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ENERGYSIM: TECHNIQUES FOR ADVANCING BUILDING ENERGY EDUCATION THROUGH IMMERSIVE VIRTUAL REALITY (VR) SIMULATION

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SUMMARY: *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 their 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 for education is difficult due to the knowledge, skill, and performance resource-related gaps. Unoptimized VR applications can adversely impact learning if user experiences are broken due to performance lags. This research, therefore, explores VR as a teaching tool for building energy education while showcasing the development process toward a visually accurate simulation and performant application. 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 heatmaps 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). The significance of this work lies in its potential to revolutionize how students, designers, and instructors approach building energy education in today's world. EnergySIM provides a hands-on and visually engaging learning experience towards the enhancement of knowledge retention and understanding. It pushes the boundaries of development for 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*

REFERENCE: *Hassan Anifowose, Kifah Alhazzaa, Manish Dixit (2023). ENERGYSIM: techniques for advancing building energy education through immersive virtual reality (VR) simulation. Journal of Information Technology in Construction (ITcon), Special issue: 'The future of construction in the context of digital transformation (CONVR 2022)', Vol. 28, pg. 539-554, DOI: 10.36680/j.itcon.2023.028*

1. INTRODUCTION

There is 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 et al., 2014).

On a macro level, designers need to be educated on the impact of building geometry, orientation, and choices of construction materials on energy consumption with respect to climate change and sustainability. Industrialized countries' energy-related carbon emissions constitute thirty-six percent of their total emissions (Metz et al., 2007). The demand for energy is growing at a very rapid rate due to the rising standard of living and population (Hafeznia et al., 2017). 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 et al., 2016).

The complexity of energy simulation principles makes the subject very challenging to understand even to design education students. 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 et al., 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. It, therefore, becomes crucial to research the possibility of enhancing learning in design education by the exploration of teaching techniques that new technologies offer. This provides motivation for the development of EnergySIM in the attempt to help learners combine visual, auditory, and kinesthetic learning modalities.

Immersive Virtual Reality (VR) experiences allow learners to embody their presence in simulated environments. This level of immersion helps learners better understand complex concepts such as building energy simulations. This can help reduce misinterpretations of conventionally presented energy data. Computer screens and building energy software do not provide this high level of immersion where users can experience improved spatial understanding, visualize accurate geometric representation in terms of scale, and better interpret spatial relationships of objects to one another. VR provides a powerful way of energy visualization that is effective and easy to grasp; providing an easier pathway for design education. This paper offers a step-by-step approach toward the development of a VR application which is aimed at simplifying the learning curve of complex subjects.

1.1 VR in Architectural Education

Remote learning was widely used when the world was fighting a pandemic, and BIM + VR gave a foundation for creating remote learning situations for architecture students. For students in architectural education and their institutions, visiting architectural predecessors is expensive. Additionally, because local visits lack layers of involvement (Kharvari & Höhl, 2019), the memory of learning objectives often differs between students depending on several additional factors. The research also suggests that, in a gaming setting, VR enhances spatial memory and recall of such virtual worlds of architectural predecessors. However, there is little data on how reproducing such precedents can enhance learning results, thus further research is needed to firmly establish this.

Bourdakis contends that constructing spaces in virtual worlds naturally turns into an architectural difficulty and that design itself is a problem in architectural education (Bourdakis & Charitos, 1999). The study made clear the necessity of changing the course of architectural education to produce a new generation of virtual environment architects.

There are few programs in architecture schools nowadays that teach students how to design in virtual environments (VE). This is a potential opportunity to expand the use of VEs by exploring architectural education and the design of spaces all within VEs.

According to Kamath, it has been demonstrated that pushing VE learning further in tutored settings "benefits young architects on their initial step towards comprehending the essence of architecture" (Kamath et al., 2012). Availability of talent is now a barrier to the creation of content for augmented reality (AR) and virtual reality (VR). A special set of abilities is needed for development, including proficiency in 3-D modeling and rendering, video knowledge, problem-solving, interaction design, storytelling, and user experience design. The specialty skill pool experiences a retention issue as a result (Cacho-Elizondo et al., 2018).

