

# Integrating Virtual Reality and Energy Analysis with BIM to Optimize Window-to-Wall Ratio and Building's Orientation for Age-in-Place Design at the Conceptual Stage

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**How to cite this paper:** Rostamiasl, V. and Jrade, A. (2024) Integrating Virtual Reality and Energy Analysis with BIM to Optimize Window-to-Wall Ratio and Building's Orientation for Age-in-Place Design at the Conceptual Stage. *Open Journal of Civil Engineering*, 14, 305-333.  
<https://doi.org/10.4236/ojce.2024.143016>

**Received:** June 20, 2024

**Accepted:** July 26, 2024

**Published:** July 29, 2024

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## Abstract

This study unfolds an innovative approach aiming to address the critical role of building design in global energy consumption, focusing on optimizing the Window-to-Wall Ratio (WWR), since buildings account for approximately 30% of total energy consumed worldwide. The greatest contributors to energy expenditure in buildings are internal artificial lighting and heating and cooling systems. The WWR, determined by the proportion of the building's glazed area to its wall area, is a significant factor influencing energy efficiency and minimizing energy load. This study introduces the development of a semi-automated computer model designed to offer a real-time, interactive simulation environment, fostering improving communication and engagement between designers and owners. The said model serves to optimize both the WWR and building orientation to align with occupants' needs and expectations, subsequently reducing annual energy consumption and enhancing the overall building energy performance. The integrated model incorporates Building Information Modeling (BIM), Virtual Reality (VR), and Energy Analysis tools deployed at the conceptual design stage, allowing for the amalgamation of owners' inputs in the design process and facilitating the creation of more realistic and effective design strategies.

## Keywords

Building Information Modeling (BIM), Virtual Reality (VR), Game Engine, Energy Analysis, Window-to-Wall Ratio, Building Orientation, Computer Integration and Automation

## 1. Introduction

In Canada, the total energy demand, in 2018, was 12,204 petajoules (PJ), where

the building sector accounted for approximately 25% of the energy consumption [1]. Space heating, cooling and lighting are responsible for over 68% of the energy consumed by a building, broken as, 56%, 5% and 7%, respectively [2]. The energy performance of a building is largely impacted by design decisions such as building form, orientation, and window(s) size at the conceptual design stage [3]. Windows can affect the building's total energy consumption in many ways. Zhang and ONG [4] believe that architectural daylighting design is at the heart of sustainable building design. Daylighting, which is the use of natural light in a building, plays a significant role in reducing artificial lighting and can significantly save energy when properly designed and effectively integrated with the electric lighting system. Daylight reduces the electricity needed for artificial lighting systems. Consequently, the amount of cooling demand decreases due to the lower internal load but can cause higher energy use of heating systems during the winter. On the other hand, solar radiation heats the building at all times, especially in the winter, which decreases the heating load. However, it increases the cooling load and consequently increases the energy use of the cooling system in the summer. Heat loss in winter and heat gain in summer due to the conduction of heat transmission through the windows would increase the amount of energy used by the heating and cooling systems to compensate for the corresponding heat loss and gain. Therefore, the building's windows have a crucial role in controlling the energy used for lighting, heating, and cooling and yet highlight the importance of the optimal window-to-wall ratio in buildings [5]. The energy consumed by a building could be reduced by up to 40% without any additional cost by selecting the appropriate building shape, orientation and window size, but unfortunately, the current methods and software used for running energy simulations lack the exchange of information and efficient interoperability between the modelling and energy simulation tools. This is of utmost importance for the architects who are the main players during the conceptual design stage, where adequate data are needed, preferably in the visual format rather than numerical datasets [6]. The divergence between the design tools used to generate the building's geometry and energy analysis is one of the most significant barriers, which are keeping designers from investigating the different design options related to energy performance [6].

A study by Sayadi *et al.*, [5] argues that the total annual energy use, when utilizing the optimal WWR, could be reduced by 50% if compared to the windowless configuration as the natural light can reduce the energy usage of the artificial lights.

BIM, as a revolutionary technology for the Architecture, Engineering, and Construction (AEC) industry, enables the coordination of information such as 3D geometries, materials, building structures, Mechanical, Electrical, and Plumbing (MEP) systems, and schedules for different disciplines during the building's lifecycle. It helps designers assess the building performance early during the design stages to optimize the design parameters such as location, orienta-

tion, glazing ratio and fabric properties [7].

On the other hand, as the aged population rises, new challenges are significantly affecting the design of housing and the living environment. Thus, architects and designers must consider those challenges when adopting new design solutions for the built environment [8]. Aged adults tend to spend considerably more time at their own homes if compared to other age groups because they provide them with their particular physical setting and emotional attractions based on their personal experiences [9]. Therefore, age-friendly built environments have been promoted by the World Health Organization (WHO) under the Global Age-Friendly Cities (AFC) movement [10]. Age in place is described as the creation of a situation where seniors can remain at their homes for a longer time without being forced to move to long-term care facilities [11]. Thus, to improve the capabilities and well-being of seniors and to have effective age-in-place dwellings, the built environments should enhance the opportunities for independence and self-reliance. Multiple design features can improve the physical and mental welfare of both the elderly and young adults [12]. Findings show that the window size has a significant influence on the perceptual impressions of the presented spaces. For instance, large window size leads to a more positive evaluation of how pleasant, interesting, exciting, bright, complex, and spacious the space was perceived, as well as to higher levels of satisfaction with the amount of view [13]. Therefore, as an occupant's comfort is directly related to a range of environmental factors, particularly daylight distribution, glare and indoor air temperature, the need to align the design requirements with environmental issues is important in establishing a well-balanced approach between aesthetics, occupant welfare and energy use [14]. However, studies show that there are considerable communication barriers between designers and users in interpreting their project's expectations and conveying the design intentions, which is a big obstacle in the current practice of design-for-aging. Designers do not often receive meaningful feedback from their clients to consider in the design so it will reflect their expectations and satisfaction, which is a challenge in clarifying the design's intentions to clients [15]. Virtual Reality (VR) and Game Engines (GEs) are increasingly used as valuable platforms to engage non-professional users in the design process [16]. Visualization is a critical factor for the design development, communication, and collaboration between the involved team. Effective design visualizations can enhance users' perception and help develop better insight into the design artifact [17]. VR provides new perspectives of visualization for designers through an immersive experience. Game Engines (GEs) create dynamic interactive activities to achieve accurate and timely feedback from users' interaction with the design elements in a virtual environment. Therefore, coupling BIM and VR extends the capabilities of BIM and makes it a more powerful tool [18]. This integration facilitates the active engagement of clients in the design process, which is a challenge in the case of conventional architectural design for age-in-place houses [19].

Many studies have been conducted in order to find the optimum WWR and building orientation, however, the role of the occupants/end-users of the buildings in the window design, especially for age-in-place homes, is missing. The user's visual comfort should be considered when the window is designed. Therefore, the primary purpose of this study is to evaluate how interactive BIM and VR integrations can influence the design process, particularly in optimizing design elements such as WWR and building orientation to enhance living conditions and energy efficiency in homes designed for aging populations. This study introduces a real-time, interactive simulation, which is provided by an integrated model that had been developed to enable the assimilation of the aging population's specific needs and preferences and to allow for more personalized, and user-centric designs. This tactic ensures that the designed houses are optimized for energy consumption and contribute to the overall comfort and quality of life for the inhabitants, especially the elderly. The proactive engagement of owners and designers facilitated by the said model would also allow for more informed and inclusive decisions, which are critical in developing solutions that support the aging population to live independently and comfortably within their homes. By stressing energy efficiency and user-centric design, this study will significantly contribute to advancing the design strategies for sustainable age-in-place homes. It is important to note that in this study, the term "building" is broadly applied, particularly in relation to the WWR and orientation analysis. While the term "house" is specifically referenced to the design for aging and serves as the focus of the case project used to test the developed model.

