INTEGRATING BUILDING INFORMATION MODELING (BIM) AND VIRTUAL REALITY (VR) FOR SUSTAINABLE UNIVERSAL DESIGN AT THE CONCEPTUAL STAGE OF HOUSING PROJECTS

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To

My Mother

My Husband and My Daughter

and

My Siblings

Acknowledgments

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ABSTRACT

INTEGRATING BUILDING INFORMATION MODELING (BIM) AND VIRTUAL REALITY (VR) FOR SUSTAINABLE UNIVERSAL DESIGN AT THE CONCEPTUAL STAGE OF HOUSING PROJECTS

While Canada is witnessing a significant demographic alteration due to the aging population, particular re-evaluation, and revolutionary methodologies in the designing domains, notably in residential construction, are becoming a necessity. This thesis elucidates the complicated challenges and paradigm shifts in the housing demands, which is caused by this demographic evolution, focusing primarily on the development of a computer model that integrates Universal Design (UD), Building Information Modeling (BIM), Virtual Reality (VR), Energy Analysis (EA), Life Cycle Assessment (LCA), and Life Cycle Cost Analysis (LCCA) to be used when creating homes for optimal aging-in-place.

The said model is innovative by utilizing new plug-ins and databases, allowing for the application of UD principles at the conceptual stage in an efficient and cost-effective manner. It enables designers and owners to select the best design options based on their predefined criteria and offers real-time simulation in an interactive environment, improving communication and interaction between owners and designers. This helps in minimizing future modifications by aligning designs more closely with the inhabitants' needs. The model accommodates the incorporation of various universal and accessible design guidelines, fostering the automated retrieval of essential information and components, thereby facilitating designers and homeowners in opting for optimal design and providing an exclusive real-time interactive simulation environment, effective communication and cooperation between designers and owners, and mitigating future architectural modifications by aligning designs closely with the inhabitants' needs. The model has the form of a cloud-based integration between BIM, UD, Aging-in-Place (AIP) prerequisites, and Virtual Reality (VR), which enhances owner engagement early during the initial design stages and optimizes the overall design outputs. Furthermore, it incorporates energy analysis tools through novel plug-ins developed to improve the design of elements such as window design and building orientation, to enable optimized energy consumption, and to enhance the building's performance toward sustainable universal design (SUD). In addition, the model incorporates a module that is dedicated to Life Cycle Assessment (LCA). That module facilitates the automatic calculation of carbon emissions by enabling designers to select optimal materials for components such as walls and roofs. Incorporating LCA into the model offers a framework for evaluating the environmental impacts of design choices, besides enhancing the sustainability and ecological considerations of aging-in-place residential design. Whereas, LCCA, which is integrated into this automated model, offers a framework to evaluate the economic impacts of incorporating UD principles by assessing the entire life cycle of a building, from conception to renovation or disposal. It elucidates the economic possibility of long-term investments in UD, showcasing substantial cost reductions in future renovations due to upfront incorporations of accessibility features.

This research emphasizes the importance of integrating BIM, UD, VR, EA, LCA, and LCCA during the decision-making processes that are related to aging-in-place design, offering a foundational approach for designing homes that improve the quality of life for seniors. This holistic approach underscores the importance of addressing environmental concerns alongside functional and economic considerations in creating homes tailored for optimal aging-in-place experiences. These homes are financially sustainable and support the aging population's desire to live independently and comfortably in their later years, contributing significantly to the development of inclusive and adaptive residences for Canada's aging demographic.

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List of Abbreviations

ACA	Accessible Canada Act
AD	Accessible Design
AEC	Architecture, Engineering and Construction
AECO	Architecture, Engineering, Construction, Owner-operated
AFC	Age-friendly Cities
AIA	American Institute of Architects
AIP	Aging in Place
AODA	Accessibility for Ontarians with Disabilities Act
API	Application Programming Interface
AR	Augmented Reality
BEM	Building Energy Modeling
BIM	Building Information Modeling
BOM	Bill of Material
BOQ	Bill of Quantity
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CAVE	Cave Automatic Virtual Experience

DBMS	Database Management System
EI	Environmental Impact
ES	Energy Simulation
FBX	Filmbox
GBC	Green Building Challenge
GBDSS	Green Building Design Support System
gbXML	green building XML
GUI	Graphical User Interface
HMD	Head-Mounted Device
HVAC	Heating, Ventilation, and Air Conditioning
I/O	Input /Output
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LEED	Leadership in Energy and Environmental Design
LOD	Level of Detail
MEP	Mechanical, Electrical and Plumbing
NBC	National Building Code
NBCC	National Building Code of Canada
NBS	National BIM Survey
NRC	National Research Council
QTO	Quantity Take-Off
RVT	Revit Project File
SDK	Software Development Kits
SUD	Sustainable Universal Design
UD	Universal Design
UI	User Interface
USGBC	United States Green Building Council
VR	Virtual Reality
WHO	World Health Organization
WWR	Window to Wall Ratio

CHAPTER 1

INTRODUCTION

1.1 General Overview

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. 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). 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 (AIP), 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).

Universal Design (UD) is defined as a design to accommodate all people to the greatest extent possible. It emphasizes the design's usability by people regardless of their age, gender and ability, and it aims to house everyone irrespective of their chronic health conditions.

Universal Design philosophy is inspired by the social responsibility of using the built environment with no discrimination. This philosophy led to a systematic development of the design guidelines for architectural and urban projects to render the accessibility of the built environment to all (Bianco, 2020). The term universal design was first used in 1985 in the US, which referred to an approach to incorporate products and buildings that everyone can use to the greatest extent possible. Internationally, several terms are used that direct to the UD concept, such as accessible design, usable design, barrier-free design, and inclusive design. Design for aging aims to accommodate the rapidly increasing senior’s population and to promote innovative design solutions in order to create desired physical and service environments facilitating a sustainable aging process (Wu and Handziuk, 2013). An age-friendly design needs to be accessible for older people with varying needs and abilities to promote their physical activities and to reduce the risk of many health and medical problems of particular concern to elderly Canadians (McCunn and Gifford, 2014). There is growing evidence that physical activity prevents or delays cognitive impairment and improves sleep (Ahrentzen & Tural, 2015).

Building Information Modeling (BIM) is a concept used by the AEC industry all over the lifecycle of a project, from design and documentation passing through construction to operation (Jalaei and Jrade, 2015). BIM has significant benefits related to the rich project information, geometry, materials properties, and the building process through the project’s life cycle (Wu & Kaushik, 2015). The increased use of BIM in the construction industry provides a unique opportunity for integrating Universal Design principles into the building’s model (Owens, 2014) as a fundamental strength of the interoperability of BIM tools to other programs (Jalaei and Jrade, 2015). Coupling BIM and UD have the potential to produce high-performance and universally designed facilities. Applying UD guidelines to the built environment at the early design stage facilitates the creation of homes based on owner's needs. It would be adequate throughout their lifespan despite of the changes in the circumstances or abilities (Jalaei and Jrade, 2014).

Virtual Reality (VR) is defined as the sum of the hardware and software systems that seek to perfect an all-inclusive, sensory illusion of being present in another environment. The main characteristics of VR technologies are immersion, presence, and interactivity. *Interactivity* is the degree of modification that a user can do in the VR environment in real-time. *Presence* is the subjective experience of being in one place or environment, even when physically situated in another. *Immersion* is the extent to which a computer display can deliver an inclusive, extensive surrounding and a vivid illusion of reality (Radianti et al., 2020). VR offers designers more than a virtual mockup or digital representation, users can dive into the virtual environment to simulate experiential space interactions through the self-guided or automated virtual walkthrough. They can perform interactive tasks and provide designers with meaningful real-time feedback, design comprehension and satisfaction (Yan et al., 2011). Integrating BIM and VR allows design professionals to experience the project designs before the construction starts. It provides an interface to enhance the interaction and communication between designers and owners to design a facility based on owner's needs and requirements. It can be used throughout the design process, from the initial stage to the preliminary and detailed design.

Adopting the sustainability concept in the construction industry can lead to the design buildings that use less natural material and energy and produce less pollution and waste (Wong & Fan, 2013). The main pillars of sustainability are environmental, economic and social, which can be further analyzed for human well-being, climate change mitigation, environment protection, fossil fuel replacement, security of supply, and living standards (Zanni et al., 2014). To achieve sustainable projects in an effective way, it is required to incorporate environmental issues at the early design stage. To have a valuable assessment of the environmental methods, this must be considered as early as possible in the design to collaborate between the design and the assessment (Ding, 2008).

Integrating sustainable design strategies with BIM technology can change traditional design practice by producing more efficient design and accordingly delivering high-performance homes. BIM technology can support the design and analysis of different housing systems at the early stage. Coupling UD concepts with sustainable design principles to design highly accessible and sustainable homes for Canadians is very helpful and needed (Jalaei and Jrade, 2014).

Building energy's performance is largely impacted by design decisions such as building form, orientation, and window(s) size at the conceptual design stage (Gao et al., 2019). Windows can affect the building's total energy consumption in many ways. Zhang and ONG (2017) believe that architectural daylighting design is at the heart of sustainable building design. Therefore, the building's windows have a crucial role in controlling the energy used for lighting, heating, and cooling and yet highlights the importance of the optimal window-to-wall ratio in buildings (Sayadi et al., 2021). 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 (Elbeltagi et al., 2017).

Life Cycle Assessment (LCA) is a systematic approach to evaluate the environmental impacts of a product, process or activity by identifying and quantifying the used energy and materials and produced waste to the environment over the product's life span, from the extraction of raw materials to the disposal. It is the most accepted method for assessing environmental impacts (Ding, 2008). Total life cycle energy of buildings includes embodied energy (sequestered in construction materials during production, transportation, construction, demolition and disposal), and operating energy (expended in maintaining the indoor environment through a process such as heating, cooling, lighting and operating appliances). LCA can assess the sustainability of the built environment and can provide comprehensive coverage of the product’s energy consumption. It is beneficial to apply it at the conceptual design stage of a project, where the designer must acquire, store, and organize LCA data of the selected components to generate feedback during the design process. To analyze the environmental impact (EI) of selected components to be used in sustainable universal homes, a methodology that integrates BIM models with LCA systems is required to streamline LCA’s processes and facilitate the rigorous management of the environmental footprint of constructed facilities (Jalaei and Jrade, 2014).

Life cycle cost analysis (LCCA) is a method to assess the total cost of a facility’s ownership. It considers all the costs of acquiring, owning, and disposing of a building or building system. LCCA is especially useful when project alternatives that fulfill the exact performance requirements but differ concerning initial costs and operating costs have to be compared to select the one that maximizes net savings (ASTM, 2007). The LCCA method is used to estimate a project's overall cost and select the design that would provide the lowest overall cost of ownership without sacrificing its quality and function. It should be performed during the early design stage while there is still an opportunity to refine the design to ensure a low operating cost and optimize the life cycle cost (Rad et al., 2021). Incorporating LCCA and BIM during the early design stage facilitates the environmental and economic assessments of facilities to have a better overview of the cost related to applying the features of sustainable universal design to the built environment.

Therefore, this study seeks to introduce the development of an integrated model that interrelates BIM, VR, UD and AIP requirements at the conceptual design stage of building projects to accommodate Canadians to age in their homes regardless of their chronicle health conditions and age. It will help designers and users to have effective design communication to understand the design intention. Users will be involved in having a design based on their needs, requirements, expectations and satisfaction. Using the integrated model at the conceptual design stage of a building project will enable designers and users to easily incorporate the universal design standards, accessible design standards and sustainable materials into the design and to select optimal design alternatives based on the set multiple criteria. In addition, the model will facilitate the evaluation of the sustainability performance of buildings and their associated components in a BIM environment by using various applications, which are automatically interrelated to BIM tool. It will evaluate the energy and cost-efficiency of a building's components to help designers and users compare different components and select the one that meets their needs.

1.2 Problem Statement

In 2015, Statistics Canada revealed that 16.9% of Canadians were aged 65 years or older, out of which 2.2% were aged 85 years or older, which represented a 20.0% increase in the age of that group since 2011. A projection of the Canadian population showed that the number of persons aged 65 years and older will continue to increase to reach 20.1% of the whole population in 2024 (Statistics Canada, 2015). Generally, aging relates to increased chronic health issues and functional disabilities. A report by Mustel Group and Sotheby's International Realty Canada (GLOBE NEWSWIRE, 2020) uncovered trends related to aging and its impact on seniors' housing aspirations, expectations, and realities across Canada. The report showed that 86% of Canadian seniors want to live in their homes for as long as they can (Lloyd, 2020) rather than going to long-term care facilities. On the other hand, on its website in 2021, the Government of Ontario reported that between April 2020 and April 2021, the number of Canadian seniors who died due to the pandemic (Covid-19) in Ontario's long-term care facilities reached 3,785 cases (3,772 residents and 13 staff). As a result, adopting the concept of aging in place becomes of top priority and high importance. Currently, the design methods do not fully accommodate seniors' needs to let them age in place, which forces them to move to long-term care facilities. Therefore, more design strategies should be considered to overcome the issues of aging in place (Alsayyar and Jrade 2017). Universal Design aims to simplify the life of people regardless of age, size or ability to achieve an inclusive society where every person has equal opportunities to participate, whether young, senior, disabled or non-disabled (Nygaard, 2013). Incorporating UD at the conceptual design stage will facilitate the design of high-performance and universally designed facilities. Applying UD guidelines to the built environment at the early stage enables the design and construction of homes that meet owner's needs and requirements and facilitates the aging in place process.

On the other hand, the biggest obstacle in the current design-for-aging practices is the lack of effective communication between designers and owners/inhabitants to understand the actual design intention. Designers do not often receive meaningful feedback from their clients to modify the design to their expectations and satisfaction. It is a challenge to clarify design’s intentions to clients and communicate with them so all parties can reach an absolute consensus (Wu and Kaushik, 2015). Virtual reality equips designers with the ability to experience the project designs 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 and Coloma, 2018). Integrating BIM and VR provides an interface to improve the interaction and communication between designers and users to create a facility based on users' needs and requirements. It can be used throughout the design process, from conception to the final and detailed design. Incorporating sustainability principles with UD to attain sustainable universal design (SUD) supports the building’s design to accommodate people of different ages and abilities and facilitate access to healthier and environmentally friendly places to live in (Jalaei and Jrade, 2014). Sustainable universal design requires attention to various issues such as energy efficiency, environmental impact, cost efficiency, etc. To properly evaluate them, energy analysis, life cycle assessment (LCA) and life cycle cost analysis (LCCA) should be incorporated at the conceptual stage of the design. Many studies looked at BIM's potential to extend its capabilities related to VR, QTO, LCA or LCCA technology, while limited studies were related to BIM-UD’s integration especially to address aging-in-place needs. Up to the author’s knowledge, no study has combined all these systems. Therefore, this research intends to introduce various BIM-based integrations at the conceptual design stage. Integrating BIM, VR and UD at the conceptual design stage of building projects helps accommodate seniors to age in their homes. It allows designers and users to communicate effectively where the outcome will be a design that fulfils users’ needs and requirements. It facilitates selecting optimal design alternatives based on multiple criteria. Other techniques such as the Life Cycle Cost Analysis (LCCA) and sustainability will be applied at this stage. LCCA will evaluate the economic performance of various building components and materials and sustainability will provide healthy, comfortable and environmentally friendly buildings.

1.3 Research Objectives

The main objective of this study is to develop an automated model that incorporates BIM, UD and VR at the conceptual design stage of buildings to be used by designers to facilitate the adoption of universal design standards, accessible design standards and aging-in-place requirements and processes. The model will simplify the communication and interaction between owners (especially seniors) and designers to accommodate users’ needs and help them age in place, so they won’t be forced to move to long-term care facilities that were among the most critical locations during the Covid-19 pandemic in terms of the virus transition and increased fatalities. Therefore, the sub-objectives of this study are as follows:

- **Sub-Objective 1:** To enhance the functionality and capabilities of Building Information Modeling (BIM) tool by integrating Universal Design (UD) principles through the development of a dedicated database. This database will store Universal Design, Accessible Design standards, and aging-in-place requirements, providing instant access to essential data and families in an automated manner.
- **Sub-Objective 2:** To facilitate effective communications and interactions between homeowners and designers by integrating BIM and Virtual Reality (VR) environments. This integration aims to meet project needs, reduce human errors, and enhance the overall design process.
- **Sub-Objective 3:** To identify the gaps in the integration framework and enhance the functionality extensions of various tools by customizing their Application Programming Interface (API). This sub-objective aims to address challenges and optimizes the integration of BIM, UD, and VR technologies.
- **Sub-Objective 4:** To create a gaming environment to support a user-design interaction and generate potential scenarios aligned with users' needs. This sub-objective seeks to enhance user engagement and explore design possibilities within an interactive and immersive setting.
- **Sub-Objective 5:** To investigate the critical factors that influence the economic and environmental sustainability of designs tailored for the aging population. This sub-objective aims to provide insights into the long-term viability and ecological impact of design choices, contributing to informed decision-making processes.

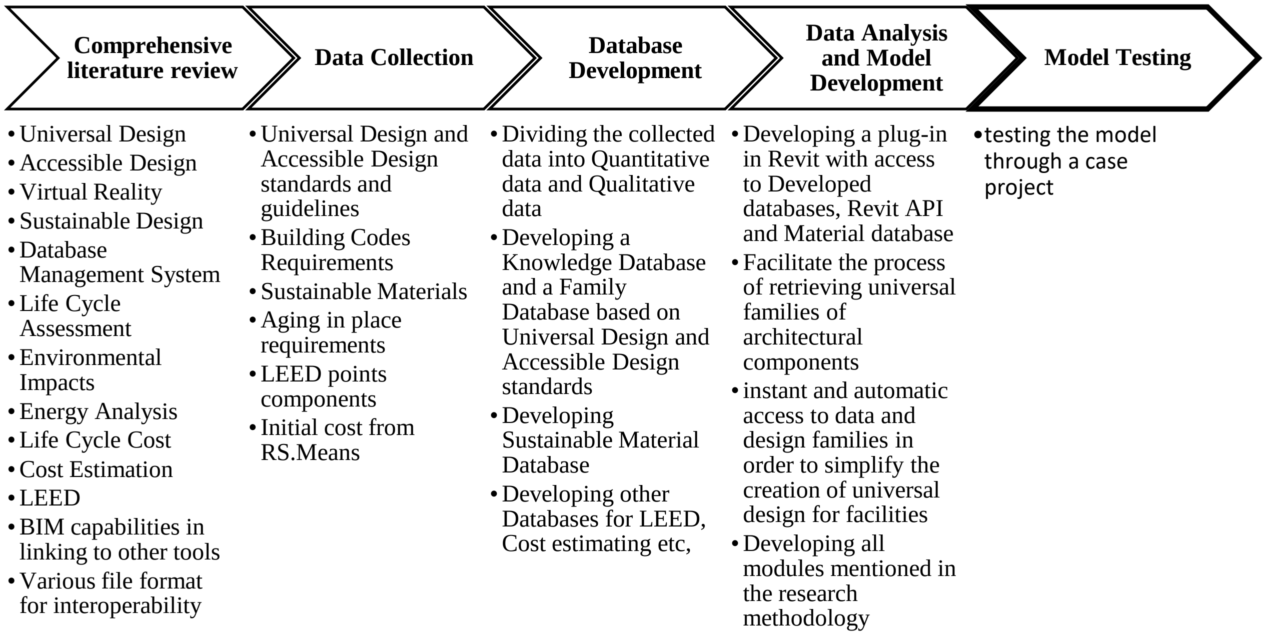
- **Sub-Objective 6:** To develop and validate a reliable workflow integrating BIM, VR, and UD methodologies, alongside energy analysis, Life Cycle Assessment (LCA), and Life Cycle Cost Analysis (LCCA). This sub-objective aims to establish a robust framework for holistic design assessment, ensuring the creation of functional, sustainable, and age-friendly living spaces.

1.4 Methodology

This study presents a comprehensive methodology aimed at developing an integrated model that integrates universal design standards, sustainable design principles, aging-in-place requirements and virtual reality technology within a Building Information Modeling (BIM) environment. The methodology outlines a systematic approach to enable designers to incorporate universal design considerations from the conceptual stage of a project. The integration of BIM and universal design necessitates the establishment of instant and automatic access to data and design families, streamlining the creation of universally accessible facilities. This integration aims to empower designers and owners to select optimal designs based on predefined criteria. Central to this methodology is the systematic incorporation of Universal Design Standards and aging-in-place requirements into BIM environment through the development of a dedicated database. This database will store the required standards and data and link them to BIM tools, facilitating the retrieval of universal design data and families during the design process.

The methodology incorporates an integrated model that will help designers and users perform sustainable universal design for new housing projects. It will comprise the following six modules that will share data and information automatically and efficiently: 1) A Database Management System (DBMS) module, 2) A 3D BIM design module, 3) A Virtual Reality module, 4) An Energy

Analysis module, 5) A Life Cycle Assessment (LCA) module, and 6) A Life Cycle Cost Analysis (LCCA) module. Each module will be linked to one or more databases encompassing necessary data and information. The primary task of the model will be collecting universal design and accessible design standards and guidelines and aging-in-place requirements and linking them to the building database in BIM tool. Part of this integrated methodology is to develop new plug-ins and customize BIM tool to assist users in connecting their design module with the other modules efficiently and consistently. Figure 1.1 shows the research methodology.



Comprehensive literature review

- Universal Design
- Accessible Design
- Virtual Reality
- Sustainable Design
- Database Management System
- Life Cycle Assessment
- Environmental Impacts
- Energy Analysis
- Life Cycle Cost
- Cost Estimation
- LEED
- BIM capabilities in linking to other tools
- Various file format for interoperability

Data Collection

- Universal Design and Accessible Design standards and guidelines
- Building Codes Requirements
- Sustainable Materials
- Aging in place requirements
- LEED points components
- Initial cost from RS.Means

Database Development

- Dividing the collected data into Quantitative data and Qualitative data
- Developing a Knowledge Database and a Family Database based on Universal Design and Accessible Design standards
- Developing Sustainable Material Database
- Developing other Databases for LEED, Cost estimating etc,

Data Analysis and Model Development

- Developing a plug-in in Revit with access to Developed databases, Revit API and Material database
- Facilitate the process of retrieving universal families of architectural components
- instant and automatic access to data and design families in order to simplify the creation of universal design for facilities
- Developing all modules mentioned in the research methodology

Model Testing

- testing the model through a case project

Figure 1.1 – Research Methodology

1.5 Thesis Organization

The thesis is organized through the following chapters:

Chapter 2 provides a comprehensive literature review focusing on Universal Design, its principles, standards, codes and guidelines, Accessible Design standards and codes, Building Information Modeling (BIM) and its application, implementation, tools and file formats, along with Virtual Reality and game engines with their application, hardware and tools. The chapter delves into various areas, definitions, terminologies, and previous works pertaining to BIM, elucidating its potential intersections with other areas in this study. It thoroughly examines the application, adoption, and implementation of BIM concepts in the construction industry, with a particular emphasis on integrating BIM with UD and VR. The literature review underscores the significance of BIM in promoting sustainable aging in place design. Additionally, the chapter reviews four main divisions of sustainable design, namely Life Cycle Assessment (LCA), Green Building Rating Systems, Energy Analysis, and Life Cycle Cost Analysis (LCCA), along with their respective tools. Furthermore, the chapter examines previous research studies

Chapter 3 outlines the adopted methodology for implementing the integrated BIM model. This methodology streamlines the integration process by customizing and utilizing BIM tools to allow users to seamlessly connect their design models with various modules within the BIM design environment.

Chapter 4 presents Technical Paper I, which details the development of an automated computer model designed to facilitate the adoption of Universal Design (UD) standards and processes. This model introduces a novel approach by employing an automated method that utilizes newly created plug-ins and databases to streamline the incorporation of UD standards at the conceptual stage, ensuring efficiency and cost-effectiveness. The study outlines a methodology that involves collecting, categorizing, and storing data from various universal design and accessible design guidelines in dedicated databases. Additionally, new plug-ins are developed within the Building Information Modeling (BIM) tool to establish links with the databases, automating the process of retrieving necessary information and components. This integrated approach enables designers and owners to select optimal design alternatives based on predefined criteria, thereby enhancing the overall efficiency and effectiveness of the design process. List that this paper is published by giving the journal’s name, number, year and link.

Chapter 5 consists of Technical Paper II, which 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. Same as for paper 1.

Chapter 6 includes Technical Paper III, which presents 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) and building orientation. This study introduces the development of a semi-automated computer model designed to offer a real-time, interactive simulation environment, fostering on improving the 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. List the status of the paper as submitted by fiving the journal name and date of submission.

Chapter 7 includes Technical Paper IV, that describes a methodology for the integration of Building Information Modeling (BIM) and Life Cycle Cost Analysis (LCCA) to assess the economic implications of designing aging-in-place (AIP) homes at the conceptual stage. It introduces a semi-automated model for the economic evaluation of AIP homes, enabling the estimation of costs throughout the houses' entire life cycle, from design and construction to operation, maintenance, and eventual renovation or disposal and facilitates the exploration of the long-term economic feasibility of design's related decisions with an emphasis on the importance of considering the life cycle costs early during the design process to optimize the functionality and economic viability. Similar to paper 3.

Chapter 8 comprising the Conclusion, Contribution, Limitations, and Recommendations, provides an overview of the developed model, encompassing its various integrated modules explored throughout this research. The chapter outlines the contributions made by the research, discusses its limitations, and presents recommendations for further enhancements and future expansions.

Chapter 9 lists all the references used in the literature review and methodology chapters.

CHAPTER 2

LITERATURE REVIEW

Universal Design (UD), Building Information Modeling (BIM), Virtual Reality (VR) and Sustainability Modules for Aging-in-Place Houses

2.1 Introduction

Universal Design (UD), which is a design that accommodates all people to the greatest extent possible regardless of their age, gender, and ability, aims to house everyone irrespective of their chronic health conditions. Building Information Modeling (BIM) significantly helps advance the development in the Architecture, Engineering, and Construction (AEC) industry in a more collaborative and automated way. BIM assists AEC professionals in planning, designing, constructing, and operating a facility. Integrating BIM and UD allows designers to incorporate Universal Design standards easily and efficiently at the conceptual design stage of buildings by using the functionalities and capabilities of BIM tools. Visualization is a critical factor for the design development, communication and collaboration between the design team. Compelling design visualizations will enhance user’s perception and help develop a better insight into the design artifact (Akın et al., 2018). Virtual reality (VR) provides new perspectives of visualization for designers through an immersive experience. Game engines create dynamic interactive activities to achieve accurate and timely feedback from users' interaction with building elements in a virtual environment. Therefore, coupling BIM and VR extends BIM capabilities and makes it a powerful tool (Natephra et al., 2017). This integration facilitates the active engagement of clients in the design process which is a challenge in conventional architectural design for aging-in-place projects (Wu and Handziuk, 2013). Integrating BIM and Virtual Reality (VR) allows immersive visualizations of proposed buildings' design models. It offers users a unique real-time simulation in an interactive environment while enhancing communication and interaction between owners and designers to meet occupants' satisfaction and needs by reducing future modifications and alterations for their dwellings to age in them.

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 lifespan 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 reducing the resources spent on institutional care facilities (Chau & Jamei, 2021).

Windows play a vital role in enhancing the building's energy efficiency by significantly influencing its energy load (Kim et al., 2016). According to Kim et al., (2016), windows contribute to over 10% of the building's energy load, underscoring their substantial impact on the overall energy consumption. Hence, it is imperative to explore the optimal WWR Ratio to achieve energy efficiency (Chi et al., 2020).

Estimating the cost of embodied carbon emissions in buildings primarily focuses on assessing the carbon outputs across all the stages of a building’s life, including material extraction, processing, construction, operation, and end-of-life phases (Dixit et al., 2012). The primary aim is to quantify the carbon emissions in carbon equivalent units to measure the building's total environmental impact. The process comprises the calculation of the embodied carbon, which includes emissions from materials' production to construction, and the operational carbon, which consists of emissions during the building's use. Effective strategies for reducing embodied carbon involve using low-carbon materials, optimizing building design to minimize material usage, and improving the recycling and reusing of materials. Methods for estimating these emissions have evolved, focusing on life cycle assessments (LCAs) that account for all related activities and processes to provide a comprehensive carbon footprint of building projects (Akbarnezhad & Nadoushani, 2014; Akbarnezhad & Xiao, 2017).

LCCA is a method for evaluating the total cost of owning, operating, and maintaining an asset or system throughout its entire lifespan. Adopting LCCA into the overall cost estimation helps in selecting the best option between projects with similar applications but with varying cost parameters throughout their life cycle (Younis et al., 2018; Guo et al., 2019). LCCA becomes particularly pertinent in the context of AIP design by helping designers implement systematic and comprehensive evaluations of the economic implications associated with various design alternatives. It allows for the prediction and evaluation of the long-term costs linked to different AIP features and modifications, and accordingly identifies the cost-effective design solution(s) that contribute to both the immediate and long-term economic sustainability. LCCA enables the comparison of different design alternatives, allowing designers to make informed choices that optimize both the functionality and economic feasibility of assets. Younis et al., (2018) emphasized the importance of employing LCCA during the initial phases of design. This early application allows for refinement and improvement in the design, ultimately aiming to minimize project’s future costs.

Hence, this chapter provides an extensive literature review encompassing various applications and practices within the following domains:1) Universal Design, principles, standards, codes and requirements; 2) Building Information Modeling (BIM) concept, application, adoption and implementation in the construction industry; 3) Virtual Reality, technology, tools, and applications, emphasizing the integration of BIM with UD and VR for engineers during the conceptual design stage; 4) Energy analysis with the focus on factors such as window-to-wall ratio, building orientation, and relevant tools; 5) Life Cycle Assessment (LCA), with the consideration of embodied carbon and other environmental impacts; 6) Life Cycle Cost Analysis (LCCA); and 7) Sustainability measurement systems such as LEED along with enhancing BIM applications to facilitate the delivery of LEED-certified projects.

2.2 Universal Design

Universal Design (UD) hypothesis is to design products or environments that can be used by people of different ages and abilities without adaptation. This theory is worldwide growing and has been expanded towards the scope of inclusive design, which extends the definition of UD by counting inhabitants who have been excluded by the rapid change of technology, particularly the aging population (Mustaquim, 2015). The main objective of UD is to provide inclusivity and prohibit exclusivity (Kadir et al., 2013).

2.2.1 Universal Design Terminology

When it comes to the UD term, many different terminologies have been used internationally, such as: 1) Universal Access (Universally Accessible); 2) Accessible Design; 3) Adaptable Design; 4) Usable Design; 5) Barrier-Free Design; 6) Design for All; 7) Inclusive Design; 8) User Sensitive Inclusive Design; 9) Cooperative Design; and 10) User-Oriented Design.

Some of these terms imply different ideas, while others have the same meaning (Nygaard, 2013). Iwarsson et al., (2003) described accessibility as a term for all the parameters that influence human functioning in the environment. Accessible environment must match the abilities of an individual or a group. It describes usability as a measure of the effectiveness, efficiency, and satisfaction with which specified users can achieve established goals in a particular environment. Accessibility and usability concepts divide people into two main groups; i) abled and ii) disabled people, which results in segregation, but universal design considers the whole population as only one group, individuals representing diverse characteristics and abilities (Iwarsson et al., 2003). Design for all is another term used more frequently in Europe and is defined as the design for human diversity, social inclusion and equality (Watchorn et al., 2021).

2.2.2 Universal Design's Scope

Universal design is about achieving an inclusive society where everyone has equal opportunities to participate, whether they are young, old, disabled or able-bodied. It means a design of products, environments, programmes or services that everyone can use to the greatest extent possible without the need for adaption or specialized design. However, it does not exclude assistive devices for particular persons with disabilities where needed (Nygaard, 2013). This issue is illustrated in the accessibility triangle, as shown in Figure 2.1. The triangle is divided into four sections, where the primary section contains the universal design as the main strategy. The following section includes adjustments for specific groups or inclusive design. The third section shows the need for individual adjustments and individual guidance. The top peak of the triangle focuses on a few individuals who require personal assistance. Persons with large and complex disabilities often need a personal assistant to participate in different activities (Moseid, T.E., 2006).

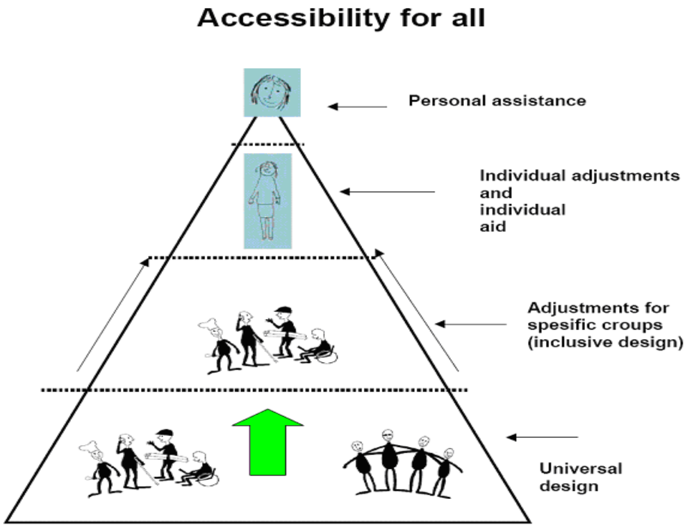


Figure 2.1 – Accessibility Triangle, source: (Moseid, T.E., 2006)

2.2.3 Universal Design Principles

The most frequently cited explanations of the universal design concept consist of seven principles (Persson et al., 2015). Those seven principles provide the framework for designers to foresee the possible benefits of a design for all users with or without disabilities. The City of Calgary (2010), in its Universal Design guideline, provided a better explanation of those principles along with examples for each of them as shown in Table - 2.1.

Table 2.1 – Principles of Universal Design, (Source - The City of Calgary, 2010)

Principles	**Details**
Principle 1: **Equitable Use**	**The design is useful and marketable to people with diverse disabilities**
	• Provide the same means of use for all users. • Avoid segregating or stigmatizing any users. • Provisions for privacy, security and safety should be equally available to all users. • Make the design appealing to all users.
Principle 2: **Flexibility in Use**	**The design accommodates a wide range of individual preferences and abilities.**
	• Provide choice in methods of use. • Accommodate right- or left-handed access and use. • Facilitate the user's accuracy and precision. • Provide adaptability to the user's pace.
Principle 3: **Simple and Intuitive Use**	**Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills or current concentration level.**
	• Eliminate unnecessary complexity. • Be consistent with user expectations and intuition. • Accommodate a wide range of literacy and language skills. • Prioritize based on importance. • Provide effective prompting and feedback during and after task completion.
Principle 4: **Perceptible Information**	**The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities.**
	• Use different methods of communication (pictorial, verbal, tactile) to present essential information. • Provide adequate contrast between essential information and its surroundings. • Maximize legibility of essential information. • Differentiate elements in ways that can be described (make it easy to give instructions or directions). • Provide compatibility with a variety of techniques or devices used by people with sensory limitations.
Principle 5: **Tolerance for Error**	**The design minimizes hazards and the adverse consequences of accidental or unintended actions.**
	• Arrange elements to minimize hazards and errors: most used elements, most accessible, hazardous elements eliminated, isolated or shielded. • Provide warnings of hazards and errors. • Provide fail-safe features.

	- Discourage unconscious action in tasks that require vigilance.
Principle 6: **Low Physical Effort**	**The design can be used efficiently, comfortably and with a minimum of fatigue.**
	- Allow user to maintain a neutral body position. - Use reasonable operating forces. - Minimize repetitive actions. - Minimize sustained physical effort.
Principle 7: **Size and Space for Approach and Use**	**Appropriate size and space are provided for approach, reach, manipulation and use, regardless of the user's body size, posture or mobility.**
	- Provide a clear line of sight to important elements for any seated or standing user. - Make the reach to all components comfortable for any seated or standing user. - Accommodate variations in hand and grip size. - Provide adequate space for the use of assistive devices or personal assistance.

2.2.4 Universal Design Standards and Codes

Only half of the countries around the world have developed accessibility criteria in their building codes and standards. Some countries have well-developed technical specifications, and others are still introducing accessibility into their building codes. The first comparative study of the existing codes and standards worldwide was published in 2000 by the Canadian Human Rights Commission and was prepared by Betty Dion Enterprises Ltd. The study compared the Canadian B651-M95 Barrier-Free Design Standard, the National Building Code of Canada, with other international codes and standards (Canadian Human Rights Commission, 2006).

Accessibility standards have been in place for many years in Canada, intending to create equitable, barrier-free access to communities, workplaces, and services for people with disabilities. Nationally, some provinces and cities have adapted national standards or have implemented their standards. Provincially, Ontario was one of the first jurisdictions in the world to enact legislation (the Accessibility for Ontarians with Disabilities Act (AODA) in 2005) that set specific enforceable goals for accessibility. Manitoba (2013) and Nova Scotia (2017) followed suit. Very recently, the Accessible Canada Act (ACA) was passed through legislation to create communities, workplaces, and services that enable all persons, including persons with disabilities to participate fully in the society without barriers. These various legislations have resulted in many cities and provinces adopting accessibility standards, which vary from province to province and city to city (Lau et al., 2020). The National Building Code of Canada (NBCC) has been introducing accessibility requirements since 1965. In 1965, accessibility was mentioned for the first time as a Supplement to the National Building Code entitled “Building Standards for the Handicapped” (Jrade and Valdez., 2012). Provincial and territorial governments have the authority to enact legislation that regulates building design and construction within their jurisdictions. This legislation may include adopting the National Building Code (NBC) without change or with some modifications to suit local needs (CNRC, 2015). Many Canadian provinces and cities have provided Accessibility requirements guidelines based on the National Building Code of Canada with or without modifications to meet their needs. In this study, various guidelines from Canadian provinces and cities will be collected, evaluated and stored in the developed database to help designers from across Canada to incorporate universal/accessible design standards into the project easily and efficiently. In addition, different related guidelines from other countries such as the US will be collected, stored and used to make the developed database more comprehensive and usable for more users.

2.3 Building Information Modelling

Building Information Modelling (BIM) is defined as the process of generating, storing, managing, exchanging, and sharing building information in an interoperable and reusable way. It represents the process of developing and using a computer-generated model to simulate the planning, design, construction and operation of a facility (Sampaio, 2017)

Ding et al. (2014) defined BIM as a digital representation of a facility's physical and functional characteristics. It is a shared source of knowledge and information about a facility forming a reliable basis for decisions during its life cycle, from earliest conception to demolition. Wu et al. (2019) described BIM as a novel approach in the AEC industry that can be implemented in a data center, which integrates geometric and functional information during the life cycle of a building that is presented in a visualized 3D model. BIM supports solid spatial cognition by revealing most design issues early during the design stage (Wu et al., 2019).

Automation in the modelling process, improving the accuracy of construction documents, enhancing the communication among parties during the design and reducing the field coordination problems are the most critical factors that lead to BIM adoption in a project (Kamel and Memari, 2019). BIM can generate and maintain information produced during the life cycle of a building project and can be applied to various fields. Abanda et al. (2015) highlighted that a common feature in all definitions of BIM is that it is a process facilitated by its tools and driven by people that consists of three dimensions: process; technology; and people, so the strategies approach to BIM adoption should incorporate all these dimensions.

Zhang et al. (2021) stated that by rapidly increasing elderly population, housing issues are the main barrier to implementing aging in place strategy and encouraging people to age in their residences. Although many studies have contributed to age-friendly cities and communities, few studies have focused on measuring age-friendly housing. Numerous data are required to assess the housing age-friendliness and offer enough tangible actions or recommendations for planners and policymakers. Digital techniques such as BIM have been utilized to facilitate the data collection and accelerate the computation process of the assessment in actual projects.

2.3.1 BIM Applications

Nowadays, the application of BIM in different areas is expanding due to the potential value that BIM can offer. Kamel and Memari (2019) illustrated that BIM application was used for structural and energy analysis at a frequency of 27% and 25%, respectively. BIM adoption offers a holistic view of the building, consolidating drawings, specifications, details, and other pertinent information within a single-source model (Montaser & Moselhi, 2015). The significant use is for faster development of 3D geometric models and 3D coordination with a use frequency of 60%. It is not limited to architects and engineers. Homeowners, facility managers, contractors, and fabricators can also benefit from BIM (Kamel and Memari, 2019). It can be used in many areas such as visualization, fabrication/shop drawings, cost estimating, conflict interference and collision detection, and facility management (Azhar, 2011). The most important factors that lead to adopting BIM in a project are focused on the automation in the modeling process, improving the accuracy of construction documents, improving the communication among parties in the design and construction process, automatic reflection of changes in all views after modifying one view and reducing the field coordination problems (Kamel and Memari, 2019).

Many studies looked at the application of BIM in other areas such as energy analysis and modeling, green building assessments, life cycle assessments, material quantity take-offs, life cycle cost analysis, and virtual reality. Coupling BIM and UD have the potential to produce high-performance and universally designed facilities. Although significant studies used BIM during the various phases of a project, limited research has been conducted about integrating BIM and UD. Jrade and Valdez (2012) described the methodology used to develop and implement a model that incorporates a database management system to store detailed information about the architectural components and elements used to execute universal design based on the inhabitant's requirements and needs. They created a database storing newly developed families based on the National Building Codes of Canada and linked it to BIM tool (Autodesk Revit) at the conceptual design stage. Jrade and Jalaei (2014) presented a methodology to develop and implement an integrated model that links BIM with energy analysis and LCA tools to execute sustainable universal design at the conceptual stage for Canadian houses. Their model evaluates and compares the life cycle cost and benefits of conventional and sustainable universal houses. Alsayyar and Jrade (2017) proposed a methodology to integrate BIM with 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. This study will introduce the design and development of a comprehensive model that will integrate BIM and Universal Design standards and accessible design guidelines through an extensive database linked to BIM tools at the conceptual design stage.

2.3.2 BIM Tools

Abanda et al. (2015) stated that Building Information Modeling (BIM) is a global digital technology that has the potential to revolutionize the construction industry due to worldwide interest in promoting BIM uptakes to improve efficiency and quality in delivering construction projects accompanied by the release of an incredible number of available BIM tool. They conducted a comprehensive study of BIM tools that are currently used in managing construction project’s information in the architecture, engineering and construction (AEC) industry, including

ArchiCAD, 3ds MAX, Revit, Maya, MicroStation, SolidWorks, Vico, Navisworks, Calcus, Autodesk QTO, and Bently. Based on their study, Revit revolutionized the BIM world by creating a platform that utilized a visual programming environment to develop parametric families and allow time's attributes to be added. The critical factor for collaborative practices is exchanging graphical or nongraphical project documents between different tools. The exchange of project documents is included in the interoperability concept. There are four types of interoperability: 1) syntactic interoperability; 2) technical interoperability; 3) semantic interoperability; and organization interoperability. Syntactic interoperability refers to the ability of two or more separate systems or software programmes to communicate and exchange data (or information) with each other and use the data that has been exchanged. The successful information exchange between systems depends on the data file formats that facilitate the importing and exporting into/from other software systems. In general, different file formats common with BIM are categorized into four types: i) native file formats that are restricted to a particular type of software. Such as RVT file format (native Revit file extension) that can be read by Revit software only; ii) file formats that facilitate the exchange of models between similar authoring software. The most popular are the Industry Foundation Classes (IFC); iii) files that are aimed for use in specialized applications such as green building Extensible Markup Language (gbXML), which is widely used for building energy analysis; iv) plug-in or add-in, extension or add-on, is a software component that adds a specific feature to an existing software application (Abanda, 2014).

Revit is a well-known BIM tool that aims to solve different architectural and design problems. It is the most popular tool developed by Autodesk. The constraint of Revit is its interoperability with other software such as game engines. Although Revit supports model export in various 3D file formats, it loses crucial information such as the model elements’ textures and materials. The solution is to export the Revit model as an FBX file (type of file format developed by Autodesk) to middleware (software that enables communication or connectivity between two or more applications or application components) and then export it to a game engine (Wu and Kaushik, 2015).

2.4 Virtual Reality

Modern technologies play a considerable role in the Industry. They are accompanied by many benefits, such as lower costs and risks, faster processes, better quality of individual proposals, and improved efficiency (Chudikova & Faltejsek, 2019). Virtual Reality (VR) is a comprehensive technology that couples various technologies such as advanced computer technology, sensing and measuring technology, simulation technology and microelectronics technology, forming a realistic virtual world with a three-dimensional feel (Li and Wang, 2016). The characteristics of VR technology are immersive, interactive and imaginative. Immersive includes visual and hearing immersion whereas, interactive is the user's interaction with the object and virtual scene operability, while imaginative satisfies the user's personal requirements (Li and Wang, 2016). The unique benefits of VR persuade researchers to investigate its uses in various areas of the Architecture and Construction Industry (Huang and Odeleye, 2018). Wolfartsberger et al. (2018) stated that using VR technology to enhance engineering design reviews has been an area of interest for researchers since the advent of modern VR. Engaging the users in a 3D virtual world and letting them interact with the virtual engineering models is an essential but often neglected capability. With the rise of affordable, high-quality VR devices and tracking solutions, 3D engineering data can be visualized in a VR environment in no time and with a minimum knowledge of programming. Also, VR is becoming increasingly active in the research area, innovations, and investigations and can be experienced through several forms and representations (Muhanna A., 2014). Li and Wang, (2016) stated that the core values of integrating BIM with VR are: 1) improving the authenticity of simulation; 2) supporting the project cost control; and 3) improving the interoperability of simulation work.

2.4.1 VR Technologies

Wang et al. (2018) Categorized VR and related technologies into the following five major types:

1- **Desktop-Based VR** is the most adopted VR technology in the early stages. It displays a 3D virtual world on the desktop screen without any support from the tracking equipment.

2- **Immersive VR** relies on special hardware such as the head-mounted device (HMD) and sensor gloves to provide users with an immersive environment. Users can feel the virtual world as a realistic environment. Also, it can be used with supportive control tools, especially tracking equipment for interactions, such as game controllers and motion tracking devices, to provide immersive feelings to the users. They are commonly adopted to detect and demonstrate the movements of subjects in a virtual environment.

3- **3D Game-Based VR** aims to enhance user collaboration and interactions by integrating visual, interactive, network and multi-user operating technologies.

4- **BIM-Enabled VR** is related to creating and using 3D objects containing relevant properties' information. The relevant properties' information mainly refers to the necessary data that is required in a practical building project over its entire life cycle, including design, planning, construction, operation, and maintenance stages. It relies on the model, emphasizing the data binding and connections behind other VR categories to simulate construction processes and operations. Visualization is one of the most critical characteristics of BIM.

5- **Augmented Reality** (AR) uses sensory technology to provide a live direct or indirect view of a physical environment with augmented virtual information.

All categories except for Augmented Reality are used in this study. First, the desktop VR is developed to test the model development. Then, a gaming environment is created to enhance the collaboration and interaction with the design by users. In addition, by using a head-mounted device (HMD), sensor gloves, game controllers and other related devices, an immersive VR environment will be experienced to provide users with an environment that feels realistic. Also, BIM-Enabled VR as the integration of BIM and VR is one of the main parts of this study.

2.4.2 VR Hardware

Various types of hardware are used to provide an immersive VR experience to users (Coburn et al., 2017). For instance, head-mounted displays (HMD) such as Samsung Gear VR and Oculus Rift improve the communication between both the designer and the user. It allows the user to be immersed in the project model to understand better and assess new design concepts, which are created with BIM tools (Sampaio, 2018). A display system that presents images in the 3D format and a head tracking system to be the minimum set of requirements for an immersive VR experience. This requirement is considered as the core capability for a VR experience. Usually, some additional features are included to enhance the experience. Figure 2.2 shows typical components of VR experience requirements. Inner components must be included, while outer components are optional depending on the objectives of the application (Coburn et al., 2017).

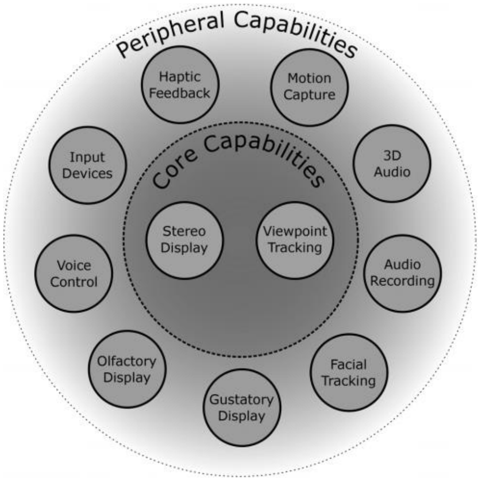


Figure 2.2 – VR experience requirements, source; (Coburn et al., 2017)

Coburn et al. (2017) discussed various devices and categorized them into three groups: 1) Displays; 2) Input; and 3) additional devices as follows:

1. **Displays** are essential components of VR experiences, with options like cave automatic virtual experience (CAVE) or head-mounted displays (HMDs). CAVE, introduced in 1992, uses large projection screens to create immersive environments, while modern versions can project scenes onto multiple surfaces. HMDs, worn by users, offer fully immersive experiences with small screens displaying scenes directly to each eye, providing a wide field of view and enabling head tracking for interactivity (Muhanna A., 2014).