1.2 VR in Construction Education

Teaching methods place significant restrictions on how building composition is studied in construction education classrooms. This inspires our study concept to use BIM and a virtual building lab environment to give students a platform to apply their knowledge and abilities to address education challenges in the real world. However, many configurations for such environments need to be tested to see which one offers flexibility and enhances learning (Ghosh, 2012). Ghosh considered the design of an experimental space that examines participation in a virtual learning environment. 3D game-based VR continuously shows that it supports learning especially in Construction Engineering Education and Training (CEET). These new technologies continue to alter instruction from being teacher-centered to student-centered (Wang et al., 2018).

According to Goedert, the gamification of construction learning is one way to continually engage the younger generation (Generation Y) in the construction sector who find it challenging to engage with conventional educational techniques (Goedert et al., 2011). This paves the way for the investigation of interactive virtual construction education with the intention of reducing dangers associated with repetitive construction. Scaling up gamification systems can offer instruction and training to a larger population of students and workers who study equipment and construction scheduling, based on a simulated environment that is designed to reflect the real-world scenarios (Goedert et al., 2011). One benefit of VR in construction education is that it allows students to access materials used to teach courses repeatedly while teachers can continuously enhance such materials over time (Shiratuddin & Sulbaran, 2006). The technology shown by Immersive Learning in a Virtual Reality Environment (ILVRE) study, improved students' capacity to have a high degree of control over learning speed and navigation via VR environments in addition to the chance to interact with models within a 3D virtual construction site. This background provides motivation for the EnergySIM development and study.

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 et al., 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 et al., 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 Proven 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 et al., 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 et al., 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. Architectural design students tend to be highly visually inclined to learning (Demirkan, 2016; Mostafa & Mostafa, 2010) therefore, we are proposing a more defined approach to showcasing building energy simulation with a focus on visual and interactive development.

2.3 BIM+LOD – Farnsworth House

By showing off the investigation of architectural precedents and duplicating the assembly of the same with various game difficulty levels that correlate with various BIM levels of development, we evaluated the gamification hypothesis in a game design presentation in virtual reality (LODs). Students were among the participants, and they were asked to show it and talk about how using a gamified approach to teaching architecture may help with content creation and implementation. The Farnsworth House was utilized for this investigation.

This idea was demonstrated in an earlier VR game design, by demonstrating the investigation of architectural predecessors and duplicating the assembly of the same with varied BIM levels of development (LODs). The abstract concept addition for the architectural antecedent, according to the demonstrators' feedback, improved their knowledge after the exploration and made the assemblage process easier. Snap features helped to increase interactivity and interest during the game's assembly phase. The demonstration revealed the potential for raising learning goals in an ongoing gamified construction assemblage research.

The inability to create custom scripts and the difficulties in retaining all geometry data in BIM files migrated to Unity game engine were limitations encountered during the game's development. The development of mechanics to prevent users from creating an excessive number of items inside the game presented more difficulties.

The study revealed that adding specialized VR game features during assembly and creating geometric abstract concepts for game material may be instrumental to students' increased understanding of architectural precedents. It has been demonstrated in our ongoing gamification study that these characteristics boost users' confidence for comparable activities in real-world assemblies. These features also resulted in increased intuition levels in users as they interacted with the components during assembly which also contributed to their ability to finish the tasks. An object spawning and object destruction system is important for game optimization which reduces the need to consistently keep large files present in the game scenes. The experiment's findings showed that including abstract notions in places more than just building geometry improves memory and knowledge retention. During the exploration stage, players also reported a deeper understanding, based on the in-game audio and video commentary.