## 2. Literature Review

Windows play a vital role in enhancing the building's energy efficiency by significantly influencing its energy load [20]. According to Kim *et al.* [20], windows contribute to over 10% of the building's energy load, underscoring their substantial impact on the overall energy consumption. Furthermore, the proportion of glazing to opaque areas on a building's facade greatly affects indoor visual and thermal comfort, as well as energy usage. Hence, it is imperative to explore the optimal WWR Ratio to achieve energy efficiency [21]. Studies conducted by Borkel [22]; Montaser Koohsari *et al.* [23]; and Leskovar and Premrov [24] focused on the effect of windows' design on the building energy load concerning factors such as window size, position, glazing properties, and orientation. On the other hand, the built environment is known as a significant factor that influences the health outcomes of people's lives [25]. Studies by Benfield, *et al.* [26] and Kaplan [27] demonstrated that fostering a connection to the outside nature in the built environment has positively impacted the occupants' well-being and has been demonstrated to have a positive influence on the attention restoration, stress alleviation, and overall health and comfort. Windows serve as the principal conduit for integrating this connection within the indoor spaces. Despite that the presence of nature views through a window has been observed to evoke compa-

rable effects on occupants, the significance of incorporating such elements in built environments for fostering well-being is not recognized [28]. Window size establishes the physical and visual connection to the exterior. [29] permits daylight and provides views and thermal enclosure in buildings. Therefore, windows represent one of the most important components of a building's envelope [30]. Investing in the building's envelopes, including walls, windows, etc., is one of the key approaches for lowering the energy consumption. While various studies have focused on energy efficiency in window design, but limited studies have been conducted on analyzing the combined effects of the window size, its position, and orientation on the consumption of energy [31].

Building Information Modelling (BIM) encompasses the generation, storage, management, exchange, and sharing of building information in an interoperable and reusable manner. It serves as a digital representation of a facility's physical and functional characteristics, facilitating the process of decision-making throughout its lifecycle, from conception to demolition [32] [33]. BIM integrates geometric and functional information, which are presented in a visualized 3D model, thereby supporting spatial cognition and aiding in the early detection of design issues [34]. Recognized for its potentials to enhance the performance in the Architecture, Engineering, Construction, and Owner-Operated (AECO) sector, BIM has garnered significant attention from both the academia and the industry [35]. The dynamic nature of BIM and its capacity for automation in the modelling process, has improved the accuracy of the construction documents, enhanced the communication among stakeholders, and reduced the issues of the field coordination, all have contributed to its widespread adoption in construction projects [36]. BIM represents the prevailing approach to revolutionizing the design, construction, and maintenance of buildings [37]. It involves generating and employing coordinated, consistent, and computable information about a building project. This parametric information serves various purposes, which include making design-related decisions, production of precise construction documents, prediction of building performance, estimating the costs, and construction planning [38]. BIM offers users the potential to create more energy-efficient buildings. Typically, energy analysis is complex and costly, which leads to delays until the final stages of design [39]. However, BIM's integrative nature enables the use of coordinated and dependable information about a building project from its initial design stage. The cohesive and interconnected information within a BIM model can streamline building energy analysis at the initial design stage [38].

VR integrates multiple technologies, including advanced computing, sensing, simulation, and microelectronics, to create an immersive three-dimensional environment [40]. Unlike conventional 3D modeling tools, VR enhances immersion and interaction, allowing designers to explore their designs with more advanced concepts [41]. VR technology is characterized by its immersive, interactive, and imaginative qualities. It engages users through visual and auditory sti-

multi, enables interaction with virtual objects and scenes, and fulfills individual user needs [40]. Wolfartsberger *et al.* [42] claimed that leveraging VR technology to improve the evaluation of engineering designs has intrigued researchers since the inception of modern VR. While engaging users in a 3D virtual environment and facilitating virtual interaction with designed models are vital, their potential is frequently overlooked. With the decreasing costs of tracking solutions and the availability of high-quality VR devices, visualizing 3D engineering data in a VR setting has become quicker and demands minimal programming knowledge. VR allows designers to preview project designs before physical construction. The utilization of VR extends across the entire design process, spanning from the conceptual to the preliminary and detailed stages. According to Prabhakaran *et al.* [43], the early design phase of a building holds utmost significance for its outcomes, since many of the building's characteristics and costs are established during that stage. Consequently, the opportunity to influence the final design diminishes as the costs of alterations or rectifying design errors escalate. Integrating immersive technologies and game engines with BIM goes beyond mere virtual mockups and digital representations. It enables users to immerse themselves in a virtual environment, facilitating experiential space interactions through self-guided or automated virtual walkthroughs. Users could engage in interactive tasks and offer designers real-time feedback, enhancing design comprehension and satisfaction [44].

Autodesk Revit is widely recognized as BIM tool in the Architecture, Engineering, and Construction (AEC) industry. It holds a prominent position as the most utilized tool in Canada and is acknowledged as a leading choice for conducting energy analysis for buildings [45]. This study opted for Autodesk Revit due to its extensive use in the construction industry and its prominence as one of the primary BIM software platforms in academic research [45]-[47]. Design Builder is extensively known and utilized in the AEC industry for simulating the building performance and analysing its energy. With its user-friendly interface and comprehensive features, Design Builder enables architects, engineers, and building professionals to evaluate and optimize the energy efficiency, thermal comfort, and environmental performance of buildings throughout the design process. In a comparative study conducted by Elnabawi [45], various Building Energy Modeling (BEM) tools were evaluated, where Design Builder was identified as the tool that was best suited to meet performance criteria and practical application, closely followed by Virtual Environment. Notably, Design Builder and Virtual Environment were distinguished by their capability to import and export files in the gbXML format, as well as their unique ability to enhance data exchange with Autodesk Revit through custom plug-ins. Design Builder, a commercially available CAD software specializing in 3D building modeling for energy-efficient design and operation, offers the most comprehensive interface for Energy Plus when compared to other tools [48]. Consequently, Design Builder

was chosen as the BEM tool for this study.

### 2.1. Relevant Studies Related to WWR and Its Integration with BIM

While there is a wealth of research on integrating BIM and BEM tools, with notable studies by Jalaei and Jrade [49], and Wafra, *et al.* [50], comparatively less focus has been placed on their integration concerning WWR and building orientation. HeeKo *et al.* [28] conducted an experiment involving 86 participants, comparing spaces with and without windows. The study revealed that participants in spaces with windows reported higher levels of positive emotions (e.g., happiness, satisfaction) and lower levels of negative emotions (e.g., sadness, drowsiness) compared to those in windowless spaces. Moreover, participants in spaces with windows demonstrated enhanced working memory and concentration abilities in comparison to those in windowless environments. Kim *et al.*, [20] conducted a study by evaluating the influence of window design elements, such as WWR ratio, position, and orientation, on building energy consumption. Through various scenario combinations, they provided designers with insights into how these factors affect the overall energy load of buildings. Sayadi *et al.* [5] investigated multiple scenarios to determine the optimal WWR ratio across seven distinct climate conditions. Their analysis was based on minimizing total yearly energy usage (including cooling, heating, and lighting), also on exploring the impact of overhangs and automatic blinds on WWR optimization, particularly in buildings equipped with integrated automatic lighting control. Zhang and Ong, [4] conducted a sensitivity analysis study to examine the relationship between the U-values of walls, windows, and WWR ratio and building energy performance. Their study, encompassing both embodied energy in materials and operational energy during the building lifecycle, highlighted the significant impact of targeting the thermal properties of windows when adjusting WWR on the overall building's energy consumption. Chi *et al.* [21] conducted a study on the impact of building orientation and WWR on indoor environmental conditions in traditional dwellings. They selected Sizhai traditional dwellings in Zhejiang Province, China, as representative housing samples for rural residences. The researchers systematically varied the building orientation and WWR and conducted the indoor environment simulations to assess parameters such as daylight factor, air temperature, and air velocity. Based on the national codes and thermal comfort ranges, they identified three optimal WWR intervals corresponding to specific criteria. Validation techniques were employed to ensure the accuracy of their findings. Abanda and Byers, [38] investigated how building orientation impacts energy consumption in small-scale construction and explored the role of BIM in this process. Using Autodesk Revit and Green Building Studio, they modeled a real-life building and assessed various orientations' energy impacts. Results showed significant energy savings with well-oriented buildings. Their study emphasized the importance of considering orientation for

energy efficiency and highlighted BIM's potential in facilitating such assessments. Bokel, [22] investigated the influence of window's size and vertical position on energy consumption in an office room, by examining all combinations of these factors using nine and three values, respectively. The study revealed that both window's size and vertical position significantly impacted the energy consumption, with the effect of position diminishing as window's size increased. Similarly, Koohsari *et al.*, [23] analyzed changes in the window's vertical position, width, and height separately in a residential room. Although the variation in the window's width and height used in the study did not maintain a fixed window area, the results primarily demonstrated the effects of size variations. However, in their context, it was observed that the height had a more pronounced impact on the energy consumption than the width, implying that the window's shape also plays a role.

