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Design and Development of an Interactive Virtual Tour for Enhancing Architectural Design Communication in Civil Engineering Projects

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Abstract
This study addresses the limitations of traditional two-dimensional (2D) architectural drawings in effectively communicating spatial design to diverse stakeholders in civil engineering projects. The research aims to design and develop an interactive virtual tour system and to evaluate its effectiveness in improving architectural design communication. A Design and Development Research approach was employed, consisting of analysis, design, development, testing, and evaluation stages. The system was developed using SketchUp, Lumion, and Unity, and evaluated by 24 participants, including 12 professional designers and 12 non-technical clients. Data were collected through observation, questionnaires, and interviews, and analyzed using descriptive statistics and paired-samples t-tests. The results show that the virtual tour significantly outperformed 2D drawings across all evaluation aspects, with usability scores of 4.6 ± 0.28 compared to 3.2 ± 0.45, aesthetics scores of 4.7 ± 0.25 compared to 3.5 ± 0.40, and interactivity scores of 4.6 ± 0.30 compared to 2.9 ± 0.50, all with p-values < 0.01. These findings indicate that the virtual tour enhances spatial understanding, user engagement, and communication clarity. The novelty of this study lies in the explicit integration of realistic three-dimensional rendering, interactive navigation, and user-centered design principles within a Design and Development Research framework, combined with empirical evaluation involving both technical and non-technical stakeholders in a real project context. This study contributes to both theory and practice by demonstrating that interactive virtual tours serve as an effective communication medium, reducing misinterpretation and supporting more informed decision-making in civil engineering design processes.

Keywords: *Architectural Design Communication, Civil Engineering Projects, Interactive Virtual Tour, User-Centered Design, Virtual Reality Visualization.*

I. INTRODUCTION

Effective communication of architectural design plays a critical role in ensuring the successful implementation of civil engineering projects. Architectural concepts must be clearly understood by stakeholders, including engineers, architects, contractors, and clients, to minimize design errors and construction inefficiencies. Traditionally, architectural ideas are conveyed through two-dimensional (2D) drawings such as plans, elevations, and sections. Although these representations remain standard practice in the industry, they often fail to communicate spatial depth, scale, and the experiential qualities of a space intuitively. As a result, non-technical stakeholders often struggle to interpret complex design information, leading to misunderstandings, repeated revisions, and delays in project execution. The increasing complexity of modern building designs further amplifies the need for more effective, user-friendly

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visualization media to bridge the communication gap between technical and non-technical participants.

The use of digital visualization technologies has been increasingly studied as a means to improve architectural design communication, particularly in situations where stakeholders have difficulty interpreting spatial information in traditional drawings. (Leite & Silva, 2025) reported that interactive multimedia visualization helps users understand spatial layouts more effectively than static 2D representations. Similarly, (Sugiarto & Anindita, 2025) found that three-dimensional digital models provide clearer insight into building geometry and circulation, enabling stakeholders to evaluate design alternatives more accurately during the planning stage. (Purhita & Rudjiono, 2024) further showed that interactive visualization systems can enhance user engagement and support more informed decision-making in building design processes. In practical residential projects, clients often approve floor plans based on 2D drawings but later request significant changes during construction because the perceived spatial experience does not align with their expectations, highlighting the limitations of conventional visualization methods.

Despite the growing use of digital visualization technologies in architectural design communication, several studies reveal limitations, indicating a clear research gap. (Díaz González et al., 2025; Partarakis & Zabulis, 2024) demonstrated that immersive virtual environments can improve users' perception of spatial depth and scale. However, the study primarily focused on technological immersion rather than on the effectiveness of communication between designers and clients. (Ehab et al., 2023) reported that virtual reality enhances spatial cognition and engagement, although the experiments were conducted in controlled settings that did not represent real construction project interactions.

(Bastardo et al., 2024; Y. Liu & Liu, 2025), showed that interactive, three-dimensional visualization can improve users' understanding and engagement. Yet, their studies were limited in their evaluation of usability, decision-making processes, and implementation in practical civil engineering environments involving both technical and non-technical stakeholders. Therefore, this study aims to design and develop an interactive virtual tour based on user-centered design principles and to empirically evaluate its effectiveness as a communication medium in real civil engineering project scenarios where traditional two-dimensional drawings often lead to misinterpretation and repeated design revisions.

This study is guided by the hypothesis that interactive virtual tour technology can significantly enhance stakeholders' spatial understanding, perceived usability, and engagement compared with traditional two-dimensional drawings in civil engineering design communication. Based on this assumption, the main research question addressed in this study is how effectively an interactive virtual tour can improve the clarity and efficiency of architectural design communication among both technical and non-technical stakeholders. The novelty of this research lies in the integration of realistic three-dimensional rendering, interactive navigation, and user-centered design principles within a Design and Development Research framework, followed by empirical usability evaluation involving real project participants. Unlike previous studies that focused primarily on technical visualization or immersive experience, this research emphasizes the communicative function of virtual tours as a practical tool in real design workflows. It is expected that the results of this study will provide both theoretical contributions to digital visualization research and practical guidelines for implementing interactive virtual tour systems to reduce misinterpretation, minimize design revisions, and support more informed decision-making in civil engineering projects.

II. LITERATURE REVIEW

A. Digital Visualization in Civil Engineering

Digital visualization has become an essential component of civil engineering projects because it enables complex structural and architectural information to be presented in a clearer, more interpretable form. (Mazzetto, 2024) explained that three-dimensional modeling enables engineers to simulate building geometry and detect design conflicts during the early stages of design development. Visualization tools also facilitate collaboration by providing a shared visual reference that multidisciplinary project teams can understand. (Fernández Rodríguez, 2023) reported that the integration of visualization within Building Information Modeling environments improves coordination and reduces inconsistencies in design documentation. These capabilities have led to the widespread adoption of visualization technologies in planning, design, and presentation phases of construction projects.

Realistic rendering techniques further improve the communicative value of digital visualization by representing lighting, textures, and material properties in a visually convincing manner. (Alkhresheh, 2025) stated that visual realism enhances users' perception of architectural quality and spatial atmosphere when evaluating design alternatives. Digital visualization is also beneficial for communicating design intent to non-technical stakeholders who may find technical drawings difficult to interpret. (Kossakowski, 2023) observed that interactive visual representations help clients understand spatial layouts and building functions more effectively than static drawings. (Marzouk & Thabet, 2023) explained that visual simulation tools allow project teams to explore multiple design scenarios before construction begins, which supports more informed decision-making.

B. Virtual Reality and Spatial Understanding

Virtual reality technology provides users with an immersive environment that allows architectural spaces to be experienced from a first-person perspective. (Han et al., 2026) introduced the virtuality continuum to describe how digital environments can simulate real spatial experiences with varying degrees of immersion. This immersive characteristic distinguishes virtual reality from conventional visualization methods that rely on static images or screen-based interaction. The ability to navigate freely within a virtual environment enables users to perceive depth, scale, and spatial relationships more naturally than through two-dimensional representations. Such spatial perception is closely related to spatial cognition, which describes how individuals mentally process spatial information.

(Chen et al., 2024) reported that users interacting with virtual environments develop more accurate mental models of building layouts compared with those relying on traditional drawings. (Wang et al., 2024) found that virtual reality environments increase user engagement and support a more comprehensive understanding of complex spatial arrangements. (Torrens & Kim, 2024) explained that simulated navigation in virtual environments allows users to evaluate circulation paths and visibility as in real-world exploration. (Yang et al., 2024) added that immersive environments enhance users' perception of architectural depth and scale, which contributes to more realistic design evaluation. These findings indicate that virtual reality can significantly support spatial comprehension during architectural design review.

