VR DEVELOPMENT TECHNIQUES: A COMPARATIVE STUDY FOR BUILDING ENERGY SIMULATION TOWARDS DESIGN EDUCATION

Hassan Anifowose
Department of Construction Science, College of Architecture, Texas A&M University, College Station, Texas, USA

Kifah Alhazzaa
Department of Architecture, College of Architecture, Texas A&M University, College Station, Texas, USA
Department of Architecture, College of Architecture and Planning, Qassim University, Qassim 52571, Saudi Arabia

Manish Dixit
Department of Construction Science, College of Architecture, Texas A&M University, College Station, Texas, USA

ABSTRACT: *An important practice for reducing the effects of global warming is the design and construction of energy-efficient buildings. In design education, the full comprehension of thermal behavior in buildings based on their geometry and material composition is required. The complexity of energy simulation principles, vis-a-vis the number of elements that impact the energy loads, their linkages and relationships to one another all combine to make this a challenging subject to absorb. Virtual Reality (VR) provides an immersive way to learn the concepts of building energy responses; however, the development of VR applications towards education is difficult due to the knowledge, skill and performance resource related gaps. This research explores VR as a teaching tool for building energy education. We developed EnergySIM; a multi-user VR building energy simulation prototype of the famous Farnsworth House. Using this prototype, we document rigorously tested development workflows for improved VR game performance, high visual fidelity, and user interaction, the three key factors which positively contribute to user knowledge retention. The study combines menu-driven interaction, virtual exploration, and miniature model manipulation approaches with the aim of testing user understanding and knowledge retention. Highlighted results provide reduced barriers of entry for educators towards developing higher quality educational VR applications. EnergySIM showcases pre-simulated building exterior surface heatmap response from four seasons (winter, summer, fall and spring) alongside an all-year-round sun-hour scenario. Four different material pre-simulated scenarios (single glazing, double glazing, concrete, and wood) for interior atmospheric temperature mapping are also explored. Preferred interaction methods are documented by allowing users' visual appraisal of alternative building materials based on insulation capacity or resistance to heat flow (R-value). This prototype pushes the boundaries of visual fidelity using geometry/mesh modeling input from various software into game engines and optimizing game performance using the HTC Vive Pro Eye and Meta Quest Pro headsets.*

KEYWORDS: *Virtual Reality, Design Education, Building Energy, Simulation, Visualization, Energy Efficiency*

1. INTRODUCTION

There is a rising need for combating the effects of global warming and design education is a crucial channel to sensitize the designer on roles they play in the creation of energy efficient buildings. There is also an incumbent need to increase awareness of energy usage and waste by consumers as the average person is typically unable to mentally picture the amount of energy they consume (Haefner, Seeßle, Duecker, Zienthek, & Szeliga, 2014). The complexity of energy simulation principles, however, makes the subject very challenging to understand even to design education students.

On a larger scale, the effects of climate change are being felt all over the globe in the form of devastating natural catastrophes. According to the Intergovernmental Panel on Climate Change (IPCC), the construction, operation, and maintenance of buildings account for a combined total of forty percent of the world's annual energy sources. As a result, industrialized countries' energy-related carbon emissions constitute thirty-six percent of their total emissions (Metz, Davidson, Bosch, Dave, & Meyer, 2007). The demand for energy is growing at a very rapid rate due to the rising standard of living and population (Hafeznia, Aslani, Anwar, & Yousefjamali, 2017). Most of the objects in our buildings are powered by electrical energy in some way. Despite this, energy is one of the aspects of building construction that is most often overlooked and misunderstood. This is because energy cannot be recognized as a tangible object or component. A significant amount of a building's overall energy usage is attributable to the process of cooling or heating the interior space in order to satisfy the occupants' desired thermal conditions (John Dulac, 2020). A revolutionary shift in energy management with the primary emphasis being placed on the energy efficiency of buildings should be one of the primary goals of future generations, both from an economic and an environmental point of view (Lin, Li, Ma, & Zhou, 2016).

One of the first and most immediately applicable methods is the enhancement of active and passive solutions, able to supply the energy needs of our buildings via the design of optimized building envelope, HVAC, and lighting systems (de Gracia et al., 2018) as well as the use of new innovative materials (Pisello, Rossi, & Cotana, 2014) and other passive techniques (Amirifard, Sharif, & Nasiri, 2019). Energy consumption in buildings may, therefore, be predicted with increasing accuracy using predictive models like dynamic simulation models or energy consumption models (Zhao & Magoulès, 2012). Envelopes, which are one of the many components that compose a building, are one of the most important aspects to consider while doing research on energy use. The building envelope is the structural barrier that prevents the passage of air, heat, noise, light, and water between the conditioned and unconditioned spaces of a structure. There is a significant correlation between the market penetration of current technologies and the efficiency with which they are implemented in the building envelope. Recognizing the most important technologies, as well as their existing and potential future growth in the market and research, is crucial in the construction sector due to the relevance of energy consumption (Aslani, Niknejad, & Maghami, 2017). The complexity of energy modeling concepts, the number of factors that affect the conclusion, and their links and interactions make this a difficult topic to comprehend. This may lead to misinterpretations of conventionally presented energy data. Therefore, a way of energy visualization that is effective and easy to grasp is essential for design education as well as for enhancing public awareness of energy efficiency. This will provide a more direct awareness of energy usage as design learners can visually see the influence of different building geometry and materials on overall energy consumption as well as indoor temperatures. This is a vital step toward simplifying the learning curve.

