, lowering carbon footprint by eliminating commuting and business travel while allowing for remote collaboration (Lo et al., 2024). The paradigm for sustainable adoption includes XR infrastructure, a collaborative environment, social interaction, and an evaluation of environmental effects (Lo et al., 2024).

3.3.3.5. Education, behavior, and environmental awareness

XR is often utilized in architectural and AEC education to promote spatial awareness, design experimentation, and sustainability insights, particularly in design studios and metaverse-like settings (Agbobli & Mo, 2024; Mohamed, 2024; Zhang & Huang, 2024; Andalib et al., 2025). Systematic evaluations reveal that XR improves instructional approaches and simulations for occupant behavior-related energy usage, although mixed reality is underutilized, and longitudinal data is scarce (Agbobli & Mo, 2024). More generally in environmental themes (climate, biodiversity), XR seems to have potential for participation, although actual effect data are limited (Cosio et al., 2023).

3.3.3.6. Cross-cutting reviews and trends

Critical and bibliometric evaluations indicate the following:

- The majority of XR applications are focused on preconstruction / design rather than construction and long-term operation (Li et al., 2023; Casini, 2022; Liu et al., 2024).
- Despite the dispersed and cyclical nature of research (3-5year tech cycles), the integration with BIM and DT is expanding. However, visualization and interaction remain dominating aspects (Li et al., 2023; Liu et al., 2024).
- AR, MR, 360° VR, collaboration, and intelligent construction are emerging hotspots in smart cities using XR and BIM technology (Liu et al., 2024).

Table 9: XR Development Timeline (Evolution of XR) (Author).

Period / Year	Key Development	Citations
2000 - 2013	Early VR/AR in AEC	(Alizadehsalehi et al., 2020; Li et al., 2023)
2014 - 2017	XR and BIM emergence	(Li et al., 2023; Alizadehsalehi et al., 2020; Liu et al., 2024)
2018 - 2021	Rapid sustainability adoption	(Li et al., 2023; Casini, 2022; Allam & Jones, 2021; Alizadehsalehi et al., 2020; Liu et al., 2024)
2022 - 2023	Systematic reviews expansion	(Casini, 2022; Mohammadrezaei et al., 2024; Cosio et al., 2023; Liu et al., 2024)
2024+	Digital Twin and XR integration	(Zhou, 2024; Yeom et al., 2024; Banfi et al., 2022; Shehadeh et al., 2025; Lo et al., 2024; Agbobli & Mo, 2024; Mohamed, 2024; Zhang & Huang, 2024; Andalib et al., 2025)

4. Discussion and scientific contribution.

This research examined into how XR affects sustainable architectural decision-making via cognitive (understanding) and behavioral (engagement) mechanisms. The findings show significant empirical support for all proposed hypotheses (H1-H4), which results in verifying the conceptual model's validity and addressing the research questions.

4.1 XR: A Cognitive-behavioral system (RQ0)

The findings demonstrate that XR significantly enhances decision-making while also improving cognitive understanding and user engagement; therefore, it answers RQ 0. This indicates that XR should be thought of as an integrated decision-support system rather than just a visualization tool. This is consistent with evidence that XR technologies, especially when combined with BIM and digital twins, improve information visualization, human performance, and strategic decision-making in building systems (Casini, 2022). Similarly, XR has been demonstrated to improve interaction and simulation capabilities, thereby promoting sustainability throughout the building's lifetime (Li et al., 2023).

4.2 XR Usability and sustainability understanding (RQ1 - H1)

The findings support H1, demonstrating that XR usability has a significant beneficial impact on sustainability understanding. This responds to RQ1 and implies that immersive environments allow users to better assess environmental performance, energy consumption, and material implications. This conclusion is consistent with previous research demonstrating that XR improves spatial cognition and performance-based assessment via immersive interaction (Safikhani et al., 2022). XR-BIM systems also increase users' understanding of design alternatives and sustainability metrics (Bressan et al., 2024).

Interpretation: XR combines abstract sustainability statistics into experiential knowledge, which immediately improves cognitive processing.

4.3 XR Usability and user engagement (RQ2 - H2)

The results support H2, proving that XR usability significantly enhances user engagement, which addresses RQ2. XR environments increase immersion, engagement, and involvement in design work. Empirical research suggests that XR can enhance stakeholder involvement by up to 62% and spatial awareness by 48%, resulting in improved design participation (Shehadeh et al., 2025).

Interpretation: Engagement serves as a behavioral motivator, allowing users to actively investigate and assess design options.

4.4 Sustainability understanding and decision efficiency (RQ3 - H3)

The findings support H3, demonstrating that sustainability understanding significantly increases decision-making efficiency, which answers RQ3. This conclusion is reinforced by research demonstrating that XR-enabled simulation increases decision accuracy, decreases uncertainty, and improves the evaluation of sustainability trade-offs (Kamari et al. 2020).

