Towards a Fully Virtualised Architectural Design Studio: A holistic VR-based framework from conception to final design


Mohammed Faraj Al-Suwaidi
University of Liverpool


Asterios Agkathidis
University of Liverpool

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Mohammed Faraj Al-Suwaidi [1] Asterios Agkathidis [2] Adonis Haidar [3] Davide Lombardi [4]
[1,2,3] University of Liverpool, [4] Xi'an Jiaotang- Liverpool University
[1,2,3] {m.f.al-suwaidi|asterios.agkathidis|adonis.haidar}@liverpool.ac.uk,
[4] davide.lombardi@xjtlu.edu.cn

While Virtual Reality (VR) is gaining popularity in the architectural design field as a visualisation tool, emerging tools like Google Blocks, SketchVR and Gravity Sketch (GS) further utilise VR's immersive capabilities. Design toolsets such as 3D sketching, modelling and interaction within the virtual space, with six degrees of freedom of movement and rotation in the virtual space, enable a fully immersive design approach. We continue utilising these immersive toolset capabilities to expand our previous research on incorporating VR tools in the early stages of the architectural design process throughout an academic semester project. This paper aims to further extend this research approach by embracing a fully virtualised architectural design studio and exploring all the design stages through Virtual Reality. Our findings highlight the framework's strengths and challenges, revealing diverse approaches and design outcomes from participants throughout the semester. Evaluation methods include student surveys, External Examiner reports, focus group interviews and researcher/lecturer observations. Additionally, a comparison is made with non-virtualised design studio outputs running concurrently, utilising the same site and design brief.

Keywords: *Design Studio, Virtual Reality, Architectural Education, Gravity Sketch, Meta Quest, Hybrid Learning, Digital Design, Remote Learning*

INTRODUCTION

There is a common connection between the evolution of technology and its effect on the consumer's development approach in the design industry (Myers et al., 1999). To elaborate on this point, we can highlight some of the recent trending applications in the architecture field. This includes Rhinoceros/ Grasshopper: a parametric and algorithmic design software, and Revit: industry-standard BIM software. Each software offers contrasting toolsets which result in dissimilar design outcomes. This is due to the user interface (UI) design, the input methods of each software and how they influence the design's final results. In line with these trending tools, Virtual Reality (VR) also serves as a major asset in the design field for spatial visualisation, providing users with an immersive first-person experience by enabling the exploration of their design at a 1:1 scale in the digital space.

A major feature of VR is its unique hardware tracking system that contradicts the common keyboard button and mouse inputs used in desktop/laptop systems which are also limited to flat-screen visuals. The VR hardware incorporates accurate, IR-based, controller tracking methods that enable the headset and controllers to be tracked through six degrees of freedom (6DoF), this includes movement and rotation for both the controller and the headset in the X, Y and Z axis. This seems to be a more intuitive method to interact with the design space by allowing a direct translation of both hands and head movement from reality to the virtual space when the headset and controllers are worn. The organic input gestures and movement produce a richer immersive capability that inspires users to further interact with VR software. This leads to creating new possibilities to cultivate novel learning opportunities and potential psychological interventions and assessments that influence the creative process (Barbot et al., 2023).

Gravity Sketch (GS) is a 3D sketching and modelling software that utilises the VR hardware capability by transforming the controllers into drawing input tools. Based on a comparative study of various VR software from previous literature (Al-Suwaidi et al., 2022), The UI of this application supports efficient access to a wide array of starter and advanced techniques to sketch, conceptualise and develop their architectural designs in the 3D platform.

Building on our previous research about implementing VR design as part of the early stages of the architectural design process during one academic semester (Al-Suwaidi *et* al., 2023). *W*e aim to investigate the possibility of utilising a fully virtualised architectural design studio in all the design phases of the project. In line with this aim, we address the following questions:

- How can we develop a pedagogical framework for incorporating virtual reality as the main design tool in a fully virtualised architectural design studio?
- How effective is a VR-based design framework when applied in various stages of the architectural design process in comparison to conventional/non-virtualised design studio environments?

To answer these questions, we develop a VR-based framework and test its suitability in various stages of the architectural design process. The framework consists of VR site master planning, 3D scan/collage import, model modification and design development in VR with the aid of game-engine-based simulation software (Al-Suwaidi et al., 2022). Considering the increase in VR-plugin integration in trending design software such as SketchUp, Revit and Rhinoceros, further opportunities arise that enable users to integrate their preferred CAD design software into the workflow while also providing the option to utilise VR. The design methodology is updated to incorporate newly introduced application plugins that enable VR integration into their preferred design medium (Figure 1).