Yeom *et al.*, [51] aimed to determine the optimal WWR to enhance workers' task performance and energy efficiency in office buildings. Through cognitive tests and energy simulations, they found that increasing the WWR had improved the task performance and had reduced the task load. The study identified the optimal WWRs for different façade orientations, providing valuable insights for designing office buildings that would balance energy efficiency and a healthy work environment.

## **2.2. Relevant Studies Related to the Integration of BIM-VR and Game Engines**

To engage end-users in the design process, Balali *et al.*, [52] introduced a BIM-VR integrated model that enables various stakeholders to visualize and compare different wall alternatives and their associated costs, aiding in the selection of the optimal option during the preconstruction phase. Panya *et al.*, [53] introduced a methodology for integrating BIM with VR and Augmented Reality (AR). This integrated approach enhances BIM capabilities, allowing various stakeholders to mitigate the impact of design changes by identifying errors early in the design process. Wu *et al.*, [34] introduced a communication platform named VBR (Virtual Building Information Modeling Reviewer), which utilizes avatars and integrates BIM with VR. The platform aims to tackle communication challenges by enabling users to immerse themselves in the BIM model and identify issues from their unique perspectives. Chao-Yung, *et al.*, [54] developed a BIM-based Visualization and Interactive System (BIM-VIS) that integrates BIM, game engine, and VR technologies. The system offers a VR environment to enhance visual communication between designers and medical staff during the design phase of healthcare facilities. Lin Y., *et al.*, [55] proposed the creation of a model that integrates a database with BIM, game engine, and VR technologies for healthcare design. The model operates within a Semi-immersed VR environment, facilitating an effective communication system between the design teams and the healthcare stakeholders. It aids in managing the healthcare design

tasks during the design phase, by benefiting both the design teams and stakeholders. On the flip side, Du *et al.*, [56] presented a BVRS, which is a real-time synchronization system that merges BIM with VR. The system is based on a Cloud-based BIM metadata interpretation and communication approach, which enables users to implement changes to the BIM design model through VR technology. Davidson *et al.*, [57] examined the fusion of BIM and VR to engage clients in the critical decision-making processes during the design phase and to enhance the creation of a refined Bill of Quantity. Additionally, Wu and Kaushik, [15] introduced a BIM-Based gaming prototype that integrates BIM inputs with a game engine, to facilitate the communication between users and designers and to support the development of tailored scenarios for sustainable aging projects. While these studies emphasized on the integration of VR with game engines for effective communication in the design process, it is evident that various sectors within the construction industry stand to benefit from utilizing VR. Several other studies, including those referenced as [34] [58]-[61] have delved into the utilization of VR within the realm of construction safety. These studies have investigated various applications, such as enhancing the inspection processes, developing realistic simulations for potentially hazardous scenarios, and providing training for workers.

In conclusion, the reviewed studies have provided valuable insights into the impact of window design elements on building energy consumption. While these investigations offer comprehensive analyses of factors such as WWR, it is noteworthy that, to the best of the authors' knowledge, there is a gap in the literature concerning the integration of BIM and VR for specifically exploring the optimization of WWR ratio. This presents an opportunity for this study to explore the potential synergies between BIM and VR in addressing energy efficiency considerations, which are related to windows' design in buildings, while also enhancing the communication between designers and occupants. Moreover, integrating VR into the design process could facilitate the engagement of occupants in discussions surrounding WWR ratio, thus ensuring that design choices align with occupants' preferences and needs.

### 3. Model's Development Methodology

The model requirements are established based on an extended literature review, outlining the key characteristics for consideration in a practical model. Emphasis is placed on enhancing the model's benefits within its categorized requirements and development constraints. The methodology aims to streamline the process of integrating BIM, VR, and Energy Analysis tools for proposed Age-In-Place housing projects during the conceptual design stage, prioritizing automated access to necessary data. The functions performed within each model's components and their local developments are illustrated in **Figure 1**. Since the proposed methodology integrates different applications, the development will be implemented through four phases: 1) WWR Base Model Creation and Simula-

tion; 2) Data Communication; 3) BIM Integration; and 4) VR setup, Simulation, and Interaction. Phase 1, involves the creation of a base model in the energy analysis tool (Design Builder in this study) and parametric analysis on WWR for each building façade across the fifteen major Canadian cities. The large numerical output datasets generated out of that phase are stored in an external database for subsequent use in BIM (Autodesk Revit) and VR (Unity game engine) environments. Phase 2, focuses on the development of new plug-ins in Autodesk Revit by using its API (Application Programming Interface). These plug-ins enable automatic access to the databases developed in Phase 1, aiding designers in optimizing building's orientation and WWR based on the energy performance during the early design stage. Phase 3, entails the design and creation of a 3D BIM design model by using the databases and plug-ins developed in Phases 1 and 2, respectively. Phase 4, integrates BIM and VR environments to facilitate immersive user experiences and communications. This phase configures the parameters and adjustments within the game environment, allowing users' interactions and permitting them to incorporate their feedback into the 3D design model. The described model aims to provide optimized recommendations for WWR and building orientation to designers and end-users during the conceptual design stage.

### 3.1. Phase 1—WWR Base Model's Creation and Simulation

During Phase 1, a base model was created, featuring a rectangular building measuring 96 square meters (8 m × 12 m) and adhering to the specified properties as outlined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard. The building has no interior partitions, it stands at a height of 3 meters, and it includes double-pane windows with clear glass. For simplicity, the influence of window's frames is excluded from consideration in this study. Windows are centrally positioned on each façade, and the properties of these selected windows are detailed in **Table 1**. Furthermore, shading is not considered in the base model.

**Table 1.** Base Model of windows' properties.

| Number of Panes | 1 <sup>st</sup> Pane Glass type | 2 <sup>nd</sup> Pane Glass Type | Window Gas type | Glazing    | Window Frame | Frame Width |
|-----------------|---------------------------------|---------------------------------|-----------------|------------|--------------|-------------|
| 2               | Clear 3 mm                      | Clear 3 mm                      | 13 mm Air       | 30% Glazed | UPVC         | 0.04 m      |

For the base model, default heating and cooling systems are established, and a Fan Coil Unit (4 Pipe) with default settings is implemented for the HVAC system. The occupancy load is set for three occupants, utilizing the default occupancy schedule for residential spaces. Heating and cooling set point temperatures are configured at 18°C and 25°C, respectively, as depicted in **Figure 2**.