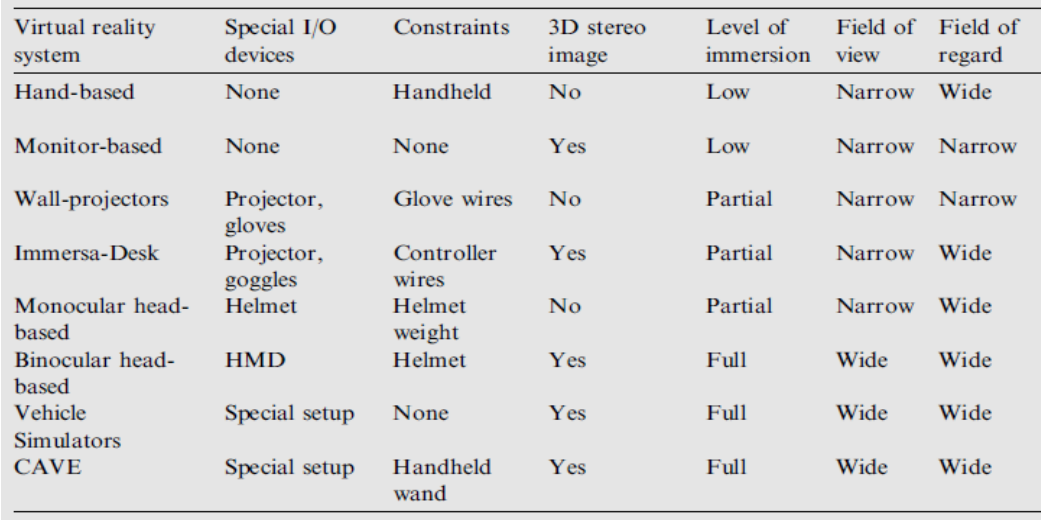
2. **Input** Input methods in interactive VR systems require consideration beyond traditional devices like keyboards and mice, which are impractical in immersive environments.

Alternative methods include wands, sensor gloves, joysticks, and voice command systems to enhance user interaction (Coburn et al., 2017).

3. **Additional Devices** are needed to provide more sensory inputs for experiencing the virtual environment through other senses. For instance, Haptic display technology allows users to "feel" the virtual environment or Audio devices localize objects through sound.

Muhanna A. (2014) provided a table to compare the VR systems based on the need for particular Input /Output (I/O) devices, the constraints on the participant to use the system, the presence of 3D stereoscopic image to the participant, the level of immersion, the field of view, and the field of regard. Table 2.2 illustrates this comparison.

Table 2.2 - A comparison of the different types of virtual reality systems, source: (Muhanna A., 2014)



Virtual reality system	Special I/O devices	Constraints	3D stereo image	Level of immersion	Field of view	Field of regard
Hand-based	None	Handheld	No	Low	Narrow	Wide
Monitor-based	None	None	Yes	Low	Narrow	Narrow
Wall-projectors	Projector, gloves	Glove wires	No	Partial	Narrow	Narrow
Immersa-Desk	Projector, goggles	Controller wires	Yes	Partial	Narrow	Wide
Monocular head-based	Helmet	Helmet weight	No	Partial	Narrow	Wide
Binocular head-based	HMD	Helmet	Yes	Full	Wide	Wide
Vehicle Simulators	Special setup	None	Yes	Full	Wide	Wide
CAVE	Special setup	Handheld wand	Yes	Full	Wide	Wide

2.4.3 Application of VR in the Design Process

Virtual reality provides designers with the ability to experience project's 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 and Coloma, 2018). It can be used throughout the design process, from the conceptual stage to the preliminary and detailed stage. Prabhakaran et al. (2020) stated the early stage of the design process is essential for the quality of the results as most of the building life cycle characteristics and costs are already committed at this stage, and the opportunity to influence the final design decreases as the cost of making the changes or correcting the design errors increases. Studies showed that technology can facilitate the inspiration process by using computer-generated collections of images and concepts related to the subject. VR has the potential to facilitate inspiration at the conceptual stage by giving designers an immersive experience in which they can examine and interact with a wide variety of artifacts. Understanding 3D objects represented on a 2D interface requires enhanced spatial reasoning but visualizing 3D models in virtual reality makes them easier to understand (Coburn et al., 2017). Since communication is the key factor in successful collaboration, Wu et al. (2019) proposed a platform named VBR (the virtual building information modeling (BIM) reviewer) by integrating BIM and VR to address communication issues. VBR is an avatar-based communication platform that allows users to enter the BIM model and find problems from their individual perspectives. They used two types of VR, desktop-based VR and immersive VR. Akin et al. (2018) proposed an integration process that incorporates building information modeling and virtual reality to visualize daylighting performance to the designers.

2.4.4 Game Engines

Game engines are tools to facilitate video game development. They were conceived to generalize and reuse properties, methods and procedures familiar to the majority of games. Designers can generate different game mechanics using the same components and scripts (Marín-Lora et al., 2019). Gaming development engines facilitate developing a VR environment by using scripting languages such as ‘C#’ (C-Sharp) and ‘JavaScript’ to manipulate objects in the three-dimensional (3D) environment. Scripting languages could also be merged with additional libraries to retrieve specific information from the database describing particular objects. The gaming development engines compile these scripting languages into native codes to ensure fast and reliable performance (Wong et al., 2020). Wu et al. (2015) stated that BIM-game engine integration could have the potential to improve design communication and client satisfaction significantly. The most critical factor in selecting a game engine is the support of 3D asset import and cross-platform integration. Also, user interface, graphical abilities, including texture library and lighting effects, and animation editing are equally important. Unity (game engine) supports assets from nearly all major 3D applications like 3ds Max and Maya. Unity is a platform-neutral that runs on Android, iOS, and Windows Phone mobile devices. It also has the development capabilities for PlayStation, Xbox360, Wii U and web browsers. Selin, J. (2019) proposed a study for an emergency exit planning and simulation platform that was implemented with a commercial center gamified data model. They compared various emergency exit location options and searched critical areas for customer evacuation. They used customized user profiles to estimate the movement capabilities of elderly and disabled people in the gaming environment. Lin, Y. et al. (2018) proposed a model development of Database-supported VR/BIM-based Communication and Simulation (DVBCS) system integrated with BIM, game engine and VR technologies for healthcare design in the Semi-immersed VR environment to provide an effective communication system for the design and healthcare teams to use during the design phase. Then, the DVBCS system was tested through a case study of a cancer center's design project in Taiwan. Autodesk Revit, 3ds MAX and Unreal Engine (as a game engine) were used for the model.

In this study, Building Information Modeling is integrated with virtual reality and universal design standards at the conceptual design stage to incorporate and evaluate UD requirements and to have effective design communication between designer and user. Unity game engine and Simlab Composer are used to create an immersive VR environment. Also, Dynamo visual programming is used to reflect modifications from the gaming environment into the BIM tool automatically using C# programming and PHP programming. Also, MySQL is used as an external database.

2.5 Sustainability Concept

The world population is rising rapidly, which is resulting in increased demand for scarce resources that leads to continued pollution. Thus, sustainability is quickly becoming the dominant issue. The American Institute of Architects (AIA) defined sustainability as the ability of society to continue functioning into the future without being forced to decline through exhaustion or overloading of the key resources on which that system depends. In 1998, John Elkington introduced the triple bottom line: economic; social; and environmental. There is no consensus on the definition of sustainable construction. However, the common interpretation of sustainability within the construction industry is the provision of buildings that use less virgin material and energy and produce less pollution and waste (Wong et al., 2013). Wong et al. (2013) described sustainability in construction as follows:

- **Environmental sustainability**: building, upkeeping, and managing the estates efficiently using natural resources and minimizing the environment's impact.
- **Social sustainability**: nurturing social cohesion and providing a safe and healthy environment for users, construction site workers and managers of the estates.

- **Economic sustainability**: building cost-effectively while functionally meeting users' requirements, keeping the operating costs low, extending the service life of the estate through total Maintenance Scheme and enforcing users to control for best utilization of existing stock.

The three main pillars of sustainability (environmental, social and economic) can be further analyzed from various perspectives: human well-being, climate change mitigation, environment protection, fossil fuel replacement, security of supply, and living standards (Zanni et al., 2014).

Ding (2008) stated that designers should incorporate environmental issues at the early design stage to effectively achieve sustainability in projects.

2.5.1 Sustainability and Aging in Place

Aging is a multifaceted process influenced by geographical and architectural factors, particularly housing, which profoundly impacts seniors' quality of life. Architecture and spatial design significantly shape individual living patterns among the elderly, highlighting the importance of supportive environments (Wu and Kaushik, 2015). Sustainability, a cornerstone of modern development, extends beyond environmental and economic concerns to encompass sociocultural aspects and individual well-being, emphasizing a human-centric approach (Grazuleviciute et al., 2020). As the aging population grows, addressing housing needs becomes crucial, with a preference for aging in familiar environments rather than institutional care facilities. This "aging in place" concept aligns with sustainable development principles, promoting individual well-being, social ties, and environmental conservation (Grazuleviciute et al., 2020). Active and healthy aging emphasizes personal well-being and social sustainability, while aging at home emphasizes economic and environmental sustainability, highlighting the importance of maintaining social connections and ties to one's living environment (Grazuleviciute et al., 2020). Figure 2.3 illustrates the pivotal role of the living environment in fostering sustainable aging.

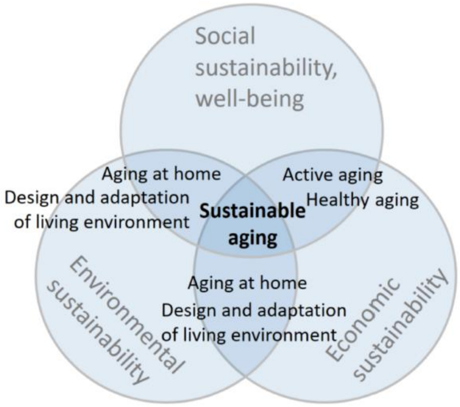


Figure 2.3 - The importance of the living environment for sustainable aging, source: (Grazuleviciute et al., 2020)

2.5.2 Sustainability Measurement Tools and Rating Systems

Environmental assessment methods are the main components to identify the sustainability of buildings. Since establishing a link between sustainable development and the environmental impact of buildings and environmental issues is increasing the fore of regulatory policy, building performance assessment has become more crucial against a backdrop of increasingly demanding building standards (Alwan et al., 2015). They reflect the sustainability’s significance concept in building design and construction work on site. The primary role of an environmental building assessment method is providing a comprehensive assessment of the building's environmental characteristics using a set of criteria and targets for building owners and designers to achieve higher environmental standards. The second role is enhancing the environmental awareness of building practices for the construction industry to move towards environmental protection and to achieve sustainability goals. Ding (2008) claimed that sustainability provides a way of structuring environmental information, an objective assessment of building performance, and a measure of progress towards sustainability. To establish the degree of accomplishment of environmental goals, guiding the planning and design processes, several methodologies such as BREEAM and LEED systems have been developed. The Leadership in Energy and Environmental Design (LEED) rating system, launched by the U.S. Green Building Council in 1998, stands out as a notable example (Nguyen et al., 2016). LEED certification evaluates buildings on their environmental performance across various sustainability categories such as energy usage, water efficiency, material selection, indoor environmental quality, and site selection (USGBC, 2024).

Canada Green Building Council (CaGBC) manages LEED certification within Canada, adapting the system to fit local environmental and market conditions while maintaining consistency with USGBC standards. This adaptation includes a focus on regional priorities and innovative design specific to Canadian environments (CAGBC, 2024). Both the USGBC and CaGBC aim to promote sustainable building practices that reduce environmental impacts and improve quality of life, making LEED-certified buildings more attractive, cost-effective, and beneficial for occupants. These certifications not only signify advanced environmental performance but also contribute to economic and health benefits for building users. Despite LEED's widespread acclaim, different areas may also adopt their regional standards for green building. The core of these certification schemes involves collecting points from several categories to reach the desired certification level. The LEED system provides multiple methods for accumulating these points, such as pilot credits, regional priorities, and exemplary performance (Gurgun & Arditi, 2018).

BIM's role in early-stage design significantly aids in achieving higher LEED certification levels by allowing for the early integration of sustainability criteria and facilitating the assessment of multiple design alternatives. It enhances the LEED certification process by providing detailed insights into sustainable design parameters and expected performance outcomes, thereby reducing the time and resources required for certification (Azhar et al., 2011). Jalaei & Jrade, (2015) discussed a methodology integrating BIM with the Canadian Green Building Certification System (LEED), focusing on automating the calculation of LEED certification points and related costs for materials in sustainable building design. They present a case project to demonstrate the model's capabilities. This capability is critical for optimizing material selection and energy usage throughout the building's lifecycle. The tool calculates the total number of LEED certification points early in the design process, aiming to optimize material selection and sustainability. However, they highlighted the need for more integrated tools that link BIM with sustainability databases to enhance early design decisions, suggesting a gap in fully automated, data-rich BIM applications for sustainability. Rahman et al., (2021) explored a BIM technology-based prototype model for LEED pre-certification of a residential project, highlighting significant lifecycle cost reductions achieved through extensive simulations. They conducted simulations across nine LEED categories to estimate lifecycle costs and impact on certification levels, focusing on cost-effective sustainable design. Their study indicates a lack of research on the cost implications of LEED certifications when using BIM, pointing towards the need for detailed cost-benefit analyses in green building projects. Jalaei et al., (2020) developed a BIM-LEED integrated framework using K-Nearest Neighbour (KNN) method to predict LEED credits and an API for plugin development to automate sustainability assessments, designed to estimate potential LEED credits at the conceptual design phase, using predictive analytics. They pointed out that there is a necessity for improving predictive accuracy and integration depth in BIM tools for LEED credit estimation, suggesting that existing tools may lack the capability to handle complex data integrations efficiently.

2.5.3 Using BIM for Sustainable Design

BIM allows for multi-disciplinary information to be covered through one model. It creates an opportunity for sustainability measures to be incorporated throughout the design process (Jalaei and Jrade, 2015). BIM and sustainability concepts look for practical proposals for new architecture and engineering procedures to preserve the natural environment and ecosystems. BIM methodology has already been applied in different sustainable fields, such as energy modelling, acoustic analysis, water-use reduction, lifecycle analysis, construction waste management, and even supporting managers during the building's operation(Carvalho et al., 2020). However, Jalaei and Jrade, (2014) and Azhar et al. (2010) affirm the potential benefits of coupling sustainable design strategies and BIM technology to change traditional design practices by producing a more efficient design that leads to high-performance buildings in their studies.

Existing studies indicated that BIM could assist in the following aspects of sustainable design (Gupta et al. (2014); Krygiel and Nies (2008); and Zanni et al. (2014): 1) Building orientation (selecting a proper orientation can reduce energy costs); 2) Building massing (to analyze building form and optimize the building envelope); 3) Daylighting analysis; 4) Water harvesting (reducing water needs in a building); 5) Energy modelling (reducing energy needs and analyzing renewable energy options can contribute to low energy costs); 6) Sustainable materials (reducing material needs and using recycled materials); and 7) Site and logistics management (to reduce waste and carbon footprints). Furthermore, Olawumi and Chan. (2018) conducted a study to identify the perceived benefits of integrating BIM and sustainability principles. Their study details the significant benefits as follows: 1) facilitate sharing, exchange, and management of project information and data; 2) better design of products and facilitate multi-design alternatives; 3) facilitate accurate geometrical representations of a building in an integrated data environment; and 4) ability to simulate building performances and energy usage.

Several studies (Jalaei and Jrade (2015); Alsayyar and Jrade (2017); Han et al. (2017); Taha et al. (2020)) utilized BIM technologies to expand the adoption and implementation of sustainable practices in the construction industry. The adoption and execution of sustainability principles in construction incorporating environmental, social and economic aspects ensure the implementation of sustainable development. Jalaei and Jrade (2015) proposed a model to implement an integrated platform for sustainable design for proposed buildings at the conceptual stage. The developed model simplifies designing sustainable buildings and transferring their design information to an external database to list the potential certification points they can earn based on the Canadian LEED certification system. Their methodology incorporates an integrated model to assist users when performing sustainable design for new building projects. They developed an external database that stores lists of green products and certified materials and connected it to BIM tool through a developed plug-in to instantly calculate the sum of LEED points for the proposed facility. The use of that database helps users to design sustainable buildings easily and efficiently at the conceptual stage. Automating the process of identifying the potential number of LEED points that the new sustainable building must accumulate to comply with the desired level of certification and estimating the associated costs will minimize users' input and increase the calculation efficiency. Han et al. (2017) proposed a system that integrates BIM tool with a green building rating system to help improve the building performance. This system, called the Green Building Design Support System (GBDSS), proposes a methodology to assess LEED credits for BIM models and represent them in the IFC format as the data extraction process is standard and interoperable. The system calculates the LEED credits during the design and provides design suggestions to help create a green building project. Depending on the calculation's result, a report and revision guides are provided. Their system is composed of a User Interface (UI) for interacting with the system, a Calculation Module to calculate LEED points from the extracted data, a Data Extraction Module to map data and process extraction, a Rule Checking Module to provide specific required parameters of LEED credit.

Taha et al. (2020) studied the capability of BIM to investigate the impact of design parameter alternatives such as building orientation, window to wall ratio, and window glass type on energy performance and energy cost using simulation and performance analysis tools to improve project sustainability at the early design stage.

Similarly, various studies have been conducted over the last decade regarding the concept of UD. It has mainly focused on accessibility with a limited scope on individuals' physical or mental health (Mustaquim, 2017). At the same time, the concept of UD suggests the design of products or environments for most possible users without any special design needs that reflect the primary characteristics of sustainability (Mustaquim, 2017). Alsayyar and Jrade (2017) proposed a framework that integrates BIM tools with SUD requirements and strategies such as energy use, material use, indoor environmental quality and barrier-free environment to evaluate the associated costs at the conceptual design stage. Incorporating sustainability principles with UD toward sustainable universal design (SUD) supports designing healthier and environmentally friendly homes that accommodate people of different ages and abilities. Therefore, this study will incorporate sustainability assessment tools with universal design (UD) and Building Information Modeling (BIM) at the conceptual design stage to facilitate sustainable universal design toward building homes for aging in place.

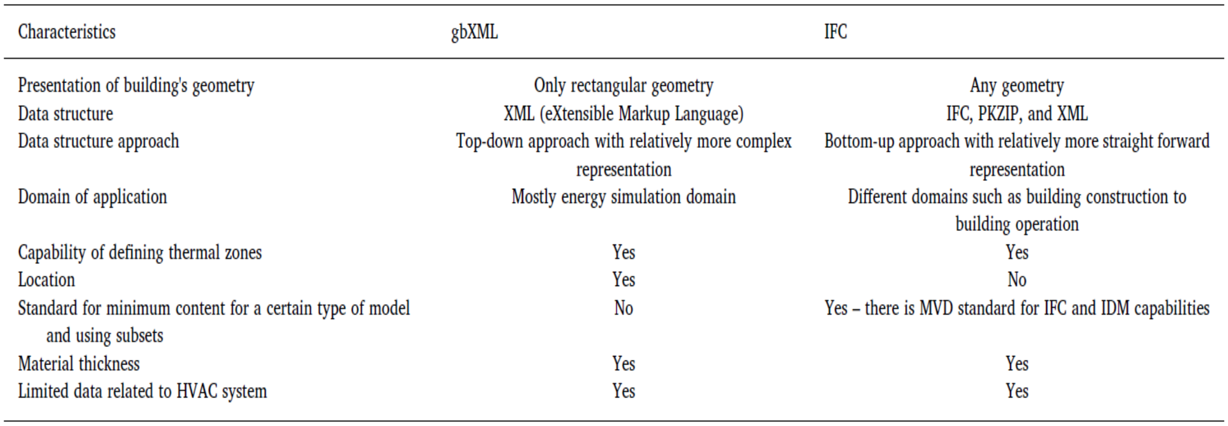
2.6 Database Management System (DBMS)

A database is a collection of electronic records that can be processed to produce useful information. These data can be accessed, modified, managed, controlled and organized to perform various data-processing operations. The data is typically indexed across rows, columns, and tables, making workload processing and data querying efficient. Database Management Systems (DBMS) is a solution method that is used to optimize and manage the storage and retrieval of data from databases. DBMS enhances the availability and consistency of data with minimum redundancy. Integrating BIM and DBMS facilitates creating an environment where the project participants can store the required data and update changes throughout the project life cycle. It enhances data security by the framework of security policies, sharing data with other parties, minimizing inconsistent data when exchanging data on various platforms, and saving time and cost for data collection (Le et al., 2020).

2.7 Integration and Interoperability

The ability to exchange data within a BIM-enabled project is vital to ensure that parallel processes within the design meet deadlines; and help in interpreting different applications (Alwan et al., 2015). Eastman et al. (2008) and Alwan et al. (2015) identified four formats of the data exchanges between two applications: 1) direct links between specific BIM tools; 2) proprietary file exchange dealing with geometry; 3) public product data model exchange format; and 4) XML-based exchange formats. Zanni et al. (2014) stated that several schemas had been developed to extract the environmental data in a neutral format. The green building XML (gbXML) and Industry Foundation Classes (IFC) are interoperability standards to enhance data integration (buildingSMART, 2013). The Industry Foundation Class (IFC) was developed by an international organization formerly known as the International Alliance for Interoperability (IAI) that was renamed to BuildingSmart in 2005. Hence, Fernald et al. (2018) noted that IFC and gbXML are considered the most common data schema responsible for the data exchange process within the industry. Using these formats facilitates the exchange of information between project partners without losing accuracy or design intent. Jalaei and Jrade (2014) stated that the green building XML schema (gbXML) facilitates the transferring process of the information stored in building information models to enable the integration and interoperability between the design models and other engineering analysis tools. Also, gbXML facilitates the exchange of the building information, including product characteristics and equipment performance data, between the manufacturer's database, the BIM models and the simulation engines. One of gbXML's benefits is its ability to carry detailed descriptions of a single building or a set of buildings that can be imported and used by simulation tools (Jalaei and Jrade, 2014). Kamel and Memari, (2019) discussed the differences between capabilities of IFC and gbXML formats in terms of general properties and data related to energy simulation, as shown in Table 2.3. The current versions of both file formats use XML but with different approaches. The top-down structure approach is used for gbXML, and the bottom-up data structure approach is used for IFC. Both provide material properties, limited data for HVAC systems, and thermal zone data; however, the location data is only provided in gbXML file format.

Table 2.3 – Comparison between gbXML and IFC, source: (Kamel and Memari, 2019)



Characteristics	gbXML	IFC
Presentation of building's geometry	Only rectangular geometry	Any geometry
Data structure	XML (eXtensible Markup Language)	IFC, PKZIP, and XML
Data structure approach	Top-down approach with relatively more complex representation	Bottom-up approach with relatively more straight forward representation
Domain of application	Mostly energy simulation domain	Different domains such as building construction to building operation
Capability of defining thermal zones	Yes	Yes
Location	Yes	No
Standard for minimum content for a certain type of model and using subsets	No	Yes – there is MVD standard for IFC and IDM capabilities
Material thickness	Yes	Yes
Limited data related to HVAC system	Yes	Yes

Several studies discussed and compared the two main approaches (top-down and bottom-up) used in BIM schemas for IFC and gbXML (Jalaei and Jrade, 2014; Dong et al., 2007; Cheng and Das, 2014; Gao et al., 2019). However, Elnabawi (2020) distinguished IFC as an object-oriented with a top-down structure that has all information illustrated in an organized approach, while gbXML is a bottom-up structure and is easy to comprehend. According to Jalaei and Jrade (2014) "top-down" approach is defined as a relatively complex schema with a large file size that is hard to program and use in software applications. It can trace back the semantic changes in a value within the schema. On the other hand, the "bottom-up" approach is flexible, open-source, and has a relatively straightforward data schema. Also, some of the data might not be transferred through an IFC BIM model, such as location, construction assignments, assumptions for lighting, equipment and people loads, airflow data, and units. It could be explained due to limitations in tools, which read the BIM file instead of shortcomings in BIM files. While the gbXML can transfer data related to shape, areas, volumes, location, construction assignments, building type (e.g., residential or commercial), and building services.

2.8 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is an assessment method that facilitates the tracking of possible changes associated with different stages of a project cycle, which results in improvements in its environmental profile (Kamari et al., 2021). LCA enables a scientific assessment, which facilitates locating the possible changes associated with different cycle stages, which results in improvements in its environmental profile (Bueno & Fabricio, 2018). LCA is an analysis process focusing on input and output flows of materials, energy and pollutants from the life cycle perspective. Ding G. (2008) illustrated the process of LCA as shown in Figure 2.4.

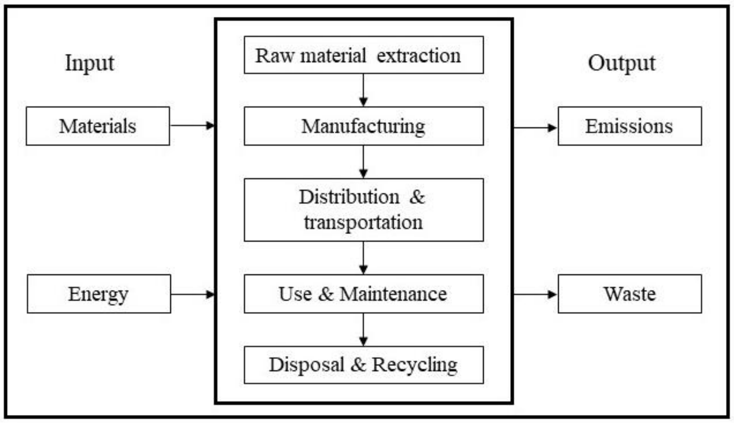


Figure 2.4 – Input and Output flows from a life cycle perspective, source: (Ding G., 2008)

LCA is a powerful tool to assess environmental impacts during the entire life cycle of a building. It evaluates the material and energy flow over the different life cycle phases, from production, construction, operation and demolition stages. It has been widely applied in the construction sector. To perform an LCA for a building, considerable information related to the building materials, the building processes, the operation phase and the demolition of a building should be collected. This step is very demanding and time-consuming. To reduce the efforts of LCA, Building Information Modeling (BIM) can be used.

BIM and LCA integration has excellent potential to reduce the time for life cycle inventory data acquisition and improve the simulation details of the LCA study for the specific building (Yang et al., 2018). Therefore, integrating LCA with BIM platforms will promote sustainable solutions by linking buildings' 3D models to various analysis tools and provide opportunities to improve building quality. A BIM-based LCA tool can be valuable as a decision-making method for designers and users to choose materials or design options for the project (Kamari et al., 2021). Hence, this study will adopt the integration method that consists of BIM tool, LCA, and plug-in to execute analysis within a BIM environment in order to ascertain the environmental impact of a building design.

2.8.1 Embodied Carbon, Integration with BIM and Associated Cost

Estimating the cost of embodied carbon emissions in buildings primarily focuses on assessing the carbon outputs across all the stages of a building's life, including material extraction, processing, construction, operation, and end-of-life phases (Dixit et al., 2012). The primary aim is to quantify the carbon emissions in carbon equivalent units to measure the building's total environmental impact. The process comprises the calculation of the embodied carbon, which includes emissions from materials' production to construction, and the operational carbon, which consists of emissions during the building's use. Effective strategies for reducing embodied carbon involve using low-carbon materials, optimizing building design to minimize material usage, and improving the recycling and reusing of materials. Methods for estimating these emissions have evolved, focusing on life cycle assessments (LCAs) that account for all related activities and processes to provide a comprehensive carbon footprint of building projects (Akbarnezhad & Nadoushani, 2014; Akbarnezhad & Xiao, 2017). A study by Schmidt et al., (2020) used a comprehensive approach to estimate the cost of embodied carbon emissions in the construction and maintenance of a building through its life cycle. It involved quantifying the life-cycle of greenhouse gas (GHG) emissions, for both operational and embodied, of a building and then applying economic evaluation techniques to those emissions. This process accounted for initial construction emissions, recurring emissions from materials that need replacement, and operational emissions over the building's lifecycle. The financial implications were estimated by multiplying these emissions by the current market price of carbon and then employing income methods (capitalization and discounted cash flow) to assess their economic value over time

Several studies, such as Llatas, et al., (2020) and Nwodo & Anumba, (2019) have been proposed to assess the environmental impact and cost of construction projects by translating the embodied carbon into a monetary value. Schmidt, et al., (2018) advocated for the implementation of a carbon tax applied to the lifecycle carbon emissions of buildings. This strategy aimed to effectively communicate greenhouse gas (GHG) emissions to stakeholders and to provide incentives for reducing emissions.

2.9 Energy Analysis, WWR, Building Orientation and BIM Integration

There are two traditional methods for energy simulation. The first is to input architectural information by using numerical data, and the second is to make a two-dimensional model by using an integrated user interface in the simulation software. The traditional modeling method consumes a lot of time and effort to put the architectural information into the energy simulation software. Building Information Modeling (BIM) reduces the actual time needed to model the architectural geometries. BIM data can be integrated with building performance simulation applications such as Green Building Studio, Ecotect, Project Vasari, VE, etc. This integration enables them to be powerful decision-making tools for the design of a high-energy performance building (Ryu & Park, 2016). BIM brings significant technological advantages if compared with conventional methods of producing and handling project information and can assist in green and sustainable building design areas such as building massing, daylight, solar and wind analysis, and energy modelling (Alwan et al., 2015).

Windows play a vital role in enhancing the building's energy efficiency by significantly influencing its energy load (Kim et al., 2016). According to Kim et al., (2016), 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 (Chi et al., 2020). Studies conducted by Bokel, (2007); Montaser Koohsari et al., (2015); and Leskovar and Premrov, (2011) focused on the effect of windows’ design on the building energy load concerning factors such as window size, position, glazing properties, and orientation.

2.10 Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is an economic assessment method for a project considering all costs of owning, operating, maintaining, and ultimately disposing of a facility to achieve the long-term value of money. It is considered an economic evaluation of existing assets or a potential investment, considering the immediate and the long-term costs. It is the cost of an asset or its parts throughout its life cycle while fulfills the performance requirements. It examines the building's sustainability by comparing energy costs and the maintenance costs of different design alternatives and ensuring that the design meets the project's environmental requirements. For example, (Le et al., 2020) inform that LCCA assists the economic evaluation of the project at the early project stage, which contributes to environmental sustainability. In practice, the purpose of LCC analysis is to facilitate the decision-making process to reasonably evaluate the building's economic performance through its life cycle (Marzouk et al., 2018). However, Rashed et al., (2019) emphasized that there are many other economic evaluation techniques such as 1) LCC; 2) benefit-to-cost ratio or savings-to-investment ratio; 3) internal rate of return; 4) net benefits; and 5) payback period can be used for buildings to compare their financial performance and reach the best cost-effective decision. According to Rad et al., (2021), LCCA should be performed during the early design stage when there is still an opportunity to refine the design to ensure a low operating cost and optimize the life cycle cost. Although LCCA has benefits in evaluation and investment decision-making, a practical framework for its implementation is required. Khodabakhshian et al., (2021) stated that BIM is the best-integrated support system for life cycle processes performed by stakeholders. Alsayyar & Jrade (2017) proposed an LCCA framework that integrates the quantities of materials of a 3D BIM model (using the sustainable universal design) and LCCA tool (using BEES TM) for performing economic analysis at the conceptual design stage. While the LCCA method estimates a project's overall cost for selecting the design that would provide the lowest overall cost of ownership, the process must not sacrifice the project's quality and function.

2.10.1 Incorporating LCCA with BIM

Conventional LCCA is a complex and time-consuming process due to the complicated repetitive calculations based on various requirements. In addition, it requires a large amount of construction-related data from different sources throughout the project life cycle. Data are usually stored in the form of papers and input into the systems manually. This process results in data loss and inconsistent data, contributing to inaccurate life cycle costs. Although the advantages of building LCCA have been widely recognized, previous studies have revealed several barriers related to the availability and reliability of required data, limiting the applications of building LCCA for actual construction projects. Inadequate time and high data collection costs were critical barriers to implementing building LCCA in practice. Also, the quality of available data had a vital role in implementing building LCCA. Building Information Modeling (BIM) is a technology that can potentially overcome the severities of the conventional building LCCA. However, existing BIM tools cannot build LCCA due to their limited capabilities (Le et al., 2020). As a solution, many researchers attempt to present workflows that include Life Cycle Costs (LCC) techniques and Building Information Modeling (BIM), and the possibility of integrating BIM with LCC has been tested by several researchers and showed great promise (Rashed et al., 2019). Integrating BIM and LCCA can be used for different purposes, such as construction design simulation, automatic extraction of the bill of quantities, decision making, asset valuation, automatic/semi-automatic environmental and economic assessment, and the incorporation of sustainability-related information (Khodabakhshian & Toosi, 2021).

2.11 Summary

This chapter presented an extensive review of the literature on Universal Design (UD), Virtual Reality (VR), Building Information Modeling (BIM), focusing on window-to-wall ratio and building orientation, Life Cycle Assessment (LCA) considerations such as embodied carbon, Life Cycle Cost Analysis (LCCA), and Leadership in Energy and Environmental Design (LEED). Specifically, it delved into the integration of BIM with Universal Design standards and VR during the conceptual design stage of buildings. Virtual Reality (VR) offers immersive visualization experiences that go beyond digital representation, allowing for virtual walkthroughs and interactive tasks to provide real-time feedback and enhance design comprehension and satisfaction. Moreover, the incorporation of BIM enhances collaboration and cooperation efforts among designers, with detailed discussions on various BIM definitions, terminologies, and current practices. Additionally, the chapter explored the potential linkage between BIM, UD standards, VR, EA, LCA, LCCA, and LEED. While numerous studies have examined the integration of BIM and VR, limited research exists on the integration of BIM and UD. Furthermore, no study was found that simultaneously integrates BIM, VR, UD, EA, LCA, LCCA, and LEED, which is a highlight on an existing gap in the current literature.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter describes the development methodology of a model that integrates BIM with universal design and virtual reality at the conceptual design stage of housing projects by considering the sustainability requirements, environmental impact, energy analysis, sustainability assessment and cost. The model simplifies the communication and interaction between owners and designers to accommodate users' needs and to help inhabitants age in their homes. Furthermore, it facilitates the design of sustainable universal houses by evaluating their environmental impacts, analyzing and simulating their energy, listing their potential collected certification points and estimating their life cycle cost. This integration systematically incorporates Universal Design Standards into BIM environment at the conceptual design stage by using a developed database for Universal Design, Accessible Design standards and aging-in-place requirements to enhance the functionalities and capabilities of BIM tools. It facilitates the process of retrieving universal families of architectural components by implementing UD standards into the design. Furthermore, it helps designers and owners define the best practical scenario that would meet owners' requirements and permits owners to live and walk through the house virtually before its physical construction starts and to do necessary modifications based on their needs and requirements. The implemented workflow in this study is as follows:

1. **Literature review**: Studying the relevant literature related to the feasibility of looking into the aging in place, its needs, gaps, and expectations in relation to sustainable design of houses and the applicability of integrating BIM with universal design standards and virtual reality. Also, to find the deficiencies in the functionalities of BIM tools that are currently used in the industry to incorporate the standards of universal design and sustainability at the conceptual design stage.

2. **Data collection:** Collecting the necessary universal design and accessible design guidelines, building codes requirements, aging-in-place requirements, window-to-wall ratio and building orientation data, and cost related modifications' factors to aging-in-place requirements to be stored in external databases that are used by designers at the conceptual design stage of houses.

3. **Database development:** Developing several external databases to store the collected data. These data is retrieved automatically by BIM tool after creating new plug-ins and customizing the tool to assist designers in incorporating them into their designs. This would facilitate instant and automatic access to the required data and design families in order to simplify the creation of universal design houses.

4. **Data analysis and model development**: The model comprises six modules that will share data and information automatically and efficiently, which are: a Database Management System (DBMS) module; a 3D BIM design module; a Virtual Reality module; an Energy Analysis module; a Life Cycle Assessment (LCA) module; and a Life Cycle Cost Analysis (LCCA) module. Each module is linked to one or more databases covering necessary data and information.

5. **Model Testing:** The integrated model is verified by creating several interfaces of the abovementioned modules as new plug-ins for BIM tool and is tested through case studies.

3.2 Model Architecture

The integrated model consists of six modules named as: Database Management System (DBMS) module; 3D BIM design module; Virtual Reality module, Energy Analysis module; Life Cycle Assessment (LCA) module; and Life Cycle Cost Analysis (LCCA) module. The 3D BIM design module is linked to the external database, which is managed by a database management system. Figure 3.1 illustrates the model architecture. The input section includes different parameters related to each module, such as universal design standards, game environment parameters, project information, project quantity take-off and sustainable information. The criteria section consists of aging-in-place requirements, client needs, green building rating system, and the environmental performance and principles toward a sustainable design of houses. Also, to meet the integrated model's automation requirements, the programming capabilities of BIM tools are considered by developing new plug-ins. The primary output of the model is a sustainable universal 3D BIM model and a virtual interactive model in the form of a gaming environment that includes environmental impact and energy analysis simulation results. Also, initial cost, running cost, replacement costs, etc., LCCA results, and a visual cash flow of the project are considered as outcomes. These results provide valuable information about a systematic design of a sustainable universal house where its performance in accordance with the owners’ needs, construction costs, design parameters analysis, environmental impact and energy consumption is optimized. The novelty highlighted in this study resides in integrating different modules such as Universal Design, Building Information Modeling and Virtual Reality through an automated process by sharing data and information among them by using newly created plug-ins to assist designers in incorporating UD standards into the design of houses at the conceptual stage in a timely and cost-effective manner.

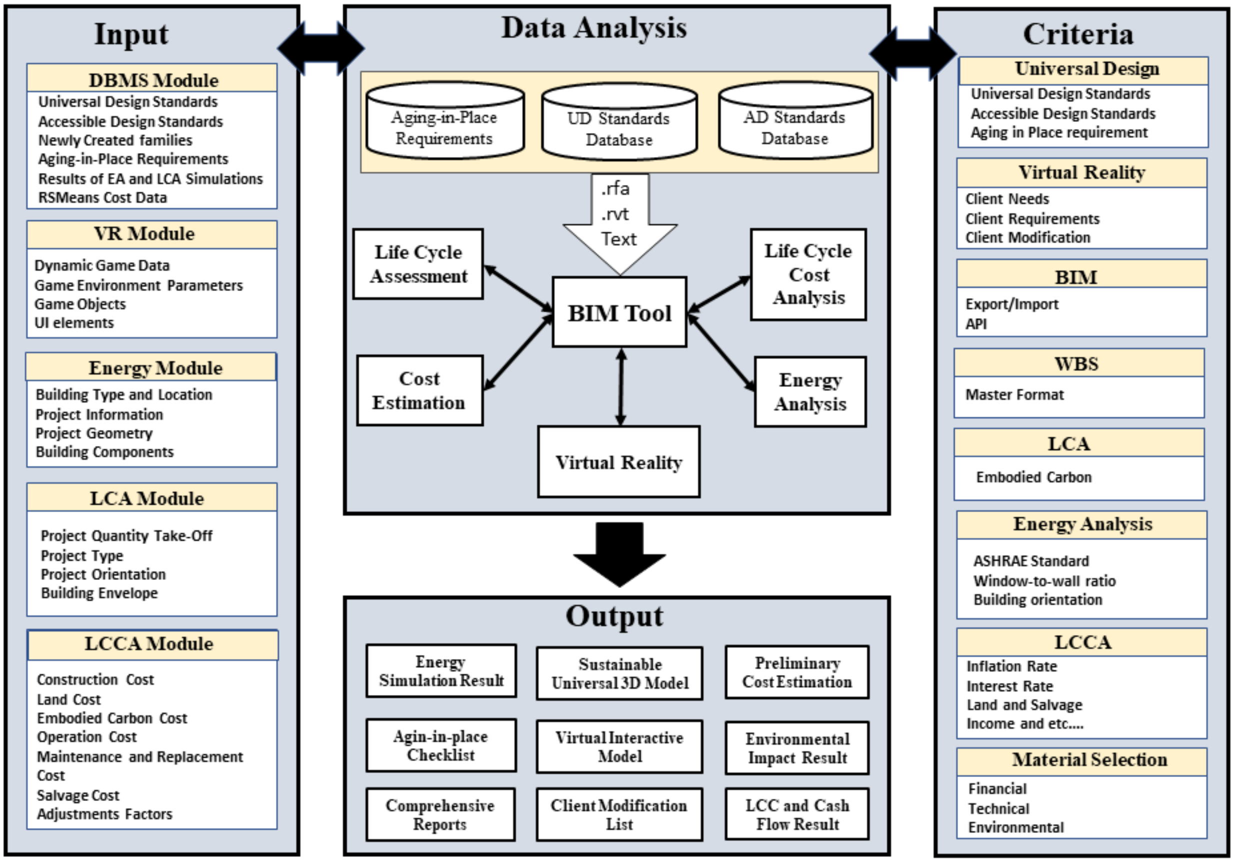


Figure 3.1 –Model Architecture

3.3 Model Components

The model components, as shown in Figure 3.2, consist of the aforementioned six modules so that each module is linked to one or more databases that encompass necessary data and information. If a module’s requirement can be met by using the existing functionalities, the internal operation in BIM tool is adequate to have direct data feedback. Otherwise, new functionalities may have to be developed by customizing the Application Programming Interface (API) and connecting it to BIM tool as a plug-in or exchanging data through specific file formats such gbXML.

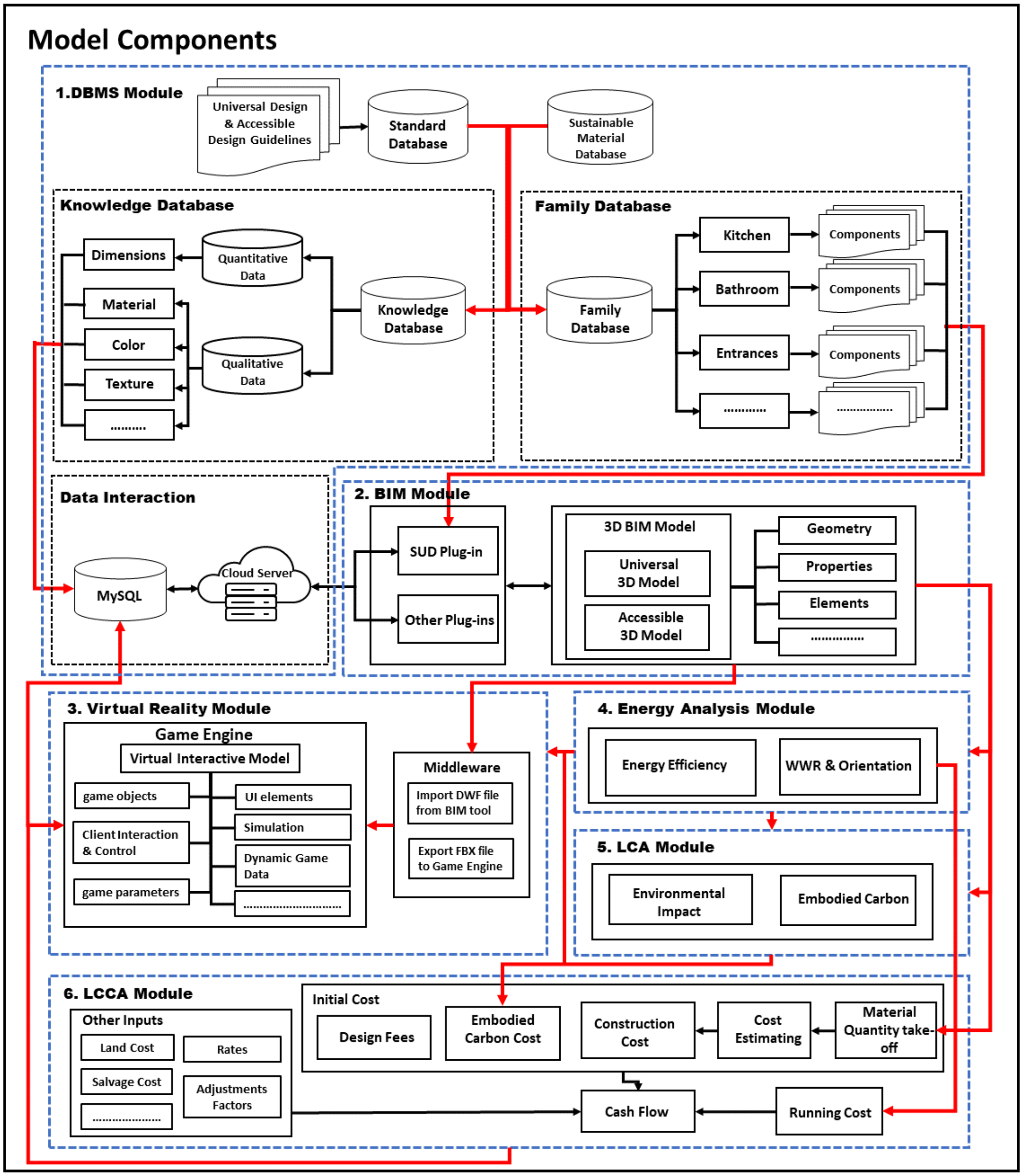


Figure 3.2 –Model Components

3.3.1 Module 1 - Database Management System (DBMS)

This module aims to design the model’s relational database to store information related to the universal design and accessible design standards and aging-in-place requirements, which is needed to design sustainable universal houses. To accomplish the database, data from universal design guidelines and accessible design guidelines such as the National Building Code of Canada (NBCC, 2015) and Canada Mortgage and Housing Corporation (CMHC, 2019) is collected and stored in the database. However, in this database, the collected data is divided into two parts: 1) quantitative data; and 2) qualitative data. The qualitative data consists of all the descriptive information related to the objects and components that is used in the 3D model, such as the components' colour, texture, type, and associated materials. In contrast, the quantitative data comprises numerical information, mainly in the form of dimensions extracted from the guidelines. Data is stored in a series of tables that form the Knowledge Database, which will hold over sixteen guidelines that is collected from various sources.

The Family Database is formed to store newly created and/or modified families that already exist in BIM tool (i.e., Autodesk Revit) based on the stored information and data in the knowledge database. These families are made as Revit Family (RFA) or Revit project (RVT) file formats and are stored in the corresponding database. Once the designer selects a specific standard, then a particular guideline from the database and its related families will be loaded in a pre-defined path that is linked to the library of BIM tool. The process of collecting and storing universal design and accessible design standards is shown in Figure 3.3.

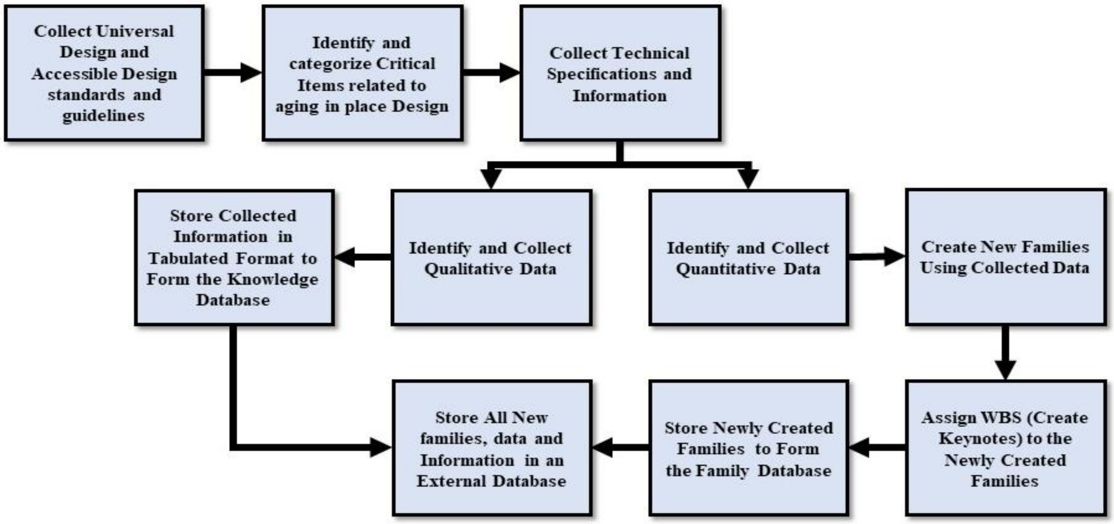


Figure 3.3 - Standard Database Collection Process

The significant expected contribution of the developed databases is by enhancing the functionality and capability of BIM tools at the conceptual design stage to help users incorporate Universal Design standards and Accessible Design standards easily while designing houses. The aim of developing a separate database of families is to load them every time BIM tool opens. This is done via a newly created plug-in that accesses them by a predefined path that is linked to the library of families in BIM tool. This makes the created families instantly accessible when they are needed during the design process. The information and data are categorized and stored in the external database to facilitate using the knowledge and family databases, as shown in figure 3.4.

