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Design and Evaluation of a Virtual Reality Architectural Walkthrough System for Immersive Spatial Learning

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A B S T R A C T S

This paper aims to design, implement, and empirically evaluate a modular Virtual Reality (VR) architectural walkthrough system that, through immersive spatial computing, enhances architecture students' perceived spatial understanding, engagement, and early-stage design confidence. Architectural education relies heavily on static 2D drawings and screen-based modelling tools, which impose high cognitive demands on students and limit embodied spatial understanding and experiential design reasoning. A design science research approach was adopted to develop a VR-based architectural walkthrough platform using Unity, Blender, WebXR, and VR head-mounted displays. The system was evaluated through functional testing and user testing with 40 architecture students. The study presents a scalable and extensible spatial computing platform that integrates 2D-to-3D model transformation, immersive walkthroughs, and interactive design manipulation for architectural education. The findings suggest that the system improves students' perceptions of spatial content engagement and reduces apprehensions about the early stages of design, and that most participants preferred the VR workflow to traditional 2D design representations. Architecture educators should integrate immersive VR walkthroughs into early-stage design studios to support experiential learning, spatial reasoning, and iterative design feedback. Future research should investigate collaborative multi-user VR studios, AI-assisted design feedback, and cloud-based rendering to improve accessibility and scalability. The platform supports the growth of a digitally skilled, progressive generation of architectural graduates who are strong in spatial reasoning and experiential design and are aligned with modern built-environment professions. Future developments focus on creating collaborative VR environments and integrating them into a seamless cloud-based rendering infrastructure for longitudinal studies of learning outcomes.

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Keywords / Kata Kunci — ***architectural education, virtual reality, VR, spatial computing, immersive learning, 3D modelling, design pedagogy***

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1. INTRODUCTION

Historically, architectural education has widely used two-dimensional and three-dimensional design holographs, information technology (e.g., computer-aided design) models, and pedagogical discourse as media for conveying ideas. In the digital world, these media are overshadowed by others, yet they linger on in generally executed architectural classroom processes, though arranging more cognitive loads on students by trying to

imagine abstract plans in real spatial dimensions that mainly hinder the clarity of their spatial cognition, embodied cognition, and focused design intuition [1], [2], [3]. In most instances, this spatial loss creates a divide between the theoretical representation and the students' intuitive, playful understanding of design.

Digital design tools, such as Computer-Aided Design (CAD) and Building Information Modelling (BIM), have enhanced technical documentation and construction workflows. Unfortunately, they remain so bound to the screen that they afford neither embodied interaction nor perceptual immersion. Although these tools offer advantages for detailing and visualisation, they place the learner before imposed flat displays, limiting the scale, depth, circulation, and spatial atmospheres they may experience intuitively [4], [5]. This limitation is concerning because, during the early years of architectural education, when conceptual understanding and spatial reasoning take precedence, it would severely restrict how students might contemplate and internalise various architectural forms and spatial interrelationships.

Virtual Reality (VR) is a much more effective alternative learning method, allowing students to interact with architectural plans through a full-scale virtual experience. Students can move around in VR environments to assess spatial relationships, observe lighting effects, and physically evaluate materials in context [6], [7]. This is because simply having access to interactive environments enables learning through experiential systems of spatial content rather than through intricate, abstract modes of model-based cognition [8]. VR has been validated as an effective educational tool that encourages active student involvement, stimulating the development of spatial skills while keeping them engaged in learning [9], [10], [11].

VR allows architectural students to be within their designed spaces, helping them rethink their work in situ. These students, using immersive environments, can examine spatial arrangements and test different materials and lighting options in relation to full-scale architectural models, thus providing an immediate feedback mechanism [12], [13], [14]. Teaching material offers students practical experience, connects classroom work to real-world applications, and helps them familiarise themselves with the architectural design techniques used by professional architects.

However, the adoption of VR in architectural education remains at an early stage [15]. Existing applications are often limited in scope, lacking flexibility, scalability, or seamless integration with commonly used modelling tools such as Blender [16]. Furthermore, few systems incorporate iterative feedback mechanisms or are supported by empirical educational evaluation, which constrains their effectiveness within pedagogical settings [2], [17].

The other platforms sacrifice educational efficiency in favour of visual realism because these systems offer few options for students to modify designs, receive feedback, or link their work to studio tasks [18]. The cost, technical barriers, and need for specialised hardware are hurdles to implementing VR in schools that lack resource-rich environments [1], [8]. The number of studies involving the use of VR/AR systems in real architectural learning environments is very low because most focus on technology testing rather than on user experience, student engagement, and learning [19], [20].

Existing experimental frameworks have tried to address these problems. Researchers [21] developed a BIM-VR system that provides virtual-reality-based construction education experiences, as its data-visualisation capabilities do not support use during the preliminary stages of architectural design. Another research [22] also proposed a pedagogically oriented framework, but one that lacks flexibility for rapid student-led iteration. Collaborative systems such as VR Bubble [23] and multi-user virtual design environments [24] demonstrate the potential of social interaction in immersive spaces, yet often omit detailed design manipulation and individualised feedback, which are essential for formative learning in studio-based education.

Several research gaps emerge from this body of work. First, there is a lack of unified VR platforms that seamlessly integrate student-authored models, such as those produced in Blender, into immersive walkthrough environments designed for iterative design feedback. Second, few systems support real-time architectural customisation during walkthroughs, a pedagogical feature critical for spatial experimentation and reflective learning [12]. Third, empirical evidence of VR systems deployed within live architectural education settings remains limited, with insufficient evaluation of usability, engagement, and perceived learning impact [25] . Furthermore, the absence of open, modular, and scalable platforms restricts institutional adoption and long-term curricular integration [20].

There is therefore a need for a modular, scalable VR-based architectural learning platform that integrates 2D-to-3D model transformation, immersive walkthroughs, and interactive design exploration, and is empirically evaluated in an authentic educational context. To address this need, this study presents the design and evaluation of a VR architectural walkthrough system that enables students to upload 2D floor plans, automatically convert them into 3D models, and explore them through immersive VR environments using commodity head-mounted displays. The platform supports real-time navigation, material switching, lighting configuration, and spatial inspection as part of an iterative design workflow.

Research Questions

This study is guided by the following research questions:

RQ1: How can a modular, virtual-reality–based architectural walkthrough system be designed and implemented to transform 2D architectural floor plans into immersive, navigable 3D learning environments?

RQ2: To what extent does an immersive VR walkthrough environment support architecture students' spatial understanding, engagement, and early-stage design confidence compared to traditional 2D design representations?

RQ3: How do interactive design features such as object manipulation, material switching, and lighting configuration within a VR environment influence students' spatial exploration and design experimentation?

RQ4: How usable and accessible is the VR architectural walkthrough system for architecture students with limited prior experience in immersive technologies?

RQ5: What technical, usability, and scalability constraints emerge during system deployment in an academic setting, and how can these inform future development of collaborative and cloud-enabled architectural learning environments?

