Pertanika J. Sci. & Technol. 34 (3): 1655 - 1683 (2026)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Gamification for Extended Reality Informative Space (XRIS) Visualisation in the Construction Industry

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ABSTRACT

Intuitive visualisation tools are essential for the effective coordination of construction projects to convey complex spatial and technical information to diverse stakeholders. Traditional design documentation using 2D drawings and static 3D models cannot accurately depict complex spatial relationships and construction sequences. This results in design misinterpretations, inefficient constructability reviews and rework costs. Most of the current extended reality (XR) deployments in construction are essentially used as visualisation tools. Gamification usage in the industry is mainly oriented to the educational workflow context. This study develops an Extended Reality Information Space (XRIS), a HoloLens-based system that spatially anchors construction data onto physical environments. The system operates through gaze-triggered information tags and embedded game-based mechanics. Three functional layers covering immersive visualisation, information management, and interaction and gamification were comprised in this system. Semi-structured interviews were conducted with eight construction professionals and two XR specialists to identify the benefits of XRIS implementation and the impact of gamification on XRIS. Data were then analysed using thematic analysis. The findings suggest that XRIS enhanced spatial understanding, user accessibility, team communication, and motivation. Gamification integrated in the visualisation layer maintained the users' engagement through the behaviour of spatial exploration and task completion. Both mechanisms supported deeper retention and more precise articulation of design logic than passive documentation review. This study contributes a professional-oriented, empirically evaluated XRIS configuration advancing immersive tool design for construction practice.

Keywords: Construction industry, extended reality, Extended Reality Informative Space (XRIS), gamification, visualisation

ARTICLE INFO

Article history:
Received: 01 December 2025
Accepted: 31 May 2026
Published: 19 June 2026

DOI: https://doi.org/10.47836/pjst.34.3.16

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e-ISSN: 2231-8526

INTRODUCTION

Design coordination, stakeholder communication, and spatial information delivery are still significant challenges in the construction sector. Costly rework and schedule delays are a result of design misinterpretation, information asymmetry, and inefficient constructability reviews (Le et al., 2024). A survey found that 48% of all reworks arise from poor project data and miscommunication, leading to an estimated USD 31.3 billion in avoidable rework costs (FMI & PlanGrid, 2018). Traditional two-dimensional (2D) drawings and static three-dimensional (3D) models cannot represent complex spatial relationships and construction sequencing (Abouelkhier et al., 2025). These emphasise the need for more intuitive, interactive approaches that support collaborative decision-making.

Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has emerged as a key digital development in architecture, engineering, and construction (AEC). Integrations between XR and Building Information Modelling (BIM) provide spatial awareness, clash detection and constructability analysis (Safikhani et al., 2022). On-site progress monitoring and information overlay are also enabled through AR applications. However, most XR deployments remain as standalone visualisation tools, and limited evidence can be found of professional benefits or continued use in the daily work of projects (Trindade et al., 2023).

Gamification has shown potential to address engagement and motivation in professional settings. In construction, it has demonstrated benefits for hazard recognition, safety behaviour, and sustainable design involvement (Oke et al., 2024). Its broader application, though, is constrained by technical complexity, usability barriers, and poor integration with live project data (Davila Delgado et al., 2020). While the individual merits of XR and gamification in construction are documented, empirical evaluations of integrated, gamified XR systems targeting professional end-users remain scarce. Limited study has examined the perceived benefits and adoption performance of a gamified XR platform that spatially anchors construction data within an immersive environment for professional use.

To address these gaps, this study presents the Extended Reality Informative Space (XRIS), a gamified XR platform that integrates spatially anchored construction data with interactive game-based mechanisms in an immersive environment. This study includes two objectives: (1) to identify the benefits of XRIS implementation in the construction industry, and (2) to evaluate the impact of gamification on XRIS use. It delivers empirical evidence on the integration of gamification and XR for professional construction workflows, an area currently underrepresented in the literature. These findings guide the design of gamified XR tools supporting spatial understanding, stakeholder engagement, and collaborative decision-making.

LITERATURE REVIEW

There has been a growing amount of research interest on the use of gamification in construction practice. A keyword co-occurrence analysis of the current research landscape was performed using VOSviewer software based on a Scopus database search of documents with the keywords "construction" and "gamification", resulting in 375 documents. The VOSviewer keyword network in Figure 1 shows that "gamification" is strongly linked to educational terms such as "students", "teaching", and "learning systems". A separate cluster, however, consisting of professional construction-related terms like "construction projects", "construction management", and "project management", can be perceived but is relatively less dense.

These clusters are structurally separated, suggesting that gamification studies in the construction domain have focused on educational gamification. Its use as an operational mechanism within professional construction workflows, particularly in combination with immersive XR environments, remains largely unexamined. This gap is not merely topical but methodological. Existing studies have not empirically assessed the perceptions of construction professionals toward gamified, immersive visualisation tools designed for project-level tasks such as design review, spatial coordination, and information retrieval.

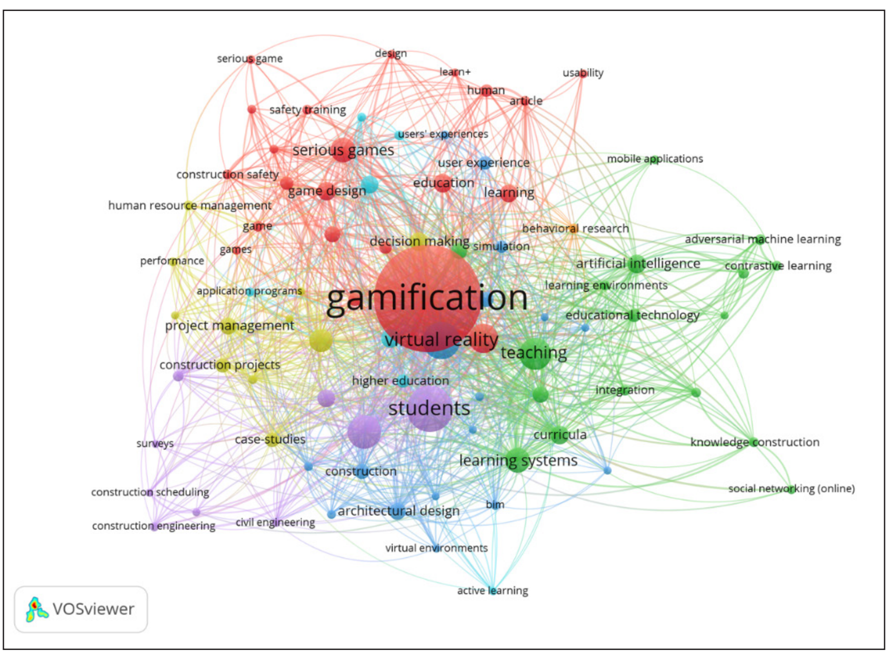

Figure 1. Keyword co-occurrence analysis

Gamification in Digital Technologies

Gamification applies game design elements such as points, challenges and leaderboards to non-game contexts (Koivisto et al., 2014). Reward systems, feedback, and progression mechanisms are organised to influence user behaviour. Reward systems are points or badges for completing tasks. Feedback loops provide immediate feedback and help users take certain actions. Progression mechanics allow for a progression of levels, milestones, or unlockable content to give the player a sense of progression. These elements transform routine activities into structured, goal-oriented experiences. These principles have been applied in education, corporate training and health and wellness. The evolution of gamification further reflects a shift from entertainment-oriented video games to productivity-focused tools. This is gradually integrating with new technologies such as AR and VR (Lee et al., 2022).

In construction, gamified applications have emerged to support stakeholder engagement and project monitoring (Yu et al., 2024). Guimarães et al. (2024) developed a game-like BIM application for on-demand monitoring of construction projects. Further research has confirm the integration of gamification techniques with BIM-based VR has enabled public engagement in architectural design (Yalçın, 2024). A BIM-VR system with gamified simulations was also developed for health risk assessment in urban infrastructure (Chen et al., 2024). Collectively, these developments illustrate the growing integration of gamification digital construction tools across diverse project functions, highlighting the need for more immersive and interactive approaches that sustain user engagement with construction information.