For a detailed description of this module, please refer to Technical Paper I.

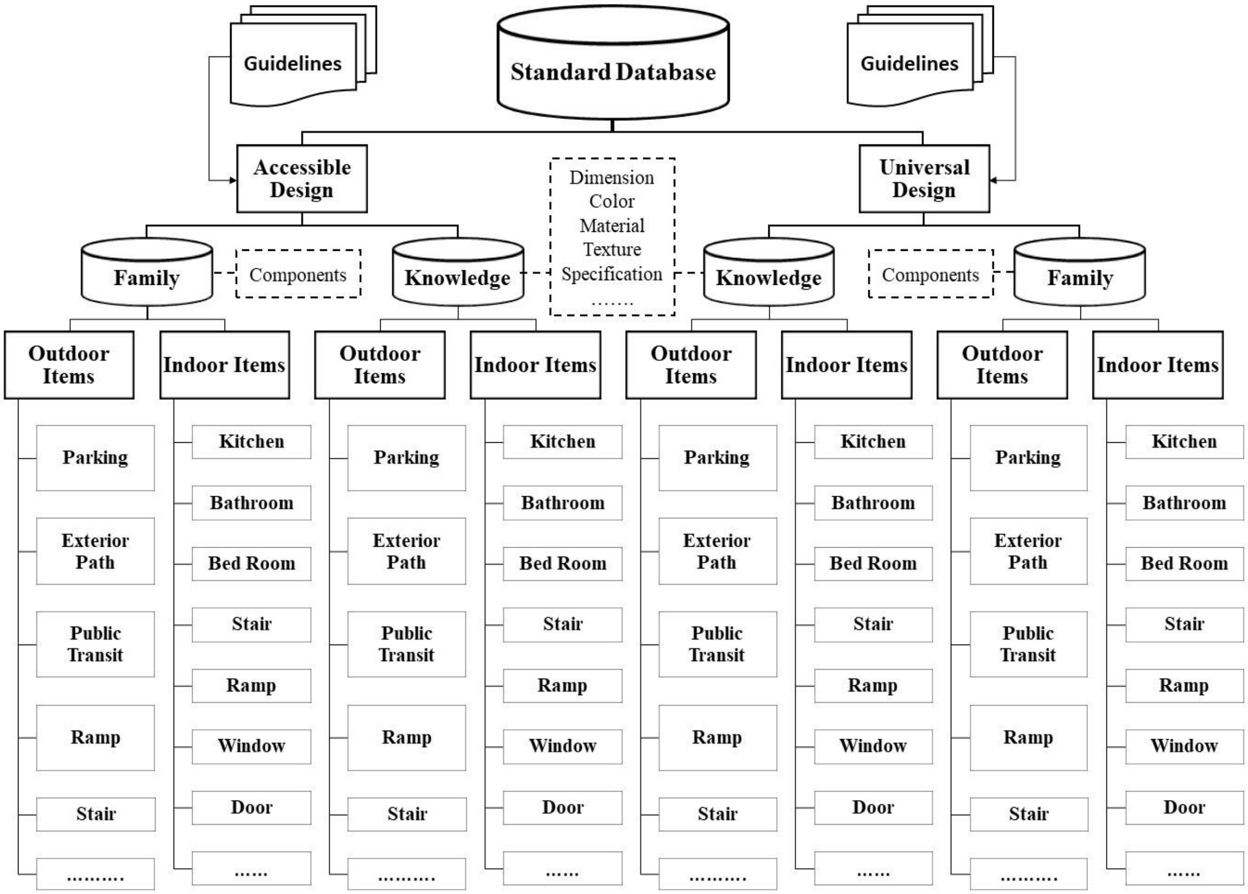


Figure 3.4 – Standard Database Components and Categorization

3.3.2 Module 2 - Building Information Modeling (BIM)

This module focuses on customizing BIM tool by creating new plug-ins to incorporate the developed databases into BIM model, containing the model's UD/SUD requirements. To begin, new plug-ins in BIM tool are created and linked to the developed database to manage and simplify the selection and retrieval of the new families used in creating 3D models of houses. Autodesk provides powerful APIs (Application Programming Interfaces) and SDKs (Software Development Kits) for its tools, allowing users to customize and tailor the software based on their needs. The customized families are automatically loaded into the predefined library of BIM tool, enabling designers to use them while modeling the project. The 3D model is created in BIM tool with all associated geometry components using the newly created families from module 1, loaded into the project through the developed plug-in. Designers can retrieve compatible guidelines from the Universal Design standard or Accessible Design standard from the created databases in module 1, based on the owner's needs. When a guideline and its specific component(s) are selected during the design process, all related families are automatically placed in the predefined path alongside the general families of Autodesk Revit, ready for direct use in the model. Figure 3.5 illustrates the sequence of the newly created families and where they will be stored. In this integration, the cloud server has a two-way interaction with the plug-in developed in BIM tool to import and export data from and to the database and BIM tool. It is important to note that in this thesis the cloud is solely utilized for data storage, and not for computational purposes.

For a detailed description of this module, please refer to Technical Papers I and II.

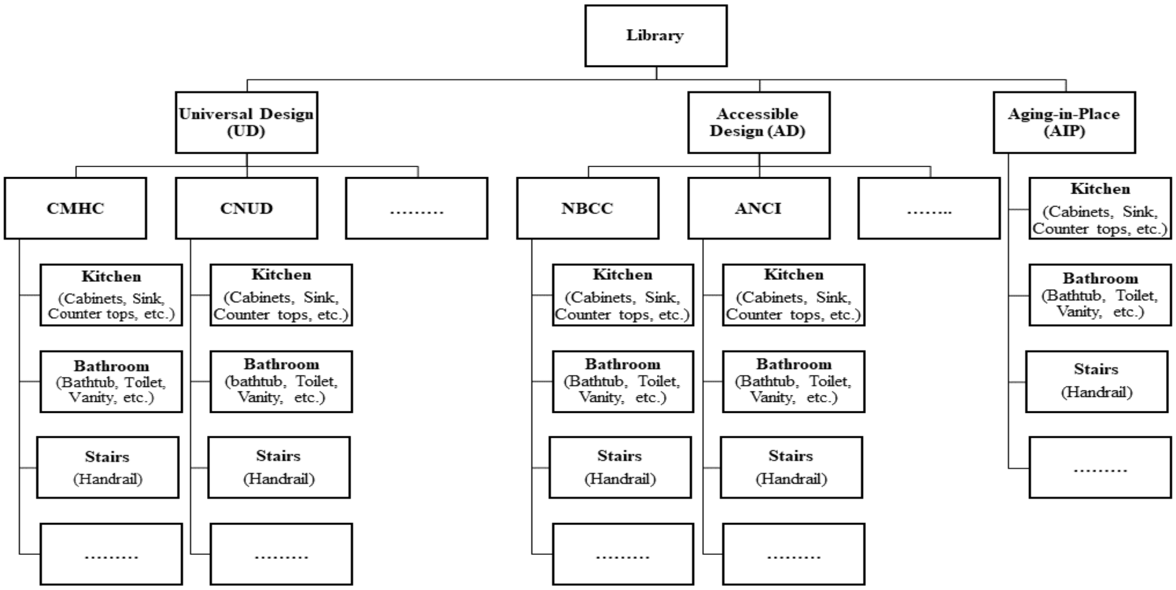


Figure 3.5 – The sequence of the newly created families in the BIM library

3.3.3 Module 3 - Virtual Reality (VR)

This module focuses on creating a virtual environment and setting up the game environment parameters and adjustments, such as adding an avatar and a camera and developing a game application. Integrating BIM with gaming environments allows users/owners to experience the house before the actual construction. It creates an interactive environment with the 3D BIM model that enables users/owners to experience, analyze, assess and modify the building's components based on their needs and requirements. The most fundamental factor in selecting game engines is their support for 3D asset import and cross-platform integration. Besides, user interface, graphical abilities, including texture library and lighting effects, and animation editing are essential for this study. Unity game engine supports assets from nearly all major 3D applications like 3ds Max, Maya, Softimage, CINEMA 4D and Blender. It is a platform-neutral and runs on Android, iOS, and Windows Phone mobile devices. It also has the capabilities of development for PlayStation, Xbox360, Wii U and web browsers. It has no actual modeling or building features, so everything will need to be created in a third-party 3D application, such as 3ds Max (Wu and Kaushik, 2015). This module will be comprised of six major steps to be accomplished, as shown in Figure 3.6.

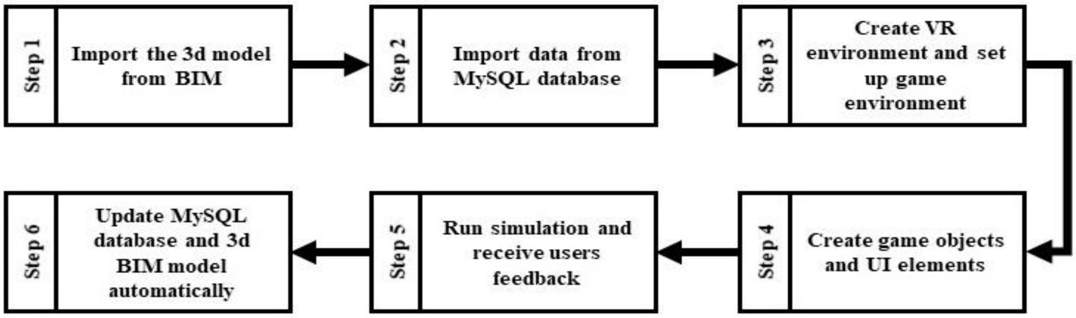


Figure 3.6 – VR module process flow

Step 1; Importing the 3D BIM model into the VR environment involves exporting 3D models created with BIM tools, like Autodesk Revit, to VR engines via file formats such as FBX. This process may encounter errors such as missing materials' information and interoperability issues between BIM and VR. To address this, the 3D model is transferred from BIM tool to the game engine, Unity, using a middleware tool like 3dMax or Simlab Composer..

Step 2; Importing related data from the BIM model to the VR environment entails creating a MySQL database to automatically import and export data. This database acts as a link between the BIM tool and the game engine, requiring C# and PHP programming to establish the connection.

Step 3; Creating the VR environment involves setting up gaming objects, adjusting the imported model, adding a camera, and an avatar. The camera is positioned at the user's eye height for a realistic experience, and the avatar is adjusted to interact with objects without falling through them by adding colliders.

Step 4; The creation of a communication panel using User Interface (UI) elements is crucial. This panel, designed for 3D model components, displays detailed information such as objects' names, IDs, and dimensions based on the BIM tool database. A virtual keyboard allows users to modify object dimensions.

Step 5; Running the simulation and receiving feedback from the user involves creating apps for Android, iOS, and Windows using game engines like Unity. This enables users unfamiliar with game engines to efficiently communicate with and modify the 3D model based on their needs.

Step 6; Updating the database and 3D model in BIM tool based on modifications made in the VR environment will automate the process, reducing human errors and minimizing associated time and cost. Figure 3.7 illustrates the framework of this VR module and the integration process of the three main modules: DBMS, BIM, and VR.

For a detailed description of this module, please refer to Technical Papers II and III.

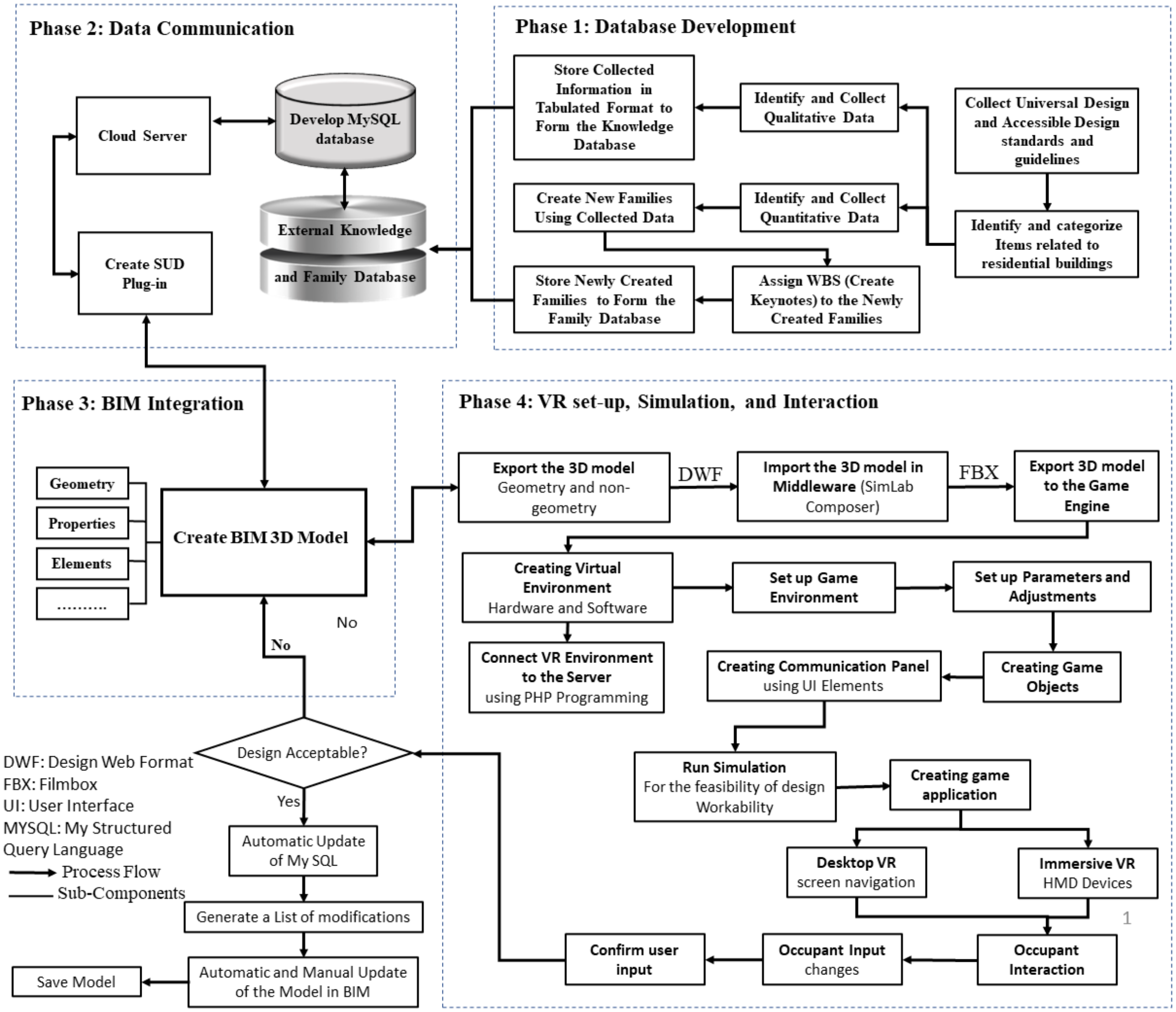


Figure 3.7 – Framework of the VR module and integration with BIM module and DBMS module

3.3.4 Module 4 - Energy Analysis Module

This module focuses on energy modeling at the conceptual design stage to provide feedback on the building's environmental impacts and annual energy consumption to the design team and owners. It aims to streamline the process of integrating BIM, VR, and Energy Analysis tools for Age-In-Place housing projects during the conceptual design stage, prioritizing automated access to necessary data. Illustrated in Figure 3.8 are the functions performed within each of the model's components and their local developments. Since the methodology integrates different applications, the development will be implemented through four phases: 1) WWR Base Model Creation and Simulation; 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 (DesignBuilder 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 selecting 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 different scenario recommendations for WWR and building orientation to designers and end-users during the conceptual design stage.

For a detailed description of this module, please refer to Technical Paper III.

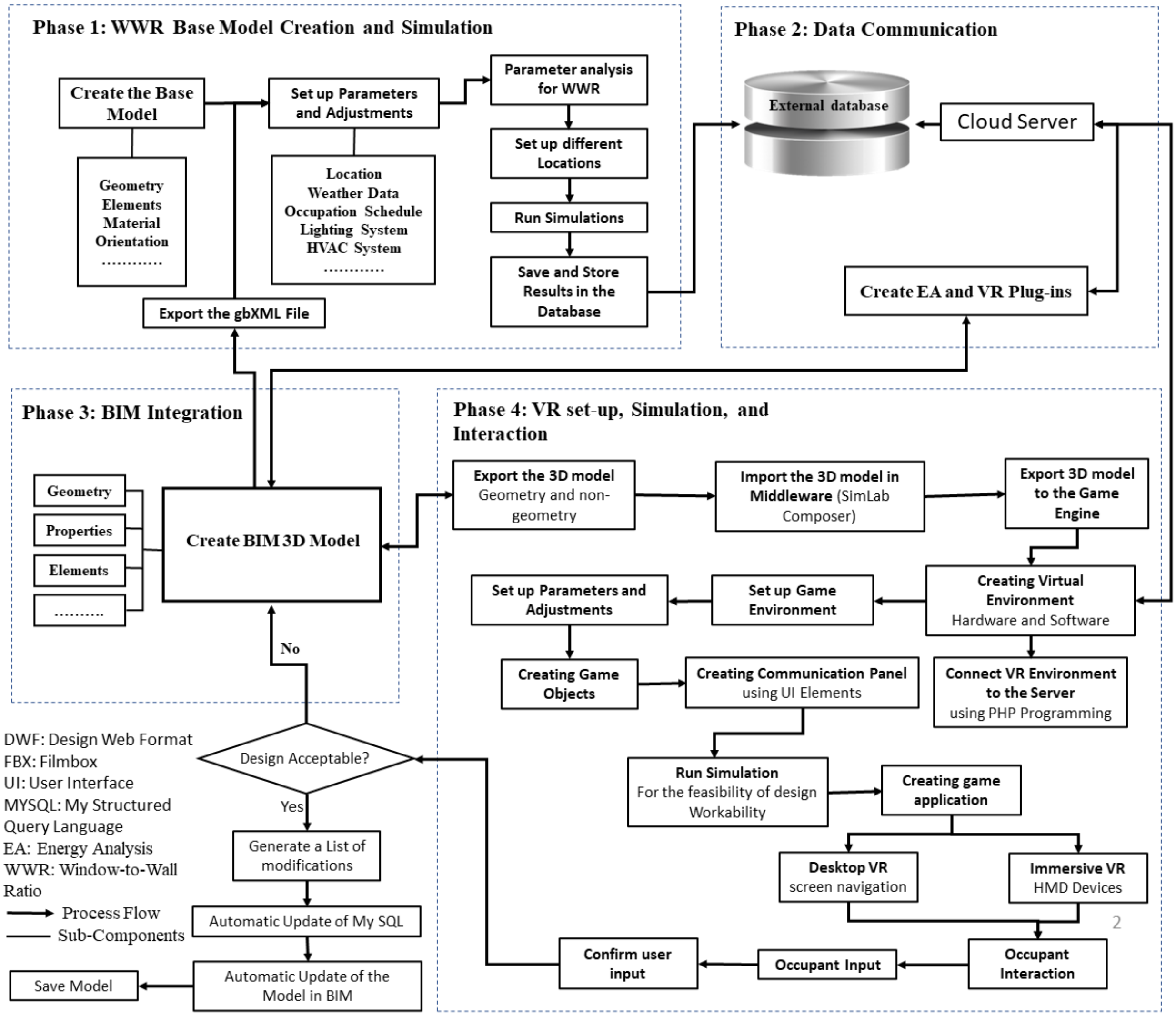


Figure 3.8 – Energy Analysis Flowchart

3.3.5 Module 5 - Life Cycle Assessment (LCA)

This module concentrates on designing LCA module that integrates the 3D BIM design with LCA tool. A new plug-in is created to automate the integration and conduct a life cycle assessment (LCA) to generate the embodied carbon. The primary focus of this module in relation to the LCA is on the envelope components of houses, specifically the walls, roofs, and windows as these components play a critical role in the overall energy consumption and environmental impact of buildings. The scope of this study involves the production stage of building materials (including raw material extraction and manufacturing), which is defined as cradle to gate. The assessment of the embodied carbon within this scope involves the quantification of the embodied carbon associated with the extracting, processing, and manufacturing processes. By analyzing the embodied carbon, this study seeks to identify the chances for reducing carbon emissions and promoting environmentally sustainable building practices. This analysis generates valuable insights into the environmental impact of house envelopes and supports the decision-making process aimed at mitigating carbon emissions and promoting the adoption of low-carbon building's materials and construction practices.

For a detailed description of this module, please refer to Technical Paper IV.

3.3.6 Module 6 - Life Cycle Cost Analysis (LCCA)

This module incorporates LCCA into the design process at the early design stage of the building. the developed LCCA plugin automatically receives data inputs from the AIP, LCA, and energy analysis plugins, ensuring real-time and accurate integration. It also brings in RSMeans cost data and user inputs, forming a complete dataset for thorough LCCA. The plugin is designed to explore various design alternatives and their economic impacts through scenario analyses. Also, it has the ability to conduct sensitivity analysis to identify the most sensitive parameters and to check how the model responds to changes in the input constraints. The integrated model then produces a detailed LCCA by considering the design, construction, operation, and maintenance costs. These results are visually presented and analyzed to identify the cost-effective design's option, empowering designers and owners to make informed decisions. Ultimately, the plugin produces detailed reports that summarize the results of the LCCA, sensitivity analysis, and scenario analysis by offering accessible insights for the decision-making processes as seen in Figure 3.10.

For a detailed description of this module, please refer to Technical Paper IV.

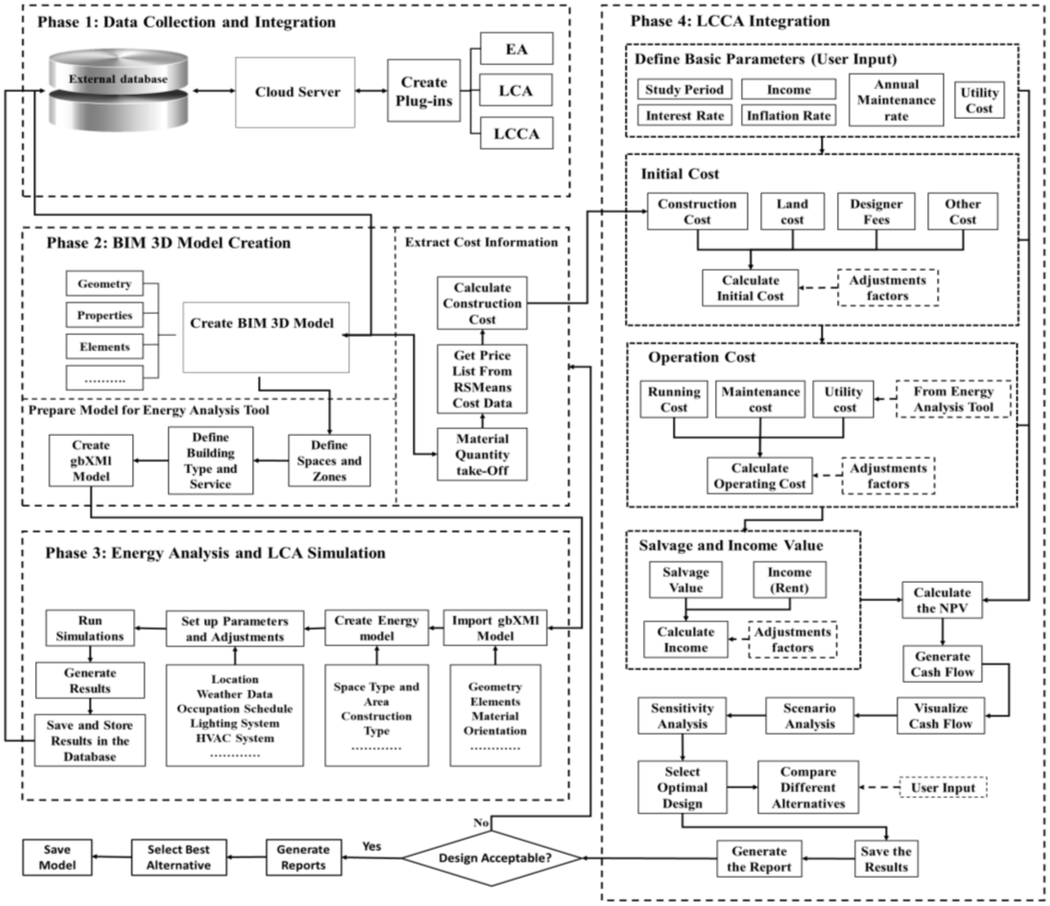


Figure 3.9 – Integrating LCCA and BIM process Flowchart

3.4 Level of Automation in the Model

The developed framework incorporates several modules that have different levels of automation. The Building Information Modeling (BIM) module is fully automated, facilitating the seamless integration of Universal Design (UD) standards and Aging-in-Place (AIP) requirements at the conceptual design stage. The Energy Analysis (EA) and Life Cycle Assessment (LCA) modules are semi-automated, where manual inputs of initial data are required, but all subsequent analyses and simulations are automated. The Life Cycle Cost Analysis (LCCA) module operates in a similar way, requires manual entry of cost data before automatically executing all the calculations and projections. On the other hand, certain elements such as manual review and interpretation of compliance with the building codes, as well as some specific design adjustments based on users' feedback within the Virtual Reality (VR) environment, remain to be manually processed. This variation in the levels of automation ensures a balanced approach, combining the efficiency of automated processes with the precision and contextual understanding that is provided by manual interventions.

3.5 Summary

This study focuses on the conceptual design stage of houses, where the available data is limited, but important decisions have to be taken. Any additional information would help the designer and owner to support their decision. This study introduces the development of an integrated model that interrelates BIM, VR and UD at the conceptual design stage of houses to accommodate Canadians to age in them regardless of their health conditions and age. The expected novelty highlighted in this study is by representing different modules integrated into each other based on an automated process by creating new plug-ins and by improving the functionality of the existing ones to help designers and users to do sustainable universal design of houses at the conceptual stage in a timely and cost-effective manner. Also, it allows them to have effective design communication to understand the design intention. Users could give feedback to have a design based on their needs, requirements, expectations and satisfaction. Using the integrated model at the conceptual design stage of a house enables designers and owners to easily incorporate the universal design standards, Accessible design standards and aging-in-place requirements into the design and to select optimal design alternatives based on multiple criteria. Using predefined families that meets owners' needs and requirements during the design process facilitates establishing sustainable universal design for houses. The integration of the methodology is attained by implementing an interface that is written in visual C# programming language, especially for the modules that require the creation of new plug-ins. The model is simple and user-friendly and helps in evaluating and comparing multiple design alternatives based on different criteria, especially the economic aspects of the design.

CHAPTER 4

TECHNICAL PAPER I

Integrating Universal Design Standards and Building Information Modeling at the Conceptual Design Stage of Buildings

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ABSTRACT: A projection of the Canadian population shows that in 2024 one in five Canadians will be over 65 years old. This shift forces designers to consider the entire lifetime of occupants during the design of new buildings. Universal Design (UD), which is a design that accommodates all people to the greatest extent possible and aging in place design that is deeply rooted in the principles of UD, aim to house people irrespective of their age, ability, and chronic health conditions. Building Information Modeling (BIM) significantly helps advancing the development of the Architecture, Engineering, and Construction (AEC) industry in a more collaborative and automated way. Integrating BIM and UD allows designers to incorporate UD standards easily and efficiently at the conceptual design stage of buildings by using the functionalities and capabilities of BIM tools. Therefore, this study presents the development of an automated computer model to facilitate the adoption of UD standards and processes. The novelty highlighted in this model resides in the creation of an automated method that employs a newly created plug-in and databases to assist designers incorporate UD standards at the conceptual stage in a timely and cost-effective manner. Furthermore, the study introduces the methodology consisting of collecting, categorizing, and storing data from various universal design and accessible design guidelines in the developed databases and developing new plug-ins in BIM tool to link the developed databases in order to

automate the process of retrieving necessary information and components to help designers and owners select optimal design alternatives based on their predefined criteria.

Keywords: Building Information Modeling (BIM), Universal design, Accessible Design, Aging in Place, Computer Integration and Automation.

4.1 Introduction

In 2015, Statistics Canada revealed that 16.9% of Canadians were aged 65 years or older, out of which 2.2% were aged 85 years or older, which represented a 20.0% increase in the age of that group since 2011. Thereafter, a projection of the Canadian population showed that the number of persons aged 65 years and older will continue to increase to reach 20.1% of the whole population in 2024 [1]. Generally, aging relates to increased chronic health issues and functional disabilities. A recent report by Globe Newswire [2] uncovered trends related to aging and its impact on seniors' housing aspirations, expectations, and realities across Canada. The report showed that 86% of Canadian seniors want to live in their homes for as long as possible rather than going to long-term care facilities. On the other hand, in 2021, the Government of Ontario [3] reported that between April 2020 and April 2021, the number of Canadian seniors who died due to Covid-19 in Ontario’s long-term care facilities reached 3,785 cases (3,772 residents and 13 staff). As a result, adopting the concept of aging in place becomes of top priority and high importance. Therefore, more design strategies should be considered to overcome the issue of aging in place [4]. Universal Design philosophy is inspired by the social responsibility of using the built environment with no distinction. This philosophy led to a systematic development of the design guidelines for architectural and urban projects to render the accessibility of the built environment to all [5]. It aims to simplify the life of people regardless of their age, size, or ability to achieve an inclusive society where every person has equal opportunities to participate, whether young, senior, disabled, or non-disabled [6]. Thus, the term Accessibility, which is one of the critical factors for aging in place, is used for that purpose. Andersson [7] stated that architecture and gerontology are two fields of research that closely need to be explored to be prepared for senior citizens in an aging society. Design for aging aims to accommodate the rapid increase in the senior population and to promote innovative design solutions to create desired physical and service environments facilitating a sustainable aging process [8]. An age-friendly design needs to be accessible for older people with varying needs and abilities to promote their physical activities and to reduce the risk of many health and medical problems of particular concern to elderly Canadians [9]. There is growing evidence that physical activity prevents or delays cognitive impairment and improves sleep [10]. "Aging in place means having access to health services and social supports for elderlies who need to live safely and independently in their homes or their community for as long as they wish and are able" [11]. To enable aging-in-place, environmental barriers must be removed, including indoor physical modifications and accommodations to enhance the accessibility and usability of the home environment, increase safety, and reduce difficulties in activities' performance [12]. Physical modifications involve installing ramps in staircases and safety bars in bathrooms, making premises more accessible and useable [13]. Liu and Lapane [14] stated that environmental modifications in a residential building, such as street-level entrance, railings, automatic doors, bathroom and kitchen modifications and elevator or lift, could potentially influence an individual’s ability to perform basic tasks necessary for daily functioning. Building Information Modeling (BIM) is a concept used in the AEC industry all over the lifecycle of a project, from design and documentation passing through the construction stage to operation [15]. BIM has significant benefits related to the rich project information, geometry, materials properties, and the building process through the project's life cycle [16]. The increased use of BIM in the construction industry provides a unique opportunity for integrating Universal Design principles into buildings' model as a fundamental strength of the interoperability of BIM tools to other programs. Coupling BIM and UD have the potential to produce high-performance and universally designed facilities. Applying UD guidelines to the built environment at the early design stage would facilitate the creation of homes based on owners' needs. It would be adequate throughout their lifespan despite of the changes in their circumstances or abilities [17]. While existing studies such as [17] and [18] gfdsa models to incorporate universal design standards at the conceptual design stage, these studies are limited to creating design families and integrating them into BIM tools based only on the National Building Codes of Canada. The authors were not able to find literature about an integrated/automated model that has the capability of combining various standards and guidelines in a single model that couples universal design and accessible design standards with Building Information Modeling to help designers apply them at the conceptual design stage. This study adequately incorporates various universal design and accessible design standards and guidelines to enhance the design for aging in place and help designers have instant access to such type of data as well as newly created design families that are compatible with those standards and guidelines through an automated model. This paper presents the development of an automated model that integrates Building Information Modeling with Universal Design (UD) and Accessible Design (AD) standards at the conceptual design stage of proposed buildings. The said integration will systematically incorporate Universal Design Standards into BIM environment by developing a database that stores those standards and links it to BIM tools. The database stores newly created and modified families of architectural components that comply with the different Universal Design (UD) and Accessible Design (AD) guidelines. That database is integrated with

BIM tool by using the tool’s API and by creating an innovative plug-in, which is developed for that purpose. This integration would facilitate the process of retrieving universal design families while producing the design of new buildings under UD/AD standards. Therefore, the main objective of this study is to develop an automated computer model that integrates BIM and UD/AD standards to help designers incorporate those standards into the design of buildings at the conceptual stage to accommodate Canadians despite of their age and health conditions and to help inhabitants age in place; hence when aged, they will not be forced to move out to long-term care facilities. The proposed model will provide designers with instant access to information related to the desired standards and guidelines, and it will automatically check the associated design elements to find the ones that do not comply with the selected guidelines.

4.2 Literature Review

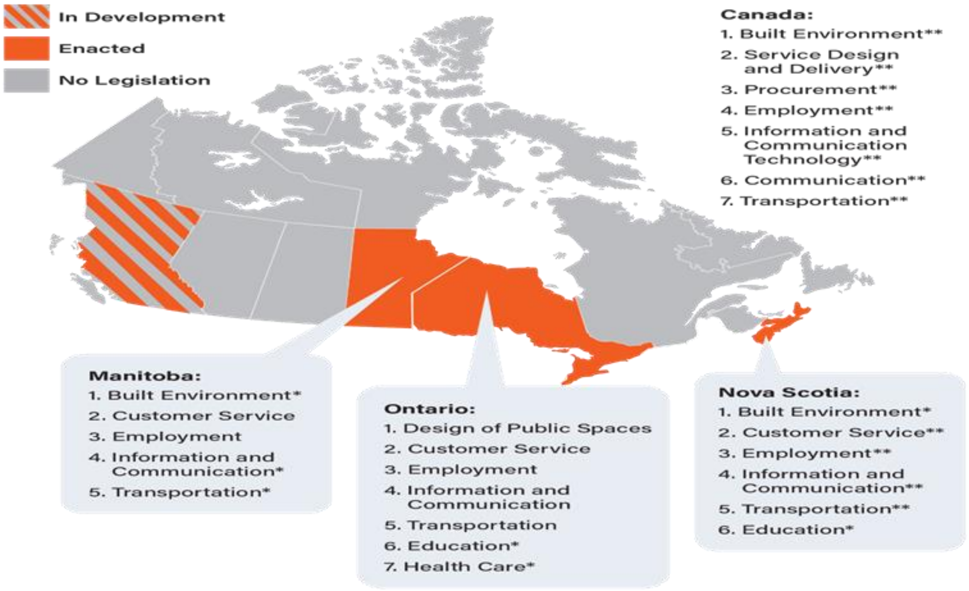
4.2.1 Universal Design and Accessible Design

Universal Design (UD) hypothesis is to design products or environments that can be used by people of different ages and abilities without adaptation. This theory is widely growing, and it has been expanded towards the scope of inclusive design, which extends the definition of UD by counting inhabitants who have been excluded by the rapid change of technology, particularly the aging population [19]. The main objective of UD is to provide inclusivity and prohibit exclusivity [20]. The term universal design was first defined by the US in 1985 as a design approach that incorporates products and building features to the greatest extent possible that everyone can use [21]. Globally, different terminologies have been used to guide to the terms of UD, such as Universal Access (Universally Accessible), Accessible Design, Adaptable Design, Barrier-Free Design, Design for All, Inclusive Design, User Sensitive Inclusive Design, Cooperative Design and User-Oriented Design. Some of those terms imply different ideas, while others have the same meaning [6]. Iwarsson and Ståhl [21] described accessibility as a term for all parameters that influence human's functioning in the living environment. The accessible environment must match the abilities of a single individual or a group of individuals. They describe usability as a measure of the effectiveness, efficiency, and satisfaction with which specified users can achieve established goals in a particular environment. Accessibility and usability concepts group people into abled and disabled individuals, which result in segregation, but universal design considers the whole population as one single group of individuals that represents diverse characteristics and abilities [21]. Design for all is another term more frequently used in Europe and is defined as the design for human diversity, social inclusion, and equality [22].

Persson et al. [23] stated that the most cited explanations of the universal design concept consist of the following seven principles: Equitable Use; Flexibility in Use; Simple and Intuitive Use; Perceptible Information; Tolerance for Error; Low Physical Effort; and Size and Space for Approach and Use, which provide a framework for designers to foresee the benefits of the design for all users with or without disabilities. Carr et al. [24] provided examples to better conceive those principles. For instance, automatic sliding doors at the entrance of a public building meet at least 6 of those principles. They provide equal access for individuals with diverse abilities and needs (Principles 1 and 2). They are straightforward and intuitive to use (Principle 3). Since they are using sensors to detect the presence of a person within a range, they require no physical effort to operate (Principle 6). These sensors also ensure that the sliding door will remain open for as long as the person stays within the sensor's range, which minimizes the risk of injury (Principle 5). Finally, automatic sliding doors usually are more expansive than typical swinging doors, making them easier to maneuver through the doorway for people using ambulatory aids such as canes, walkers, scooters, wheelchairs, crutches, etc. (Principle 7).

4.2.2 Building Codes

Building code provides the mandatory minimum technical specifications for the built environment, while the given comments and suggestions are to have a higher standard for designers [25]. Improving accessibility is attained through the enactment of new legislation and the development of new policies or modifying the existing standards and policies [26]. 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. Nationally, few provinces and cities have either adopted the national standards or implemented their own standards. The province of Ontario was one of the first jurisdictions in the world to enact the Accessibility for Ontarians with Disabilities Act (AODA) in 2005, which sets specific enforceable goals for accessibility. While Manitoba and Nova Scotia were next in 2013 and 2017, respectively. The proposed Accessibility Act in British Columbia (B.C.) is currently under review after its first reading was completed in 2019, as illustrated in Figure 4.1 [26]. However, the authors noticed that the accessibility legislation has just been passed by B.C.’s government. In recent times, the Accessible Canada Act (ACA) passed through legislation to create communities, workplaces, and services that enable all persons, including persons with disabilities, to fully participate in society without barriers. The different legislations forced many cities and provinces to adopt the accessibility standards; however, that adaptation varies from one province to another and from one city to another [26]. The National Building Code of Canada (NBCC) was introducing the accessibility requirements since 1965 when accessibility was mentioned for the first time as a Supplement to the National Building Code entitled “Building Standards for the Handicapped” [18]. Provincial and territorial governments have the authority to pass legislation that regulates buildings’ design and construction within their jurisdictions. That legislation may adopt the National Building Code (NBC) without any changes or with some necessary modifications to make it suits the local needs [27]. Many Canadian provinces and cities provide guidelines for accessibility requirements and guidelines based on the National Building Code of Canada, either as it is published or after modifying it based on their business needs.



(*) refers to standards that are currently in development,

(**) refers to areas in which standards will be soon developed.

Figure 4.1. Provinces with accessibility legislation [26]

The Canadian Human Rights Commission [25] published a study entitled “International Best Practices in Universal Design,” in which they claimed that only half of the countries around the world have developed and included accessibility criteria in their building codes and standards. Some countries have well-developed technical specifications, while others are still working on including accessibility criteria in their building codes. The study compared the Canadian B651-M95 Barrier-Free Design Standard and the National Building Code of Canada with other codes and standards used in different countries around the world, such as the UK, US, Japan, Australia, Nordic countries, and Fiji, to determine the optimum practices based on UD principles by providing and comparing accessibility codes and standards for different design elements in a tabulated format and then to determine the best practice for the selected elements. The result of the study described UD's best practice as being the affordable building practices and procedures that comply with UD principles and that meet the needs of the broadest range of people [25]. Nwadike & Wilkinson [28] listed several challenges when using building codes and standards, such as: Poor understanding of building code compliance documents; Lack of qualified technical staff on the part of the building codes; and Inadequate training for code users. Soliman-Junior et al. [29] believe that regulatory requirements might be subjective because they rely on designers' interpretation and creativity. On the other hand, with the demographic shifts and growth in the aging population, expectations for using universal design standards and accessibility design standards have increased significantly in recent years. Moreover, the COVID-19 pandemic has accelerated the need to provide inclusively designed homes for all. Therefore, several researchers, such as Soliman-Junior et al. [29], recommend automation to help designers access and use the standards and codes and to provide them with the necessary information whenever it is needed.

4.2.3 Building Information Modeling

Building Information Modelling (BIM) is defined as the process of generating, storing, managing, exchanging, and sharing building information in an interoperable and reusable way. It represents the process of developing and using a computer-generated model to simulate the planning, design, construction, and operation of a facility [30]. Ding et al. [31] defined BIM as a digital representation of a facility's physical and functional characteristics. It is a shared source of knowledge and information about a facility forming a reliable basis for decisions during its lifecycle, from earliest conception to demolition. Wu et al. [32] described BIM as a novel approach in the AEC industry that is implemented in a data center, which integrates geometric and functional information during the lifecycle of a building that is presented in a visualized 3D model. BIM supports solid spatial cognition by revealing most design issues early during the design stage. Antwi-Afari et al. [33] considered that BIM has received considerable attention from academia and industry because of its latent potential and capability to achieve performance improvement in the architecture, engineering, construction, and owner-operated (AECO) sector. It is a dynamic, rapidly changing and expanding system that can revolutionize the construction industry. Automation in the modeling process, improving the accuracy of construction documents, enhancing the communication among parties during the design and reducing the field coordination problems are the most critical factors that lead to BIM adoption in a project [34]. Abanda et al. [35] emphasized that the common feature in all the provided definitions of BIM is its process, which is facilitated and driven by people through its tools that consists of the three following dimensions that need to be incorporated when adopting BIM approach: process; technology; and people. Zhang et al. [36] stated that by rapidly increasing the elderly population, housing issues are the main barrier to implementing aging in place strategy and encouraging people to age in their residences. Although many studies have contributed to age-friendly cities and communities, few studies had the focus on measuring age-friendly housing. Numerous data are required to assess the age-friendly housing and to offer enough tangible actions or recommendations for planners and policymakers. Digital techniques such as BIM tools are utilized to facilitate the data collection and to accelerate the assessment in actual projects. BIM techniques are widely applied in different types of assessment for housing. Even though age-friendly housing is complicated, and its evaluation is a time-consuming process, utilizing BIM would significantly optimize the traditional assessment flow by integrating multi-sources of data. Integrating Universal Design (UD) with Building Information Modeling is an efficient way to monitor the compliance of buildings' design with the UD guidelines. BIM model is a virtual representation of the facility's physical and functional characteristics in a digital format, which provides detailed and reliable information for decisions during the facility's life cycle. BIM has the potential to share a platform API that provides users with a chance to integrate external applications [37]. Therefore, accessibility requirements can be integrated into BIM during the design of a project at the conceptual stage and thereafter during the construction phase. Coupling BIM and UD has the capability to produce high-performance and universally designed facilities.

4.2.4 Overview of the Existing Studies

Although there are substantial studies that used BIM during the various phases of a project, but limited research work was conducted about the integration of BIM and UD. Jrade and Valdez [18] described the methodology used to develop and implement a model that incorporates a database management system, which stores detailed information about architectural components and elements that are used to execute universal design based on the inhabitant's requirements and needs. They created a database storing newly developed design families based on the National Building Codes of Canada, and they linked it to BIM tool (Autodesk Revit©) at the conceptual design stage. Jrade and Jalaei [17] presented a methodology to develop and implement an integrated model that links BIM with energy analysis and LCA tools to execute sustainable universal design at the conceptual stage for Canadian houses. Their model evaluates and compares the life cycle cost and benefits of conventional and sustainable universal houses.

However, one of the limitations of the above-mentioned studies is in creating UD families based only on the National Building Code of Canada (NBCC) and then incorporating them into the design, while the described model in this paper provides the designers with the option to have full access to various universal design and accessible design standards and guidelines including the NBCC also in addition to multiple guidelines and standards collected from other countries in an attempt to increase the efficiency and variety of the information needed for the design of universal buildings regardless of their locations. Furthermore, the model has the ability to automatically check the design elements and compare them with the selected standard or guideline to make sure they meet their requirements. Several studies implemented in the past by Cheng J. and Das M. [38]; Choi J. and KIM I. [39]; Kincelova, et al. [40]; Patlakas et al. [41]; Narayanswamy et al. [42]; Häußler et al. [43]; Khattra et al. [44] focused on integrating BIM and building codes or standards in different areas such as architecture, structures or green buildings. However, their emphasis was mainly on automating building code compliance checking within a BIM environment by using different ways and methods, such as IFC or gbXML file format, Dynamo visual programming, C# programming and BIM tool Application programming interface (API), MATLAB computing environment and rule-based checking engines or commercial software such as Solibri Model Checker (SMC). However, the current study is not limited to building code compliance checking. Yet, it uses various standards and guidelines related to both universal design and accessible design and integrates them into BIM tool by using its API and C# programming. One of the functions of the proposed model is its capacity to check and compare the design items with the various sources simultaneously, mainly in the form of the design items' dimensions. Another innovation of the presented model is its ability to help designers retrieve detailed information concerning the selected design elements in the form of dimensions, colour, and texture in addition to other descriptive information and to access the original associated documents of the selected standard instantly while doing the design. Alsayyar and Jrade [4] proposed 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. Türkyılmaz E. [45] stated that accessible design is critical to the social integration of disabled people by improving their quality of life. Design's decisions that comply with the inhabitants' needs can create a more compatible and high-quality living space. Furthermore, they stated that conventional methods of design are currently used, while their results are not compatible with the accessibility regulations. BIM is an excellent option to control and evaluate the accessibility criteria. Therefore, they proposed a BIM-based analyzing method that integrates BIM tool with a model checker software to compare the designed model with a set of accessibility rules, which were generated from the Turkish accessibility standards to analyze the living spaces based on the standards, then to generate a report to show whether the design is compatible with the standards or not and to list the incompatible items.

Thus, this paper describes the design and development of an automated model that integrates BIM and Universal Design standards and accessibility guidelines through an extensive database, which is linked to BIM tool. The model would help owners and designers do the design of universal and accessible buildings at the conceptual stage. Guidelines from several Canadian provinces and major cities were collected, evaluated, and stored in a database developed for that purpose and linked to the model to help designers incorporate universal/accessible design standards while doing the design of buildings regardless of their location in an easy and efficient way. In addition, different related guidelines from other countries, such as the United States, were collected and stored in that database to increase the efficiency and variety of the data for designing universal buildings that are outside Canada. It is worth mentioning that only publicly available documents, including accessibility legislation, standards, or guidelines, were included in this study. This process is fully automated and achieved via a newly developed plug-in by using and modifying the API's of BIM tool.

4.3 Development Methodology

The development of the integrated model requires an instant and automatic access to the necessary data in the form of design families to simplify the creation of facilities that comply with the universal design standards and to help designers and owners select an optimal design based on their defined criteria. Generally, a computer model should meet three requirements known as flexibility, transparency, and functionality in order to help designers incorporate universal design standards and guidelines while creating the design of homes to accommodate inhabitants so they would age in them. The functionality requirement is to help designers have quick access to all the data and design families that are compatible with the different universal design and accessible design standards and guidelines. Whereas the transparency requirement is to aid designers identify and understand the reliability, suitability and relationships between the data used in the model. Where flexibility is to have the model easily manageable during its implementation, operation, and maintenance by enabling designers to add and modify the stored data in a user-friendly way, in addition to automation, which gives designers instant access to the data and the newly created design families in a computerized way. Moreover, the model meets the automation requirements by having the capability to automatically check and compare the design elements based on the selected standards or guidelines to ensure they comply with their requirements. To achieve the main objective of this study, which is the development of an automated computer model to facilitate the adoption of universal design and accessible design standards and guidelines at the conceptual design stage of building projects, the required data and information for the proposed integrated model were collected from different sources, such as the literature, published standards and guidelines, and governmental agencies. The integration process flow, as shown in Figure 4.2, consists of three phases in order to achieve the integration of UD, AD and BIM: A Knowledge and family Database development phase; A Data interaction environment phase; and A BIM 3D model design phase. The first phase consists of developing two databases, the first is a knowledge database and the second is a design families database to store the newly created design families and the collected information and data, which are related to universal design and accessible design guidelines in an attempt to simplify the process of designing universal and accessible buildings at the conceptual stage. The second phase focuses on developing new plug-ins to be inherited into BIM tool (i.e., Autodesk Revit$^{©}$) by using the tool's API. The plug-ins will be used to link the developed databases in phase 1 with BIM tool to facilitate the selection of new design families and the retrieval of the associated data and information. This integration will systematically incorporate Universal Design Standards into BIM environment at the conceptual design stage. It will facilitate the process of retrieving universal families of architectural components by incorporating the UD standards into the design. The third phase focuses on designing and creating a 3D BIM design model by using the databases and newly created plug-ins developed in phases 1 and 2, respectively. The design is based on pre-defined criteria set by owners to incorporate UD standards to achieve the best practical scenario to meet inhabitants' requirements and expectations.