Interpretation: Improved comprehension leads to faster decision-making, improved accuracy in assessments, and reduced design mistakes.

4.5 User engagement and decision efficiency (RQ4-H4)

The results verify H4, suggesting that user interaction improves decision efficiency, which addresses RQ4. A previous study has shown that XR enhances perceived utility, attention, and decision performance in design processes (Chi et al., 2022).

Interpretation: Engage users to explore additional alternatives, make more informed decisions, and reduce rework and inefficiency.

4.6 Mediating mechanism (RQ 5)

The results indicate that sustainability understanding and user engagement influence the link between XR usability and decision efficiency, which answers RQ5. This finding is important since it indicates that XR does not immediately enhance decision-making; rather, its impact is indirect and human-centered, functioning via cognitive and behavioral processes. This builds on prior studies, which mostly focused on technology capabilities without considering causative human aspects (Li et al., 2023; Casini, 2022).

4.7 Integration with systematic review findings

The discussion aligns with the systematic review findings, which demonstrated that XR applications are significantly concentrated in the design process (~40%) and have the greatest cognitive and decision impacts. However, the limited applicability in operational and behavioral domains shows that the mechanisms revealed in this research have not yet been completely employed throughout the construction lifetime (Li et al., 2023).

4.8 Key contribution

- XR is a decision-support system that integrates cognitive and behavioral processes. Its impact on design outcomes is indirect and human-centered, achieved via understanding and engagement rather than direct technical competence alone.
- The cognitive pathway (understanding) has a greater impact on decision efficiency than the behavioral pathway (engagement), indicating the importance of comprehension in sustainable design decisions.

- This study advances the field by:
- Providing empirical SEM validation of XR’s impact.
- Integrating technology, cognition, and behavior.
- Demonstrating XR as a decision-support system.
- Addressing gaps in human-centered sustainability research.

The appraised discussion stresses how XR helps create sustainable design via cognitive and behavioral mechanisms. According to the results, XR usability dramatically enhances sustainability understanding and user engagement, resulting in more efficient architectural decisions. Importantly, sustainability understanding had a greater impact on decision efficiency than user involvement, emphasizing the significance of cognitive comprehension in sustainability-oriented architectural practice. The research also shows that XR should not be considered exclusively to be an immersive visualization tool. Instead, XR functions as a human-centered decision-support system, including real-time environmental input, collaborative interaction, and sustainability assessment in the design process. This contribution is especially significant since prior XR studies focused mostly on vision performance and technological implementation, while only a small body of empirical data confirmed cognitive and behavioral processes via SEM analysis.

5. Conclusion

The findings show that XR functions as a cognitive-behavioral system, with its influence on decision-making mediated by users' understanding and participation rather than direct technology consequences. This emphasizes the need of incorporating human-centered elements into XR-based design processes. XR sustainability conceptual framework shown in (Figure 11) proposed that XR influences decision – making both directly (via engagement) and indirectly (via understanding).

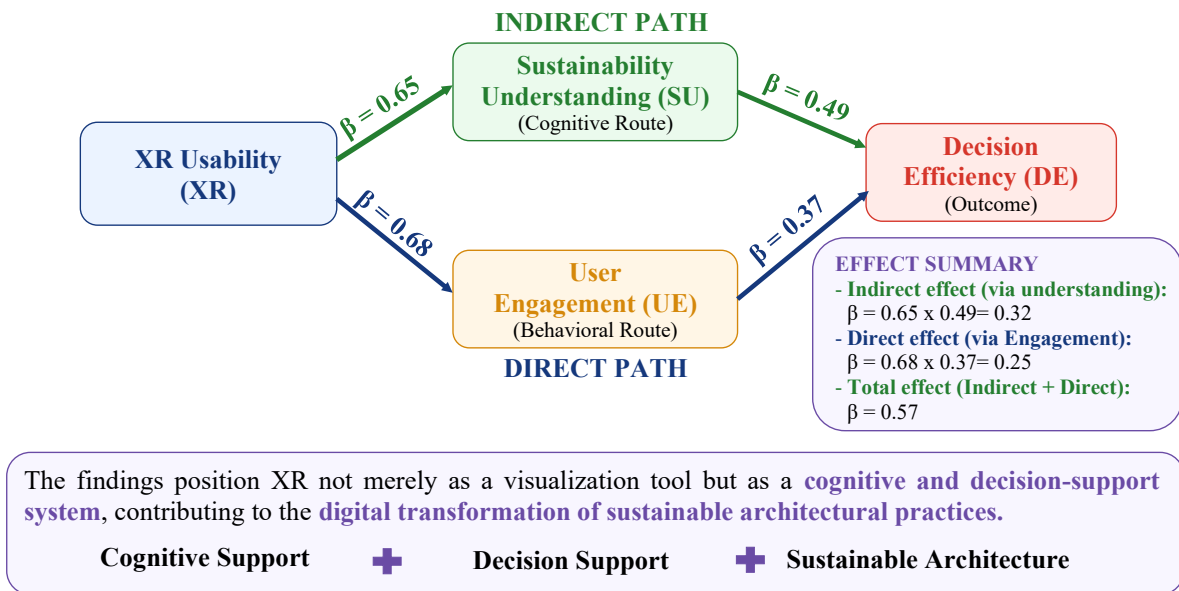


Figure 11. “An integrated XR–sustainability conceptual framework” (Author).