The research study has three main contributions to computing education research. The first contribution of the study presents a modular VR-based architectural walkthrough system that enables users to create 3D models through 2D model transformation and to experience virtual-reality spatial environments. The second contribution presents a system architecture that enables real-time user interaction with standard VR equipment, supporting both embodied navigation and design work. The third contribution, based on real educational deployment data, shows that students demonstrated greater engagement, spatial understanding, and confidence design at the early stages of their work

2. LITERATURE REVIEW

VR functions as an educational tool because it provides immersive learning experiences that extend beyond conventional teaching methods [26]. The system enables students to explore real-world environments through play-based learning, which supports their cognitive development, spatial understanding, and overall learning motivation [27]. Research shows that immersive technologies enable students to learn actively and retain knowledge by requiring them to participate as active learners rather than remain passive observers [8], [10], [11]. STEM and design education experiences break this abstraction barrier because digital technologies enable students to interact with scientific concepts through virtual learning environments [28]. VR technology employs spatially interactive features to help learners translate theoretical understanding into real-world experiences, according to research studies [29], [30].

VR technology creates educational opportunities for teaching architecture because architectural education depends on students learning through visual representation and spatial understanding and receiving repeated assessments of their progress. The traditional educational methods that use 2D plans, CAD models, and physical mock-ups have been criticised for failing to depict how real spaces function, their actual dimensions, and their movement patterns. The authors [2] provide that students using static methodologies find it hard to learn 3D spatial relationships and pathways of human beings moving through architectural spaces. Augmented reality and VR systems help students to observe their design work as a whole while testing different materials and lighting options, and experimenting with studio feedback [12]. These learning landscapes also challenge students to develop theoretical and practical knowledge by offering virtual paths to spaces they do not have direct access to, thus allowing them to simulate how their work will be used in the very real, practical environment [13], [14].

Architectural education now uses VR technology more frequently than before, but current educational systems face three main challenges: their inability to function as complete systems, their complex technical requirements, and their insufficient alignment with educational objectives. Commercial VR applications provide modular VR learning systems that must meet academic requirements through industry-oriented design, but fail to offer suitable options for academic use because they lack essential student-focused elements [16]. The other platforms do not provide any practical teaching tools because they focus exclusively on visual accuracy and presentation standards [18]. The use of proprietary hardware and complex system configuration requirements poses additional obstacles for institutions, as these elements create operational difficulties that most institutions cannot manage [8], [31]. Educational systems seeking to reach classrooms through modern solutions face obstacles due to a lack of two vital elements: educational research instruments and the capacity to transform their systems and implement large-scale educational programs [21], [32].

In recent years, experimental educational VR frameworks have been developed as complete systems, each with its own advantages and disadvantages. The system developed in [21] presents BIM-VR as an educational VR tool integrating Building Information Modelling and VR. The method focuses on data visualisation, which limits its applicability to the initial phases of architectural design. The framework presented by [22] focuses on instructional outcomes but provides students with insufficient resources to develop multiple design versions. The social interaction value of collaborative tools is demonstrated through VR Bubble [23] and [24] multi-user design environments, which fail to provide essential individual support and design assessment methods needed for studio-based learning.

The landscape discloses the variety of key gaps. The foremost one stems from the fact that no VR platforms with open-source tools support programs that enable students to create content in environments such as Blender. Another research gap is that only a few systems allow users to adjust the architectural design in virtual walkthroughs, a fundamental pedagogical tool for students to interpret and understand their environment while advancing their analytical skills [12]. Another gap lies in the acknowledgement that there is limited evidence on how VR systems operate in real learning environments. Most articles published on this line focus solely on technical design, bypassing any discussion of user experience or impact on learning outcomes [25]. The absence of open, flexible systems creates a barrier to educational institutions making the necessary efforts to introduce or modify VR systems for educational purposes [20].

The literature highlights the need for integrated, flexible VR platforms that support both immersive exploration and iterative design feedback within authentic educational contexts. This gap motivates the development and evaluation of the proposed system

3. RESEARCH METHODOLOGY

This study uses Design Science Research (DSR) methodology to design, implement, and test any VR-based architectural walkthrough system as a pedagogical computing artefact. The focus of the research is to develop a modular spatial computing platform that combines 2D-to-3D model transformation, real-time immersive rendering, and full-body interaction through VR head-mounted displays within a single frame. The methodology requires educational professionals to create educational materials, which they will validate through technical tests and direct assessment of their use in real classroom environments. The Waterfall model was chosen as the engineering process model for building the computing artefact because Design Science Research served as the primary research framework.

3.1 Waterfall Methodology Justification

The VR architectural walkthrough system was developed using the Waterfall development methodology precisely because it follows a sequence of steps and addresses the integration of complex, separately developed 2-D-to-3D construction, a 3D immersive VR walkthrough, backend data operations, and so on [34]. Through the Waterfall methodology, structured development advanced through a plan/analysis phase, systems design and implementation phase, and testing through to maintenance phases. The Waterfall stages followed necessarily supported construction, since the previous phase was successfully completed and fully certified, hence secure and traceable with impeccable documentation. Waterfall's sequential configuration was required at several points to link technical tasks of converting a 2D floor plan to a 3D model with the creative UXD for walk-through VRs. The plan articulated stakeholders' expectations. System requirements were crystallised in the research, based on feedback from InfoDOT and architectural students. The implementation involved a diverse set of technology warehouses, in which a particular platform was brought together using technologies such as Blender, Unity, and WebXR. A cycle of testing was performed with more units and functionalities, sequencing the system toward the underlying needs of educational needs within architectural education.

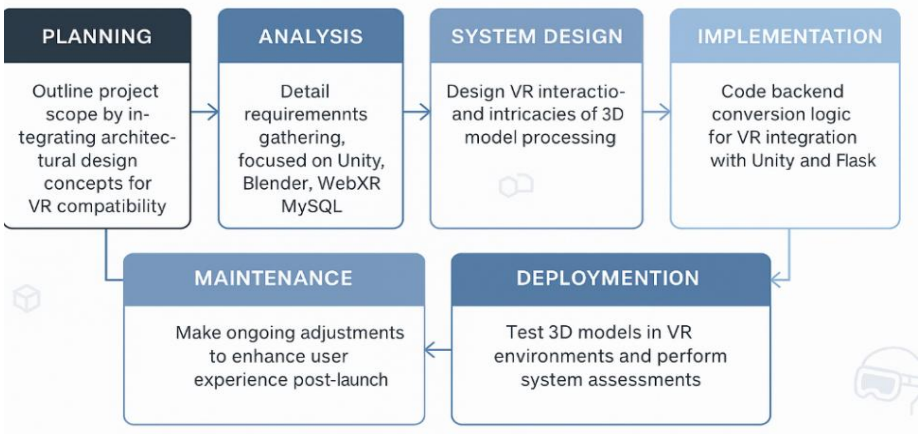


FIG 1. Adaptive Waterfall Methodology

The Waterfall model in Figure 1 depicts the methodology developers use during project execution. The implementation sequence followed the methodology, although developers did not adhere strictly to it. The development process followed all project phases and was customised by developers based on system goals, user needs, and available tools.

3.2 Planning

In planning, the research activities included determining essential system purposes and conducting feasibility studies, as well as determining user needs and conducting tool and technology surveys. In the planning phase, the system's main functions are used to define project success based on their performance; the project used VR technology to teach architecture. Students must convert their 2D floor plans into 3D models and then view them through VR viewing headsets. The system development entailed advancing instructional delivery to an educational platform that requires minimal technical requirements of students to support educational objectives and classroom processes.

The feasibility study assessed three important features: existing technologies, available resources, and user accessibility. The study's intended development systems were Unity, Blender, and WebXR tools to create a comprehensive VR environment accessible via web browsers and Oculus VR systems. The technical feasibility study was instrumental in verifying that the project's consistency will be maintained even on moderate-level computers, while the project's economic analysis established that all relevant tools are either open-source or free of charge.