Phase 1: Database Development

This phase consists of developing two major databases, a standard database, and a design families database. To accomplish the standard database, data from universal design and accessible design guidelines are collected and stored in it and categorized into four different levels. The first is at the national level, such as the National Building Code of Canada (NBCC) and CAN/CSA B-651-18 Accessible design for the built environment. The second is at the provincial/territorial level, such as Barrier-Free Design Guide, Alberta, and Building Design Guide - Barrier-Free Design, Government of Saskatchewan. The third is at the municipal level, such as Accessibility Design Standards, City of Ottawa and Facility Accessibility Design Standards, City of Mississauga. While the fourth is at the international level, such as American National Standards Institute (ANSI). However, in this database, the collected data is divided into quantitative data and qualitative data. The qualitative data consists of all the descriptive information related to the objects and components used in the 3D model, such as components' colour, texture, type, and associated materials. In contrast, the quantitative data comprises numerical information, mainly in the form of dimensions extracted from the guidelines. Data is stored in a series of tables forming the Knowledge Database that holds over seventeen guidelines collected from various sources, as displayed in Table 4.1. Unique abbreviations are created to identify the guidelines in an effort to simplify recalling and storing them, as shown in Table 4.1. Some guidelines have their own abbreviation, such as NBCC, CMHC and ANSI. The Families 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 information and data in the knowledge database. Those design families have either the Revit Families (RFA) or the Revit projects (RVT) file formats and are stored in the corresponding database.

The data and information used in this study are collected, grouped, and stored based on two sets the Residential dwellings Data and Families (Indoor Items), as shown in Table 4.2, and the Public Area Data and Families (Outdoor Items), as represented in Table 4.3. Those tables clearly state the type of data related to any item stored in the knowledge database or the design families' database by placing an asterisk (*) beside the item. All the stated guidelines were examined and evaluated in order to collect all the relevant data. The evaluation showed that some indoor or outdoor items were not covered in all the guidelines; therefore, all the data covered by each specific guideline are listed in Tables 4 and 5. Under the guideline's name, an asterisk (*) is inserted, which indicates that the item is fully covered by the guideline, while "N/A" implies that the item is not covered, and "limited" means that the item is partially covered, and its associated data or information is limited. The significant contribution of the developed database residents in enhancing the functionality and capability of BIM tools at the conceptual design stage to help designers incorporate Universal Design standards and Accessible Design guidelines easily while designing proposed buildings. The aim of developing a separate database of families is to load them every time BIM tool (i.e., Autodesk Revit©) opens and to access them via the newly created plug-in. This makes the created families instantly accessible when they are needed during the design process. The developed databases in this phase can be easily updated whenever new or modified versions of the standards and guidelines are released. These accurate standards and guidelines are published by the federal or provincial governments, who are trustful sources. However, the version and the year of publication are indicated in the original documents, which are instantly accessible by the designers through the model. While currently updating those documents is done manually, the authors are working on making that update automatic.

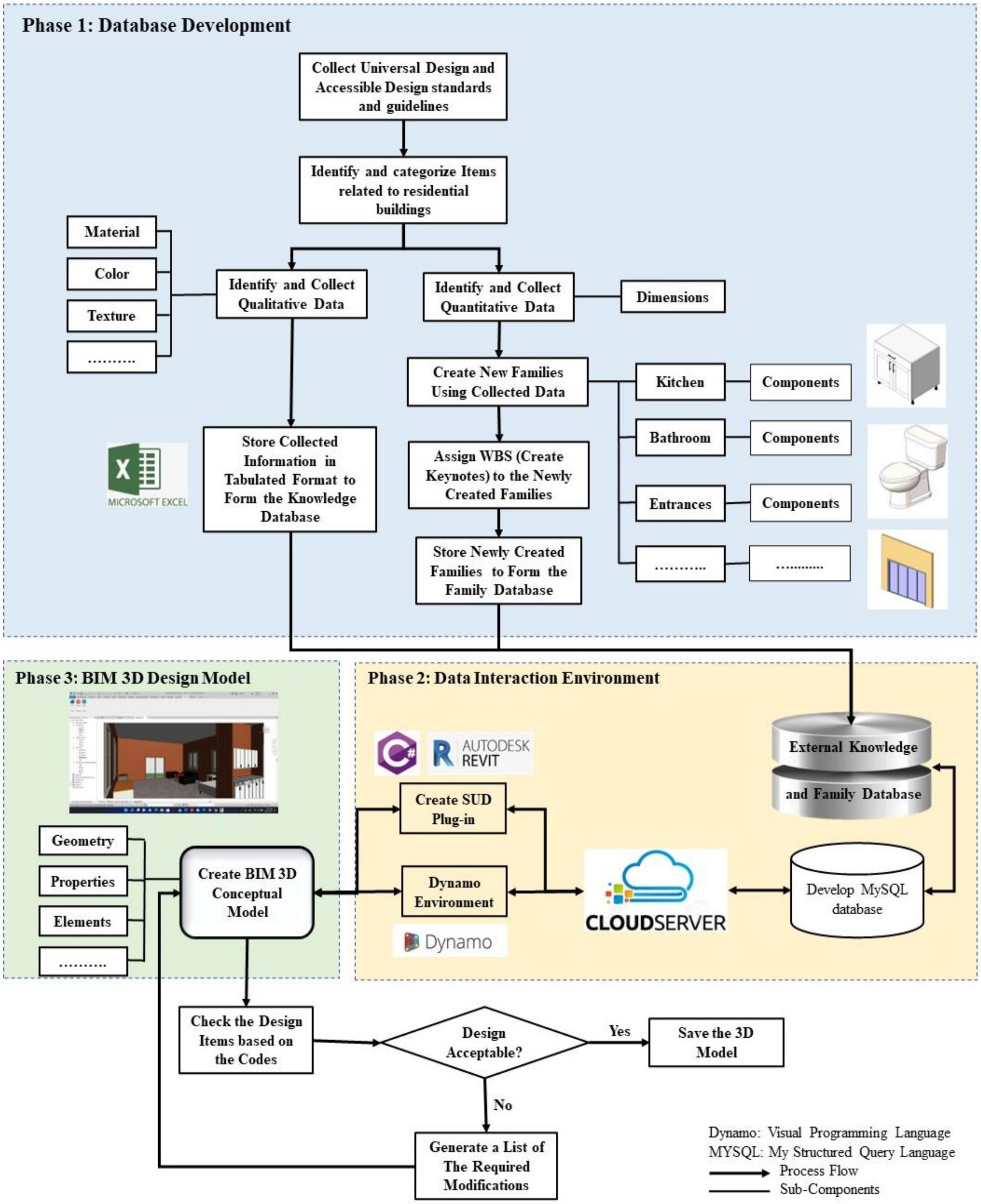


Figure 4.2 - BIM-UD Integration Process Flow

Table 4.1- Various Guidelines Stored in the Standard Database

Level	**Standards Database**	
	Accessible Design Guidelines	**Universal Design**
Level 1: national level	National Building Code of Canada (NBCC) CAN/CSA B-651-18 Accessible design for the built environment (CAN/CSA)	Canada Mortgage and Housing Corporation (CMHC)
Level 2: provincial/ territorial level	Barrier-Free Design Guide Alberta (BFDGA) Barrier-Free Design Guideline, Yukon (BFDGY) Barrier-Free Design Saskatchewan (BFDS)	
Level 3: municipal level	Accessible Design Guideline, City of Toronto (ADGT) Facility Accessibility Design Standards, City of Mississauga (FADSM) Ottawa Accessibility Design Standards (OADS) Facility Accessibility Design Standards, London, Canada (FADSL)	Universal Design Handbook, Calgary (UDHC)
Level 4: International level	American National Standards Institute (ANSI) Fair Housing Act Design Manual, USA (FHADM) Uniform Federal Accessibility Standards (USA) (UFAS)	The Centre for Excellence in Universal Design, Ireland NDA (CNUD) Universal Design by Selwyn Goldsmith

Phase 2: Data Interaction Environment

This phase focuses on developing new plug-ins in BIM's tool (i.e., Autodesk Revit$^{©}$) by using its API and C# programming language to link the developed databases in phase 1 to it in order to facilitate the selection of new design families and the retrieval of their associated data and information while creating 3D design models of proposed buildings. Autodesk provides powerful APIs (Application Programming Interface) and SDKs (Software Development Kits) that allow users to customize and alter the used tool based on their needs. At first, designers need to access the various universal design standards and associated families by using the created plug-in before starting the design process. Then after, 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 C# and Dynamo visual programming are used to automate the process of transferring the data. The variation of the relational database servers depends on how the information is stored and how users can access that information concurrently. In general, databases are either remote databases, such as Structured Query Language (SQL) that reside on separate machine/machines or local databases, such as MS Access, that reside on a local drive or network. Local databases are tied to a fixed location, such as a device or a local network. In contrast, remote databases and cloud servers are available and accessible via the internet by any PC or mobile device from any location. Therefore, in this study, MySQL and a cloud server are used to allow designers instantly access the created databases. For that purpose, different tables are created in MySQL after making Microsoft Excel tables in the knowledge database. Data is automatically transferred from MS Excel tables to MySQL through a set of rules coded by C#. Next, SQL Server is linked to a cloud server to facilitate accessing the created databases while the cloud server is connected to the created plug-in in BIM tool. All the connections between MySQL, cloud server, and the plug-in in BIM tools are automated and coded by C#. Furthermore, other data in the form of design families and original documents (guidelines) were separately stored in the cloud server. The newly created plug-in connects directly to the cloud server to recall those design families and original guidelines whenever they are needed, while Dynamo was used to connect the plug-in with the cloud server and to retrieve the necessary data stored in the MySQL, such as dimensions and descriptive data, and then provide them to the designer while using the plug-in.

Also, the developed model automatically checks the design elements and compares them with the selected standards or guidelines to verify that they meet their requirements. This is achieved when the newly created plug-in reads the families' properties, which are used in the 3D design created in BIM tool, 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 of those elements related to the selected guideline. The created plug-in has the ability to convert the units of measurements used in BIM tool to match the units of the stored data in the cloud server in an automatic manner that was coded by using C# programming language.

Phase 3: BIM 3D Design Model

In this phase, the 3D BIM design model of the proposed building is created in BIM tool. That step is achieved by using the newly created families and their associated components, which are automatically loaded and used via the developed plug-in. Designers would be able to select and retrieve the compatible guidelines from the Universal Design standard or Accessible design standard stored in the databases of phase 1. 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 BIM tool (i.e., Autodesk Revit©) are positioned to facilitate their use in the design model. In that stage, the cloud server will have a two-way interaction with the newly created plug-in in BIM tool to help importing and exporting the data from and to the database. Dynamo visual programming connects the database to BIM tool so that any modification in the design is automatically executed whenever is needed. Once the design is complete, the developed 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 used to modify the design accordingly.

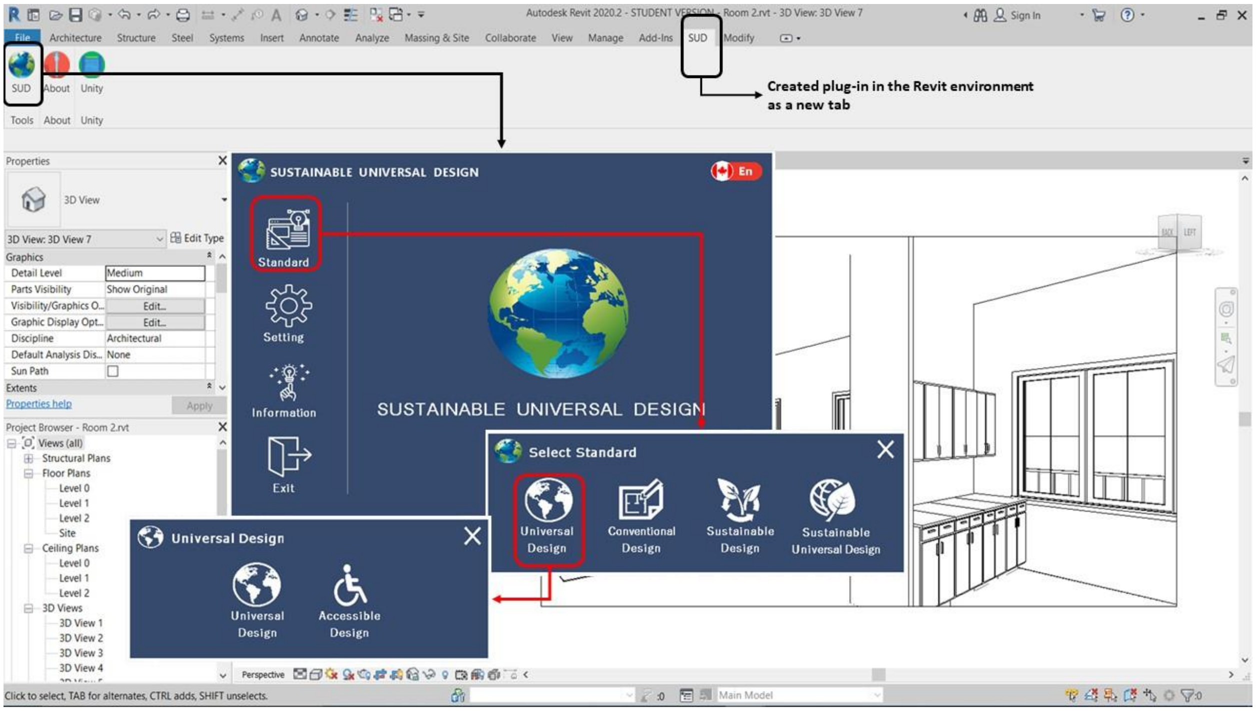
Although the model is somehow fully automated, adequate notes have been provided in each section to enhance its transparency and useability. In such a case, designers can effectively use the model and gain full knowledge of its performance. It is worth mentioning that this study is ongoing, where it incorporates four major databases: 1) Universal Design Database; 2) Conventional Design Database; 3) Sustainable Design Database; and 4) Sustainable Universal Design Database; however, this paper focuses on the Universal Design Database in addition to its Accessible Design sub-category.

4.4 Model Implementation and Testing

To test the developed model and to examine its performance and capabilities, a single-floor residential building located in Ottawa, Ontario, Canada, is used. Autodesk Revit© is selected as BIM tool to create the building's 3D design model with all its components such as walls, doors, windows, floor, stairs, cabinets, and railings and their associated geometry. To create the 3D design model of the proposed building, the families stored in the external database are retrieved through the created plug-in, which is named SUD, in Autodesk Revit©. SUD helps designers select and incorporate the appropriate standard and guidelines from the database. After making the selection, designers must choose the next step from different options, such as reading the related documents; comparing the different standards and guidelines; checking the created components based on the selected guideline; and using the associated design families to implement the selected standard into the building's 3D design model. Once the designer clicks the SUD plug-in, as shown in Figure

4.3, a form appears with a list of options allowing designers to access the other sections. The most important option in that form is the Standard option, so as once picked, the designer is given access to the information related to the selected design standard. Upon selecting the Universal Design standard, the designer must choose either the Universal Design standards or the Accessible Design standards, as illustrated in Figure 4.3.

Once a selection is made, a new screen opens, as shown in Figure 4.4, for the designer to choose a specific guideline, then a category, indoor or outdoor, and after that, select the items that are needed for the 3D design model. An efficient numeric coding system is used to symbolize the relationships between the stored data in the databases and to simplify the retrieval of the necessary information. These codes are unique for each item in the form of five-digit keynote codes. They represent the division, subdivision, elements, and materials' names.



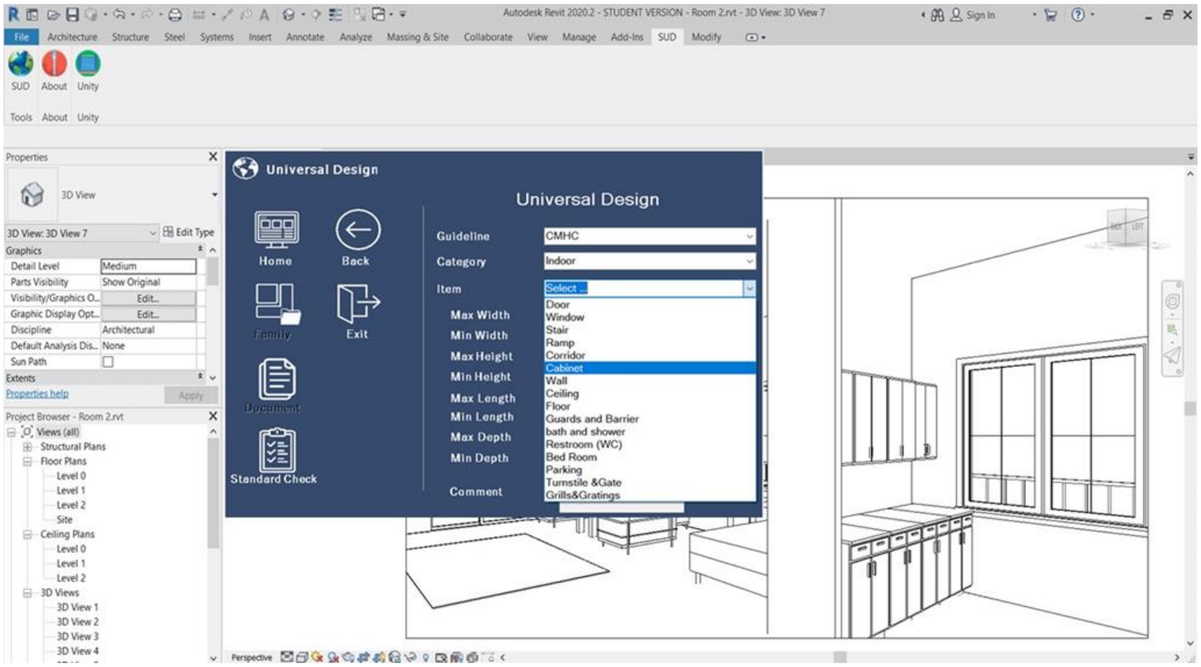
Detail Level: Medium
Parts Visibility: Show Original
Visibility/Graphics O...: Edit...
Graphic Display Opt...: Edit...
Discipline: Architectural
Default Analysis Dis...: None
Sun Path: ☐

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Created plug-in in the Revit environment as a new tab

Figure 4.3- Snapshot of the Created Plug-in and the 3D design Model

Next, the designer will have access to additional information about the selected item(s) in the form of numerical data, such as the item’s dimensions, and descriptive data in the form of comments retrieved from the knowledge database. Figure 4.5 shows an example of a selected cabinet and its related data. Such data helps the designer to anticipate the item's requirements and ensure that they meet the occupants’ needs. Having instant access to this type of data is vital since it reduces the possibility of making errors and significantly saves time. Once the Document button is clicked, that designer gain access to both the original documents of the selected guideline and the specific item, as shown in Figure 4.6. Furthermore, the designer can view, read, share, save, and print those documents. As soon as the “Family” button is clicked, the families’ database is activated, as shown in Figure 4.7, then the families related to the selected item are automatically placed in the library of Autodesk Revit© to be used in the proposed project. The flexibility of the model, besides being user-friendly, resides in the ability of managing and modifying the associated databases in an easy and simple way. In addition to the abilities that were mentioned above, which include selecting standards and guidelines, retrieving related data and design families for design elements instantly, having access to the original documents, etc., clearly demonstrate the functionality requirement of the described model.



Universal Design

Guideline: CMHC

Category: Indoor

Item: Select ...

Max Width

Min Width

Max Height

Min Height

Max Length

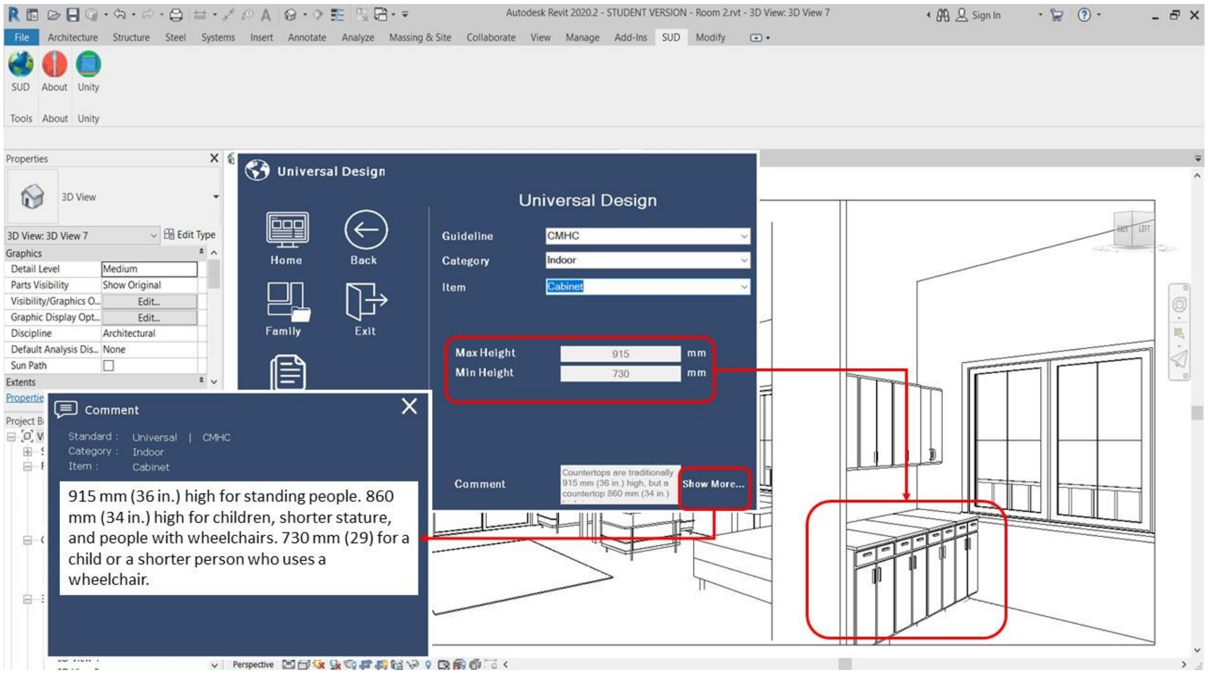
Min Length

Max Depth

Min Depth

Comment

Figure 4.4 - Access All the Items Listed in Tables 2 and 3 via the Created Plug-in



Universal Design

Guideline: CMHC

Category: Indoor

Item: Cabinet

Max Height: 915 mm

Min Height: 730 mm

Comment: Countertops are traditionally 915 mm (36 in.) high, but a countertop 860 mm (34 in.)

Comment

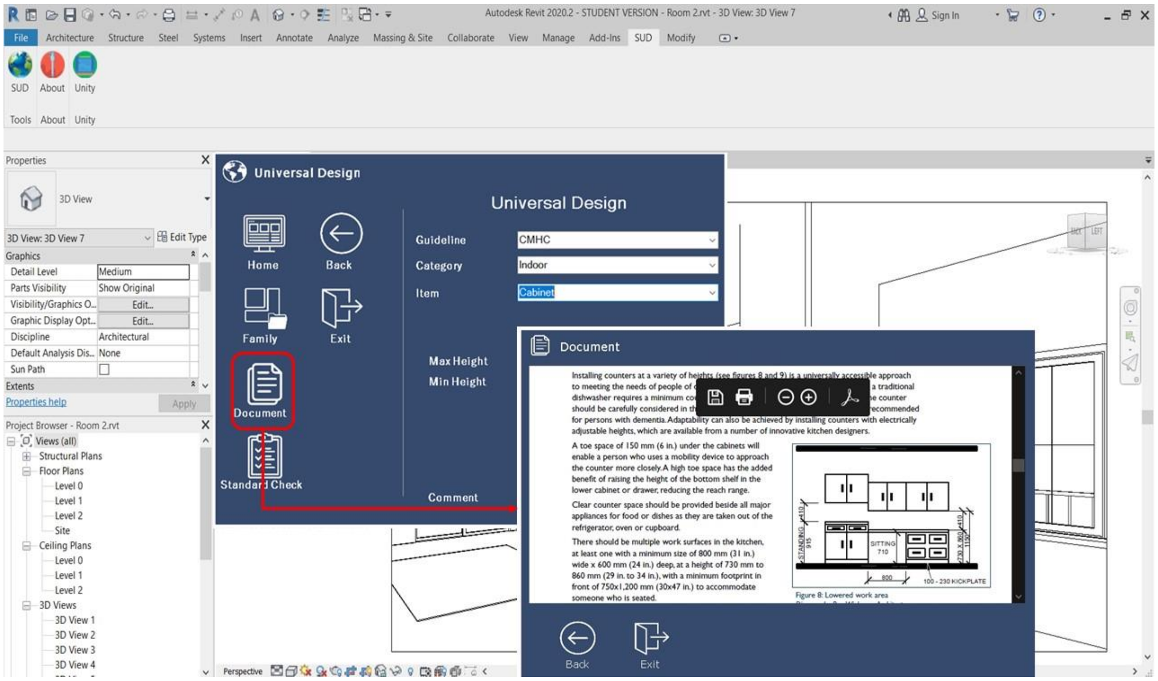
Standard : Universal | CMHC

Category : Indoor

Item : Cabinet

915 mm (36 in.) high for standing people. 860 mm (34 in.) high for children, shorter stature, and people with wheelchairs. 730 mm (29) for a child or a shorter person who uses a wheelchair.

Figure 4.5 - Selecting Appropriate Guideline and Item and Receiving Related Data



Universal Design

Guideline: CMHC

Category: Indoor

Item: Cabinet

Installing counters at a variety of heights (see figures 8 and 9) is a universally accessible approach
to meeting the needs of people of a traditional
dishwasher requires a minimum co e counter
should be carefully considered in th recommended
for persons with dementia. Adaptability can also be achieved by installing counters with electrically adjustable heights, which are available from a number of innovative kitchen designers.

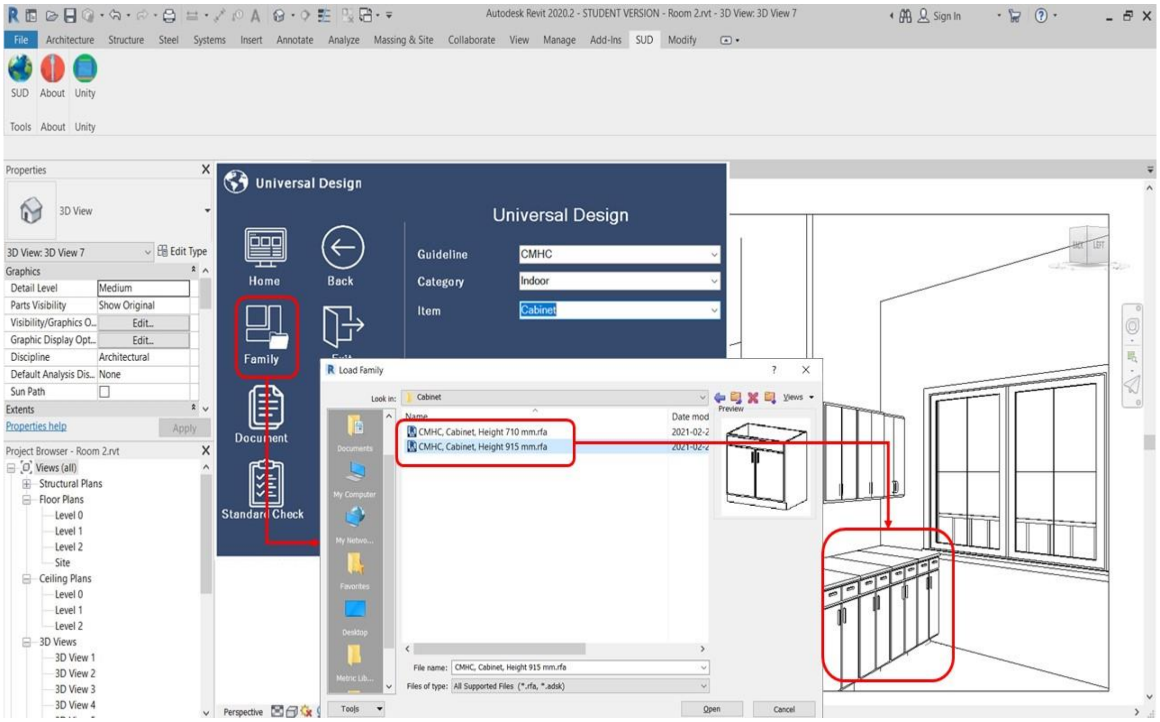
A toe space of 150 mm (6 in.) under the cabinets will enable a person who uses a mobility device to approach the counter more closely. A high toe space has the added benefit of raising the height of the bottom shelf in the lower cabinet or drawer, reducing the reach range.

Clear counter space should be provided beside all major appliances for food or dishes as they are taken out of the refrigerator, oven or cupboard.

There should be multiple work surfaces in the kitchen, at least one with a minimum size of 800 mm (31 in.) wide x 600 mm (24 in.) deep, at a height of 730 mm to 860 mm (29 in. to 34 in.), with a minimum footprint in front of 750x1,200 mm (30x47 in.) to accommodate someone who is seated.

Figure 8: Lowered work area

Figure 4.6 - Viewing Original Documents



Universal Design

Guideline: CMHC

Category: Indoor

Item: Cabinet

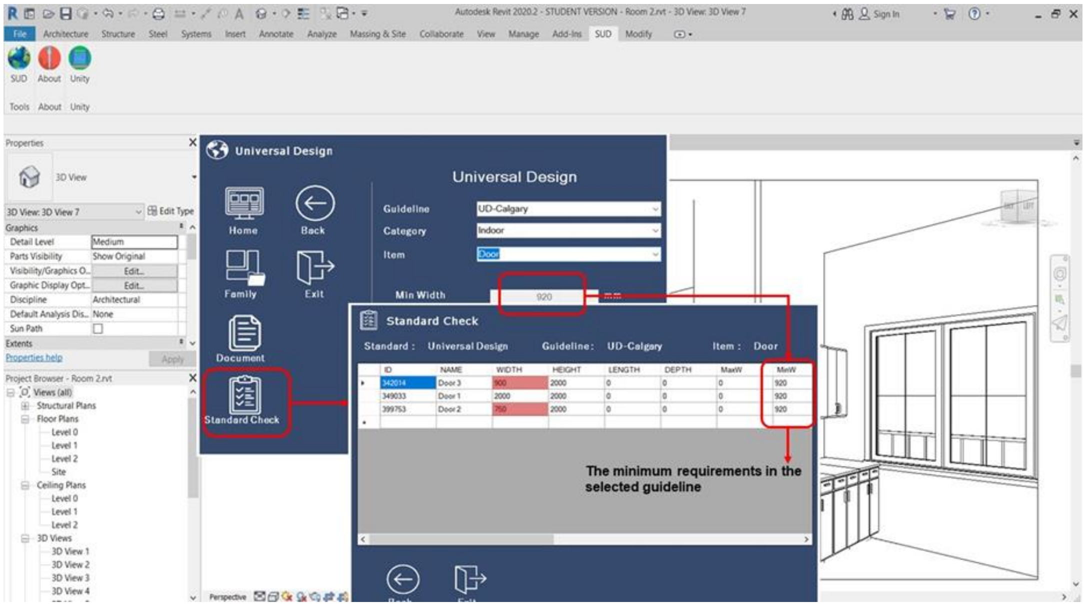
CMHC, Cabinet, Height 710 mm.rfa
CMHC, Cabinet, Height 915 mm.rfa

File name: CMHC, Cabinet, Height 915 mm.rfa

Files of type: All Supported Files (*.rfa, *.adsk)

Figure 4.7- Automatically Placed families in the appropriate location and ready to use in the design

The last button on the form is the “Standard Check” button. By clicking that button, the designer can check if the components used in the 3D design model comply with the selected guideline and to make sure the standard’s requirements are met. If errors are found, they will be highlighted in red. For example, if the designer selected the Universal Design guideline from the city of Calgary, the Indoor category, and Door as an item, as shown in Figure 4.7, a new screen opens upon hitting the “Standard Check” button, where all the standard selections, guidelines and the specific item are listed. The item(s) that does/do not meet the requirements of the selected guideline are highlighted in red, as shown in Figure 4.8, where doors number 2 and 3 have their width less than the minimum width of 920mm as stated in the selected guideline. To fulfill the model's transparency requirement, adequate notes were added for each section to help designers better understand the functions of the selected section and its use, as shown in Figure 4.9. The developed model is bilingual; therefore, designers can select their language of preference before using the model and its associated components, As shown in Figure 4.10.



Detail Level: Medium
Parts Visibility: Show Original
Discipline: Architectural
Default Analysis Dis..: None

Universal Design

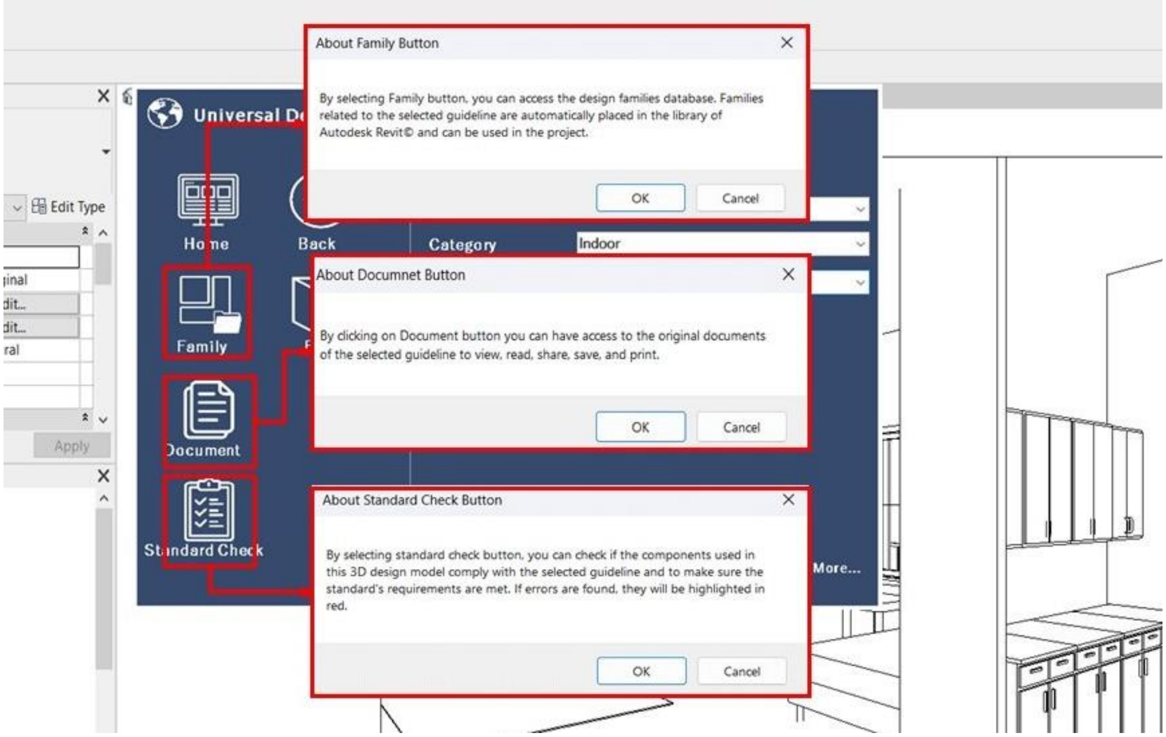
Guideline: UD-Calgary
Category: Indoor
Item: Door
Min Width: 920 mm

Standard Check

Standard : Universal Design Guideline : UD-Calgary Item : Door

ID	NAME	WIDTH	HEIGHT	LENGTH	DEPTH	MaxW	MinW
342014	Door 3	900	2000	0	0	0	920
349033	Door 1	2000	2000	0	0	0	920
399753	Door 2	750	2000	0	0	0	920

Figure 4.8 - Comparing Items Dimensions in the 3D model with the Selected Guideline



About Family Button

By selecting Family button, you can access the design families database. Families related to the selected guideline are automatically placed in the library of Autodesk Revit© and can be used in the project.

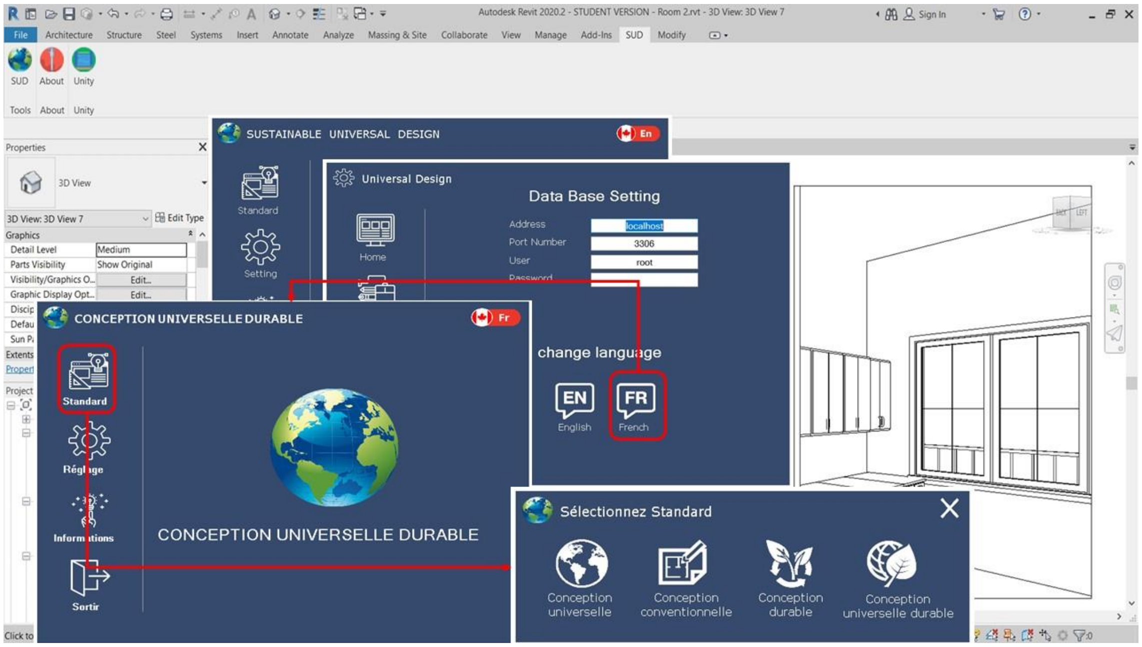
About Documnet Button

By clicking on Document button you can have access to the original documents of the selected guideline to view, read, share, save, and print.

About Standard Check Button

By selecting standard check button, you can check if the components used in this 3D design model comply with the selected guideline and to make sure the standard's requirements are met. If errors are found, they will be highlighted in red.

Figure 4.9 - Function and use of each section



Autodesk Revit 2020.2 - STUDENT VERSION - Room 2.rvt - 3D View: 3D View 7

Data Base Setting

Address	localhost
Port Number	3306
User	root

Figure 4.10 - Bilingual Capability of the Created Model

4.5 Discussion

The automated model described in this study helps designers to have full access to the various standards and guidelines related to universal and accessible designs along with the National Building Code of Canada (NBCC), as well as to access multiple guidelines and standards from other countries in an attempt to increase the efficiency and variety of the data needed to design universal buildings. Comparing the presented model with the ones listed in the literature, which integrate BIM with UD and incorporate Universal Design standards used at the conceptual design stage, reveals that the current model is comprehensive, merges different standards and guidelines, supplies designers with build-in copies of those standards and has a one step further by being able to check the design if it meets the selected standard and guideline. While the ones listed in the literature are limited to one single standard, which is the NBCC.

They have reduced the number of predefined design families for components most commonly used in designing buildings. For instance, Jrade and Valdez [18] proposed a model to include a database management system that stores architectural components and elements that are universally designed based on the National Building Codes of Canada, while Jrade and Jalaei [17] continued the work of Jrade and Valdez [18] and presented a model that links BIM with energy analysis and LCA tools to execute sustainable universal design at the conceptual stage for designing Canadian houses. One of the advantages of the current model is its competency to provide designers with a variety of information about all the design elements in the form of dimensions, colour, texture, and other descriptive information, in addition to providing instant access to the original documented standards in an automatic way. Despite that some of the existing studies are related to the integration of universal design standards and Building Information Modeling at the conceptual design stage, but those are focused on creating design families based only on the National Building Codes of Canada and integrating them into BIM tools, whereas this study incorporates various universal design and accessible design standards and guidelines including the NBCC to help designers have instant access to various type of data as well as newly created design families that are compatible with those standards and guidelines including multiple guidelines and standards collected from other countries via an automated model in an attempt to increase the efficiency and variety of the information needed for the design of universal buildings regardless of their locations. Another innovation of the developed model is its ability to automatically check the design elements and compare them with the selected standard or guideline to verify that the design elements meet the selected standard and guidelines' requirements. Regardless of the many advantages of the described model (i.e., reducing future modification and alteration, minimizing the associated costs of designing homes based on inhabitants' needs), it has several limitations and constraints. One of its major limitations is that not all the building components were converted as Autodesk Revit© families to meet the UD standards. Therefore, designers must read the guidelines and apply their requirements while designing and using those components. Designers can access those guidelines from within the described model via a plug-in that was developed and inherited into BIM tool. Once a specific item is selected, the designer has instant access to the guideline and the descriptive data related to that item. Another limitation of the model is that most of the guidelines cover policies related to accessibility in buildings only, while universally designed buildings need additional information beyond the ones of accessibility, which means it does not cover all the areas that are necessary to achieve a complete universally designed building. Thus, for future work, it is recommended to enhance the model's efficiency by storing additional data and suggestions concerning universal design to accommodate more people to the greatest extent possible. The authors are working on adding aging-in-place policies to the model to extend and enhance its database to help designers consider seniors' needs when designing age-in homes. Moreover, the databases are cloud-based; while there are several advantages of cloud storage services over physical/local storage methods, such as easily sharing files and collaborating with others, but they still have some limitations as well (i.e., designers must have continuous access to the internet when using the model to benefit from all the data and newly created design families stored in the external database).

4.6 Conclusion

This paper described the development of an integrated model that couples BIM and universal design standards and accessibility guidelines to be considered by designers when modeling the design of building projects for Canadians to age in them. The philosophy of universal design, UD, persuades the development of design guidelines used during the design process. UD makes facilities usable over the entire lifespan of inhabitants. The increased use of BIM by the AEC industry due to its integration capabilities with external applications provides an opportunity to incorporate universal design and accessible design standards into the BIM environment at the early stage of designing building projects. One of the novelties highlighted in the developed model residents is the development of an automated method that employs a newly created plug-in to assist designers in instantly accessing UD standards and incorporating them while designing proposed buildings at the conceptual stage. The model's development was implemented through three phases; phase 1 focused on collecting, categorizing and storing data from various universal design and accessible design guidelines, then databases were created to store these data as well as the newly created/modified design 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 and C# in order to automate the process of retrieving necessary information and components from the database; phase 3, comprised the creation of a 3D BIM model by using the data from the databases of phase 1 and the plug-ins of phase 2. This study focuses on the conceptual design stage of facilities, where designers need to have access to vital information when selecting and applying the UD standards to proposed projects that should meet owners’ goals. Reducing future modification and alteration and minimizing associated costs are parts of the utmost advantages of the developed model. Adopting UD principles early during the design stage contributes to creating and constructing buildings that comply with elderlies’ requirements who want to age in their homes rather than going to long-term care facilities where there is a high risk for them to be affected by unpredictable situations such as Covid-19 pandemic. Future work can explore integrating plan review systems and building code checker software into the model to enhance the capability of the model’s code compliance checking. Furthermore, adding aging-in-place policies to the model enhances the efficiency of the database and helps designers consider seniors' needs when designing age-in homes.