2.4 BIM+VR Construction Lab

A VR Construction Lab prototype which is a spinoff of the BIM+LOD prototype was developed in a related study. This enables a VR user to explore game levels where they assemble various construction components in accordance with predefined game rules. In timed exercises, this prototype investigated a player's capacity to put together previously examined construction assemblages. Users are shown in-depth representations of components that have been prepared at various stages of development. To give higher degrees of authenticity to simulate a physical construction environment, the virtual construction lab studies novel techniques for BIM object integration along with scene population, texturing, and lighting to enhance player performance (Anifowose et al., 2022). The player is allowed to study a pre-assembled wall. Thereafter they are provided with a set of geometric objects which are replicas of the studied materials. They can create more objects by hand-to-object collision gestures, also known as object spawning, and object placement features including gentle snap-into-place. Translucent shaders are used to highlight specific areas of the work to make it simple to finish and maintain the player's motivation. Object interaction and manipulation techniques from the VR construction lab study are adopted for further development in this study.

2.5 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 was 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 was 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 et al., 2015).

3. METHOD

EnergySIM presents pre-simulated building exterior surface sun hour 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 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 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 fidelity 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 fidelity 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 fidelity.

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 real-time data 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 fidelity 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.

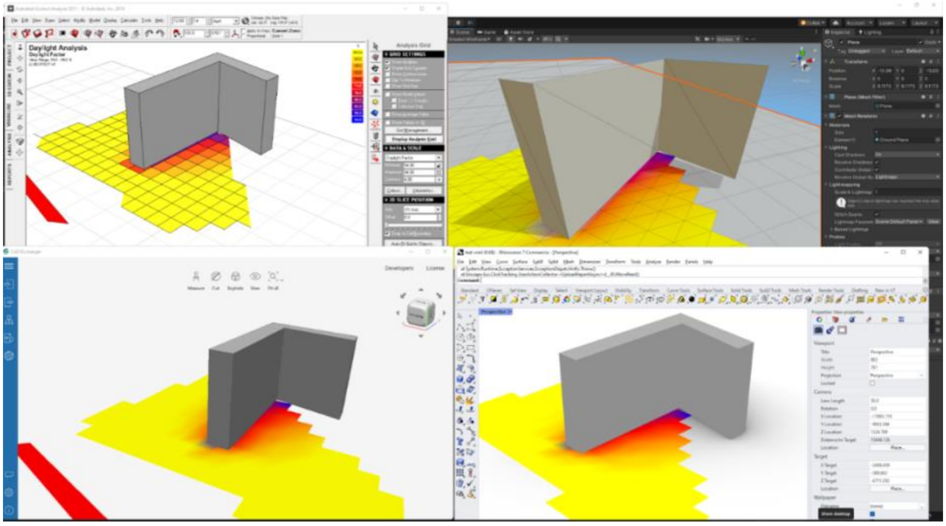

FIG. 1: Visually consistent workflow between Ecotect, CAD exchanger, Rhinoceros and Unity

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. The recommended optimized workflow is shown in FIG. 2.

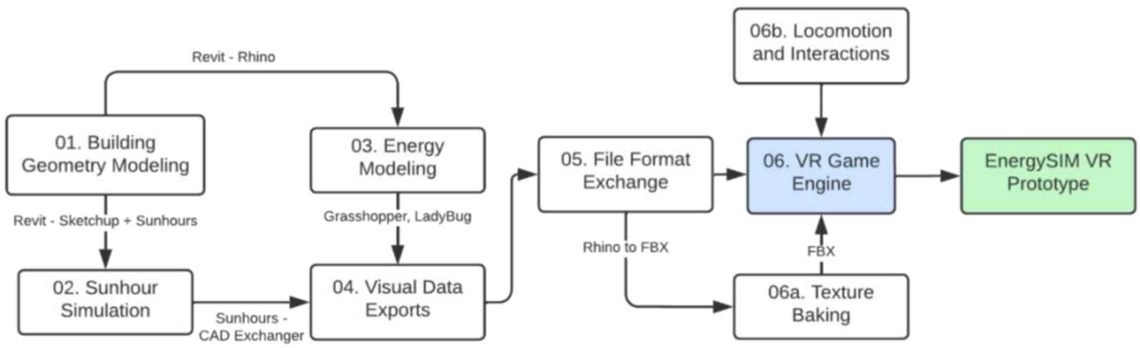

FIG. 2: EnergySIM file exchange recommended optimized workflow.