2. RELATED WORKS

This real-world problem of providing high fidelity visual simulation of building energy usage has been a subject of interest however, it has not been researched widely. Researchers have used tools such as Energy Experience Lab (EELab) for real-time visualization of power consumption in public buildings with the aim of generating insights from complex data. This application was considered for potential users such as facility owners and energy consultants at the post-occupancy phase of a project (Haefner et al., 2014). This provided the groundwork for further investigation however, using more recent education tools such as Virtual Reality to explore and develop new frameworks.

2.1 Current development frameworks

Considering the upward adoption of Virtual Reality techniques in developing design education content, researchers have previously explored workflows for best daylighting and lighting analysis. Software such as Autodesk Insight have been used with Revit to visualize energy analysis containing numerical data (Ergün, Ş, Dino, & Surer, 2019). Although this method provides raw data files useful for numerical data analysis, we found this method inadequate for detailed visual results hence the suggested method in this paper. Previous works also show that selecting the right tools for VR development is not the only important aspect. Knowing the end user, outlining the problem, expectations and end goals are factors which must be considered alongside the deployment platform (desktop or mobile), integration methods and development time (Al-Adhami, Ma, & Wu, 2018). In this paper, we provide a clear detail of methods and best practices for developing improved visual content for building energy simulation in VR, useful for design education cases. EnergySIM is developed for entry level design students with difficulty of learning building energy response. Expected outcomes include increased levels of understanding about the impact of building forms and construction material choices on energy consumption in buildings.

2.2 Workflows in VR

According to a previous research conducted in our laboratory, the benefits of building a VR prototype outweighs verbal explanation and with increased realism, usability can be improved due to near-reality experiences (Anifowose, Yan, & Dixit, 2022). Established workflow in previous research tested VR precision features such as snap-to-position and snap-to-angle for task-based systems providing ease of entry into developing such learning content. The previously published development approach is adopted for the prototype discussed in this paper. Various workflows were also studied (Beach, 2018; Nugraha Bahar, Landrieu, Pére, & Nicolle, 2014), showing attempts to create efficient CAD data for thermal simulation and visualization in VR. Thermal simulation software are not typically developed to showcase results in useful geometry but mostly in charts or graphs (Nugraha Bahar et al., 2014). Recent software platforms however have embraced visual representations, however, there are still difficulties surrounding their usability in cross-software developments. Methods to solve data transfer problems have been developed however, the challenge about visual clarity remains unsolved. Design students are mostly visual and, therefore, we are proposing a more defined approach to showcasing building energy simulation with a focus on visual and interactive development.

2.3 Interactive Visualization of Building Energy Efficiency

The purpose of this exploratory research is to investigate the use of virtual reality (VR) technology as a platform for visualizing schematic energy simulations at an entry level. We seek to answer questions such as -

- Can VR provide immersive and visual understanding of buildings response to sunlight and heat?
- What best development methods in VR are crucial for visual representation of building energy usage?
- Can users in VR exhibit understanding of buildings' heat response based on material change?

EnergySIM is a VR prototype that is being developed with the intention of enhancing the audience's knowledge of building energy simulations and the influence of materials properties on the interior temperature and the annual energy consumption. This is accomplished by presenting visual outputs of the simulations in the virtual environment with full building scale to assist users in correlating understanding building response to daylighting and thermal exchange using a visual approach rather than data. In the last two decades, virtual reality (VR) technology has evolved in a variety of fields. Users may experience what it's like to be fully immersed in a simulated version of a real-world setting (Diemer, Alpers, Peperkorn, Shiban, & Mühlberger, 2015).

3. Method

EnergySIM presents pre-simulated building exterior surface sunhour exposure for each of the four seasons (winter, summer, fall, and spring) calculated based on the number of average sun hours impacted on the building floor, roof and vertical surfaces throughout the calendar year. In addition, for total building energy consumption, cooling and heating loads, and interior atmospheric temperature mapping, four pre-simulated energy simulation scenarios are investigated utilizing single glass, double glazing, concrete, and wood materials in the north wall of the building. Documentation of preferred interaction techniques is accomplished by facilitating users' visual evaluation of different construction materials with respect to their ability for thermal insulation or resistance to the heat transfer (R-value). The EnergySIM prototype went through a lot of different stages of development, each of which included a different platform. The prototype's prime focus is to include the building energy simulation into a high-fidelity virtual reality environment while also including simulation outputs that are visually pleasing and simple to comprehend. The primary structure of the EnergySIM prototype is shown in Figure 1. The subsequent section will provide an in-depth discussion of each stage in the process.

3.1 Case Study

The Farnsworth House (Figure 2.) is a renowned architectural landmark designed and built by Ludwig Mies van der Rohe between the years 1945 and 1951. For the purposes of this research, the Farnsworth House has been used as a case study in the virtual reality experience as well as the thermal and energy simulation. Considering that its design and layout were controversial during the time it was being built, the Farnsworth House is a well-known project, not just among architects and engineers but also among the general public. Additionally, it is a symbol of the modernist movement together with the works of Mies van der Rohe. The walls of the home are almost entirely made of glass, which has a significant influence on its energy consumption. Our research questions the possibilities of visualizing such building energy footprints and conveying the information in a visual manner while comparing changes in wall materials and corresponding energy usage. These are the primary factors that contributed to the decision to utilize the Farnsworth House as the basis for the EnergySIM prototype. The location of the home is Plano, Illinois, United States. In Plano, the summers are exceptionally long, warm, humid, and rainy; the winters are freezing, snowy, and windy; and it is consistently partially overcast throughout the year (Places).