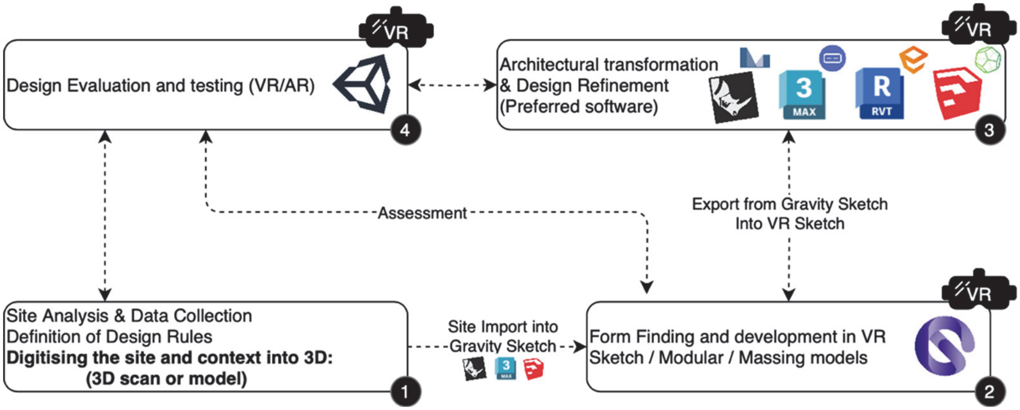

Figure 1
Proposed VR Design Methodology (Updated VR integration)

The selected hardware and software used in the developed framework, consisting of the Meta Quest 2 VR headset running Gravity Sketch, with the addition to the Unity game engine for simulation and virtual environment development. The framework also enables users to integrate their preferred CAD/3D modelling toolset to further enhance and refine their design in the digital platform with the option to integrate VR through external plugins during this stage.

We then apply the framework for one semester, providing full access to a VR headset to each student and the design studio tutor, to utilise as a design development and collaborative medium, during class tutorial sessions, these would take place either remotely or in-person through VR. The communication is achieved by using customised avatars that represent each user in the virtual space while further enhancing their interaction with other users in VR.

Our findings highlight the framework's strengths and challenges, revealing diverse approaches and design outcomes from participants throughout the semester. Evaluation methods include student surveys, External Examiner reports, focus group interviews and researcher/lecturer observations. Additionally, a comparison is made with non-virtualised design studio outputs running in parallel, utilising the same site and design brief.

BACKGROUND AND LITERATURE

The nature of 3D sketching is guided by a series of free-handed, sketch-based, design exercises. These exercises encourage constant iteration during the conception stages of the initial design process. Similar to paper-based 2D sketching, which enables unique hand expressions and stylistic gestures, the exploration of 3D form through VR sketching also produces unique design results that would be difficult to replicate in non-immersive software, this is due to organic input methods in the X, Y and Z axis that are not limited by grid-snapping, orthogonal lines or rigid tools. A performative-based case study highlights this freeform aspect through applying VR-based shape-finding techniques. This is done by recording performative dance gestures, simply tracked by the hand controllers, resulting in a unique and rich set of individual forms (Barczik, 2018).

The freedom of organic expression that is enabled through the VR medium contrasts the controlled outputs created by the parametric design and BIM tools, commonly applied in the architectural industry. By taking traditional design exercises such as trace-forming, collage making and physical modelling, and later translating them into the virtual environment, we highlight a primary aspect and drive of the research that sheds light on the emerging potential, to embrace traditional techniques and design approaches from a modern and innovative perspective.

The initial starting point of this research delves into the literature review investigation, identifying various projects utilising Virtual Environment (VE) as a platform for education, virtual collaboration and design exercise integration. The outcomes of the paper reveal various potential approaches derived from diverse design platforms and even video games such as Minecraft (Delaney, 2022), enabling unique remote and/or in-person collaborative experiences based on the VE-based software used. The paper concludes by proposing a novel design framework catered to utilising VR and immersive tools as a design medium, in various stages of the architectural design process (Al-Suwaidi et al., 2022). The developed framework also adapts to newly introduced software and hardware that complements the implementation of immersive technology.