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. Prior to the development of the vertex shading technique, the application suffered from poor frames per second (FPS) performance causing discomfort to players due to the numerous rendered faces and vertices. Unlike surface shading, vertex shading improved the game performance by 45%.

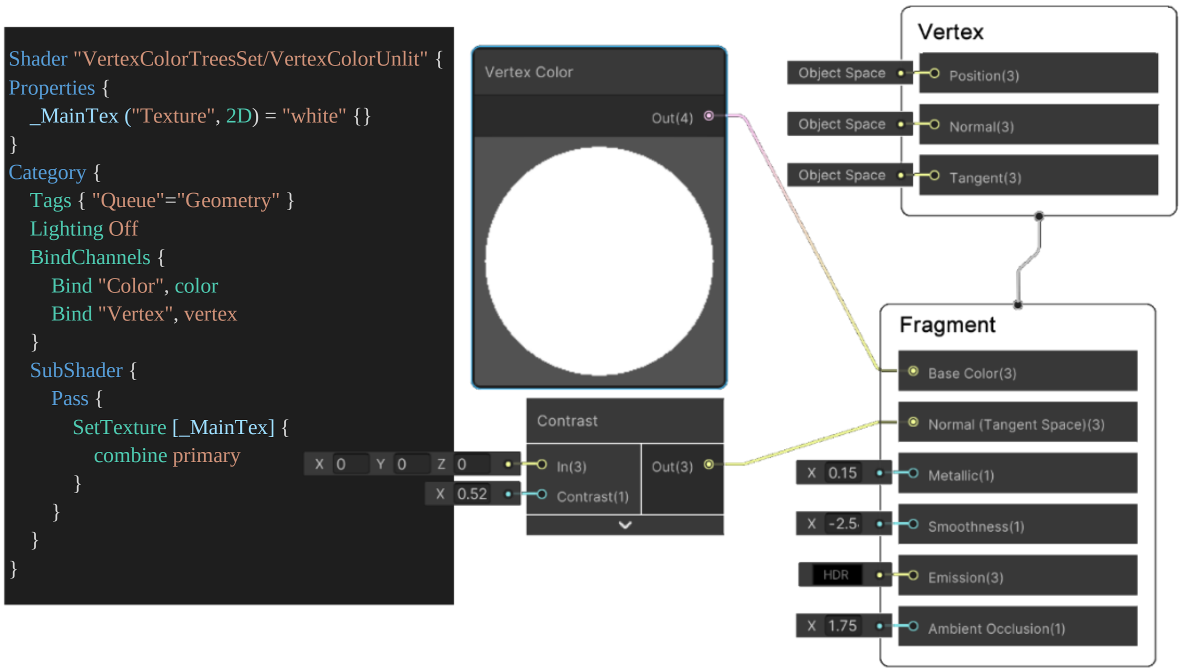

FIG. 3: Shadergraph custom script in Unity for Optimized Vertex Shading

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 chosen metrics i.e. price, geometry modeling, learning curve, energy simulation, visual data export, file format compatibility, texture mapping, game development and interaction. This comparison guide is aimed at helping developers select applications based on their expected development outcome and available resources. Results may vary in individual cases however, this guide shows our most recommended tool(s) in order of preference, measured across each metric.