C. User Centered Design and Visual Communication

User-centered design is an approach that emphasizes understanding user needs, expectations, and limitations throughout the system development process. (Caschera & Guzzo, 2026) explained that systems designed with user-centered principles tend to be more intuitive because they align with users' mental models and natural interaction patterns. In interactive architectural visualization systems, interface design elements such as navigation controls, camera movement, and information layout play a crucial role in determining how effectively users can explore digital environments. (Grobelna et al., 2025) stated that clear navigation structures and responsive interfaces improve the efficiency and comfort of user interaction in complex digital systems. These usability considerations are particularly important when visualization tools are intended for both technical professionals and non-technical stakeholders.

Visual communication principles are also essential for presenting spatial information in a visually organized, easy-to-interpret way. (Guo et al., 2024) described visual communication as the strategic arrangement of visual elements such as color, lighting, and composition to guide user attention and convey functional meaning. (Ma, 2025) highlighted that Gestalt principles such as proximity, continuity, and figure-ground relationships support users in organizing visual stimuli into meaningful patterns. (C. Liu & Qu, 2026) reported that reducing cognitive load through clear visual structure enables users to process information more efficiently when interacting with visually rich digital interfaces. These theoretical perspectives provide a foundation for designing virtual environments that are both usable and visually effective.

D. Previous Studies on Interactive Media and Virtual Tours

Interactive media and virtual tour technologies have been widely explored as tools to enhance architectural presentation and spatial communication. (Angelova et al., 2025) reported that interactive multimedia environments improve user comprehension by presenting building information in a dynamic and accessible format. Researchers have implemented virtual tours using various platforms, including web-based visualization, game engines, and immersive virtual reality systems. (Stanga et al., 2023) explained that users were able to interpret building layouts more accurately when using three-dimensional visualization compared with traditional two-dimensional drawings. These developments indicate a growing interest in using interactive visualization to support more effective design communication.

Other studies have examined how interactive features influence user experience and engagement during design exploration. (Zhang et al., 2024) stated that interactive navigation features encourage users to explore digital environments rather than passively observe visual representations. (Renganathan et al., 2025) observed that virtual environments help users form more accurate mental representations of spatial layouts through experiential interaction. (Stabryła & Grudzińska, 2025) described that immersive visualization enhances the perception of depth and scale when evaluating architectural spaces. A comparison of these previous studies, including their methods and limitations, is presented in Table 1.

Table 1. Comparison of Previous Studies

Author	Technology Used	Research Focus	Limitation
(Angelova et al., 2025)	Interactive multimedia	Improving user understanding of building layouts	Limited to non-immersive interaction
(Stanga et al., 2023)	3D visualization	Spatial interpretation in architectural review	Did not evaluate user experience factors
(Stanga et al., 2023)	Virtual tour system	User engagement during exploration	Lacked quantitative usability measurement
(Renganathan et al., 2025)	Virtual reality	Spatial cognition and mental models	Focused on the experimental environment only
(Stabryła & Grudzińska, 2025)	Immersive VR	Perception of depth and scale	Did not examine interface usability

III. RESEARCH METHOD

A. Research Design

This study applied a Design and Development Research approach to develop and evaluate an interactive virtual tour system intended to improve architectural design communication in civil engineering projects. The research design was selected because the study not only focuses on analyzing an existing phenomenon but also on creating a functional digital product, followed by systematic user evaluation. The development process was conducted iteratively so that feedback obtained during testing could be incorporated into subsequent refinement stages. In addition to system construction, the research emphasized measuring user experience and spatial understanding as indicators of communication effectiveness. This integrated approach allowed the study to investigate both the technical feasibility and the practical usability of the developed virtual tour system.

B. Research Framework

The research process followed a structured framework comprising five main stages: analysis, design, development, testing, and evaluation. The analysis stage focused on identifying problems in interpreting two-dimensional architectural drawings and gathering user requirements from designers and non-technical clients. During the design stage, the architectural layout, navigation structure, and visual composition of the virtual environment were planned to ensure that the system would support intuitive spatial exploration. The development stage involved constructing the three-dimensional model, applying realistic rendering, and integrating interactive navigation features. The testing and evaluation stages were conducted to measure user experience and identify aspects of the system that required refinement; the overall structure of this process is illustrated in Figure 1.

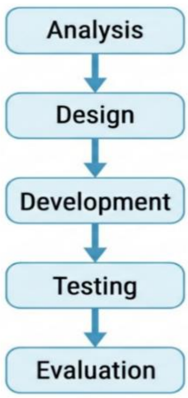

Figure 1. Design and Development Research Framework

Figure 1 illustrates the sequential flow of activities conducted in this research, from the identification of communication problems to the evaluation of the final system. The diagram shows how each stage is logically connected and how feedback from the testing phase can influence revisions during the evaluation stage. The visualization also clarifies that the development of the virtual tour was not a single linear process but involved iterative refinement based on empirical findings. By presenting the framework in a diagrammatic form, the relationship between conceptual planning and technical implementation becomes easier to understand. This representation also helps readers follow the methodological structure adopted throughout the study.