Extended Reality (XR) in Construction

Computer graphics simulation in the manufacturing and defence sectors has led to the development of Extended Reality (XR). It has since evolved into a transformative technology within the AEC industry. XR refers to a set of technologies that have the capacity to integrate digital content with physical environments to varying degrees. It is applied in the construction process from the design to the operation and maintenance (Li et al., 2024). The early applications were on architectural walkthrough systems (Brooks, 1987). These showed the potential of immersive visualisation to reduce design misinterpretation. XR was then extended to 4D construction simulation and scheduling visualisation (Dawood et al., 2003). As computing power matured, XR advanced into safety training and hazard simulation. Immersive environments enabled workers to practise high-risk tasks without physical exposure (Sacks et al., 2013). The release of head-mounted devices later broadened access across project teams. This development also accelerated research output within the AEC domain. More recently, XR has supported on-site assembly guidance, inspection, progress monitoring, and remote collaboration (Gornall et al., 2025).

Visualisation remains one of XR's strongest assets in construction. It enhances spatial understanding of building structures and construction sequencing across project stages (Safikhani et al., 2022).

Benefits of Gamification

Gamification boosts user engagement by fulfilling psychological needs for competence, autonomy, and relatedness (Bitrián et al., 2021). Repetitive tasks are less boring with interactive activities and rewards. Well-designed game mechanics tap into intrinsic motivation, supporting goal attainment and challenge-oriented behaviours (Manzano-León et al., 2021). Beyond engagement, gamified challenges, levels, and real-time feedback promote active learning, deepen understanding, and enhance long-term recall (Liu et al., 2023; Ortiz-Rojas et al., 2025). Badges, milestones, and progress indicators make effort visible and motivate users to complete tasks more efficiently and consistently (Encarnação et al., 2021; Bizzi, 2023; Oke et al., 2023). At the group level, team-based quests and shared rewards foster collaboration and collective problem-solving, stimulating communication and trust among respondents (Patricio et al., 2022). Table 1 summarises the benefits of gamification identified in recent studies that are relevant to this research.

Table 1
Benefits of gamification

Benefits	References
Enhancing User Engagement	(Bitrián et al.,2021; Chang et al., 2022; Manzano-León et al., 2021)
Improved Learning and Retention	(Jato-Espino et al., 2024; Liu et al., 2023; Ortiz-Rojas et al., 2025)
Motivation and Productivity	(Bizzi, 2023; Encarnação et al., 2021; Oke et al., 2023)
Collaboration and Teamwork	(Bizzi, 2023; Encarnação et al., 2021; Patricio et al., 2022)

Challenges of Gamification

The interrelated challenges of gamification adoption in construction impede its progress from controlled environments to real projects. Usability represents the most immediate barrier, as gamified systems misaligned with complex, time-sensitive construction workflows risk disrupting site activities and undermining operational efficiency (Guimarães et al., 2024; Oke et al., 2023). User fatigue occurs even in well-designed systems, where prolonged exposure erodes the novelty effect that initially drives engagement (Almeida et al., 2023; Priyantini et al., 2023; Yang et al., 2024). Attributing performance gains solely to gamification remains difficult, as its effects are rarely separable from other factors (Klein, 2021; Monteiro et al., 2021; Oke et al., 2024). Competitive mechanics such as leaderboards may reinforce hierarchical tensions and discourage equitable participation across diverse cultural and demographic groups (Gomez et al., 2024; Henry et al., 2024; Othman et al., 2023). These challenges, summarised in Table 2, suggest that successful gamification requires careful contextualisation.

Table 2
Challenges of gamification

Challenges	References
Usability issues	(Guimarães et al., 2024; Oke et al., 2023; Priyantini et al., 2023)
User fatigue	(Almeida et al., 2023; Guimarães et al., 2024; Yang et al., 2024)
Outcome attribution difficulty Cultural and demographic constraints	(Gomez et al., 2024; Henry et al., 2024; Klein, 2021; Monteiro et al., 2021; Oke et al., 2024; Othman et al., 2023)

Impacts of Gamification

There is evidence that gamification has an impact, but this relates to conditions where gains are shown to exist or to vanish. Reported outcomes hinge on task characteristics, organisational context, and design quality. Similar interventions yield different results across settings (Hammedi et al., 2024; Jacobides et al., 2024). A major constant constraint is the lack of motivation. Feedback, rewards and structured tasks influence work practices in the short term (Patricio et al., 2022), but behavioural change rarely persists beyond the mechanics that engender it (Manzano-León et al., 2021; Mohanty & Christopher, 2024). Collaboration follows a similar pattern. Cooperation can be facilitated by shared goals, although primarily when working relationships already exist (Bizzi, 2023; Cheng & Chau, 2022; Leite et al., 2022). While efficiency improvements have been documented (Leite et al., 2023; Rahiman et al., 2023), it is challenging to clearly separate the impact of gamification from organisational and task-related factors (Jacobides et al., 2024). Table 3 summarises these impacts.

Table 3
Impacts of gamification

Impact	References
Context-dependent engagement	(Hammedi et al., 2024; Jacobides et al., 2024; Sailer & Homner, 2020)
Extrinsic motivation dependency	(Manzano-León et al., 2021; Mohanty & Christopher, 2024; Patricio et al., 2022)
Conditional collaboration Attribution difficulty in performance gains	(Bizzi, 2023; Cheng & Chau, 2022; Jacobides et al., 2024; Leite et al., 2022; Leite et al., 2023; Rahiman et al., 2023)

Benefits of XR

XR introduces capabilities that address longstanding limitations in construction project workflows. Enhanced visualisation is the most frequently cited benefit. XR enables stakeholders to interact with 3D representations before construction begins, supporting clash detection, design review, and client communication more effectively than 2D drawings (Arslan et al. 2024; Alhady et al. 2024; Pham et al. 2025). Real-time feedback further strengthens spatial immersion, as XR platforms allow users to manipulate models and receive immediate system responses, reducing reliance on sequential review processes (Bhatarai et al., 2025; Hajji et al., 2022; Yu et al., 2024). XR also supports training and simulation in controlled settings, allowing workers to rehearse high-risk tasks without physical exposure (Alzarrad et al., 2024; Liu et al., 2022; Speiser & Teizer, 2024). Additionally, immersive environments support decision-making during design and constructability assessments by enabling project teams to evaluate alternatives spatially rather than abstractly (Chen et al., 2024; Delgado et al., 2020; Wang & Tung, 2023). Table 4 summarises these capabilities.

Table 4
Benefits of XR

Impact	References
Enhanced Visualisation	(Arslan et al.,2024; Alhady et al., 2024; Pham et al.,2025)
Real-Time feedback and interaction	(Bhatarai et al., 2025; Hajji et al., 2022; Yu et al., 2024)
Training and simulation	(Alzarrad et al., 2024; Liu et al., 2022; Speiser & Teizer, 2024)
Decision-Making	(Chen et al., 2024; Delgado et al., 2020; Wang & Tung, 2023)

Challenges of XR

XR adoption in construction remains constrained by interrelated resource, technical, and organisational barriers. High hardware prices and content development expenses restrict access, particularly for small and medium-sized enterprises with limited budgets (Ali et al., 2024; Davila Delgado et al., 2020; Pavlou et al., 2021). These pressures are compounded by technological limitations, as processing constraints and limited device performance reduce the reliability of real-time XR environments (Gornall et al., 2025; Heo et al., 2023; Struye et al., 2024). Even where financial and technical conditions are met, organisational factors introduce further friction. Cultural resistance and reluctance to adopt unfamiliar workflows slow uptake (Jalo & Pirkkalainen, 2024; Schwarz et al., 2024). Poor compatibility between XR platforms and legacy software infrastructures further weakens integration into existing project processes (Fernández-Caramés & Fraga-Lamas, 2024; Vona et al., 2025). These barriers diminish XR's reliability as a decision-support tool during critical construction phases. Most evaluations focus on technical feasibility, leaving user perceptions of usability and engagement within professional workflows underexamined. These challenges are outlined in Table 5.