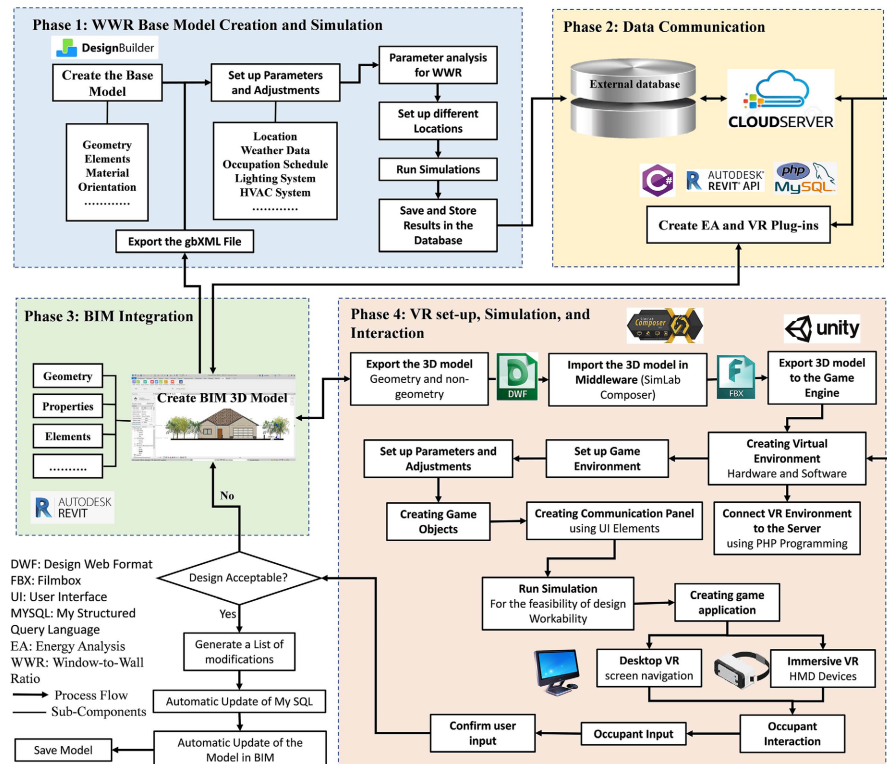


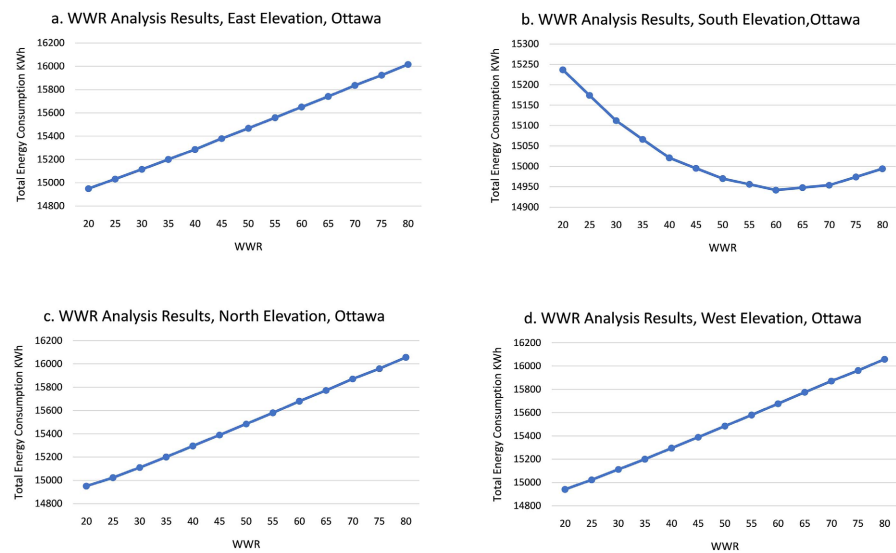
Figure 1. Model’s components and development process.

| Heating Setpoint Temperatures |      |
|-------------------------------|------|
| 🔥 Heating (°C)                | 18.0 |
| 🔥 Heating set back (°C)       | 12.0 |
| Cooling Setpoint Temperatures |      |
| 🧊 Cooling (°C)                | 25.0 |
| 🧊 Cooling set back (°C)       | 28.0 |

Figure 2. Heating and cooling temperatures setting.

The foremost essential step in ensuring accurate energy simulation is identifying the location and selecting the appropriate weather file. Design Builder provides access to a wide range of weather files based on Energy Plus, a widely known and used energy simulation engine. These weather files cover various locations worldwide and contain detailed meteorological data necessary for performing energy simulations in Design Builder. Users can select the relevant weather file correlated with their project’s location to ensure accurate simulation results that account for the local climate conditions. This study conducted a parametric analysis of WWR using a sample of fifteen representatives from ten Canadian provinces. **Figure 3** illustrates a sample result of the simulations, depicting the total energy consumption based on WWR for all windows across the south, west, east, and north façades. The x-axis represents the WWR as a percentage unit (ranging from 20% to 80% with intervals of 5%), while the y-axis denotes the annual energy consumption in kWh for the base model, which is located in Ottawa, Ontario. The results reveal a consistent rise in the annual energy consumption with larger window sizes across all the window orientations

(East, North, or West-facing), except for the South-facing windows. This trend holds true for all the Canadian provinces except for British Columbia, where the energy load for South-facing windows aligns with that of other façades. **Table 2** displays the optimal and worst values of WWR for each building façade across the fifteen major cities in Canada. Following the analysis and data extraction, the results are stored in an external database for utilization in the subsequent phases of this study.



**Figure 3.** Sample Chart for WWR analysis for each building's facade (north, south, east, west).

### 3.2. Phase 2—Data Transmission

This phase is dedicated to modifying Autodesk Revit® to meet the modular requirements of the model, via a process that involves several steps. Initially, new plug-ins are developed in BIM's tool, Autodesk Revit®, by utilizing its API and C# programming language. These plug-ins establish a connection between the databases developed in Phase 1 and Autodesk Revit®, to facilitate the calculation and analysis of the WWR and the retrieval of associated data while creating 3D design models of proposed houses. Additionally, another plug-in is created to enable direct communication with the VR environment from within Autodesk Revit®, to assist in the interaction with end-users. Autodesk provides robust APIs (Application Programming Interface) and SDKs (Software Development Kits) that allow for customization and adaptation of the tool as per specific requirements.

Designers first access various WWR data for each façade using the created plug-in during the design phase. Subsequently, they can select the project's location from the fifteen cities addressed in Phase 1 and instantly view different WWR results. Moreover, the plug-in automatically calculates the WWR for each façade based on users' input or the 3D model, which minimizes design errors and saves time. Microsoft Excel® and MySQL® are used to create the external

**Table 2.** Parametric analysis results for fifteen cities in Canada.

| Province              | City          | Optimal WWR (%) for each façade |      |       |      | Worst WWR (%) for each façade |      |       |      |
|-----------------------|---------------|---------------------------------|------|-------|------|-------------------------------|------|-------|------|
|                       |               | North                           | East | South | West | North                         | East | South | West |
| Ontario (ON)          | Ottawa        | 20                              | 20   | 60    | 20   | 80                            | 80   | 20    | 80   |
|                       | Toronto       | 20                              | 20   | 40    | 20   | 80                            | 80   | 80    | 80   |
| Quebec (QC)           | Quebec City   | 20                              | 20   | 60    | 20   | 80                            | 80   | 20    | 80   |
|                       | Montreal      | 20                              | 20   | 60    | 20   | 80                            | 80   | 20    | 80   |
| British Columbia (BC) | Vancouver     | 20                              | 20   | 20    | 20   | 80                            | 80   | 80    | 80   |
|                       | Victoria      | 20                              | 20   | 20    | 20   | 80                            | 80   | 80    | 80   |
| Manitoba (MB)         | Winnipeg      | 20                              | 20   | 80    | 20   | 80                            | 80   | 20    | 80   |
| Saskatchewan (SK)     | Regina        | 20                              | 20   | 50    | 20   | 80                            | 80   | 20    | 80   |
|                       | Saskatoon     | 20                              | 20   | 60    | 20   | 80                            | 80   | 20    | 80   |
| Alberta (AB)          | Edmonton      | 20                              | 20   | 45    | 20   | 80                            | 80   | 80    | 80   |
|                       | Calgary       | 20                              | 20   | 40    | 20   | 80                            | 80   | 80    | 80   |
| New Brunswick (NB)    | Fredericton   | 20                              | 20   | 60    | 20   | 80                            | 80   | 20    | 80   |
| Newfoundland (NL)     | St. John's    | 20                              | 20   | 60    | 20   | 80                            | 80   | 20    | 80   |
| Nova Scotia (NS)      | Halifax       | 20                              | 20   | 50    | 20   | 80                            | 80   | 20    | 80   |
| Prince Edward (PE)    | Charlottetown | 20                              | 20   | 60    | 20   | 80                            | 80   | 20    | 80   |

database, while PHP (an open-source general-purpose scripting language) and C# (an object-oriented programming language) are employed for automation purposes. In this study, MySQL and Microsoft Azure serve as the cloud server, providing designers with instant access to the created databases. Data is seamlessly transferred from MS Excel tables to MySQL through a set of rules coded in C#. Next, SQL Server is linked to the cloud server to aid in accessing the created databases while the cloud server is connected to the created plug-ins in Autodesk Revit®. Connections between MySQL, the cloud server, and the plug-in in Autodesk Revit® are automated and coded by C# and PHP. The inclusion of SQL Server in the system's architecture created a bridge to the cloud server to ensure rapid access to the databases. The intricate network connecting MySQL, the cloud server, and the plug-in in Autodesk Revit® is carefully coded by using a combination of C# and PHP. C# language is specifically used to handle all the programming tasks, except for connecting the plug-in to MySQL on the cloud server, where PHP is utilized for that purpose. This strategic use of both languages allowed them to leverage their strengths, addressing specific needs and optimizing the overall performance of the integrated system.