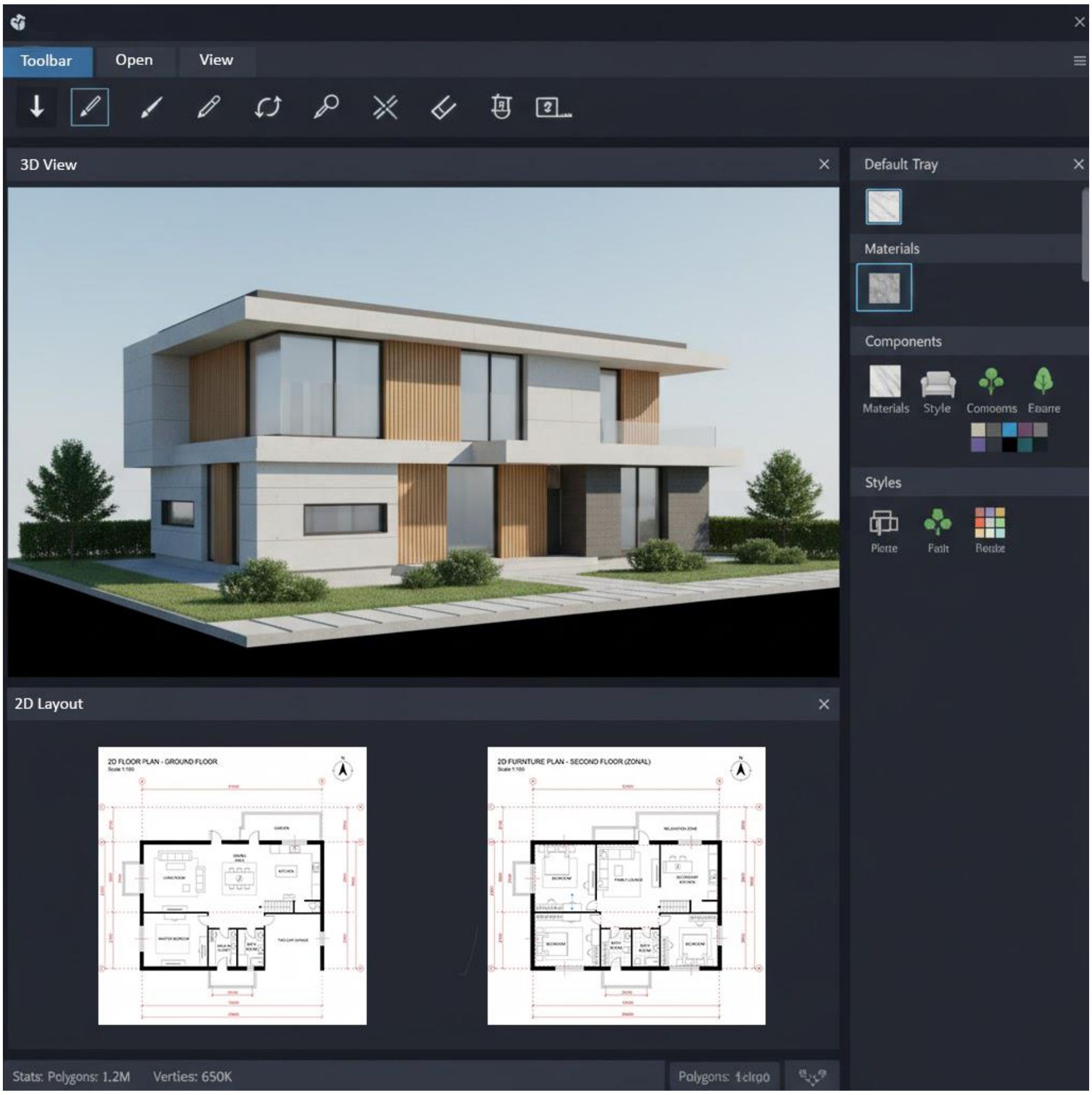

Figure 2. User Interface Overview

C. System Development

The development of the virtual tour system involved several software applications that were used sequentially to transform an architectural design into an interactive digital environment. The initial stage focused on constructing a three-dimensional model of the building in SketchUp, enabling an accurate representation of the spatial layout and structural components. The model was then processed in rendering software to enhance visual realism by applying textures, lighting, and environmental settings. After the visual quality was refined, the model was imported into Unity to enable user interaction, navigation control, and camera movement within the virtual environment. An overview of the visual workspace used during these stages is presented in Figure 2.

Figure 2 shows the visual workspace used for preparing and visualizing the architectural model before its integration into the interactive environment. The central viewport displays the building model in three-dimensional perspective, allowing the researcher to observe spatial composition and material appearance. Surrounding panels provide access to various tools for adjusting scene parameters, camera position, and visual settings that affect the final rendered output. This interface provides real-time visual feedback to help evaluate the model's aesthetic and spatial quality before it is deployed to the virtual tour system. The use of this workspace facilitated efficient iteration and ensured consistency between the design intent and the visualized result.

The development of the virtual tour required multiple software tools, each selected for its ability to support a specific stage of the production pipeline. The modeling stage required software that allows precise geometric construction and easy modification of architectural components. The rendering stage demanded an application capable of producing realistic lighting, material reflection, and environmental effects to enhance visual credibility. The integration stage required a platform that supports real-time interaction, navigation control, and deployment into an executable virtual environment. A summary of the software tools and their respective roles in the development process is presented in Table 2.

Table 2. Software Used in System Development

Stage	Software	Function	Output
Modeling	SketchUp	Three-dimensional modeling	Building geometry
Rendering	Lumion	Lighting and material setup	Realistic visualization
Integration	Unity	Interactive system creation	Virtual tour system
Interface	Unity UI	Navigation and interface	User interface layout

Table 2 shows that each software application was used for a specific role within the virtual tour development pipeline. SketchUp was used at the initial stage to produce accurate, editable architectural geometry. Lumion was employed to enhance visual realism through advanced lighting simulation and material rendering capabilities. Unity served as the integration platform, transforming the static model into an explorable virtual environment with user-controlled navigation. The Unity UI module was used to design simple interface elements, ensuring users could navigate the virtual space without visual clutter or cognitive overload.

D. Participants

The evaluation phase involved a group of participants selected to represent both professional and non-professional stakeholders in architectural projects. The inclusion of users from different backgrounds was intended to examine how the virtual tour system performed across varying levels of technical knowledge and experience in reading architectural drawings. Professional designers were included because they are accustomed to interpreting plans, sections, and three-dimensional models, while non-technical clients were included because they often rely on visual media to understand spatial information. This combination allowed the study to observe differences in spatial comprehension, navigation behavior, and subjective satisfaction between expert and lay users. The demographic composition and background characteristics of the participants are presented in Table 3.

Table 3. Participant Characteristics

Category	Description	Number
Designer	Architecture background	12
Client	Non-technical	12
Total Participants		24

Table 3 shows that the number of participants in each category was balanced to ensure equal representation of both professional and non-professional perspectives in the evaluation. The designers included in the study had prior experience in interpreting architectural drawings and participating in design review processes. The client group consisted of individuals without formal training in architecture or civil engineering, which reflects typical stakeholders involved in residential design decision-making. This balanced composition enabled the study to compare how different user groups perceived and interacted with the virtual tour system. The total number of participants also met the minimum requirement for conducting basic inferential statistical analysis in user experience studies.

E. Evaluation Criteria

The effectiveness of the virtual tour system was assessed using three primary criteria, namely usability, aesthetics, and interactivity, which are commonly used to evaluate digital visualization systems. Usability referred to the ease with which users could control navigation, understand interface elements, and move through the virtual environment without confusion. Aesthetics addressed the visual quality of the environment, including lighting realism, color harmony, and overall visual appeal. Interactivity focused on the extent to which users felt engaged and actively involved while exploring the digital space. The indicators used to measure these criteria are summarized in Table 4.

Table 4. Evaluation Aspects and Indicators

Aspect	Indicator	Description
Usability	Navigation	Ease of control and movement flow
Aesthetics	Lighting and color	Visual quality and harmony
Interactivity	Engagement	Level of user involvement

Table 4 explains the specific indicators used to translate abstract evaluation aspects into measurable observation points. The usability indicator focused on the smoothness of navigation and the clarity of control mechanisms during exploration. The aesthetics indicator evaluated how visual elements contributed to the perception of realism and spatial comfort. The interactivity indicator measured the degree to which users felt motivated to continue exploring the environment. These indicators were later used to construct questionnaire items and observation guidelines during user testing.

F. Data Collection Methods

Data were collected using a combination of observation, questionnaires, and semi-structured interviews to obtain both quantitative and qualitative perspectives on user experience. During the testing sessions, participants were asked to explore the virtual tour and complete specific navigation tasks while their interaction behavior was observed and documented. After the exploration phase, participants completed a questionnaire based on the System Usability Scale and additional Likert scale items that measured visual satisfaction and engagement. Semi-structured interviews were then conducted to capture subjective impressions, difficulties encountered during navigation, and comparisons between virtual tour visualization and traditional two-dimensional drawings. This combination of methods allowed the study to capture both measurable performance indicators and detailed experiential feedback from participants.

G. Data Analysis

Quantitative data obtained from the questionnaires were analyzed using descriptive statistics to calculate mean values and standard deviations for each evaluation aspect. The comparison between virtual tour visualization and two-dimensional drawings was conducted using a paired-samples t-test because the same participants evaluated both methods. This statistical approach enabled the study to determine whether differences in user scores between the two conditions were statistically meaningful. Qualitative data from interviews were analyzed to identify recurring themes related to spatial understanding, navigation comfort, and visual perception. The integration of quantitative and qualitative analysis provided a comprehensive interpretation of how the virtual tour influenced architectural design communication and user experience.

IV. RESULT

A. Architectural Spatial Layout

The architectural design developed in this study was structured to support functional clarity and spatial hierarchy within a compact residential layout. Spatial planning considered user circulation, natural lighting distribution, and the separation between public and private activities. The ground floor was designed to accommodate social and shared functions, while the upper floor was allocated for personal and private use. Room placement and orientation were arranged to reduce unnecessary movement and to maintain logical transitions between spaces. The overall spatial configuration of the ground floor is presented in Figure 3.