Table 5
Challenges of XR

Challenges	References
High implementation costs	(Ali et al., 2024; Davila Delgado et al., 2020; Pavlou et al., 2021)
Technological limitations Resistance to change	(Alam et al., 2025; Heo et al., 2023; Irani et al., 2023; Jalo & Pirkkalainen, 2024; Schwarz et al., 2024; Struye et al., 2024)
Integration with legacy systems	(Fernández-Caramés & Fraga-Lamas, 2024; Irani et al., 2023; Vona et al., 2025)

Impacts of XR

There is emerging evidence on the impact of XR in professional settings. Improved learning outcomes are the most consistently reported impact. Immersive task rehearsal produces stronger knowledge retention and faster skill acquisition than conventional instruction (Margheritti et al., 2025; Pavlou et al., 2021). These gains feed into a second outcome of reduced errors and rework. Early clash detection and verification on design phase helps project teams resolve discrepancies before construction (Alhady et al., 2024; Alshboul and Shehadeh, 2025). Enhanced stakeholder decision-making has also been noted with the aid of immersive visualisation to help stakeholders evaluate design alternatives and construction sequences more effectively (Mi & Li, 2024; Oral et al., 2023). On an industry level, the adoption of XR can drive innovation across the industry, fostering the use of digital workflows in project delivery and organisational practice (Nyqvist et al., 2025; Radanovic et al., 2023). Table 6 summarises these impacts. Overall, the available evidence is positive but limited to context-specific and sometimes small-scale trials. The outcomes will be based on the readiness of the organisation and its digital skills, as well as its integration into the already existing platforms. Issues of pilot experience transferability to real-world site conditions, usability and motion sickness indicate that impacts of XR are mediated but not guaranteed.

Table 6
Impacts of XR

Impact	References
Improved learning outcomes	(Margheritti et al., 2025; Pavlou et al., 2021)
Reduced errors and rework	(Alhady et al., 2024; Alshboul and Shehadeh, 2025)
Enhanced stakeholder decision-making	(Mi & Li, 2024; Oral et al., 2023)
Industry Innovation	(Nyqvist et al., 2025; Radanovic et al., 2023)

Extended Reality Information Space (XRIS)

XRIS is an extension to the traditional XR visualisation that incorporates structured information management in immersive environments. XR-BIM platforms are mainly used for the rendering of 3D models for visual inspection. XRIS, on the other hand, adds a spatial information layer that binds data to the actual or virtual object when the object is gazed. This distinction matters. XR-BIM is concerned with the visualisation of the model, while XRIS is about the immersive environment as an active space of information. Users access, manipulate and react to project information in real time.

XRIS comprises three integrated layers as shown in Figure 2. The visualisation layer is an immersive visualisation that leverages XR technologies to represent construction environments. The information management layer bridges the gap between BIM, GIS, and IoT platforms to specific spatial locations (Morris et al., 2021). The interaction and gamification layer controls access to the user via spatial control, including gaze activation, proximity detection and gesture selection. It also includes elements such as points, challenges, and rewards to keep users engaged in the game.

The system boundary of XRIS is defined by spatially anchored data within a single immersive session. Users interact with a bounded set of construction components, each linked to embedded information tags. The system does not extend to live project management functions such as scheduling, procurement, or cost tracking. It focuses instead on information retrieval, spatial comprehension, and design communication within an immersive setting. Though not yet widely adopted, XRIS holds potential to improve spatial cognition, real-time decision-making, and digital collaboration among project stakeholders.

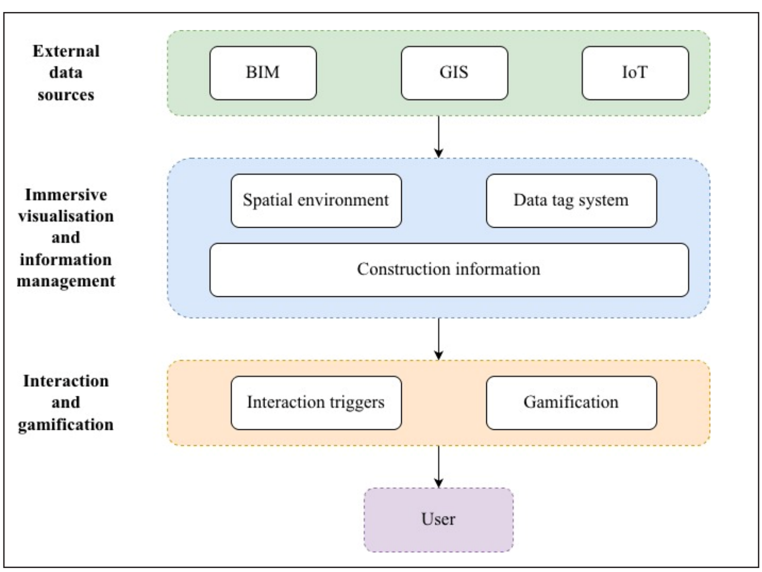

Figure 2. Functional architecture diagram of XRIS

Table 7 shows a comparison of the findings of the current study in relation to previous works. Platforms without gamification demonstrated visualisation and coordination benefits but did not address sustained engagement during information retrieval. Prior gamified platforms recorded incidental engagement from task completion and measured retention narrowly as hazard recall or procedural knowledge transfer. Neither construct was linked to gamification as a deliberate design mechanism. Unlike prior platforms where gamification functioned as an external layer, XRIS embedded it within the visualisation layer as part of the information retrieval mechanism. Gaze-triggered mechanics and spatial discovery structured sustained engagement, while active interaction supported respondent-reported conceptual retention of construction information. This gap in the existing literature informed the empirical evaluation presented in this study.

Table 7
Comparison of the present study with previous studies

Author	Technology	Engagement	Retention	Gamification	User Context
Current study	XR	Sustained engagement confirmed	Conceptual retention reported	Embedded gaze-triggered mechanics	XR specialist and Construction professionals
(Speiser & Teizer, 2024)	VR + BIM	Not measured	Hazard recall supported	None	Construction professionals
(Alhady et al., 2024)	XR + BIM	Not measured	Not measured	None	Infrastructure professionals
(Chen et al., 2024)	BIM-VR + gamification	Scenario engagement reported	Not measured	Scenario-based	Mixed (students/ professionals)
(Yalçın,2024)	BIM-VR	Participation reported	Not measured	Game mechanics	Public stakeholders
(Margheritti et al., 2025)	XR + serious games	Enhanced engagement reported	Knowledge transfer supported	Serious games	Workplace safety trainees

METHODS

A qualitative research design was adopted to identify the benefits of XRIS implementation in the construction industry and evaluate the impact of gamification on XRIS use. A qualitative method was appropriate to generate in-depth narrative data, as the research centred on subjective experiences and perceptual responses that cannot be adequately captured through numerical measurement (Creswell & Creswell, 2017).

A purposive sampling strategy recruited respondents with direct experience in XR technologies or construction project workflows. The sampling frame required at least five years of industry experience and active professional involvement. Determining an appropriate sample size was guided by the concept of data saturation, which occurs when no new information or themes emerge from additional data collection. Guest et al. (2006) demonstrated that data saturation becomes evident after six in-depth interviews. A larger sample size can hinder the depth of analysis in qualitative inquiry (Boddy, 2016).

Respondents engaged in a controlled session with a gamified XRIS prototype on a HoloLens at the Vortex XR Lab, Taylor's University, as shown in Figure 3. Each respondent explored the prototype independently within a standardised timeframe. This setup provided a consistent experiential baseline for the interviews. Each respondent then took part in a semi-structured interview. The protocol covered four thematic areas: spatial understanding, system accessibility, gamification experience, and collaborative potential.

Figure 3. XRIS prototype session at the Vortex XR Lab

Research Framework

Figure 4 presents the integrated research framework designed to guide the methodological process of this study. The framework starts with XR sessions, whereby respondents engaged with an XRIS prototype with a HoloLens. Two forms of data were collected from each session: interaction logs documenting user navigation patterns and spatial engagement, and feedback transcripts capturing verbal responses during and after the experience. These dimensions provided the basis for connecting XRIS experiences and gamification design features to user responses across the thematic categories identified in the study.