	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

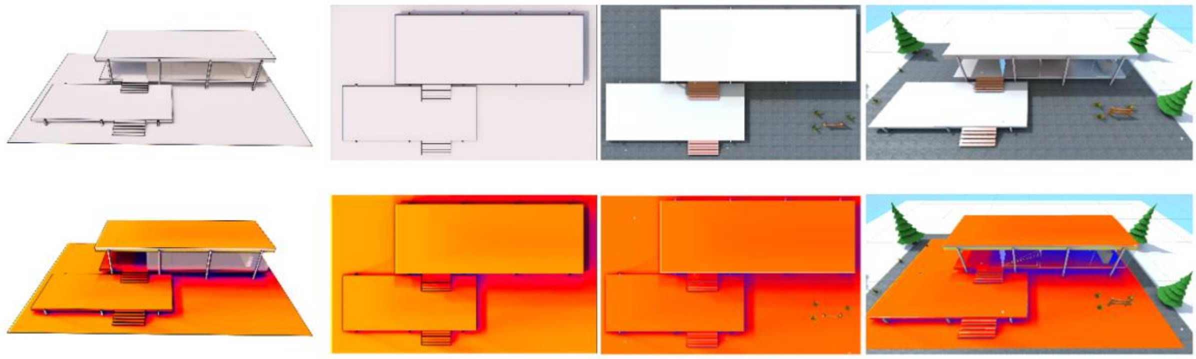

FIG. 5: Result of visually consistent shading through the workflow

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 m^2K/W (0.82 $Ft^2 \cdot °F \cdot h/BTU$) and a 55% Solar heat gain coefficient (SHGC), a cast in site uninsulated concrete floor with an R-value of 0.132 m^2K/W (0.749 $Ft^2 \cdot °F \cdot h/BTU$), and a concrete roof with m^2K/W (32.337 $Ft^2 \cdot °F \cdot h/BTU$) 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 $Ft^2 \cdot °F \cdot h/BTU$) and a SHGC of 55%. A pair of wooden exterior walls, one with an R-value of 1.995 m^2K/W (11.329 $Ft^2 \cdot °F \cdot h/BTU$) and the other with an R-value of 4.989 m^2K/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 m^2K/W (0.499 $Ft^2 \cdot °F \cdot h/BTU$).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.

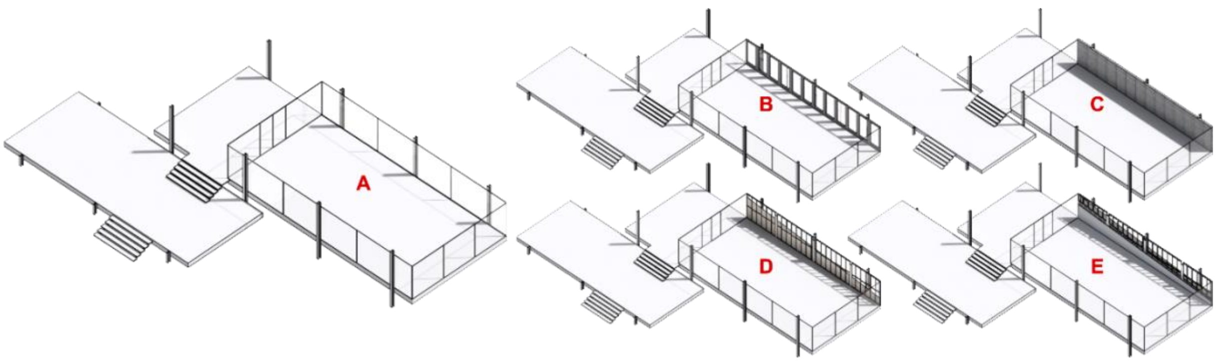

FIG. 6: Five Wall Material Variations for energy simulations (a) Single Glazing (b) High Performance Glazing (c) Uninsulated concrete wall (d) Wood Framed Wall R 12 (e) Wood Framed Wall R 28

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. 7*, *FIG. 8*, and FIG. 9. 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). 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 et al., 2020). EnergySIM provided simulations for various scenarios shown.