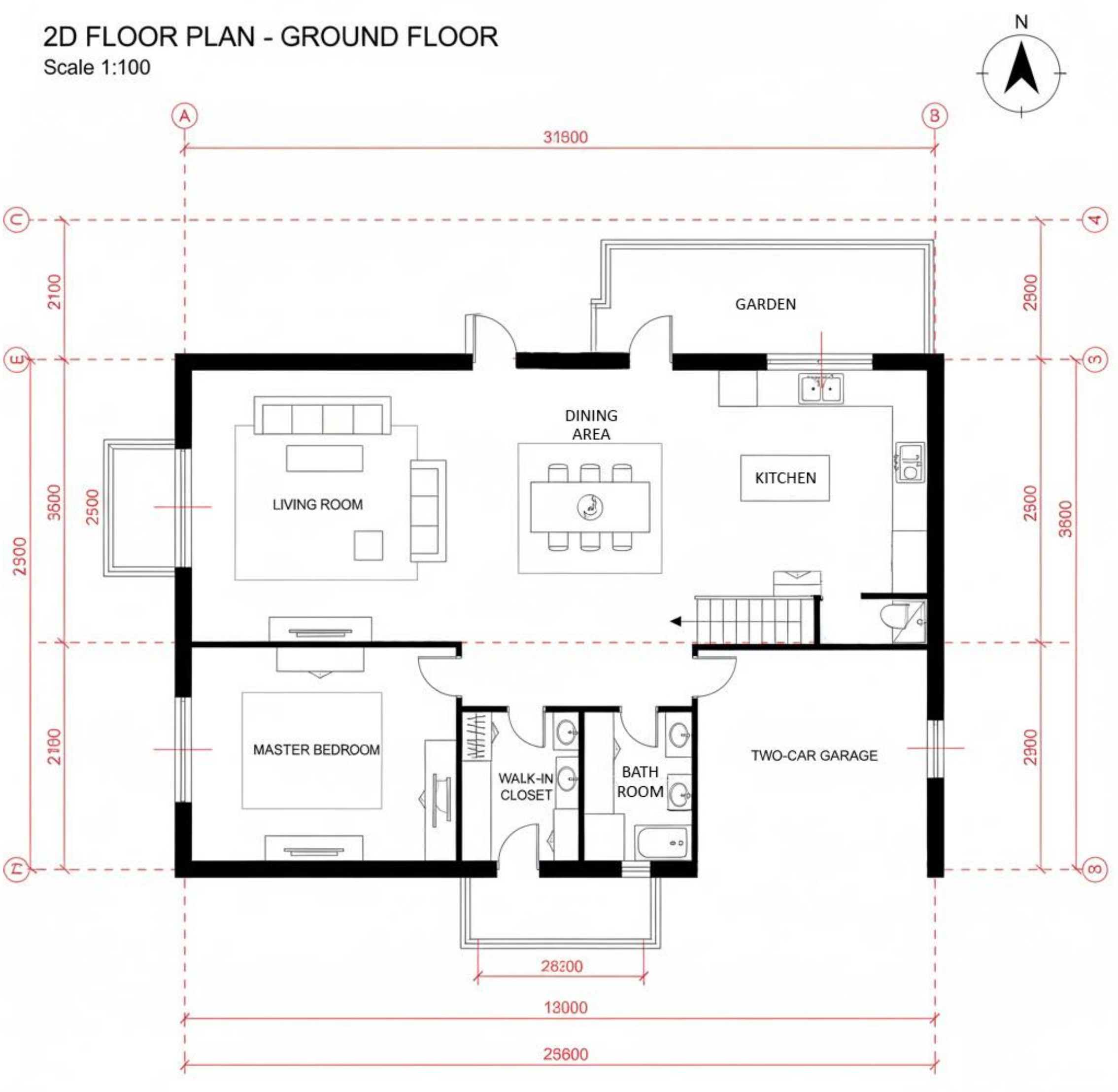

Figure 3. Ground Floor Plan

Figure 3 illustrates the arrangement of primary living spaces on the ground floor, including the living room, dining area, and kitchen. The living room is located near the main entrance to provide a direct and welcoming transition from the exterior to the interior. The dining area is positioned adjacent to the kitchen to facilitate efficient movement during food preparation and serving. Circulation paths are kept open and unobstructed, allowing users to move between functional zones without crossing through unrelated spaces. Window openings along the exterior walls allow daylight to enter the interior, improving overall visual comfort in shared areas.

The second level of the building was designed to provide greater privacy and to separate personal spaces from the more active social areas below. Bedrooms were placed on this floor to reduce exposure to noise from ground-level activities. The layout also considered access to natural light and external views by positioning rooms along the building perimeter. Vertical circulation was designed to connect both floors without disrupting the functional organization of either level. The spatial configuration of the upper floor is shown in Figure 4.

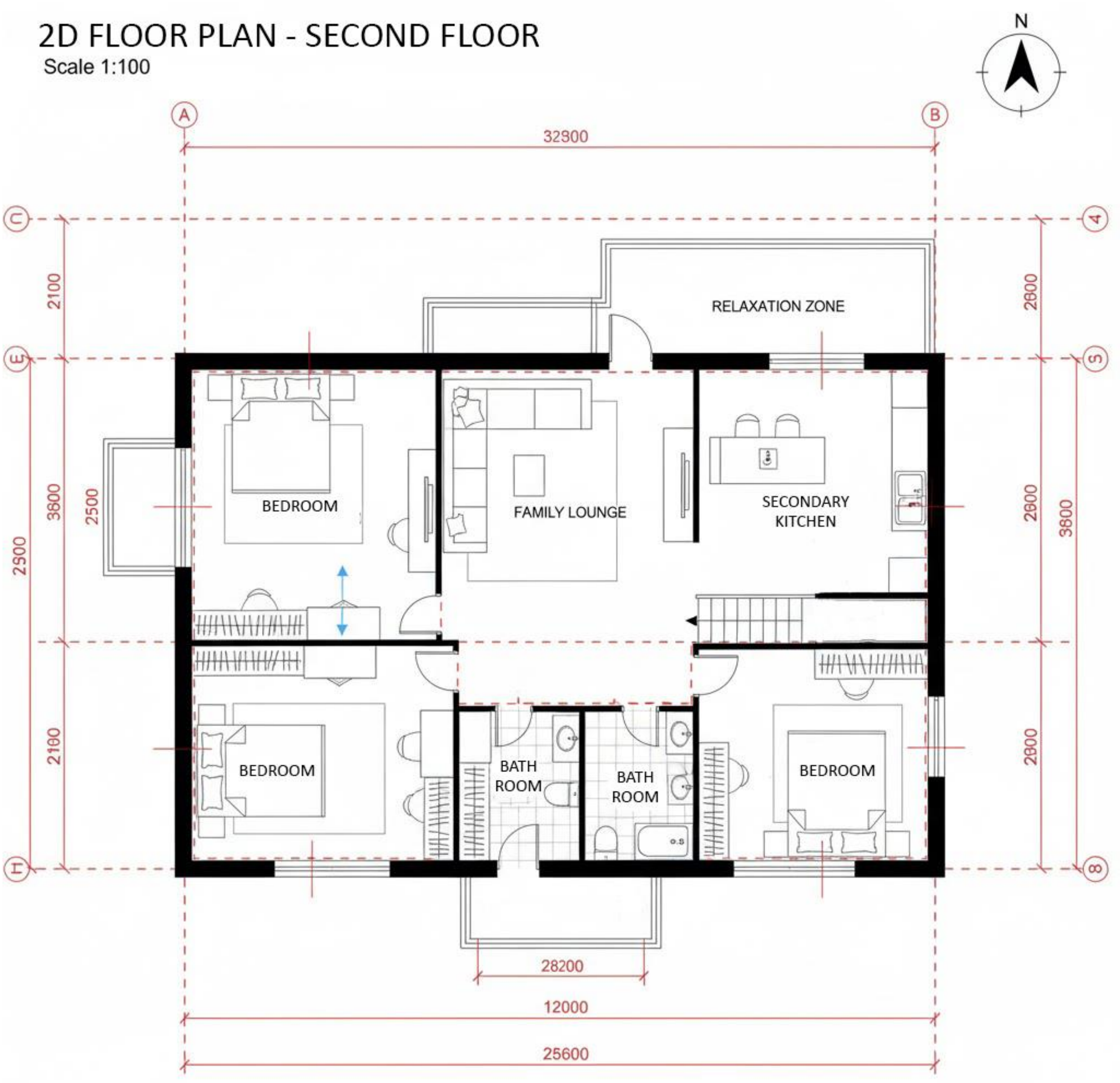

Figure 4. Second Floor Plan

Figure 4 shows that the second floor has a more compartmentalized layout than the ground floor's open configuration. Each bedroom is arranged to provide adequate space for essential furniture while maintaining clear circulation paths around the room. The staircase leads to a central landing area that provides access to each bedroom without passing through another private space. Door and window placements were arranged to balance accessibility, privacy, and daylight penetration. This arrangement supports personal comfort while maintaining clear spatial organization within the private zone.