3.2 VR Prototype Development

The EnergySIM prototype was rigorously tested for performance and visual quality while also exploring the most efficient methods to aid ease of entry to future developers without advanced modeling, simulation or coding skills. In this paper, we document optimized workflows aimed at achieving the best visual quality and file integrity for developers who can apply these methods towards more complex education VR applications. For considerably big projects, it is important to optimize objects to aid performance (Al-Adhami et al., 2018). In this prototype development, we highlight optimization techniques for improved game performance on average specification computers without compromising visual quality.

3.2.1 Workflow and challenges – Phase 1

The prototype's primary objective is to visualize how building geometry responds to solar energy. To help design students understand this, we developed a framework for visualizing 4 simulated seasons (Winter, Spring, Summer, and Fall). To make users learn better, it is best determined to provide a schematic and more simplistic rather than precisely accurate visualization. Object manipulation and game performance were chosen over data manipulation as tactile feedback is important within virtual environments. The simulation was developed using a series of modeling, simulation, texturing, lighting, and game development tools which are analyzed below based on their capabilities.

After careful consideration, we chose Autodesk Revit (Autodesk) as a primary Building Information Modeling (BIM) tool due to its industry popularity, speed and accuracy of representing building components. SketchUp was chosen as the next geometry modeling and editing tool. Since this research objective is to enhance visual output for educational VR applications, we chose Sunhours (Hall, 2022), a plugin as the preferred energy simulation tool. Several alternate comparisons and daylight analysis in various software and plugins such as Autodesk Insight (Autodesk, 2022a), Sefaira (Sketchup, 2022), Ecotect (Autodesk, 2022b)were tested rigorously for the most streamlined workflows while achieving both visual integrity and speed. Although Autodesk Insight provided great accuracy, there was no known method of exporting the geometry with the associated visual/texture data. A significant challenge to VR development is performance, while ensuring that user experience is not diminished by slow or stuttering frames. It is worth stressing that a file format converter; CAD Exchanger (CADEX, 2022), was used to retain vertex colors while working across software platforms with results in Fig. 1.

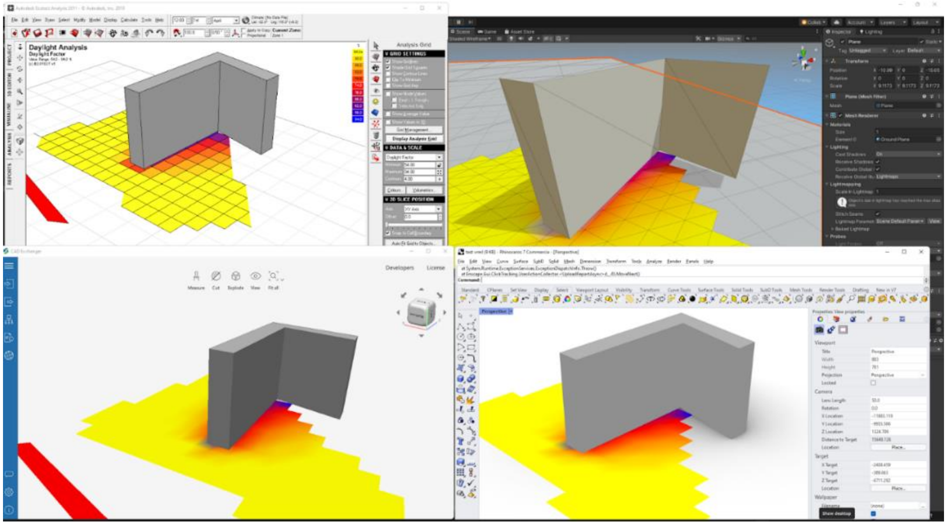

Fig. 1: Visually consistent workflow between Ecotect, CAD exchanger, Rhinoceros and Unity

Amongst several file exchange formats tested including VRML, DWG, CSV, PNG and more, the OBJ, DAE and FBX provide the best visual geometric consistency towards the best performance. File size was not a significant factor that contributed to performance however, the number of faces in the geometry directly affected game performance. We discussed game performance optimization in a later section of this paper also using strategies from a previous VR game development research (Anifowose et al., 2022). To improve understanding, it is important to present the energy simulation using the most visually accurate methods outside the simulation software. Results in Fig. 2 show the most visually appealing workflow for superimposed vertex colors by -

1. Ecotect > VRML > CAD Exchanger > 3DM > Rhinoceros > FBX > Unity.
2. SketchUp + Sunhours > FBX > CAD Exchanger > 3DM > Rhinoceros > FBX > Unity.

Since Ecotect has been discontinued, the SketchUp + Sunhours plugin combination provide the most desired visual result for daylight analysis. The CAD Exchanger software in 3DM export format provided the best model translation input and output for visual consistency between both workflows. Even though the fastest workflow is the direct FBX export from Sketchup to Unity 3D approach, it resulted in more manual work through Substance Painter. Imported geometry exhibited pixelated surfaces when shader materials are applied in Unity 3D. This breaks user experience within VR due to overlapping pixels causing a potential to increase VR sickness.