### 3.3. Phase 3—BIM Integration

This phase focuses on developing a module that connects to the external databases, which are then linked to BIM tools to create 3D design models of proposed houses. Using the newly developed plug-in for WWR and its associated

data, designers can efficiently load and operate this module. Initially, designers select a location (province and city) and the house's façade where they intend to place the windows. Afterwards, designers input the dimensions for the wall and the window(s). The plug-in automatically calculates the window(s) area(s) and WWR. Additionally, the plug-in features the options to delete, add, or modify the entered dimensions, allowing designers to compare different design options and choose the most suitable one. Furthermore, the plug-in generates an annual energy consumption diagram based on the designed WWR, by providing architects with insights into the energy consumption. Designers also have the option to choose different diagram formats and store their preferred type in the external database.

During this stage, the cloud server engages in a bi-directional interaction with the plug-in to facilitate the import and export of data to and from the database. Once the design is finalized, which incorporates all the geometric and non-geometric components, an analytical model is generated so it would be exported to Design Builder to perform the building orientation analysis and to calculate the total annual energy consumption for the 3D model. Initially, zones and spaces are identified, followed by adjustments such as location and orientation. In this study, all the adjustments are made within the Design Builder environment to ensure accuracy. The model is exported to Design Builder as a gbXML file, which is done in two ways: 1) via the Design Builder add-in in Autodesk Revit; or 2) directly from the export option in the File tab of Autodesk Revit. When using the Design Builder add-in, the setting toolbar icon is located on the analysis menu. The general tab remains at its default setting, while the merge tab allows for subsequent modifications in Autodesk Revit after transferring the model. In this instance, the merge tab remains unchecked. Finally, the "Use rooms/space volumes" and "Complex with mullions and shading surface" options are selected to generate the gbXML file.

Upon exporting the gbXML file to Design Builder, the building geometry undergoes assessment for any inconsistencies. Presently, there are no specific guidelines for verifying the geometric data, aside from the software's message indicating the number of buildings, blocks, and zones post-transfer to Design Builder [45]. In this investigation, successful exportation of the house geometry is evidenced, as depicted in **Figure 4**. However, upon examination of the windows, it is noticed that the materials and thermal properties are not part of the transferred data. Consequently, these elements are re-identified within Design Builder to match the specifications of the base model from Phase 1. Subsequently, adjustments pertaining to location, weather data, and other parameters are replicated from the base model in Phase 1. The building orientation parametric analysis, conducted for the fifteen selected cities in Phase 1, yielded results that are stored in the external database to be utilized in Autodesk Revit and the VR environment through the developed plug-ins. **Figure 5** shows the results for the Ottawa location, with the x-axis representing the building orientation, ranging

from 0 to 360 degrees with an interval of 10 degrees, and the y-axis represents the annual energy consumption in kWh.

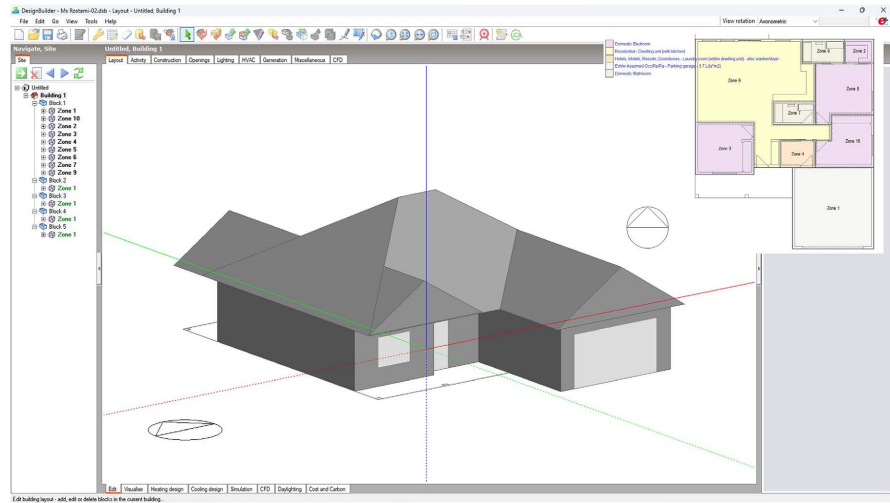


Figure 4. House's geometry and zones in design builder.

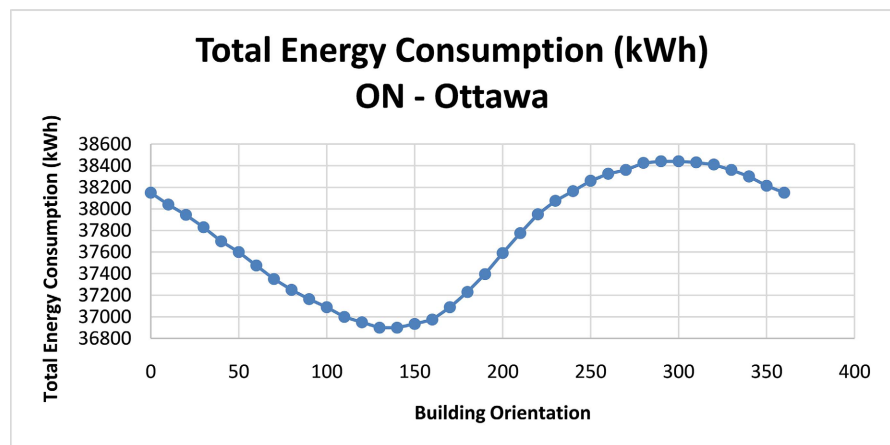


Figure 5. Sample building orientation result.

### 3.4. Phase 4—VR Setup, Simulation, and Interaction

The primary focus of this phase is on the integration of BIM and VR to leverage the immersive capabilities of virtual reality and game engine environments as highlighted by [56] and [62]. The integration process involves four key steps: 1) model transfer; 2) data transfer; 3) database development; and 4) user interface design. In the first step, the 3D design model crafted in Autodesk Revit® is transferred to the game engine for additional refinement. This step poses a significant challenge due to the potential loss of data during the transition. While Autodesk Revit supports various 3D file formats like DWF and FBX, direct exportation to the game engine may result in the loss of crucial data such as materials' properties and textures. To mitigate this risk, middleware tools such as SimLab Composer and Autodesk 3ds Max can be employed. In this study, Sim-

Lab Composer was utilized due to its support for diverse 3D file formats. Accordingly, the 3D design model is initially imported as a DWF file into the middle-ware tool (SimLab Composer) and subsequently exported as an FBX file to the game engine, ensuring a smoother transition and minimizing data loss. Steps 2 and 3 involve the creation of a dedicated database and the transmission of essential data from Autodesk Revit® to this database, which is seamlessly connected to the game engine. This database encompasses essential information such as component dimensions, names, ID numbers, and materials, facilitating an efficient data exchange between Autodesk Revit® and the game engine. The process of creating the database is automated to establish bidirectional data transfer between Autodesk Revit® and the game engine. MySQL and Microsoft Azure are utilized to create the database, while PHP and C# programming languages are employed to automate the data transitions and to establish the connections between the data server, Autodesk Revit®, and the game engine. To establish the connection between the database and Autodesk Revit®, two alternative methods were explored. Initially, the BIM 3D design model data was exported to the MySQL database using Open Database Connectivity (ODBC). However, this approach encountered challenges as certain information associated with the model's elements was lost during the transfer. Additionally, the database created through ODBC only contained limited components present in the 3D design model. Subsequently, Dynamo visual programming and the Slingshot package for Dynamo were considered, as previously investigated by Rostamiasl and Jrade [63]. However, Dynamo exhibited limitations in data transmission and connection to the cloud server. Therefore, in the present study, PHP and C# were exclusively utilized for all type of connections. All the pertinent data, including dimensions, names, and ID numbers of the components utilized in the 3D design model, are stored in the database and used within the game environment. Furthermore, any user input or modifications made within the game environment are automatically updated in the database, and subsequently reflected in the BIM 3D design model.