The spatial organization of the building was further analyzed by grouping rooms according to their accessibility and functional roles in daily activities. This classification helps clarify how the design separates social interaction areas from spaces intended only for family members. Understanding this zoning structure is important because it influences circulation patterns, privacy levels, and the overall user experience within the house. The distribution of space also reflects design decisions related to comfort, noise control, and visual exposure between rooms. The categorization of spaces into public, semi private, and private zones is summarized in Table 5.

Table 5. Spatial Zoning Distribution

Zone	Space	Function	Percentage
Public	Living Room	Social interaction	35%
Semi private	Kitchen and Dining	Shared family activity	30%
Private	Bedrooms	Personal space	35%

Table 5 describes how the total building area is divided into public, semi-private, and private zones based on their intended use. Public areas such as the living room occupy a significant portion of the ground floor because they are designed to accommodate guests and group interaction. Semi-private areas, including the kitchen and dining space, serve as transitional zones that remain accessible to family members while remaining connected to public areas. Private zones are concentrated on the upper floor to maintain separation from social activities and to support personal privacy. The proportional distribution presented in the table reflects the spatial strategy used to balance communal and personal functions within the house.

B. Virtual Architectural Visualization

The virtual tour environment developed in this study was designed to represent the architectural model in a visually realistic and spatially coherent digital format. The visualization process incorporated detailed material textures, calibrated lighting conditions, and perspective settings that simulate real-world human vision. Users can navigate continuously between rooms, allowing them to observe spatial relationships and room proportions from multiple viewpoints. Camera height and field of view were adjusted to reflect the average adult eye level in a residential space. A virtual representation of the living room environment is presented in Figure 5.

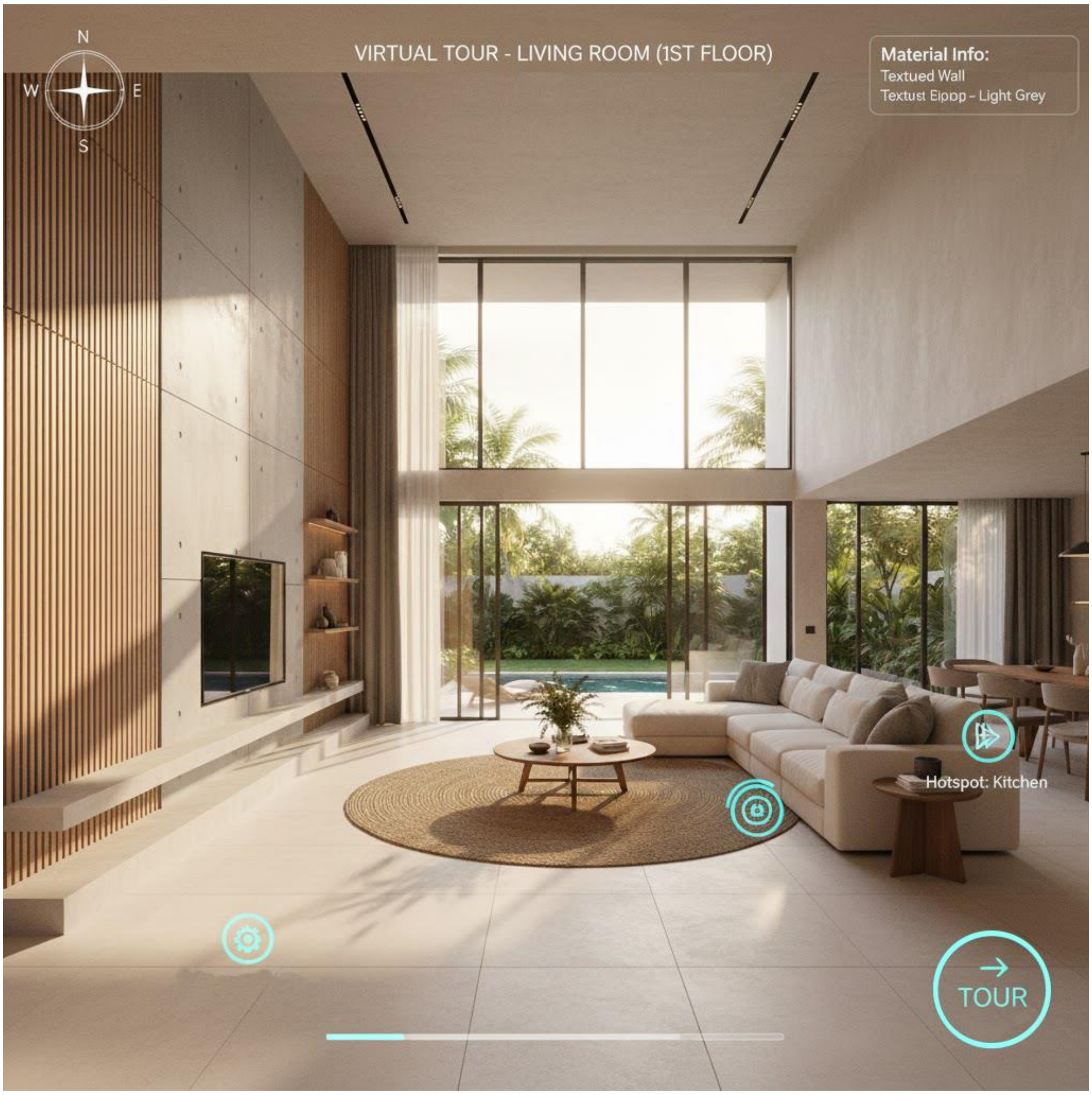

Figure 5. Virtual Tour View of the Living Room

Figure 5 displays the living room as visualized within the virtual tour system, including furniture arrangement, wall finishes, and lighting configuration. Large window openings allow simulated daylight to enter the room, creating gradual shadow transitions across interior surfaces. The seating layout was arranged to reflect typical residential use, helping users understand circulation paths and interaction zones within the space. Material textures applied to wooden panels, flooring, and upholstery were rendered with sufficient detail to convey depth and surface variation. These visual elements support a clearer interpretation of room scale and spatial proportions compared to traditional two-dimensional representations.

Private spaces were also modeled in the virtual environment to provide a comprehensive understanding of how personal areas are arranged within the building. The bedroom visualization was designed with softer lighting and neutral tones to reflect its function as a private, restful space. Furniture placement was kept proportional to the room size to allow users to evaluate available movement space around the bed and storage units. The arrangement of interior elements was simplified to reduce visual clutter and maintain focus on spatial dimensions. The virtual representation of the main bedroom is shown in Figure 6.