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Table 4.2 - Residential Dwellings Data and Families (Indoor Items)

Indoor Item	Subset	Knowledge Database	Family Database
Kitchen	Kitchen Size, Layout (Flexibility…), Minimal Effort (Low Physical Effort), Adaptability, Ease of Cleaning (Finishing material, …), Safety, Ease of Use, Furniture Size	*	
	Elements and Furniture (Counters, Cupboards, Drawers and Pantries, Sink, Oven, Microwaves, Refrigerators and Freezers, Highlights in furniture design (Equitable Use, Flexibility in Use, Simple and Intuitive, Perceptible Information, …)		*
Bathroom	Size, Layout, Framing, Adaptability, Ease of Cleaning (interior Finishes), Safety (Finishing and Grab bars)	*	
	Sanitary Facilities (Water Closets, Showers, Bathtubs, Toilets, Showers, Toilets, Vanities, Lavatories) Elements and Furniture (Drawers and Storage, Grab Bars, Lighting, Switches and Controls, Towel Dryers), Doors (Size, Opening Side, Lock System, Threshold Height...)		*
Restroom (WC)	Standard Size, Layout (Doorway, …)	*	
	Sanitary Facilities (Water Closets, Grab Bars, Lavatories, Automatic Flush Controls), Washroom amenities (hand dryers, paper towel dispensers, soap dispensers, waste bins, mirrors, changing stations and tables), Door (Size, Opening Side, Lock System, Threshold Height, ...)		*
Bedroom	Standard Size, Layout (Doorway, Closet, and …)	*	
	Furniture (Bed, Closet), Door Size and Location, Window (Easy to Operate, …)		*
Living Room	Size, Layout, Framing, Adaptability	*	
	Furniture, Door (Size and Location, lock System, Opening Side, Doorway), Window (Easy to Operate)		*
Elevator	Elevator Cabin Size, Elevator Door (Location and Type), button and Signage Requirements, Visible and Audible Indicator	*	
	Door, Cabin, Keypad (button and Signage)		*
Parking	Design and Layout (Safe & Clear Path of Travel, Close to Mail Entrance), Parking Location and distance to the elevator and exit Route & Size, Signage and Pavement Markings, Flooring Materials	*	
	Signs (International Symbols), Lighting, …		*
Stair	Ground and Floor Surfaces, Guards and Handrails, Tactile Walking Surface Indicators, Design Features, Treads and Risers, Nosing	*	
	Attachments (handrail & barrier), Nosing and Risers Type, …		*
Ramp	Ground and Floor Surfaces, Guards and Handrails, Tactile Walking Surface Indicators, Lighting, Running Slope, Cross-Slope, Edge Protection, Clear width, Landing size	*	
	Attachment (handrail& barrier)		*
Entrance Area	Size & Layout (Free Path of Travel, Suitable for Wheelchair traffic), Clear of Wind and Snow Proper Drainage, Floor and wall finishing Materials (Door Mats), Control System	*	
	Door, Control System Device		*
Door & Gate	Size and Dimension (Opening Side, Lock System, Threshold Height...), Layout (Path and Doorway…)	*	
	Doors, Attachments (lock System& Right or Left Opening, Handel, Fastening Device)		*
Window	Size and Dimension	*	
	windows, Attachments (lock System & Opening System, Easy to Operate)		*
Guards and Barrier	Size (Height, Railing or Solid Type, …)	*	
	Railing or Solid Type Model		*
Turnstile, Gate Area	Size, Layout, Wall and Floor material (Technical Information)	*	
	Attachments (handrail & barrier)		*
Grills & Gratings	material (Technical Information)	*	
	Opening Size Limit, Installation Details		*
floor	material (Technical Information)	*	

	Finishes, Grating & cover, Installation Details		*
Wall	material (Technical Information)	*	
	Opening, Attachments (sign, lighting, …)		*
Ceiling	material (Technical Information)	*	
	Installation Details, Attachments (detector, sprinkler, lighting, …)		*

Table 4.3 - Public Area data and Families (Outdoor Items)

Outdoor Item	**Subset**	**Knowledge Database**	**Family Database**
Exterior Path, Access & free path of travel	Width of Exterior Walks - Doorway Clear Width Exit Device- Clear Space at Sides of Doors - Threshold Height (Dimension & Size)	*	
	Attachments (handrail & barrier, Access control)		*
Passenger Loading Zone	Design and Layout, Relationship to Accessible Routes, Tactile Walking Surface Indicators (Floor Surface), Sign Location, Curb Ramps and Depressed Curbs, Lighting, Dimension & Size	*	
Parking	Design and Layout, Parking Location and distance to elevator and exit Route, Dimension & Size, Signage and Pavement Markings, Additional Considerations - On-Street Parking	*	
Ramp	Ground and Floor Surfaces, Guards and Handrails, Tactile Walking Surface Indicators, Lighting, Running Slope, Cross-Slope, Edge Protection, Clear width, Landing size	*	
	Handrails and Guards		*
Stairs	Ground and Floor Surfaces, Guards and Handrails, Tactile Walking Surface Indicators, Design Features, Treads and Risers, Nosing	*	
	Handrails and Railing		*
Elevator & Lift	Elevator Cabin Size, Elevator Door Requirements, Lift Platform Size, button and Signage Requirements	*	
	Door, Cabin, button, and Signage		*
Water Closet Stalls (WC)	Design and Layout, Door and Furniture Requirements (Threshold Height, Door Pull Location and Detail, Grab Bars, ...)	*	
	Furniture and Door		*
Rest Area	Ground and Floor Surfaces, Seating, Tables and Work Surfaces, Lighting, Design, and Placement, clear floor space	*	
	Furniture		*
Public Transit Area	Design and Layout, Signage and Wayfinding, Controls and Operating Mechanisms, Ground and Floor Surfaces, Tactile Walking Surface Indicators, Elevating Devices…	*	
	Elevating Devices, Shelters, Street Furniture, and Equipment		*
Inclusive Play Area	Key Design Considerations, Entry and Exit Points, Accessible Routes, Play space Ground Surface (Material)	*	
	Elevated Play Components and other Furniture		*
Refuge Area	Design and Layout, Accessibility, emergency electrical power and Lighting, fire safety, identify and designated signage	*	
	Signage, Lighting, …		*

Public Space Furniture	Service and Payment Counter, Signage and Wayfinding, Lighting, Benches and Seats, Public Telephones, Waterspout…		*

Table 4.4 - Covered items in different guidelines (Indoor Items)

Indoor Item	Qualitative Data	Quantitative Data	CMHC	UDHC	UDSG	UFAS	OADS	BFDS	FHADM	FADSL	BFDGH	FADSM	ADGT	CNUD	BFDGA	ANSI	BFDGY
Kitchen	*		*	limited	N/A	N/A	*	N/A	*	limited	limited	limited	limited	*	*	*	limited
		*	*	limited	limited	limited	*	N/A	*	*	limited	*	limited	*	*	*	limited
Bathroom	*		*	N/A	*	N/A	limited	limited	*	limited	*	*	limited	*	*	*	*
		*	*	N/A	limited	*	limited	limited	*	*	limited	*	limited	*	*	*	*
Restroom (WC)	*		*	limited	*	*	*	*	*	limited	*	*	limited	*	*	*	limited
		*	*	limited	*	*	*	*	*	*	*	*	limited	*	*	limited	limited
Bedroom	*		limited	limited	limited	N/A	N/A	N/A	N/A	N/A	limited	N/A	limited	N/A	N/A	N/A	N/A
		*	N/A	limited	limited	N/A	N/A	N/A	N/A	N/A	limited	N/A	limited	N/A	N/A	N/A	N/A
Living Room	*		limited	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		*	N/A	N/A	limited	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Elevator	*		N/A	N/A	*	*	*	N/A	N/A	*	*	*	*	*	*	*	limited
		*	N/A	N/A	*	*	*	N/A	N/A	*	*	*	*	*	*	*	limited
Parking	*		N/A	limited	*	limited	*	N/A	N/A	*	*	*	*	*	*	limited	*
		*	N/A	N/A	limited	limited	*	N/A	N/A	*	*	*	*	*	*	limited	*
Stair	*		N/A	limited	limited	limited	*	N/A	N/A	limited	*	*	*	*	limited	limited	*
		*	N/A	*	*	*	*	N/A	N/A	*	*	*	*	*	*	*	*
Ramp	*		N/A	limited	*	limited	*	*	N/A	*	*	*	*	*	limited	*	*
		*	N/A	*	*	*	*	limited	N/A	*	*	*	*	*	*	*	*
Entrance Area	*		limited	*	*	limited	*	*	*	limited	*	*	*	*	*	*	*
		*	N/A	*	*	limited	*	*	limited	limited	*	*	*	*	*	*	limited
Door & Gate	*		N/A	*	*	limited	*	*	*	*	*	*	*	*	*	limited	*
		*	N/A	*	*	limited	*	*	limited	*	*	*	*	*	*	limited	*
Window	*		N/A	N/A	limited	N/A	limited	N/A	N/A	limited	limited	limited	*	*	limited	N/A	N/A
		*	N/A	N/A	limited	N/A	limited	N/A	N/A	N/A	N/A	limited	*	*	*	N/A	N/A
Guards & Barrier	*		N/A	*	limited	limited	*	limited	N/A	*	*	limited	limited	*	limited	N/A	limited
		*	N/A	*	limited	limited	*	limited	N/A	*	*	limited	*	*	limited	N/A	limited
Turnstile, Gate Area	*		N/A	limited	limited	limited	*	N/A	N/A	limited	limited	*	N/A	*	N/A	N/A	limited
		*	N/A	*	*	*	*	N/A	N/A	limited	limited	*	limited	*	N/A	N/A	limited
Grills & Gratings	*		N/A	limited	N/A	N/A	*	N/A	N/A	limited	*	*	*	N/A	*	N/A	N/A
		*	N/A	limited	N/A	N/A	*	*	N/A	limited	*	*	*	*	*	N/A	N/A
floor	*		N/A	N/A	N/A	N/A	limited	N/A	limited	N/A	limited	*	N/A	*	N/A	N/A	limited
		*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	limited	*	N/A	*	N/A	N/A	N/A
Wall	*		N/A	N/A	N/A	N/A	N/A	N/A	limited	N/A	N/A	limited	N/A	limited	N/A	N/A	N/A
		*	N/A	N/A	N/A	N/A	N/A	N/A	limited	N/A	limited	limited	limited	limited	limited	limited	N/A
Ceiling	*		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

CAN /CSA	NBCC
*	limited
*	limited
*	*
*	*
*	*
*	*
*	N/A
*	N/A
*	N/A
*	N/A
*	limited
*	limited
*	*
*	*
*	*
*	*
*	*
*	*
*	*
*	limited
*	*
*	*
*	N/A
*	N/A
*	limited
*	limited
limited	limited
limited	limited
*	N/A
*	N/A
*	limited
*	N/A
limited	N/A
limited	N/A
limited	N/A
limited	N/A

Table 4.5 - Covered items in different guidelines (Outdoor Items)

Outdoor Item	**Qualitative**	**Quantitative**	CMHC	UDHC	UDSG	UFAS	OADS	BFDS	FHADM	FADSL	BFDGH	FADSM	ADGT	CNUD	BFDGA	ANSI
Exterior Path, Access	*		limited	limited	limited	*	*	*	*	*	*	*	*	*	*	*
		*	N/A	limited	limited	limited	*	*	*	*	*	*	*	*	*	limited
Passenger	*		N/A	limited	N/A	limited	limited	limited	*	*	limited	limited	limited	*	limited	N/A
Parking	*		N/A	limited	limited	*	N/A	N/A	N/A	*	*	*	*	*	limited	limited
Ramp	*		N/A	limited	*	*	*	*	N/A	*	*	*	*	*	limited	*
		*	N/A	*	limited	*	*	*	N/A	*	*	*	*	*	*	*
Stairs	*		N/A	limited	*	*	*	N/A	N/A	*	*	*	*	*	limited	*
		*	N/A	*	limited	*	*	N/A	N/A	*	*	*	*	*	*	*
Elevator & Lift	*		N/A	limited	*	*	*	N/A	N/A	limited	*	*	limited	*	limited	*
		*	N/A	N/A	*	*	*	N/A	N/A	limited	*	*	limited	*	limited	*
Water Closet Stalls	*		N/A	limited	*	*	*	*	*	*	limited	*	*	*	*	*
		*	N/A	limited	*	*	*	*	*	*	*	*	limited	*	*	limited
Rest Area	*		N/A	limited	N/A	limited	*	N/A	N/A	*	limited	*	*	N/A	N/A	N/A
		*	N/A	limited	N/A	limited	*	N/A	N/A	*	limited	*	*	N/A	N/A	N/A
Public Transit Area	*		N/A	limited	N/A	N/A	*	N/A	limited	limited	limited	limited	limited	N/A	N/A	limited
		*	N/A	N/A	N/A	N/A	*	N/A	limited	limited	limited	limited	limited	N/A	N/A	limited
Inclusive Play Area	*		N/A	N/A	N/A	N/A	*	N/A	N/A	N/A	limited	limited	limited	N/A	N/A	N/A
		*	N/A	N/A	N/A	N/A	*	N/A	N/A	N/A	limited	limited	limited	N/A	N/A	N/A
Refuge Area	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		*	N/A	limited	N/A	limited	limited	N/A	N/A	limited	limited	limited	*	N/A	*	limited
Public Space		*	N/A	N/A	N/A	limited	limited	limited	N/A	limited	limited	*	*	limited	limited	limited

BFDGY	CAN/CSA	NBCC
limited	*	limited
limited	*	limited
N/A	*	N/A
*	*	*
*	*	*
*	*	*
*	*	*
*	*	*
limited	*	limited
limited	*	limited
*	*	*
*	*	*
N/A	*	limited
N/A	*	limited
N/A	*	N/A
N/A	*	N/A
N/A	limited	N/A
N/A	limited	N/A
[illegible]	[illegible]	[illegible]
N/A	*	N/A
limited	*	limited

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CHAPTER 5

TECHNICAL PAPER II

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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Abstract: 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.

5.1 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.

5.2 Literature Review

5.2.1 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.

5.2.2 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.

5.2.3 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).

5.2.4 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).

5.3 Development Methodology

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. 5.1. 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.

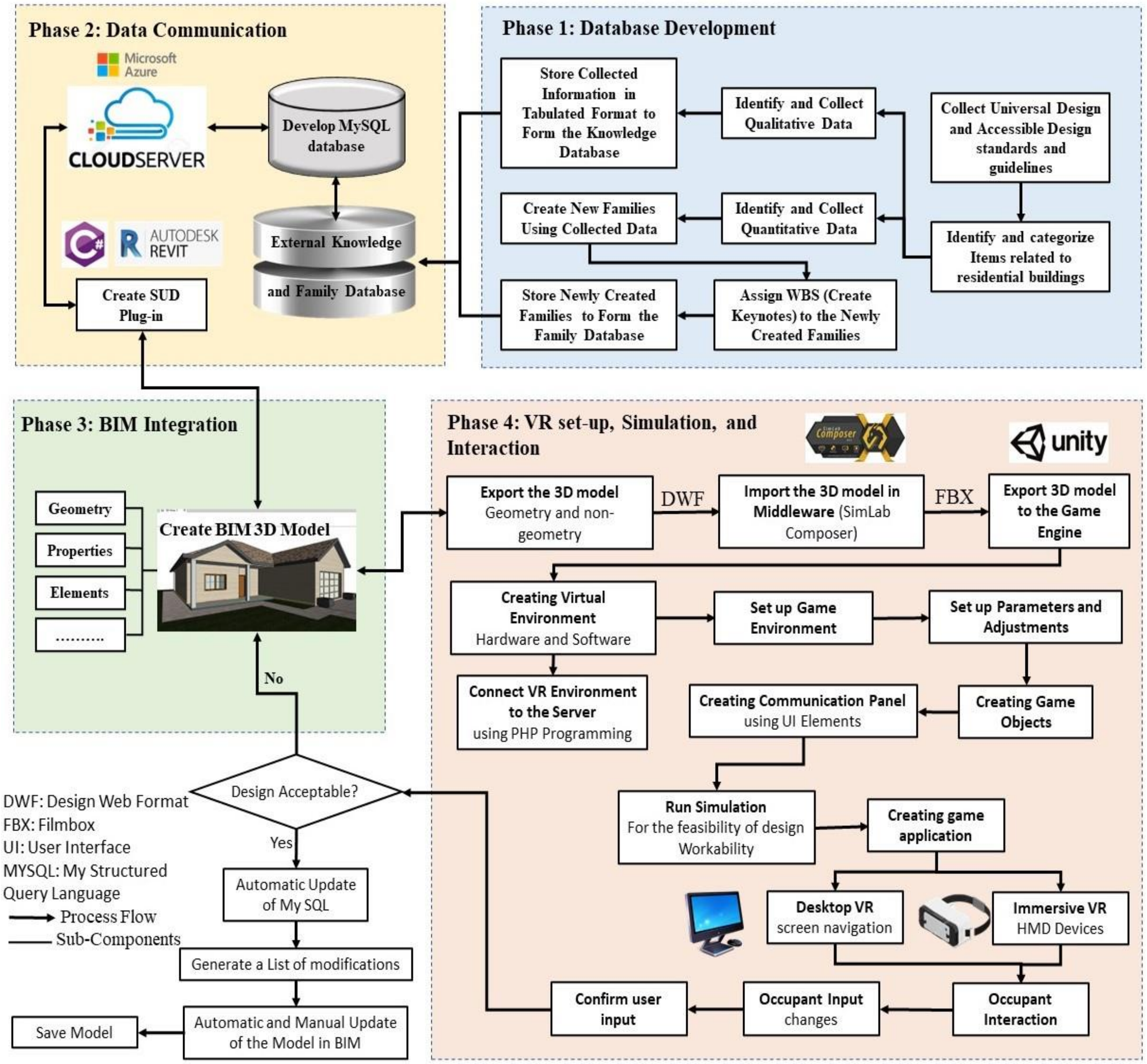


FIG.5.1 - Proposed Model's Components and Development Process

5.3.1 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.

5.3.2 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.

5.3.3 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.

5.3.4 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.

5.3.5 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.

5.4 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 Fig. 5.2. 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 Fig. 5.3. 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 Fig. 5.4, 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. Fig. 5.4 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 Fig. 5.5. 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, Fig. 5.6 shows that all doors in the created 3D design model for the house obey Ottawa's Accessible Design Standard.

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 Fig. 5.7. 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 Fig. 5.7. 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. Fig.s 5.8 and 5.9 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.

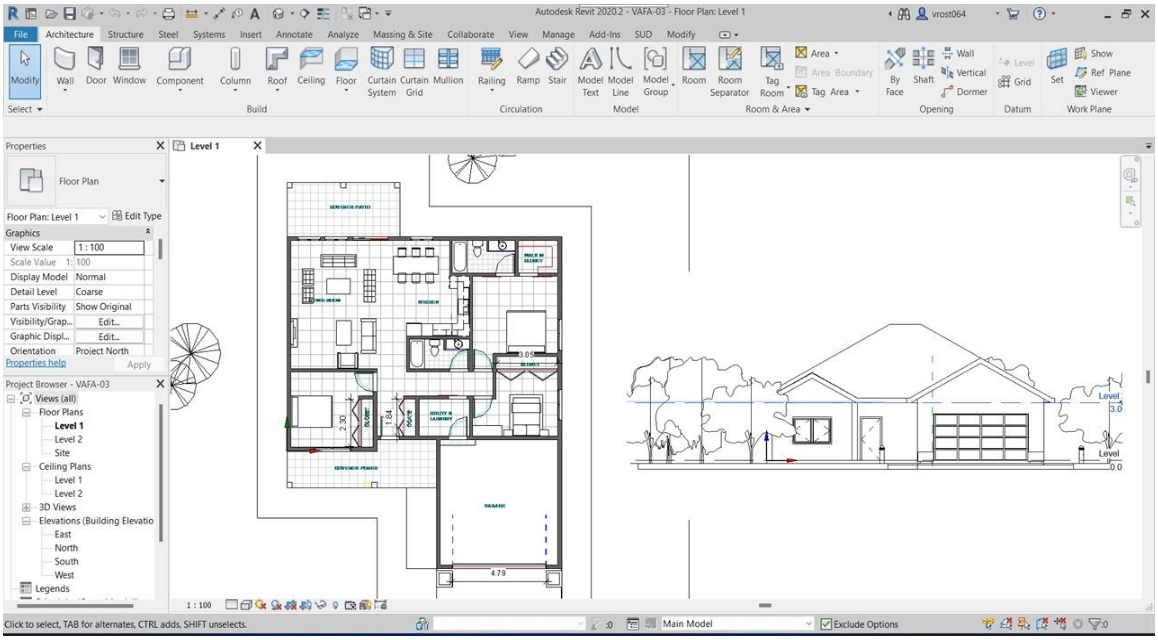


FIG. 5.2 - Plan & Elevation of the Proposed Model

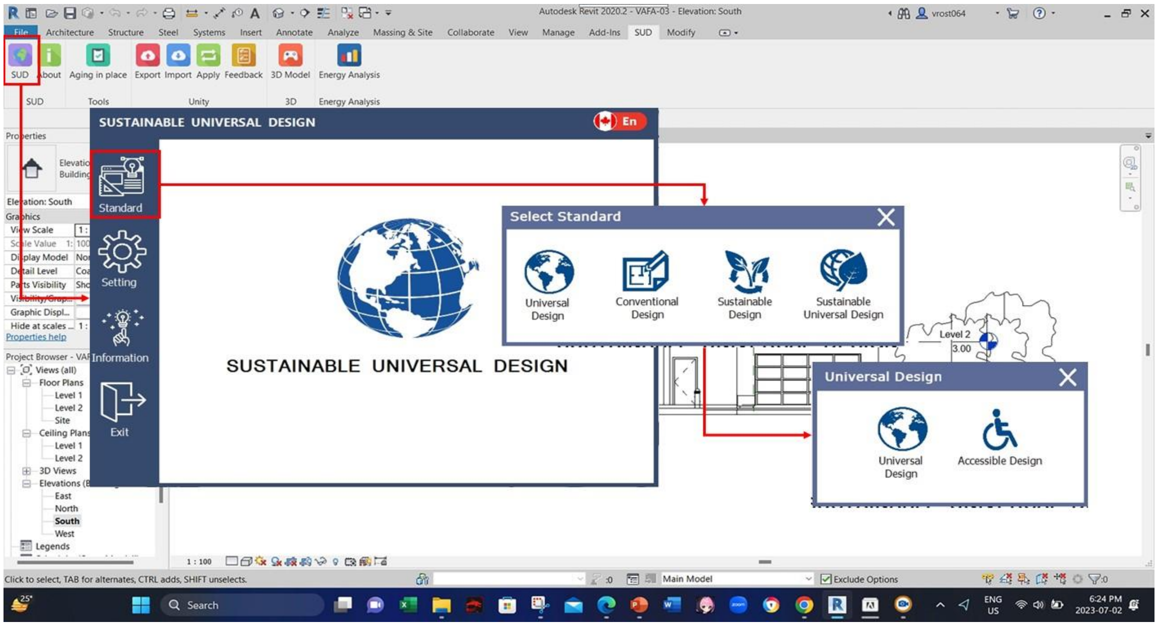
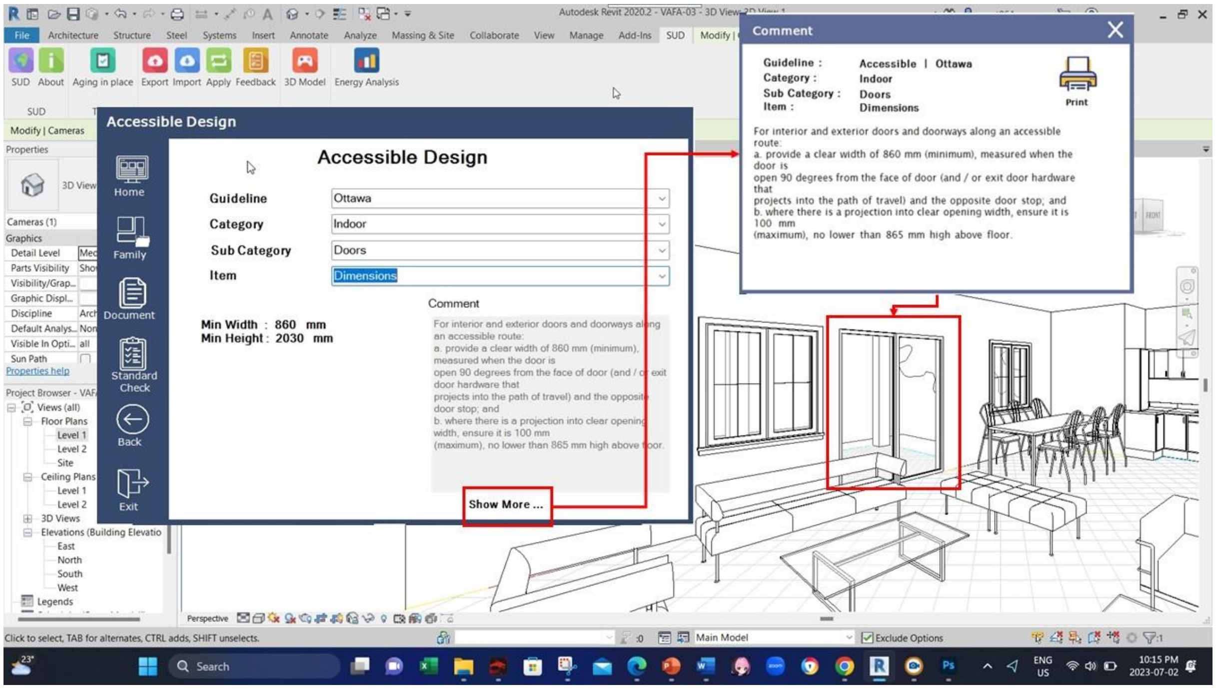


FIG. 5.3 - SUD Plug-in and Selecting Specific Guideline



Accessible Design

Guideline: Ottawa
Category: Indoor
Sub Category: Doors
Item: Dimensions

Min Width : 860 mm
Min Height : 2030 mm

Comment

For interior and exterior doors and doorways along an accessible route:
a. provide a clear width of 860 mm (minimum), measured when the door is
open 90 degrees from the face of door (and / or exit door hardware that
projects into the path of travel) and the opposite door stop; and
b. where there is a projection into clear opening width, ensure it is 100 mm
(maximum), no lower than 865 mm high above floor.

Comment

Guideline : Accessible | Ottawa
Category : Indoor
Sub Category : Doors
Item : Dimensions

For interior and exterior doors and doorways along an accessible route:
a. provide a clear width of 860 mm (minimum), measured when the door is
open 90 degrees from the face of door (and / or exit door hardware that
projects into the path of travel) and the opposite door stop; and
b. where there is a projection into clear opening width, ensure it is 100 mm
(maximum), no lower than 865 mm high above floor.

FIG. 5.4 - Retrieving Data from Selected Guideline

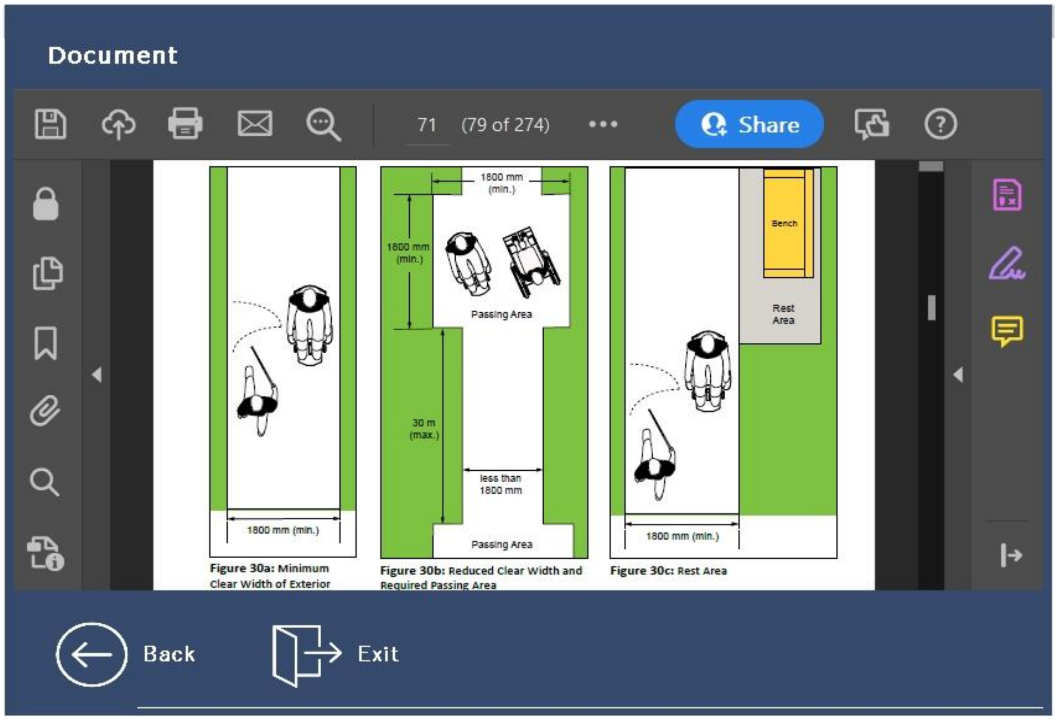
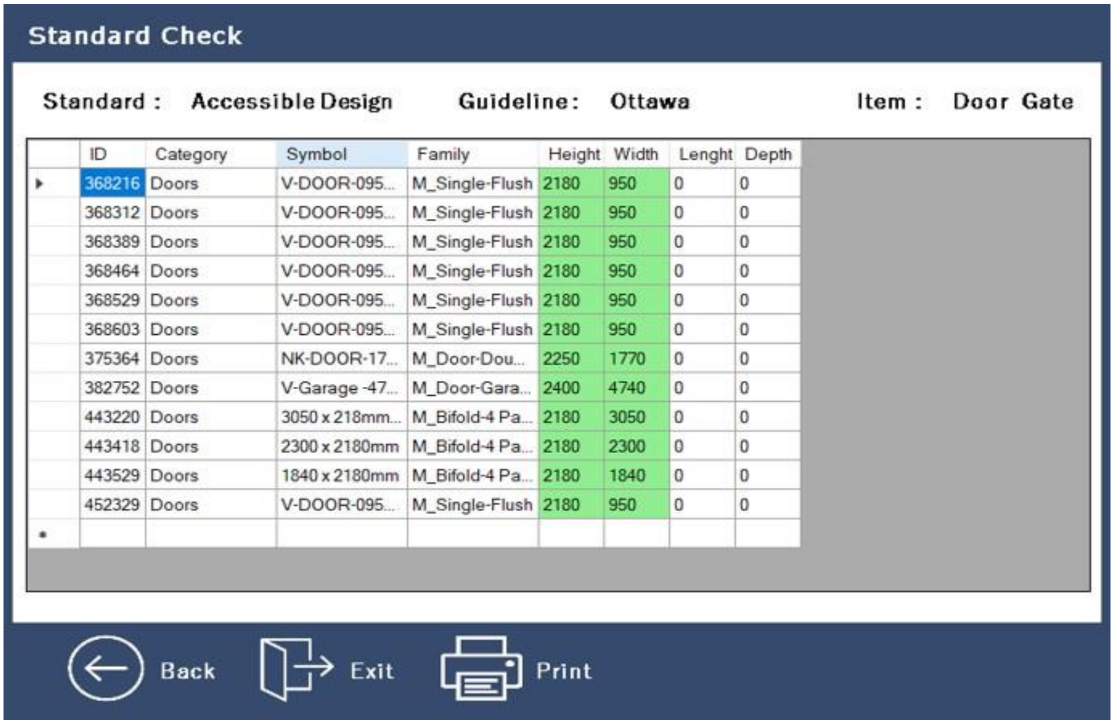


Figure 30a: Minimum Clear Width of Exterior

Figure 30b: Reduced Clear Width and Required Passing Area

Figure 30c: Rest Area

FIG. 5.5 - Retrieving Original Document

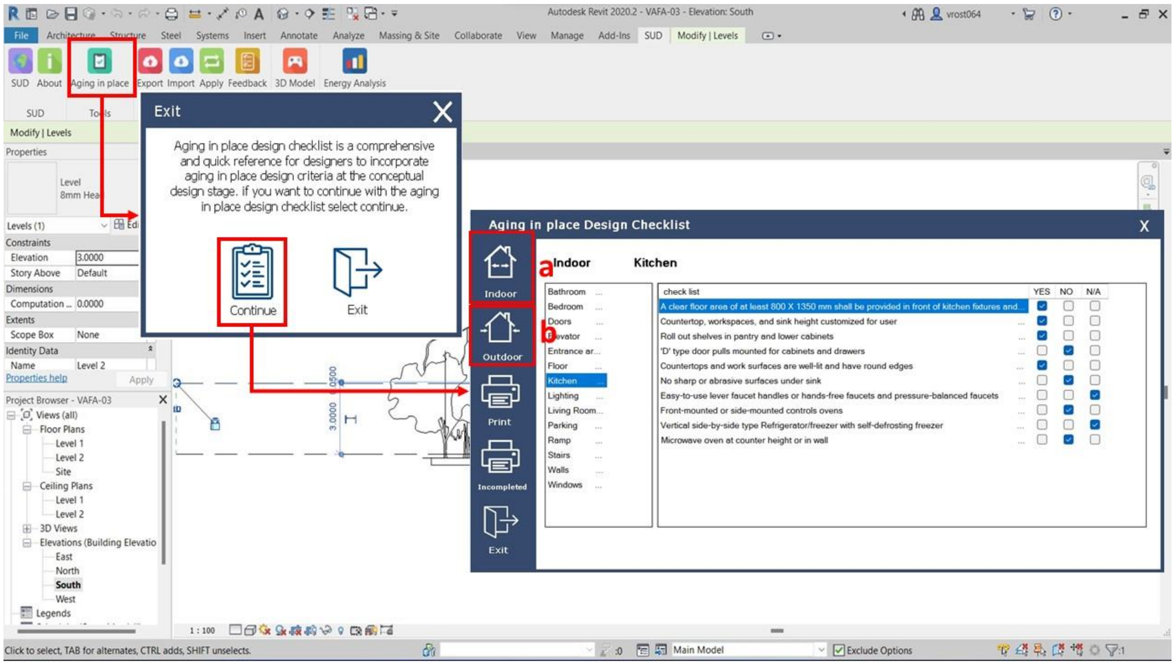


Standard Check

Standard : Accessible Design Guideline : Ottawa Item : Door Gate

ID	Category	Symbol	Family	Height	Width	Lenght	Depth
368216	Doors	V-DOOR-095...	M_Single-Flush	2180	950	0	0
368312	Doors	V-DOOR-095...	M_Single-Flush	2180	950	0	0
368389	Doors	V-DOOR-095...	M_Single-Flush	2180	950	0	0
368464	Doors	V-DOOR-095...	M_Single-Flush	2180	950	0	0
368529	Doors	V-DOOR-095...	M_Single-Flush	2180	950	0	0
368603	Doors	V-DOOR-095...	M_Single-Flush	2180	950	0	0
375364	Doors	NK-DOOR-17...	M_Door-Dou...	2250	1770	0	0
382752	Doors	V-Garage -47...	M_Door-Gara...	2400	4740	0	0
443220	Doors	3050 x 218mm...	M_Bifold-4 Pa...	2180	3050	0	0
443418	Doors	2300 x 2180mm	M_Bifold-4 Pa...	2180	2300	0	0
443529	Doors	1840 x 2180mm	M_Bifold-4 Pa...	2180	1840	0	0
452329	Doors	V-DOOR-095...	M_Single-Flush	2180	950	0	0

FIG. 5.6 - Code Compliance Checking Sample



Exit

Aging in place design checklist is a comprehensive and quick reference for designers to incorporate aging in place design criteria at the conceptual design stage. if you want to continue with the aging in place design checklist select continue.

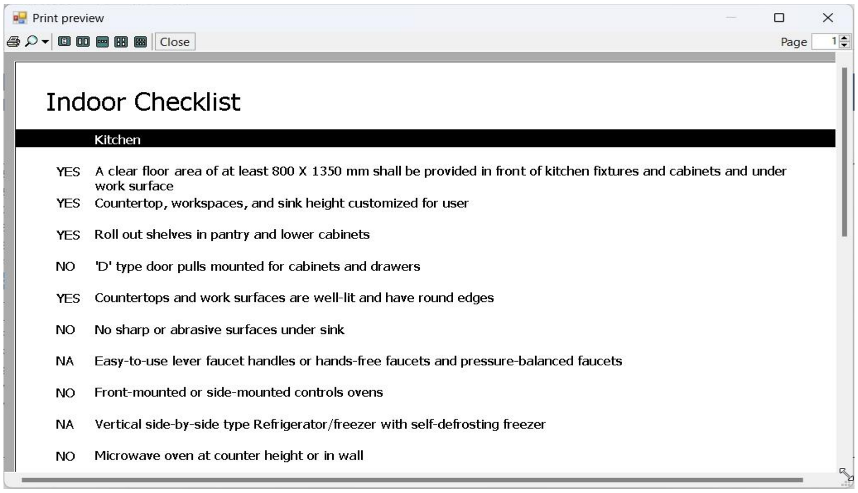
Aging in place Design Checklist

Indoor Kitchen

- Bathroom
- Bedroom
- Doors
- Elevator
- Entrance ar...
- Floor
- Kitchen
- Lighting
- Living Room...
- Parking
- Ramp
- Stairs
- Walls
- Windows

check list	YES	NO	N/A
A clear floor area of at least 800 X 1350 mm shall be provided in front of kitchen fixtures and...	☑	☐	☐
Countertop, workspaces, and sink height customized for user	☑	☐	☐
Roll out shelves in pantry and lower cabinets	☑	☐	☐
'D' type door pulls mounted for cabinets and drawers	☐	☑	☐
Countertops and work surfaces are well-lit and have round edges	☑	☐	☐
No sharp or abrasive surfaces under sink	☐	☑	☐
Easy-to-use lever faucet handles or hands-free faucets and pressure-balanced faucets	☐	☐	☑
Front-mounted or side-mounted controls ovens	☐	☑	☐
Vertical side-by-side type Refrigerator/freezer with self-defrosting freezer	☐	☐	☑
Microwave oven at counter height or in wall	☐	☑	☐

FIG. 5.7 - Plug-in for Age in Place Design (AIP) Requirements

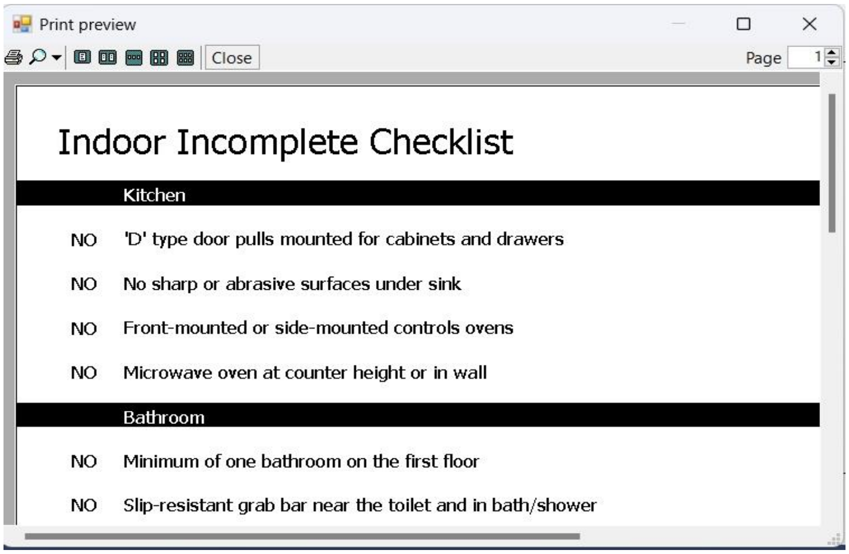


Indoor Checklist

Kitchen

YES	A clear floor area of at least 800 X 1350 mm shall be provided in front of kitchen fixtures and cabinets and under work surface
YES	Countertop, workspaces, and sink height customized for user
YES	Roll out shelves in pantry and lower cabinets
NO	'D' type door pulls mounted for cabinets and drawers
YES	Countertops and work surfaces are well-lit and have round edges
NO	No sharp or abrasive surfaces under sink
NA	Easy-to-use lever faucet handles or hands-free faucets and pressure-balanced faucets
NO	Front-mounted or side-mounted controls ovens
NA	Vertical side-by-side type Refrigerator/freezer with self-defrosting freezer
NO	Microwave oven at counter height or in wall

FIG. 5.8 - Sample of Checklist Report



Indoor Incomplete Checklist

Kitchen

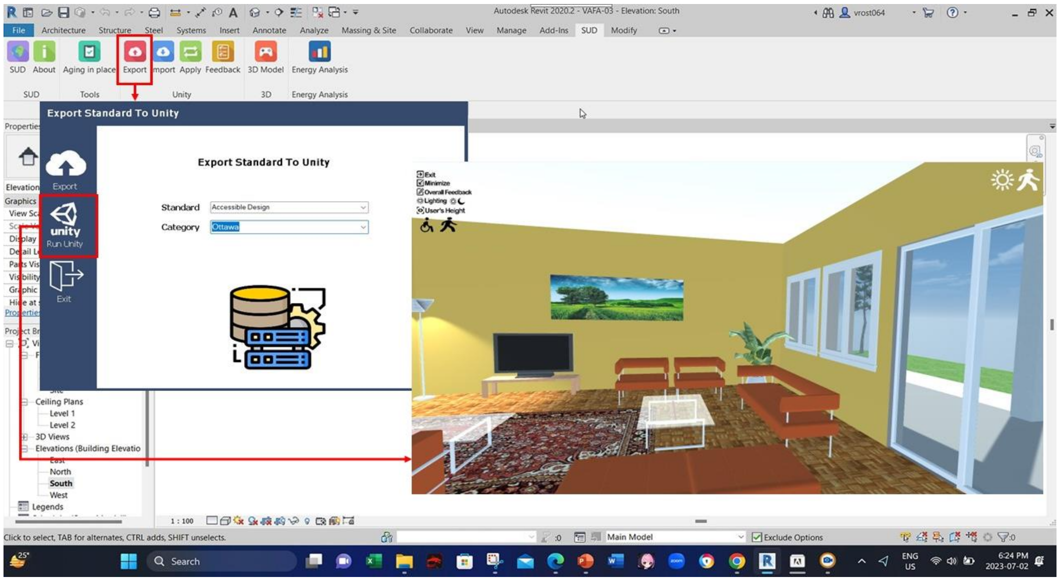
NO	'D' type door pulls mounted for cabinets and drawers
NO	No sharp or abrasive surfaces under sink
NO	Front-mounted or side-mounted controls ovens
NO	Microwave oven at counter height or in wall

Bathroom

NO	Minimum of one bathroom on the first floor
NO	Slip-resistant grab bar near the toilet and in bath/shower

FIG. 5.9 - Sample of the Incomplete Item's 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 Fig. 5.10.



Export Standard To Unity

Standard: Accessible Design

Category: Ottawa

FIG. 5.10 - 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 Fig. 5.10. 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. Fig. 5.11 shows the developed game environment and its primary functions.

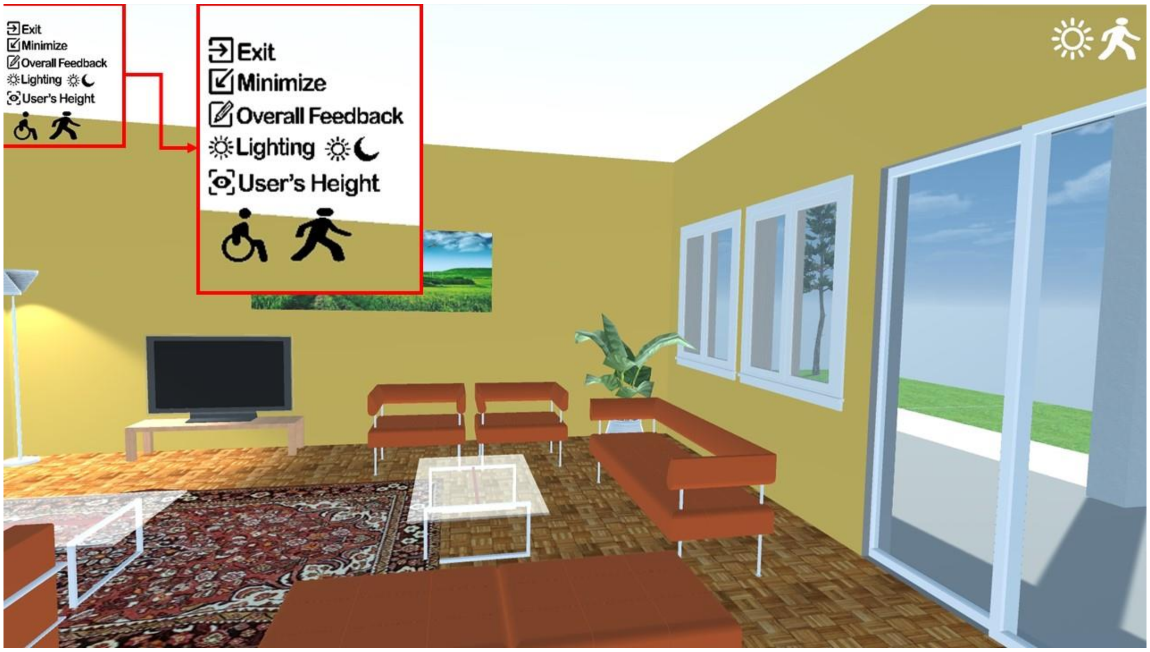


FIG. 5.11 - The Developed Gaming Environment and Its Functions

These functions are: 1) switching between day or night modes, as illustrated in Fig. 5.12; 2) a text box for users to write their overall/general feedback from the design or their comments, as displayed in Fig. 5.13; and 3) adjusting the camera’s height based on the user’s actual height as shown in Fig. 5.14. 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 Fig.s 5.15 and 5.16, 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.

FIG. 5.12 - Selecting Day or Night Mode

FIG. 5.13 -Writing General Feedback and Comments by Users

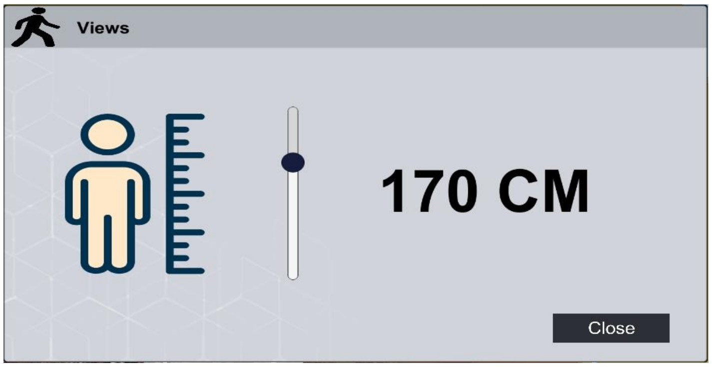
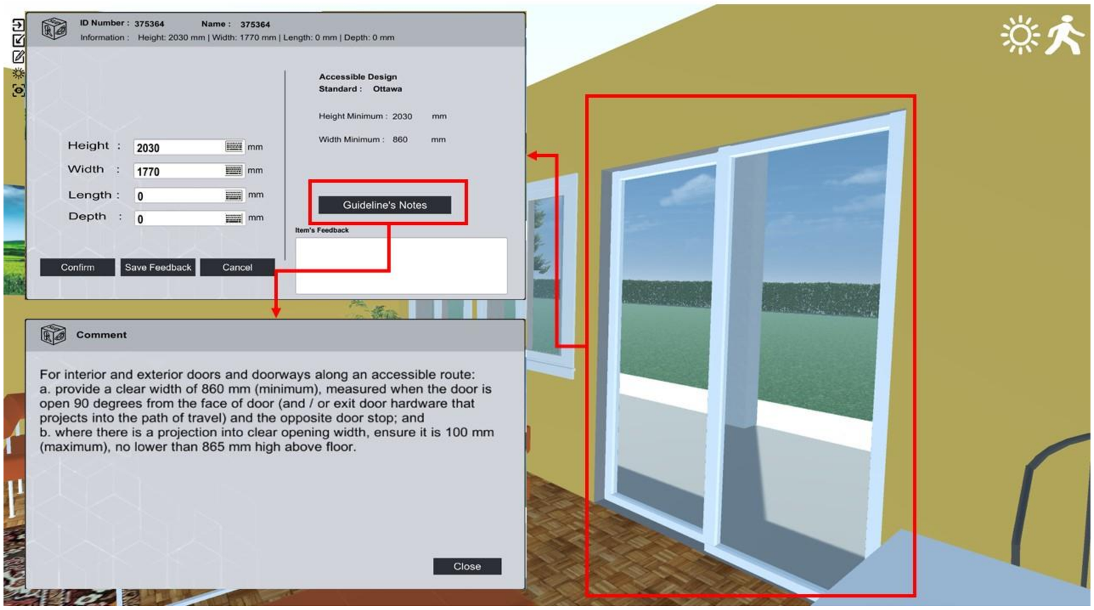


FIG. 5.14 - Adjusting the user’s Height and Level of Vision


ID Number : 375364 Name : 375364

Information : Height: 2030 mm | Width: 1770 mm | Length: 0 mm | Depth: 0 mm

Height : 2030 mm

Width : 1770 mm

Length : 0 mm

Depth : 0 mm

Accessible Design Standard : Ottawa

Height Minimum : 2030 mm

Width Minimum : 860 mm

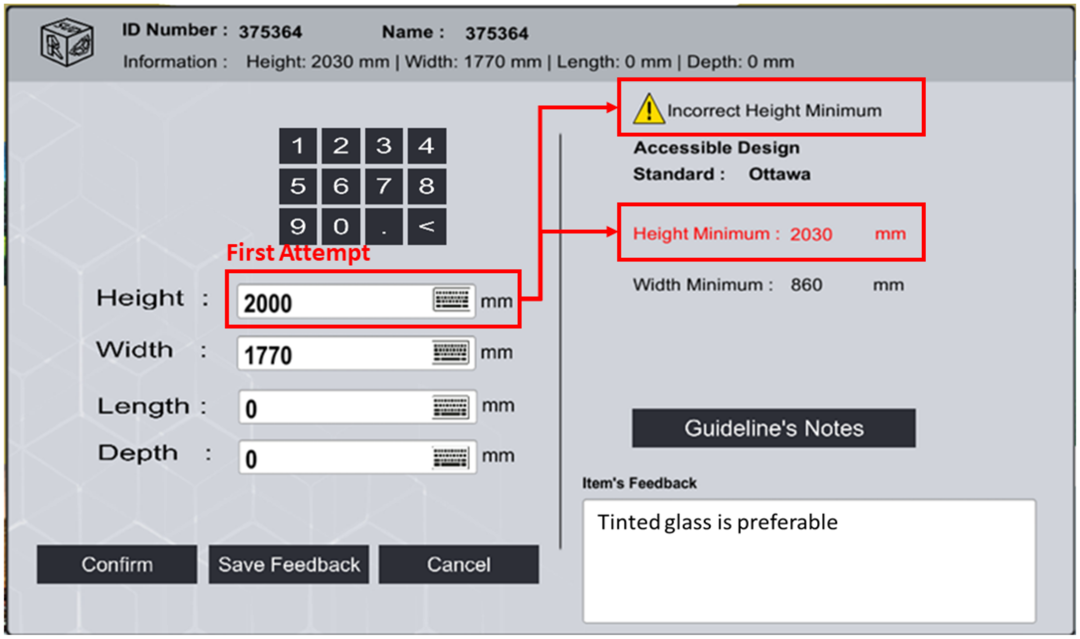
Comment

For interior and exterior doors and doorways along an accessible route:
a. provide a clear width of 860 mm (minimum), measured when the door is open 90 degrees from the face of door (and / or exit door hardware that projects into the path of travel) and the opposite door stop; and
b. where there is a projection into clear opening width, ensure it is 100 mm (maximum), no lower than 865 mm high above floor.

FIG. 5.15 - Communication Panel in the Game Environment

Fig. 5.16 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. Fig. 5.17 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 Fig. 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 Fig. 5.18. 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.

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.



ID Number : 375364 Name : 375364
Information : Height: 2030 mm | Width: 1770 mm | Length: 0 mm | Depth: 0 mm

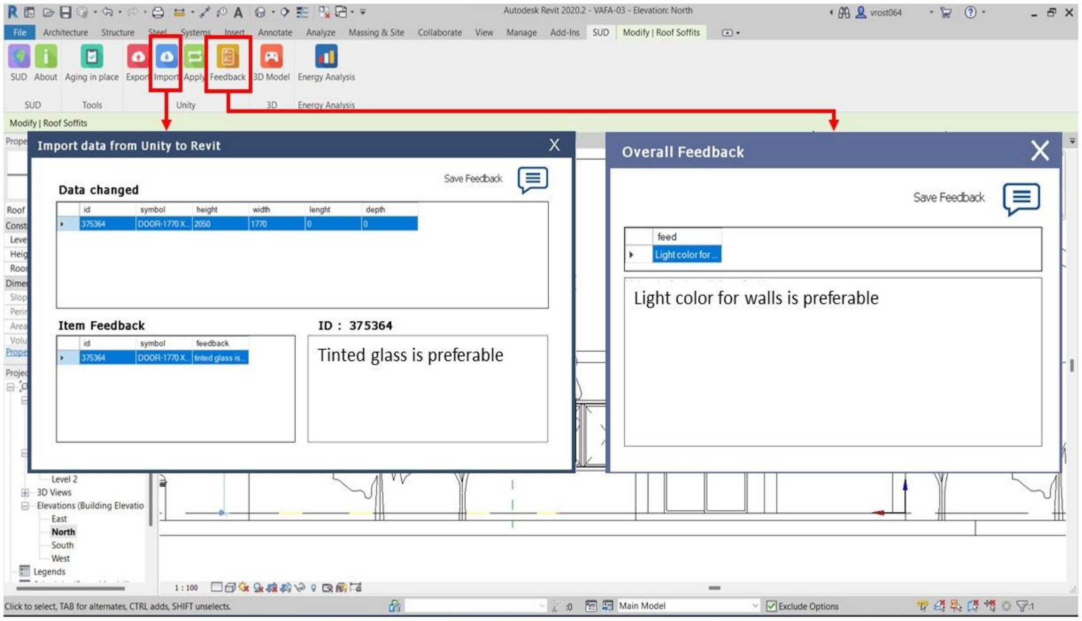
Height : 2000 mm
Width : 1770 mm
Length : 0 mm
Depth : 0 mm

⚠ Incorrect Height Minimum
Accessible Design
Standard : Ottawa
Height Minimum : 2030 mm
Width Minimum : 860 mm

Item's Feedback
Tinted glass is preferable

FIG. 5.16 - User's Communication With the 3D Model

FIG. 5.17 - Selecting Different Material by User



Import data from Unity to Revit

Data changed

id	symbol	height	width	lenght	depth
375364	DOOR-1770 X...	2050	1770	0	0

Item Feedback

id	symbol	feedback
375364	DOOR-1770 X...	tinted glass is...

