A CLOUD-BASED INTEGRATION OF BUILDING INFORMATION MODELING AND VIRTUAL REALITY THROUGH GAME ENGINE TO FACILITATE THE DESIGN OF AGE-IN-PLACE HOMES AT THE CONCEPTUAL STAGE

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SUMMARY: While the Canadian population ages, designers are encountering new challenges that significantly affect the design of new houses. This demographic shift will impose major changes in the demand for housing toward more adaptable and specialized homes that require designers to develop new strategic design solutions. Presently, the main challenge to designers when creating age-in-place houses is lacking the knowledge about the requirements of that type of homes. Therefore, this study describes the development of a Semi-automated computer model that offers designers and users a unique opportunity to do real-time simulation in an interactive environment while enhancing the communication and interaction between owners and designers to meet inhabitants' needs by reducing future modifications and alterations of houses to age in them. The said model is a cloud-based integration between BIM, Universal Design (UD), Age-in-Place (AIP) design requirements, and Virtual Reality (VR) that allows owners to be engaged in the design process at the early stage to achieve efficient outcomes.

KEYWORDS: Building Information Modeling (BIM), Universal Design (UD), Accessible Design (AD), Age in Place (AIP), Virtual Reality (VR), Game Engine, Computer Integration and Automation.

1. INTRODUCTION

Predictions show that the aged population in Canada will continue to rise over the coming decades. In line with that, the proportion of Canadians aged 65 years and over will accelerate during the next era, which means the proportion of people aged 65 and older will expand from 18.5% in 2021 to 23.1% in 2043 and 25.9% in 2068 as a medium-growth scenario (Statistics Canada, 2022). The demographic shift is globally extended. Based on the United Nations' World Population Prospect (2022), the share of the global population aged 65 years and above is projected to rise from 10% in 2022 to 16% in 2050 worldwide. Forecasts show that 1 in 6 people will be over the age of 65 by 2050. This means that, globally, the number of people aged 65 years and over will be more than twice the number of children under the age of 5 years and about the same as those under the age of 12 (United Nations, 2022). One of the expected challenges of the rise in the aged population will be an escalation in the cost of healthcare. This increase in the cost will push policymakers and people to prioritize successful aging, which includes reducing the burden of chronic diseases and greater functional independence (Haselwandter, et al., 2014). Therefore, the concept of designing age-in-place houses is getting more attention worldwide. On the other hand, during the pandemic and the stay-at-home restrictions issued by governments around the globe, besides the crash in the aged care systems and the increasing prevalence of telehealth, the role of the private residence in supporting physical, cognitive, and social well-being outcomes has increased (Sinclair, et al., 2020). Under the impact of COVID-19, long-term care facilities experienced significant challenges in controlling the spread of infections and minimizing disease transmission (Estabrooks, et al., 2020). According to the Canadian Institute for Health Information (CIHI), between March 1, 2020, and August 15, 2021, over 56,000 residents and 22,000 staff in Canada's long-term care homes and retirement homes were infected with COVID-19, resulting in more than 14,000 deaths among staff and residents (CIHI, 2021). One of the crucial factors causing the high fatality rate in long-term care homes in Canada is that many nursing homes are physically not designed for infection control practices, which are needed to avoid the spread of future pandemics (Estabrooks, et al., 2020). As the aged population rises, new challenges are significantly affectting 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 (Varma, 2018). The built environment is a human creation of physical spaces for living, working, and recreation, including houses, public buildings, neighbourhoods, and communities, which significantly impacts the quality of life and well-being of older adults (Chau & Jamei, 2021). The built environment must provide opportunities for seniors to participate in social and daily activities (Carr, et al., 2013). Seniors should actively be living in a broader community, such as being active in their homes, neighbourhood, and recreation centers, besides managing their personal lives. All those are forms of engagement in society. Aged adults tend to spend considerably more time at their homes, if compared to other age groups, because they provide them with their own physical setting and emotional attractions based on their personal experiences (Chau & Jamei, 2021). Therefore, age-friendly built environments have been promoted by the World Health Organization (WHO) under the Global Age-friendly Cities (AFC) movement (WHO, 2007). Although aging may cause deterioration in mobility and visual or hearing abilities and affect cognition and mental capability, it is still desirable for elderlies to continue living in their own homes as long as possible under the notion of AIP (Chau & Jamei, 2021). AIP 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 (P.P.J., 2010). Thus, to improve the capabilities and well-being of elders and to have effective age-in-place, the built environments should enhance opportunities for independence and self-reliance. Multiple design features can improve the physical and mental well-being of both the elderly and young adults. This is identified as part of the UD's features (Crews & Zavotka, 2006). UD aims to simplify the life of people regardless of their age, size, and ability to achieve an inclusive society where every individual has equal opportunities to participate despite their age and capability (Rostamiasl & Jrade, 2022). UD facilitates accessibility for a spectrum of people without specialized adaptations by creating opportunities for elderly people to participate in daily activities. Also, it has the potential for seniors to increase the easiness of completing daily activities, which promotes continual engagement in life and well-being (Carr, et al., 2013). Sinclair et al. (2020) believed that Universal Housing Design can also reduce government's health costs due to the decline in fall hazards at homes, fewer accidents, and prosperous AIP. This leads to a cut in healthcare costs and to decrease in the associated expenses for home modifications and home assistance, in addition to freeing up carers to return to the workplace (Sinclair, et al., 2020). Despite the significant benefits of UD, a major challenge exists during the design for aging due to the lack of adopting the age-in-place requirements and modifying the building codes to facilitate the design of age-in-place houses. Wu and Kaushik (2015) believed that there are considerable communication barriers between designers and users in interpreting their project expectations and conveying 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 to reflect their expectations and satisfaction, which is a challenge in clarifying the design's

intentions to clients. VR and Game Engines (GEs) are increasingly used as valuable platforms to engage non-professional users in the design process (Akanmu, et al., 2020). 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 developing a better insight into the design artifact (Akin, et al., 2018). 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 (Natephra, et al., 2017). 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 (Wu & Handziuk, 2013). It offers designers more than a virtual mockup or digital representation. Building upon the authors' prior research (Rostamiasl and Jrade, 2022), this paper extends the investigation into the integration of VR and BIM to enhance users' engagement during the conceptual design stage of age-in-place homes, which is a challenge during the design of similar conventional residences. In their earlier study, the authors introduced a semi-automated model that integrated BIM with UD and AD standards, to aid designers incorporate these standards during the conceptual design stage of buildings. However, this integration lacked direct engagement with end users and their specific needs. Consequently, the present research takes a deeper dive into advocating for users involvement in the design of age-friendly homes. Additionally, age-in-place design requirements have been integrated into the previously established databases, as thoroughly detailed in the authors' earlier publication. Furthermore, the present study distinguishes itself from the published one through variations in both the automation approach and the database connections, which will be expounded upon in the methodology section. Therefore, this study presents the development of a semi-automated model that integrates BIM with UD standards, age-in-place requirements, and VR at the conceptual design stage of proposed houses to advocate the involvement of users to achieve age-friendly homes. The presented model captures users' comments and perceptions through their interaction with the design to evaluate and improve its effectiveness to make sure it complies with the UD standards and age-in-place requirements. This allows designers and users to explore, communicate, and evaluate the design and helps them define the best practical scenario that meets their requirements. While users can make necessary modifications to meet their needs so that any alteration while in VR environment will be automatically reflected in the 3D BIM model of the proposed houses.

2. LITERATURE REVIEW

2.1 BIM, UD, and Age-in-Place

Several studies revealed that the type of design adopted by the Architecture, Engineering and Construction (AEC) industry has a significant impact on people's health, life satisfaction, well-being, social participation, and fulfillment of human rights (Watchorn, et al., 2021), (Varma, 2018), (Crews & Zavotka, 2006). This industry, which contains physical buildings, open spaces, and supporting infrastructure such as transportation, water, and energy networks, provides venues for people to engage in social and community activities. Social participation is an essential indicator of the good health and well-being of people during their lifespan, as they have connections to various social entities and groups. However, people with a disability may encounter challenges while engaging in social and community activities. UD recognizes the diverse needs and abilities of people by creating an environment or product that is designed to be usable by most people without adaptation or stigma, which continues to meet inhabitants' needs throughout their lifespan (Watchorn, et al., 2021). UD creates safe, accessible, and usable environments that would accommodate people with various abilities and needs and that would potentially reduce their inability to foster engagement in social and productive activities later in their life (Carr, et al., 2013). Crews and Zavotka (2006) believed that the growth of frailty and disability is proportional to the increase in age. Therefore, the need for more significant development and use of universal and accessible design in all aspects of the built environment does exist. As the global population age, more pressure is put on families, communities, and governments in relation to an increased need for health care, in-home caregiving, and appropriate housing (Crews & Zavotka, 2006). A report by Sinclair et al. (2020) listed that "The Australian Housing and Urban Research Institute" (AHURI) estimated that the cost savings in the Australian health system would be in the range of $37 million to $54.5 million per year if 20% of the newly constructed homes were created by adopting the UD guidelines. While a 100% adoption in new homes may lead to a yearly saving in the range of $187 and $273 million (Sinclair, et al., 2020). Verma (2018) stated that there is an increased demand for universally designed homes and living environments to promote residents regardless of their functioning capacities. The social environment and UD housing are solutions that may enhance inclusion and Age-in-Place (Varma, 2018). UD helps elderlies to age in their homes rather than acquiring the need of retirement communities and nursing homes to

receive their essentials of life (Crews & Zavotka, 2006). Age-in-Place (AIP) encourages aged adults with some degree of independent living ability to remain in their homes as long as possible and to facilitate their daily activities, habits, and ongoing social connections (Chau & Jamei, 2021). Adopting the concept of AIP requires changing the ways engineers are using to comply with the needs of residents through their life span by supporting accessibility and facilitating the ease of movement for a wide range of residents to enable them to live independently, safely, and comfortably and to minimize the demand for subsequent alternation and retrofitting. Age-friendly housing would benefit residents in aging well and in reducing the resources spent on institutional care facilities (Chau & Jamei, 2021). The National Building Code (NBC) provides the minimum technical specifications for the built environment, however, its inherited comments and suggestions need to be of high standard for designers (Canadian Human Rights Commission, 2006). Accessibility improvement is attained by either passing new legislation and developing new policies or by modifying existing standards and policies (CSA, 2020). Accessibility standards have been in place for many years in Canada; they intend to create equitable, barrier-free access to communities, workplaces, and services for people with disabilities (Rostamiasl & Jrade, 2022).

Zhang et al. (2021) stated that housing issues are the main barrier to implementing an age-in-place strategy and to encourage people to age in their homes. Numerous data are required to assess the age-friendliness of housing and to offer enough tangible actions and/or recommendations for designers and policymakers. Digital techniques, such as BIM, are utilized to facilitate the collection of data and to accelerate the computation process of assessing actual projects. BIM techniques are widely applied in assessing the different types of housing. Even though age-friendly housing is complicated and its evaluation is a time-consuming process but utilizing BIM has significantly optimized the traditional assessment methods by integrating different sources of data. Wu et al. (2019) described BIM as a novel approach implemented in a data center and used by the AEC industry by integrating the geometric and functional information of a building during its life cycle that reveals most of the design issues early during the design stage. Abanda et al. (2015) stated that BIM is a global digital technology that has the potential to revolutionize the construction industry due to the universal interest in promoting BIM and its tools to improve efficiency in delivering quality construction projects. The utmost factors that lead to adopting BIM in a project are focused on the automation in the modeling process, improvement in the accuracy of construction documents, minimizing the lack of communication among parties involved in the design and construction processes, and the automatic reflection of changes made in one view on all the other views and reducing the field coordination problems (Kamel & Memari, 2019). Coupling BIM and UD has the potential to produce universally designed facilities with high performance.