Figure 6. Virtual Tour View of the Master Bedroom

Figure 6 illustrates the spatial configuration of the bedroom, including the placement of the bed, wardrobe, and circulation space around major furniture elements. The lighting configuration combines ambient and directional sources to simulate typical indoor conditions during evening hours. Surface materials such as painted walls and wooden flooring were rendered with consistent color properties to maintain visual harmony within the scene. The camera perspective allows users to observe both horizontal and vertical dimensions of the room within a single view. This presentation supports spatial comprehension by allowing users to evaluate both layout and interior atmosphere simultaneously.

Service spaces such as bathrooms were included in the virtual tour to ensure that all functional areas of the building could be assessed visually. Bathrooms often feature compact layouts and multiple fixtures, making them important spaces to evaluate in three dimensions. The placement of the sink, toilet, and shower area was modeled carefully to maintain realistic proportions and appropriate distances between fixtures. Reflective materials, such as tiles and mirrors, were configured to respond to simulated lighting conditions in the scene. The virtual visualization of the bathroom is presented in Figure 7.

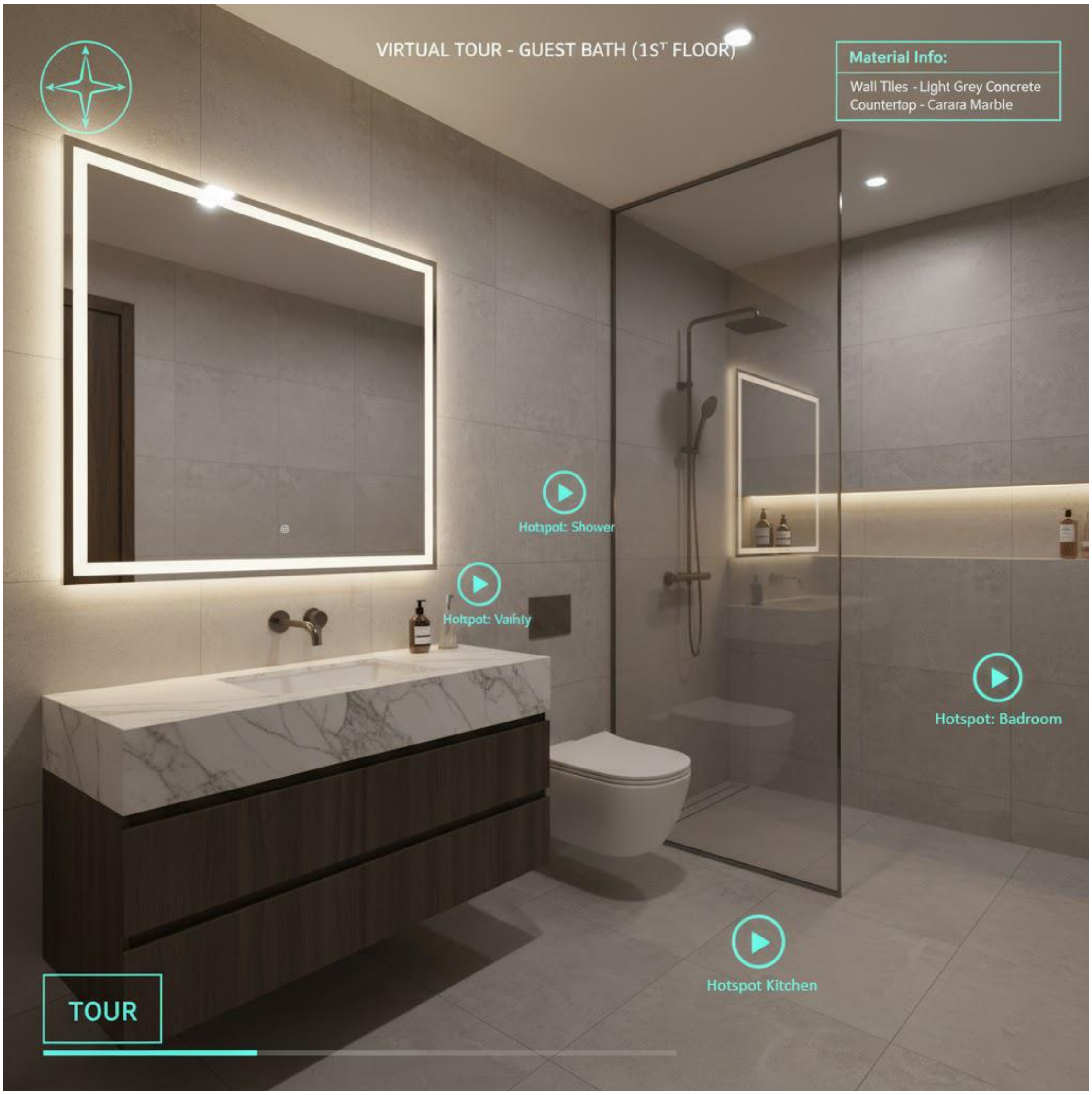

Figure 7. Virtual Tour View of the Bathroom

Figure 7 shows how sanitary fixtures and reflective surfaces are arranged within a limited floor area. The mirror surface reflects the surrounding geometry and lighting, which contributes to a more realistic perception of depth within the compact space. Ceramic tiles were rendered with subtle gloss to simulate real material behavior under artificial lighting. The camera angle allows users to observe spatial clearances between fixtures and evaluate usability within the confined environment. This representation helps identify potential spatial constraints that may not be evident in static plan drawings.