The study provides theoretical value by incorporating experiential learning, embodied cognition, and human-centered sustainability frameworks into XR research. Methodologically, it provides empirical SEM validation using a mixed-method study approach. Practically, the results encourage the integration of XR with BIM and digital twin technologies to increase sustainability performance across the building's life cycle.

This study's results establish Extended Reality (XR) as a cognitive and decision-support system that actively impacts long-term architectural outcomes, rather than just a visualization tool. Unlike conventional visualization tools, XR allows users to grasp complicated environmental data via immersive and interactive experiences, which improves sustainability knowledge and supports more informed decision-making. This is consistent with emerging evidence that XR, particularly when integrated with BIM and digital twin systems, improves human cognition, technical task performance, and data-driven decision-making in the built environment (Casini, 2022). Furthermore, XR-based systems have been demonstrated to enhance perceived utility, spatial cognition, and design efficiency, emphasizing their position as decision-support platforms rather than passive visualization tools (Chi et al., 2022).

Empirical evidence confirms that XR usability enhances sustainability understanding and user engagement, which in turn improve decision efficiency in architectural design as shown in (Figure 12). By mediating decision-making via cognitive (understanding) and behavioral (engagement) mechanisms, XR contributes to the larger **digital transformation of sustainable architecture** practices, allowing for a shift from static design approaches to dynamic, data-driven, and human-centered processes. This transformation is especially important in dealing with complex sustainability challenges, where real-time interaction, modeling, and stakeholder involvement are critical for maximizing environmental performance and lifecycle outcomes.

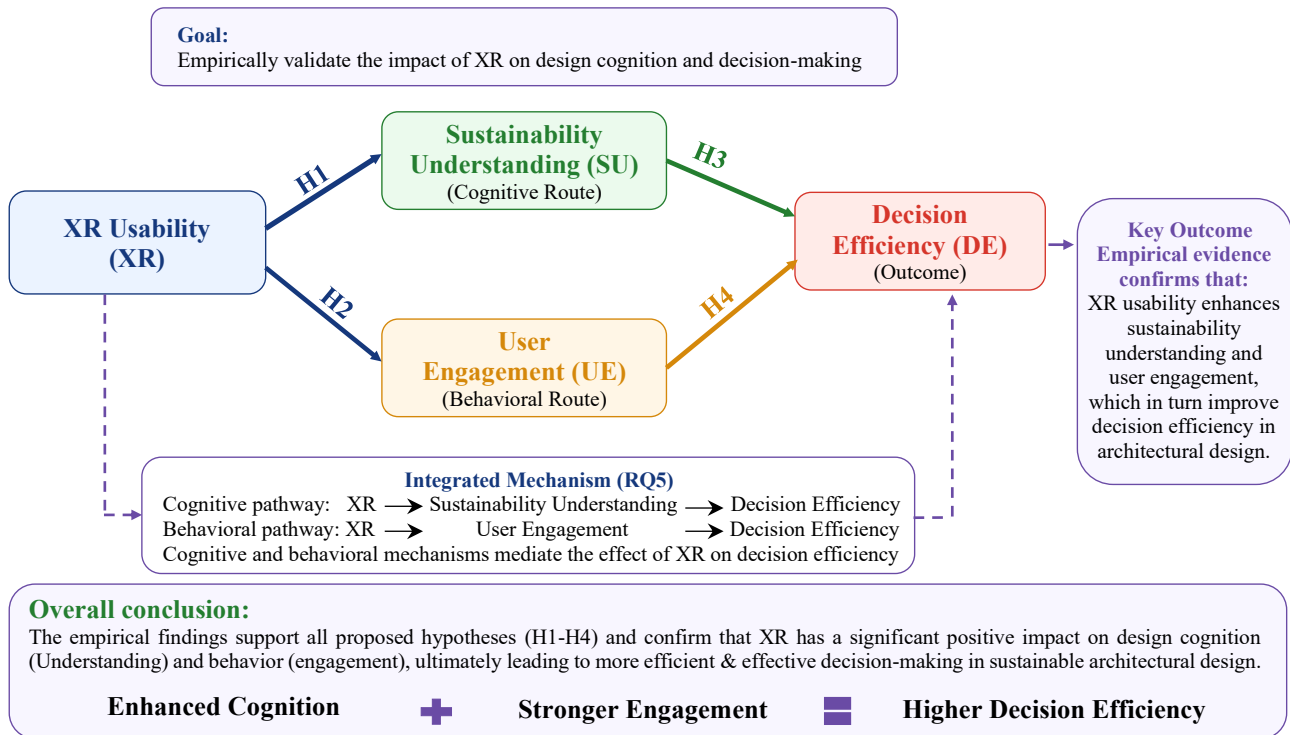


Figure 12. “Empirically validate the impact of XR on design cognition and decision-making” (Author).