Identification of user needs were made through informal interviews and the involvement of architectural students who had previously taken 3D design courses; these students reported both problems with visualisation depth and a preference for interactive environments where dimensions make sense. The collected data established the project's boundaries, demonstrating that VR immersion, user-friendly design, and educational use were the project's primary focus areas.

The system required a comprehensive technology ecosystem comprising multiple components. The team selected each tool based on three criteria: compatibility, scalability, and support for VR application development.

- Unity 3D -it is the primary engine used by developers to create interactive three-dimensional virtual environments. The engine Unity enabled real-time rendering while allowing users to access VR content via WebXR API support in web browsers.
- Blender: Used to pre-process and optimise 3D models created from converted floor plans. Blender helped smooth the geometry and align the user's perspective for immersion.
- WebXR: Enabled integration with Oculus Quest 2 headsets, allowing users to enter VR sessions directly from a browser interface.
- Flask (Python): developed a REST API that transforms 2D architectural drawings into 3D models using a processing system. The system processed input images using its custom libraries and produced downloadable 3D assets.
- JavaScript & HTML5: Built the client interface for floorplan upload, user login, and navigation menus.
- Tailwind CSS: Ensured responsive and clean user interface styling.
- MySQL: Served as the relational database for storing user data, file metadata, and system logs.
- Node.js: Acted as the central server logic, handling authentication, requests, and communications between the frontend and backend modules.

The component system used secure API connections, enabling developers to build their software modules and test and deploy the system on Windows 11.

3.3 Requirement Analysis

The requirements analysis involved identifying both functional and non-functional requirements.

Functional Requirements

The system needed to deliver these essential functions to operate.

- Students need to upload their 2D floor plans using supported formats, which include JPG and PNG.
- The platform uses a backend Flask API to transform 2D plans into 3D models through its automated conversion process.
- Model Upload: Students must upload 2D floorplans in supported formats (JPG, PNG).
- Automated Conversion: The platform converts 2D plans to 3D models via a backend Flask API.
- Real-Time Walkthrough: Users should explore the generated 3D models using VR headsets such as Oculus Quest 2.
- Editing Features: Real-time material and lighting editing must be available within the VR environment.
- Model Download: Converted 3D models can be downloaded in multiple formats (.glb, .fbx, .obj) for presentation or further refinement.

Non-Functional Requirements

Non-functional requirements focused on usability, performance, and security:

- The system needs to operate efficiently on mid-range hardware with no more than minimal lag time.
- The system interfaces need to provide a responsive design that enables architecture students who lack technical expertise to use the interface effectively.

- Secure authentication protocols must protect user data and project files.
- The platform must support both desktop and VR environments for accessibility.

User Requirements and Prioritisation

Architecture students provided feedback that helped determine which features to develop first. The team selected essential learning support functions, including walkthroughs, lighting adjustments, and user-friendly upload capabilities, as its primary development focus. The system maintained its educational purpose because all features were designed to support studying.

3.4 System Architecture

The system architecture was designed to support two primary functions: real-time spatial computing and low-latency immersive rendering. It also enabled educational institutions to extend their systems through modular components. The architecture follows a three-tier distributed model comprising a client interaction layer, an application logic layer, and a persistence layer to support system growth, maintenance, and device compatibility. System operations depend on the individual functions of each component.

- The Client-Side handles input and visualisation. Students upload floor plans, initiate walkthroughs, and interact with 3D models here. Unity, HTML, and WebXR drive these components.
- The API Layer should supervise authentication units, 2D-3D conversion processes, and file management mechanisms. Flask should handle requests for model conversion. On the other hand, the user session management and API backend services are maintained by Node.js.
- The Data Layer should maintain user and project records in MySQL, as well as a secure, cloud-based folder, and properly store 3D models. The modular architecture addresses scalability and high-availability requirements while maintaining secure processing through distributed task management.

The distributed task management provides a modular architecture that is scalable and highly available, thus enabling secure processing.

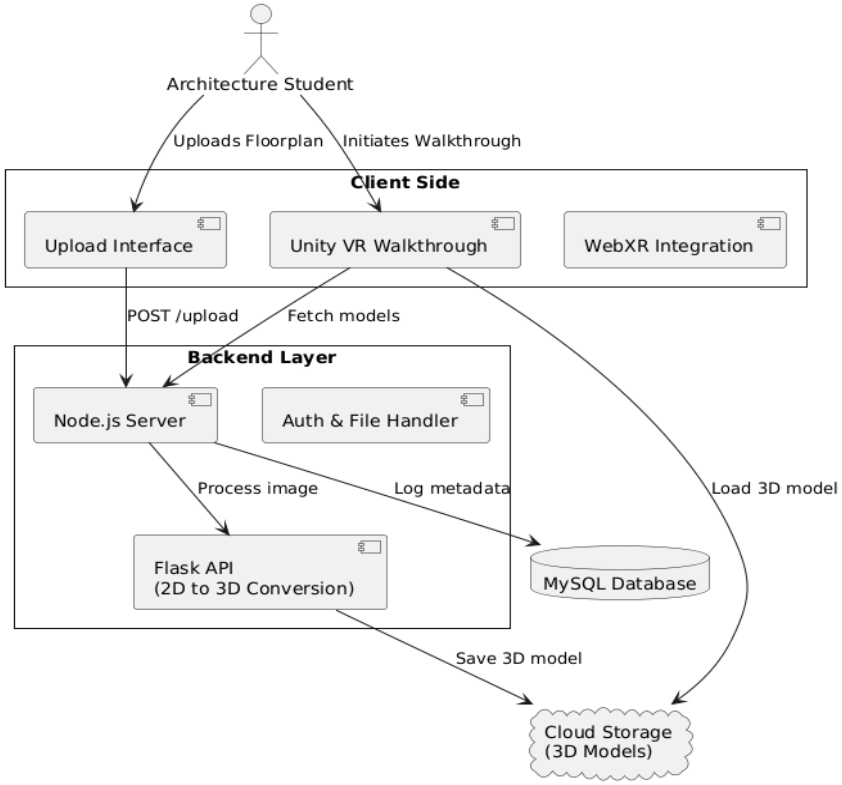


FIG 2. System Architecture Diagram

As shown in Figure 2, the system architecture illustrates client-side VR devices connecting to server systems and data storage components. The architecture is composed of a modularised design supporting real-time data exchange between user interfaces, application programming interface endpoints, and 3D rendering systems.

3.5 Entity Relationship Diagram (ERD)

The entity-relationship diagram (ERD) illustrates the physical design of the database backend for this system. The database was designed utilising normalisation principles to maintain data integrity, eliminate redundancy, and enable efficient access to user data across different project sessions.

The main components of the database are User, Floorplan, Model, and SessionLog.

User Entity

This entity stores each user's authentication details and personal information. Fields include:

- user_id (Primary Key)
- username
- email
- password_hash
- role (student/admin)
- created_at

The user ID is referenced in other tables to establish relationships. Passwords are securely hashed using a salted algorithm to prevent unauthorised access.

Floorplan Entity

The Floorplan entity records details about each uploaded 2D image, including:

- floorplan_id (Primary Key)
- user_id (Foreign Key)
- filename
- upload_date
- status (e.g., pending, converted, failed)

Between users and floor plans, the system has a one-to-many relationship, meaning each user may upload multiple floor plans directly linked to their account.