This paper further expands on previous research focused on the initial application of Virtual Reality in a design studio, using the proposed framework with three student participants. The initial implementation of the framework focused on introducing the students to the VR hardware and software for the first time and providing an accessible physical-to-digital transition between their preferred conventional toolset, this included physical models and 2D sketches imported directly into the digital studio. This supported a primary focus on exploring the various toolsets accessible in the VR software to facilitate teaching, collaboration and design development, all within the virtual studio (Al-Suwaidi et al., 2023). The paper concludes with showcasing design results developed by the students using the VR headset primarily via Gravity Sketch, followed by an analytical discussion covering the findings based on the design framework outcomes.

The findings of this initial implementation showcased the framework's adaptive influence on each participant, as the immersive tools introduced became an expansion to the users' existing design toolset. As a result, the final outcome of each project guided by the framework was diverse and not constrained by the VR platform.

MATERIALS and Methods

The proposed methodology showcased in Figure 1 involves VR design techniques and immersive tools in four stages that cycle through the architectural design process, users are also able to loop or revisit each exercise for reiteration. The stages of the framework consist of the following: *Stage 1: Site Analysis & Data Collection; Stage 2: Shape Finding & Conceptual Development; Stage 3: Architectural Transformation & Design Refinement and finally, Stage 4: Design Evaluation*.

Stage 1, incorporates various data collection methods to familiarise the designer with the site through digitising points of interest within the physical space. This stage includes photo, video and sketch documentation of the site. Additional data compliments the second stage of the VR-based design process, this includes 2D texture captures of specific details within the site, in addition to 3D scans and 360 photography. Most of the data collection methods mentioned above can be completed using a smartphone running specific applications that take advantage of photogrammetry techniques to create 3D scans and others that enable the user to automatically stitch multiple 2D photos to create a panoramic 360 image. The efficiency and quality of collecting 360 photos or 3D scanned data can also be achieved through specialised hardware such as 360 cameras and infrared-based LiDAR-enabled devices, for accurate 3D scanning results.

The second stage incorporates shape-finding techniques that take place in VR using Gravity Sketch to explore forms at 1:1 scale in context. This stage caters to both experienced and new users who do not have prior knowledge of the GS design toolset. This is done by providing a series of exercises as indirect tutorials to enable first-time users to familiarise themselves with the VR hardware and software UI before delving into advanced and complex tools. Stage 2 introduces a beginner and advanced set of exercises that enable each user to efficiently transition from their preferred conventional workflow and later prioritise different aspects of the framework based on their style of work (Figure 2).

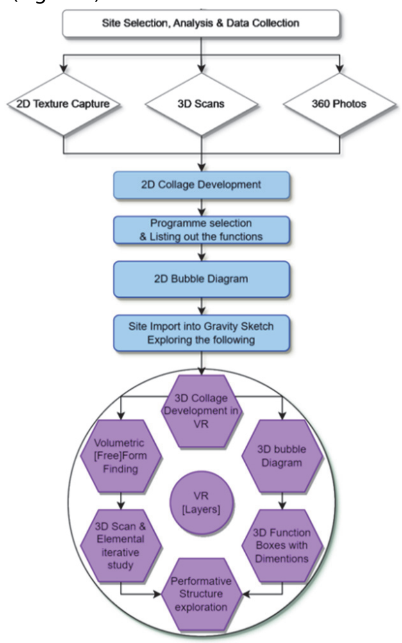

Figure 2
Stage 2 Breakdown of Digital Shape Finding Methods: transitioning from traditional to Immersive design techniques

This stage consists of two separate phases (Figure 2), highlighted in blue and purple, the blue highlights a set of traditional exercises, which later evolved into the virtual environment through a set of VR-based 3D design techniques highlighted in purple. Based on the collected data from each participant, the users are able to switch between a series of traditional approaches modernised into an immersive set of design exercises, through VR. Incorporating virtual environments allows users to also import their chosen site at a 1:1 scale to explore and aid the shape-finding design process of their building design.