2.2 BIM and Standards Integration Related Works

Although considerable studies applied BIM during the different phases of projects, limited research focused on integrating BIM and UD (Rostamiasl & Jrade, 2022). The philosophy of UD persuades the development of design guidelines used by engineers during the design process. The increased use of BIM by the AEC industry due to its capabilities to be integrated with external applications provides an opportunity to incorporate UD and AD standards in a BIM environment at the early stage of designing houses (Rostamiasl & Jrade, 2022). Numerous studies, such as the ones of Cheng J. and Das M. (2014); Choi J. and KIM I. (2017); Kincelova et al. (2020); Patlakas et al. (2018); Narayanswamy et al. (2019); Häußler et al. (2021); Khattra et al. (2022) concentrated on the integration of BIM and building codes or standards in different areas, such as architecture, structures or green buildings. Jrade and Valdez (2012) presented a methodology used in the development of a model that incorporates a database that stores architectural design families based on the National Building Codes of Canada and linked it to BIM tool. Alsayyar and Jrade (2017) developed a methodology to integrate BIM with Sustainable Universal Design (SUD) principles and requirements through a Visual Basic interface (VB.NET) to evaluate the benefits and costs of adopting such type of design for buildings over their anticipated life.

2.3 Virtual Reality and its Integration with BIM

VR is a comprehensive environment that couples various technologies, such as advanced computer technology, sensing and measuring technology, simulation technology, and microelectronics technology, which form a realistic virtual world with a three-dimensional feel (Shengyi & Jia, 2016). VR adds immersion and interaction to three-dimensional computer-generated models by enabling designers to experiment their design with advanced ideas compared to conventional 3D modeling tools that only visualize models in an immersive first-person (Park, et al., 2018). The characteristics of VR technology are immersive, interactive, and imaginative. Immersive because it includes visual and hearing immersion, whereas interactive because it allows the user's interaction with the object and virtual scene operability, while imaginative because it satisfies the user's personal requirements (Shengyi &

Jia, 2016). Wolfartsberger et al. (2017) stated that using VR technology to enhance the review of engineering design has been an area of interest for researchers since the advent of modern VR. Engaging users in a 3D virtual world and letting them virtually interact with the designed models is essential, but its capability is often neglected. Since high-quality VR devices are costly and tracking solutions are getting more affordable, 3D engineering data can be visualized in a VR environment in no time and with a minimum knowledge of programming. VR provides designers with the ability to experience projects' design before they are built. VR is the most advanced three-dimensional interface for enhancing the interaction and communication between designers and their digital models (Zaker & Coloma, 2018). It can be used throughout the design process, from the conceptual to the preliminary and detailed stages. Prabhakaran et al. (2020) stated that the early design stage of a building is essential for the quality of its results since most of the building's characteristics and costs are already committed at that stage, and the opportunity to influence the final design decreases as the cost of making changes or correcting the design errors increases. Integrating immersive technologies and game engines with BIM would offer an experience beyond virtual mockups and digital representation. Users can walk into the virtual environment to simulate experiential space interactions via a self-guided or automated virtual walkthrough, perform interactive tasks and provide designers with meaningful real-time feedback, design comprehension, and satisfaction (Yan, et al., 2011).

2.4 BIM – VR Integration Related Works

The core values to integrate BIM with VR include: 1) refining the authenticity of simulation; 2) supporting the project cost control; and 3) improving the interoperability of simulation's work (Shengyi & Jia, 2016). Therefore, the unique benefits of VR convince researchers to investigate its application in various areas of the Architecture and Construction Industry (Huang & Odeleye, 2018). For instance, to involve end-users in the design process, Balali et al. (2018) introduced a BIM-VR integrated model enabling various stakeholders to visualize and compare different wall alternatives and their related costs to select the best option during the preconstruction phase. Panya et al. (2023) presented a BIM-VR/AR (Augmented Reality) integrated methodology to improve BIM capabilities to be used by various stakeholders to reduce the effect of changes in the design by capturing the design errors at the early stages. Wu et al. (2019) proposed an avatar-based communication platform called VBR (the virtual building information modeling (BIM) reviewer) by integrating BIM and VR to address the communication issues allowing users to animate into the BIM model to find problems from their individual perspectives. Whereas Chao-Yung, et al. (2017) developed a BIM-based Visualization and Interactive System (BIM-VIS) integrated with BIM, game engine, and VR technologies that provides a VR space to improve the visual communication between designers and medical staff during the design of healthcare facilities. While Lin Y. et al., (2018) proposed the development of a model by integrating a Database with BIM, game engine, and VR technologies for healthcare design in the Semi-immersed VR environment to provide an effective communication system between the design teams and healthcare stakeholders. It assists design teams, and stakeholders in handling healthcare design work during the design phase. On the other side, Du et al. (2018) introduced a BIM/VR real-time synchronization system called BVRS, which is based on a Cloud-based BIM metadata interpretation and communication method. BVRS allows users to make changes to the BIM design model and apply them automatically and simultaneously via VR technology. However, Davidson et al. (2020) studied the integration of BIM and VR to involve clients while making important decisions during the design and creation of an improved Bill of Quantity. Wu and Kaushik (2015) proposed a BIM-Based gaming prototype that was developed based on BIM inputs and integrated it with a game engine to facilitate users and designers' communication and to support the creation of different scenarios tailored for sustainable aging projects. Although the aforesaid studies showed that more focus was put on incorporating VR and game engines during the design process with the aim of an effective communication between designers and users, it is evident that other areas in the construction industry would benefit from using VR. Zhao et al. (2023), Li et al. (2018), Dela Cruz and Jobelle (2021), Tan et al. (2022), and Wu et al. (2022) explored the application of VR in the area of construction safety, such as inspection processes, creating realistic simulations for potentially hazardous scenarios and workers' training.

On another side, Shahinmoghadam et al. (2021) integrated BIM and VR to develop an immersive VR application for real-time monitoring of thermal comfort conditions by using a semi-automated method to stream raw thermal images from a sensor that was processed on a computing device to enable near real-time calculation of Mean Radiant Temperature (MRT). Natephra and Motamedi (2019) proposed a method for an automated sensor for live data visualization of building indoor environment conditions by integrating environmental sensors, BIM, and VR technology to utilize an immersive and live sensing technology for improving data visualization. Natephra et al. (2017) proposed a methodology to develop a BIM-based lighting design feedback (BLDF) prototype system for realistic visualization of lighting conditions and efficient calculation of energy consumption by integrating BIM

tool with a game engine by using Dynamo visual programming.

Although communication is a key factor for a successful collaboration, especially in the design for age-in-place houses, there are limited published studies that focused on considering the needs of end-users, particularly seniors, during the design process to apply their desires and to comply with the requirements of AIP design at the conceptual stage. As highlighted in this manuscript, some relevant research includes works done by Balali et al. (2018), Chao-Yung et al. (2017), Wu and Handziuk (2013), and Wu and Kaushik (2015).

3. DEVELOPMENT METHODOLOGY
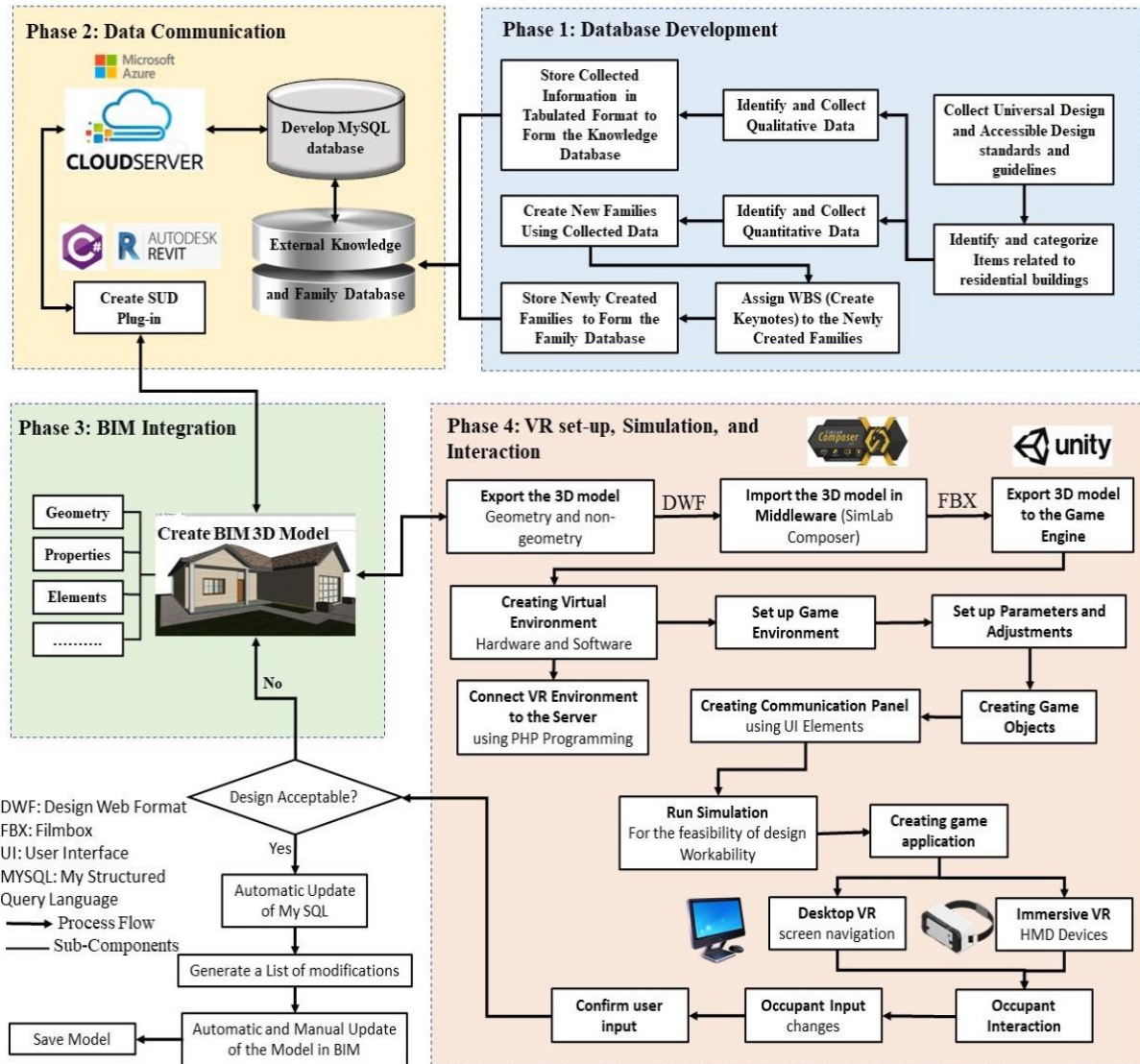
Figure 1: Proposed Model's Components and Development Process.