Model Entity

This table records the metadata of the converted 3D models:

- model_id (Primary Key)
- floorplan_id (Foreign Key)
- filename_3d
- format (.glb/.fbx/.obj)
- conversion_time
- view_count

Every floor plan can have several 3-D models, depending on the requirements for reprocessing or format, thereby establishing a one-to-many relationship between floor plans and models.

SessionLog Entity

To enhance auditability and analytics, each login and logout event is recorded in this table:

- session_id (Primary Key)
- user_id (Foreign Key)
- login_time
- logout_time
- device_type

This data supports system usage analysis, peak usage hours, and security traceability.

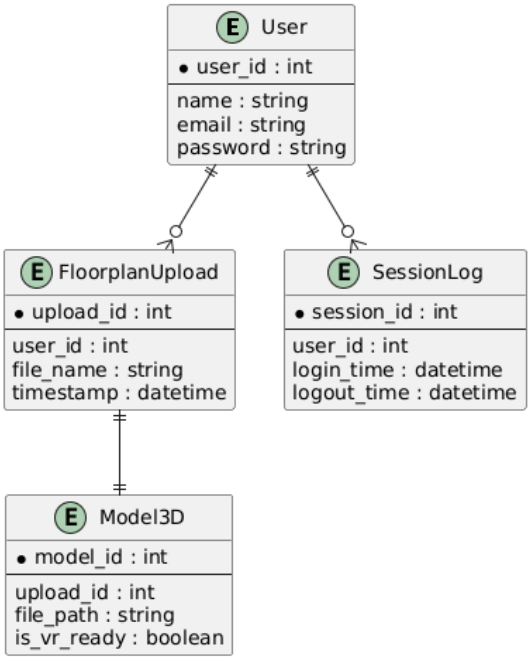


FIG 3. Entity Relationship Diagram (ERD)

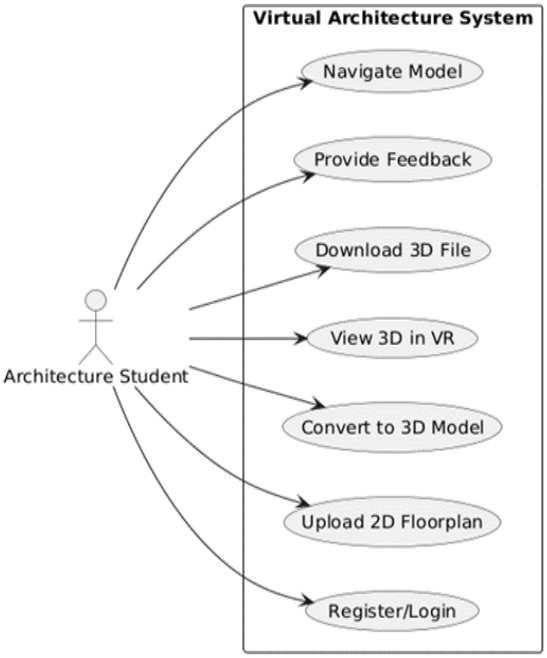


FIG 4. Use Case Diagram

The virtual lab database is represented in the ERD diagram shown in the image on Figure 3. In this diagram, key entities such as User, Project, and Model are defined, along with the relationships among them. The authority a user has over multiple architectural projects and their models is also indicated. The system proposes to provide storage and facilities for 3D modelling.

3.6 Use Case Diagram

The Use Case Diagram depicts the primary interactions among students, other users, and the VR architectural platform. System, on the other hand, describes its operational needs in terms of functional requirements and establishes back-end system-user connections.

Primary Actor: Student (End User) The student is the key actor utilising this system. They go through different uses that the system practices:

- Login/Register: Users authenticate to access the platform. The system will ascertain that the upload or access of walkthrough models occurs only for genuine users.
- Upload Floorplan: Students may upload their 2D architectural plans in PNG or JPG format and run the file size check against the backend requirements through an interface that has already verified the file type at the same time.
- Set Off Conversion: The user starts the process to create a 3D model after they upload the file. The system processes the data through its Flask-based backend before creating a model that works with Blender.
- Viewing or Editing the Model: Users can view the converted model via a web browser or Unity software. Students are afforded some basic editing capabilities, such as changing the materials and adjusting the lighting.
- Launch VR Walk-through: The VR immersive experience is initiated by the WebXR module while the student holds the VR equipment. Students use the motion controller to explore the entire virtual environment.
- Download Model: Students can obtain the model in multiple formats, either for presentation or editing.

Figure 4 demonstrates end-to-end system interaction from login to download, emphasising real-world usage.

3.7 Conceptual Design

The design concept of a system is how the user interacts with it through inputs, which the system processes to produce educational outputs. This system shows how user engagement, back-end logic, and interactive immersive technologies combine to create a learning platform within architectural education. Three (3) definable layers or separate domains should be understood to be operative at an overall level in a set chronologically.

Input Layer

Starting with an architectural floor plan, the user will first upload a 2D architectural drawing (a JPG or PNG image). The input function is triggered when students submit their first design, after which they engage in the design process again. Users can further provide any missing project information, e.g., the project name and description.

System Processing Layer

The platform transforms its sub-components, multiplying transformations as it receives input.

1. The Conversion Module (Flask + Blender) converts 2D images to 3D object files supporting (.obj/.glb) formats.
2. Model Optimisation (Blender Script) generates mesh cleanup and wall extrusion models for each file, then textures them.
3. The Walkthrough Environment (Unity + WebXR) allows users to experience a VR environment in which they can walk around, view 3D objects from several angles, alter lighting settings and environmental properties, and maybe adjust some material properties.
4. Under User Interaction (VR Panel tools), users can interact with immediate push-buttons or sliders via general UI components and/or, using feedback on the Oculus Quest 2 controller, pass feedback back to the application in real-time.

Output Layer

Results are generated by the system's actual operation.

1. The student is given real-time spatial knowledge of the concept's immaterial position through immersive design feedback.
2. Models optimised for 3D rendering are available for free download for use in presentations or further development by the user base.
3. The system itself, meanwhile, is still promoting user satisfaction and learning gains, and is also collecting baseline data, such as usability feedback, through a post-handling usability questionnaire.
4. Drawing on his walkthrough experience, the students were aware of their mistakes, which gave them the option to regulate their work more effectively in the process and ultimately submit far clearer floor plans.

The layout suggests animated learning experiences that incorporate multiple static assets, helping the learner play around with their design before implementing it in a physical prototype. The conceptual design is displayed in Figure 5, starting with the system flow (from the input: 2D floor plan) through the conversation/walkthrough to the output (feedback/download).