Stage 3: Architectural Transformation and Design Refinement - This focuses on elevating the designs from conception, to architectural realisation and later refining the design via the VR platform or the user's preferred CAD design software. This stage merges both existing and newly introduced toolsets into the design process, enabling designers to branch out into their preferred style of design and refinement approaches. This transition is done through the LandingPad web app, which supports users to upload or export 2D images and 3D models to-and-from the Gravity Sketch VR platform to their PC/Mac devices. This provided consistent cloud access to all design files to efficiently transition between VR-based and external design software. LandingPad also hosts the virtual collab room which enables multiple VR users using Gravity Sketch to communicate and collaborate in a single virtual space, the ImDeCo virtual collab room became the main digital studio for tutorials, discussions and design development for all participants.

The process in Stage 3 is similar to the steps taken in the initial implementation of the workflow (Al-Suwaidi et al., 2023). In this paper, the approach is updated by introducing various plugins that complement various desktop software to facilitate VR utilisation in different ways:

- Rhinoceros/Grasshopper > Mindesk
- Revit > Enscape VR plugin
- Sketch-Up > SketchVR
- 3DS Max > Sentio VR

Some of the highlighted VR plugins primarily enable quick visualisation, while others provide a direct connection to the working model and offer design adjustment options and model editing capability within the VR headset.

The final stage (Stage 4: Design Evaluation & Testing) applies the Unity game engine to enable users to export their designs in FBX (FilmBox) 3D model format and import the file into the virtual Unity scene. The selected format supports 'higher-fidelity' data exchange and transfer between various 3D modelling software, including the tools highlighted in the proposed framework (Autodesk, n.d.), this complements our design methodology incentive to enable users to cycle through the design stages with each iteration.

The flexibility of the Unity game engine enables the designer to customise interactive first/third-person virtual walk-throughs of the 3D model to assess and evaluate the quality of their design. The walk-through can also be developed for both VR and non-VR platforms. The fourth stage also expands on the previous implementation by introducing a virtualised heliodon tool used to analyse and assess the building design response to the sun path and light intrusion at a 1:1 scale. This is done through the development of a custom Unity asset specifically designed for the project site. This is shared with the students to import into their unity project, enabling them to cycle through the winter, summer, autumn and fall solstice from sunrise to sunset with a press of a button (Figure 3).

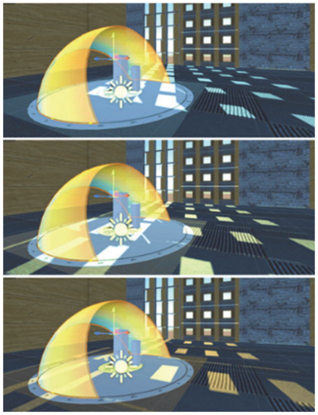

Figure 3
Custom Developed Virtual Heliodon Asset Imported in Unity: Showcasing Winter, Autumn/Fall and Summer Solstice Sun-Path At 3 PM (GMT)

ImDeCo Design Studio 2 outline

ImDeCo (Immersive Design & Collaboration) is a 12-week Design Studio that embraces Immersive design tools, specifically mixed and virtual reality. This studio runs in parallel to other non-virtualised design studios during the Spring 2023 academic semester. Similar to ImDeCo Design Studio 1, implemented in the previous semester in Winter 2022 (Al-Suwaidi et al., 2023), all the design studios follow the same design brief in Studio 2 and provide three site options, all located in the same city. Providing the same project brief across all design studios to investigate buildings for housing typologies in the Liverpool City Centre and develop a proposal focused on contemporary living appropriate to the selected site. This fostered a consistent set of project outcomes from students to be used for comparative evaluation during the assessment and analysis stage of the research.

Figure 4
Isometric model for Design Studio 2 project site options highlighted as S1, S2 and S3

The three selected sites for the semester 2 design project were located in the Liverpool City Centre. Each Site served unique attributes and specific challenges (Figure 4). Site 1 (blue) was located closer to the docks and Liverpool waterfront commercial area, with a smaller plot but site-specific potential to develop a skyscraper design. Site 2 (green) was located in a residential/commercial spot which currently acts as a parking lot, this is the second largest site which encourages contextual adaptation to the surrounding buildings. Site 2 also includes a small pub building in the corner of the building area and the back of a 5-storey apartment/office building. Site 3 (orange) is the largest site option, covering an entire parking lot with added vacant structures with no current function and the addition of a nearby connection to the Moorfields underground train station and railway line.