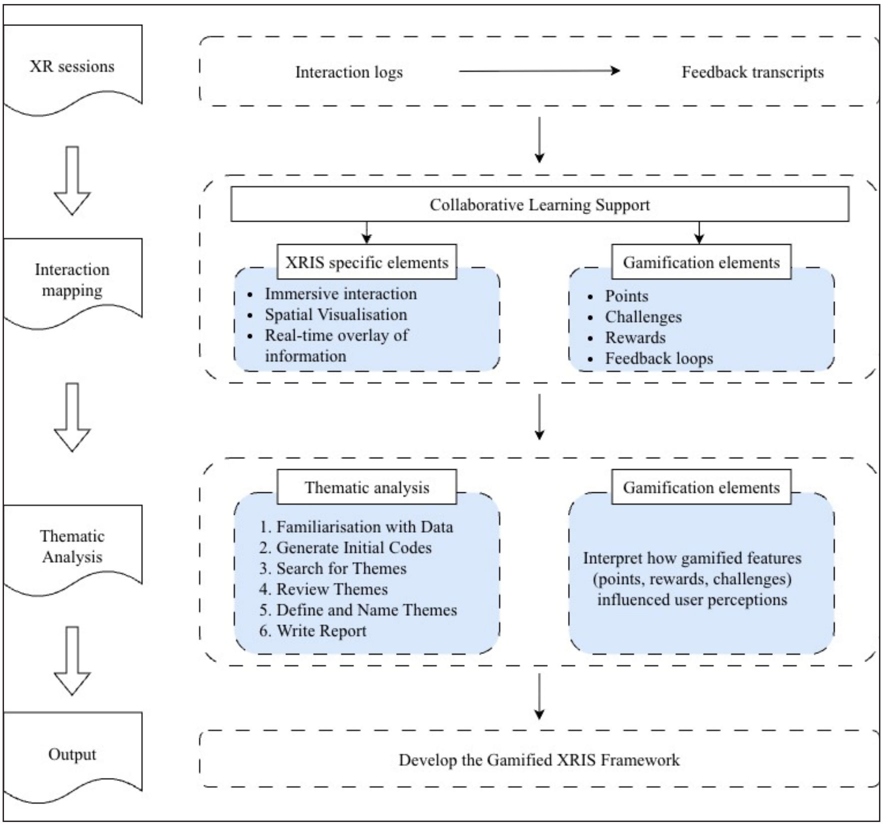

Figure 4. Research framework

Thematic Analysis

A thematic analysis was conducted following Braun and Clarke's (2006) six-phase framework. After familiarisation with the transcripts, descriptive and interpretive codes were generated and iteratively reviewed to refine emerging patterns into coherent themes. The findings were consolidated into two primary categories: (A) Benefits of XRIS in construction and (B) Impact of Gamification on XRIS Use.

The coding structure followed a two-tier sub-theme system within each thematic group. Two sub-themes were constructed for each main theme. For example, Improved Visualisation comprised easier spatial relationship comprehension (A1a-i) and a more immersive experience than 2D drawings (A1a-ii), while User Engagement was split into encouragement of extended use (B1a-i) and stimulation of curiosity and task completion (B1a-ii). This allowed for more in-depth analysis and for different perceptions to be captured. Table 8 presents the complete coding structure along with the themes, sub-themes and distribution of respondents.

Table 8
Summary of responses on findings

Finding / Coding Group	Theme	Sub-theme	Code	Respondent									
				R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Finding 1 – Benefits of XRIS in Construction													
Improved Visualisation	Spatial understanding	Easier spatial relationship comprehension	A1a-i		✓	✓	✓	✓	✓	✓	✓	✓	✓
		More immersive than 2D drawings	A1a-ii	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
User Accessibility	Information access	Information is easy to locate	A2a-i		✓	✓	✓	✓	✓	✓	✓	✓	✓
		Intuitive interaction with the system	A2a-ii	✓	✓	✓		✓	✓	✓			✓
Team Communication	Collaboration	Easier to explain design decisions	A3a-i		✓	✓		✓	✓		✓	✓	✓
		Supports through shared view	A3a-ii	✓	✓	✓	✓			✓		✓	✓
User Motivation	Engagement	More interesting than traditional tools	A4a-i		✓	✓	✓	✓	✓	✓	✓	✓	✓
		Encourages learning through experience	A4a-ii	✓	✓	✓			✓		✓		
Finding 2 – Impact of Gamification on XRIS Use													
User Engagement	Motivation	Encourages extended use	**B1a-i**		✓	✓			✓	✓	✓	✓	
		Stimulates curiosity and task completion	**B1a-ii**	✓	✓	✓		✓	✓			✓	
Game Features	Challenges and Rewards	Makes learning fun	**B2a-i**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Increases system exploration	**B2a-ii**	✓	✓	✓			✓		✓		
Learning Experience	Knowledge Retention	Enhances understanding via interaction	**B3a-i**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Supports better memory of construction concepts	**B3a-ii**	✓	✓	✓			✓		✓	✓	✓

RESULTS AND DISCUSSION

Respondents' Profile

The various professional positions from the respondents covered the entire project lifecycle. From design advisory and feasibility assessment (consultant) to coordination and construction sequencing on site (contractor), and evaluation from XR specialists and academics. Ten respondents came from four different occupational groups, providing cross-disciplinary coverage in the evaluation. The XR specialists had experience in XR facility management, hardware deployment, and immersive content development, with firsthand experience in applications using HoloLens. This background enabled them to assess the technical fidelity and interaction design of the prototype from a development standpoint. Table 9 provides succinct details about the interviewees' backgrounds. By the eighth interview, no new themes emerged, confirming that the sample was sufficient for thematic saturation (Lim, 2025). The final two interviews confirmed existing patterns without adding new codes.

Table 9
Demographic profile of respondents

Respondent ID	Discipline	Years of Industry Experience	XR Experience Level
R1	XR Specialist	> 10	Advanced
R2	XR Integration Designer	> 5	Advanced
R3	Consultant	> 5	Basic
R4	Consultant	> 10	Basic
R5	Consultant	> 15	Basic
R6	Contractor	> 20	Basic
R7	Contractor	> 10	Basic
R8	Contractor	> 5	Basic
R9	Academia	> 10	Basic
R10	Academia	> 15	Basic

Benefits of XRIS in Construction

Improved Visualisation

The empirical findings demonstrated that XRIS significantly enhanced visualisation as it allowed users to view the spatial relationship and get access to information more intuitively compared to the traditional two-dimensional way of representation. The respondents stressed that the direct overlay of the data on virtual objects fixed the gap between the abstract data and the physical layout. The system eliminated the need of cross-referencing external manuals or fixed slides as it spatially anchored the information related to the component.

The page made it easier to comprehend the spatial relationship between components. -R6

The spatial placement allowed me to link each element with its function without confusion. -R8

The way the info popped up next to each component made it easier for me to understand what I was looking at. It's clearer than trying to read a manual. -R3

The info tag comes out beside the item, so I can understand straight away what it is for. -R4

It helps to give more of your space differently, give a new meaning to what spatial spaces mean. -R1

These results support the findings obtained by Arslan et al. (2024), who found that immersive 3D environments can promote spatial knowledge and reduce misunderstanding. The ability of the users to find their way through interrelations and absorb data conforms to the propositions of Azmi et al. (2017), who argued that XRIS facilitates a deeper understanding of intricate designs and spatial relationships in the design planning processes. In addition, this finding aligns with more generalised evidence that suggests interactive visualisation helps to promote a better understanding of choices compared to non-interactive media (Mi & Li, 2024; Oral et al., 2023). Hence, this allows the users to manipulate complicated data without the frustration that is often caused by conventional documentation.

User Accessibility

The empirical results indicated that the XRIS environment was concomitant with high user access, as indicated by an extraordinarily short learning curve. These are the results compared to the current fears of digital complexity in the context of construction. Users claimed an intuitively easy experience that requires minimal training, which highlights the instantaneous usability of the system.

Honestly, it didn’t take more than a minute to figure out. Everything felt intuitive. -R3

Didn’t need any guide. I just wear and explore already. -R7

Very easy to use. Just try one time, already can use. -R5

These outcomes contradict the usability issues described by Priyantini et al. (2023), suggesting that the problematic usability can be alleviated by an effective interface design. The ability of the respondents to communicate with each other using simple gestures was consistent with the long-term interaction goal expressed by Bitriany et al. (2021). Moreover, the users noted that the system is responsive, especially in the efficiency of gaze-based triggers, which were used to achieve smooth and hands-free access to information.