The fourth step involves the creation of a Virtual Reality Environment (VRE) and the configuration of the game engine parameters. This involves the use of an avatar and camera to facilitate effective communication, visualization, and navigation within the model. Within the game environment, users and designers have the ability to interact with various game objects, including avatars, canvases, prefabs, buttons, cameras, labels, text boxes, and assets. The avatar, representing the user or designer, is equipped with rigid body and collider components to enhance realism and prevent collisions with house elements. The canvas incorporates the User Interface (UI) and Raycaster for user interaction, featuring a communication panel displaying detailed information about components extracted from Autodesk Revit's database. Prefabs integrate the 3D design model, which was exported from the BIM environment into the VRE, while buttons allow users to confirm or cancel actions. The camera provides a realistic line of

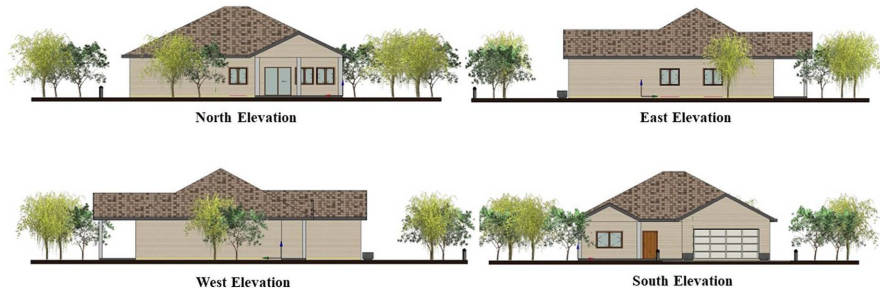
sight, adjustable to the user's needs. Labels convey specific information such as units, and text boxes enable user input. Assets represent items used in the game environment, extracted from the 3D design model or obtained from external asset stores or libraries.

In this study, Unity® was chosen as the cross-platform game engine for its support of 3D assets imported from Autodesk Revit® and its compatibility with Android, iOS, and Windows Mobile Phones. Desktop VR was utilized to test the developed model. Subsequently, a gaming environment was established to enhance user collaboration and interaction with the design. As users interact within the game environment, any modifications they make will be automatically reflected in both the database and the 3D design model. This automated process, which is the primary objective of this study, significantly reduces human errors and minimizes associated time and costs. Moreover, the immersive VRE is experienced using a head-mounted device (HMD), sensor gloves, game controllers, and other related devices, offering users a realistic environment akin to inhabiting the design itself.

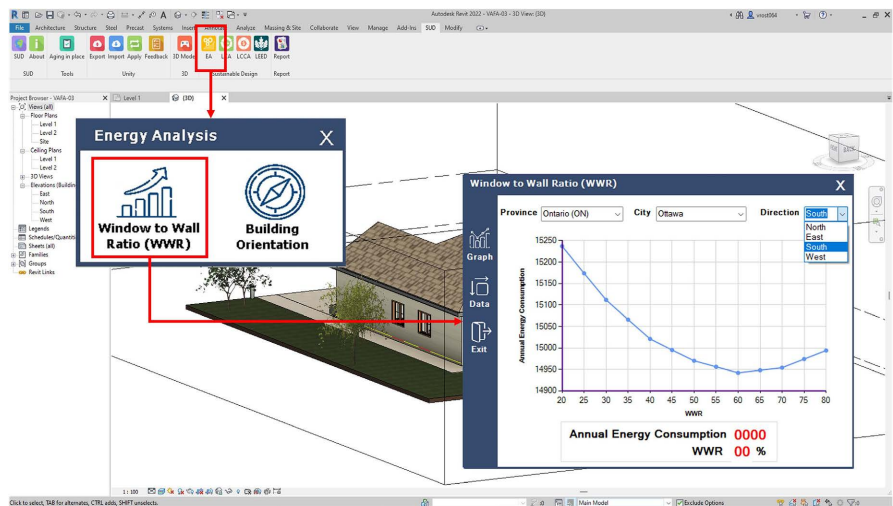
#### 4. Model Testing

To test the developed model and evaluate its performance and capabilities, a one-story single-family house located in Ottawa, Ontario, Canada, is chosen for that purpose. This selected house comprises two bedrooms, a guest room, a living room, a kitchen, two bathrooms, a utility room, and an attached garage, with a total gross area of 176.3 square meters. Autodesk Revit® is employed as BIM tool to create the 3D design model of that house, encompassing all its geometric and non-geometric components, including walls, doors, floors, stairs, and cabinets, as depicted in **Figure 6**. The creation of windows involves retrieving data from the external database via the newly developed plug-in named as EA (Energy Analysis) plug-in within Autodesk Revit®. This plug-in helps designers in calculating, selecting, and incorporating the appropriate window size for the model. When the Energy Analysis (EA) plug-in is initiated, a window prompts the user to make a selection out of two options: 1) Window-to-Wall Ratio (WWR): or 2) Building Orientation. However, designers must start with the WWR option to proceed with the design, as depicted in **Figure 7**. Upon selecting the WWR option, another window appears, allowing designers to specify the location, province, city, and façade where they intend to place the window as seen in **Figure 7**. Following this selection, a new window emerges, enabling designers to input the dimensions of the wall and subsequently the dimensions of the window(s). Users have the flexibility to add or delete windows as needed. Subsequently, the plug-in automatically calculates the area of each window in square meters, the WWR as a percentage, and the total energy consumption in kilowatt-hours (kWh) based on the data already stored in the database from the base model as illustrated in **Figure 8**. Moreover, the plug-in generates diagrams in various formats, giving designers the option to select their preferred format as

depicted in **Figure 9**. Additionally, a “Data” button is provided to allow users to navigate into the input data window of the plug-in at any instance during the design process.



**Figure 6.** 3D design model for the selected house.



**Figure 7.** EA plug-in and its features.



**Figure 8.** Input data for wall and windows dimensions.

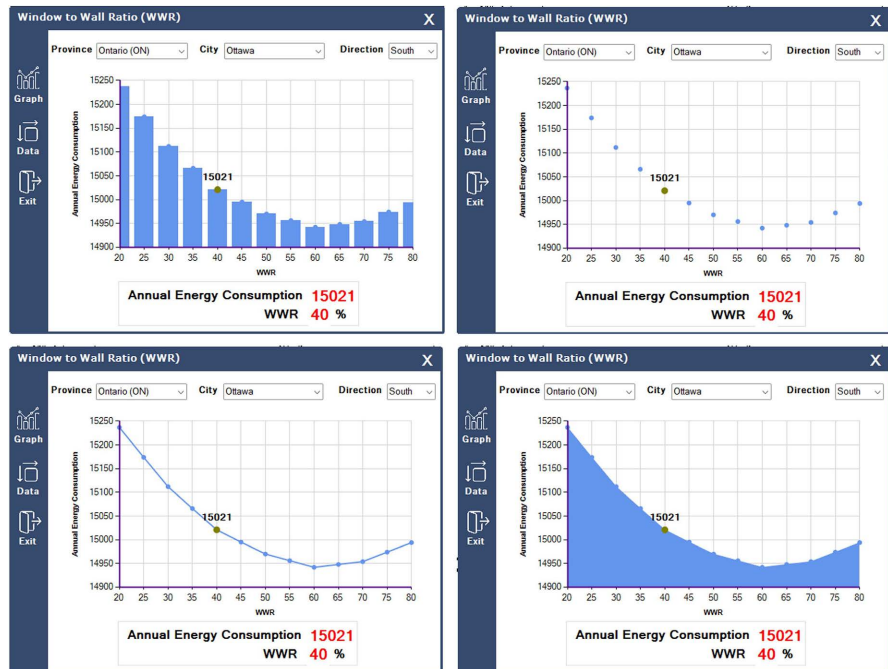


Figure 9. Selection from different diagrams' format.