ID : 375364

Tinted glass is preferable

Overall Feedback

feed
Light color for ...

Light color for walls is preferable

FIG. 5.18 - BIM-VR Integration

5.5 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.

5.6 References

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CHAPTER 6

TECHNICAL PAPER III

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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Abstract: This study unfolds an innovative approach aiming to address the critical role of building design in the 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 on improving the 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.

6.1 Introduction

In Canada, the total energy demand was 12,204 petajoules (PJ) in 2018, where the building sector accounted for approximately 25% of the energy consumption (Canada Energy Regulator, 2023). Space heating, cooling and lighting are responsible for over 68% of a building energy’s use, broken as, 56%, 5% and 7%, respectively (Government of Canada, 2020). Building energy’s performance is largely impacted by design decisions such as building form, orientation, and window(s) size at the conceptual design stage (Gao et al., 2019). Windows can affect the building's total energy consumption in many ways. Zhang and ONG (2017) 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 the 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 highlights the importance of the optimal window-to-wall ratio in buildings (Sayadi et al., 2021). 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 (Elbeltagi et al., 2017). 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 (Elbeltagi et al., 2017).

A study by Sayadi et al., (2021), 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 to assess the building performance early during the design stages to optimize the design parameters such as location, orientation, glazing ratio and fabric properties (CHEN et al., 2018).

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 (Varma, 2018). 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 (Chau and 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). 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 (P.P.J., 2010). 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 (Crews and Zavotka, 2006). 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 (Moscoso et al., 2021). Therefore, as 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 (Magri et al., 2019). However, studies show that there are considerable communication's 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 (Wu & Kaushik, 2015). Virtual Reality (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 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).

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, 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 are contributing 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 on energy efficiency and user-centric design, this study will significantly contribute in 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.

6.2 Literature Review

Windows play a vital role in enhancing the building's energy efficiency by significantly influencing its energy load (Kim et al., 2016). According to Kim et al., (2016), 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 (Chi et al., 2020). Studies conducted by Bokel, (2007); Montaser Koohsari et al., (2015); and Leskovar and Premrov, (2011) 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 (Engelen, et al., 2022). Studies by Benfield, et al., (2013) and Kaplan (1993) 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 comparable effects on occupants, the significance of incorporating such elements in built environments for fostering well-being is not recognized (Hee Ko, et al., 2020). Window size establishes the physical and visual connection to the exterior

(Islam, et al., 2014), permits daylight and provides views and thermal enclosure in buildings. Therefore, windows represent one of the most important components of a building's envelope (Troup, et al., 2019). 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 (Persson, et al., 2006).

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 (Sampaio, 2017); (Ding, et al., 2014). 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 (Wu, et al., 2019). 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 (Antwi-Afari, et al., 2018). 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 (Kamel and Memari, 2019). BIM represents the prevailing approach to revolutionizing the design, construction, and maintenance of buildings (Bryde, et al., 2013). 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 (Abanda and Byers, 2016). BIM offers users the potential to create more energy-efficient buildings. Typically, energy analysis is complex and costly, which is leading to delays until the final stages of design (Esmaeili Moakher and Pimplikar, 2012). 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 (Abanda and Byers, 2016).

VR integrates multiple technologies, including advanced computing, sensing, simulation, and microelectronics, to create an immersive three-dimensional environment (Shengyi and Jia, 2016). Unlike conventional 3D modeling tools, VR enhances immersion and interaction, allowing designers to explore their designs with more advanced concepts (Park, et al., 2018). VR technology is characterized by its immersive, interactive, and imaginative qualities. It engages users through visual and auditory stimuli, enables interaction with virtual objects and scenes, and fulfills individual user needs (Shengyi and Jia, 2016). Wolfartsberger et al., (2017) 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., (2020), 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 (Yan, et al., 2011).

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 (Elnabawi, 2020). 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 (Elnabawi, 2020); (Kurul, et al. 2013); (Han, et al. 2018). DesignBuilder is extensively known and utilized in the AEC industry for simulating the building performance and analising its energy. With its user-friendly interface and comprehensive features, DesignBuilder 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 (2020), various Building Energy Modeling (BEM) tools were evaluated, where DesignBuilder was identified as the tool that best suited to meet performance criteria and practical application, closely followed by Virtual Environment. Notably, DesignBuilder 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. DesignBuilder, a commercially available CAD software specializing in 3D building modeling for energy-efficient design and operation, offers the most comprehensive interface for EnergyPlus when compared to other tools (Maile, et al., 2007). Consequently, DesignBuilder was chosen as the BEM tool for this study.

6.2.1 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 (2014), Watfa, et al., (2021), and Elnabawi (2020), comparatively less focus has been placed on their integration concerning WWR and building orientation. Hee Ko et al., (2020) 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., (2016) 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., (2021) 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, (2017) 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., (2020) 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, (2016) 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, (2007), 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., (2015), 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., (2020) 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.

6.2.2 Relevant Studies Related to the Integration of BIM-VR and Game Engines

To engage end-users in the design process, Balali et al., (2018) 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., (2023) 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., (2019) 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., (2017) 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., (2018) 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., (2018) 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., (2020) 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, (2015) 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 (Zhao, et al., 2023); (Li, et al., 2018); (Dela Cruz and DAJAC, 2021); (Tan, et al., 2022); and (Wu, et al., 2022) 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.

6.3 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. Illustrated in Figure 6.1 are the functions performed within each model’s components and their local developments. Since the proposed methodology integrates different applications, the development will be implemented through four phases: 1) WWR Base Model Creation and Simulation; 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 (DesignBuilder in this study) and parametric analysis on WWR for each building façade across the fifteen major Canadian cities.

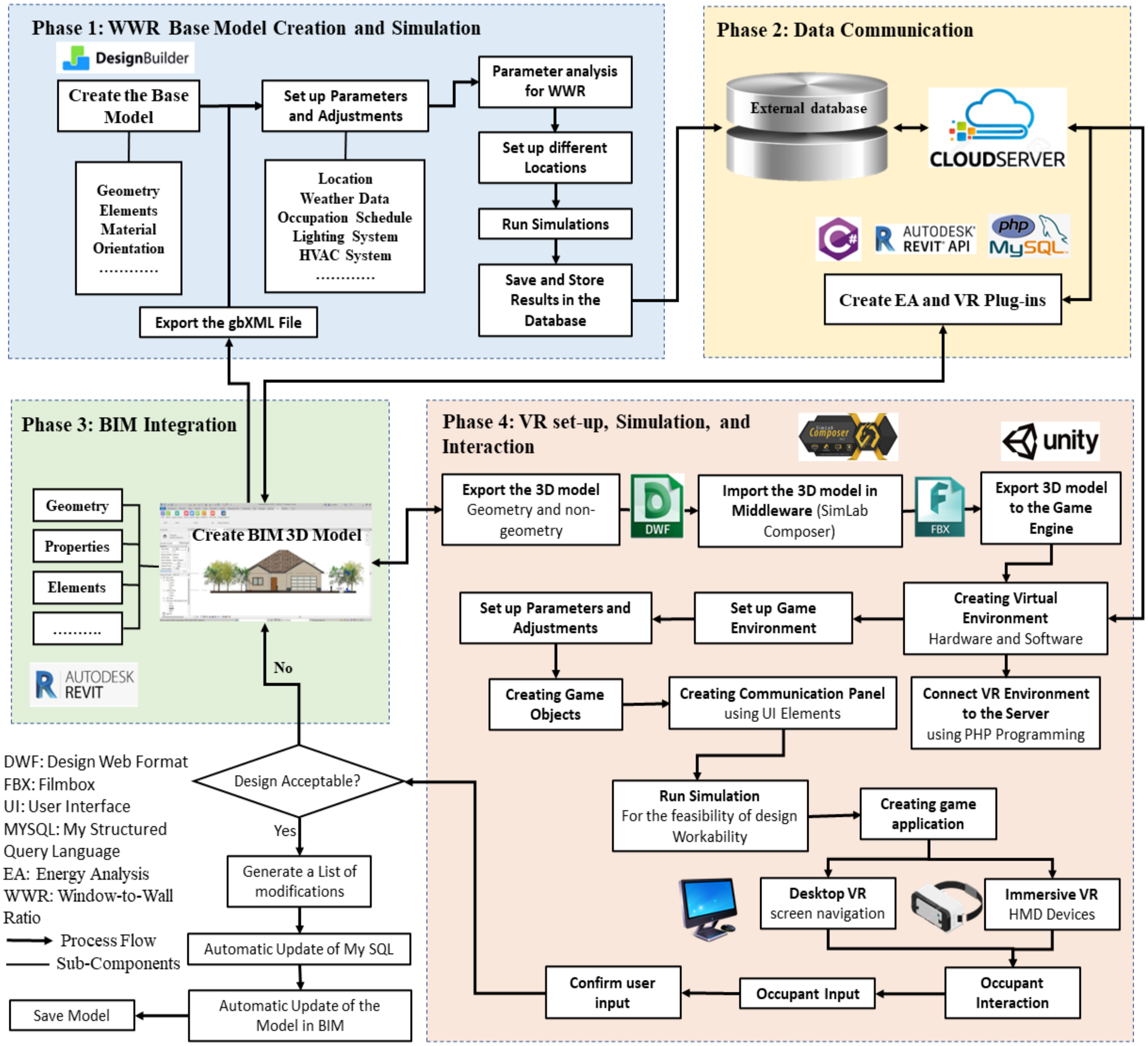


Figure 6.1- Proposed Model's Components and Development Process

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.

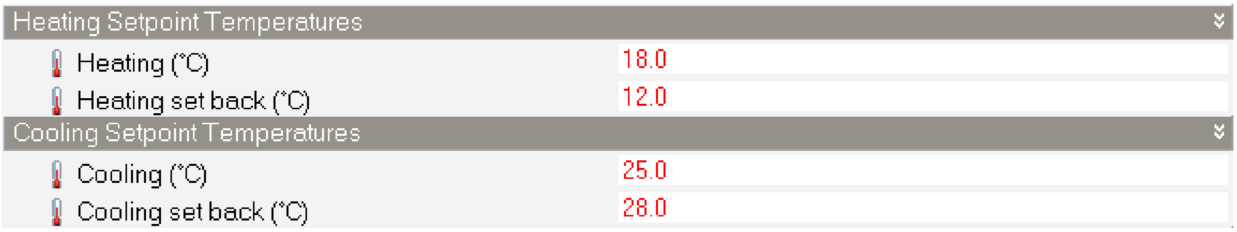
6.3.1 Phase 1 - WWR Base Model's Creation and Simulation

During Phase 1, a base model was created, featuring a rectangular building measuring 96 square meters (8m x 12m) and adhering to the specified properties as outlined in 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 6.1. Furthermore, shading is not considered in the base model.

Table 6.1- Base Model of Windows' Properties

Number of Panes	1st Pane Glass type	2nd 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 setpoint temperatures are configured at 18°C and 25°C, respectively, as depicted in Figure 6.2.



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 6.2 - Heating and Cooling temperatures Setting

The foremost essential step in ensuring accurate energy simulation is identifying the location and selecting the appropriate weather file. DesignBuilder provides access to a wide range of weather files based on EnergyPlus, 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 DesignBuilder. 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 6.3 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 6.2 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.

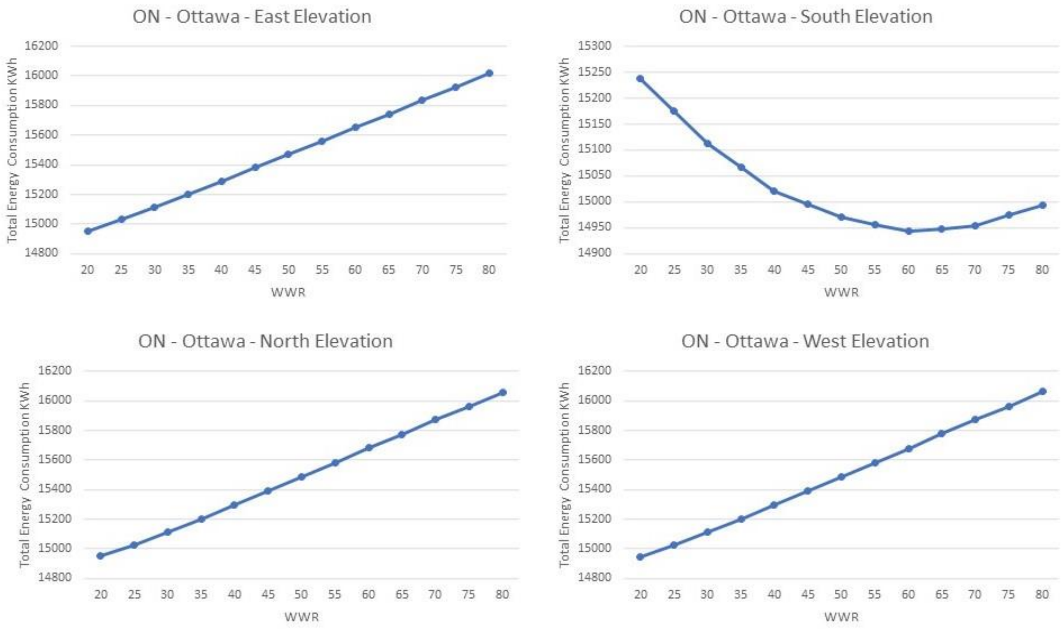


Figure 6.3 - Sample Chart for WWR analysis for each building's facade (north, south, east, west)

Table 6.2 - 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 Colombia (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

6.3.2 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 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.

6.3.3 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 DesignBuilder 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 DesignBuilder environment to ensure accuracy. The model is exported to DesignBuilder as a gbXML file, which is done in two ways: i) via the DesignBuilder add-in in Autodesk Revit; or ii) directly from the export option in the File tab of Autodesk Revit. When using the DesignBuilder 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 DesignBuilder, 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 DesignBuilder (Elnabawi, 2020). In this investigation, successful exportation of the house geometry is evidenced, as depicted in Figure 6.4. 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 DesignBuilder 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 6.5 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.

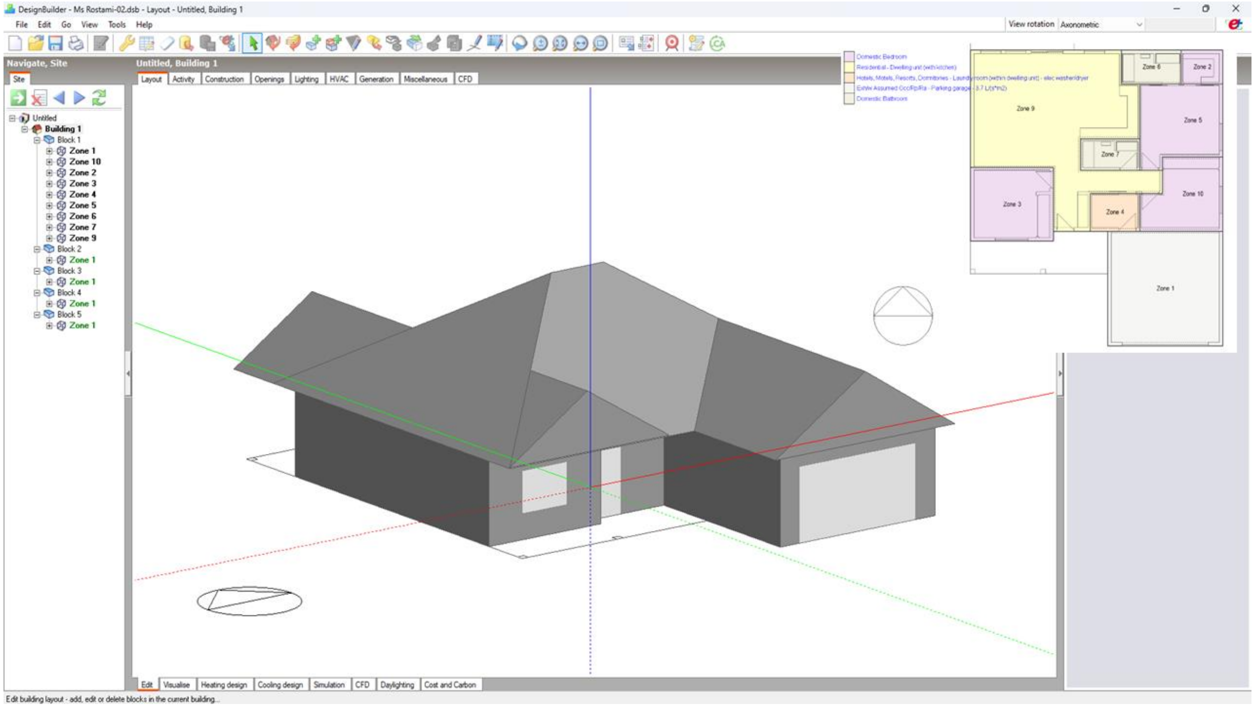


Figure 6.4 - House's Geometry and Zones in DesignBuilder

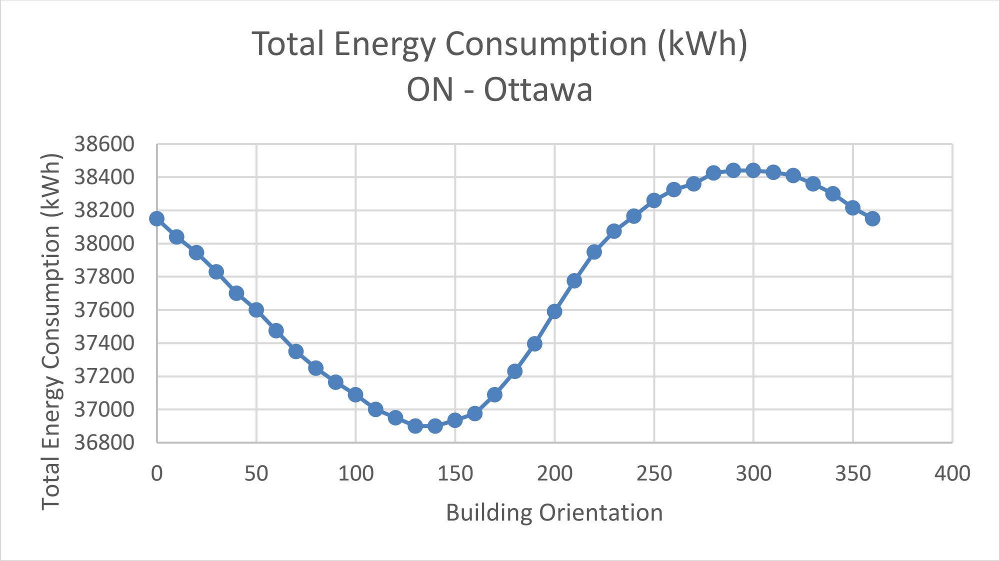


Figure 6.5 - Sample Building Orientation Result

6.3.4 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 game engine environments as highlighted by (Du, et al., 2018). 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, SimLab 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 middleware 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 (2022) (Rostamiasl and Jrade 2022). 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.

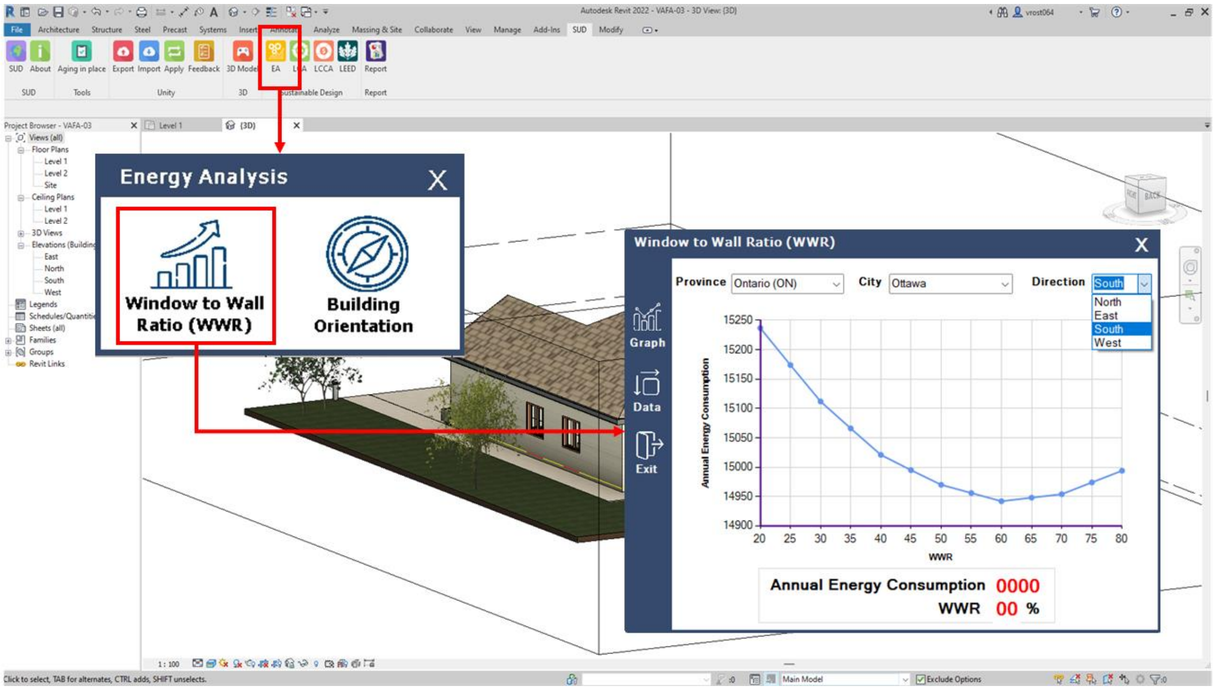
The fourth step involves the creation of a Virtual Reality Environment (VRE) and the configuration of the game engine parameters. This involves the use of an avatar and camera to facilitate effective communication, visualization, and navigation within the model. Within the game environment, users and 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.

6.4 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 6.6. 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: i) Window-to-Wall Ratio (WWR): or ii) Building Orientation. However, designers must start with the WWR option to proceed with the design, as depicted in Figure 6.7. 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 6.7. 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 6.8. Moreover, the plug-in generates diagrams in various formats, giving designers the option to select their preferred format as depicted in Figure 6.9. 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 6.6 - 3D Design Model for the Selected House



Province Ontario (ON)
City Ottawa
Direction South

Annual Energy Consumption 0000
WWR 00 %

Figure 6.7 - EA Plug-in and Its Features

Province Ontario (ON)
City Ottawa
Direction South

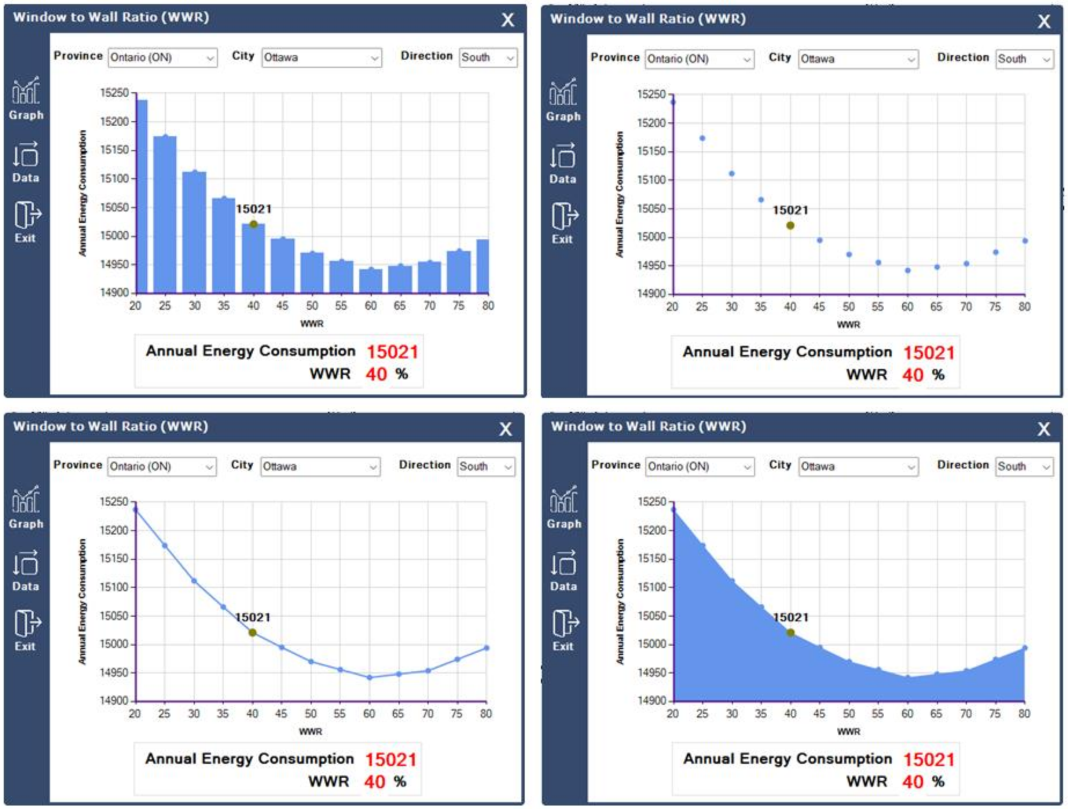
Wall size CM
Width 420 Height 280

Window size CM
Width 140 Height 150

Width	Height	Area (M2)
1. 160	150	2.4
2 140	150	2.1

Annual Energy Consumption 15174
WWR 25 %

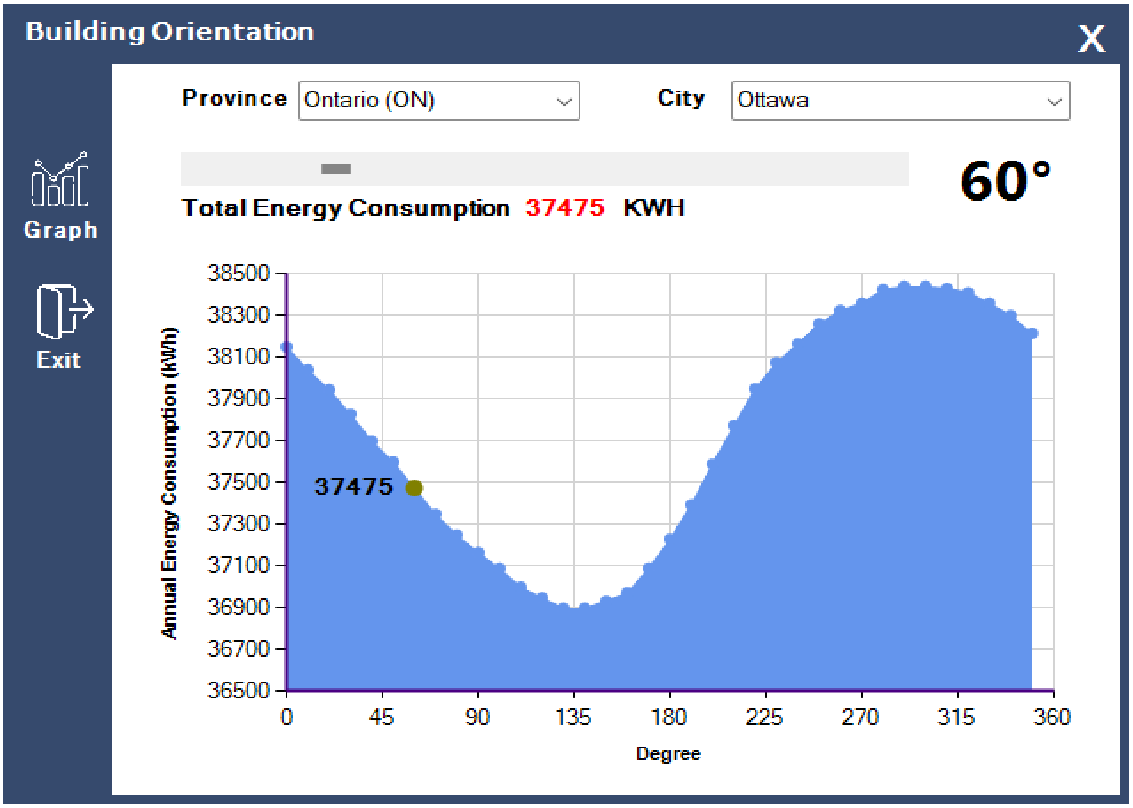
Figure 6.8 - Input Data for Wall and Windows Dimensions



Province Ontario (ON)
City Ottawa
Direction South
Annual Energy Consumption 15021
WWR 40 %

Figure 6.9 - Selection from Different Diagrams' Format

Once the design is completed, the analytical model is generated and exported to DesignBuilder 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 6.10.


Building Orientation

Province: Ontario (ON)

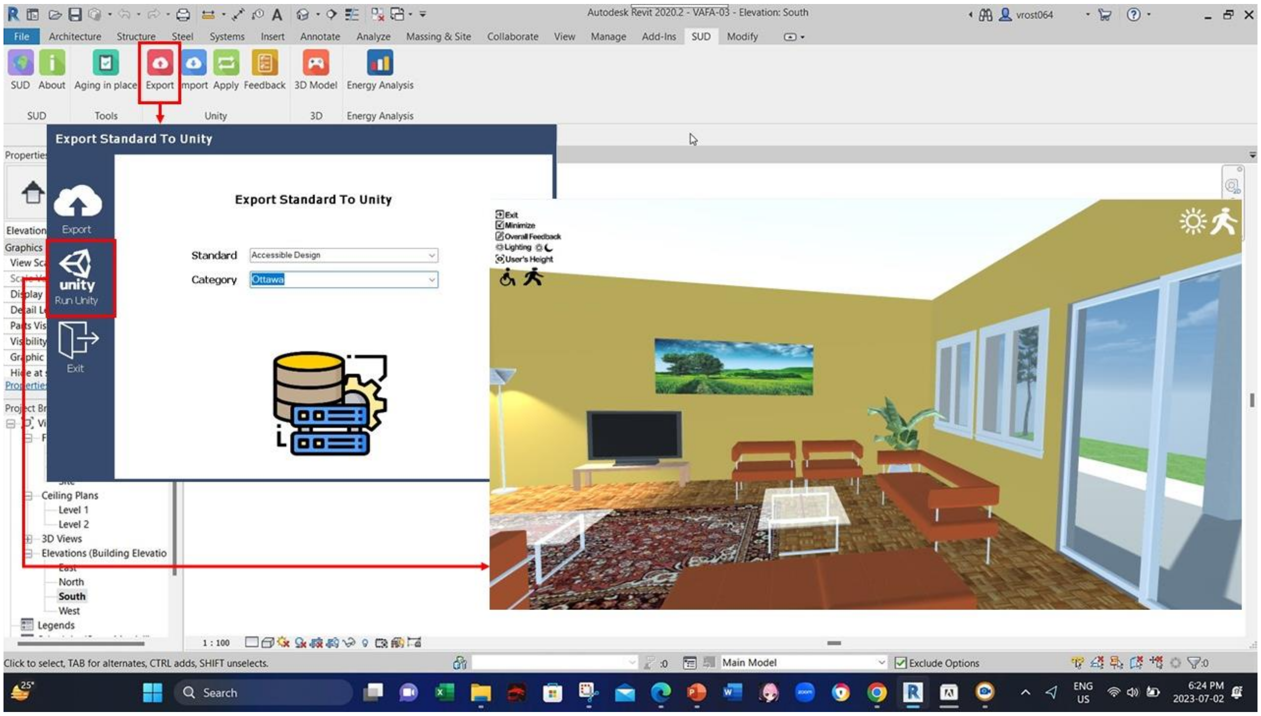
City: Ottawa

60°

Total Energy Consumption 37475 KWH

Figure 6.10 - 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 6.11.



Export Standard To Unity

Standard: Accessible Design

Category: Ottawa

Figure 6.11 - 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 6.12. 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.

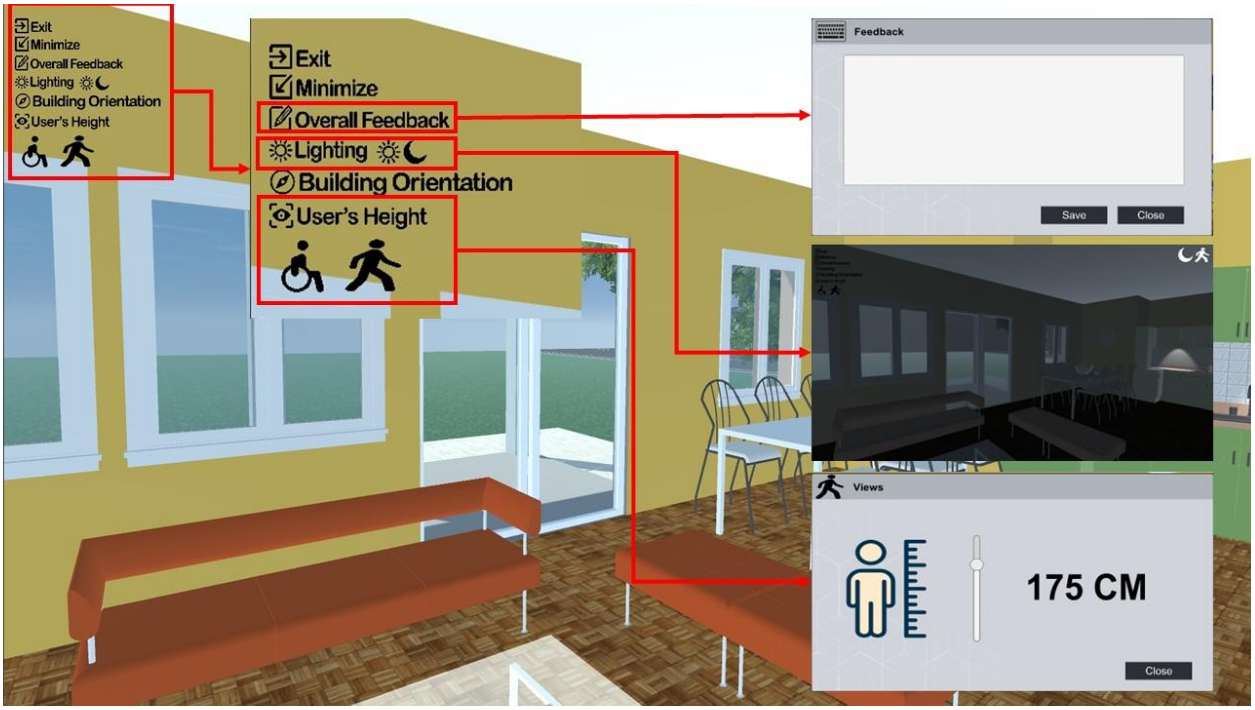
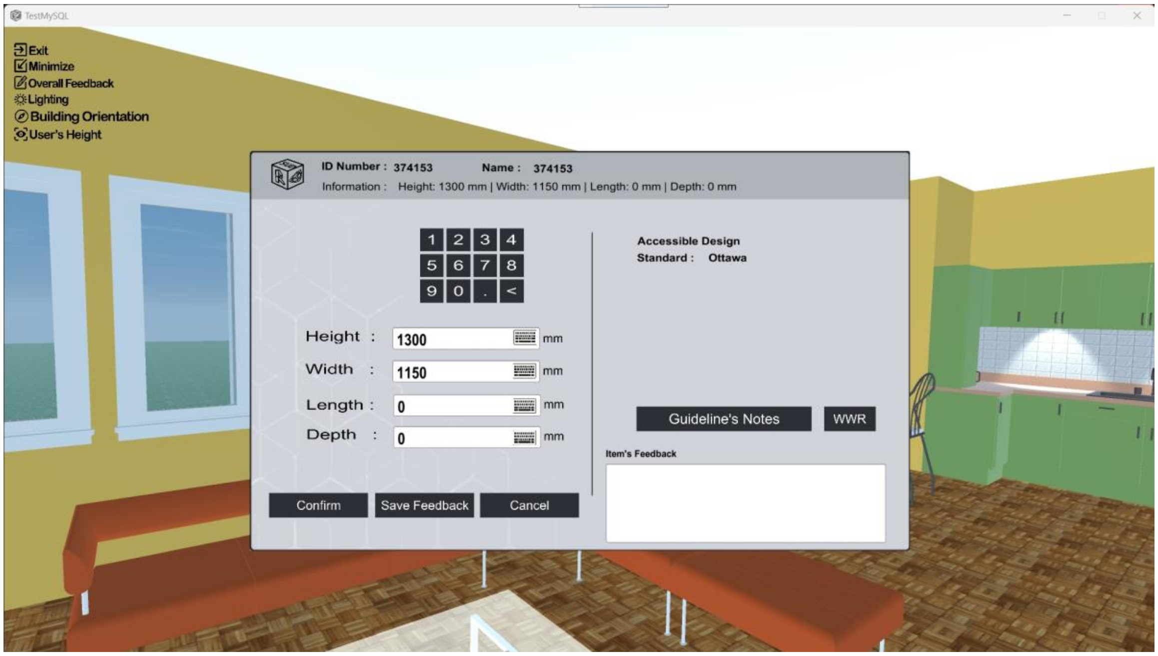


Figure 6.12 – The Developed Gaming Environment and its Functions

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 6.13. 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 6.13, 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 6.14. When users modify the window's dimensions, the updated dimensions, WWR percentage, and the associated graph are displayed, allowing users to confirm or revise them as pictured in Figure 6.15. 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 Figure 6.12. 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 Figures 6.16 and 6.17. 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.



ID Number : 374153 Name : 374153
Information : Height: 1300 mm | Width: 1150 mm | Length: 0 mm | Depth: 0 mm

Height : 1300 mm
Width : 1150 mm
Length : 0 mm
Depth : 0 mm

Accessible Design
Standard : Ottawa

Figure 6.13 - Retrieving The Selected Window's Data From the Database

Window to wall ratio ON Ottawa
Height : 1300 mm
Width : 1150 mm

New WWR (%) 20
Provinces Ontario
Cities Ottawa

Total Energy Consumption
20425KWH

Figure 6.14 - The Current Dimensions and WWR for the Selected Window

Window to wall ratio ON Ottawa

Height : 2000 mm
Width : 3000 mm

New WWR (%) 45

Provinces Ontario
Cities Ottawa

Total Energy Consumption
20470KWH

Figure 6.15 - The Modified Dimensions and Corresponding WWR for the Selected Window

Building Orientation ON Ottawa

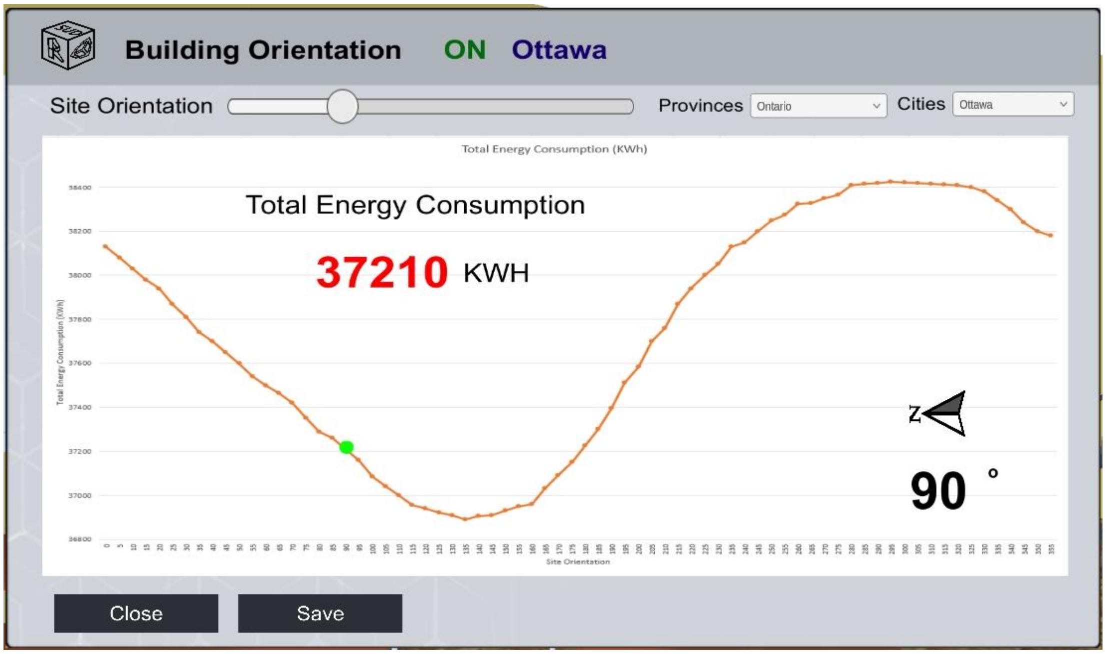
Site Orientation

Provinces Ontario
Cities Ottawa

Total Energy Consumption
38130 KWH

0 °

Figure 6.16 - The Created UI for Windows in The VR Environment


Building Orientation ON Ottawa

Site Orientation

Provinces: Ontario

Cities: Ottawa

Total Energy Consumption

37210 KWH

90 °

Figure 6.17 - The Building Orientation Panel in VR and its Features

6.5 Conclusion, 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 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 enhancing 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, which can provide more nuanced insights into the dewellings' 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.

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CHAPTER 7

TECHNICAL PAPER IV

Integrating Building Information Modeling (BIM) and Life Cycle Cost Analysis (LCCA) to Evaluate the Economic Benefits of Designing Aging-in-Place Homes at the Conceptual Stage

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Abstract: This paper presents a methodology for the integration of Building Information Modeling (BIM) and Life Cycle Cost Analysis (LCCA) to assess the economic implications of designing aging-in-place (AIP) homes at the conceptual stage. With the global increase in the aging population, there is an increased demand for housing solutions tailored to the needs of elderly individuals. Focusing on the importance of the early phase of design, this study aims to improve the process of making efficient decisions by providing a comprehensive assessment of the life cycle costs associated with AIP homes. The study introduces a semi-automated model for the economic evaluation of AIP homes, enabling the estimation of costs throughout the houses' entire life cycle, from design and construction to operation, maintenance, and eventual renovation or disposal. The said model facilitates the exploration of the long-term economic feasibility of design's related decisions with an emphasis on the importance of considering the life cycle costs early during the design process to optimize the functionality and economic viability. By investing in accessible and universal design features upfront, the initial costs for modifications can lead to long-term savings by reducing the need for extensive retrofits. The model can easily do comparison between different design alternatives in terms of their lifecycle costs, allowing designers to assess the financial impact of using important features in their design such as wider doorways, accessible bathrooms, and elevators. Overall, this study provides valuable insights for designers and homeowners about the economic aspects of designing AIP homes as a support for efficient decision-making during the early stages of the design process.

Keywords: Building Information Modeling (BIM), Life Cycle Cost Analysis (LCCA), Aging in Place (AIP), Computer Integration and Automation.

7.1 Introduction

Presently, Canada is navigating through a profound demographic transition, anticipating that by 2031, almost 25% of its population will fall into the age group of 65 years and older. This demographic shift poses challenges for the healthcare system, as individuals aged 65 and older represent 19% of the population, which already account for almost half (47%) of healthcare spending (NIA, 2022). A national survey conducted by the National Institute on Ageing (NIA) in collaboration with TELUS Health in year 2020 has revealed a noteworthy shift in Canadians' perspectives on aging, post-COVID-19. The survey indicates that 60% of the Canadian population and 70% of older Canadians have reconsidered moving to long-term care or retirement homes. A vast number of Canadians, almost 91%, and nearly 100% of older Canadians express the desire to age in their own homes. AIP is emphasized for its benefits in providing comfort, familiarity, and enhanced well-being for seniors, minimizing the stress associated with major life changes (Koeppel, 2022). Housing plays a pivotal role in AIP, as architectural space is intimately connected to human existence (Wu and Handziuk, 2013). In the absence of an initial design aligned with AIP requirements, existing homes may require substantial renovations, incurring significant costs and potentially affecting resale value if not executed with aesthetic consideration. For example, the need for widening doorways would cost between $20,000 and $40,000, depending on the home's architecture, the cost of installing an elevator ranges from $80,000 to $100,000, bathroom refurbishments would cost around $20,000 to $30,000, while the cost of a kitchen overhauls is between $40,000 and $80,000, underscores the financial impact of retrofitting. It is important to note that these costs are based on the year 2022, which would be much higher in future years. Proactively integrating these considerations during the conceptual design phase can substantially mitigate these costs (Jermyn, 2022). The strategic integration of AIP requirements during the conceptual design stage holds the potential to significantly reduce the costs associated with retrofitting and modifying of a house over the long run. This proactive approach minimizes the need for extensive retrofitting later, as the home is originally structured to accommodate potential mobility challenges and accessibility requirements. Consequently, the costs correlated with retrofitting, which can be substantial, are mitigated. Investing in thoughtful AIP design during the conceptual phase not only enhances the overall functionality of the space but also serves as a prudent economic strategy, offering a cost-effective alternative to reactive modifications that may become necessary in the absence of such foresight. LCCA is a method for evaluating the total cost of owning, operating, and maintaining an asset or system throughout its entire lifespan. Adopting LCCA into the overall cost estimation helps in selecting the best option between projects with similar applications but with varying cost parameters throughout their life cycle (Younis et al., 2018; Guo et al., 2019). LCCA becomes particularly pertinent in the context of AIP design by helping designers implement systematic and comprehensive evaluations of the economic implications associated with various design alternatives. It allows for the prediction and evaluation of the long-term costs linked to different AIP features and modifications, and accordingly identifies the cost-effective design solution(s) that contribute to both the immediate and long-term economic sustainability. LCCA enables the comparison of different design alternatives, allowing designers to make informed choices that optimize both the functionality and economic feasibility of assets. Younis et al., (2018) emphasized the importance of employing LCCA during the initial phases of design. This early application allows for refinement and improvement in the design, ultimately aiming to minimize project's future costs. This study explores the integration of LCCA and Building Information Modeling (BIM) in the context of AIP design at the conceptual design stage by introducing a novel plugin developed and inherited into Autodesk Revit as BIM tool. This integrated approach offers architects and stakeholders a robust analytical tool that would enhance the efficiency of making important decisions early during the design stage. The overarching goal is to create adaptive, sustainable, and economically feasible living environments for the aging population. The developed model via its unique plugin facilitates the execution of comprehensive LCCA for AIP designs and allows for the comparison of various design alternatives in an automatic manner. Incorporating LCCA into BIM for AIP homes (AIPHs), through this innovative algorithm (plugin), allows for holistic assessments of the construction costs and the long-term financial implications for design decisions. This approach considers numerous factors, such as maintenance, adaptability, and energy efficiency, and redefines the design of AIPH by merging the economic sustainability with advanced digital modeling. The integration of LCCA and BIM supports real-time design adjustments, making homes more adaptable as residents age, and therefore, reduces the need for expensive future modifications, which will offer financial ease for residents over the long term. Ultimately, this approach ensures that homes are not only functional and attractive but also financially sustainable over their life. This study extends from the authors' prior research, Rostamiasl and Jrade (2022), which concentrated on the integration of BIM, Universal Design (UD), and AIP design requirements during the conceptual design stage. It is important to note that in this current study, the term "building" is broadly applied, particularly in the cases related to the energy analysis, LCA and LCCA. 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.

7.2 Literature Review

LCCA is a methodology employed to assess the financial aspects of a project throughout its service life and plays a central role in estimating future expenses starting from the design stage onward. It encompasses the total cost of an asset throughout its life cycle, including investment, construction, operation, maintenance, rehabilitation, and the residual value at the end of service life. LCCA offers a way to optimize design alternatives, ensuring financially sound decision-making early in a project’s design stage. This method strikes a balance between initial and future costs (such as operating, maintenance, repair, or replacement costs), ultimately aiming to reduce the overall project cost (Huang et al., 2018). BIM concept serves as a valuable method for managing project’s information, which facilitates the evaluation of the Life Cycle Cost (LCC) while creating project’s models at the various stages of its design. BIM speeds up the process of estimating the costs with fewer mistakes, less errors and simplified decision-making procedures. This streamlined approach contributes to improve the structure’s performance over its lifespan. Moreover, BIM facilitates the utilization of visual tools and specific information about various components and activities, enhancing LCC results for effective use by decision-makers (Zoghi & Kim, 2020). One of the most significant tasks facilitated by BIM is the execution of the Quantity Takeoff (QTO) process

(Valinejadshoubi, et al., 2024), which is one of the most important items needed to conduct the LCCA.