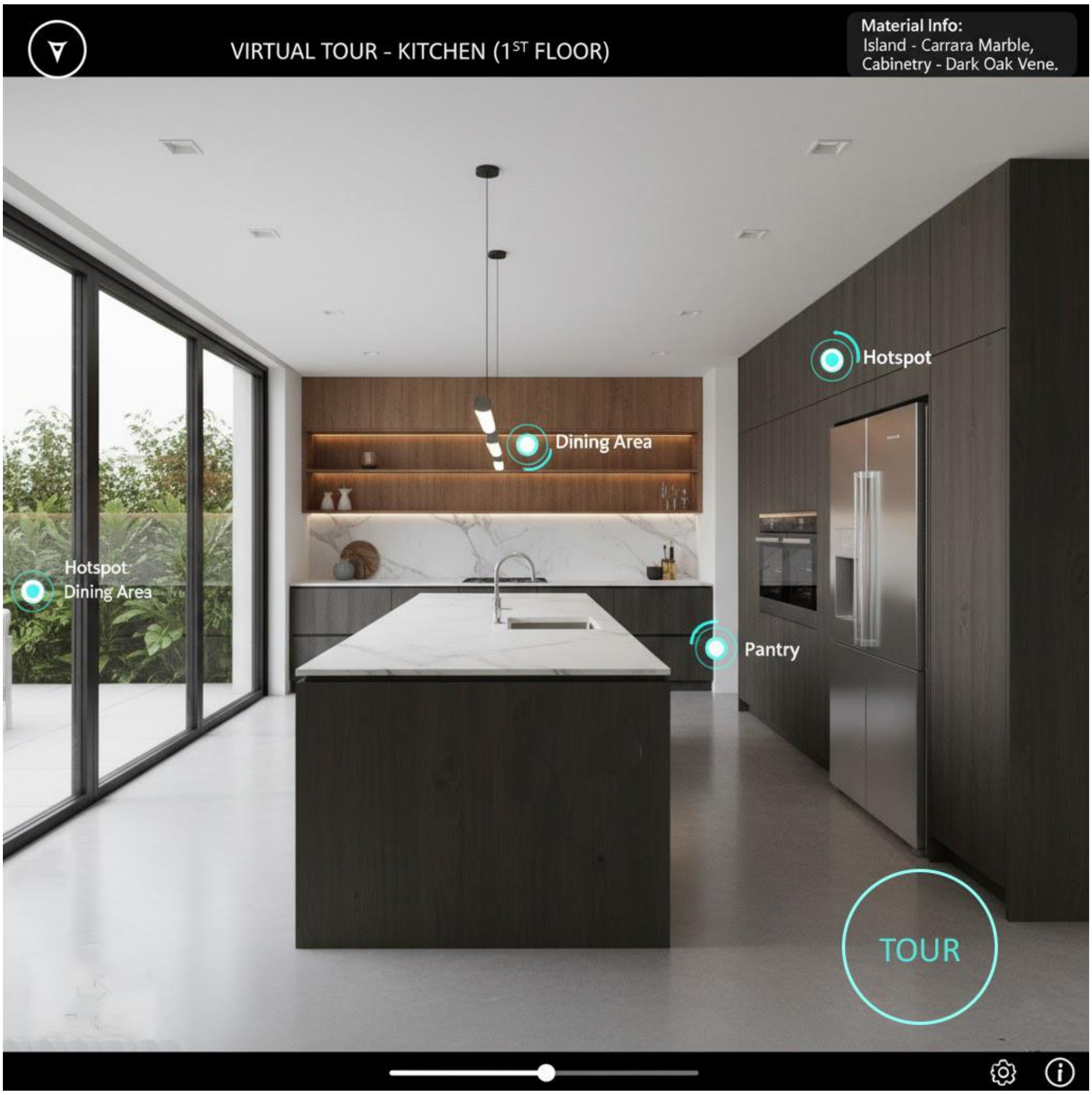

Figure 8. Virtual Tour View of the Kitchen

Semi-private spaces, such as the kitchen, were visualized to demonstrate how functional work areas are arranged within the residential layout. The kitchen scene focuses on the positioning of cabinets, countertops, and circulation paths between preparation zones. The lighting configuration was designed to simulate both general illumination and task lighting above work surfaces.

Material continuity between the kitchen and adjacent rooms was maintained to support visual coherence across the interior. The virtual visualization of the kitchen is shown in Figure 8.

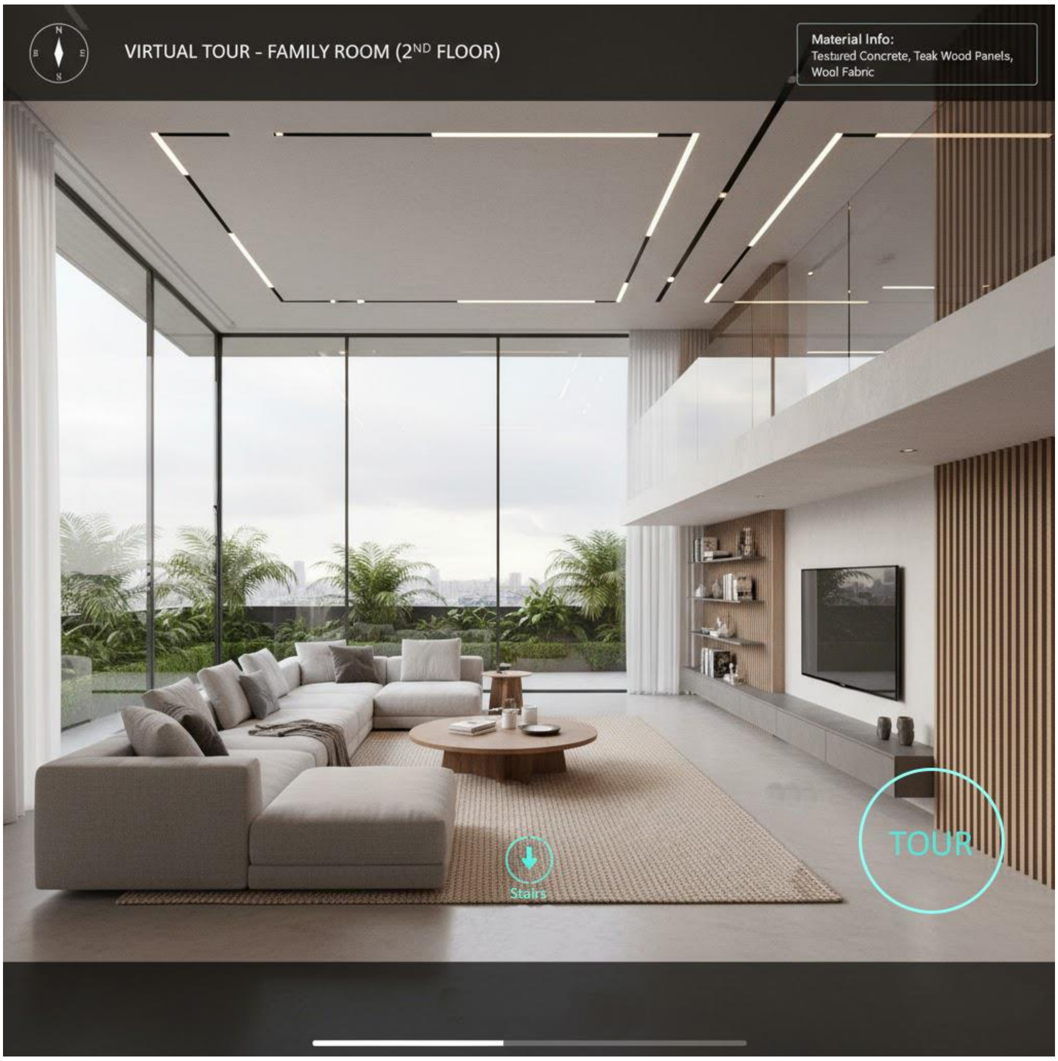

Figure 9. Virtual Tour View of the Family Lounge

Figure 8 presents the kitchen layout in detail, showing the arrangement of upper and lower cabinets, appliance placement, and working space between surfaces. The lighting arrangement above the countertop ensures that key work areas remain visible within the virtual environment. Textures applied to cabinet panels and flooring were rendered to simulate realistic surface patterns and color variation. The camera perspective allows users to evaluate the efficiency of the kitchen work triangle and movement between functional zones. This visual representation helps users understand how the kitchen supports daily activities within a constrained floor area.

The family lounge was also included in the virtual tour to represent shared relaxation and interaction space within the house. This room was designed with an open layout to support flexible seating arrangements and unobstructed movement. Visual continuity between the lounge and adjacent areas was maintained through consistent flooring materials and aligned ceiling geometry. The spatial openness of this room allows users to perceive its connection with nearby spaces during navigation. The virtual visualization of the family lounge is presented in Figure 9.

Figure 9 shows the arrangement of seating elements and open floor space within the family lounge. The furniture layout was designed to encourage face to face interaction while still maintaining clear circulation paths around the seating area. Lighting was configured to produce a balanced distribution of brightness without creating strong shadow contrasts that might obscure spatial boundaries. The virtual camera perspective enables users to observe the relationship between the lounge and adjacent circulation routes. This visualization supports an understanding of how the lounge functions as a central social space within the residential layout.

C. Interactions & Navigation

The interactive features of the virtual tour were designed to provide users with a natural and intuitive method for exploring architectural spaces. Participants were able to move freely within the environment, adjust camera perspectives, and access interactive points of interest that contained additional information about materials, finishes, or functional purposes. The navigation system simulated real-world movement patterns, including forward and backward walking as well as rotational viewing, which allowed users to experience the building as if they were physically present. Camera controls supported both vertical and horizontal adjustments, enabling detailed observations of room proportions, furniture layout, and spatial relationships. The user interface was deliberately minimalistic to reduce visual clutter and maintain focus on the spatial experience. An overview of the system's interactive features is presented in Table 6.