Once the design is completed, the analytical model is generated and exported to Design Builder following the process outlined in Phase 3. Subsequently, parametric analysis is conducted for the designated cities, and the outcomes are stored in the external database to be automatically used in the Revit Environment through the EA plug-in. To utilize the building's orientation feature, designers can access the EA plug-in from within Revit. Upon selecting this option, a window prompts the designer to choose the province and city. Using the built-in bar, the designer can then rotate the house to visualize the total energy consumption for any selected orientation, as illustrated in Figure 10.

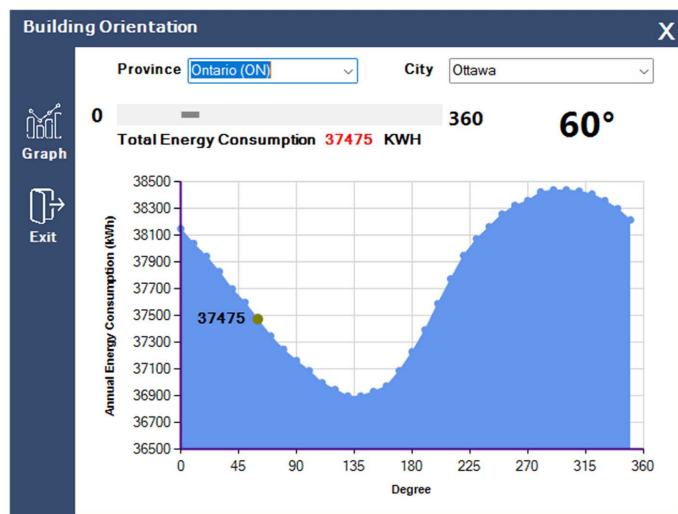
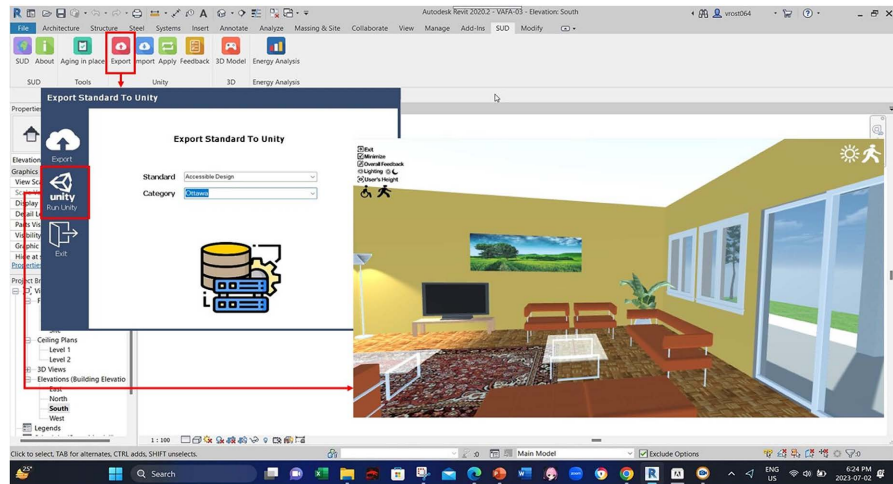


Figure 10. Building orientation window and its features.

To integrate BIM with a game engine, the first step starts by transferring the created 3D design model from Autodesk Revit to the Unity game engine by using SimLab Composer as a middleware tool. Subsequently, a database is established in MySQL on a cloud server, facilitating the automatic import and export of data between Revit and the Unity game engine via the MySQL database, utilizing C# and PHP programming languages. This database acts as the crucial link between BIM tool and the game engine. Once the BIM 3D design model is transferred to the Unity game engine, a VRE is established, where further adjustments are made to enhance users' interaction. This includes adding an avatar to represent the user, configuring a camera, integrating a communication panel using UI, and adjusting collisions to ensure realistic movement within the environment. In that instance, users can explore the designed house by walking through it. Additionally, doors are programmed to open automatically when the avatar approaches and close when it moves away, enhancing the immersive experience. Moreover, collision adjustments enable the avatar to interact with objects such as doors and walls, preventing it from passing through them. Once all adjustments are completed and necessary elements are added to the Unity game engine, the gaming environment is fully developed and ready for designers to utilize. In this phase, initiating the Export plug-in in Revit triggers the opening of a new window, as depicted in **Figure 11**.



**Figure 11.** The plug-in created to transfer data to the game engine and automate the integration.

Upon selecting the Export button within the window, all pertinent data concerning the components utilized in the 3D design model, including their names, IDs, and dimensions, is automatically transmitted to the MySQL database and the cloud server. Subsequently, upon clicking the Run Unity button, designers gain immediate access to the VRE and the game application generated within the Unity game engine, as depicted in **Figure 12**. This plug-in helps designers in exploring the design seamlessly within the BIM environment, enabling bilateral

navigation between the game scene and the 3D design model. **Figure 12** illustrates the developed game environment along with its core functionalities.



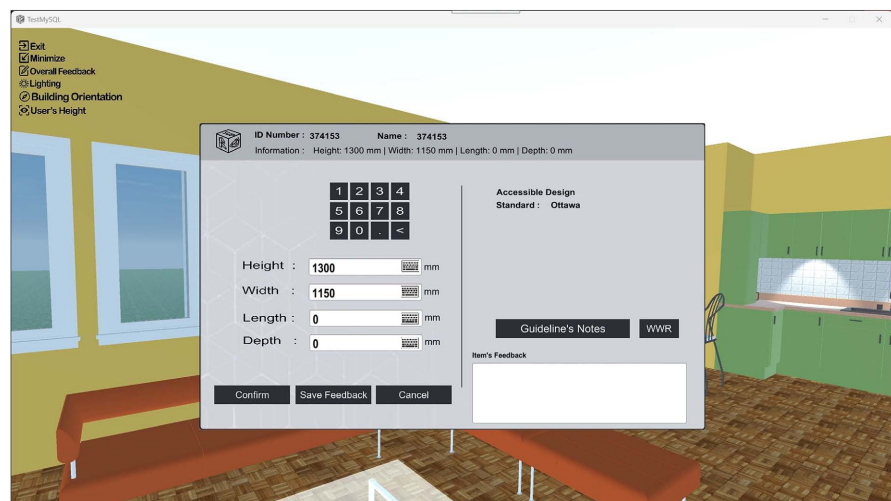
**Figure 12.** The developed gaming environment and its functions.

These functions encompass: 1) switching between day and night modes; 2) allowing users to enter in the allocated text box their feedback or comments on the design; and 3) adjusting the camera height to match the user's actual height, enhancing realism by placing the camera at the user's eye level. Upon adjusting the camera height to match their own, the position of the camera is automatically modified. Additionally, wheelchair mode can be activated to accommodate users with mobility challenges. One of the most important aspects of this phase involves the creation of a communication panel using UI elements, as depicted in **Figure 13**. This panel is specifically tailored for windows and the exterior glass door, which are pertinent to the WWR calculation in this study. It becomes accessible to users upon clicking on these objects within the game application. The panel, depicted in **Figure 13**, incorporates the following components: 1) Object's ID number and name, sourced from the BIM 3D design model; 2) Object dimensions, including width and height, extracted from Revit's database; 3) Virtual keyboard for users' input; 4) Interactive menu bars for adjusting dimensions, accessible via physical or virtual keyboard; 5) WWR button for navigating to the WWR window; 6) Confirmation or cancellation buttons; and 7) Text box enabling users to provide feedback about each object individually. Upon selecting the WWR button, a new window emerges displaying the current WWR percentage and a corresponding graph as shown in **Figure 14**. When users modify the window's dimensions, the updated dimensions, WWR percentage, and the associated graph are displayed, allowing users to confirm or revise the mass pictured in **Figure 15**. Also, users can write a comment in the object's feedback text box to notify designers of their requests. Subsequently, users can access the building orientation feature from the main menu options, as illustrated in **Fig-**

**Figure 12.** This feature enables users to adjust the building's orientation using the provided built-in bar and observe the corresponding total energy consumption based on the selected orientation as shown in **Figure 16** and **Figure 17**. Upon confirming and saving the modifications, the MySQL and cloud databases are automatically updated. Subsequently, designers can import all the changes into Autodesk Revit® using the Import Plug-in, which was developed for this purpose. Upon activating the plug-in, a comprehensive report is generated listing all the modifications made by users to the 3D design model while in the game environment, along with the comments provided by users. Additionally, a Feedback plug-in is implemented in Autodesk Revit®, enabling designers to access and review all the comments gathered while interacting with the game environment. This serves as a bidirectional communication channel between BIM and VRE. Through this integration, designers can immediately observe the results of users' input regarding the window(s) size and building orientation within a Revit environment. The prompt incorporation of design changes is automated. Consequently, designers can evaluate multiple design iterations more efficiently to enhance performance and align with users' requirements. The developed model offers users and designers an immersive platform to adapt their design based on occupants' needs, minimize potential errors, and foster effective communication through the game scene.