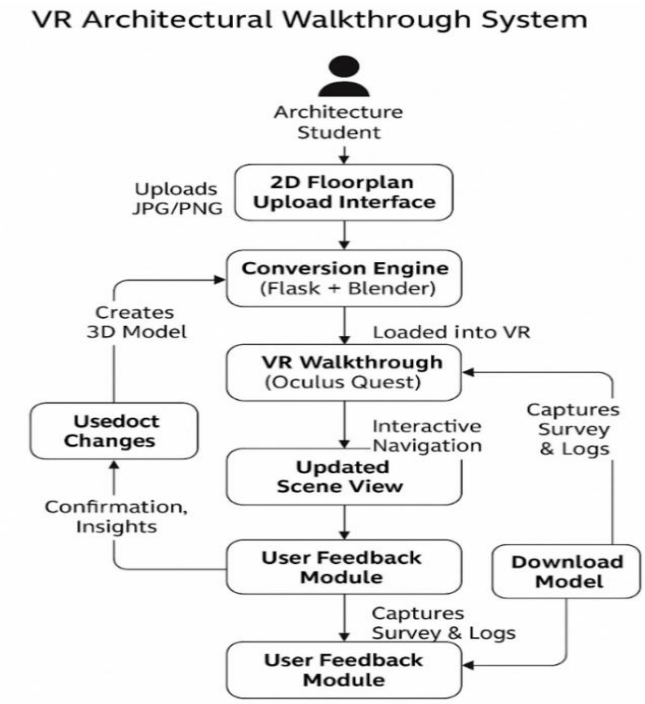


FIG 5. Conceptual Design

3.8 Implementation

A single modular application was created through the system implementation process, integrating both frontend and backend components. This time around, development was carried out on the frontend using HTML, JavaScript, and Tailwind CSS, among others, enabling users to easily upload a floor plan, start VR walkthroughs, edit materials, and even download models. The server was Flask, which processed 2D images to generate 3D models, while Node.js handled user authentication, session management, and routing. The modules used MySQL for data management, in conjunction with the file system, to ensure data integrity and deliver fast system responses. Finally, we were able to showcase immersive walkthroughs for the Oculus Quest 2: a serene closing of the loop from upload to creation to feedback, with the help of Unity and WebXR.

```
// Save model
router.post('/save', isAuthenticated, async (req, res) => {
    const { data } = req.body;
    try {
        const model = await Model.create({ ownerId: req.user.id, data });
        res.status(201).json({ message: 'Model saved successfully' });
    } catch (err) {
        res.status(400).json({ message: 'Error saving model', error: err.message });
    }
});

// Load models
router.get('/load', isAuthenticated, async (req, res) => {
    try {
        const models = await Model.findAll({ where: { ownerId: req.user.id } });
        res.json(models);
    } catch (err) {
        res.status(400).json({ message: 'Error loading models', error: err.message });
    }
});
```

FIG 6. Model Upload and Save Code

As shown in Figure 6, this code snippet handles uploading and saving architectural models to the system. It allows users to persist work-in-progress files before rendering into VR.

```python
@app.route("/upload",methods=["POST"])
def convert():
    global floorplan,hold,check,s
    if request.method=="POST":
        print(request.files)
        if "image" in request.files:
            num=random.randint(1000,9999)
            file=request.files["image"]
            num=str(num)+file.filename
            num1=num.replace(".jpg","")
            num1=num1.replace(".png","")
            file.save(r""+s+"/img/"+num)
            pic=r""+s+"/img/"+num
            path=r""+s+"/Model/"+num1+".blend"
            if check==0:
              config_path = "./Configs/default.ini"
              activate=floorplan.new_floorplan(config_path)
              hold=activate
              check=1
              createModel(pic,num1,activate)

            else:
                createModel(pic,num1,hold)

            return jsonify({"model":num1})
        else:
            return jsonify({"code":"Not Okay"}),200
```

FIG 7. Floorplan Conversion (Flask)

Figure 7 shows the code snippet for creating a Flask server endpoint that receives a 2D floor plan from a client and processes it into a 3D model. After that, the code sends the model ID back to the client, enabling the user to download the generated 3D model.

```
database.js
Virtual Lab > config > database.js > ...
1   const { Sequelize } = require('sequelize');
2   const dotenv = require('dotenv');
3
4   dotenv.config();
5
6   const sequelize = new Sequelize(process.env.DB_NAME, process.env.DB_USER, process.env.DB_PASSWORD, {
7       host: process.env.DB_HOST,
8       port: process.env.DB_PORT,
9       dialect: 'mysql'
10  });
11
12  module.exports = sequelize;
```

FIG 8. MySQL Database Integration

In Figure 8, the connection logic between the virtual lab and the MySQL database is shown. This enables persistent storage of project metadata, user profiles, and model files.

```
document.getElementById('vr-toggle-btn').addEventListener('click', () => {
if (renderer.xr.isPresenting) {
    renderer.xr.getSession().end();
} else {
    renderer.xr.setSession(renderer.xr.getSession() || navigator.xr.requestSession('immersive-vr'));
}
});
```

FIG 9. WebXR Connection to Oculus VR headsets

Figure 9 shows how the WebXR API connects the virtual lab for Oculus VR devices. This script commences by setting up the headset environment and attaching 3D scenes to the user's motion in VR.

3.9 Testing

Three kinds of tests were carried out: unit testing (to validate the functionality of code modules), system testing (to run the uploading-to-VR walkthrough pipeline), and user testing (for some 40 architecture students). The testing verified that the system met some initial functional requirements and supported social features that non-techy folks could use.

TABLE 1. Unit Testing Summary

TEST SCENARIO	EXPECTED RESULT	ACTUAL RESULT	STATUS
Invalid login credentials	Access denied	ok	Pass
Missing file upload	Error prompt displayed	ok	Pass
Floorplan conversion trigger	3D model generated	ok	Pass
Oculus headset connects to VR scene	VR session starts	ok	Pass
Model download	File saved to local machine	ok	Pass

We executed the performance benchmarks on several configurations. For instance, scraps from a medium-level laboratory (Intel i7, 16 GB RAM, GTX 1660 GPU) with an average FPS of 58-72 during walkthroughs. Models of high complexity averaged 42-55 FPS; conversion from end-to-end floorplan to 3D took less than 12.6 seconds per model. However, performance results are based on a limited set of test scenes with varying geometric complexity; therefore, performance may vary with larger or more complex architectural models.

3.10 Ethical Considerations and Data Privacy

Ethical considerations were taken into account throughout the user testing phase of this study. Participation was voluntary, and all participants were informed of the study's purpose and the nature of their involvement prior to data collection. No personally identifiable information was collected, and all responses were anonymised to ensure participant confidentiality.

In addition, the VR system was designed to minimise potential discomfort associated with immersive environments. Participants were allowed to withdraw at any point, and usage sessions were kept within reasonable time limits to reduce the risk of motion-related discomfort.

From a data privacy perspective, the system does not store or process sensitive personal data beyond user interaction logs required for system functionality. All data handling procedures were aligned with standard ethical practices for educational research.

4. RESULTS AND DISCUSSION

This section provides complete results of the VR system's use. In our linked learning architecture system, architecture students can upload their 2-D floor maps and have them converted to 3-D, on which they can insert spatial features for further navigation using the Oculus VR headset. Results include visual outputs, the utilisation of interaction feedback, eye-tracking measures, and user testing, which have shown the system's effectiveness in fostering spatial grasping and iterative design thinking.