> Information access was seamless. It appeared automatically as I focused on a component. -R6

> Basically, you just look at wherever you want, and then basically the information is there. -R1

> It auto comes out when I look at it. Very fast, very simple. -R10

The automaticity can be linked to the benefits of real-time feedback and interaction described by Hajji et al. (2022) and Yu et al. (2024). The system also made it easier to navigate and interactively manipulate datasets in immersive settings, which supports the propositions of Morris et al. (2021).

Team Communication

According to the respondents, the XRIS system greatly helped in the presentation of design logic and construction concepts to the team members. The respondents noted that the direct interaction with the spatial model allowed them to come up with eloquent explanations. This further helped them to properly coordinate their individual understanding to the group observation.

> After I tried XRIS, I had a clearer idea how to explain my design logic in the group. – R3

> When I talked to my friends, I just walked them through what I saw. That made my explanation clearer. – R9

> It can support my ability to explain construction ideas if I communicate with teams in the future. – R6

These results support the existing body of literature about team dynamics in which shared visual tools are linked to better shared objectives and more transparency (Cheng and

Chau, 2022; Bizzi, 2023). The internalisation of spatial data allows stakeholders to exchange knowledge more efficiently, which justifies the findings by Encarnação et al. (2021) on improved communication and trust in a team-based environment. Additionally, the respondents identified how the use of spatial referencing can be useful to minimise ambiguity in discussions. The ability to recognise and highlight visual items allowed users to produce more accurate messages.

> You want to point out to a specific location or specific object... it makes it easier to send the message to your team member. -R1

> When our group discuss the assignment, we can just share what we see in the VR. -R10

This is in line with the advantages reported by Hajji et al. (2022) and Yu et al. (2024), who established that XR will help in remote coordination and immediate reactions to design alterations. The fact that it is possible to anchor the discussion on specific visual objects confirms the possibility of XRIS to facilitate group problem-solving (Patricio et al., 2022).

User Motivation

Active interaction in the XRIS system significantly contributes to the element of user motivation as it transforms passive observation into an active exploration. The respondents also noted that they always found the experience interesting, and they rated the experience highly when compared to traditional industry practices, such as didactic presentations or when using manuals. The immersive features embedded in the system made the users engage in the project data understanding voluntarily and give extra time and effort.

> Besides just looking at a website, [users] can walk around... it makes the [process] much more fun. -R2

> Better engaging way... unsuspectingly spending more time, engaging more time with the application. -R1

> I think it is more engaging instead of looking at the [static] slide. -R6

These findings are in line with the research on gamification in the workplace, which argues that interactive exercises are attention-grabbing and lead to long-term engagement (Bitrián et al., 2021; Chang et al., 2022). The unintentional time expenditure of the respondents is consistent with the results of Encarnação et al. (2021) and Bizzi (2023), who found that motivational cues strengthen effort and prompt users to perform tasks more effectively. Respondents indicated that physical movement and exploration resulted in better memory retention compared to passive briefing.

> Since I was exploring actively, I think I retained more than usual. -R3
>
> I retained the concepts better because I was actively involved. -R6
>
> It makes me feel like I want to learn more after the testing to XRIS. -R8

These results confirm the hypotheses of Ortiz-Rojas et al. (2025) who argue that gamified tasks provide active learning experiences, enhance a better understanding, and enhance long-term memory of information. The shift in the consumption to the active enquiry and the inquiry shows how XRIS can support the adoption and continuation of preferred work practices, as Kim and Castelli (2021) propose.

Impact of Gamification on XRIS Use

User Engagement

The qualitative data revealed that the gamified mechanisms within the XRIS system significantly prolonged user engagement, fostering a state of sustained interaction, whereby stakeholders voluntarily invested more time in exploration than anticipated. Respondents described a compelling attraction to the system, whereby the drive to complete tasks overrode the perception of time passing. Curiosity-driven engagement was observed in respondents who voluntarily extended their session time due to an intrinsic interest in the immersive experience. These users described an unplanned desire to continue exploring without external instruction or prompting.

> That would encourage you to stay more without realising it because you are trying to achieve a particular gamified task within the application. -R1
>
> I spent more time than expected. I didn’t want to stop halfway. -R3
>
> I engaged with the content longer because the feature grabs my [attention]. -R6

The results were congruent with the literature on gamification mechanics, which claimed that these activities were successful in attracting attention, maintaining engagement and avoiding disengagement by satisfying psychological needs for competence and autonomy (Bitrián et al., 2021; Chang et al., 2022). Gamification also produced an excitement that enhanced the level of attentional investment. The treasure-hunt framing of XRIS drew respondents in before task-driven engagement became a conscious goal. This distinction matters analytically, as sustained interaction describes persistence while excitement-driven attention capture prevents disengagement. Self-Determination Theory further illuminates this, as the spatial challenge structure satisfied the need for competence by triggering intrinsic curiosity rather than extrinsic reward-seeking (Ryan & Deci, 2000). This effect was magnified in the immersive environment, which focused attention on the gamified content (Smith & Mulligan, 2021).

> The layout encouraged full exploration of all elements. -R6

> I want to stay longer just to make sure I got through all the parts. -R9

> Besides just looking at a website, [users] can walk around, doing treasure hunting, it makes the [process] much more fun. -R2

This behaviour validated Encarnação et al. (2021) and Bizzi (2023), who noted that progress indicators reinforce effort and task completion. The immersive aspect of XRIS transformed routine information retrieval into an active task, reducing boredom caused by repetitive technical tasks (Almeida et al., 2023). High engagement translates into readiness to adopt XRIS professionally, supporting well-designed gamified systems, maintaining desired work practices (Kim & Castelli, 2021).

> For me, I think I will continue to use it in the future if it’s developed in the construction industry. -R8

> I would say it encouraged more, for example, how can I apply VR and XR in construction architecture? -R2

Game Features

XRIS effectively developed a mission-oriented attitude, transforming traditional information retrieval into a systematic challenge. The respondents repeatedly compared the experience to a treasure hunt, a mini mission. They also noted that the implicit gamification encouraged them to search proactively and find certain data points in space. This task structure provided an intrinsic compass, ensuring that all the contents were covered even where no specific guidelines were given.

> It gamified the learning without needing traditional scores or points. -R8

> The learning is like a game, because we need to walk around the room and search for the info... the system guided me naturally. -R6

> Similar to game elements, like having to find where the spot is located, making it challenging and fun. -R10

> It felt like I was completing a task, kind of gamified. -R3

These results correspond to the existing literature on gamified challenges, which are the ones that have been found to facilitate active learning and further comprehension (Liu et al., 2023; Ortiz-Rojas et al., 2025). The fact that the respondents have specifically mentioned the aspect of natural guidance. On the other hand, facilitated the discussion that effective gamified interfaces can enhance usability and lessen the cognitive burden of intricate navigation. Completionist behaviour was one of the results of this mechanic that was notable. There was a psychological desire to check every node reported by its users to make sure that they did not miss any important information, which is not so inherent in the traditional document reviews.

> I explored every tag just to make sure I didn't miss anything. -R3

> I moved through the entire layout because it felt like a complete learning sequence. -R8

> User can walk around, doing treasure hunting, it makes the [process] much more fun. - R2

This confirmed the claim of Encarnação et al. (2021) and Bizzi (2023) that gamified features, including progress indicators or the design of a quest, strengthen the effort and motivate users to perform tasks more regularly. The system should make the users eager to explore the content more carefully by positioning the construction data inspection as a discovery process, thus increasing the likelihood of retaining the information (Ortiz-Rojas et al., 2025).

Learning Experience

The findings indicated that XRIS was interactive, which led to a better understanding of elements of construction in comparison to the passive modes of learning. The respondents highlighted that they could perceive spatial elements and labels directly, which contributed to the increased conceptual clarity. Through the interaction with the information in a spatial environment, they indicated having greatly improved their capacity to understand the logic behind the construction assemblies.