6. Recommendations

Based on the study's results, various practical and strategic suggestions are produced to improve the successful use of XR technologies in sustainable building design.

First, it is advised that AEC professionals use XR as an integrated decision-support tool rather than just a visualization technology. The findings reveal that XR usability considerably enhances sustainability understanding and user engagement, hence improving decision efficiency. As a result, XR should be included in design processes, especially in early-stage decision-making, when the highest sustainability consequences occur (Li et al., 2023).

Second, organizations should emphasize the integration of XR with BIM and digital twin (DT) technologies to allow real-time, data-driven decision-making throughout the building's lifespan. Such integration has been found to increase cooperation, performance monitoring, and sustainability results, especially throughout the operation and maintenance phases (Casini, 2022).

Third, it is critical to engage in training and capacity development to improve users' cognitive and behavioral interactions with XR systems. Because the research demonstrates that comprehension and engagement influence decision efficiency, developing user skills and familiarity with XR technologies is critical to maximizing their usefulness (Khan et al., 2021).

Fourth, policymakers and industry stakeholders should provide standardized frameworks and rules for using XR in sustainable construction. The absence of interoperability and standardization remains a significant obstacle, and developing unified protocols may help with greater acceptance and scalability (Alizadehsalehi & Hadavi, 2023).

Fifth, organizations should explore the possibilities of Mixed Reality (MR) for real-time, context-aware applications, notably in construction and facilities management. Despite its present underutilization, MR has considerable benefits in linking physical and digital worlds, allowing for more effective on-site decision-making (Li et al., 2023).

Finally, collaborative and multidisciplinary techniques that combine architects, engineers, policymakers, and end users inside XR settings should be encouraged. Such cooperation promotes common knowledge, communication, and decision-making processes, resulting in more inclusive and sustainable outcomes.

7. Study Limitations

Despite the study's significant contributions, we should note a number of limitations. First, the research is based on cross-sectional survey data, which restricts its potential to demonstrate a causal relationship over time; longitudinal studies are required to evaluate the long-term influence of XR on sustainable decision-making. Second, the sample is predominantly taken from the MENA area and certain AEC stakeholders, which may restrict the results' generalizability to other geographical and professional settings. Third, while the SEM model captures cognitive (understanding) and behavioral (engagement) mechanisms, it excludes other potentially influential factors such as organizational readiness, technological infrastructure, and cost constraints, all of which have been identified as critical barriers to XR adoption. Furthermore, the study focuses on perceived decision efficiency rather than objective performance measurements (e.g., real energy savings or carbon reduction), highlighting a significant gap in XR research. Finally, similar to previous research, XR applications are currently mostly centered in the design phase, and the model does not completely account for lifetime integration, especially during operation and post-occupancy. These limitations emphasize the necessity of more thorough, longitudinal, and multi-context research to fully realize the sustainability potential of XR technology.

8. Future Research Directions

Future study should concentrate on longitudinal and experimental investigations to validate XR's long-term effects, especially in terms of assessing real sustainability results like energy and carbon performance. There is also a need for integrated lifecycle frameworks that extend XR applications beyond design into building, operation, and post-occupancy phases, particularly via integration with digital twin and IoT technologies. Furthermore, future research should take a more human-centered approach, encompassing wider cognitive, behavioral, and organizational aspects that influence decision-making. Expanding research into Mixed Reality (MR) and performing cross-regional investigations would improve the scalability and usability of XR in sustainable building.

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Conflict of Interests

The Author declare that there is no conflict of interest.

Data Availability Statement

Anonymized survey data may be provided by the corresponding author upon reasonable academic request.

Institutional Review Board Statement

This study used an anonymous survey with human participants and followed the ethical principles of the Declaration of Helsinki. Participants were informed about the study purpose, voluntary participation, confidentiality, anonymity, and their right to withdraw. Because the study involved no personal data, clinical intervention, vulnerable group, or more-than-minimal risk, formal institutional review board approval was not required.

CRedit Author Statement

Hebatallah Hamdy Mohamed: Conceptualization; methodology; formal analysis; investigation; resources; data curation; writing – original draft; writing – review & editing; visualization; project administration.

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