4.1 Walkthrough Interface

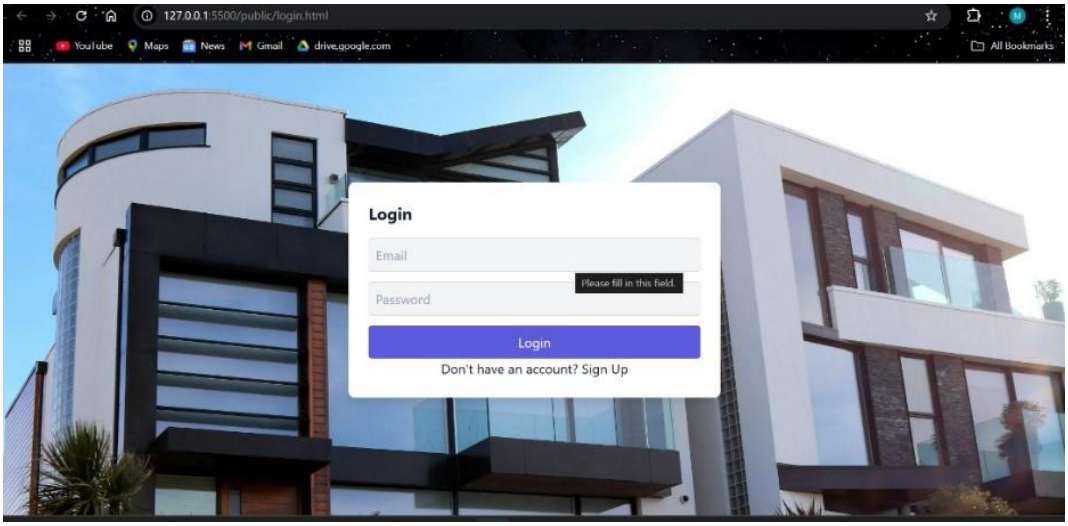


FIG 10. Login Interface

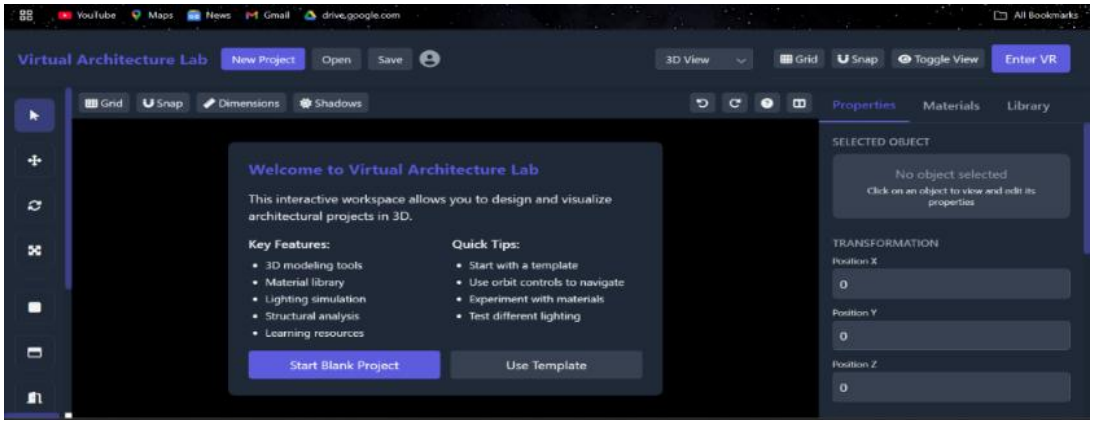


FIG 11. Main Interface after Login

To achieve a more immersive walkthrough experience, Unity was used with WebXR. After the user has authenticated, they are taken to a central menu accessible from the interface. The main menu offers choices to Upload Floorplan, 3D Conversion, Walkthrough Launch, Model Edit, and Model Download. This centralised interface is designed primarily for presentation on both desktop and VR displays. When the Walkthrough Mode is selected, the system will populate the architectural scene with a six-degree-of-freedom virtual space for interaction. The architecture is navigated with the Oculus Quest 2 controllers to move the model, investigate the floor plan, switch between day and night, and enable contextual editing via an editorial GUI placed nearby.
For the walkthrough itself, the real-time editing consists traditionally of:

- Individually selecting and moving objects (you know...walls and furniture)
- Texture swaps from dropdown menus (tile, wood, brick, paint)
- Tune the lights with a one-touch to a setting's appearance
- Get access to metadata that acts like BIM metadata, such as fire ratings and insulation properties.

Figure 10 depicts the initial access screen, allowing secure authentication before entering main dashboard

As shown in Figure 11, the welcome overlay provides users with a dashboard upon login. The interface provides functions that let users create new projects by choosing from pre-existing templates and accessing their saved models. The user interface provides seamless access to the complete immersive design environment, as shown in Figure 12.

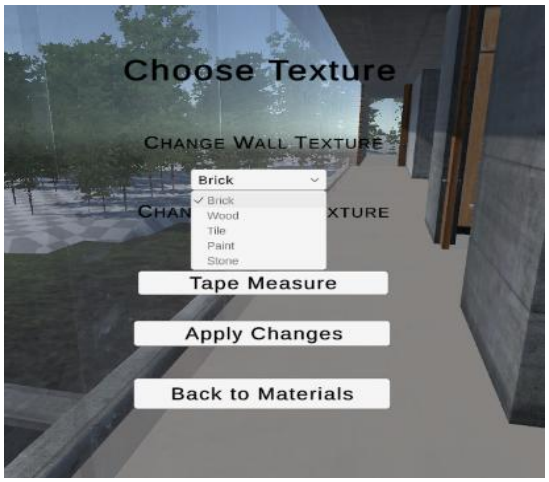


FIG 12. Default scene before editing

Figure 13 displays a three-dimensional model of the scene as it exists before any user interactions occur. The system displays the original raw geometric data it received after the conversion process.

Environment after material switches and lighting adjustments.

The Texture Editing Panel: an Interactive material editor UI for real-time spatial customisation during walkthroughs. The walkthrough experience lets users interact with design elements as active designers, controlling their movements within animated design spaces.

4.2 Floorplan Upload and Conversion Process

Students can use the modular upload module to submit their 2D architectural drawings in JPG or PNG format. The module connects to a Flask-based API that runs a custom conversion script to convert flat plans into 3D geometry that Blender and Unity can render.

The upload interface includes functionality to:

- Preview selected image
- Clear/reset selection
- Start 3D conversion
- closeness with download possibility

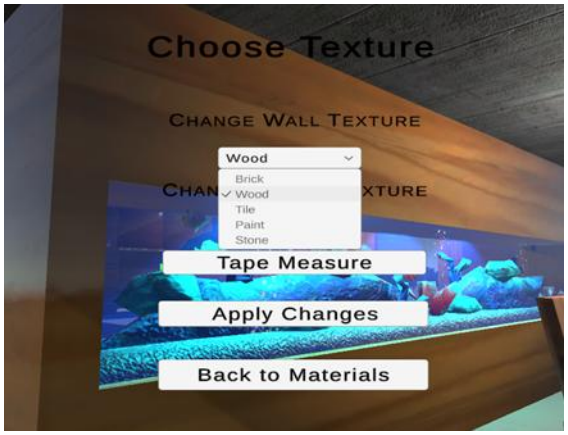


FIG 13. Scene after editing

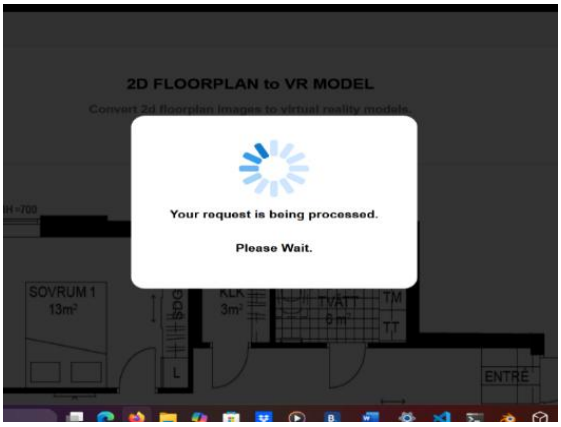


FIG 14. Processing Model Plan

After conversion, the system collects feedback and allows the end-user to download or view the virtual walkthrough. Functional testing was carried out to unearth any bugs in the software, which were then tracked and mended.