The model requirements are established based on the extended literature review, along with the characteristics to be considered in a practical model. The process of introducing a practical methodology is considered in order to enhance the benefits of the model under its categorized requirements and development constraints. The basis of a methodology that simplifies the process of establishing the integration between BIM, VR, and UD to be used at the conceptual design stage for proposed age-in-place housing projects in a timely and efficient way incorporates the importance of having access to the needed data at any time in an automated mode. The model consists of components designed in a modular format and is managed by a database management system. The functions performed within each of the model components and their local developments are illustrated in Fig*ure* 1. Since the

proposed methodology integrates different applications, the development will be implemented through four phases: 1) Database Development; 2) Data Communication; 3) BIM Integration; and 4) VR setup, Simulation, and Interaction. Phase 1 consists of designing the model's relational database to store all the collected data and information necessary for the integrated model from different sources, such as the literature, published standards and guidelines, governmental agencies, and expertise in the field of AIP design. Therefore, two databases, named Knowledge and Design Families, will be designed and created. Phase 2 consists of developing new plug-ins in BIM tool by using its API (Application Programming Interface), offering users with automatic and instant access to the databases developed in Phase 1. This will systematically incorporate UD Standards and AIP design requirements into a BIM environment at the conceptual design stage. Phase 3 aims at designing and creating a 3D BIM design model by using the databases and newly created plug-ins developed in phases 1 and 2, respectively. Phase 4 intends to integrate BIM and VR environments and to provide an immersive experience for a better means of communication and interaction between users and designers. This phase focuses on setting up the parameters and adjustments of the game environment, such as adding an avatar and a camera for users' interactions, for receiving their input and feedback, and to automatically incorporate them into the 3D design model.

3.1 Phase 1 - Database Development

The design and development of the databases are accomplished through two steps, starting with the conceptual modeling and ending with the physical implementation. Therefore, two major databases, a standard database and a design families database, will be developed. The standard database stores collected data about UD, AD, and AIP design guidelines; however, the collected data is divided into quantitative data, qualitative data, and AIP design requirements. The data is collected from various sources covering over seventeen guidelines and is stored in a series of tables forming the Knowledge Database. The Family Database is formed to store newly created and/or modified design families, which are already inherited in BIM tool (i.e., Autodesk Revit©) based on the stored data and information in the knowledge database. It is important to note that, although the principles of the methodology could potentially be applied to other BIM software, the specific implementation detailed in this manuscript is specifically customized for Autodesk Revit© environment. These design families have Revit Families (RFA) or Revit projects (RVT) file formats and are stored in the corresponding database. The aim of developing separate databases is to link them to the predefined paths in Revit's library. This linkage ensures an automatic loading whenever the plug-in is activated and thereafter a standard is selected by the designer. As a result, these families remain in the library so they would be easily accessed by the designer throughout the entire design process. The collected data and information used in this study are grouped into two sets: 1) the Residential Dwellings Data and Families (Indoor Items) and 2) the Public Area Data and Families (Outdoor Items). The significant benefit of the developed database resides in enhancing the functionality and capability of Autodesk Revit© at the conceptual design stage to help designers incorporate UD standards, AD guidelines, and AIP design requirements easily while designing proposed houses through instant access to the stored data during the design process.

3.2 Phase 2 - Data Communication

This phase focuses on customizing Autodesk Revit© to fit the modularity requirements of the model. The first step is to create new plug-ins in BIM's tool (i.e., Autodesk Revit©) by using its API and C# programming language to link the developed databases of phase 1 to it with the goal to facilitate the selection of new design families and the retrieval of their associated data and information while creating 3D design models of proposed houses. Autodesk provides powerful APIs (Application Programming Interface) and SDKs (Software Development Kits) that allow users to customize and alter the tool based on their needs. Initially, designers need to access the various UD standards, associated families, and AIP design requirements by using the created plug-in before starting the design process. Thereafter, they can view, download, share, and print the associated documents of the selected standards easily and instantly. Microsoft Excel© and MySQL© are used to create the knowledge database, while PHP (an open-source general-purpose scripting language) and C# (an object-oriented programming language) are used for the automation. In this study, MySQL and Microsoft Azure, as the cloud server, are used to help designers get instant access to the created databases. Data is automatically transferred from MS Excel tables to MySQL through a set of rules coded by 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-in 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© was carefully coded by using a combination of C# and PHP. C# language, specifically used to handle all the programming tasks, except

for connecting the plug-in to MySQL on the cloud server, where PHP was utilized. This strategic use of both languages allowed to leverage their strengths, addressing specific needs and optimizing the overall performance of the integrated system.

In the present study, a distinct approach involves the utilization of Microsoft Azure in conjunction with C# and PHP programming, whereas the authors' previously published study exclusively employed C# programming alongside using Dynamo. Dynamo's exclusion in the current research is attributed to its limitations in the capabilities of transferring the data. These adaptations were made to address specific challenges and enhance the efficiency of the integrated model.

The other type of data in the form of design families and original documents (guidelines) are stored in the cloud server separately. The created plug-in directly connects to the cloud server to query those design families and selected guidelines whenever they are needed. Also, the integrated model automatically evaluates the design elements and checks them to make sure they meet the requirements of the selected standards or guidelines. This is achieved when the created plug-in reads the properties of the selected and used families in the 3D design model in Autodesk Revit©, such as their width, height, length, etc., to make sure they are compatible with the data stored in the cloud server, which are specific to the guideline selected by the designer. In case of any discrepancies, the plug-in highlights the elements that do not comply with the selected guideline and proposes the correct data for those elements in relation to the selected guideline. Also, the plug-in can convert the units of measurements used in Autodesk Revit© to match the units of the stored data in the cloud server in an automatic manner.

3.3 Phase 3 - BIM Integration

This phase concentrates on designing and implementing a module that is linked to the external databases, which, in turn, are associated with BIM's tool to create 3D design models for proposed houses. This is achieved by using the newly created families and their associated components, which are automatically loaded and operated via the developed plug-in. Designers would be able to select and retrieve the compatible guidelines from the UD standard or AD standard stored in those databases. Once a guideline and its component(s) are selected during the design process, all the related design families are automatically loaded and placed in the same location where the general families of Autodesk Revit© are positioned to facilitate their use in creating 3D design models for proposed houses. At that stage, the cloud server will have a two-way interaction with the plug-in to help importing and exporting the data from and to the database. Once the design is complete, the plug-in will check all the design components based on the selected standard and guideline. If the design is acceptable, it will be saved; otherwise, a list of required modifications will be generated and shown for the designer to modify the design accordingly. The next step is checking the design based on the AIP design requirements and creating a checklist that is automatically accessible from another plug-in that has already been created in Autodesk Revit©. Designers can check the whole design and complete the checklist by providing/selecting the appropriate answer for each item. The items in that checklist are categorized as indoor and outdoor items, similar to the UD standard categories. Upon completing the checklist, two types of reports can be generated: 1) a tabulated list that shows the items that need modification or has not been completed yet, and 2) a status result list of the items that are generated based on the answers provided by the designer while completing the checklist.

3.4 Phase 4 - VR Setup, Simulation, and Interaction

The focus of this phase is on integrating BIM and VR. The development of VR applications in a game engine environment provides an immersive experience for users (Du, et al., 2018). This integration consists of four main steps: 1) model transfer; 2) data transfer; 3) database development; and 4) user interface design. The first step aims at transferring the 3D design model created in Autodesk Revit© to the game engine for additional development, which is one of the most prominent challenges designers would face. However, Autodesk Revit, as a BIM tool, supports various 3D file formats such as DWF and FBX. Exporting the 3D design model directly to the game engine leads to a loss of data, such as material properties and textures, during the transition. For that reason, it is necessary to configure them manually while in the game engine environment. To reduce the potential loss of data, middleware tools (i.e., SimLab Composer and Autodesk 3ds Max) can be used. This study used SimLab Composer because it supports various 3D file formats. Thus, the 3D design model is imported as a DWF file to the middleware tool and then as an FBX file to the game engine.

Steps 2 and 3 consist of developing a separate database and transferring specific data, such as components' dimensions, names and ID numbers, and material from Autodesk Revit© to the database linked to the game engine. The creation process of that database is automated and links Autodesk Revit© and the game engine to allow bilateral data transfer between them. MySQL and Microsoft Azure are used to create the database, then PHP and C# programming languages are used to automate the data transition and to link the data server to both Autodesk Revit© and the game engine. To link the database to Autodesk Revit©, two alternative methods were tested. In the first method, the Revit 3D design model is exported via Open Database Connectivity (ODBC) to MySQL database, while the other method is to read the model's information directly from the database into Unity. However, both methods proved to be problematic because some of the transmitted information of the model's elements and their associated properties were lost during the transfer from Revit to MySQL. Also, the database created by using the ODBC holds limited components and not all the ones used in the 3D design model. Then, Dynamo visual programming and the Slingshot package for Dynamo, which has built-in nodes used to create a database, were used. Rostamiasl and Jrade (2022) previously investigated this approach. Nonetheless, Dynamo appeared to be limited in terms of data transmission and connection to the cloud server. Therefore, in this present study, all connections are made by using PHP and C#. Data such as dimensions, names, and ID numbers of all components used in the 3D design model are stored in that database and are used in the game environment. Also, any user input or alteration while in the game environment will be automatically updated in the database and then reflected in Autodesk Revit's library.

The fourth step involves establishing a Virtual Reality Environment (VRE) and configuring the game engine parameters. This includes adding an avatar and camera to facilitate effective communication, visualization, and navigation within the model. In the game environment, users and designers can interact with various game objects, such as avatar, canvas, prefab, buttons, camera, label, text boxes, and assets. The avatar, representing the user or designer, has a rigid body and collider components to enhance realism and prevent collision with the building elements. The canvas incorporates the User Interface (UI) and Raycaster for user interaction, featuring a communication panel displaying detailed information about the components extracted from Autodesk Revit's database. The prefab integrates the 3D design model exported from the BIM environment into the VRE. Buttons enable users to confirm or cancel actions, while the camera provides a realistic line of sight, adjustable to the user's needs. Labels convey specific information like units, and text boxes allowing for user's inputs. 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© is selected to be a cross-platform game engine that supports 3D assets imported from Autodesk Revit© and because it runs on Android, iOS, and Windows Mobile Phones. The desktop VR is created to test the development of the proposed model. Then, a gaming environment is established to enhance the user's collaboration and interaction with the design. While users interact in the game environment, any desired modification(s) they make will be automatically reflected in both the database and the 3D design model. This automation, which is one of the main objectives of this study, will significantly reduce human errors and minimize the associated time and cost. Furthermore, by using a head-mounted device (HMD), sensor gloves, game controllers, and other related devices, an immersive VRE will be exercised, providing users with a realistic environment similar to if they are living in the design.

3.5 System Architecture and Integration Details

The system requirements for hardware, software, and network are as follows: A desktop or laptop computer with a minimum Intel Core i5 processor (or equivalent), a dedicated graphics card with at least 4GB VRAM, 8GB RAM or more, and a VR headset compatible with the chosen VR platform (e.g., Oculus Rift, HTC Vive). Software requirements include Windows 10 (64-bit), Autodesk Revit©, Unity© for VR environment development, Microsoft Excel© for database creation and management, MySQL© for database storage and retrieval, and programming languages C# for BIM plug-in development and PHP for cloud server interactions. A stable internet connection is required for cloud server access.