> It helps me understand more about the elements of the construction. -R2

> Interactive learning enhanced my conceptual clarity. -R6

> By interacting with each label, I think it makes my understanding better. -R8

These observations were also supported by the knowledge about XR-based training, which implied that spatial knowledge is better learned in immersive environments and is less prone to misinterpretation (Arslan et al., 2024). The claim by the respondents that the system enhances conceptual understanding was in line with Azmi et al. (2017), who argued that XRIS visualisation enables users to have a better understanding of complex designs and spatial relationships.

Out of direct understanding, the data indicated that the practicality of the experience was a great enhancer of the memory. Respondents observed that the process of physically navigating and interacting with the data produced a greater cognitive impression as compared to traditional reading, and, therefore, they were able to remember the information much better.

> Interacting with the system helped me understand the content more deeply... I can still recall what I saw because I was hands-on. -R3

> The experience is unique, and I can memorise things better through the visualisation. -R9

> The key takeaways remain with me because of the immersive experience. -R6

This supports the research of Ortiz-Rojas et al. (2025), who assumed that gamified interactive challenges facilitated active learning and increased long-term information retention. Moreover, it proves the conclusion made by Pavlou et al. (2021) that knowledge retention and practical preparedness can be improved through XR-based skills training.

Lastly, the findings indicated improved efficiency in learning. Respondents also said that the interactive model made them quicker at processing information, partly because the device was hands-free and therefore, they could do multiple activities at the same time and access information instantly. This was in line with the literature that reported enhanced task performance and skill learning as the main advantage of XR integration (Liu et al., 2022; Speiser and Teizer, 2024).

> When I interact with myself, I understand faster. -R4

> Can understand the elements faster besides just searching the info on the internet. -R7

> You free your hands when you are using it to get data... basically you can do other stuff like hold other things. -R1

CONCLUSION

This study presents a gamified Extended Reality Informative Space (XRIS), a HoloLens-based platform that spatially anchors construction data within an immersive environment through gaze-triggered information retrieval and embedded game-based mechanics. These advances address persistent challenges in the construction industry, such as design misinterpretation, information asymmetry, and inefficient constructability reviews that arise from conventional 2D documentation and static 3D models. Through semi-structured interviews with industry stakeholders and XR specialists, this study identified the benefits of XRIS implementation and the impact of gamification on XRIS use.

The findings indicated that XRIS supported spatial cognition and improved access to construction information relative to traditional methods. Respondents described the system as intuitive, reporting gains in perception, retention, and articulation of design logic. Gamified discovery cues were associated with sustained user engagement throughout the controlled prototype sessions. Respondents distinguished curiosity-driven exploration from task-driven persistence prompted by completion goals and progress cues.

This study goes beyond existing XR-BIM and gamification research by integrating spatially anchored information retrieval, immersive interaction triggers, and embedded gamification within a single professional workflow configuration. In contrast to the generic XR-BIM, XRIS is a system that integrates motivational elements into the visualisation layer as opposed to being an external layer. This configuration was evaluated with practising construction stakeholders, a population underrepresented in gamified XR research. This positions the study as a meaningful contribution to the design of immersive tools for professional construction practice.

Several limitations bound these findings. The primary purpose of this study was to focus on the development of an XRIS prototype that can be applied practically in the industry and establishing proof of concept in controlled conditions before its deployment in the field. The controlled laboratory environment was hence not entirely representative of environmental conditions and pressures on working construction sites. Respondents also voiced concerns over long-term use of the devices and the learning curve for new users. The constraints of ergonomic and usability may affect the feasibility of adoption.

Future research should consider the performance of XRIS with alternative head-mounted devices over longer periods. Comparative experimental designs would enhance causal claims by benchmarking XRIS with non-gamified XR and conventional review to assess whether there is discomfort reduction or onboarding time reduction. The collaborative potential suggested by respondents requires multi-user deployment studies to be conducted. A mixed-method assessment, utilising efficiency, error, and decision quality measures, along with qualitative feedback, would evaluate the impact of workflow.

ACKNOWLEDGEMENT

The authors wish to pay gratitude to Taylor's University Malaysia for providing a conducive research environment.

REFERENCES

Abouelkhier, N., Rauf, A., Luyten, L., & Shafiq, M. T. (2025). Mitigating early-phase miscommunication between architects and structural engineers: A systematic review and framework linking BIM/VR strategies to communication barriers. *Architectural Engineering and Design Management*, 1-23. https://doi.org/10.1080/17452007.2025.2586665

Alam, N., Saha, N., Gadow, V., Harik, R., & Ryu, J. (2025). Role of extended reality (XR) technologies in maintenance operations: Trends, challenges, and integration in Industry 4.0. *Manufacturing Letters, 44*, 1545-1557. https://doi.org/10.1016/j.mfglet.2025.06.174

Alhady, A., Alanany, M., Khodair, Y., Salem, S., & El Maghraby, Y. (2024). Integrating building information modelling (BIM) and extended reality (XR) in the transportation infrastructure industry. *Advances in Bridge Engineering, 5*(1), Article 22. https://doi.org/10.1186/s43251-024-00132-6

Ali, O., Murray, P., Al-Ahmad, A., & Tahat, L. (2024). An integrated framework for addressing the challenges and strategies of technology adoption: A systematic review. *Emerging Science Journal, 8*(3), 1215-1242. https://doi.org/10.28991/ESJ-2024-08-03-025

Almeida, C., Kalinowski, M., Uchôa, A., & Feijó, B. (2023). Negative effects of gamification in education software: Systematic mapping and practitioner perceptions. *Information and Software Technology, 156*, Article 107142. https://doi.org/10.1016/j.infsof.2022.107142

Alshboul, O., & Shehadeh, A. (2025). Adaptive integration of BIM and Navisworks for real-time clash detection using the XGBoost algorithm. *Journal of Construction Engineering and Management, 152*(1), Article 04025232. https://doi.org/10.1061/JCEMD4.COENG-16001

Alzarrad, A., Miller, M., Durham, L., & Chowdhury, S. (2024). Revolutionising construction safety: Introducing a cutting-edge virtual reality interactive system for training US construction workers to mitigate fall hazards. *Frontiers in Built Environment, 10*, Article 1320175. https://doi.org/10.3389/fbuil.2024.1320175

Arslan, O., Akdoğan, A., & Dogan, M. D. (2025). TinkerXR: In-situ, reality-aware CAD and 3D printing interface for novices. In *Proceedings of the ACM Symposium on Computational Fabrication* (pp. 1-19). Association for Computing Machinery. https://doi.org/10.1145/3745778.3766651

Azmi, N. F., Chai, C. S., & Chin, L. W. (2017). Building information modelling (BIM) in the architecture, engineering, and construction (AEC) industry: A case study in Malaysia. In *Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate* (pp. 401-412). Springer. https://doi.org/10.1007/978-981-10-6190-5_36

Bhatarai, R., Banihashemi, S., Shakouri, M., & Antwi-Afari, M. (2025). Integration of augmented reality with building information modelling: Design optimisation and construction rework reduction perspective. *Archives of Computational Methods in Engineering, 32*(4), 2233-2254. https://doi.org/10.1007/s11831-024-10211-6

Bitrián, P., Buil, I., & Catalán, S. (2021). Enhancing user engagement: The role of gamification in mobile apps. *Journal of Business Research, 132*, 170-185. https://doi.org/10.1016/j.jbusres.2021.04.028

Bizzi, L. (2023). Why to gamify performance management? Consequences of user engagement in gamification. *Information & Management, 60*(3), Article 103762. https://doi.org/10.1016/j.im.2023.103762

Boddy, C. R. (2016). Sample size for qualitative research. *Qualitative Market Research: An International Journal, 19*(4), 426-432. https://doi.org/10.1108/QMR-06-2016-0053

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

Brooks, F. P., Jr. (1987). Walkthrough-A dynamic graphics system for simulating virtual buildings. In *Proceedings of the 1986 Workshop on Interactive 3D Graphics* (pp. 9-21). Association for Computing Machinery. https://doi.org/10.1145/319120.319122

Chang, D., Xiang, Y., Zhao, J., Qian, Y., & Li, F. (2022). Exploration of brain–computer interaction for supporting children's attention training: A multimodal design based on attention network and gamification design. *International Journal of Environmental Research and Public Health, 19*(22), Article 15046. https://doi.org/10.3390/ijerph192215046

Chen, Q., Li, C., Xu, X., Mao, P., & Xiong, L. (2024). Intelligent systems integrating BIM and VR for urban subway microenvironmental health risks management. *Buildings, 14*(7), Article 1912. https://doi.org/10.3390/buildings14071912

Cheng, C., & Chau, C. L. (2022). Gamification-based intervention for enhancing team effectiveness and coping flexibility: Randomised controlled trial. *Frontiers in Psychiatry, 13*, Article 941252. https://doi.org/10.3389/fpsyt.2022.941252

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. SAGE Publications.