The screenshots in Figure 14 show that the transformation of conceptual planning into an interactive spatial experience was a success. Students felt that the movement was "fluid and intuitive", but some interruptions were noticed because of rendering overhead.

4.3 3D Walkthrough and Visualised Models

Once the floor plan is processed, users can view the live 3D model immediately from a first-person perspective, as in Figure 15. Geometries are reconstructed with Blender and further optimised for Unity deployment. Walk-through, support:

- Full six degrees of freedom controller movement
- Bird's eye and side views
- Scene lighting toggles (Morning, Afternoon, Night)
- Object interaction (select, highlight, info panel)
- Material editing and undo/redo support

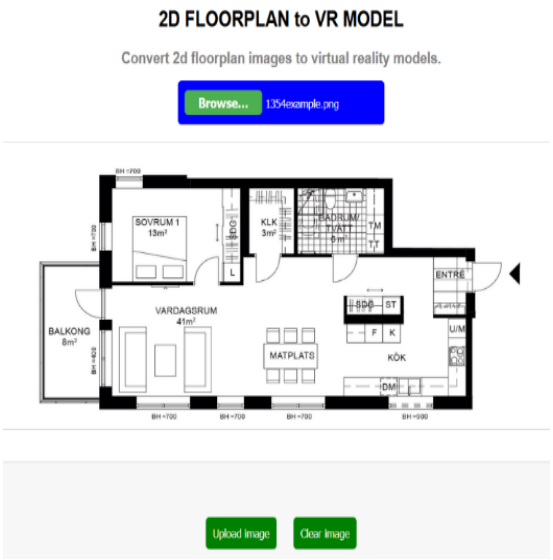


FIG 15. Uploaded 2D Floorplan Image

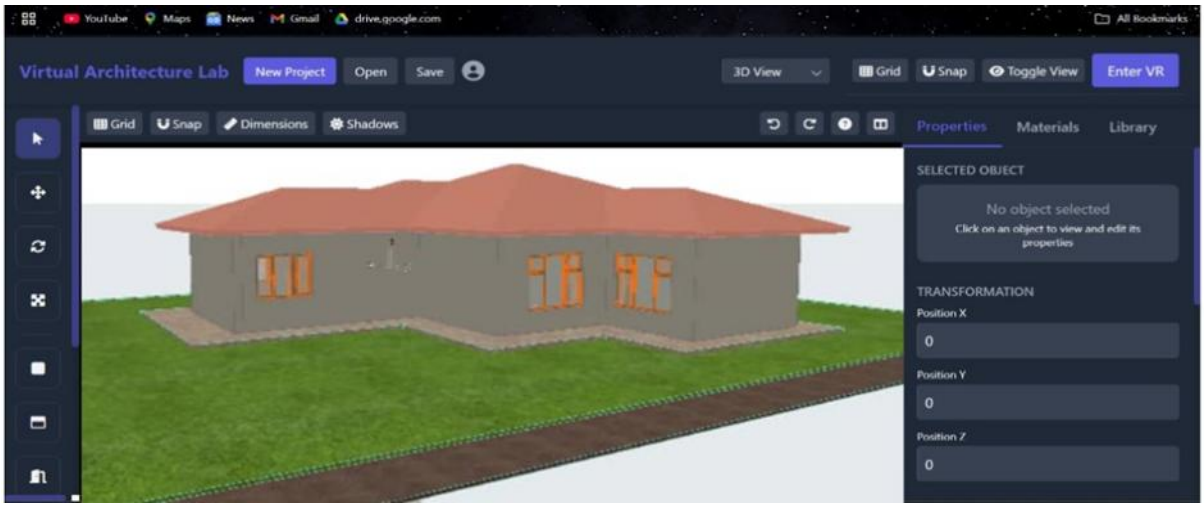


FIG 16. Converted 3D Model undergoing edits

The interface displays the upload status, reset options, and a success confirmation once the model is processed, as depicted in figure 16. Student-provided drawing used as input for the 3D conversion pipeline. Figure 17: Shows the User Navigating the model in a virtual environment utilising the Oculus VR goggles in real time.



FIG 17. User Navigation in VR

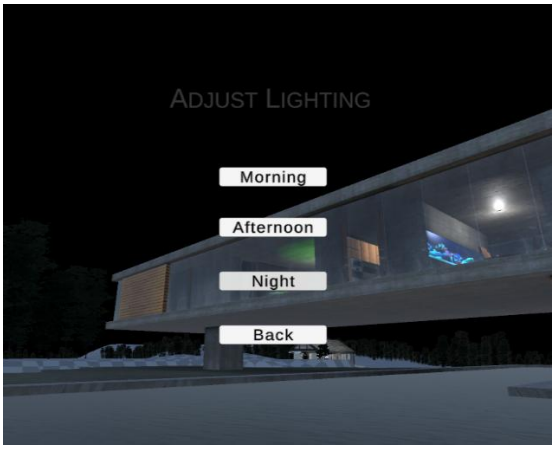


FIG 18. Day Time Lighting Toggle Interaction

In Figure 18, a user will control the switching of three lighting setups through the interface to see how architectural elements affect mood lift and light distribution in the room. This allows the VR environment to serve as a design laboratory, featuring interactive switches and adjustable material properties.

4.4 User Testing and Feedback Summary

The user evaluation is a formative design science evaluation that assesses usability, user engagement, and learning impact, rather than measuring learning outcomes through summative assessment. The system was evaluated by assessing its usability and examining learners' perceptions. The educational technology acceptance evaluation framework used the experiential learning theory to assess pedagogical value through four indicators: perceived usefulness, perceived ease of use, immersion, and learning confidence. The user survey with 40 architecture students assessed the system's effectiveness in improving architectural learning. The goal was to assess:

- Usability of the interface
- Clarity and accuracy of model conversion
- Engagement and immersion of the walkthrough
- Overall satisfaction and learning impact

The survey employed a 5-point Likert scale across 10 key questions. Key responses are summarised in Table 2.

TABLE 2. Key Response Results

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
VR improves perceived spatial understanding more than traditional 2D drawings	20	16	4	0	0
Walkthrough is immersive and helpful for design comprehension	10	17	5	1	7
Converted models were usable and spatially accurate	13	23	4	0	0
Upload/conversion process was smooth and easy	12	21	5	1	0
I would use this tool instead of CAD for early-stage design	16	14	9	1	0
High hardware requirements affected my experience	8	19	11	2	0
I feel more confident now designing in 3D	12	21	5	1	0

Displays test scenarios, expected results, actual outcomes, and pass/fail status. Participants were selected via convenience sampling from architecture students enrolled in design courses, who are typical end-users of the system

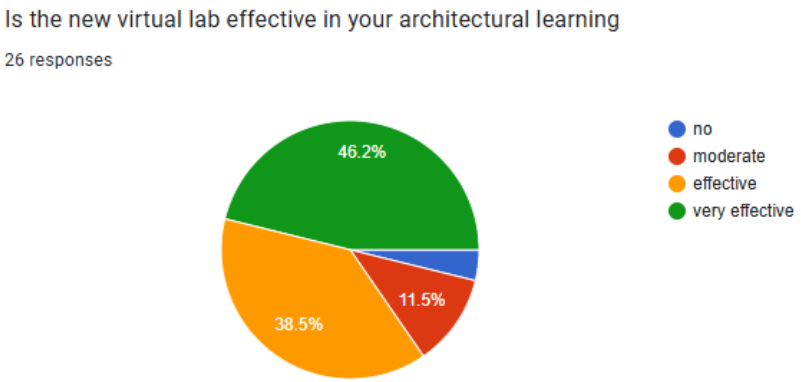


FIG 19. User feedback

5. DISCUSSION

The VR Architectural Walkthrough System presented foundational information on how spatial computing technologies, including VR, floorplan-to-3D conversion, and immersive walkthroughs, support architectural learning. Here we present the successes and limitations observed during implementation and testing, and we propose future plans for system improvements.