## 5. Conclusions, Limitation and Future Works

In this study an integrated model was developed that interrelates Building Information Modeling (BIM), Virtual Reality (VR), and Energy Analysis (EA) tools to optimize window-to-wall ratio (WWR) and building orientation during the early design stages of residential houses. Through a series of sequential phases that incorporate model creation, data communication, BIM integration, and VR setup, the applied methodology streamlines the design process, enhances



**Figure 13.** Retrieving the selected window's data from the database.



Figure 14. The current dimensions and WWR for the selected window.

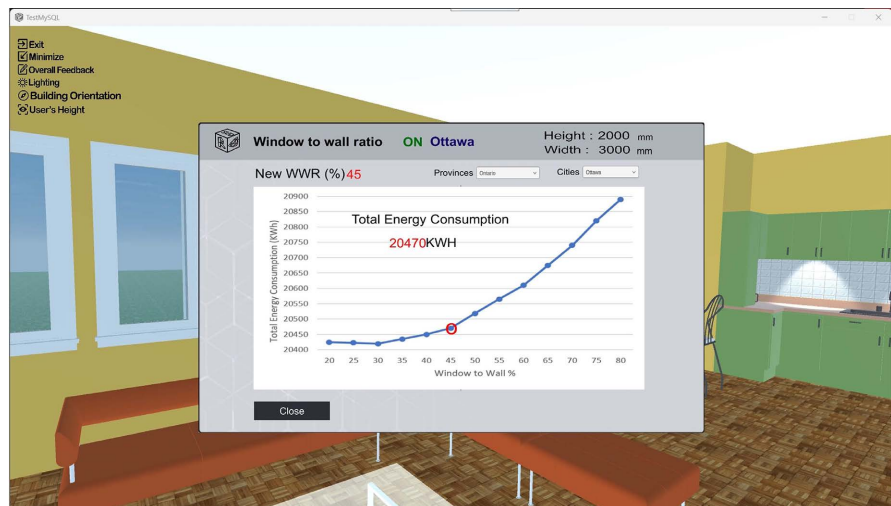


Figure 15. The modified dimensions and corresponding WWR for the selected window.

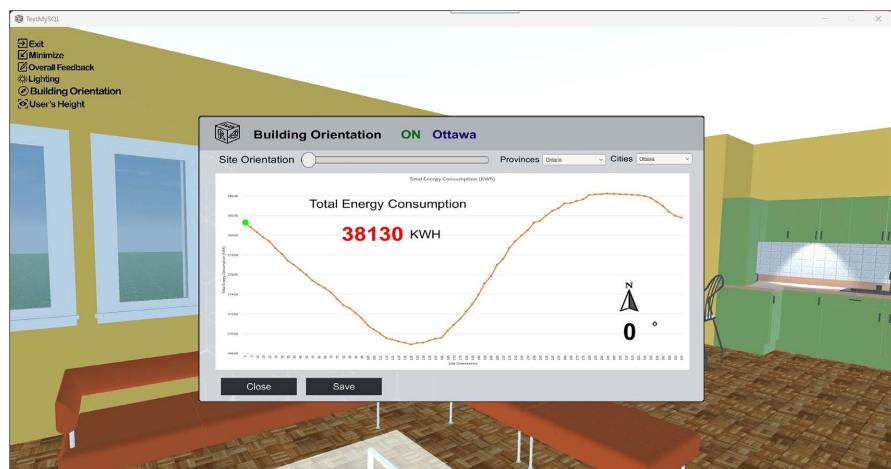
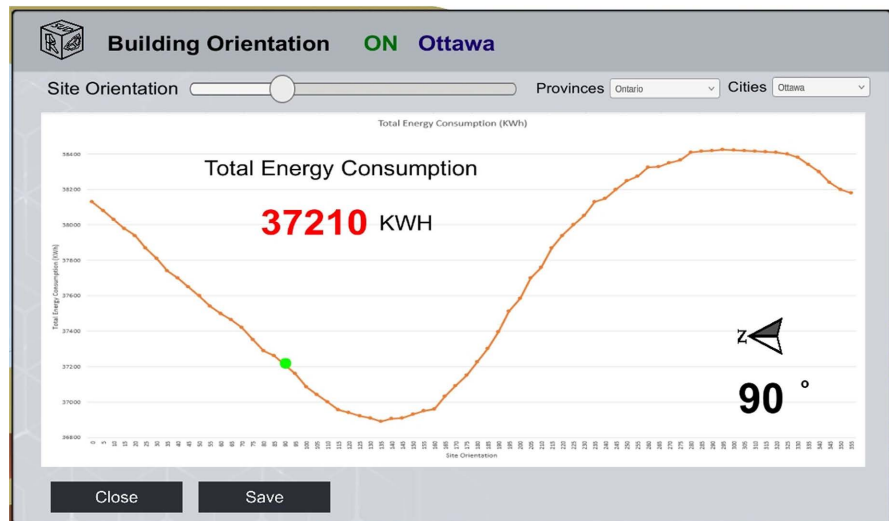


Figure 16. The created UI for building orientation in the VR environment.



**Figure 17.** The building orientation panel in VR and its features.

energy efficiency, and fosters user engagement. The results demonstrate the feasibility and effectiveness of the developed model in facilitating informed decision-making regarding WWR and building orientation. By leveraging BIM capabilities and VR immersion, designers can visualize and assess the impact of design choices on energy consumption and occupants' comfort, ultimately leading to more sustainable and user-centric house designs.

The study introduces a novel approach to integrate BIM with VR environments and EA tools, by offering an immersive platform for the designers to efficiently explore, modify, and optimize building designs in real-time interaction and communication, to ultimately enhance collaboration, decision-making, and design outcomes. In addition, designers can incorporate WWR considerations at the conceptual design stage within the BIM environment by using novel plug-ins that enhance the efficiency and accuracy of design related decisions while promoting energy-efficiency in housing projects. This unique model represents a significant advancement in the integration of energy analysis during the early design stages.

Despite its advancements, this study holds several limitations. First, the exclusion of lighting load analysis and shading systems restricts the comprehensiveness of the energy analysis. Future research should incorporate these factors to provide a more holistic understanding of the energy performance of houses. Additionally, the current study may overlook certain aspects of visual perception, such as glare, due to the limited luminance range of HMD VR displays. Furthermore, the adopted methodology may encounter challenges related to data transfer and compatibility between different software platforms. Addressing these technical barriers is essential to ensure seamless integration and to enhance the usability of the developed model.

Moving forward, future research should focus on expanding the capabilities of the integrated model to encompass a broader range of building types and design

scenarios. Incorporating advanced simulation techniques, such as dynamic daylighting analysis and thermal comfort assessment, can provide more nuanced insights into the dwellings' performance. Moreover, efforts should be made to enhance users' experience within the VR environment by refining interaction mechanisms and incorporating realistic sensory feedback. Additionally, exploring the potential of emerging technologies, such as augmented reality (AR) and artificial intelligence (AI), could further enrich the design process and optimize performance. Furthermore, conducting empirical studies to validate the accuracy and effectiveness of the integrated model in real-world design projects will be crucial for its practical implementation and widespread adoption within the architecture and construction industry. By addressing these areas of future work, scholars can advance the state-of-the-art in housing design and contribute to the development of sustainable and user-centric built environments

### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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