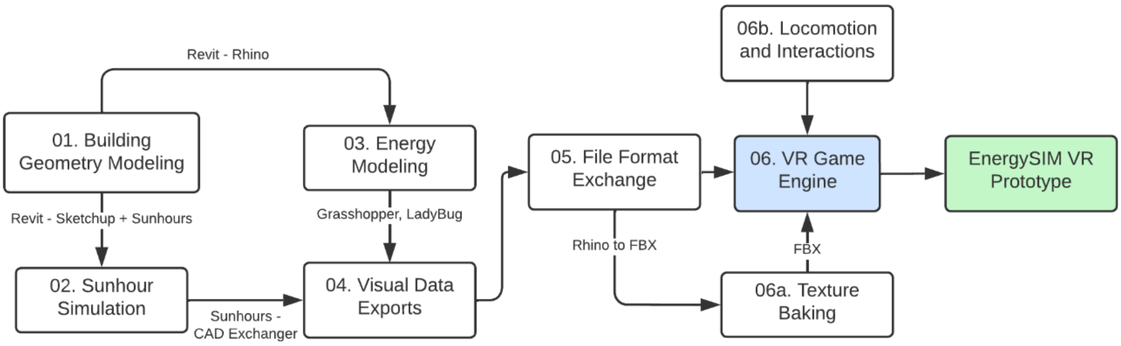

Fig. 2: EnergySIM file exchange recommended workflow

3.2.2 Visual optimization and Results

The results demonstrate visual consistency throughout the workflow. This was developed further into a second phase where building energy consumption is visualized via the use of indoor temperature mapping. To retain the geometry's best visual appearance, vertex shading strategies were developed via the game engine software with snippet code shown in Fig. 3.