5.1 Successes

The project successfully demonstrated the integration of VR with architectural model visualisation in an educational context. Major milestones achieved include:

Functional Floorplan Conversion

Leveraging a custom Flask pipeline, user-uploaded 2D floor plans could be converted into structured 3D models. The pipeline was used to process in real time and preview directly in Unity. There were no major issues with format or complexity variations in the files handled by the system (all tested model uploads and conversions completed successfully across the evaluated scenarios). This is consistent with previous work, for example, [33] note that the early availability of design data in interactive visual formats supports early-stage design iteration and spatial intuition.

Immersive *VR Walkthrough*

Spatial immersion was effectively facilitated through the WebXR and Unity connection. The students found the VR walkthrough to be "intuitive" and "useful to identify layout flaws", in line with the results of [20], which showed how immersive experiences could increase spatial cognition by over 60%. High-fidelity visuals and motion tracking in space have increased users' sense of immersion and presence and have proven more effective than standard floorplan reviews.

The use of Oculus Quest 2 further validated the effectiveness of head-mounted displays (HMDs) for architectural learning environments. In spacetime, high-fidelity visuals and motion tracking increase users' immersion and presence and help them understand abstract concepts.

High User Satisfaction

The survey results confirmed that the advantages of the system, as understood by the students, included: easily uploading floor plans and getting an accurate representation of their design models. Similarly, the activity was seen as useful for active learning. The research [1] states that VR tools have proved invaluable as educational media that introduce students to practising architectural design through a self-study, iterative design (learning) process.

The findings address RQ2 and RQ3 by demonstrating that immersive walkthroughs and interactive features enhance perceived spatial understanding and engagement. RQ4 is addressed through usability feedback, while RQ5 is reflected in the identified technical and scalability constraints

Limitations and Threats to Validity

While the study demonstrates the feasibility of the proposed VR-based system, several limitations should be acknowledged. The evaluation focused primarily on usability, engagement, perceived spatial understanding, and design confidence. As such, it did not include direct measurement of learning outcomes. No pre- and post-intervention assessments of spatial cognition were conducted, nor was there a controlled comparison with traditional learning methods. Consequently, the findings reflect students' perceptions of learning rather than objectively verified improvements in spatial ability.

The user evaluation was conducted with 40 architecture students drawn from a single academic context. Although this sample size is acceptable for an early-stage design science evaluation, it limits the generalisability

of the findings. The results may not fully represent students from other institutions, curricular structures, or varying levels of technical proficiency. Future studies should include more diverse participant groups to strengthen external validity.

System performance was also influenced by the hardware used during testing. Participants using lower-specification devices experienced rendering delays and reduced frame rates, which affected overall immersion and usability. These observations suggest that system performance may vary across different deployment environments and highlight the need for optimisation strategies or alternative solutions, such as cloud-based rendering, to support broader adoption.

In its current form, the system supports only single-user interaction. It does not yet accommodate collaborative features such as studio-based critiques, peer review, or instructor-led walkthroughs, which are integral to architectural education. This limits its applicability within more interactive and socially driven learning settings.

The evaluation was conducted over a relatively short period, which restricts insight into long-term use, learning progression, and integration into curriculum workflows. Further research is needed to examine how such systems influence design thinking, learning practices, and student outcomes over extended periods.

Finally, although the system does not currently process sensitive personal data, the wider adoption of VR-based educational platforms raises important considerations related to data privacy, user safety, and prolonged exposure to immersive environments. Future work should explore privacy-aware system design and investigate the potential long-term cognitive and behavioural effects associated with sustained VR use.

5.2 Future Work and Expansion Opportunities

The listed extensions extend the platform to create a design environment that allows users to interact and collaborate while incorporating highly advanced intelligent capabilities.

Multi-User Collaboration

The project will allow multiple students to meet in a virtual environment and work in teams with faculty. The project will collaborate synchronously using Photon and Unity Netcode, with screen sharing and a voice chat. This will encourage collaborative interaction while also providing tools for maintaining synchronised scrolling.

Voice Command and Gesture Input

Audio-driven inputs (e.g., "zoom into entrance" and "rotate model") can help reduce device dependencies and ease accessibility. Integrating Unity’s Speech SDK and Oculus's hand tracking APIs will also make the system more natural and accessible. This will be helpful for those with physical disabilities or limited experience with VR controllers.

Cloud Integration and Device Agnosticism

Accessibility and performance should be improved: the system we designed runs only on desktop computers and is not available on mobile devices; we intend to optimise it by offloading heavy rendering tasks to cloud GPUs and expanding the range of supported devices (such as smartphones and tablets). This hybrid system will flexibly provide access to the online system to those with weak hardware via streamed interfaces and scale adaptation in low-resource educational environments.

Collectively, although the evaluation demonstrates strong perceived learning impact and engagement, future studies should incorporate pre- and post-tests of spatial cognition to more rigorously quantify learning gains

6. CONCLUSIONS

This study presented the design, implementation, and empirical evaluation of a modular VR architectural walkthrough system developed to enhance perceived spatial understanding, engagement, and early-stage design confidence among architecture students. Grounded in a design science research methodology, the system integrates a 2D-to-3D model transformation pipeline with immersive spatial computing, real-time interaction, and embodied navigation using commodity VR hardware.

The research results demonstrate that the proposed platform operates successfully, supports educational needs, and is accepted by students in real-world teaching environments. User testing with 40 architecture students showed that participants found the system useful and reported high levels of presence and active participation; most students chose the VR-based workflow for their design work over traditional 2D methods. The interactive system components, which included material changes and lighting adjustments, along with comprehensive building simulations, enabled students to develop their spatial understanding during design-testing exercises.

The research establishes a spatial computing system that businesses can scale by leveraging their web-based model ingestion system and real-time 3D modelling and VR capabilities, implemented through a component-based service architecture. The platform enables educational institutions to reduce cognitive load through mental-spatial transformation processes by providing students with authentic experiential learning opportunities that form the basis of architectural education.

While the current implementation is limited by hardware dependency, single-user interaction, and perception-based evaluation, the system establishes a validated foundation for immersive architectural learning environments.

Future work will focus on collaborative multi-user studios, cloud-based rendering, AI-assisted design feedback, and longitudinal evaluation of learning outcomes.

Overall, this research demonstrates the potential of immersive spatial computing as a pedagogical infrastructure for architectural education and contributes a replicable model for integrating VR technologies into computing-supported design learning environments

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Declaration of interest statement
The authors declare no competing interests.

Data availability
The data used for this study are available from the author upon reasonable request and at a reasonable time.

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