ImDeCo Studio 2 participants were all provided or had already owned a Meta Quest 2 headset to use during and out of class times. This encouraged ongoing utilisation of the VR headset to learn, collaborate and develop their designs within the virtual environment. Participants were also provided with the option to work in groups or individually. An additional design task added to the ImDeCo design Studio was to also explore performative elements integrated within the building design in the form of kinetic canopies, facades or structures, this task encouraged users to begin exploring animation techniques that can be tested through the Unity game engine (Morse & Soulos, 2019).

All students participating in the ImDeCo framework are encouraged to come from a design and creative background such as a BA in Architecture or equivalent, this assures a consistent control group that confirms that each participant has the initial architectural design fundamentals that will be expanded upon in VR throughout the semester.

In Semester 2: ImDeCo design studio, we have a total of six participants. Three of them have completed ImDeCo Design 1 and three others are new to the virtual design studio. To ensure a smooth adaption to the VR design methodology by the new participants, the studio offers the flexibility to use VR as a primary development tool while also encouraging students to adapt and interchange between their preferred CAD software.

Doubling the number of participants since semester 1, allows us to slowly gauge the capacity and limitations of the proposed methodology. In addition, we are provided with a contrasting set of design outputs from students who have prior experience with the framework applied in the previous semester, vs students who do not. It is expected that previous ImDeCo students would have acquired further familiarity with the VR tools due to applying them in a previous design project. To counter-balance this, the new students were provided with an introductory session for the first number of weeks. This assured that the new ImDeCo students were also briefed and familiarised with the

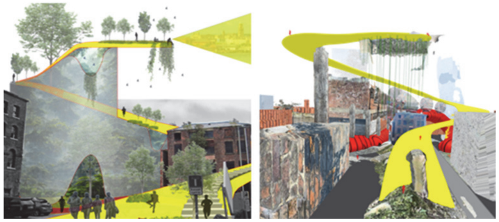

Figure 5
Conceptual Collage Exercise Developed for Site 3, (Left) 2D Collage Made with Photoshop, (Right) 3D Collage Made with Gravity Sketch in VR

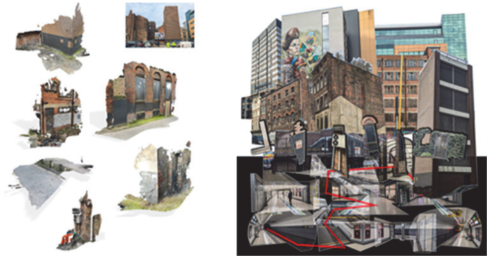

Figure 6
Conceptual Collage Exercise for Site 3, (Left) 3D Scanned Data, (Right) 2D Collage

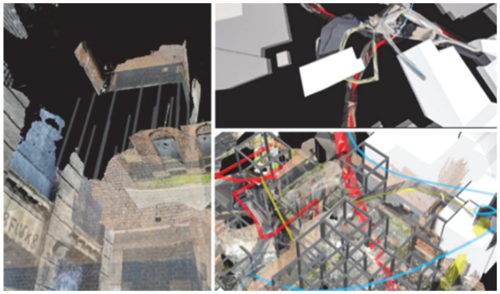

Figure 7
Conceptual Collage Exercise for Site 3, (Left) 3D Scan Composition with Materiality, (Right) 3D Contextual Collages in Response to Site Functions.

VR design tools prior to starting the design studio session each week, allowing for all to progress with their designs at the same pace throughout the semester.

The framework outcomes were evaluated through interim reviews combining the VR and non-VR design studios throughout the semester with the addition of design tutor observations, moderation, external examiner reports and distributed surveys complemented by focus group interviews.

The Design Studio Context

The design project started with the three site visits from Week 1, with the provided data collection tools for the ImDeCo design students. This included the iPad with the built-in LiDAR for 3D scanning, and a 360 camera (insta360 Nano S) for 360-degree photography. Students visited each site and were provided a week to select one of the three options or purposes and justify their own design site. They were also given the freedom to revisit the site at any point with the provided data collection tools to gather more information if required. All six students chose site 2 or 3 and all decided to work individually.

Each headset was set up with each student briefed with a guided health and safety introduction to adjust the size and fit of the VR for comfortable use during the design sessions. Gravity Sketch was already installed, and each student was able to fully customise their virtual avatar to represent themselves in the virtual studio space. Additional software was also installed in each VR headset including Arkio and SketchVR available to explore in their own time to further familiarise themselves with the headset. A university-based ImDeCo collab room was set up by the design tutor on LandingPad and shared between all 6 student accounts. During individual or group tutorial sessions, the collab room served as a platform to share student tutorial content, iterations and design progress.