The VRE has its own database schema that stores information related to the virtual world, including assets, user interactions, and any specific data relevant to the VR environment. In this study, another database was added to VRE that stores information about different materials that are compatible with Autodesk Revit's library to be used by the user based on their preferences. BIM system, in this case, Autodesk Revit©, has its own database schema designed to store information about the 3D model, design families, materials, and other architectural elements. The schema includes tables for categories such as elements, materials, parameters, and relationships, allowing

Revit to maintain a structured representation of the building model. Furthermore, a comprehensive standard database was added as described in phase 1 of the methodology.

The synchronization process involves 1) Data transfer from Revit to VRE, including exporting the 3D model and materials; 2) User interactions in VRE, such as adjusting dimensions; 3) Data transmission from VRE to Revit; 4) Automated and manual updates to the Revit model; 5) Automated compliance checks; and 6) Database compatibility for VRE and Revit, requiring compatible structures and mappings. This may involve scripting, middleware, or API connections to facilitate communication between the two environments, as detailed in phases 1 through 4 of the methodology.

Technical choices include C# language for its robust object-oriented programming capabilities and compatibility with Autodesk Revit© through its API, and PHP for web-related tasks, particularly communication between Revit and the cloud server. MySQL was chosen for its capabilities as a relational database management system (RDBMS) and because it is suitable for managing structured data. Microsoft Azure (Cloud Server) was selected for its scalability, flexibility, and ease of integration with Microsoft technologies, and for enabling instant database access for designers. Unity was chosen as the game engine for the VR environment due to its widespread adoption, robust features, and compatibility with various platforms.

In the data processing pipeline, data encoding involves the systematic transformation of information into a format compatible with the developed system. The system employed industry-standard encoding methods to ensure the accuracy and integrity of the stored data. Data fetching from the databases is organized through a series of programmed procedures. Upon retrieval, the parsing mechanisms are meticulously applied to structure the obtained data for seamless integration into the system. The communication infrastructure between the local and distant servers is established through robust protocols, including secure data transfer mechanisms. The local server, hosting Microsoft Excel© and MySQL© databases, communicates with a distant server hosted on Microsoft Azure. This connectivity is coordinated through a combination of C# and PHP scripts, automating data transfer between the two environments. Specifically, C# is utilized for the encoding, fetching, and parsing processes, while PHP is employed for facilitating communication and data synchronization. This strategic use of languages enhances the efficiency and reliability of the developed system by contributing to the overall robustness of the adopted methodology in this study.

This study presented the development of a semi-automated model that integrates BIM with Universal Design standards, age-in-place requirements, and VR at the conceptual design stage of proposed houses to advocate the involvement of users to achieve age-friendly homes. The model consisted of four phases and the level of automation in each phase is as follows: In Database Development (Phase 1), a combination of automated and manual processes is employed. Manual processes include data extraction from various sources, stored in Excel files, and automatically transferred to MySQL and Cloud servers by using scripts and programming languages. For Data Communication (Phase 2), the development of new plug-ins in Autodesk Revit© is automated through the tool's API and C# programming language. The data transfer from Microsoft Excel© to MySQL© is automated, while the connections between MySQL, the cloud server, and Autodesk Revit© are scripted in C# and PHP. BIM Integration (Phase 3) involves an automated module for selecting and retrieving guidelines, but the final decision-making stage requires manual validation by designers to ensure compliance with the end-user needs. In VR Setup, Simulation, and Interaction (Phase 4), manual configuration in the game engine environment is acknowledged. The export of 3D design models from BIM to the game engine is partly manual due to the potential of data loss during the direct export. However, the data transfer from the VR environment to Autodesk Revit© is automated.

4. MODEL TESTING

To test the developed model and to examine its performance and capabilities, a one-story single-family house in Ottawa, Ontario, Canada, is used. The selected house has two bedrooms, a guest room, a living room, a kitchen, two bathrooms, a utility room, and an attached garage. Autodesk Revit© is selected as BIM tool to create the 3D design model for the house with all its geometry and non-geometry components, such as walls, doors, windows, floor, stairs, and cabinets, as illustrated in Figure 2. To create the 3D design model of the selected house, the data and families stored in the external database are retrieved through the newly created plug-in named as SUD (Sustainable Universal Design) in Autodesk Revit©. SUD plug-in helps designers to select and incorporate the appropriate standard and guidelines from the database. For the selected house, the City of Ottawa's Accessibility Design Standard is used. After making the selection, designers must choose from different options for their next

step, such as reading the related documents; comparing the various standards and guidelines; checking the created components based on the selected guideline; or using the associated design families to implement the selected standard into the house's 3D design model. By running the SUD plug-in, designers have access to different design options such as UD, AD, Sustainable Design, or Sustainable Universal Design. This paper focuses on UD, AD and Age-in-Place Design (AIP), as shown in Figure 3. Upon selecting the UD or AD option and then clicking the standard button, designers are given access to the information related to the selected design standard via a new screen, as displayed in Figure 4, so designers can choose a specific guideline, then a category, indoor or outdoor, and then select the items needed for the 3D design model. After that, designers will have access to additional information about the selected item(s) in the form of numerical data, such as items' dimensions (width, length, height, depth, ratio, or degree), and descriptive data in the form of comments retrieved from the knowledge database. The developed model is bilingual; therefore, designers can select their preferred language when running the model and its associated components. Figure 4 shows a door selected from the Accessibility Standard (City of Ottawa) and its related data. Such data helps designers view the item's requirements to ensure they meet the expected occupants' needs. Also, it reduces the possibility of making errors and significantly saves time. As soon as the "Family" button is clicked, the families' database is activated, then the families related to the selected item are automatically placed in the library of Autodesk Revit© to be used in the house project. By selecting the Document button, designers gain access to both the original documents of the selected guideline and the specific item, as illustrated in Figure 5. Furthermore, designers can view, read, share, save, and print those documents.

The last button is the "Standard Check", which helps designers check if the components used in the 3D design model for the house comply with the selected code or standard. If errors are found, they will be highlighted in red and presented to designers for corrective actions. Otherwise, they will be highlighted in green, which means they comply with the code. For example, Figure 6 shows that all doors in the created 3D design model for the house obey Ottawa's Accessible Design Standard.
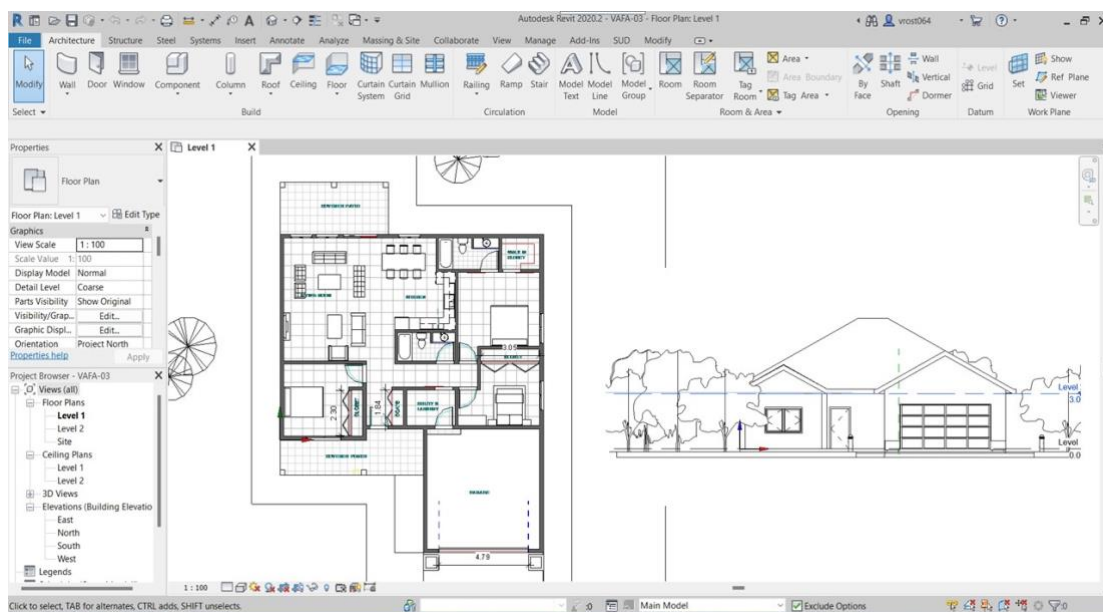

Figure 2: Plan & Elevation of the Proposed Model.

Upon completing the design and closing the SUD plug-in's view, a new window pops up and asks designers if they need to continue checking the AIP design requirements, as displayed in Figure 7. If designers continue with this option, a new window opens so that they can use the comprehensive checklist of the AIP design requirements to ensure their design meets the requirements. To simplify the use of the checklist, it is divided into two main groups similar to the items of the UD standards (indoor and outdoor items). By selecting any category, a list of its sub-categories appears for designers to check the requirements of each item, as shown in Figure 7. Three options are related to each requirement as follows: 1) Yes, which means the design meets the requirement; 2) No, which means the design does not meet the requirement; and 3) N/A, which means not applicable to the design. Also, the checklist can be accessed through another plug-in that is created in Autodesk Revit©. Once the checklist is