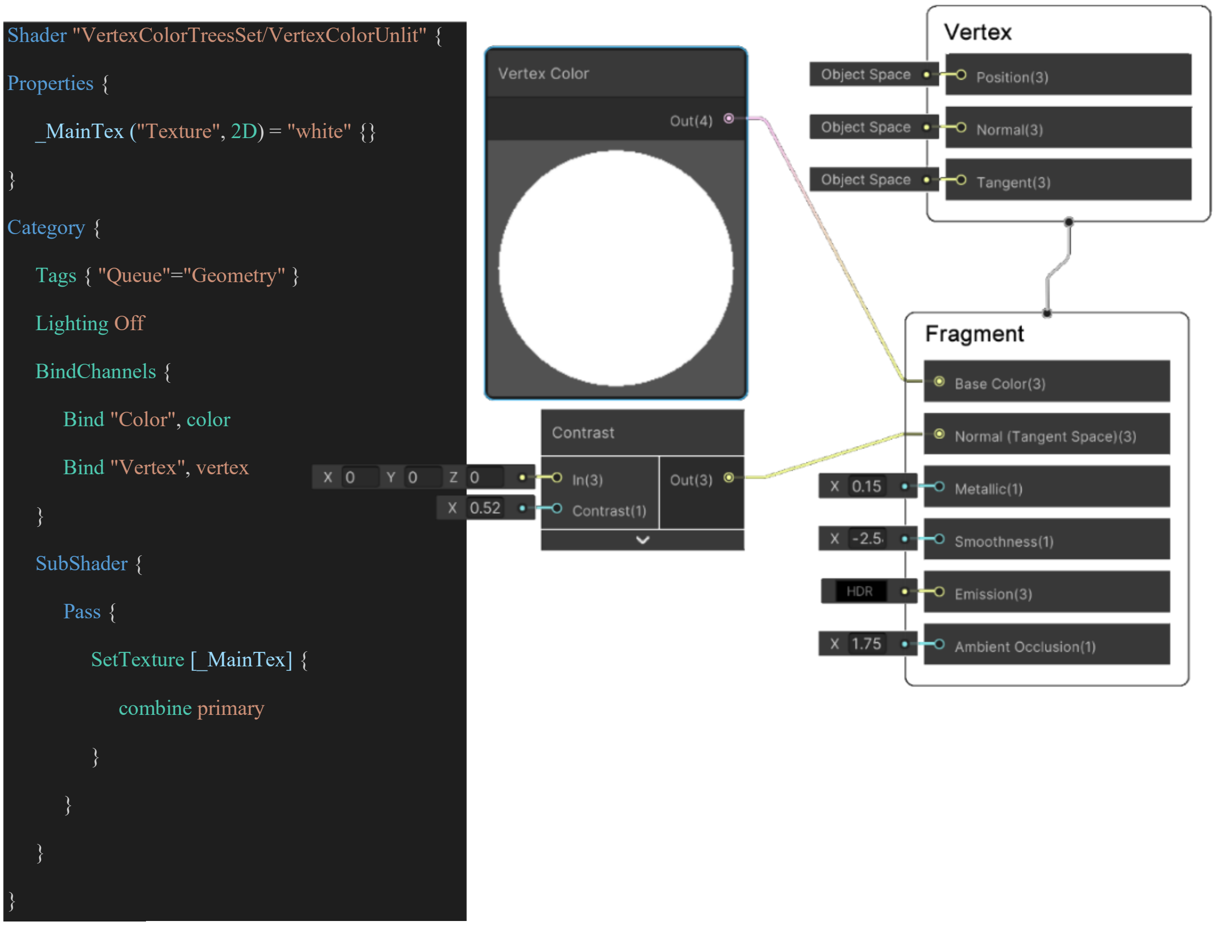

Fig. 3: Shadergraph custom script in Unity for Vertex Shading

For best results, we selected all nine (9) tools used in the entire process and compared them based on eight (8) different factors of varying strengths and weaknesses resulting in a 56-box matrix. This comparison matrix shown in Fig. 4 is generated from weighted factors with ratings between 0 (not applicable) to 3 (most recommended). Although these software/tools have different functionalities, their overall rating indicates their significance to the entire development process and results. Following rigorous testing evident in Fig. 5, we suggest the best tools based on factors such as price, geometry modeling, learning curve, energy simulation, visual data export, file format compatibility, texture mapping, game development and interaction.

	Revit + Insight	SketchUp + Sunhours	SketchUp + Sefaira	Autodesk Formit	Ecotect	CAD Exchanger	Substance Painter	Rhino + Ladybug	Unity + Oculus XR
Price	High	Low	High	Medium	N/A	High	High	Medium	Low
	1	3	1	2	0	1	1	2	3
Geometry Modeling	Fastest	Faster	N/A	Faster	N/A	N/A	N/A	Fast	N/A
	3	2	0	2	0	0	0	1	0
Learning Curve	High	Low	Medium	Medium	High	Low	High	Medium	High
	1	3	2	2	1	3	1	2	1
Energy Simulation	Best	Better	Best	Good	Best	N/A	N/A	Better	N/A
	3	2	3	1	3	0	0	2	0
Visual Data Export	Unusable	Better	Good	Unusable	Better	Best	Good	Better	N/A
	0	2	1	0	2	3	1	2	0
File Format Compatibility	FBX, DWG, CSV	OBJ, FBX	N/A	Unusable	VRML, 3DS	FBX, DAE, 3DM	FBX, PNG	FBX	OBJ, FBX
	0	3	0	0	2	3	2	3	3
Texture Mapping	N/A	N/A	N/A	N/A	N/A	N/A	Best	N/A	Best
	0	0	0	0	0	0	3	0	3
Game Dev + Interaction	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Best
	0	0	0	0	0	0	0	0	3
Contribution Scale	8	15	7	7	8	10	8	12	13
Final Comments	Choice for Modeling	Choice for Versatility	Fair Alternative	Poor for Visual Data	Best Visual Data Export	Best for File Conversions	Best for Texture Bake	Best Energy Analysis	Best for VR Development

Rating Scale Legend

0	Not Applicable
1	Least Preferred
2	Can Be Considered
3	Most Recommended

Fig. 4: Software/Tools Comparison Matrix showing recommended features

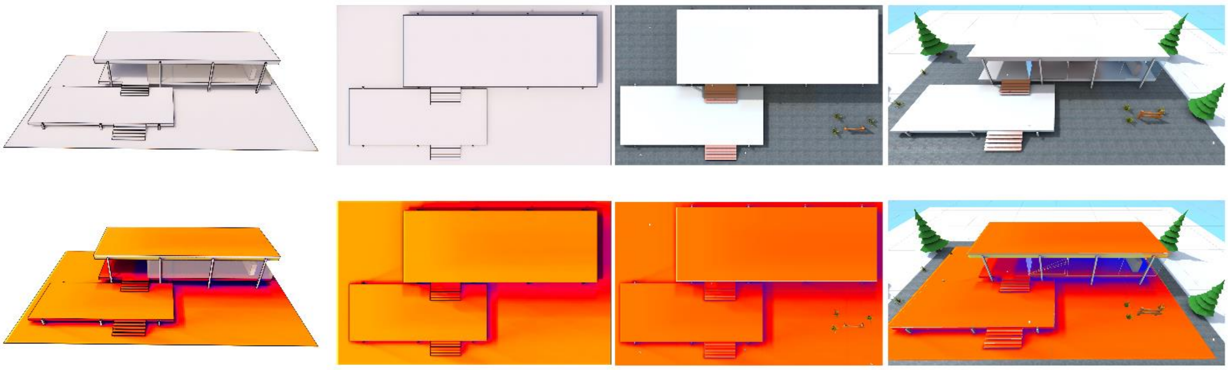

Fig. 5: Result of workflow for visually consistent shading through the workflow

3.2.3 Workflow and challenges – Phase 2

To further test the results from Phase 1, we established new objectives to visually represent the embodied energy within the building using heat transfer coefficients of various materials. When various materials are selected, a user within the VR environment can see the visual changes in heating and cooling loads based on heat sources (the sun), lighting sources or aperture/opening sizes based on the insulation material characteristics.