According to Altaf et al., (2020), the integration of LCC and BIM mitigates potential conflicts and errors in the cost-estimating process. Early integration of BIM and LCCA during the project's design has the potential to minimize the operation, repair, and maintenance costs (Altaf, et al., 2020) as the early design stage has a significant impact on the performance of a building during its life span (Kovacic & Zoller, 2015). Designers and investors require an efficient tool to predict the LCC during the initial design phases of facilities. This tool should help in estimating, not only, the construction costs but also the life cycle operating costs, savings and benefits. Emphasizing the life cycle costs over the construction costs would facilitate the process of making more informed decisions (Muller et al., 2019; Kneifel, 2010). Various studies have explored the integration of LCCA with Building Information Modeling (BIM) and have demonstrated promising outcomes. For instance, Kehily et al., (2013) investigated the feasibility of utilizing the data extracted from BIM models to conduct comprehensive LCC calculations, which was achieved by employing a cost-estimating tool in their approach. Jalaei et al., (2015) conducted a study that integrated a Decision Support System (DSS) with Building Information Modeling (BIM). They aimed to assess the feasibility of combining BIM, DSS, and Life Cycle Cost Analysis (LCCA). They developed a DSS to optimize the selection of sustainable materials during the conceptual design phase. Subsequently, design alternatives recommended by the DSS were evaluated within an integrated environment that merged the concepts of BIM and LCCA methods. Their integrated approach allowed for the analysis of the operational costs of the entire building. Santos et al., (2020) assessed the benefits of integrating BIM and LCC by incorporating an external database for LCCA into a BIM environment. The findings indicated that this integration played a significant role in promoting sustainability during the initial stages of projects. Ansah et al., (2020) stated that the integration of BIM and LCC is a practical approach for assessing the advantages of implementing façade systems with improved environmental impacts. Rad et al., (2021) introduced an LCCA framework that was designed for the use during the conceptual design stage of buildings. The framework aimed to enhance resilience and to optimize construction costs by developing a plugin within BIM tools. The plugin facilitates the selection of resilient components at the early stages of design. Viscuso et al., (2022) devised a model's framework that integrates BIM, LCC and Life Cycle Assessment (LCA). Interoperability was achieved through Dynamo, linking BIM models, which were generated in Autodesk Revit, with the LCA tool (One-Click LCA). This integration can be spanned over various stages of a project, with the aim to deliver more sustainable designs that are aligned with LEED protocols. The framework extended its consideration to the economic aspects by employing LCCA to attain optimal cost solutions at every stage of a project. Shin and Cho (2015) developed an Excel spreadsheet-based framework that allowed for the implementation of LCA and LCCA by obtaining necessary information from BIM models to select appropriate design alternatives. Juan and Hsing (2017) developed three design proposals that target different service lives (30 years, 50 years, and 100 years), based on the building's expected life, and used BIM technology to simulate the life cycle cost and design performance, built on scenario analysis of a building's renovation over its life cycle. Le et al., (2020) developed a BIM-integrated RDBMS (Relational Database Management System) for compiling and organizing the required data and information from BIM models to compute buildings' LCC. The system integrated BIM authoring program (tool), a database management system, a spreadsheet system, and a visual programming interface to perform building LCCA. Lee et al., (2020) proposed a method for preparing preliminary cost estimates based on BIM's levels 1 & 2 of details and the actual construction cost data to support the decision-making early in the design phase. Rashed et al., (2019) proposed a method that combines the capabilities of BIM and energy simulations with LCC through a case study that can be used by facility managers or building design teams to select the most cost-effective assembly of building's envelope.

Furthermore, building upon the comprehensive review of the literature, it is evident that the early stages of design play a critical role in minimizing the environmental footprint of buildings. As highlighted by Anton and Díaz (2014) and Yang et al. (2018), this phase offers the greatest flexibility for improvements, whereas the opportunities for changes diminish and the cost of implementing alterations escalates rapidly as projects progress. Therefore, a strategic approach to make efficient design decisions during the initial stages is imperative for achieving the sustainability outcomes

Estimating the cost of embodied carbon emissions in buildings primarily focuses on assessing the carbon outputs across all the stages of a building's life, including material extraction, processing, construction, operation, and end-of-life phases (Dixit et al., 2012). The primary aim is to quantify the carbon emissions in carbon equivalent units to measure the building's total environmental impact. The process comprises the calculation of the embodied carbon, which includes emissions from materials' production to construction, and the operational carbon, which consists of emissions during the building's use. Effective strategies for reducing embodied carbon involve using low-carbon materials, optimizing building design to minimize material usage, and improving the recycling and reusing of materials. Methods for estimating these emissions have evolved, focusing on life cycle assessments (LCAs) that account for all related activities and processes to provide a comprehensive carbon footprint of building projects (Akbarnezhad & Nadoushani, 2014; Akbarnezhad & Xiao, 2017). A study by Schmidt et al., (2020) used a comprehensive approach to estimate the cost of embodied carbon emissions in the construction and maintenance of a building through its life cycle. It involved quantifying the life-cycle of greenhouse gas (GHG) emissions, for both operational and embodied, of a building and then applying economic evaluation techniques to those emissions. This process accounted for initial construction emissions, recurring emissions from materials that need replacement, and operational emissions over the building's lifecycle. The financial implications were estimated by multiplying these emissions by the current market price of carbon and then employing income methods (capitalization and discounted cash flow) to assess their economic value over time. Similarly, Sun & Park, (2020) used BIM to estimate the cost of embodied carbon emissions for tunnel's construction, integrating CO_2 emission factors of materials and equipment into a 3D model in Autodesk Revit. These emissions were converted to costs using the EU emissions trading system prices, enabling an economic analysis of the construction process. Their approach provided a method to assess and manage the environmental and financial impacts of construction projects. Both studies aimed to embed environmental costs into the evaluation of projects to achieve better decision-making in construction.

Robati et al., (2021) employed a Carbon Value Engineering (CO_2VE) framework for estimating the cost of embodied carbon emissions during the design of buildings. The approach integrated the reduction of embodied carbon and capital costs by using a detailed Bill of Quantities to assess initial designs by applying the Pareto Principle to focus on key impact areas and proposing alternative materials and structural systems to reduce both the costs and emissions. The effectiveness of their framework was demonstrated through its application to an 18-storey building in Sydney, where significant savings in carbon emissions and construction costs were attained by optimizing the design and material selection. Langston et al., (2018) developed a method to estimate embodied carbon emissions costs by analyzing new-build versus refurbished projects using hybrid input-output analysis and LCA, to assess the embodied carbon and link it to construction costs, demonstrating that refurbished projects typically exhibit lower embodied carbon and costs per square meter compared to new-builds. The study highlighted the economic and environmental advantages of refurbishment over new construction.

Several studies, such as Llatas, et al., (2020) and Nwodo & Anumba, (2019) have been proposed to assess the environmental impact and cost of construction projects by translating the embodied carbon into a monetary value. Schmidt, et al., (2018) advocated for the implementation of a carbon tax applied to the lifecycle carbon emissions of buildings. This strategy aimed to effectively communicate greenhouse gas (GHG) emissions to stakeholders and to provide incentives for reducing emissions.

Despite of the extensive body of research on the integration of BIM, LCA and LCCA, a notable gap exists in the reviewed literature. To the authors' knowledge, there is a scarcity of studies that specifically concentrate on this integration within the context of AIP design during the conceptual design stage. This gap underscores the need for a dedicated exploration of how BIM and LCCA can be synergized to address the unique requirements of AIP design within the early phases of conceptualization. In addition to quantifying the environmental impact of buildings in terms of carbon emissions, guiding efforts to reduce carbon footprints in the construction industry. The main challenges include the standardization of measurement methods and the improvement of data's quality to ensure consistency and reliability in the estimates. This gap underscores the need for a dedicated exploration of how BIM, LCA and LCCA can be synergized to address the unique requirements of AIP design at the early stages of projects. Considering the requirements of the aging population, LCCA within a BIM environment facilitates the implementation of a comprehensive evaluation of the economic implications associated with the different design alternatives for AIP. This approach not only helps optimizing the construction costs but also enables decision-makers to gauge the long-term financial feasibility and sustainability of AIP homes. The streamlined integration of BIM and LCCA at the conceptual design stage can guide designers and stakeholders toward making informed decisions that prioritize both the well-being of aging residents and the economic efficiency of AIP designs, thus addressing the identified gaps in the existing literature and contributing to the advancement of AIP-focused designing practices.

7.3 Development Methodology

The adopted BIM-LCCA integration method introduces a novel approach through the development of a semi-automated model and the creation of a tailored plug-in within BIM tool (i.e., Autodesk Revit). This innovative process streamlines the assessment of LCCA for AIP homes, specifically by addressing the significant influence of AIP requirements on future modification and alteration costs. By accounting for all types of costs, starting from initial, through operational, repairs and maintenance, major replacements, and ending by salvage/resale, from the early design phase, the integrated framework ensures comprehensive cost considerations.

The framework for integrating BIM and LCCA comprises four distinct and sequential phases. Phase 1, focuses on collecting and storing data related to aging-in-place requirements and the anticipated retrofitting costs for improved accessibility. This data is then stored in a dedicated database, which is subsequently linked to a BIM tool (i.e., Autodesk Revit) through C# coding. Within Autodesk Revit, novel plug-ins are developed to facilitate the retrieval of data needed for LCCA, LCA, AIP prerequisites, and energy analysis. Phase 2, consists of creating detailed 3D models that include materials quantity take-off and integrating it with RSMeans cost data. Concurrently, preparations are made for the model to interface with the energy analysis and LCA tools. Phase 3, focuses on analyzing and simulating energy usage, extracting vital data about the energy consumption and associated costs, and conducting an LCA to calculate the embodied carbon. These results are subsequently integrated into the LCCA module to contribute in the calculation of both the initial and operational costs. Finally, Phase 4, focuses on developing the LCCA plugin, which autonomously receives data from the energy analysis and LCA plugins, RSMeans cost data, and user inputs. The sophisticated design of this plugin facilitates the implementation of scenario and sensitivity analysis and therefore generating detailed reports, charts, and visual representations. These resources are tailored to provide designers and owners with the necessary insights for making optimal decisions throughout the design process. Fig. 7.1 illustrates the framework of the integrated model.

7.3.1 Phase 1- Data Collection and Integration

During this initial phase, a systematic review of the relevant literature and standards related to AIP requirements is conducted. Data pertaining to AIP requirements, with a specific focus on accessibility features and anticipated retrofitting costs for AIP considerations, is meticulously compiled. Subsequently, a relational database is designed by utilizing MySQL and a cloud server to ensure efficient data retrieval and manipulation whenever needed. To establish the connectivity, C# coding and PHP programming are employed to create a bidirectional link between the database and the selected BIM tool (i.e., Autodesk Revit). Several plugins are developed in this phase, which include: 1) an AIP requirements plugin, to facilitate the integration of specific design considerations into the BIM model; 2) an Energy Analysis plugin that extracts detailed energy consumption data with cost implications and seamlessly transferring this information to the LCCA plugin; 3) an LCA plugin that calculates the model's embodied carbon and transfers it to the LCCA plugin along with the associated carbon cost; and 4) an LCCA plugin, which is equipped with functionalities to retrieve and process data from the connected database while accepting input parameters related to design alternatives, cost data, and AIP features.

7.3.2 Phase 2 – Creation of BIM 3D Model

During this phase, a detailed 3D model is created, serving as a cornerstone for the comprehensive evaluation of AIP home designs. This intricate modeling process extends beyond the architectural aspects to encompass specific AIP requirements as identified in Phase – 1, to ensure a holistic representation. The BIM 3D model will be the basis for all the subsequent calculations, analysis and integration of LCCA. Concurrently, a detailed materials' quantity take-off is executed. Quantity can be measured from BIM models by extracting geometric data and semantic properties of each building element called BIM-based Quantity Takeoff (QTO) (Valinejadshoubi, et al., 2024). This phase also incorporates RSMeans cost data to estimate the construction costs, encompassing the costs of materials, equipments and labour, contractor costs, and O&P (Overhead and profit) establishing the initial cost based on the MasterFormat and Uniformat divisions for all the building elements. During this stage, the cloud server engages in a bi-directional interaction with the plug-ins 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 DesignBuilder (energy analysis tool) to calculate the total annual energy consumption and embodied carbon for the 3D model. Initially, zones and spaces are identified, followed by adjustments such as location and orientation. The model is exported to DesignBuilder as a gbXML file, which is done in two ways: i) via the DesignBuilder add-in in Autodesk Revit; or ii) directly from the export option in the File tab of Autodesk Revit. When using the DesignBuilder 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. This interrelation is essential to predict and evaluate the energy consumption and embodied carbon aspects of the design, contributing to a more comprehensive LCCA. The meticulous coordination of these elements in Phase – 2 set the stage for a well-informed and integrated approach to the design of AIP home’s, where design, cost, LCA and energy considerations are intricately interwoven to enhance the overall project outcomes.

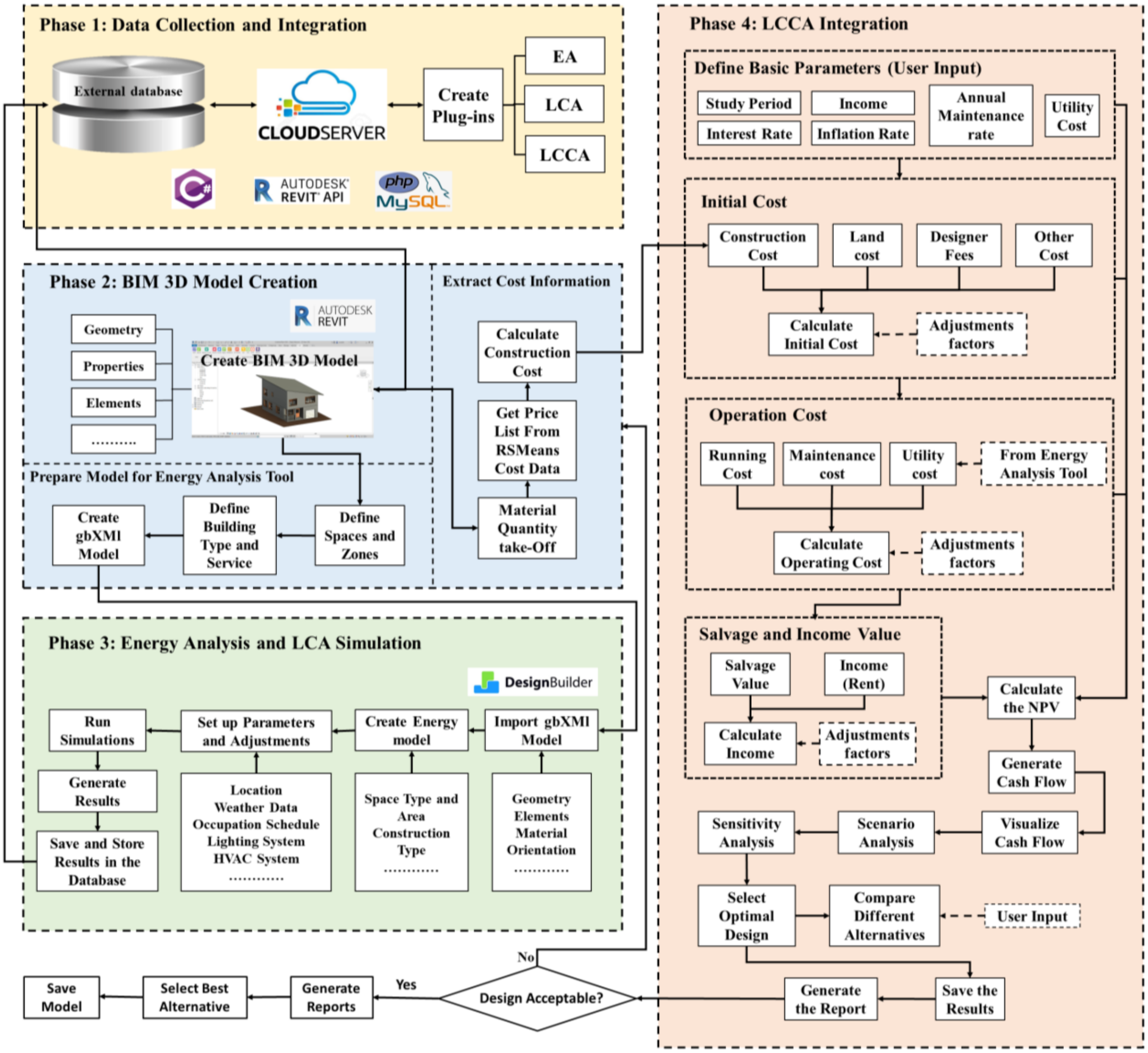


Fig. 7.1 - Framework for the Integration of BIM and LCCA

7.3.3 Phase 3 – Energy Analysis, LCA and Simulation

In this third phase, the focus shifts to energy analysis, LCA and simulation, given the significant impact of energy consumption costs on the overall operational costs and embodied carbon cost on the initial cost. The process starts by extracting detailed information about the building geometry from the 3D BIM model. This extracted information is then exported in the form of a gbXML file to facilitate the integration into the designated tool. This study elected to use DesignBuilder as the energy analysis and LCA tool due to its robust features and capabilities that align with the objectives of this research. With its user-friendly interface and advanced simulation capabilities, DesignBuilder enables accurate modeling and assessment of the energy consumption and embodied carbon of buildings.

Upon exporting the gbXML file to DesignBuilder, 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 DesignBuilder (Elnabawi, 2020). In this investigation, successful exportation of the house geometry is evidenced in Fig. 7.2. For this study, the 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 setpoint temperatures are configured at 18°C and 25°C, respectively. For additional accuracy, walls and roofs were restructured similar to the 3D BIM model’s walls and roofs’ properties. Windows are centrally positioned on each façade, and the properties of these selected windows are detailed in Table 7.1. Furthermore, shading is not considered in the base model and for simplicity, the influence of window’s frames is excluded from consideration in this study.

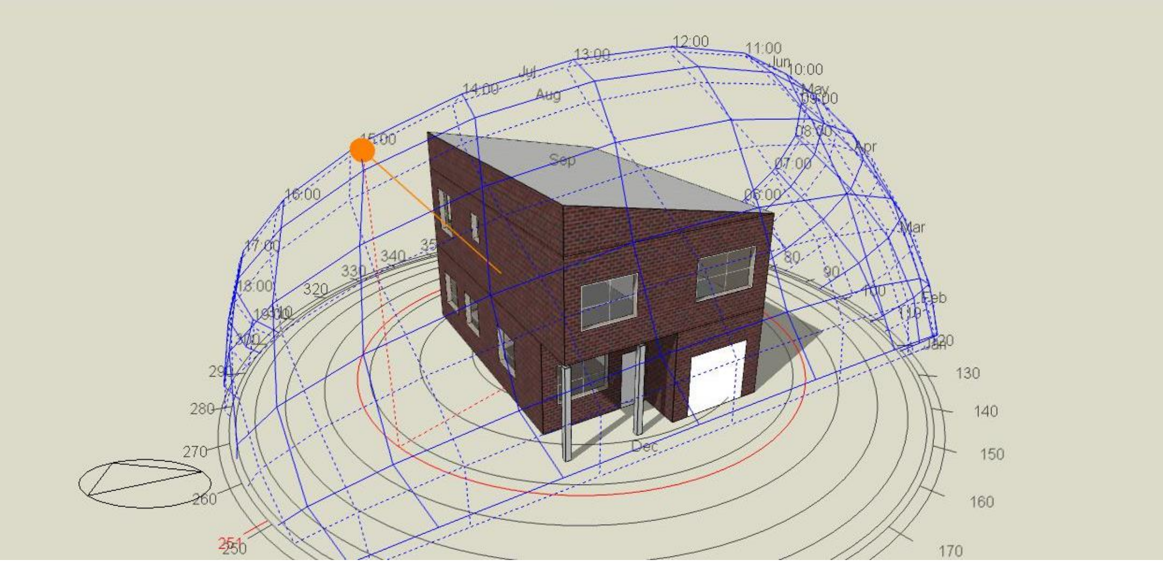


Fig. 7.2 - House's Geometry and Zones in DesignBuilder

Table 7.1- Base Model of Windows' Properties

Number of Panes	**1st Pane Glass type**	**2nd 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

The foremost essential step in ensuring accurate energy simulation is to identify the location and select the appropriate weather file. DesignBuilder provides access to a wide range of weather files based on EnergyPlus, a widely known and used energy simulation engine. 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. Then, all the relevant parameters and adjustments are incorporated to ensure a comprehensive and accurate simulation. Toward the end, the simulation process generates detailed results, encompassing the annual energy consumption of the building and the related costs. These results are stored in a dedicated database and will be used during the LCCA process. This integration ensures that the insights gleaned from the energy analysis, including operational costs, are automatically incorporated into the broader framework of LCCA. In this study, most of the adjustments are made within the DesignBuilder environment to ensure high accuracy.

The next step is to conduct a life cycle assessment (LCA) to generate the embodied carbon. The same model that is used for the energy analysis with all its parameters and adjustments is used to conduct the LCA. The primary focus of this study in relation to the LCA is on the envelope components of residential buildings, specifically the walls, roofs, and windows as these components play a critical role in the overall energy consumption and environmental impact of buildings. The scope of this study involves the production stage of building materials (including raw material extraction and manufacturing), which is defined as cradle to gate. The assessment of the embodied carbon within this scope involves the quantification of the embodied carbon associated with the extracting, processing, and manufacturing processes. By analyzing the embodied carbon, this study seeks to identify the chances for reducing carbon emissions and promoting environmentally sustainable building practices. This analysis generates valuable insights into the environmental impact of residential building’s envelopes and supports the decision-making process aimed at mitigating carbon emissions and promoting the adoption of low-carbon building’s materials and construction practices. The study aims to contribute to the development of more sustainable and eco-friendly houses especially for the aging population. To achieve this goal, an optimization analysis is conducted using different variables as shown in Table 7.2. Figures 7.3 and 7.4 show the selected walls and roofs respectively.

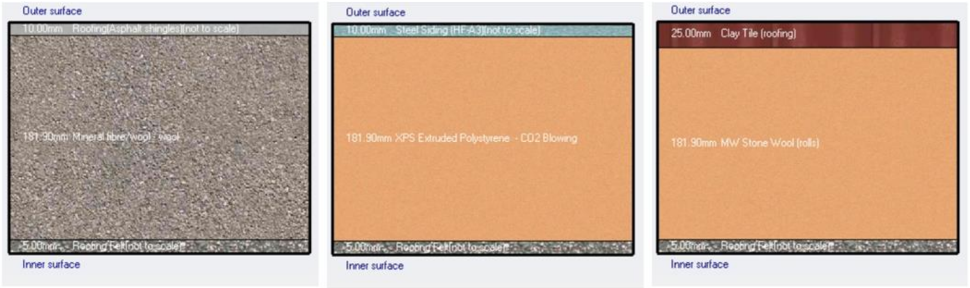
Table 7.2 - List of the Optimization Parameters

Optimization Parameters	**Design Variables**	**Objectives**
	Wall Materials (Three Alternatives) Roof Materials (Three Alternatives) Window to Wall ratio (Ranging from 20% to 80%) Windo Glazing types (single, doubled and tripled) Window frame Materials (Three Alternatives)	Embodied carbon Total Energy Consumption

The scope of this study is limited to optimizing the embodied carbon of a building envelope, therefore, it is assumed that interior items, which include interior walls, finishes, ceiling, equipment, furniture, fixtures, and furnishings will remain the same for each generated alternative. Optimization usually requires running a significant number of simulations. The setting considered for the optimization algorithm in this study is 100 simulations with a population size of 20 as recommended by the DesignBuilder tool. Open-Beagle is used as the optimization engine. Maximum population size is set at 50, Tournament size at 2, Crossover rate of 1, and Individual mutation probability of 0.4. Upon generating the optimization analysis and generating the results, all data is stored in the external database that will be used later in BIM tool to help designers select different variables. By selecting variables the associated embodied carbon value in (kg) is provided to the designer through the LCA plugin. The plug-in is able to recommend the best and worst combination of variables in term of embodied carbon emission.

Wall- Option 1 Wall- Option 2 Wall- Option 3

Fig. 7.3 - Different wall options selected for the optimization analysis



Roof- Option 1 Roof- Option 2 Roof- Option 3

Fig. 7.4 - Different roof options selected for the optimization analysis

The value of the embodied carbon emission is transferred to the LCCA plug-in along with the associated costs to compile the carbon cost, which is added to the initial cost. Carbon pricing is gaining momentum globally. In Canada, the federal government implemented a coordinated nationwide carbon price, beginning at $20 per tonne of carbon dioxide equivalent emissions (tCO_2e) in 2019 and rising to $80 per tonne as of April 1, 2024. All provinces and territories in Canada must maintain a carbon price of at least $80 per tCO_2e in 2024 (Government of Canada, 2024).

7.3.4 Phase 4 – LCCA Integration

In this phase, the developed LCCA plugin will automatically receive data inputs from the AIP, LCA, and energy analysis plugins, ensuring real-time and accurate integration. It will also bring in RSMeans cost data and user inputs, forming a complete dataset for thorough LCCA. The plugin is designed to explore various design alternatives and their economic impacts through scenario analyses. Also, it has the ability to conduct sensitivity analysis to identify the most sensitive parameters and to check how the model responds to changes in the input constraints. The integrated model then produces a detailed LCCA by considering the design, construction, operation, and maintenance costs. These results are visually presented and analyzed to identify the cost-effective design's option, empowering designers and owners to make informed decisions. Ultimately, the plugin produces detailed reports that summarize the results of the LCCA, sensitivity analysis, and scenario analysis by offering accessible insights for the decision-making processes. This phase commences by gathering essential user-defined data, including unit cost, project location, study period, and interest rate. Next, it calculates the initial cost that incorporates the capital investment for land acquisition, designer fees, construction costs, and carbon cost of the house 3D model. The evaluation of the cost data starts by acquiring the land cost, which is provided by the user, while designer fees, construction costs, and carbon cost are retrieved from the database that has been established in Phase – 2, with the model's flexibility, users can change the input values. Operation costs are automatically sourced from the energy analysis plug-in, as outlined in Phase – 3. Additionally, minor maintenance costs, integral to the operational costs, are computed as a percentage of the construction cost. While the default value, as per the literature reviews, is set at 2% of the construction cost, however, users have the flexibility to input alternative values.

Throughout the lifecycle of a building, its various components may experience wear and tear, necessitating periodic repairs and replacements. Factors such as aging deterioration and technological advancements can further drive the need for these interventions. This study places particular emphasis on the future modifications for a home that are required to align with the aging-in-place requirements, which encompass a range of accessibility and safety features tailored to accommodate the needs of elderly occupants. The decision to focus on these modifications stems from the recognition that failing to address aging-in-place considerations during the initial design phase can lead to significant retrofitting costs and potential disruptions to occupants' lives. To provide a comprehensive understanding of these anticipated modifications and their associated costs, relevant literature was thoroughly reviewed (Jermyn, 2022; Trout & Smith, 2023). The findings of reviewing the literature, including cost breakdowns, are presented in Table 7.3, shedding light on the financial implications of incorporating aging-in-place features into residential designs. Certain prices were initially denominated in US dollars and were subsequently converted to Canadian dollars for consistency and ease of comparison. The conversion was conducted using the city indexes from the RSMeans website. To obtain the costs in Canadian dollars, the specified Canadian city index was divided by the national average index to do the cost conversion. Then those values were rounded to facilitate the calculations. It is important to note that these prices are anchored in the collected data from the year 2022. Thus, to accurately project future costs, adjustments must be made to reflect the year of occurrence. This adjustment can be achieved through Equation - 1.

$$F = P(1+i)^t \qquad \text{Equation – 1}$$

Where (F) is the forecasted cost; (P) is the past/current cost; (i) is the inflation rate; and (t) is the number of time periods between the known and forecasted year.

Table 7.3 - Modification and Remodeling Costs, (Jermyn, 2022; Trout & Smith, 2023)

Project's work item(s)	**Price Range to Install***	**Average Cost***
Walk-in Tub or Shower	$5,000 to $20,000	$12,500
Ramp Installation at Entrance	$1,200 to $2,500	$1,850
Widen an Entry Door	$300 to $10,000	$5,150
Stairlift Installation	$4,000 to $27,000	$15,500
Install Entry Handrails	$1000 to $1,600	$1,300
Install an Elevator	$45,000 to $100,000	$72,500
Install Lever Taps on Faucets	$250 to $500	$375
Widen Hallways w/out Structural Changes	$1,100 to $2,000	$1,550
Widen Hallways with Structural Changes	$41,000 to $55,000	$48,000
Replace 10 Windows	$7,500 to $14,500	$11,000
Remodel Bathroom	$20,000 to $38,500	$29,250
Kitchen Countertop Height Adjustment	$20,000 to $27,500	$23,750
Replace the Bathroom floor with a nonslip surface	$9,000 to $37,500	$46,500
Through-the-Floor Lift (only links two floors)	$30,000	$30,000
porch lift	$9,000	$9,000
kitchen Renovation	$40,000 to $80,000	$60,000

*Prices vary by location

Salvage value, as defined, represents the residual worth of a product at the end of its designated lifespan. Every building has a finite lifespan, with its salvage value ultimately diminishing to zero by the end of that period. However, in this study, resale value is considered as well. This decision allows for greater flexibility and provides a more dynamic and realistic perspective into the analysis, reflecting the potential financial returns that can be realized upon the sale of the property though users retain the option to utilize salvage value if preferred.

The Present Worth Method (PWM) is utilized to adjust all costs incurred at various stages throughout the building’s life cycle to their present values. PWM converts all cash flows to an equivalent single sum at time zero. This adjustment will be made by using different equations. For recurrent costs such as annual operating costs, and minor maintenance costs, Equation – 2 is inherited in the developed model. These recurring costs are treated as a uniform series in the cashflows, ensuring a comprehensive assessment of their present value over the building’s life cycle.

$$\mathrm{PW} = \mathrm{A}[\frac{(1+\mathrm{i})^{\mathrm{n}}-1}{\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}}] \qquad \text{Equation – 2}$$

Where (PW) is the equivalent present worth; (A) is the annual magnitude of the uniform series; (i) = MARR (Minimum Attractive Rate of Return) per year; and (t) is the study period.

For non-recurrent costs such as major replacements and salvage value, which occur as a single cost over different time periods, Equation – 3 is incorporated into the developed model.

$$PW = F(1+i)^{-t} \qquad \text{Equation – 3}$$

Where PW is the present worth; (F) is future cost; (i = MARR); and (t) is the number of time periods between the occurrence and initial.

After calculating all the costs including the initial costs, operational costs, maintenance costs, replacement/modifications costs, and salvage/resale value, their summation is presented with all the details in tables and cashflow diagram formats to be used for comparative analysis. The alternative with the highest present worth serves as the favoured recommendation, denoting superior economic viability amidst the array of options. To compute the present worth value through the summation of costs, it is imperative to recognize the polarity of values. Operational costs and similar expenditures are represented as negative values since they entail an outflow of funds over time. Conversely, positive values denote inflows or returns, such as salvage value. By integrating these opposing financial implications, the net present value encapsulates the cumulative impact of costs and returns over the building's lifecycle.

The model performs sensitivity and scenario analyses based on various alternatives. In sensitivity analysis, charts and graphs are automatically generated to assist designers and owners in identifying the most sensitive parameters that need more attention due to their influence of the overall life cycle costs. The model can compare up to four different alternatives simultaneously, which are presented in the form of tables and graphs. The graphical tool offers a high level of clarity and simplicity, allowing designers to easily compare options during the conceptual design stage, which is a novel feature of the developed model.

7.4 Model Testing and Results

To evaluate the effectiveness of the developed model, testing is conducted on a two-story house situated in Ottawa, Ontario, Canada as illustrated in Fig. 7.5. The house is modeled with two different interior designs to compare their functionalities. The first design, Alternative 1, is conventional, lacking the considerations of aging-in-place requirements. The second design, Alternative 2, integrates aging-in-place features, such as wider doors and hallways, the installation of an elevator, and modifications to the bathroom and kitchen for enhanced accessibility. Both alternatives comprise three bedrooms, a living room, a kitchen, three bathrooms, and an attached garage. Utilizing Autodesk Revit© as the chosen BIM tool, a comprehensive 3D design model is constructed for the house, encompassing all the geometric and non-geometric elements, including walls, doors, windows, floors, stairs, and cabinets. The total area for both models is 185.28 square meters, with a floor height of 2.7 meters. After completing the project and conducting the energy analysis and LCA based on the described methodology, the results are stored in the database and are considered by designers to select the best alternatives based on the users' needs. Fig. 7.6 shows the developed LCA plug-in and associated features. In this plugin, designer can select different alternatives for the variables. Upon selecting the result button, the carbon emission value in kilograms is generated. Additionally, designers have the option to select alternatives with either the highest or lowest carbon emission values. The final results are automatically exported to the database so it will be used by LCCA plugin.

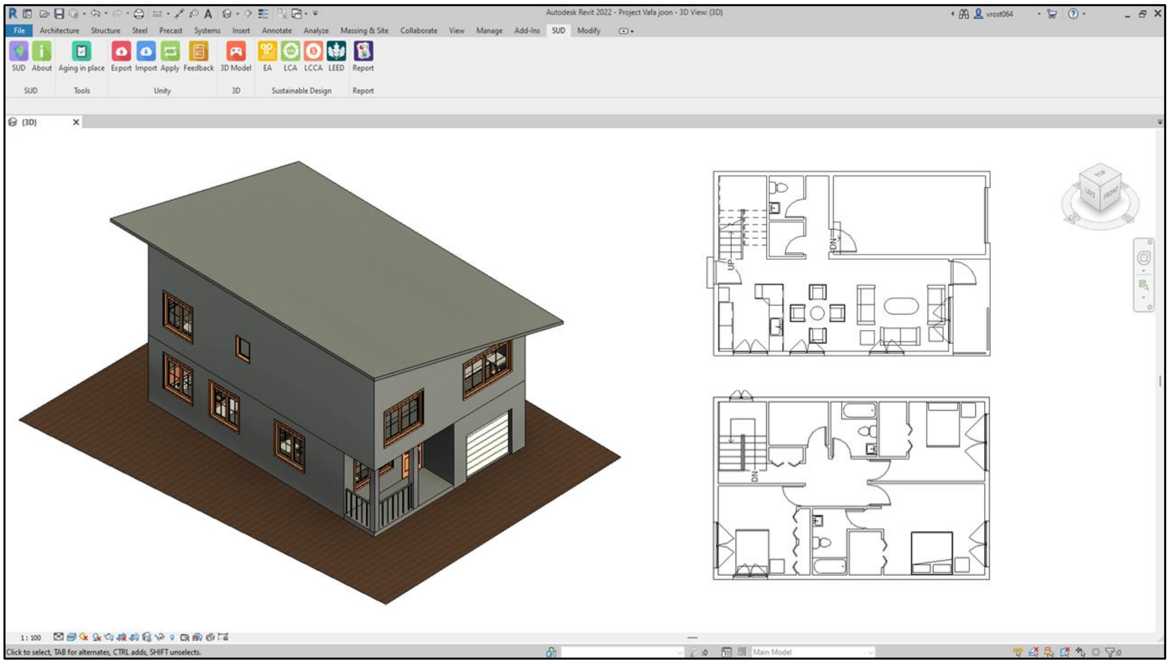
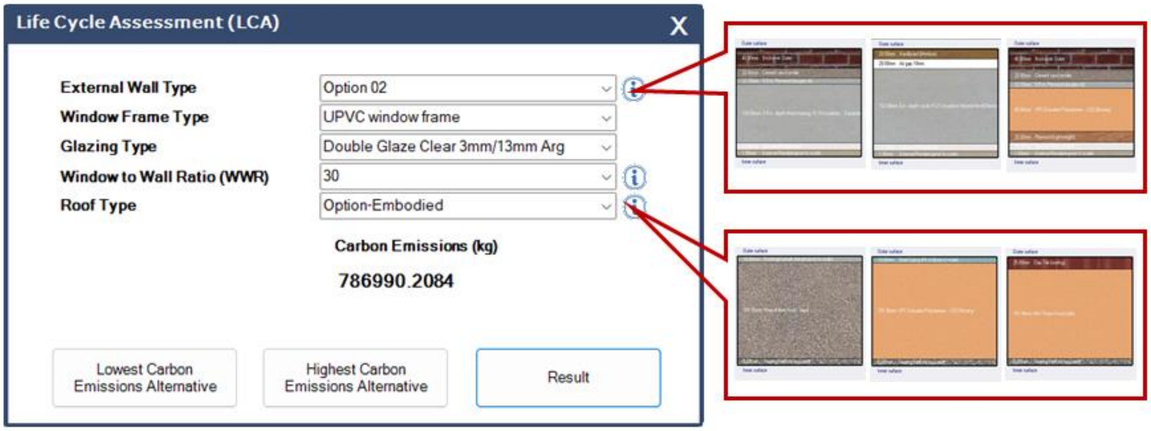


Fig. 7.5 - Proposed 3D BIM Model (Alternative 1, Conventional Design)



Life Cycle Assessment (LCA)

External Wall Type: Option 02

Window Frame Type: UPVC window frame

Glazing Type: Double Glaze Clear 3mm/13mm Arg

Window to Wall Ratio (WWR): 30

Roof Type: Option-Embodied

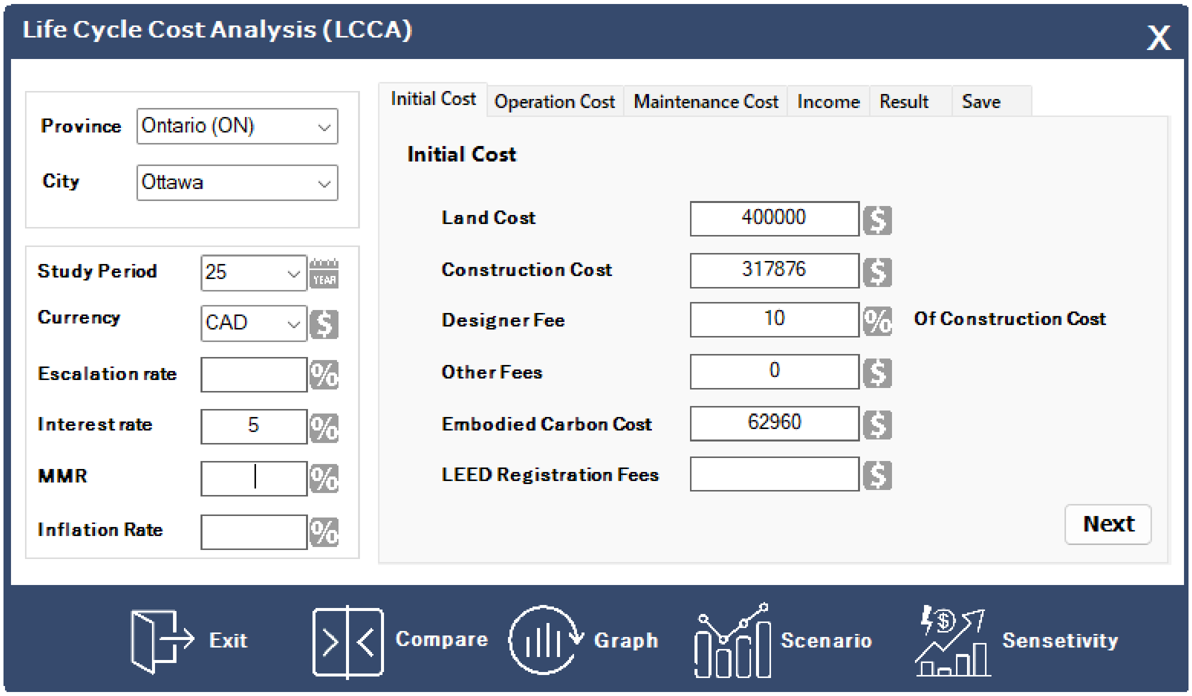
Carbon Emissions (kg)

786990.2084

Fig. 7.6 - Life Cycle Assessment Plug-in

Upon activating the Life Cycle Cost Analysis (LCCA) plug-in, a user-friendly interface is presented, guiding the user to input essential data, including the study period and the prevailing rate (MARR) as a percentage. The default values of the study period and the rate are assumed to be 25 years and 5%, respectively, in this study, however, users can modify these values if they need. The plug-in ensures meticulous data entry to guarantee the accuracy of the LCCA results. In cases where fields are left empty, the plug-in prompts users to fill in all the required information, thereby minimizing the risk of inaccuracies in the analysis.

In developing the integrated model, many tables were established to house crucial information, including detailed quantity take-off, user-entered data, energy consumption metrics, embodied carbon and associated cost and more. Microsoft Excel and MySQL were utilized as external databases to effectively store and manage this data. For the initial analysis phase, focusing on the initial cost, users are guided to enter specific information such as land cost, designer fees, and additional charges. The Quantity Take-Off (QTO) for each building element is exported to an external database, which is used to estimate the construction costs by using RSMeans cost database to retrieve the unit cost of materials and necessary labor rates for all elements. This construction cost is then automatically fetched from the database and integrated into the LCCA plug-in. The user retains the freedom to adjust the data obtained from the database as needed. Additionally, designer fees can be retrieved from the same database or be inputted by the user as illustrated in Fig. 7.7. In this study, the land cost was calculated using various local realtor applications to obtain the average land cost at the proposed project's location, which remains consistent for both alternatives. Based on RSMeans cost data, the construction cost, including contractor fees, was found to be $317,876 for Alternative 1 and $368,410 for Alternative 2. The initial cost of Alternative 2 showed an increase in the construction cost because of the inclusion of aging-in-place requirements. An entrance ramp, wider doors, an elevator, a walk-in bathtub and an upgraded kitchen were considered for Alternative 2 as being parts of the AIP requirements. Additionally, the designer fee is assumed to be 10% of the construction cost. In addition, the carbon cost is calculated and incorporated into the plugin automatically.



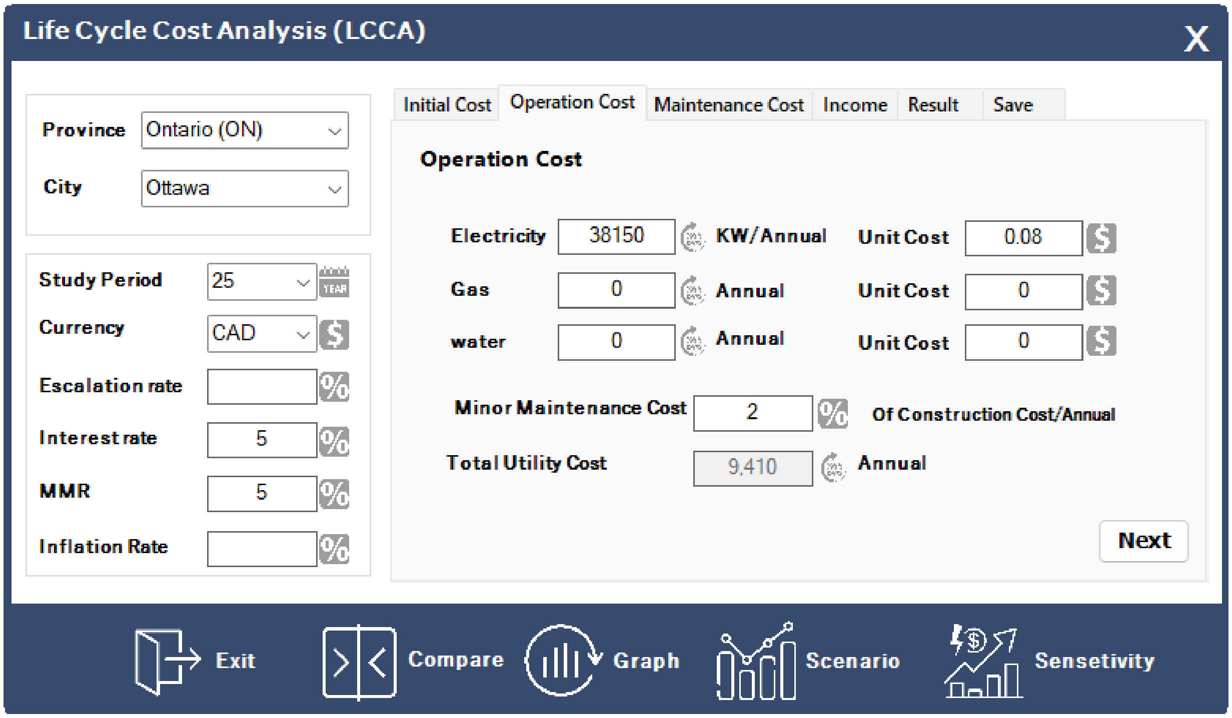
Province: Ontario (ON)
City: Ottawa
Study Period: 25
Currency: CAD
Escalation rate: %
Interest rate: 5 %
MMR: %
Inflation Rate: %

Initial Cost

Land Cost: 400000 $
Construction Cost: 317876 $
Designer Fee: 10 % Of Construction Cost
Other Fees: 0 $
Embodied Carbon Cost: 62960 $
LEED Registration Fees: $

Fig. 7.7- Initial Cost and other entries

Moving to the next step, which is dedicated to calculating the operating costs, data is sourced from the energy analysis plug-in, with DesignBuilder serving as the chosen energy analysis tool in this study. The 3D BIM models are exported and transferred to DesignBuilder as gbXML file formats for simulating their energy consumption. Subsequently, the outcomes contain the annual energy consumption, which are stored in the external database and seamlessly retrieved by the LCCA plug-in. Users are afforded flexibility in the parameters' input, including energy unit cost and annual minor maintenance or repair costs as percentages as shown in Fig. 7.8. The annual cost for minor maintenance and/or repairs can be estimated based on historical data or expert judgment with a default value of 2% of the construction cost in this study. The plug-in efficiently computes the annual utility cost and stores it in the database to be used in the life cycle cost calculation of the project. In this study, Alternative 1 exhibits an annual total energy consumption of 38,150 kW, while Alternative 2, with the addition of an elevator, shows a higher consumption of 45,300 kW annually. Continuing to the subsequent step, which delves into the major replacement costs. Over the projects' life cycle, components may necessitate their replacement or significant repairs due to aging and deterioration. Particularly, if Aging-in-Place (AIP) requirements were not integrated during the conceptual design phase, subsequent modifications and retrofitting become imperative to align with AIP concepts. Users are empowered to select the elements to be replaced from a drop-down menu or manually input the desired elements, their associated costs and the required year for replacement. Associated costs are sourced from RSMeans cost database. The plug-in diligently computes all the replacement costs and their corresponding present values. Routine maintenance costs such as painting and shingle replacement were not considered in both alternatives, since they are assumed to be the same. For Alternative 1, which lacks the aging-in-place requirements, future modifications are accounted for as seen in Fig. 7.9.