Davila Delgado, J. M., Oyedele, L., Beach, T., & Demian, P. (2020). Augmented and virtual reality in construction: Drivers and limitations for industry adoption. *Journal of Construction Engineering and Management, 146*(7), Article 04020079. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001844

Dawood, N., Sriprasert, E., Mallasi, Z., & Hobbs, B. (2003). Development of an integrated information resource base for 4D/VR construction process simulation. *Automation in Construction, 12*(2), 123-131. https://doi.org/10.1016/S0926-5805(02)00045-6

Encarnação, R., Reuter, J., Ferreira Dias, M., & Amorim, M. (2021). Gamification as a driver of motivation in organisations: A bibliometric literature review. In *Proceedings of the Ninth International Conference on Technological Ecosystems for Enhancing Multiculturality (TEEM'21)* (pp. 167-172). Association for Computing Machinery. https://doi.org/10.1145/3486011.3486440

Fernández-Caramés, T. M., & Fraga-Lamas, P. (2024). Forging the industrial metaverse towards Industry 5.0: Where augmented/mixed reality, IIoT, opportunistic edge computing, and digital twins meet. *IEEE Access, 12*. https://doi.org/10.1109/ACCESS.2024.3422109

FMI, & PlanGrid. (2018). *Construction disconnected: The high cost of poor data and miscommunication*. Autodesk. https://www.autodesk.com/blogs/construction/construction-disconnected-fmi-report/

Guimarães, A., Cavalcanti, M., & Vasconcelos, B. M. (2024). Gamification using technologies for occupational safety training in the civil construction sector. *Work, 77*(2), 477-485. https://doi.org/10.3233/WOR-220685

Gomez, M., Pahor, A., Carrillo, A., Seitz, A., & Jaeggi, S. (2024). Promoting executive functions in older adults: The role of gamification and individual differences. *Innovation in Aging, 8*(Suppl. 1), 1152. https://doi.org/10.1093/geroni/igae098.3695

Guest, G., Bunce, A., & Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. *Field Methods, 18*(1), 59–82. https://doi.org/10.1177/1525822X05279903

Gornall, J., Peña, A., Pinto, H., Rojas, J., Correa, F., & García, J. (2026). Extended reality in Construction 4.0: A systematic review of applications, implementation barriers, and research trends. *Applied Sciences, 16*(1), Article 9. https://doi.org/10.3390/app16010009

Hajji, R., Kharroubi, A., Ben Brahim, Y., Bahhane, Z., & El Ghazouani, A. (2022). Integration of BIM and mobile augmented reality in the AECO domain. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVI-4/W3-2021*, 131-138. https://doi.org/10.5194 isprs-archives-XLVI-4-W3-2021-131-2022

Hammedi, W., Leclercq, T., & Steils, N. (2024). Gamification myopia: Satiation effects in gamified activities. *Journal of Service Research, 27*(2), 213-230. https://doi.org/10.1177/10946705231190873

Henry, J., Li, F., & Arnab, S. (2024). On the pre-perception of gamification and game-based learning in higher education students: A systematic mapping study. *Simulation & Gaming, 55*(6), 985-1010. https://doi.org/10.1177/10468781241271082

Heo, J., Bhardwaj, K., & Gavrilovska, A. (2023). FleXR: A system enabling flexibly distributed extended reality. In *Proceedings of the 14th Conference on ACM Multimedia Systems* (pp. 1-13). Association for Computing Machinery. https://doi.org/10.1145/3587819.3590966

Irani, Z., Abril, R. M., Weerakkody, V., Omar, A., & Sivarajah, U. (2023). The impact of legacy systems on digital transformation in European public administration: Lessons learned from a multiple-case analysis. *Government Information Quarterly, 40*(1), Article 101784. https://doi.org/10.1016/j.giq.2022.101784

Jacobides, M. G., Ma, M. D., Trantopoulos, K., & Vassalos, V. (2024). The business value of gamification. *California Management Review, 66*(2), 91-107. https://doi.org/10.1177/00081256231218469

Jalo, H., & Pirkkalainen, H. (2024). Effect of user resistance on the organisational adoption of extended reality technologies: A mixed-methods study. *International Journal of Information Management, 75*, Article 102731. https://doi.org/10.1016/j.ijinfomgt.2023.102731

Jato-Espino, D., Vila-Cortavitarte, M., Rodriguez-Hernandez, J., & Castro-Fresno, D. (2024). Gamification as a tool to improve educational and training outcomes in civil engineering. *Journal of Civil Engineering Education, 150*(4), Article 03124001. https://doi.org/10.1061/JCEECD.EIENG-1962

Kim, J., & Castelli, D. M. (2021). Effects of gamification on behavioural change in education: A meta-analysis. *International Journal of Environmental Research and Public Health, 18*(7), Article 3550. https://doi.org/10.3390/ijerph18073550

Klein, G. (2021). Viewing gamification design limitations and weaknesses through a pandemic lens. *Societies, 11*(4), Article 137. https://doi.org/10.3390/soc11040137

Koivisto, J., & Hamari, J. (2014). Demographic differences in perceived benefits from gamification. *Computers in Human Behaviour, 35*, 179-188. https://doi.org/10.1016/j.chb.2014.03.007

Le, N., Tran, D., & Sturgill, R. (2024). Content analysis of three-dimensional model technologies and construction applications: Current trends and future directions. *Sensors, 24*(12), Article 3838. https://doi.org/10.3390/s24123838

Lee, M., Chai, C., Xiong, Y., & Gui, H. (2022). Technology acceptance model for building information modelling-based virtual reality (BIM-VR) in cost estimation. *Journal of Information Technology in Construction, 27*, 904-925. https://doi.org/10.36680/j.itcon.2022.044

Leite, R. M. C., Winkler, I., & Alves, L. R. G. (2022). Visual management and gamification: An innovation for disseminating information about production to construction professionals. *Applied Sciences, 12*(11), Article 5682. https://doi.org/10.3390/app12115682

Leite, R. M. C., Alves, L. R. G., Cardoso, L. D. S. P., & Neto, H. M. M. (2023). How has gamification in the production sector been developed in manufacturing and construction workplaces? *Buildings, 13*(10), Article 2614. https://doi.org/10.3390/buildings13102614

Li, T., Hu, H., Ma, H., Ma, J., & Li, Q. (2025). Using virtual reality to enhance learning performance and address educational resource disparities in architectural history courses. *Sustainability, 17*(3), Article 866. https://doi.org/10.3390/su17030866

Lim, W. M. (2025). Sample size in qualitative research: Moving from data saturation to theoretical saturation. *Journal of Global Marketing, 38*(5), 449-459. https://doi.org/10.1080/08911762.2025.2590757

Liu, P., Xing, J., Xiong, R., & Tang, P. (2022). *Sharing construction safety inspection experiences and site-specific knowledge through XR-augmented visual assistance* [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2205.15833

Liu, S., Ma, G., Tewogbola, P., Gu, X., Gao, P., Dong, B., … Wu, Y. (2023). Game principle: Enhancing learner engagement with gamification to improve learning outcomes. *Journal of Workplace Learning, 35*(5), 450-462. https://doi.org/10.1108/JWL-11-2022-0160

Manzano-León, A., Camacho-Lazarraga, P., Guerrero, M. A., Guerrero-Puerta, L., Aguilar-Parra, J. M., Trigueros, R., & Alias, A. (2021). Between level up and game over: A systematic literature review of gamification in education. *Sustainability, 13*(4), Article 2247. https://doi.org/10.3390/su13042247