Since there was no direct access to the building document, assumptions were made. The existing space was assumed to have a single non-reflective glazed exterior wall with an R-value of 0.144 m²K/W (0.82 Ft²·°F·h/BTU) and a 55% Solar heat gain coefficient (SHGC), a cast in site uninsulated concrete floor with an R-value of 0.132 m²K/W (0.749 Ft²·°F·h/BTU), and a concrete roof with m²K/W (32.337 Ft²·°F·h/BTU) R-value. Users are given the opportunity to engage with the EnergySIM and change the construction materials and assembly of the north wall by selecting from among four different types of building materials that each have a unique R-value. One kind of outside wall glazing has an R-value of 0.0399 m2K/W (0.227 Ft²·°F·h/BTU) and a SHGC of 55%. A pair of wooden exterior walls, one with an R-value of 1.995 m²K/W (11.329 Ft²·°F·h/BTU) and the other with an R-value of 4.989 m²K/W (28.329 Fto2F.h/BTU). The final wall assembly consists of an uninsulated concrete wall that is 8 inches thick and has R-value of 0.088 m²K/W (0.499 Ft²·°F·h/BTU).There are a total of five situations based on the findings of the energy simulations, one of which is the current state (single glazing) and four others involving different wall assemblies seen in Fig. 6.

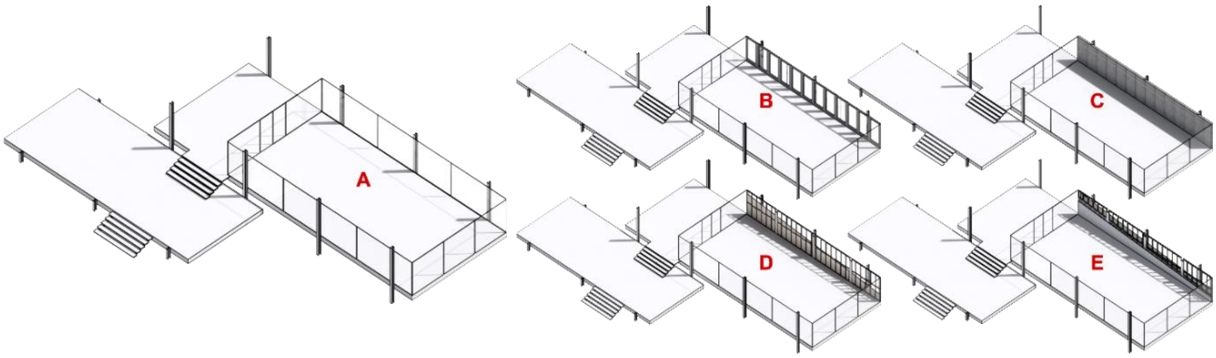

Fig. 6: Five Wall Material Variations for energy simulations (a) Single Glazing (b) High Performance Glazing (c) Uninsulated concrete wall (d) Wood Framed Wall R 12 (e) Wood Framed Wall R 28

These configurations were setup in the energy model and generated in Rhinoceros 3D when the representational building geometry model was complete. We ensured that the geometrical roles of the EnergyPlus simulation engine was considered. The EnergySIM prototype uses the simulation engines EnergyPlus and Radiance for the entire simulation type. The Grasshopper platform, which is a plugin for Rhinoceros 3D that enables algorithmic modeling, makes it possible for third-party developers to create a broad variety of helpful extensions. The simulations of the energy usage and customized thermal maps have been carried out with the help of the Ladybug Tools plugin as seen in Fig. 9, Fig. 8 and Fig. 7. Ladybug's energy simulation is powered by EnergyPlus, while its spatial analysis is a joint effort by the EnergyPlus and Radiance simulation engines. The Ladybug spatial thermal map simulation combines three spatial thermal map simulation techniques (Arens et al., 2015; Menchaca Brandan, 2012; Webb, 2012). Comparing the Ladybug simulation approach to ENVI-met software and field data, this method has been tested and displays a satisfactory range of consistency (Hongtao & Wenjia, 2018; Ibrahim, Kershaw, & Shepherd, 2020). EnergySIM provided simulations for various scenarios.

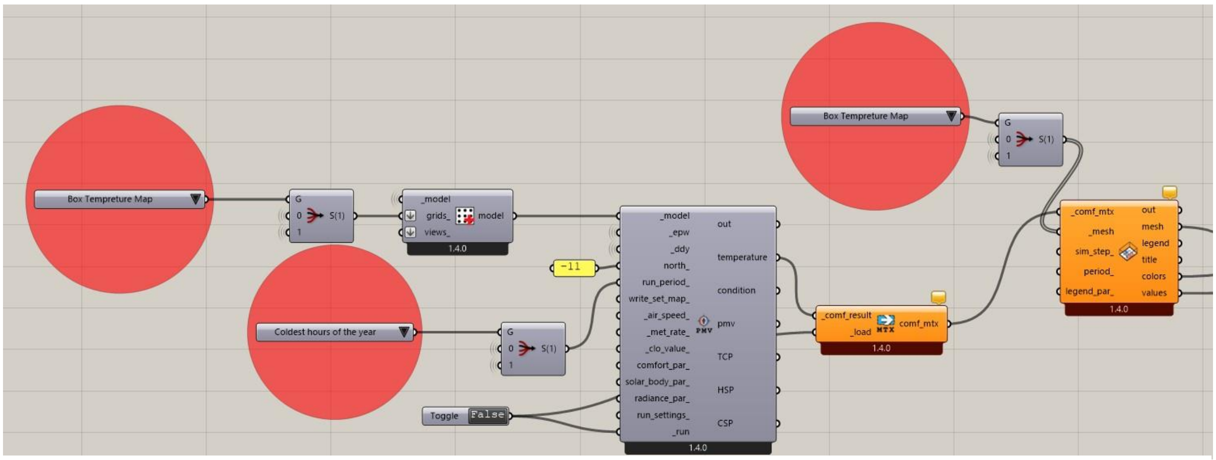

Fig. 9: Indoor temperature box map script for different seasons.