completed, two reports can be generated: 1) A report that shows a list of all the items that need to be modified or have not been completed yet; and 2) A report that lists all the requirements that have been answered by the designer beside their status. Figures 8 and 9 display samples of those reports. While the system automatically checks UD, AD, and building code compliance, the verification for Age-in-Place (AIP) requirements is manually fulfilled. Designers use the generated reports to manually ensure AIP compliance. This intentional approach allows for a detailed review, particularly for subjective aspects, aiding designers in making informed decisions.
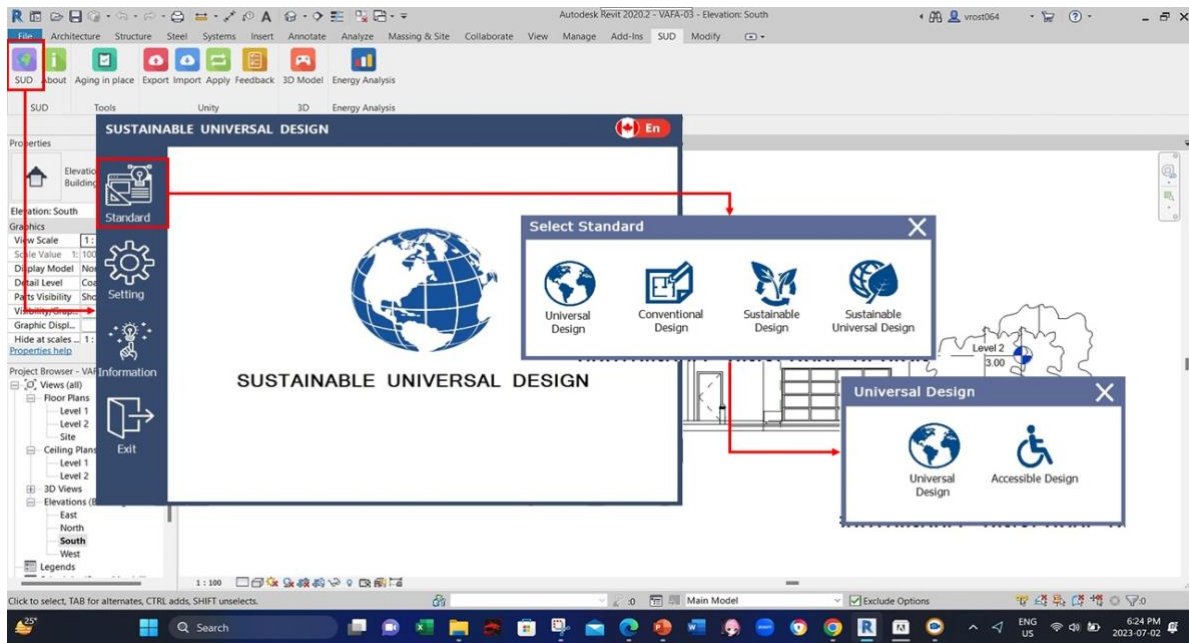
Figure 3: SUD Plug-in and Selecting Specific Guideline.
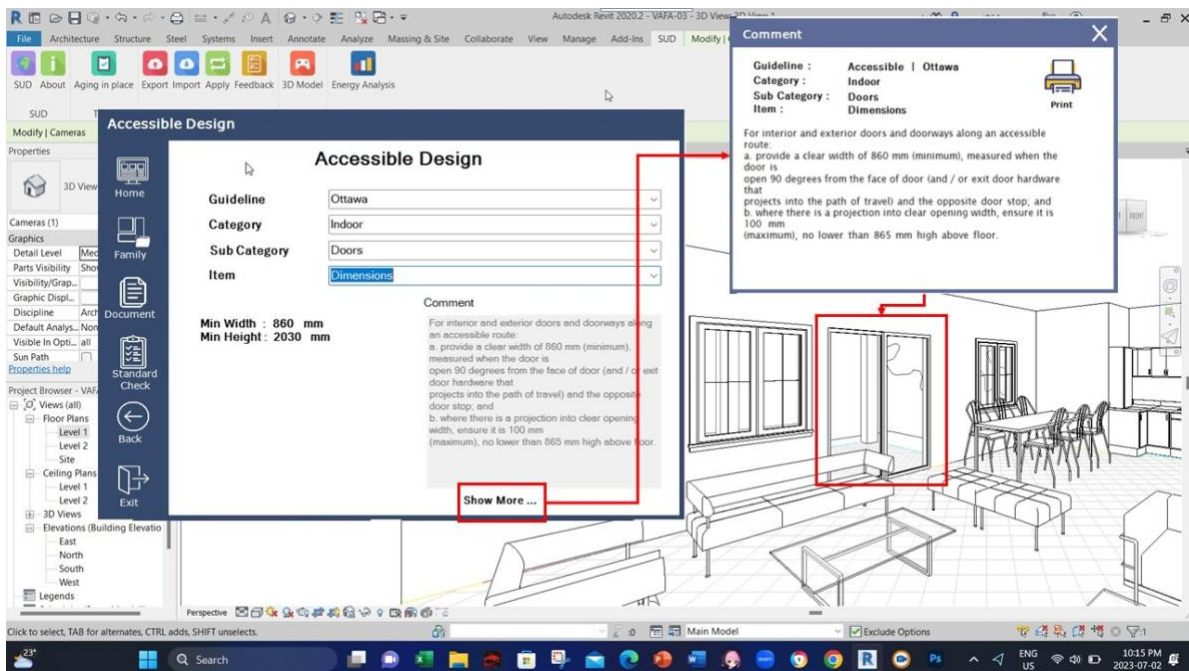
Figure 4: Retrieving Data from Selected Guideline.
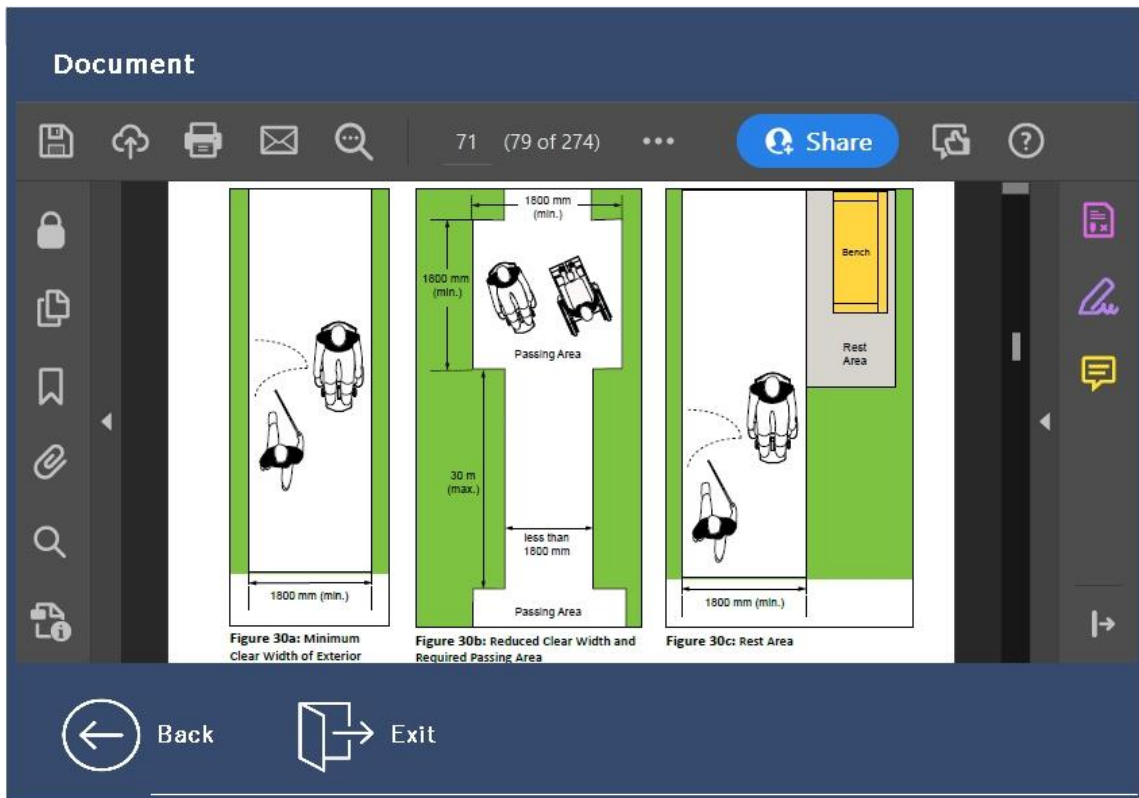
Figure 5: Retrieving Original Document.

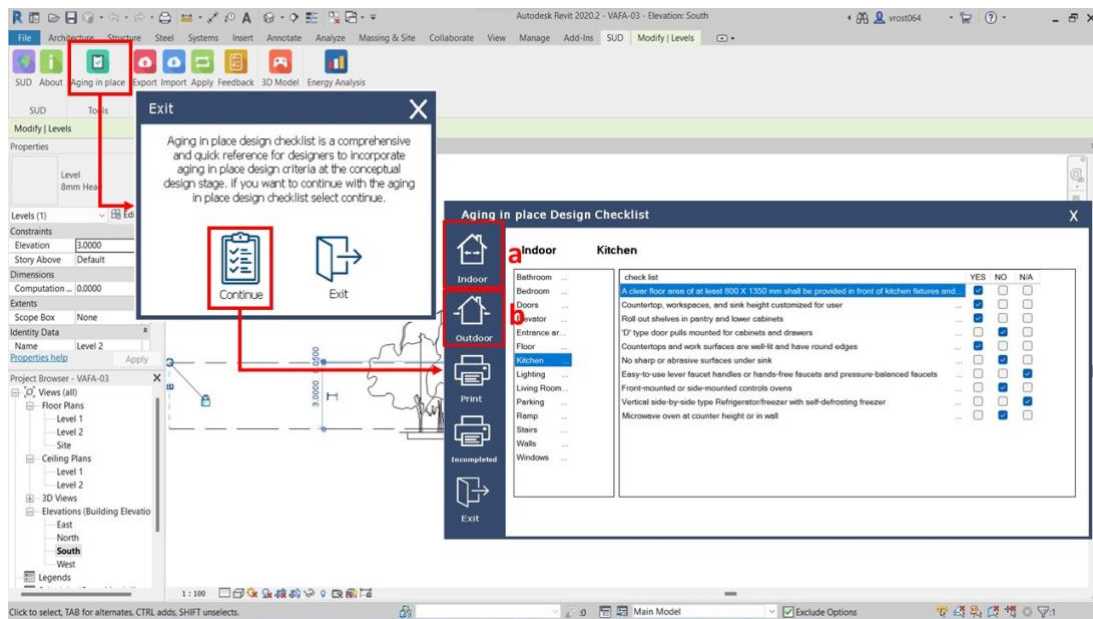*Figure 6: Code Compliance Checking Sample.*

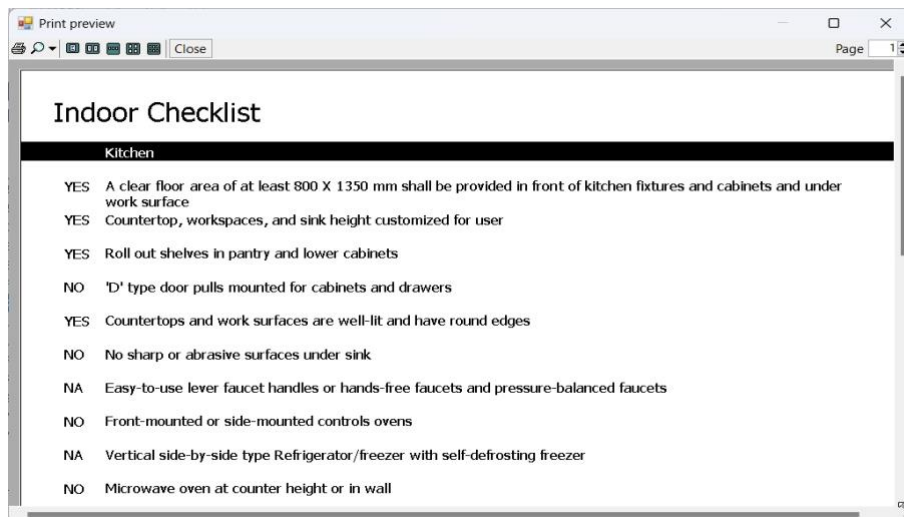*Figure 7: Plug-in for Age in Place Design (AIP) Requirements.*

Figure 8: Sample of Checklist Report.