Margheritti, S., Marcucci, S., & Miglioretti, M. (2025). Bridging the gaps: Examining the impact of technology-based active learning in workplace safety training through a systematic literature review. *Safety, 11*(1), Article 5. https://doi.org/10.3390/safety11010005

Mohanty, S., & Christopher, B. P. (2024). The role of gamification research in human resource management: A PRISMA analysis and future research direction. *SAGE Open, 14*(2), Article 21582440241243154. https://doi.org/10.1177/21582440241243154

Monteiro, R. H. B., de Almeida Souza, M. R., Oliveira, S. R. B., dos Santos Portela, C., & de Cristo Lobato, C. E. (2021). The diversity of gamification evaluation in software engineering education and industry: Trends, comparisons, and gaps. In *2021 IEEE/ACM 43rd International Conference on Software Engineering: Software Engineering Education and Training (ICSE-SEET)* (pp. 154-164). IEEE. https://doi.org/10.1109/ICSE-SEET52601.2021.00025

Morris, A., Guan, J., & Azhar, A. (2021). An XRI mixed-reality Internet of Things architectural framework towards immersive and adaptive smart environments. In *2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (pp. 68-74). IEEE. https://doi.org/10.1109/ISMAR-Adjunct54149.2021.00026

Nyqvist, R., Peltokorpi, A., Lavikka, R., & Ainamo, A. (2025). Building the digital age: Management of digital transformation in the construction industry. *Construction Management and Economics, 43*(4), 262-283. https://doi.org/10.1080/01446193.2024.2416033

Oke, A. E., Aliu, J., Tunji-Olayeni, P., & Abayomi, T. (2024). Application of gamification for sustainable construction: An evaluation of the challenges. *Construction Innovation, 24*(4), 1066-1084. https://doi.org/10.1108/CI-09-2022-0247

Oke, A. E., Aliu, J., Mwanaumo, E. M. U. M., Abayomi, T., & Kahanji, C. (2023). Leveraging gamification to enhance productivity and employee engagement in the Nigerian construction industry. *Built Environment Project and Asset Management, 13*(6), 813-829. https://doi.org/10.1108/BEPAM-04-2023-0064

Oral, E., Chawla, R., Wijkstra, M., Mahyar, N., & Dimara, E. (2023). From information to choice: A critical inquiry into visualisation tools for decision-making. *IEEE Transactions on Visualization and Computer Graphics, 30*(1), 359-369. https://doi.org/10.1109/TVCG.2023.3326593

Ortiz-Rojas, M., Chiluiza, K., Valcke, M., & Bolanos-Mendoza, C. (2025). How gamification boosts learning in STEM higher education: A mixed-methods study. *International Journal of STEM Education, 12*(1), Article 1. https://doi.org/10.1186/s40594-024-00521-3

Othman, N. A. F., Zainoddin, A. I., Jaini, A., Ismail, M., & Radzi, S. F. M. (2023). Management of gamified lesson: Understanding aesthetics and acceptance among learners. *Information Management and Business Review, 15*(4), 155-162. https://doi.org/10.22610/imbr.v15i4(SI)I.3588

Patricio, R., Moreira, A. C., & Zurlo, F. (2022). Gamification in innovation teams. *International Journal of Innovation Studies, 6*(3), 156-168. https://doi.org/10.1016/j.ijis.2022.05.003

Pavlou, M., Laskos, D., Zacharaki, E. I., Risvas, K., & Moustakas, K. (2021). XRSISE: An XR training system for interactive simulation and ergonomics assessment. *Frontiers in Virtual Reality, 2*, Article 646415. https://doi.org/10.3389/frvir.2021.646415

Pham, V. B., Wong, S. P. P., & Abbasnejad, B. (2025). *A systematic review of criteria influencing the integration of BIM and immersive technology in building projects*. https://hdl.handle.net/10779/rmit.28570676

Priyantini, D., Amalin, A. M., & Amalia, N. (2023). Designing user interface and user experience by using user-centred design on the gamified platform "Ezedu." *Jurnal Teknologi Pendidikan: Jurnal Penelitian dan Pengembangan Pembelajaran, 8*(4), 834–844. https://doi.org/10.33394/jtp.v8i4.8944

Radanovic, M., Khoshelham, K., Fraser, C. S., & Acharya, D. (2023). Continuous BIM alignment for mixed reality visualisation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, X-1/W1-2023*, 279-286. https://doi.org/10.5194/isprs-annals-X-1-W1-2023-279-2023

Rahiman, H. U., Kodikal, R., & Suresh, S. (2023). Game on: Can gamification enhance productivity? *F1000Research, 12*, Article 818. https://doi.org/10.12688/f1000research.131579.2

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist, 55*(1), 68-78. https://doi.org/10.1037/0003-066X.55.1.68

Sacks, R., Perlman, A., & Barak, R. (2013). Construction safety training using immersive virtual reality. *Construction Management and Economics, 31*(9), 1005-1017. https://doi.org/10.1080/01446193.2013.828844

Safikhani, S., Keller, S., Schweiger, G., & Pirker, J. (2022). Immersive virtual reality for extending the potential of building information modelling in the architecture, engineering, and construction sector: A systematic review. *International Journal of Digital Earth, 15*(1), 503-526. https://doi.org/10.1080/17538947.2022.2038291

Sailer, M., & Homner, L. (2020). The gamification of learning: A meta-analysis. *Educational Psychology Review, 32*(1), 77-112. https://doi.org/10.1007/s10648-019-09498-w

Schwarz, A., Verkooijen, K., de Vet, E., & Simons, M. (2024). Perceived barriers and facilitators regarding the implementation of gamification to promote physical activity in the neighbourhood: Interview study among intermediaries. *JMIR Serious Games, 12*, Article e52991. https://doi.org/10.2196/52991

Smith, S. A., & Mulligan, N. W. (2021). Immersion, presence, and episodic memory in virtual reality environments. *Memory, 29*(8), 983-1005. https://doi.org/10.1080/09658211.2021.1953535

Speiser, K., & Teizer, J. (2024). Formalising virtual construction safety training: A schematic data framework enabling real-world hazard simulations using BIM and location tracking. *Journal of Information Technology in Construction, 29*, 980-1004. https://doi.org/10.36680/j.itcon.2024.043

Struye, J., Van Damme, S., Bhat, N. N., Troch, A., Van Liempd, B., Assasa, H., Lemic, F., Famaey, J., & Torres Vega, M. (2024). Toward interactive multi-user extended reality using millimetre-wave networking. *IEEE Communications Magazine, 62*(8), 54-60. https://doi.org/10.1109/MCOM.001.2300804

Trindade, N. V., Ferreira, A., Pereira, J. M., & Oliveira, S. (2023). Extended reality in AEC. *Automation in Construction, 154*, Article 105018. https://doi.org/10.1016/j.autcon.2023.105018

Vona, F., Warsinke, M., Kojić, T., Voit-Antons, J.-N., & Möller, S. (2025). User-centric evaluation methods for digital twin applications in extended reality. In *2025 IEEE International Conference on Artificial Intelligence and eXtended and Virtual Reality (AIxVR)* (pp. 142-146). IEEE. https://doi.org/10.1109/AIxVR63409.2025.00028

Yalçın, Z. Ö. (2024). Integrating gamification with BIM for enhancing participatory design. *Journal of Computational Design, 5*(2), 317-344. https://doi.org/10.53710/jcode.1505309

Yang, H., Wang, L., Hu, Z., & Li, D. (2024). Understanding the failing of social gamification: A perspective of user fatigue. *Electronic Commerce Research and Applications, 64*, Article 101369. https://doi.org/10.1016/j.elerap.2024.101369

Yu, D., Chen, W., Meng, T., Yu, H., & Mahamadu, A. M. (2024). Applications of immersive technologies in construction computing: A systematic literature review. In *Proceedings of the 2024 European Conference on Computing in Construction* (Vol. 5). European Council on Computing in Construction. https://doi.org/10.35490/EC3.2024.230

Yu, X., Lee, B., & Sedlmair, M. (2024). Design space of visual feedforward and corrective feedback in XR-based motion guidance systems. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (pp. 1-15). Association for Computing Machinery. https://doi.org/10.1145/3613904.3642143