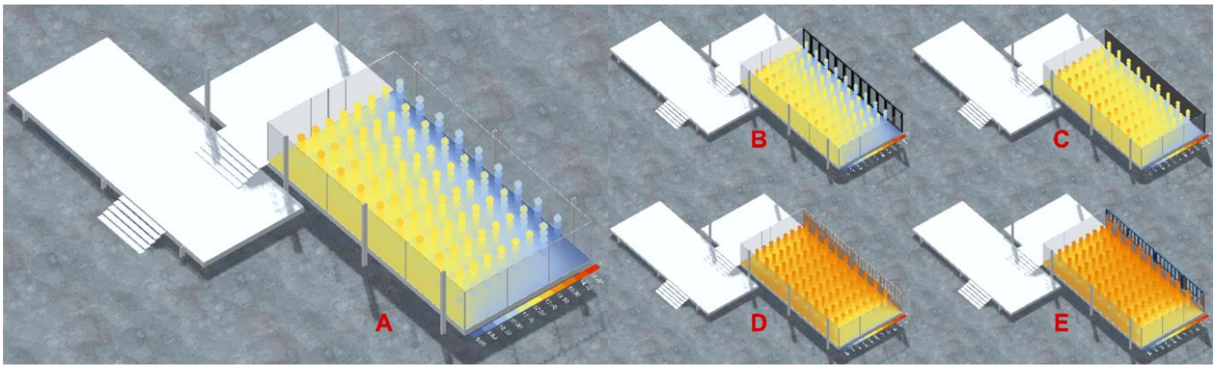

Fig. 8: Winter Box Map – (A) Single Glazing (B) Double Glazing (c) Concrete (D) Wood R12 (E) Wood R28

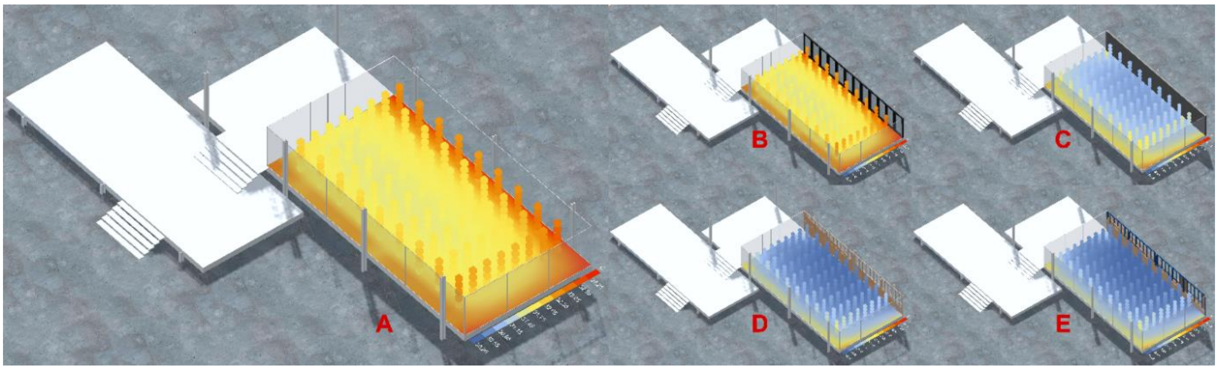

Fig. 7: Summer Box Map – (A) Single Glazing (B) Double Glazing (c) Concrete (D) Wood R12 (E) Wood R28

Total annual building energy use is calculated using data from the University of Illinois-Willard Airport EnergyPlus weather station, one of the closest to the site. According to the weather data collected by EnergyPlus, the hottest and coldest days of the year occur during the summer and winter simulation periods, respectively (EnergyPlus). Time in the summer is on the 13th of July at 3:00 PM, while time in the winter is on the 3rd of February at 7:00 AM. The interior wall temperatures, which are the wall surfaces of the interior layer, have been represented by simple single surfaces that overlay the building model. The Vertical interior temperature maps are formed by stacking 450 sensors in a vertical orientation to create a single surface. The boxes interior temperature maps are a collection of 360 sensors uniformly arranged around the buildings, with one box representing each sensor. Several other kinds of charts and graphs are used to illustrate the annual cooling and heating loads, as well as the total annual energy usage.

3.2.4 Scene Exploration and Interactions

EnergySIM is developed to enable more than one person co-experience the simulation results: a typical student and professor classroom scenario. This prototype is designed putting accessibility into consideration therefore allowing users to complete the experience in either sitting or standing positions. Although both hands can be used, it can equally be completed with only a single hand. For the Users, we segmented the VR learning experience into three strategies as shown below -

1. Exploration - A 1:1 full scale Farnsworth House model. This is provided for exploration with super-imposed simulation results from the 4 seasons and the indoor temperature maps perceived in full scale in its original material configuration (glazing, steel, concrete). This section enables users to familiarize themselves with the building in its full-scale form and understand how the components are geometrically related i.e. floor, wall/glazing, ceiling/roof. This approach provided realism and spatial perception of building scale towards the experience.
2. Miniature Model manipulation - A collection of 1:25 scale handy miniature models, allowing virtual manipulation of the simulations with varying seasons. This enables users to study the geometric form and its relationship to solar heat gain at a granular level. This approach provided grab and translation (moving 7 rotation) techniques thereby increasing tactile feedback, and perception of scale at object level, all which are essential factors which were previously documented to contribute to design learning (Anifowose et al., 2022).
3. Menu-driven Material Configuration - A non-movable 1:10 scale Farnsworth House is provided with a corresponding user interface. The interaction level features users configuring various types of materials showcasing building heating and cooling load changes based on the selected materials' R-values in Fig. 10. Users are asked to manipulate the values in the menu based on input using a pair of VR controllers. Depending on the combination or selections (season and construction material), the corresponding pre-simulated result is displayed in the 1:10 scale model alongside corresponding temperature scale.