In the second week, all students were assigned to present a site analysis for their chosen site and present a 2D collage consisting of the collected media from the site. This was directly followed by the first VR-based exercise to develop a 3D collage using 2D textures, 3D scans and 360 photos for week 3 (Figure 5). The collected data was utilised in different ways based on the stylistic choice of the user to complete the set of collage tasks (Figure 6). Unique world-building collage techniques are developed by just using the 3D scans as a textured base to develop and conceptualise the form through a series of 3D collages (Figure 7).

In Week 4 the 3D collage was presented by each student. After completing the immersive collages, various design exercises later followed focusing on building program and site response, these exercises included:

- Volumetric Shape Finding

- 3D Bubble Diagramming
- 3D Scan & Elemental Iterative Study
- 3D Function Box Zoning

Figure 8
Virtual Studio screenshot of student integrating traditional design techniques in VR

Figure 9
Students further explore their designs in VR through reimported CAD models and drawings to test forms and performative design elements

Figure 10
Students working with advanced technical modelling techniques in VR to further refine and enhance the building geometry and form designs

Each exercise was derived from traditional design approaches such as physical site massing, function distribution and 2D bubble diagramming. The added immersion in the VR space provided users with a direct contextual response and scale understanding of the site when developing each 3D iterative exercise. The session concluded with preparation for the first review taking place in Week 5 (Figure 8).

Following the first interim, design development and virtual tutorials continued to take place In VR using the Gravity Sketch virtual studio in Weeks 6 and 7, leading to the second interim review in Week 8. At this stage, students began to branch out from the VR platform and began integrating their conventional CAD tools into the process while still returning to the VR space to reiterate and explore their design in VR (Figure 9).

It also becomes prominent that some of the students' design styles feel more restricted by the VR design tools due to their freeform nature, this was typically a result of students undertaking an orthogonal design approach which is more familiar for users to achieve through software such as Autodesk Revit or Rhinoceros (Figure 9). Unity is also introduced to export the latest iterations from the 3D software in FBX format and develop the custom interactive walk-through to begin analysing their design while testing out the performative element of their building.

By Week 9, we introduced the digital heliodon asset which enabled the students to test their performative design integration in the virtual walkthrough in Unity. The implementation of this task was complex, as minor coding using C# visual scripting was required to integrate the keyboard inputs to activate specific animations linked to the digital heliodon sun path and the kinetic movement of the performative element. Students also had to be familiarised with the built-in animator linked to the button inputs to understand how to further develop and customise the interaction during the walkthrough.

Weeks 10 and 11 included ongoing tutorial sessions using both VR and PC platforms to develop and refine their final designs and presentations (Figure 10). The provided toolset for the Unity walk-through also helped elevate the student's final interim presentation in Week 12.

SURVEY FINDINGS, DISCUSSION AND CONCLUSION

Implementing this framework reveals a number of benefits and challenges, unveiling potential solutions that can be addressed in future implementations of the design methodology. The decision to mix both existing and new students in the second iteration of the framework resulted in a positive outcome aided by consistent collaboration and communication that united two diverse groups while consistently exchanging knowledge. All participants embraced the design toolset in a unique way based on their design fundamentals and existing toolset. This led to a diverse set of design approaches and VR toolset adaptation which is evident in the final output from each user, this reveals an interesting set of results which are also discussed below.

Based on the survey results, both existing and new students found the adoption of Gravity Sketch as a design tool intuitive and complimentary to their design process throughout the semester. Starting with the 3D collage exercise which extends from the traditional 2D collage technique, users found this conceptual exercise very effective to familiarise themselves with the VR tools in addition to being an important starting point for conceptualising their designs. Five out of six also found the 3D collage exercise to be potentially more effective than the traditional approach due to the direct site connection at a 1:1 scale: *"It can produce a realistic 3D spatial experience which was not easy to get before"*.

Following the 3D collage task, two additional exercises voted most effective by the students revealed to aid their design development due to the immersive scale awareness of the 3D digital model, these exercises are the volumetric and 3D function zoning exercises. These enabled users to effectively distribute their functions to scale and further refine their building circulation. This exercise is derived from the conventional bubble diagramming and physical massing techniques with the added area consideration for each function placement in response to the site. This was further complimented by the volumetric exercise to highlight the building envelope correlating to distributed functions.