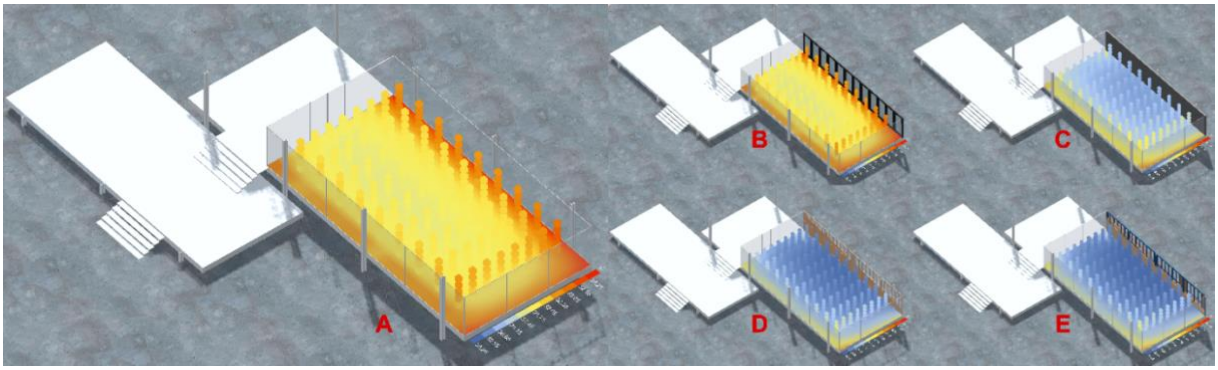

FIG. 7: Summer Box Map – (A) Single Glazing (B) Double Glazing (c) Concrete (D) Wood R12 (E) Wood R28

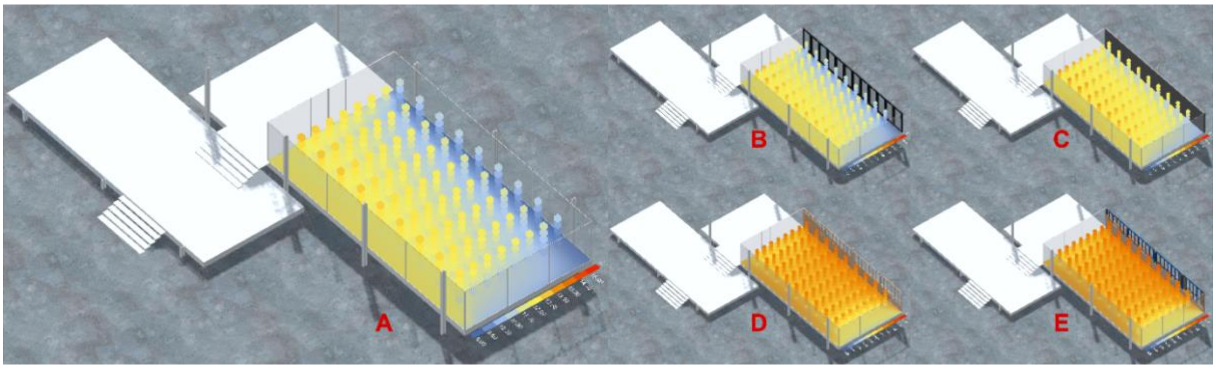

FIG. 8: Winter Box Map – (A) Single Glazing (B) Double Glazing (c) Concrete (D) Wood R12 (E) Wood R28