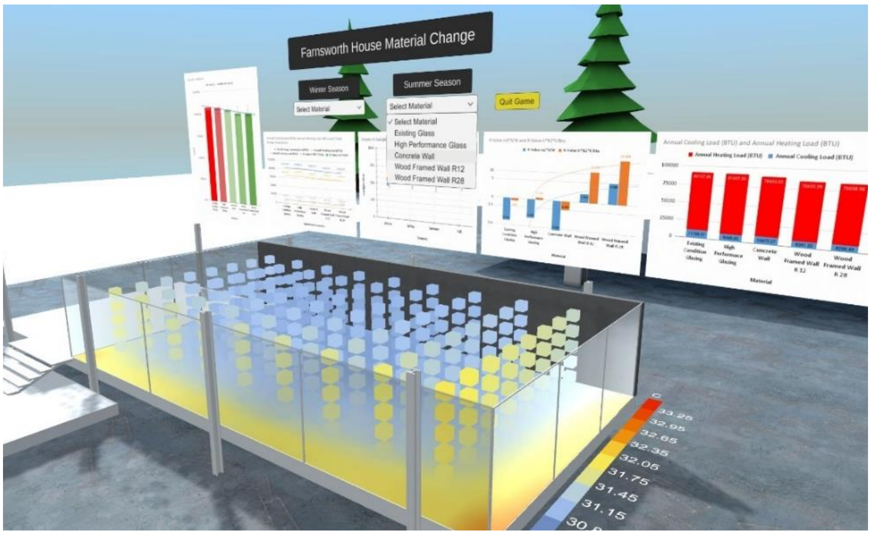

Fig. 10: In-game image showing menu and material comparison charts

These three strategies allow a wholistic experience for a wide range of users who may approach the experience with various learning strategies. Although this research did not consider comparing which strategy provided users with the highest learning impact, it may be studied in the future.

3.2.5 Performance Optimization and Improved Results

To ensure consistent game performance and frames per second (FPS) delivery, game optimization strategies were employed by merging meshes and materials to reduce draw calls on hardware resources. Plugins used to achieve these include the Mesh Combiner Script and Pro Materials Combiner. The best strategy to avoid errors require placing and retain geometry integrity require placing sub-meshes under the same parents before a merge command is executed. Turning off cast shadows if hardware resource is limited and assigning blend probes for light probes is equally proven to be best practice. This approach is confirmed to drastically reduce computation time for mesh combinations.

3.3 Demonstration results

The overall Virtual Reality experience was developed using the Oculus XR framework inside Unity (Unity, 2021) and tested using the Meta Quest 2 VR Headset. Feedback received from trial runs with a high school education content administrator and other researchers revealed that the prototype provides an entry level opportunity for students to learn about the fundamentals of building energy simulation in VR environment. A demonstration of the prototype is available in this link https://youtu.be/nV9YBI1-qYM and as shown in Fig. 11.

Fig. 11: Photographs from demonstration and feedback session

4. Discussion

4.1 Virtual Reality Validation & Future Works

This study demonstrated the potential of an Energy Simulation VR prototype development towards higher visual fidelity and improved learning outcomes. The system provides an interactive environment for learning how the Farnsworth House (case study), responds to daylighting and energy consumption across various seasons and four material scenarios: single glazing, double glazing, concrete walls, and wood construction for interior atmospheric temperature mapping. This study combined geometry optimization techniques, menu driven interactions and miniature model manipulation, with the aim of testing user understanding and knowledge retention regarding building energy usage. Although not gamified, the future objective is to make the prototype a game experience with a goal of impacting learning in high school students who have interests in building design courses at university level. The EnergySIM VR prototype pushes the boundaries of visual fidelity in simulations showing recommended tools and methods for best visual impact towards learning. The provided workflow is optimized for educational VR application developers, instructors, and design students. EnergySIM achieved the simplification of teaching advanced level building energy response, down to an enjoyable, visual yet impactful rudimentary level.

4.2 Limitations of Study

As seen in (Sidani et al., 2021), Most BIM-to-VR applications are composed of four layers; a BIM tool, a game engine, visual enhancement module and a non-geometric database component. This study did not take into cognizance, the possibility of exporting data associated with the geometries which is the 4^{th} component. Researchers must know that including data visualization performance strategies required for game optimization if data visualization is included in this workflow, may be more rigorous. It is also worthy of mention that none of the simulation texturing was baked since they are dynamic components in the scenes. Only static components such as the main building and surrounding environments were texture baked (using Substance Painter). All dynamic components and simulations are shaded vertices which received real-time lighting, shading and reflection.

4.3 Funding Sources

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