To integrate BIM with a game engine, the created 3D design model is transferred from Autodesk Revit to Unity game engine by using SimLab Composer as a middleware tool. A database is then created in MySQL in the cloud server whose data can be automatically imported and exported from Revit and the Unity game engine to MySQL database by using C# and PHP programming languages. That database is the link between Autodesk Revit© and the Game engine. After transferring the BIM 3D design model to the Unity game engine, a VRE is established where necessary adjustments are made to the 3D design model, such as adding an avatar (representing the user), a camera, a communication panel using UI, and collision adjustments. Now users can explore and walk through the designed house. By implementing additional adjustments for the doors, they will instantly open when the avatar moves toward them and will be closed when it moves away. Therefore, the user can walk through the house from the outside, move toward the entrance, and then go inside and walk into the house. Furthermore, due to the collision adjustments, the avatar is able to collide with objects such as doors and walls instead of running through them. Once all the needed adjustments are completed and the necessary items for the 3D design model are added to the Unity game engine, the gaming environment is developed and made ready for designers to use. In this phase, by running the Export plug-in that has been created in Autodesk Revit©, a new window opens, as illustrated in Figure 10.
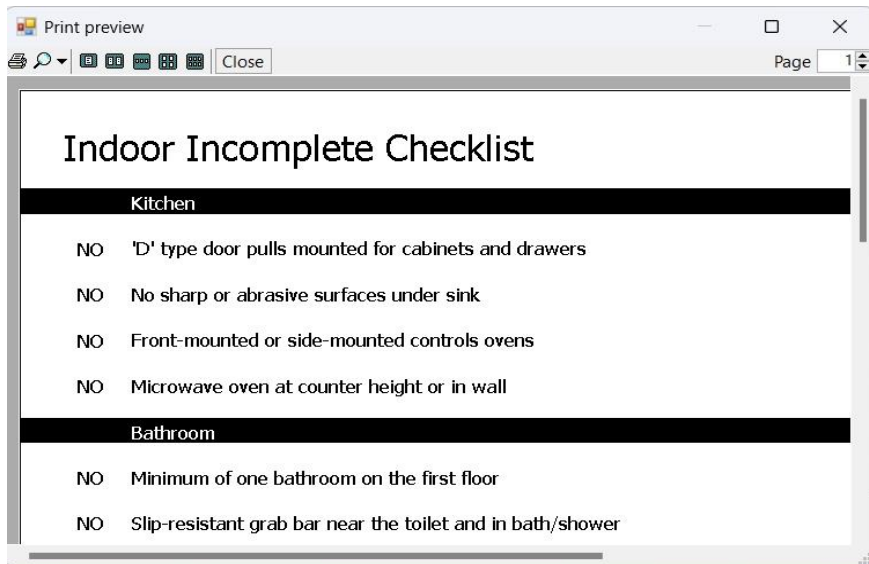
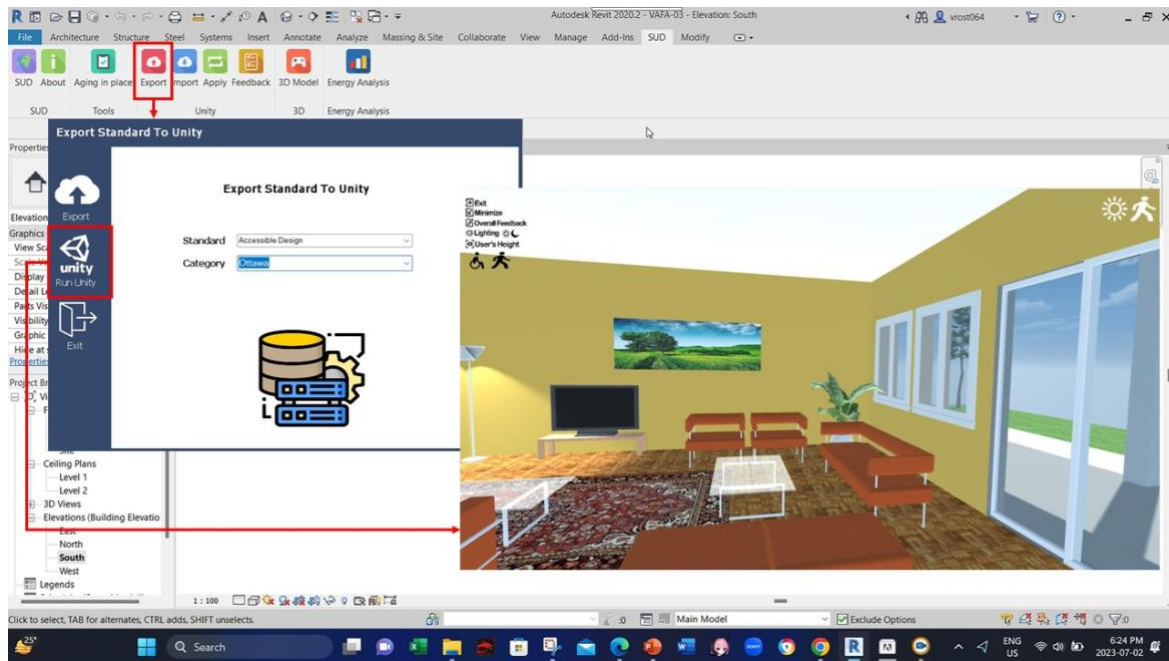*Figure 9: Sample of the Incomplete Item's Report.*

Figure 10: The Plugin Created to Transfer Data to the Game Engine and Automate the Integration.

Selecting the Export button in that window, all the data related to the components used in the 3D design model, such as their names, IDs, dimensions, and the selected standard or guideline, will be automatically transferred to the MySQL database and the cloud server. Then, once the Run Unity button is clicked, designers have instant access to the VRE and game application that is created in the Unity game engine, as shown in Figure 10. The said plug-in permits designers to access the developed game scene and instantly explore the design while in a BIM environment and to bilaterally navigate between the game scene and the 3D design model. Figure 11 shows the developed game environment and its primary functions.
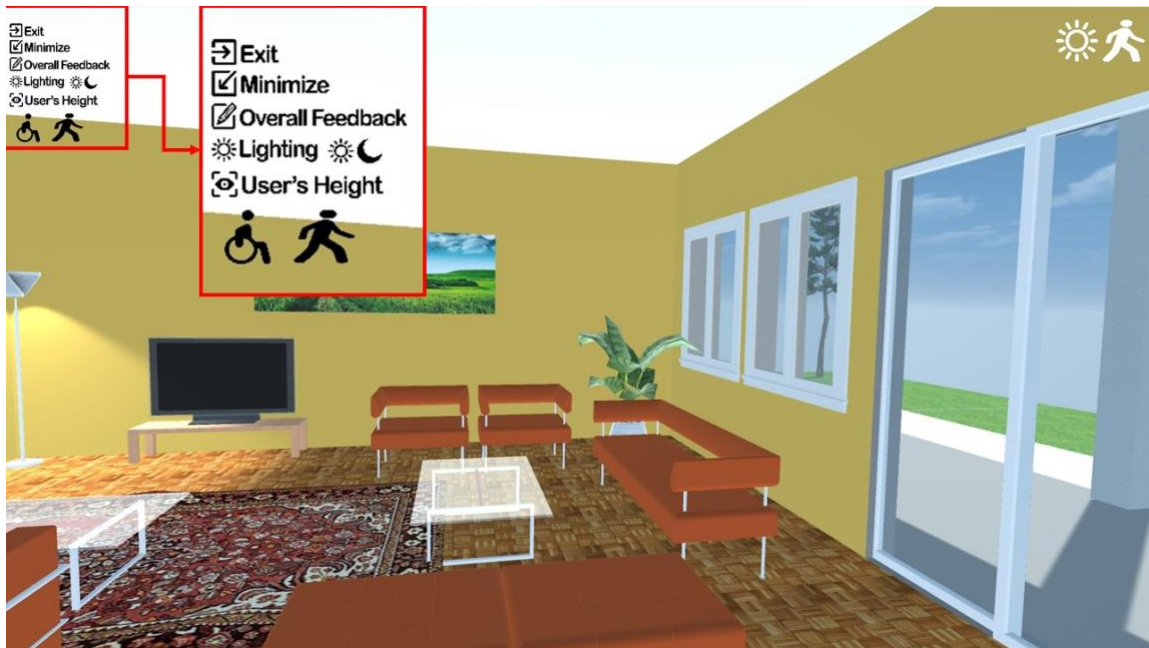
Figure 11: The Developed Gaming Environment and Its Functions.

Figure 12: Selecting Day or Night Mode.

These functions are: 1) switching between day or night modes, as illustrated in Figure 12; 2) a text box for users to write their overall/general feedback from the design or their comments, as displayed in Figure 13; and 3) adjusting the camera's height based on the user's actual height as shown in Figure 14. The camera is placed at the user's height of vision in an attempt to provide realistic scenes. Once users adjust the height based on their actual vision height, the camera's position is automatically adjusted. Also, wheelchair mode can be selected for wheelchair users. The most important part of this phase is the creation of a communication panel by using UI elements. This panel is designed for most of the model's components, such as doors, windows, cabinets, furniture, etc., and is made available for users by clicking on each object in the game application. Concerning the system families like walls and floors, it is crucial to emphasize that users have the capability to interact with and modify

specific parameters of these system families, specifically by focusing on the elements such as wall and floor finishes. The created panel, as shown in Figures 15 and 16, consists of the following elements: 1) Object's ID number and name, which are imported from the BIM 3D design model; 2) Objects' dimensions, such as width and height, according to the Revit database; 3) Virtual keyboard to input data (users' input); 4) Interactive menu bars to change the dimensions and users' entered dimensions (Users can use the physical or virtual keyboard); 5) Selected standard and guideline in the Revit's model; 6) Object's limitations based on the guideline and along with the related descriptive information that will be retrieved automatically from the selected guideline, which is stored in the database; 7) Confirmation or cancellation buttons; and 8) A text box for users to input their feedback related to each object separately.

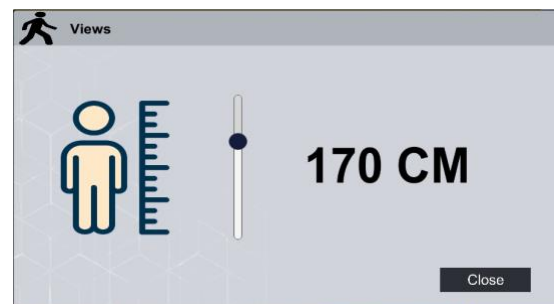
Figure 13: Writing General Feedback and Comments by Users.

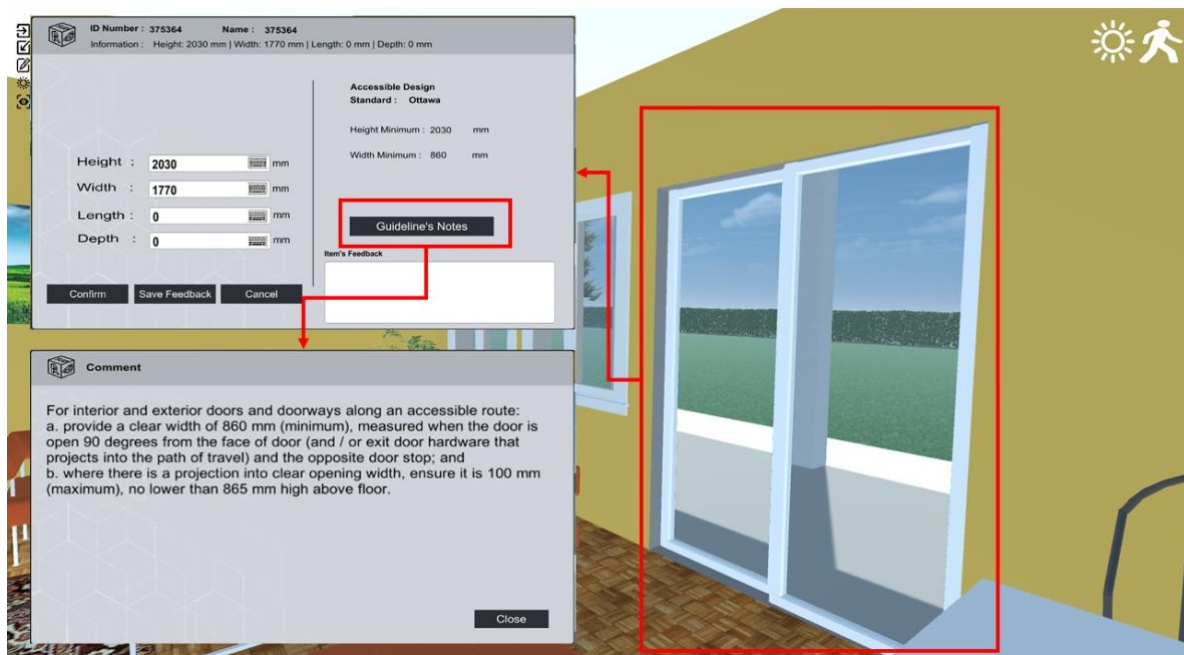*Figure 14: Adjusting the user's Height and Level of Vision.*

Figure 15: Communication Panel in the Game Environment.