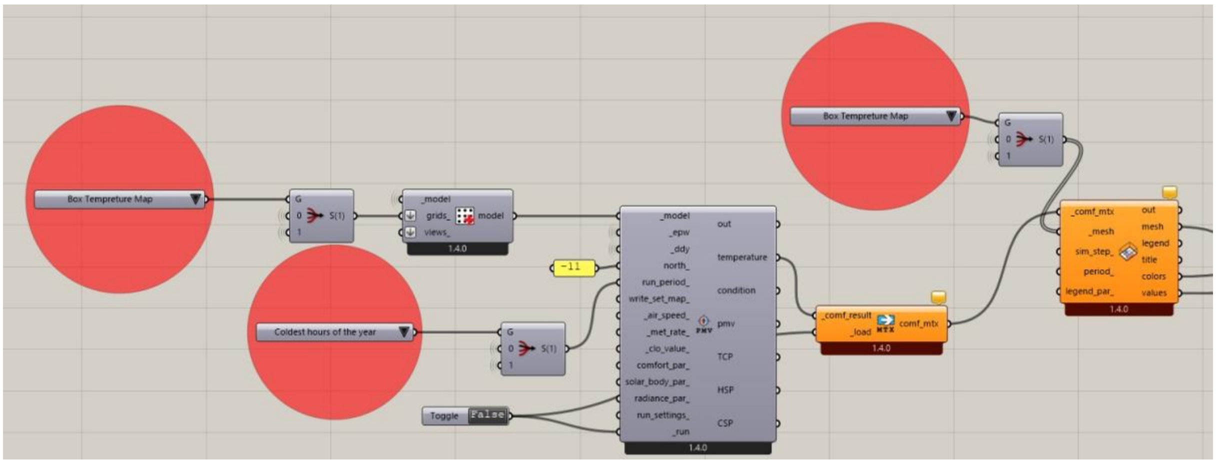

FIG. 9: Indoor temperature box map script for different seasons.

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.

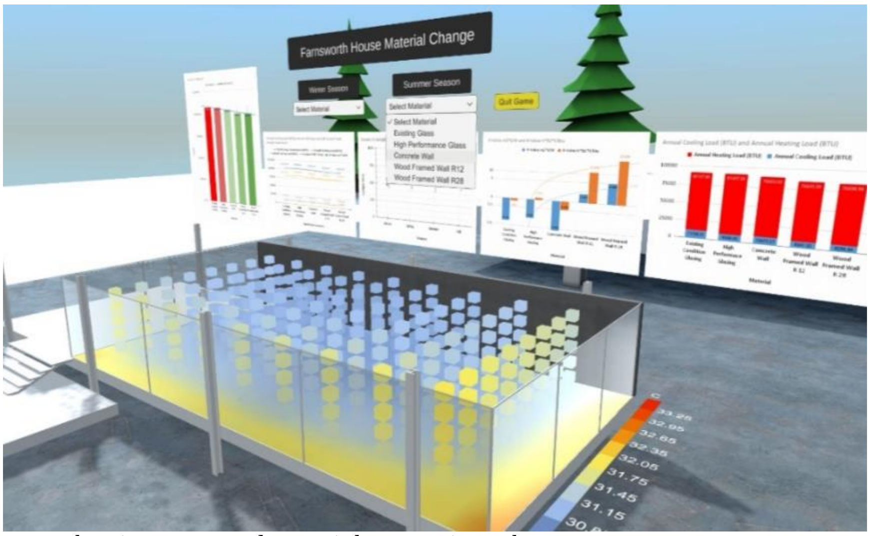

FIG. 10: In-game image showing menu and material comparison charts

The material comparison charts are provided for improved user understanding. When a user selects a specific material, the corresponding heatmap is loaded and every other heatmap is temporarily destroyed. This aimed to provide deep visual understanding of the building's specific heating or cooling state based on the selected material. The average internal temperature is also displayed in a corresponding vertical map on the side of the building which gives an idea of how hot or cold an area is. As show in the image, areas around the glazing appear warmer than the innermost sections.

These three strategies allow a wholistic experience for a wide range of users who may approach the experience with various learning strategies. Although this study did not compare which strategy provided users with the highest learning impact, that question is currently being investigated in another research.