Table 6. System Features

Feature	Description	Function
Navigation	Free movement	Exploration of spaces
Camera	Rotation & zoom	User perspective control
Hotspot	Interactive points	Additional information
UI	Minimalist design	Focus on spatial content

Table 6 summarizes the main interactive components of the system. The navigation feature enabled participants to explore rooms freely, which helped them understand circulation patterns and functional connections between spaces. Camera controls allowed users to zoom in on furniture or architectural details, supporting more accurate spatial comprehension. Hotspots presented contextual information that clarified design intentions and material choices, helping participants evaluate the architectural design beyond its visual appearance. The minimalistic interface maintained visual clarity, ensuring users could focus on spatial exploration without distractions from nonessential elements.

User observations indicated that participants naturally followed logical paths as they moved through the environment. Many explored public areas first, then progressed to semi-private and private zones, reflecting typical real-world navigation behavior. Participants frequently adjusted their camera angles to view ceiling heights, room proportions, and furniture arrangements from multiple perspectives. Interactions with hotspots encouraged users to engage actively with the environment, examining materials and finishes closely. The system design supported both freedom of movement and structured exploration, allowing participants to experience the space comprehensively.

D. User Evaluation

The virtual tour system was evaluated through both quantitative and qualitative approaches to assess its effectiveness in supporting architectural design communication. A total of 24 participants, including 12 design professionals and 12 non-technical clients, took part in the evaluation, enabling comparisons between users with varying levels of design familiarity. The assessment focused on three main aspects: usability, aesthetics, and interactivity. Participants also compared the virtual tour experience with conventional 2D drawings, which provided insight into the relative advantages of immersive visualization. The quantitative results of the evaluation are summarized in Table 7.

Table 7. User Evaluation Results (Mean ± SD)

Aspect	Virtual Tour	2D Drawing	p-value (paired t-test)	Interpretation
Usability	4.6 ± 0.28	3.2 ± 0.45	<0.01	Significant
Aesthetics	4.7 ± 0.25	3.5 ± 0.40	<0.01	Significant
Interactivity	4.6 ± 0.30	2.9 ± 0.50	<0.01	Significant

Table 7 shows that the virtual tour consistently achieved higher scores than 2D drawings across all measured dimensions. Usability received high ratings because participants were able to navigate the environment intuitively, with clear circulation paths and responsive camera controls. Aesthetic scores reflected the effectiveness of realistic lighting, material textures, and color schemes in creating a visually comfortable and engaging experience. Interactivity was enhanced by features such as hotspots and adjustable camera perspectives, which encouraged participants to actively explore and engage with spatial elements. These quantitative findings provide evidence that the virtual tour supports spatial comprehension and design evaluation more effectively than conventional 2D representations.

The qualitative feedback from participants provided additional insight into their experience and perception of the system. Many participants described the navigation as natural and similar to moving through a real residential space, which contributed to a sense of presence and spatial understanding. Several participants noted that lighting and color harmony enhanced the perception of room proportions and created a warm, inviting atmosphere. Comments also highlighted the value of interactive elements, such as hotspots, which allowed users to access additional information about materials, furniture placement, and design intentions, improving their comprehension of design decisions. Participants consistently mentioned that the virtual tour provided a clearer and more immersive understanding of both public and private spaces compared to static 2D drawings. These observations illustrate how the system facilitated active engagement, improved spatial awareness, and supported more informed evaluation of architectural designs.

V. DISCUSSION

The findings of this study indicate that the interactive virtual tour significantly improves usability, aesthetics, and interactivity compared to traditional two-dimensional drawings, as reflected in the higher mean scores across all evaluated aspects. These results suggest that users were able to interpret spatial relationships more effectively when interacting with immersive, navigable environments, thereby directly addressing the research objective of enhancing architectural design communication.

The improvement in usability, indicated by a mean score of 4.6 compared to 3.2 for 2D drawings, reflects the effectiveness of intuitive navigation and user-centered interface design in reducing cognitive effort during spatial exploration. This observation aligns with the argument presented by (Caschera & Guzzo, 2026) that systems designed with user-centered principles tend to match users' mental models and interaction expectations. The integration of realistic rendering and interactive controls also contributed to improved comprehension, indicating that communication effectiveness is closely linked to both visual clarity and experiential engagement.

Compared with previous studies, the results of this research reinforce the findings that interactive and immersive visualization enhance spatial understanding and user engagement. Studies by (Chen et al., 2024) reported that virtual environments support the development of more accurate mental models, which is consistent with participants' ability in this study to evaluate room proportions, circulation paths, and spatial organization more effectively. At the same time, this study extends prior work by emphasizing communication effectiveness rather than focusing solely on immersion or spatial cognition, as highlighted in (Díaz González et al., 2025; Partarakis & Zabulis, 2024). The inclusion of both professional designers and non-technical clients provides empirical evidence that the benefits of virtual tours are applicable across user groups, a finding that has been less explored in prior research.

The significantly higher interactivity score (4.6 compared to 2.9) also supports the findings of (Zhang et al., 2024) that interactive navigation encourages active exploration and deeper engagement with spatial content. These comparisons position the current study as a contribution that bridges technological capability with practical communication needs in civil engineering projects.

Several observations in the results reveal patterns that offer additional explanations beyond the expected outcomes. Although designers are generally accustomed to interpreting 2D drawings, their evaluation scores for the virtual tour were still significantly higher, suggesting that immersive visualization enhances even expert-level spatial analysis. This finding may be explained by the virtual environment's ability to simulate real-world perception, thereby complementing technical expertise with experiential understanding.

Some participants initially required brief familiarization with navigation controls, indicating that interaction design still plays a role in shaping first-time user experience despite overall high usability scores. This aligns with (Grobelna et al., 2025), who emphasized that interface clarity and responsiveness influence user comfort in digital systems. The qualitative feedback regarding lighting realism and material representation also highlights that visual fidelity contributes not only to aesthetics but to cognitive interpretation of space.

The implications of these findings extend to both theoretical and practical domains within architectural visualization and civil engineering communication. From a theoretical perspective, the study supports integrating user-centered design and immersive visualization as complementary approaches to improving spatial cognition and communication clarity. From a practical standpoint, the results indicate that virtual tour systems can reduce misinterpretation, minimize design revisions, and support more informed decision-making among stakeholders with diverse backgrounds.

However, several limitations should be acknowledged, including the relatively small sample size of twenty-four participants, which may limit the generalizability of the findings to larger populations. The study was also conducted within a controlled evaluation setting, which may not fully capture the complexity of real-world project environments where time constraints and collaborative dynamics influence decision-making. Additionally, the system was tested on a single residential design case, which may not represent variations in building scale, complexity, or project type.

VI. CONCLUSION AND RECOMMENDATION

The findings of this study confirm that the interactive virtual tour is effective in enhancing architectural design communication within civil engineering projects. The developed system successfully improves users' spatial understanding by allowing them to experience building layouts, proportions, and circulation paths in a more intuitive and immersive manner. In addition, integrating user-centered design principles contributes to a more positive user experience, particularly in usability, aesthetics, and interactivity. The statistical results further demonstrate that the virtual tour significantly outperforms traditional two-dimensional drawings across all evaluated aspects, as indicated by the p-value of less than 0.01. Overall, the study confirms that interactive virtual tour technology is a more effective communication medium for both technical and non-technical stakeholders in architectural design processes.

Future research is recommended to explore integrating virtual reality headsets to enhance immersion and provide a more realistic spatial experience for users. The development of artificial intelligence-based navigation systems is also suggested to enable adaptive interaction that responds to user behavior and preferences during exploration. In addition, further studies can incorporate more advanced quantitative evaluation metrics, particularly for measuring digital aesthetics and visual perception in immersive environments. Expanding the system's functionality to support real-time collaboration among multiple users may also improve decision-making in design review sessions. These directions are expected to further optimize the effectiveness of interactive virtual tour systems in supporting architectural communication and user engagement.

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