Figure 16 illustrates an example of the user's input. In this example, the user selected a glass door with an original height of 2,030 mm and a width of 1,770 mm. All the information related to the selected door is retrieved and shown automatically in the communication panel. For the first attempt, the height of the door decreased from 2,030 mm to 2,000 mm. Since the new dimension does not comply with the selected guideline, the plug-in determines the error, and a warning sign is shown in the panel besides showing the minimum acceptable height of the door that is compatible with the selected guideline. This information is highlighted in red to notify users of the error and to help them select the correct dimension. Then, users can write a comment in the object's feedback text box to notify designers of their requests. Another significant advantage of the created game environment is the ability to change some properties of the objects, such as the color or materials type instantly. For instance, users can select a different color for the wall or different flooring material. There are predefined options that are stored in the game database, which can be selected by users. The database was established by aligning it with Revit's materials' library to ensure compatibility with the materials presented in the 3D design model. Upon user's selection, the changes can be seen in the game scene immediately, and users can decide if they want to select them. Figure 17 shows an example of this function. Upon confirming and saving the modifications, MySQL and cloud database are automatically updated. Next, designers can import all the changes into Autodesk Revit© by using the Import Plug-in, which is created in Autodesk Revit© for that purpose, as displayed in Figure 18. Once that plug-in is activated, a report is generated listing all the modifications done by users to the 3D design model while in the game environment, in addition to the comments entered by users. A Feedback plug-in is created in Autodesk Revit©, allowing designers access all the comments made while in the game environment, which acts as a two-way communication channel between BIM and VRE, as pictured in Figure 18. It is worth mentioning that the system does not autonomously interpret subjective user's comments, such as 'Tinted glass is preferable,' and directly implements specific design changes. Instead, these comments serve as input for the designer. Upon reviewing the user's comments, the designer is responsible for manually implementing the desired modifications in Revit's 3D design model. The automation, in this context, pertains to changing the dimensions of components like doors, railings, and windows, as well as the finishes of walls and floors. Additionally, it facilitates the seamless transfer of user's inputs from the VR environment to the design environment, streamlining the collaboration process between users and designers.
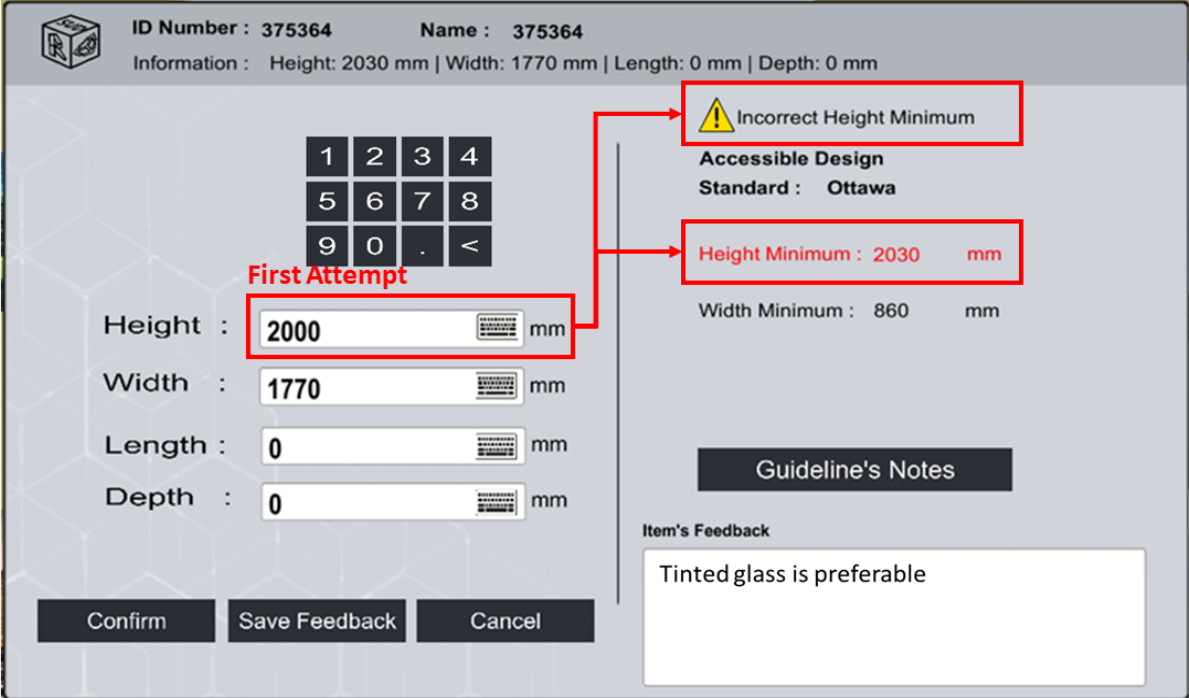

Figure 16: User's Communication With the 3D Model.

One of the main advantages of the developed model is the automatic update of the BIM 3D design model. By running the Import plug-in, all the modifications done in the game environment are automatically applied to Revit's 3D design model. This process is examined for other items as well, such as windows, doors, cabinets, and furniture, where the results appear to be efficient. The developed model gives users and designers an immersive opportunity to modify their design based on occupants' needs, to reduce potential errors, and to communicate effectively through the game scene.

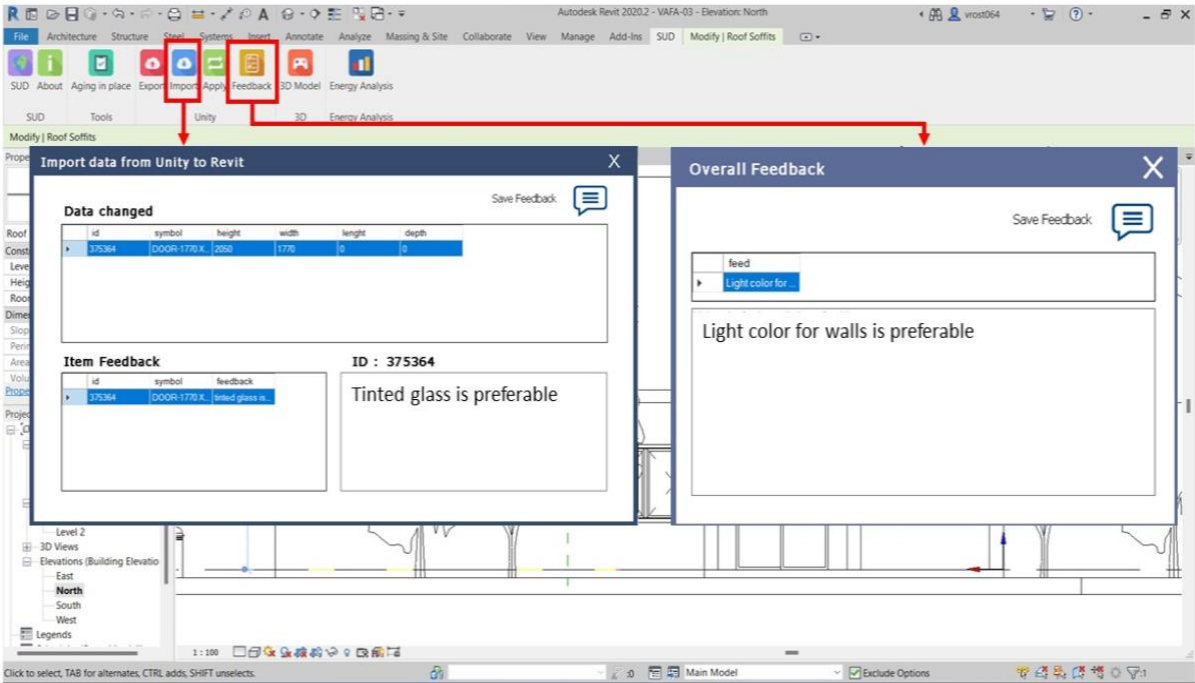*Figure 17: Selecting Different Material by User.*

Figure 18: BIM-VR Integration.

5. CONCLUSION, LIMITATIONS AND FUTURE WORKS

The integrated model described in this paper assists designers and owners in sharing various information at the conceptual design stage of Universal and AIP houses and significantly promotes communication between them. The described model focuses on automating the process of connecting the output of the BIM 3D design model with external databases and a VRE. It allows owners and designers to interact with the design of houses in a gaming environment. Also, it helps designers have full access to various standards and guidelines related to Universal and Accessible designs, as well as Age-In-Place (AIP) design requirements, with the attempt to increase the efficiency and availability of the data needed when designing universal houses. The model's development was implemented through four phases. Phase 1, focused on collecting, categorizing, and storing data from various UD and AD guidelines and AIP design requirements; then, databases were created to store these data as well as the newly created/modified design families and components. Phase 2, consisted of developing new plug-ins in BIM tool (Autodesk Revit) to link the developed databases with Revit by using its API, C# and PHP programming languages in order to automate the process of retrieving necessary information and components from the database, then integrating Autodesk Revit© with a game engine. Phase 3, comprised the creation of a BIM 3D design model by using the data from the databases of Phase 1 and the plug-ins of Phase 2. Phase 4 included VR Environment setup, game application development, and user interactions. The focus of this study is on the conceptual design stage of houses, where designers need access to vital information when selecting and applying the UD standards and AIP design requirements for proposed projects. Also, they need to have effective communication with owners/users to ensure the design meets their goals. Reducing future modifications and alterations and minimizing associated costs are parts of the model's advantages. Another advantage of the described model is its competency to provide designers with a variety of information about all the design elements in the form of dimensions, color, texture, and other descriptive information, in addition to providing instant access to the original documented standards. Furthermore, the developed model can automatically check the design elements and compare them with the selected standard or guideline to verify that those elements meet the selected standard and guidelines' requirements in both BIM and VR Environments. Regardless of the many advantages of the described model, it has several limitations and constraints. One of its major limitations is that not all the design components can be converted to Autodesk Revit© families to meet the UD standards. Therefore, for those components, designers must read the guidelines and apply their requirements while designing and using them. These guidelines can be accessed via a plug-in that was developed and inherited into Autodesk Revit©. Another limitation of the model is that the changes in Autodesk Revit© cannot be applied automatically in VRE due to the difficulties in exporting the 3D design model to the game engine. Thus, the authors are working on enhancing the model's efficiency by creating two-way automated connections between Autodesk Revit© and VRE so that any update in one of the two environments is automatically reflected in the second one.