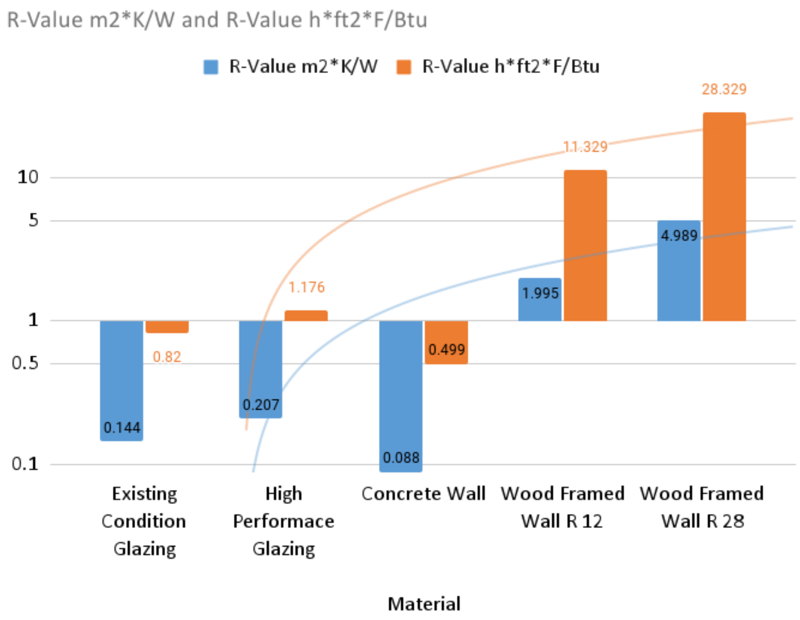

FIG. 11: Chart showing differences in material R-value

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. 12.

FIG. 12: 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. In this study, rigorously tested workflows are documented with a focus on the improvement of VR game performance, interaction of users and increased visual fidelity which are three key factors that are responsible for positive knowledge retention in users. The most optimized development workflows are shown and the demonstration impact on users has clearly answered the questions, indicating that user understanding is improved by the documented methods of interaction and miniature model manipulation. Users also showed improved understanding of the varying requirements of heating and cooling loads based on material changes from glazing, to concrete and then wood with varying R-values.

Although the development or impact of in-game audio narration is not a key component of this study, it is worthy to mention that an audio narrative of the game experience was included to allow users have preliminary understanding of the building's background, history, needs and required tasks in the VR experience. The EnergySIM introduction level welcomes the students by providing an audio narration of the history of the Farnsworth House and the building materials/features vis-à-vis heat and energy consumption and requirements. The audio component played a role in helping users with varying preferences for learning touchpoints, adjust to a virtual learning environment devoid of a physical instructor.

This study combined geometry optimization techniques, menu driven interactions and miniature model manipulation, while at the same time, 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. If researchers plan to include data visualization in their workflow, they should be aware that optimizing game performance may require additional strategies. We hypothesize that the inclusion of real-time data visualization may provide deeper immersion however, developers can expect longer development times and, significant drop in performance based on the high amount of computation required per changed variable such as material or building orientation relative to the sun's direction. It must be noted that real-time data visualization was not part of this research's objectives. It is also worthy of mention that none of the simulation texturing was baked since they are dynamic geometric components in the scenes (such as concrete wall, glass, and dry wall). Only static components such as the main building and surrounding environments were texture baked (using Substance Painter). All dynamic components and simulations have shaded vertices which received real-time lighting, shading and reflection.

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5. CONCLUSION

This research presents EnergySIM, a novel virtual reality (VR) development workflow which is designed to facilitate the understanding of building energy simulation principles. The complexity of this subject poses a huge challenge for learners which the proposed EnergySIM addresses by offering an immersive and interactive VR experience while also demonstrating a step-by-step approach for development. This paper highlights the need for an optimized workflow and an approach for developers and instructors who seek to simplify complex subjects using VR. The comparison of various software provides easy understanding of expected results depending on the chosen development pathway. Performance optimization techniques are provided in this paper for recommended vertex shading, lighting, and texturing approaches.

Feedback from trials indicates that EnergySIM opens new possibilities for learners in an entry-level platform. This research contributes to the advancement of educational VR applications, paving way for more intuitive and practical applications and approaches to studying the impact of building geometry and the choice of design materials on solar heat gains and energy efficiency or usage.

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