Even with only six students, the diversity in external software use proved effective and unique to each design project. In addition to Gravity Sketch and Unity, additional commonly used software included the following: Rhinoceros (4), AutoCAD (4), 3DS Max (3), Revit (2) and SketchUp (2). The framework leniency supported each student to branch out to other software to further evolve and refine their form: *"The tools were slightly difficult to refine the design completely in VR as a new user. Finalising my form, and the time to learn to new software and its expected outputs was a small constraint"*.

One of the issues experienced as a lecturer was remaining in VR throughout the session for an extended period throughout the day as each student was met in VR for their individual tutorial slot, occasional breaks were important to consider in this situation. Another solution is to merge tutorials into small groups when accommodating a large number of students throughout the day.

During each design studio tutorial, students consistently met in the virtual space to upload their updated 2D screenshots from CAD drawings, free-handed sketches, or exporting designs from any external 3D modelling software in FBX format into the collab space. During the discussion stage of the tutorial, students found that learning collaboratively with the lecturer in VR benefitted their design development as both student and lecturer were able to experience and discuss the updated design at different scales leading to specific feedback aiding the design process: *"I feel that we had a lot of work developed in comparison to the other studios, as we* *were able to get all these extra iterations and designs churned out really quickly in VR".*

In conclusion, ImDeCo Design 2 proved to be both challenging but also a learning experience for both existing and new students. All participants have found ImDeCo to introduce a wide range of tools which inspired their future endeavours to explore VR and immersive tools. Four out of the six students also incorporated VR in their Master's thesis project due to the studio's design influence throughout the semester.

Given the expanding nature of these design tools, the design methodology continues to evolve alongside emerging industry trends. This showcases progressive development as the framework adapts to various existing design workflows which will continue to reveal unique and diverse results.

Figure 11
Final design rendering of building façade, developed in VR.

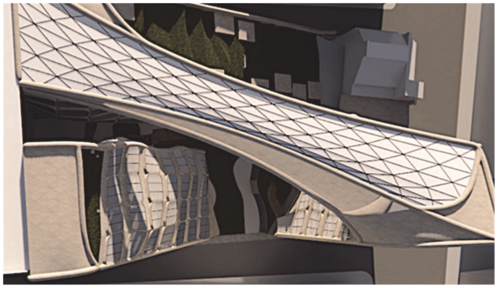

Figure 12
Final design rendering of building canopy, developed in VR.

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REFERENCES

Agkathidis, A. (2015, September 16). Generative Design Methods Implementing Computational Techniques in Undergraduate Architectural Education. eCAADe33, 47-55.

Al-Suwaidi, M., Agkathidis, A., Lombardi, D., & Haidar, A. (2022). Application of immersive technologies in the early design stage in architectural education: a systematic review. ASCAAD: Hybrid Spaces of the Metaverse - Architecture in the Age of the Metaverse Opportunities and Potentials, 313–330.

Al-Suwaidi, M., Agkathidis, A., Lombardi, D., & Haidar, A. (2023). *Immersive Technologies in Architectural Education: A pedagogical framework for integrating virtual reality as the main design tool in a fully virtualised architectural design studio environment*. eCAADe: Digital Design Reconsidered, 89-98.

Autodesk. (n.d.). *FBX, Adaptable File Formats for 3D Animation Software*. Accessed March 27, 2024: https://www.autodesk.com/products/fbx/overview

Barbot, B., Kaufman, J. C., & Myszkowski, N. (2023). Creativity with 6 Degrees of Freedom: Feasibility Study of Visual Creativity Assessment in Virtual Reality. *Creativity*

Barczik, G. (2018). From Body Movement to Sculpture to Space Employing Immersive Technologies to Design with the whole Body. Computer for a Better Tomorrow, 781–788.

Boeykens, S. (2013). Unity for Architectural Visualization: Vol. Revised (revised). Packt Publishing.

Delaney, J. (2022). Minecraft and Playful Public Participation in Urban Design. *Urban Planning*, *7*(2), 1–13.

Kuyumcu, B. (2010). Unfolding Diagrams as Generative Design Tools in Architectural Design Process. Middle East Technical University.

Morse, C., & Soulos, F. (2019). Interactive Facade Detail Design Reviews with the VR Scope Box.

Myers, B., Hudson, S. E., & Pausch, R. (1999). *Past, Present and Future of User Interface Software Tools*.