The model presented in this study facilitates the design of houses that comply with elderlies requirements who want to age in their homes rather than going to long-term care facilities to overcome potential risks that influence such facilities, as was the case during the Covid-19 pandemic.

REFERENCES

Abanda, F. H., Vidalakis, C., Oti, A. H. & Tah, J. M., (2015). A critical analysis of Building Information Modelling systems used in construction projects. *Advances in Engineering Software,* December , Volume 90, pp. 183-201.

Akanmu, A. A., Olayiwola, J. & Olatunji, O. A., (2020). Automated checking of building component accessibility for maintenance. *Automation in Construction,* 26 March.

Akin, S., Ergün, O., Surer, E. & Dino, İ. G., (2018). *An Immersive Design Environment for Performance-Based Architectural Design: A BIM-based Approach. 4th EAI International Conference on Smart Objects and Technologies for Social Good,* pp. 306-307.

Alsayyar, B. & Jrade, A., (2017). *Integrating building information modeling (BIM) with sustainable universal design strategies to evaluate the costs and benefits of building projects. Proceedings of Canadian Society for Civil Engineering,* pp. 300-309.

Balali, V., Noghabaei, M., Heydarian, A. & Han, K., (2018). *Improved Stakeholder Communication and Visualizations: Real-Time Interaction and Cost Estimation within Immersive Virtual Environments. Proceedings Construction Research Congress,* New Orleans, pp. 522 - 530.

Canadian Human Rights Commission, (2006). *International Best Practices in Universal Design.* [Online]
Available at: https://www.chrc-ccdp.gc.ca/en/resources/publications/international-best-practices-universal-design-a-global-review
[Accessed 2021].

Carr, K., Weir, P. L., Azar, D. & Azar, N. R., (2013). Universal Design: A Step toward Successful Aging. *Journal of Aging Research,* Volume 2013.

Chao-Yung, H., Yien, H.-W., Chen, Y.-P. & Yu-Chih, S., (2017). *Developing a BIM-Based Visualization and Interactive System for Healthcare Design. Proceedings of 34th International Symposium on Automation and Robotics in Construction (ISARC 2017),* Taipei, Taiwan,

Chau, H.-W. & Jamei, E., (2021). Age-Friendly Built Environment. *Encyclopedia,* pp. 781-791.

Cheng, J. & Das, M., (2014). A BIM-Based Web Service Framework for Green Building Energy Simulation and Code Checking. *Journal of Information Technology in Construction,* Volume 19, pp. 150-168.

Choi, J. & Kim, I., (2017). *A Methodology of Building Code Checking System for Building Permission Based on openBIM. Proceedings of the 34th ISARC,* Taipei, pp. 945-950.

CIHI, (2021). *COVID-19's impact on long-term care.* [Online]
Available at: https://www.cihi.ca/en/covid-19-resources/impact-of-covid-19-on-canadas-health-care-systems/long-term-care
[Accessed 01 02 2023].

Crews, D. E. & Zavotka, S., (2006). Aging, Disability, and Frailty: Implications for Universal Design. *Journal of PHYSIOLOGICAL ANTHROPOLOGY,* 02, 25(1), pp. 113-118.

CSA, (2020). *A Canadian Roadmap for Accessibility Standards Advisory Panel, Canadian Standards Association.* [Online]
Available at: www.csagroup.org/article/research/a-canadian-roadmap-for-accessibility-standards/
[Accessed 2021].

DAVIDSON, J. et al., (2020). Integration of VR with BIM to facilitate real-time creation of bill of quantities during the design phase: A proof of concept study. *Frontiers of Engineering Management,* Volume 7, p. 396–403.

Dela Cruz, O. G. & DAJAC, J. S., (2021). Virtual Reality (VR): A Review on its Application in Construction Safety. *Turkish Journal of Computer and Mathematics Education,* 12(11), pp. 3379- 3393.

Du, J., Zou, Z., Shi, Y. & Zhao, D., (2018). Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. *Automation in Construction,* January, Volume 85, pp. 51-64.

Estabrooks, C. A. et al., (2020). Restoring trust: COVID-19 and the future of long-term care in Canada. *FACETS,* Volume 5, p. 651–691.

Haselwandter, E. M. et al., (2014). The Built Environment, Physical Activity, and Aging in the United States: A State of the Science Review. *Journal of Aging and Physical Activity,* June, 23(2), pp. 323-329.

Häußler, M., Esser, S. & Borrmann, A., (2021). Code Compliance Checking of Railway Designs by Integrating BIM, BPMN and DMN. *Automation in Construction,* Volume 121.

Huang, Y. & Odeleye, T., (2018). *Comparing the Capabilities of Virtual Reality Applications for Architecture and Construction.* Proceedings of 54th ASC International Conference.

Jrade, A. & Valdez, P., (2012). *Integrating Building Information Modeling with universal design requirements for high accessible homes.* Proceedings of Construction Research Congress 2012, pp. 1290-1300.

Kamel, E. & Memari, A. M., (2019). Review of BIM's application in energy simulation: Tools, issues, and solutions. *Automation in Construction,* January, Volume 97, pp. 164-180.

Khattra, S., Rai, H. & Singh, J., (2022). Towards Automated Structural Stability Design of Buildings—A BIM-Based Solution. *Buildings (Basel),* Volume 12.

Kincelova, K., Boton, C., Blanchet, P. & Dagenais, C., (2020). Fire Safety in Tall Timber Building: A BIM-Based Automated Code-Checking Approach. *Buildings (Basel),* Volume 10.

Lin, Y.-C.et al., (2018). Integrated BIM, game engine and VR technologies for healthcare design: A case study in cancer hospital. *Advanced Engineering Informatics,* April, Volume 36, pp. 130-145.

Li, X. et al., (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Automation in Construction,* Volume 86, pp. 150-162.

Narayanswamy, H. L. & Al-Hussein, M., (2019). *BIM-Based Automated Design Checking for Building Permit in the Light-Frame Building Industry.* proceedings of the International Symposium on Automation and Robotics in Construction, Banff, pp. 1042-1049.

Natephra, W. & Motamedi, A., (2019). *BIM-based Live Sensor Data Visualization Using Virtual Reality for Monitoring Indoor Conditions.* Proceedings of 24th Annual Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2019), Wellington, New Zealand,

Natephra, W., Motamedi, A., Fukuda, T. & Yabuki, N., (2017). Integrating building information modeling and virtual reality development engines for building indoor lighting design. *Visualization in Engineering,* 5(19).

P.P.J., H., (2010). Changing Housing for Elderly People and Co-ordination Issues in Europe. *Housing Studies,* 14 Jul, 16(5), pp. 651-673.

Panya, D. S., Kim, T. & Choo, S., (2023). An interactive design change methodology using a BIM-based Virtual Reality and Augmented Reality. *Journal of Building Engineering,* Volume 68.

Park, H. et al., (2018). *BIM-based Virtual Reality and Human Behavior Simulation For Safety Design. Prpceedings of* 36th eCAADe Conference, Lodz, pp. 823-832.

Patlakas, P., Livingstone, A., Hairstans, R. & Neighbour, G., (2018). Automatic Code Compliance with Multi-Dimensional Data Fitting in a BIM Context. *Advanced Engineering Informatics,* Volume 38, pp. 216-231.

Prabhakaran, A., Mahamadu, A.-M., Mahdjoubi, L. & Manu, P. A., (2020). An Approach for Integrating Mixed Reality into BIM for Early Stage Design Coordination. *MATEC Web of Conferences,* Volume 312.

Rostamiasl, V. & Jrade, A., (2022). Integrating Universal Design Standards and Building Information Modeling at the Conceptual Design Stage of Buildings. *Open Journal of Civil Engineering,* Volume 12, pp. 492-523.

Shahinmoghadam, M., Natephra, W. & Motamedi, A., (2021). BIM- and IoT-based virtual reality tool for real-time thermal comfort assessment in building enclosures. *Building and Environment,* Volume 199.

Shengyi, L. & Jia, W., (2016). *Research on integrated application of Virtual Reality technology based on BIM.* Proceedings of 28th Chinese Control and Decision Conference (CCDC), pp. 2865-2868.

Sinclair, S., de Silva, A. & Kopanidis, F., (2020). *Exploring the economic value embedded in housing built to universal design principles,* Centre for Urban Research.

Statistics Canada, (2022). *Statistics Canada.* [Online]
Available at: https://www150.statcan.gc.ca/n1/pub/91-520-x/91-520-x2022001-eng.htm
[Accessed 31 01 2023].

Tan, Y., Xu, W., Li, S. & Chen, . K., (2022). Augmented and Virtual Reality (AR/VR) for Education and Training in the AEC Industry: A Systematic Review of Research and Applications. *Buildings,* 12(10).

United Nations, (2022). *World population prospect 2022,* New York: United Nations.

Varma, I., (2018). *Housing Design for All.* Proceedings of Universal Design & Higher Education in Transformation Congress, Dublin Castle.

Watchorn, V. et al., (2021). An integrated literature review of the current discourse around universal design. *DISABILITY AND REHABILITATION,* 43(1), pp. 1-12.

WHO, (2007). *Global Age-friendly Cities: A Guide.* Geneva: World Health Organization.

Wolfartsbkerger, J., Zenisek, J., Sievi, C. & Silmbroth, M., (2017). *A virtual reality supported 3D environment for engineering design review*, Proceedings of 23rd International Conference on Virtual System & Multimedia (VSMM), Dublin, Ireland, 1-8.

Wu, S., Hou, L., Zhang, G. & Chen, H., (2022). Real-time mixed reality-based visual warning for construction workforce safety. *Automation in Construction,* 139(2).

Wu, T.-H.et al., (2019). A virtual reality tool for training in global engineering collaboration. *Universal Access in the Information Society,* 1 June, 18(2), pp. 243-255.

Wu, W. & Handziuk, E., (2013). *Use of Building Information Modeling in Aging-in-Place Projects: A Proof of Concept. Proceedings of* Computing in Civil Engineering, pp. 443-450.

Wu, W. & Kaushik, I., (2015). Design for sustainable aging: improving design communication through building information modeling and game engine integration. *Procedia Engineering,* Volume 118, pp. 926-933.

Yan, W., Culp, C. & Graf, R., (2011). Integrating BIM and Gaming for Real-Time Interactive Architectural Visualization. *Automation in Construction,* Volume 20, pp. 446-458.

Zaker, R. & Coloma, E., (2018). Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study. *Visualization in Engineering,* 6(4), pp. 1-15.

Zhang, F., Chan, A. P., Darko, A. & Li, D., (2021). BIM-enabled multi-level assessment of age-friendliness of urban housing based on multiscale spatial framework: enlightenments of housing support for "aging-in-place". *Sustainable Cities and Society,* Volume 72.

Zhao, X. et al., (2023). Extended Reality for Safe and Effective Construction Management: State-of-the-Art, Challenges, and Future Directions. *Buildings ,* Volume 13,155.