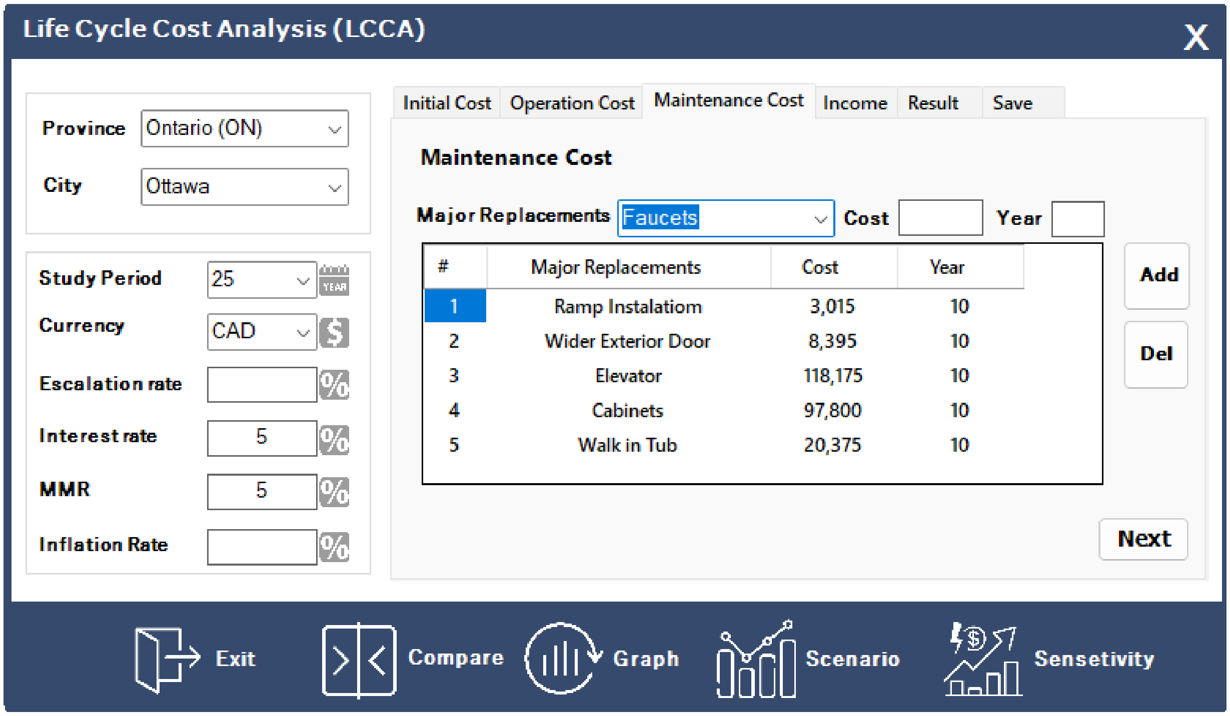


Operation Cost

Province: Ontario (ON)
City: Ottawa
Study Period: 25
Currency: CAD
Escalation rate:
Interest rate: 5 %
MMR: 5 %
Inflation Rate:

Electricity: 38150 KW/Annual — Unit Cost: 0.08
Gas: 0 Annual — Unit Cost: 0
water: 0 Annual — Unit Cost: 0
Minor Maintenance Cost: 2 % Of Construction Cost/Annual
Total Utility Cost: 9,410 Annual

Fig. 7.8 - Operational Cost data entry



Maintenance Cost

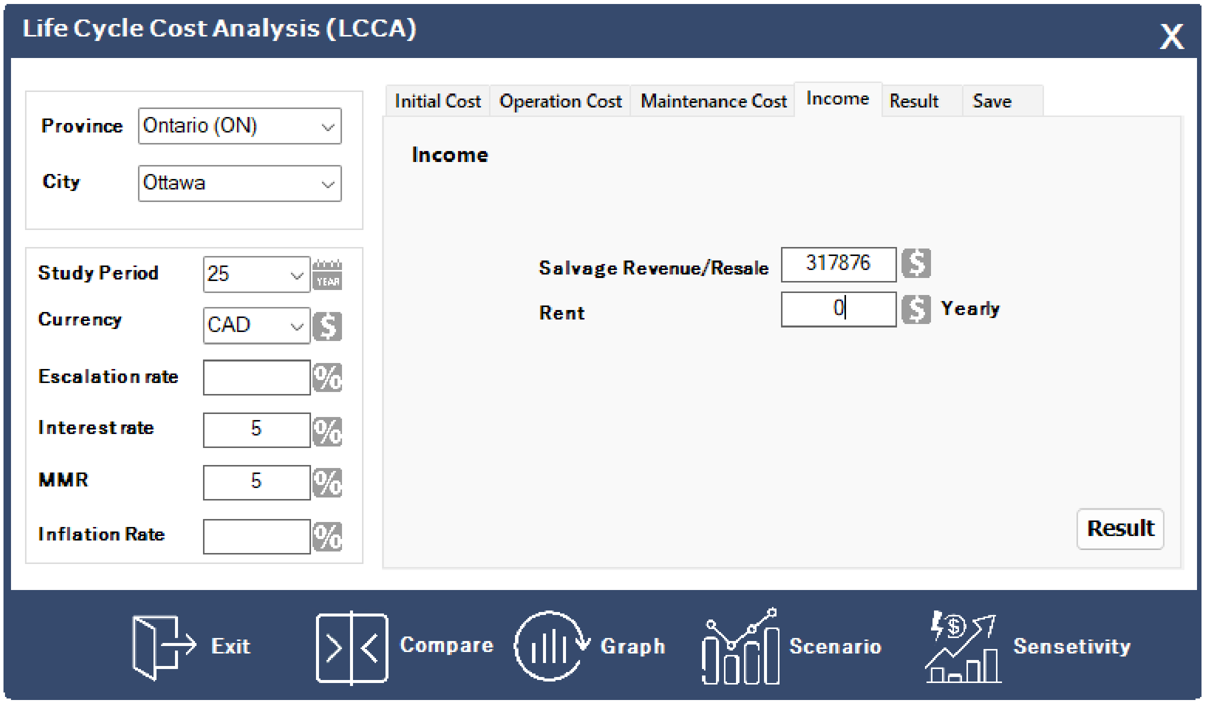
Province: Ontario (ON)
City: Ottawa
Study Period: 25
Currency: CAD
Escalation rate:
Interest rate: 5 %
MMR: 5 %
Inflation Rate:

Major Replacements: Faucets — Cost: — Year:

#	Major Replacements	Cost	Year
1	Ramp Instalation	3,015	10
2	Wider Exterior Door	8,395	10
3	Elevator	118,175	10
4	Cabinets	97,800	10
5	Walk in Tub	20,375	10

Fig. 7.9 - Major Replacement Cost data entry

The subsequent step is dedicated to entering the revenue, encompassing details such as potential rent value, salvage value, or resale value as pictured in Fig. 7.10. The resale value could potentially be equal to or greater than the construction cost, depending on various factors such as market conditions, property appreciation, and demand for the property. Unlike salvage value, which typically represents the value of the asset after its useful life, resale value refers to the amount that could be obtained from selling the asset at any time during its life cycle. Although in some cases, particularly in areas with rising property values or high demand, the resale value of a property could indeed exceed its construction cost, in this study the resale value is assumed to not exceed the construction cost. The inputs in this step contribute to the life cycle cost based on the present worth. Upon selecting the Result button, the plug-in promptly computes all the incurred costs, including the initial cost, repair and maintenance cost, operational cost, and salvage/resale value. The summation is presented in detailed tables, encapsulating the project's life cycle cost. The plug-in generates a comprehensive cashflow in a tabulated format delineating all the parameters, their respective present worths, and the net present value (NPV) as seen in Fig. 7.11. For additional clarity, users can visualize the cashflow diagram, enhancing their understanding of the financial implications as shown in Fig. 7.12. Figures 7.13 and 7.14 showcase the plug-ins automatic execution of scenario analysis and sensitivity analysis. Notably, the plug-in is equipped to save and compare up to four alternatives, facilitating a streamlined and efficient decision-making process as illustrated in Fig. 7.15. The plug-in facilitates the preservation, printing, and sharing of all the generated results. This feature facilitates the documentation, communication, collaboration, transparency, and archiving of findings, enhancing the decision-making and knowledge sharing among stakeholders.

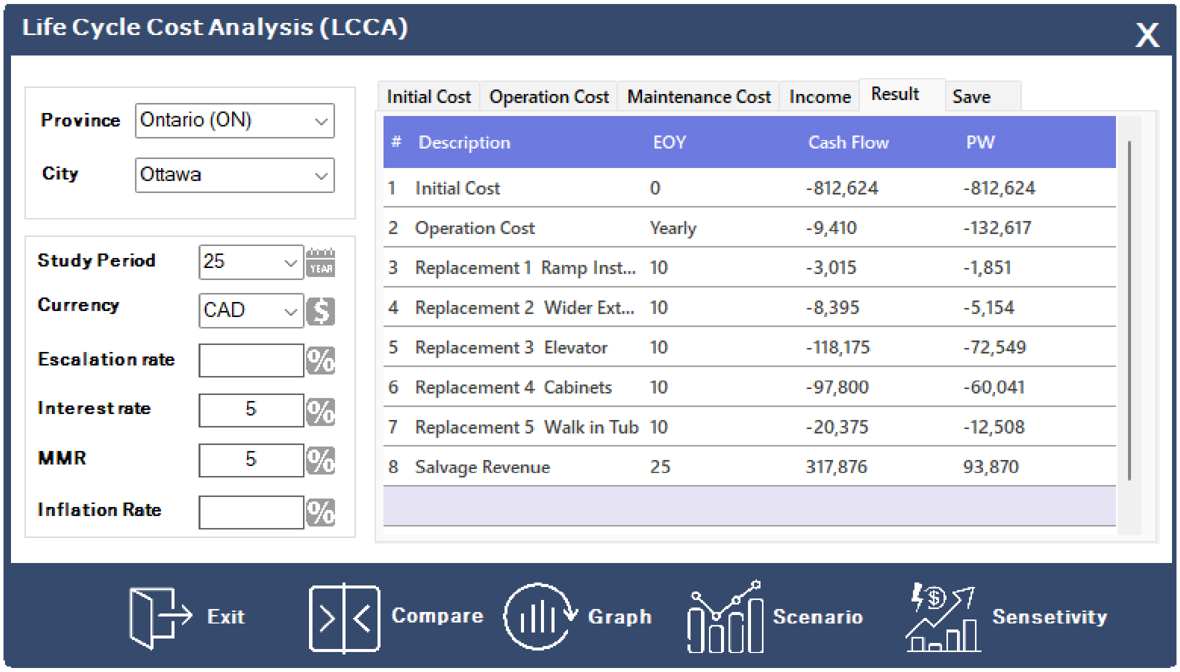


Province: Ontario (ON)
City: Ottawa
Study Period: 25
Currency: CAD
Escalation rate:
Interest rate: 5 %
MMR: 5 %
Inflation Rate:

Income

Salvage Revenue/Resale: 317876 $
Rent: 0 $ Yearly

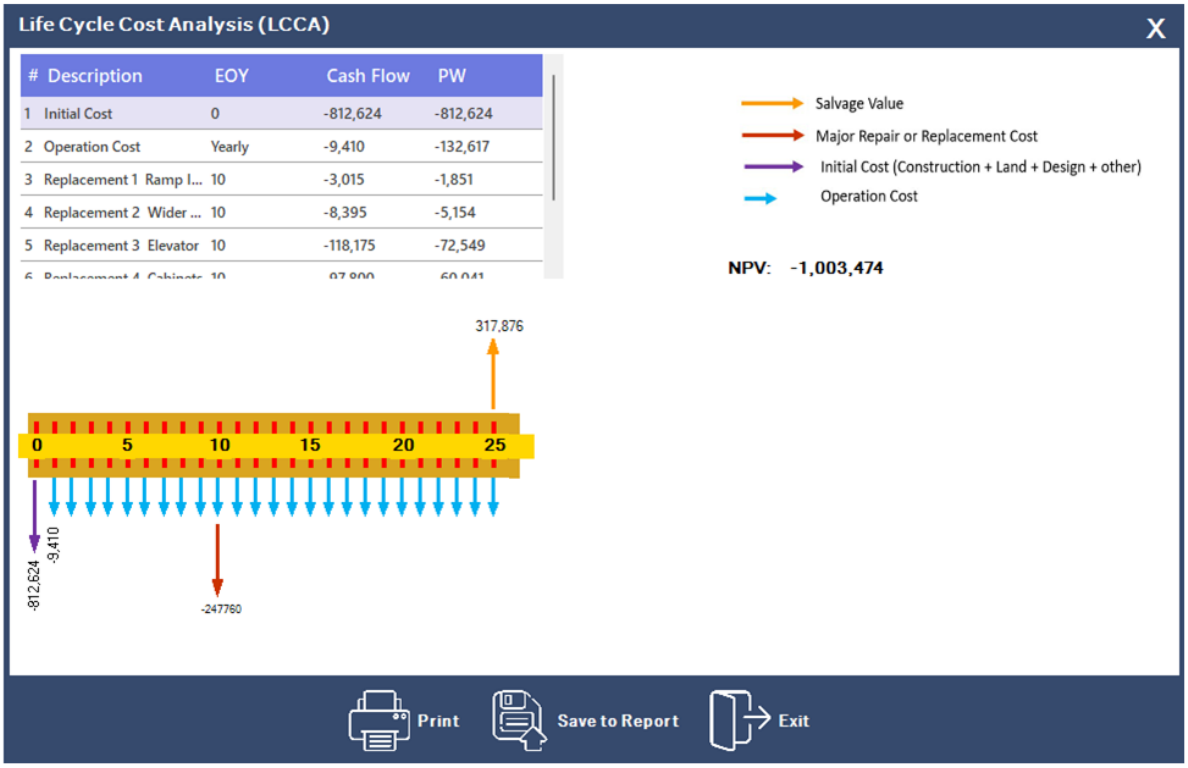
Fig. 7.10 - Income Revenue data entry



Province: Ontario (ON)
City: Ottawa
Study Period: 25
Currency: CAD
Escalation rate:
Interest rate: 5 %
MMR: 5 %
Inflation Rate:

#	Description	EOY	Cash Flow	PW
1	Initial Cost	0	-812,624	-812,624
2	Operation Cost	Yearly	-9,410	-132,617
3	Replacement 1 Ramp Inst...	10	-3,015	-1,851
4	Replacement 2 Wider Ext...	10	-8,395	-5,154
5	Replacement 3 Elevator	10	-118,175	-72,549
6	Replacement 4 Cabinets	10	-97,800	-60,041
7	Replacement 5 Walk in Tub	10	-20,375	-12,508
8	Salvage Revenue	25	317,876	93,870

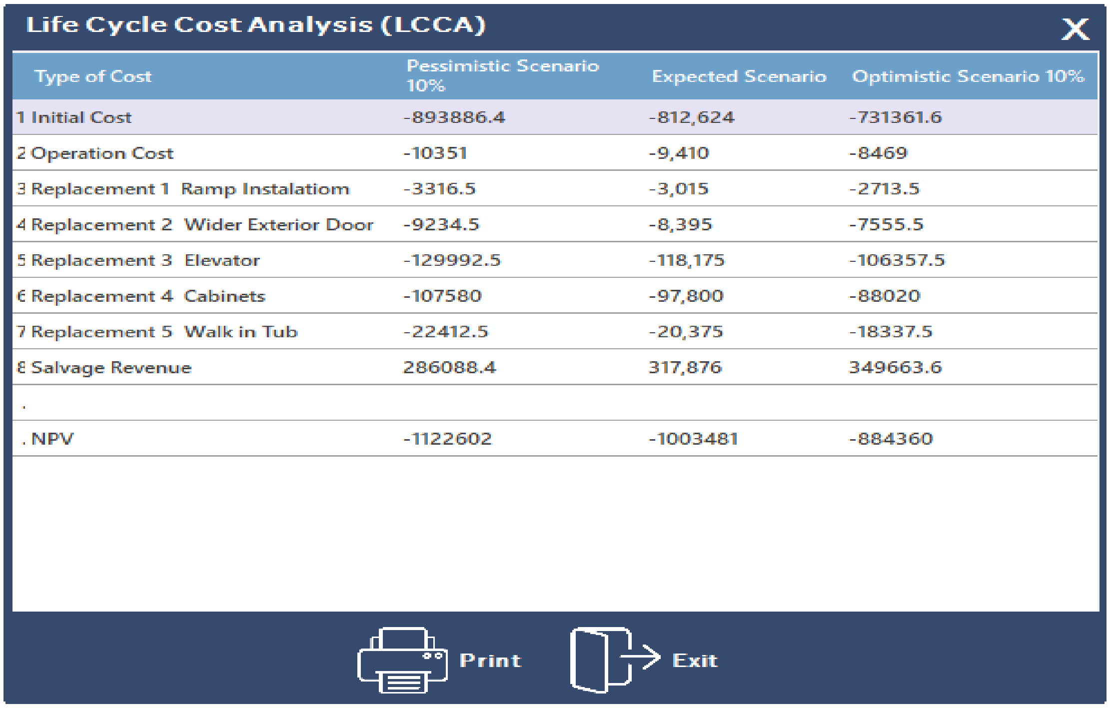
Fig. 7.11- LCCA Results



#	Description	EOY	Cash Flow	PW
1	Initial Cost	0	-812,624	-812,624
2	Operation Cost	Yearly	-9,410	-132,617
3	Replacement 1 Ramp I...	10	-3,015	-1,851
4	Replacement 2 Wider ...	10	-8,395	-5,154
5	Replacement 3 Elevator	10	-118,175	-72,549

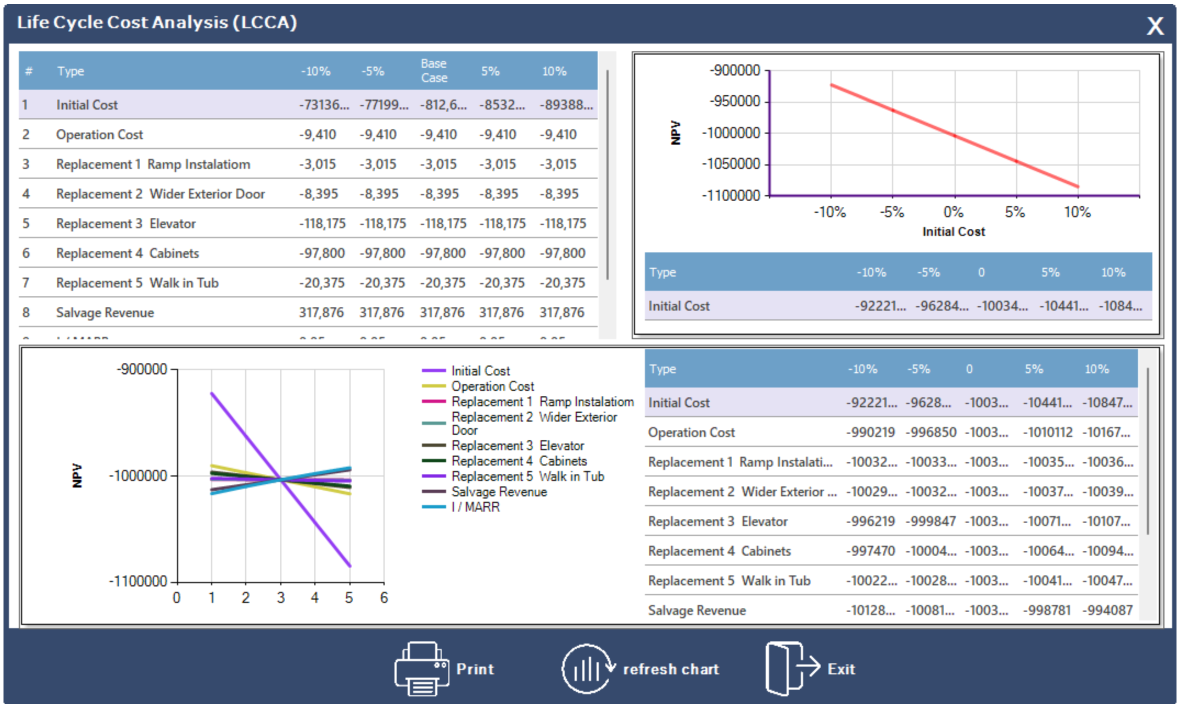
NPV: -1,003,474

Fig. 7.12 - LCCA results (Cashflow and NPV)



Type of Cost	Pessimistic Scenario 10%	Expected Scenario	Optimistic Scenario 10%
1 Initial Cost	-893886.4	-812,624	-731361.6
2 Operation Cost	-10351	-9,410	-8469
3 Replacement 1 Ramp Instalatiom	-3316.5	-3,015	-2713.5
4 Replacement 2 Wider Exterior Door	-9234.5	-8,395	-7555.5
5 Replacement 3 Elevator	-129992.5	-118,175	-106357.5
6 Replacement 4 Cabinets	-107580	-97,800	-88020
7 Replacement 5 Walk in Tub	-22412.5	-20,375	-18337.5
8 Salvage Revenue	286088.4	317,876	349663.6
.			
. NPV	-1122602	-1003481	-884360

Fig. 7.13 - Scenario Analysis Example

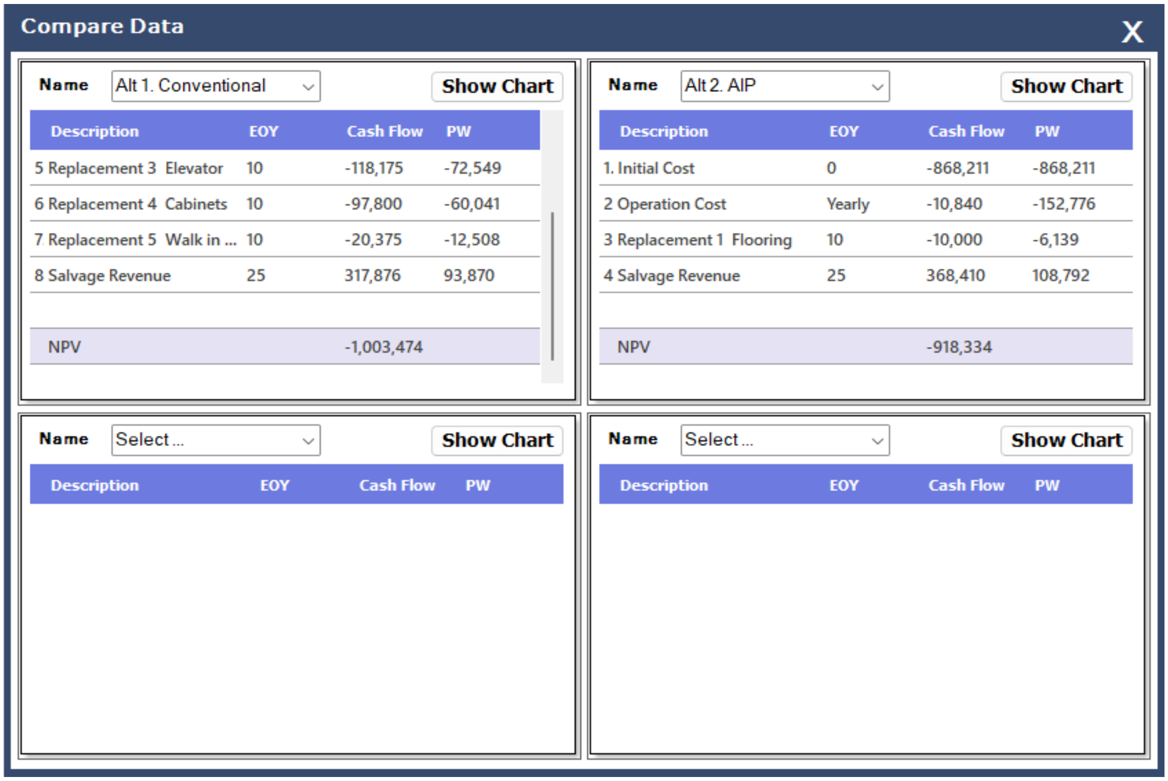


#	Type	-10%	-5%	Base Case	5%	10%
1	Initial Cost	-73136...	-77199...	-812,6...	-8532...	-89388...
2	Operation Cost	-9,410	-9,410	-9,410	-9,410	-9,410
3	Replacement 1 Ramp Instalatiom	-3,015	-3,015	-3,015	-3,015	-3,015
4	Replacement 2 Wider Exterior Door	-8,395	-8,395	-8,395	-8,395	-8,395
5	Replacement 3 Elevator	-118,175	-118,175	-118,175	-118,175	-118,175
6	Replacement 4 Cabinets	-97,800	-97,800	-97,800	-97,800	-97,800
7	Replacement 5 Walk in Tub	-20,375	-20,375	-20,375	-20,375	-20,375
8	Salvage Revenue	317,876	317,876	317,876	317,876	317,876

Type	-10%	-5%	0	5%	10%
Initial Cost	-92221...	-96284...	-10034...	-10441...	-1084...

Type	-10%	-5%	0	5%	10%
Initial Cost	-92221...	-9628...	-1003...	-10441...	-10847...
Operation Cost	-990219	-996850	-1003...	-1010112	-10167...
Replacement 1 Ramp Instalati...	-10032...	-10033...	-1003...	-10035...	-10036...
Replacement 2 Wider Exterior ...	-10029...	-10032...	-1003...	-10037...	-10039...
Replacement 3 Elevator	-996219	-999847	-1003...	-10071...	-10107...
Replacement 4 Cabinets	-997470	-10004...	-1003...	-10064...	-10094...
Replacement 5 Walk in Tub	-10022...	-10028...	-1003...	-10041...	-10047...
Salvage Revenue	-10128...	-10081...	-1003...	-998781	-994087

Fig. 7.14 - Complete Sensitivity Analysis



Name Alt 1. Conventional

Description	EOY	Cash Flow	PW
5 Replacement 3 Elevator	10	-118,175	-72,549
6 Replacement 4 Cabinets	10	-97,800	-60,041
7 Replacement 5 Walk in ...	10	-20,375	-12,508
8 Salvage Revenue	25	317,876	93,870
NPV		-1,003,474	

Name Alt 2. AIP

Description	EOY	Cash Flow	PW
1. Initial Cost	0	-868,211	-868,211
2 Operation Cost	Yearly	-10,840	-152,776
3 Replacement 1 Flooring	10	-10,000	-6,139
4 Salvage Revenue	25	368,410	108,792
NPV		-918,334	

Name Select ...

Description	EOY	Cash Flow	PW

Name Select ...

Description	EOY	Cash Flow	PW

Fig. 7.15 - Comparison of Different Alternatives

7.5 Discussion, Limitations and Future Works

The integration of BIM, LCA and LCCA presents a promising approach to facilitate the economic and environmental impact evaluation associated with AIP homes. In response to the growing global aging population, there is an increasing demand for housing solutions that cater to the needs of elderly residents while promoting independence and comfort. This study focuses on the early stage of design, due to its importance, with the aim to provide architects and stakeholders with valuable insights into the economic implications of designing AIP homes, and introduces a novel approach to integrate BIM and LCCA concepts for evaluating the life cycle costs associated with AIP homes. Through the development of a semi-automated integrated model and the creation of tailored plugins within Autodesk Revit, the methodology facilitates data integration and analysis. The integration process involves the incorporation of detailed BIM information, including design specifications and material quantifications, with cost data obtained from external databases based on RSMeans cost data. By considering all the costs associated with design, construction, operation, maintenance, and eventual disposal or renovation, the developed model provides decision-support information that optimizes both functionality and economic sustainability. Furthermore, the model allows doing scenario and sensitivity analyses by facilitating the exploration of various design alternatives and their economic implications. The developed model was tested by using an actual case project that consist of a two-story house to be built in Ottawa, Ontario, Canada, where the results yield valuable insights. Alternative 1 represents a conventional design approach while Alternative 2 incorporates AIP requirements. After evaluating the model's output and conducting a comparative analysis, it is evident that Alternative 1 presents a lower initial cost when compared to Alternative 2. The inclusion of aging-in-place features in Alternative 2 necessitates additional upfront investments to accommodate modifications such as wider doors, elevator installation, and bathroom and kitchen enhancements. Consequently, Alternative 2 demonstrates higher energy consumption and operational costs attributable to the installation and operation of an elevator. Although Alternative 1 may boast lower operational costs initially, Alternative 2 provides valuable insights into long-term operational considerations, particularly concerning aging-in-place accommodations. This comparison underscores the significance of proactive design interventions in optimizing both initial and long-term costs while addressing the evolving needs of occupants.

In terms of maintenance and replacement costs, it becomes evident that while both alternatives incur maintenance and replacement costs over their respective life cycles, the nature and magnitude of these expenses vary significantly. Alternative 1 without explicit consideration of aging-in-place requirements during the conceptual stage, may initially appear to have lower maintenance costs. However, as the building ages and the need for accessibility modifications arises, Alternative 1 necessitates extensive retrofitting and alterations. These post-construction modifications can incur substantially higher costs compared to integrating aging-in-place features from the outset. Conversely, Alternative 2, which integrates aging-in-place requirements into the initial design phase, anticipates and accommodates future accessibility needs proactively and minimizes the need for post-construction modifications and retrofitting. Consequently, while Alternative 2 may entail higher upfront investments, it ultimately offers lower long-term maintenance and replacement costs due to its inherent adaptability and readiness for aging-in-place living. In summary, while Alternative 1 may appear cost-effective in the short term, its susceptibility to higher modification and alteration expenses over time renders it less economically viable compared to Alternative 2, which prioritizes proactive integration of aging-in-place features to mitigate future maintenance expenditures. Both alternatives may exhibit differences in salvage or resale values, influenced by factors such as market conditions, depreciation rates, and the degree of adaptation to aging-in-place principles. However, future resale values for Alternative 2, with its integrated aging-in-place features, could be influenced by the growing demand for accessible and adaptable housing options. Overall, while Alternative 1 may present lower upfront costs, Alternative 2 offers enhanced functionality and adaptability for aging residents, potentially mitigating long-term costs associated with retrofitting and accessibility modifications. After comparing the NPV of both Alternatives as depicted in Fig. 15, it can be concluded that Alternative 2 is more favorable. Its higher NPV suggests the benefit of integrating AIP requirements early in the design process. The LCCA provides valuable insights into the trade-offs between initial investments and long-term operational and maintenance considerations, empowering stakeholders to make informed decisions based on their priorities and objectives.

While this study provides a solid foundation for integrating BIM, LCA and LCCA in the design process of AIP homes, there are several avenues for future research and enhancement. First, incorporating stochastic modeling techniques to consider inflation and residual values of assets could enhance the accuracy of cost estimations. Additionally, developing a simple system dynamics model of aging population could provide valuable insights into the demand for AIP homes in the coming years. Moreover, while this study utilized the present worth method and uniform series of cash flows, future research could explore alternative LCCA methods such as the annual worth method or future worth method. Additionally, incorporating different forms of cash flows such as gradient series or geometric series warrants investigation in subsequent studies.

While this study presents a comprehensive framework for integrating BIM and LCCA in the design of AIP homes, there are several limitations to acknowledge. First, the accuracy of the LCCA heavily relies on the quality of input data. Any inaccuracies or uncertainties in the data, such as construction costs, evaluation of energy consumption, and maintenance expenses, could impact the reliability of the results. Moreover, the developed integrated model and associated plugins are based on certain assumptions and simplifications, which may not have fully captured the complexity of real-world scenarios. Additionally, the scope of this study is limited to the economic evaluation of AIP homes, overlooking other important factors such as social, environmental, and health-related considerations. Future research will aim to incorporate a more holistic approach that considers a broader range of criteria to support the design decision-making related to AIP homes.

7.6 Conclusion

In conclusion, this paper presented a comprehensive methodology for integrating BIM and LCCA to support the design of AIP homes. The four-phases approach, starts with data collection and integration, progressing through 3D modeling, quantity take-off, energy analysis, and LCA simulation, and resulting in the automated LCCA, establishes a robust framework for designers and stakeholders. The integration of real-time data from aging-in-place requirements, LCA and energy analysis plugins ensures accuracy and immediacy in design-related decisions. The LCCA plugin, designed for scenario and sensitivity analyses, contributes to identifying economically viable design alternatives. The integrated model produces a detailed LCCA by considering various cost components and design factors. The ability to compare different options would aid designers and owners in selecting the most optimal design alternative. By addressing the unique requirements of AIP design in the conceptual stage, this methodology not only enhances the functionality and adaptability of homes but also provides a cost-effective and sustainable approach to accommodate the evolving needs of an aging population. The development of a dedicated plugin for Autodesk Revit represents a technological advancement, showcasing the potential for innovative solutions in the design of housing. This research contributes to the growing body of knowledge on the integration of BIM and LCCA, particularly within the context of AIP design, filling a notable gap in the existing literature. Moving forward, this methodology holds promise for advancing the field of design and fostering the creation of adaptive, sustainable, and economically feasible living environments for an aging society.

7.7 References

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CHAPTER 8 SUMMARY AND CONCLUDING REMARKS

8.1 Summary and Research Contribution

This thesis presents a comprehensive investigation into the integration of Universal Design (UD), Building Information Modeling (BIM), Virtual Reality (VR), Energy Analysis (EA), Life Cycle Assessment (LCA), and Life Cycle Cost Analysis (LCCA) to optimize house's design for aging-in-place. The research explores the development of an automated computer model that facilitates the incorporation of UD standards and processes at the conceptual stage, aiming to streamline the design process and enhance accessibility and sustainability. Through an extensive literature review and the presentation of Technical Papers, the thesis provides insights into the potential of integrating BIM with UD and VR technologies to support designers and owners in selecting optimal design alternatives based on predefined criteria and their needs. Additionally, the study investigates the economic and environmental sustainability aspects of design choices through EA, LCA and LCCA, offering recommendations for enhancing the efficiency and effectiveness of residential design practices. In this thesis, a methodology was developed the integrated model through six main modules as the main components of the described model.

The integration requirements are based on the literature review described in chapters 2. It involves data collection from different sources such as standards and guidelines, sustainability specifications, bills of quantity, environmental impact specifications, LCA and LCCA of house projects. To develop the integrated model, major steps is taken as follows:

1. Design and implement external databases to store universal design and accessible design standards and guidelines, aging in place requirements and newly created building components

linked with the BIM tool. The database provides designers with a wide variety of universal design and accessible design options.

2. Link BIM tool to these databases to facilitate the implementation of universal design based on the owner's/occupants needs.

3. Customize BIM tool to automate the exporting and importing process with the associated information and parameters of the 3D model to the external database and retrieving newly created components to the design.

4. Connect BIM tool to a virtual environment to allow users to interact and communicate with the design in a gaming environment and receive their feedbacks regarding their needs and requirements.

5. Connect BIM tool to an energy analysis tool to automate the process of analyzing energy at the conceptual design stage.

6. Calculate the environmental impacts and embodied carbon of house by linking the BIM model to LCA tool.

7. Calculate the building life cycle cost and generate cashflows for different alternatives to help designers and owners evaluate the cost and benefits of adopting sustainable universal design and aging in place requirements.

8.2 Research Contribution

The contributions of this research reside in the following:

1. Developing a unique approach to designing sustainable universal buildings by automatically incorporating universal design standards and accessible design standards at

the conceptual design stage. This automated model helps designers to have full access to the various standards and guidelines related to universal and accessible designs along with the National Building Code of Canada (NBCC), as well as to access multiple guidelines and standards from other countries in an attempt to increase the efficiency and variety of the data needed to design universal buildings. Furthermore, integrating other modules such as LCA, energy analysis and LCCA, to allow users identify the benefit of adopting universally designed buildings by comparing and evaluating different alternatives.

2. Designing external databases for universal design standards, accessible design standards, and aging in place requirements and components. Related data are saved as design family files (RFA) or Revit files (RVT), which can be identified by BIM tool and as descriptive data to assist designers in incorporating the standards into the design process. Thus, the external database contains a family database containing newly created families and a knowledge database that includes descriptive data related to the building's components and based on the aforementioned standards.

3. Developing a unique gaming environment and coupling it with a BIM environment to assist designers and users have effective design communication and interaction to meet users' satisfaction and needs to reduce future modification and alteration, which minimize the associated cost. It helps users/owners to age in their home despite their age, ability or health issues.

8.3 Limitations of the Developed Model

Despite the numerous advantages of the model outlined (such as reducing future modifications and associated costs by aligning home designs with inhabitants' needs), it is subject to several limitations and constraints as follows:

- A significant limitation is that not all building components have been converted into Autodesk Revit© families to meet Universal Design (UD) standards. Therefore, designers must refer to guidelines and apply requirements manually when designing and utilizing these components. Accessing these guidelines is facilitated within the model through a developed plug-in integrated into the BIM tool. Additionally, another limitation is that most guidelines primarily address accessibility policies in buildings, whereas universally designed buildings require supplementary information beyond accessibility considerations. Consequently, the model does not encompass all necessary areas to achieve comprehensive universal design in buildings.
- 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. Therefore, any update in BIM tool can not be reflected in the VR environment automatically.
- In addition to the aforementioned limitations, the exclusion of lighting load analysis and shading systems further restricts the comprehensiveness of the energy analysis within the described model. Lighting load analysis is crucial for assessing the energy efficiency of a building and optimizing its lighting systems. Similarly, shading systems play a significant role in controlling solar heat gain and enhancing energy performance. The absence of these

analyses may lead to incomplete assessments of energy usage and potential missed opportunities for energy savings.

- The current study may overlook certain aspects of visual perception, such as glare, due to the limited luminance range of Head-Mounted Display (HMD) VR displays. Glare can significantly impact occupants' visual comfort and productivity within a space. However, the restricted luminance range of HMD VR displays may not accurately replicate real-world glare conditions, potentially resulting in inadequate assessments of visual comfort and quality. Thus, these limitations underscore the need for further refinement and expansion of the model to ensure comprehensive analysis and optimization of building design aspects related to energy efficiency and visual comfort.
- the accuracy of the LCCA heavily relies on the quality of input data. Any inaccuracies or uncertainties in the data, such as construction costs, evaluation of energy consumption, and maintenance expenses, could impact the reliability of the results. Moreover, the developed integrated model and associated plugins are based on certain assumptions and simplifications, which may not have fully captured the complexity of real-world scenarios.

8.4 Recommendations for Future Research

Moving forward, future research should focus on expanding the following areas:

- Expanding the integrated model's capabilities to cover a wider array of building types and design scenarios is crucial. This ensures its relevance across diverse architectural projects, from residential to commercial and beyond. Achieving this involves refining the model's database, algorithms, and simulation tools to accommodate various architectural contexts effectively. This broader scope enhances its versatility and utility for designers, enabling more comprehensive analysis and decision-making throughout the design process.

- Expanding the model's capabilities to include advanced simulation techniques, like dynamic daylighting analysis and thermal comfort assessment, offers deeper insights into dwellings' performance. These techniques allow for a detailed examination of how natural light interacts with interior spaces throughout the day and how thermal conditions impact occupants' comfort levels. By integrating these analyses, designers can optimize building designs for enhanced daylight utilization and occupant comfort, contributing to more sustainable and user-friendly living environments.
- Enhancing 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), and Generative Design (GD) could further enrich the design process and optimize performance.
- 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.
- Incorporating stochastic modeling techniques to consider inflation and residual values of assets could enhance the accuracy of cost estimations. Additionally, developing a simple system dynamics model of the aging population could provide valuable insights into the demand for AIP homes in the coming years.

- While this study utilized the present worth method and uniform series of cash flows, future research could explore alternative LCCA methods such as the annual worth method or future worth method. Additionally, incorporating different forms of cash flows such as gradient series or geometric series warrants investigation in subsequent studies.
- While this study has primarily focused on the conceptual design stage of houses, future expansion of this research may explore the application of these methodologies and tools to the existing houses. Adapting the models and frameworks developed in this thesis, it would be possible to retrofit the existing houses to meet the Universal Design (UD) standards, incorporate Aging-in-Place (AIP) requirements, and enhance sustainability. This extension would provide significant benefits in improving the accessibility, functionality, and environmental performance of existing houses.

CHAPTER 9

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Appendixes

Appendix I

Codes of developed plug-ins

SUD Plug-in Codes

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Data.SqlServerCe;
using System.Drawing;
using System.Globalization;
using System.IO;
using System.Linq;
using System.Resources;
using System.Text;
using System.Threading;
using System.Threading.Tasks;
using System.Windows.Forms;

namespace VafaRostamiAslUottawa
{
    public partial class Accessible : Form
    {
        public string language = Properties.Settings.Default.Langue;

        public Accessible()
        {
            Thread.CurrentThread.CurrentUICulture = new CultureInfo(language);
            InitializeComponent();
        }

        public static void CopyAll(DirectoryInfo source, DirectoryInfo target)
        {
            Directory.CreateDirectory(target.FullName);
            foreach (FileInfo fi in source.GetFiles())
            {
                Console.WriteLine(@"Copying {0}\{1}", target.FullName, fi.Name);
                fi.CopyTo(Path.Combine(target.FullName, fi.Name), true);
            }
            foreach (DirectoryInfo diSourceSubDir in source.GetDirectories())
            {
                DirectoryInfo nextTargetSubDir = target.CreateSubdirectory(diSourceSubDir.Name);
                CopyAll(diSourceSubDir, nextTargetSubDir);
            }
        }

        private void Accessible_Load(object sender, EventArgs e)
        {
            SqlCeConnection myconnection = new SqlCeConnection();
            myconnection.ConnectionString =
                "Data Source = C:\\VafaRostamiAslUottawa\\dl\\VafaRostamiAslUottawa\\RevitSta.sdf;Persist Security Info=False";

            SqlCeCommand mycommand = new SqlCeCommand();
            mycommand.Connection = myconnection;
            mycommand.CommandText = "SELECT * FROM [AccCat]";

            SqlCeDataAdapter myDataAdapter = new SqlCeDataAdapter(mycommand);
            myDataAdapter.SelectCommand = mycommand;
```

```
            DataSet ds = new DataSet();
            myDataAdapter.Fill(ds);

            comboBox1.Items.Clear();
            for (int i = 0; i < ds.Tables[0].Rows.Count; i++)
                comboBox1.Items.Add(ds.Tables[0].Rows[i][0].ToString());
        }

        private void pictureBox3_Click(object sender, EventArgs e)
        {
            Home frm1 = new Home();
            frm1.Show();
            this.Hide();
        }

        private void pictureBox3_MouseMove(object sender, MouseEventArgs e)
        {
            R01.Visible = true;
            R02.Visible = false;
            R03.Visible = false;
            R04.Visible = false;
            R05.Visible = false;
            R06.Visible = false;
        }

        private void MouseLeave(object sender, EventArgs e)
        {
            R01.Visible = false;
            R02.Visible = false;
            R03.Visible = false;
            R04.Visible = false;
            R05.Visible = false;
            R06.Visible = false;
        }

        private void button02_Click(object sender, EventArgs e)
        {
            DialogResult dialogResult = MessageBox.Show(
                "By selecting Family button, you can access the design families database. Families related to the selected guideline are
automatically placed in the library of Autodesk Revit© and can be used in the project.",
                "About Family Button",
                MessageBoxButtons.OKCancel
            );

            if (dialogResult == DialogResult.OK)
            {
                System.Diagnostics.Process.Start(
                    "explorer.exe",
                    "C:\\VafaRostamiAslUottawa\\revit\\AccessibleDesign\\"
                        + comboBox1.Text
                        + "\\Family\\"
                        + comboBoxInOut.Text
                        + "\\"
                        + comboBox2.Text
                        + "\\"
                );

                string sourceDirectory =
                    "C:\\VafaRostamiAslUottawa\\revit\\AccessibleDesign\\"
                    + comboBox1.Text
                    + "\\Family";
                string targetDirectory =
                    "C:\\ProgramData\\Autodesk\\RVT 2020\\Libraries\\Canada\\AccessibleDesign\\"
```

Export and Import from and To BIM

```
using System;
using System.Collections.Generic;
using System.Data.SqlServerCe;
using System.Linq;
using System.Reflection;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Media.Imaging;
using Autodesk.Revit.Attributes;
using Autodesk.Revit.DB;
using Autodesk.Revit.UI;

namespace VafaRostamiAslUottawa
{
    [TransactionAttribute(TransactionMode.Manual)]
    public class Export : IExternalCommand
    {
        public Result Execute(
            ExternalCommandData commandData,
            ref string message,
            ElementSet elements
        )
        {
            SqlCeConnection myconnection = new SqlCeConnection();
            myconnection.ConnectionString =
                "Data Source = C:\\VafaRostamiAslUottawa\\dl\\VafaRostamiAslUottawa\\RevitSta.sdf;Persist Security Info=False";
            SqlCeCommand mycommand = new SqlCeCommand();
            mycommand.Connection = myconnection;

            myconnection.Open();
            mycommand.CommandText = "DELETE FROM [Test]";
            mycommand.ExecuteNonQuery();

            UIDocument uidoc = commandData.Application.ActiveUIDocument;

            Document doc = uidoc.Document;

            try
            {
                FilteredElementCollector WindowCollector = new FilteredElementCollector(doc)
                    .OfCategory(BuiltInCategory.OST_Windows)
```

```
    .WhereElementIsNotElementType();
IList<ElementId> windowIds = WindowCollector.ToElementIds() as IList<ElementId>;

FilteredElementCollector DoorCollector = new FilteredElementCollector(doc)
    .OfCategory(BuiltInCategory.OST_Doors)
    .WhereElementIsNotElementType();
IList<ElementId> DoorIds = DoorCollector.ToElementIds() as IList<ElementId>;

FilteredElementCollector RailCollector = new FilteredElementCollector(doc)
    .OfCategory(BuiltInCategory.OST_StairsRailing)
    .WhereElementIsNotElementType();
IList<ElementId> RailIds = RailCollector.ToElementIds() as IList<ElementId>;

FilteredElementCollector FurnitureCollector = new FilteredElementCollector(doc)
    .OfCategory(BuiltInCategory.OST_Furniture)
    .WhereElementIsNotElementType();
IList<ElementId> FurnitureIds =
    FurnitureCollector.ToElementIds() as IList<ElementId>;

foreach (ElementId windowId in windowIds)
{
    Element ele = doc.GetElement(windowId);

    ElementId eTypeId = ele.GetTypeId();
    ElementType eType = doc.GetElement(eTypeId) as ElementType;

    if (ele != null)
    {
        double newMyHeight = 0,
            newMyWidth = 0,
            newMyLenght = 0,
            newMyDepth = 0;

        Parameter h = eType.LookupParameter("Height");
        Parameter w = eType.LookupParameter("Width");
        Parameter l = eType.LookupParameter("Lenght");
        Parameter d = eType.LookupParameter("Depth");

        if (h != null)
        {
            double MyHeight = h.AsDouble();
            newMyHeight = UnitUtils.ConvertFromInternalUnits(
                MyHeight,
```

Aging in Place Requirements:

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Data.OleDb;
using System.Data.SqlServerCe;
using System.Diagnostics;
using System.Drawing;
using System.Drawing.Printing;
using System.Globalization;
using System.IO;
using System.Linq;
using System.Reflection.Emit;
using System.Resources;
using System.Text;
using System.Threading;
using System.Threading.Tasks;
using System.Windows.Forms;
using MySql.Data.MySqlClient;

namespace VafaRostamiAslUottawa
{
    public partial class Checklist : Form
    {
        PrintDocument printStuff = new PrintDocument();
        PrintPreviewDialog viewStuff = new PrintPreviewDialog();
        PaperSize paperSize = new PaperSize("papersize", 150, 500);
        int totalnumber = 0;
        int itemperpage = 0;
        public string language = Properties.Settings.Default.Langue;

        public Checklist()
        {
            Thread.CurrentThread.CurrentUICulture = new CultureInfo(language);
            InitializeComponent();
        }

        private void label33_Click(object sender, EventArgs e)
        {
            System.Windows.Forms.Application.Exit();
        }

        private void Checklist_Load(object sender, EventArgs e)
        {
            DGV1.AllowUserToResizeRows = false;
            DGV2.AllowUserToResizeRows = false;
            label1.Text = "";
            label2.Text = "";
        }

        private void pictureBox6_Click(object sender, EventArgs e)
        {
            string connectionString =
                "Data Source = C:\\VafaRostamiAslUottawa\\dl\\VafaRostamiAslUottawa\\RevitSta.sdf;Persist Security Info=False";
            string sql =
                "SELECT  [tittel],[text],[yes],[no],[na] FROM [check01] WHERE [cat]= '"
                + label1.Text
                + "'";
            SqlCeConnection connection = new SqlCeConnection(connectionString);
            SqlCeDataAdapter dataadapter = new SqlCeDataAdapter(sql, connection);
            DataSet ds = new DataSet();
```

```
    connection.Open();
    dataadapter.Fill(ds, "Authors_table");
    connection.Close();
    DGV3.DataSource = ds;
    DGV3.DataMember = "Authors_table";
    printStuff = new PrintDocument();
    printStuff.PrintPage += new PrintPageEventHandler(MiseEnPage_Exemple1);
    viewStuff.Document = printStuff;
    viewStuff.Document.DocumentName = "CHECKLIST";
    viewStuff.Width = 600;
    viewStuff.Height = 800;
    viewStuff.ShowDialog();
    itemperpage = totalnumber = 0;
    printPreviewDialog1.Document = printDocument1;
}

private void MiseEnPage_Exemple1(Object sender, PrintPageEventArgs e)
{
    int line = 20;
    string tittel = "";
    string ans1,
        ans2,
        ans3 = "";
    e.Graphics.PageUnit = GraphicsUnit.Millimeter;
    SolidBrush drawBrush = new SolidBrush(Color.Black);
    SolidBrush drawBrushTittel = new SolidBrush(Color.White);
    Font drawFont = new Font("Tahoma", 10);
    Font drawFontTittel = new Font("Tahoma", 20);
    float currentY = 10;
    e.Graphics.DrawString(label1.Text + " Checklist", drawFontTittel, drawBrush, 7F, 7F);
    ;
    currentY += 15;
    while (totalnumber <= this.DGV3.Rows.Count - 1)
    {
        if (tittel != DGV3.Rows[totalnumber].Cells[0].Value.ToString())
        {
            Pen blackPen = new Pen(Color.Black, 5);

            PointF point1 = new PointF(0, line + 1.8F);
            PointF point2 = new PointF(500.0F, line + 1.8F);
            e.Graphics.DrawLine(blackPen, point1, point2);
            e.Graphics.DrawString(
                DGV3.Rows[totalnumber].Cells[0].Value.ToString(),
                drawFont,
                drawBrushTittel,
                20F,
                line
            );
            line = line + 9;
        }
        tittel = DGV3.Rows[totalnumber].Cells[0].Value.ToString();
        ans1 = DGV3.Rows[totalnumber].Cells[2].Value.ToString();
        ans2 = DGV3.Rows[totalnumber].Cells[3].Value.ToString();
        ans3 = DGV3.Rows[totalnumber].Cells[4].Value.ToString();
        if (ans1 == "1" && ans2 == "0" && ans3 == "0")
        {
            e.Graphics.DrawString("YES", drawFont, drawBrush, 10F, line);
        }
        if (ans1 == "0" && ans2 == "1" && ans3 == "0")
        {
            e.Graphics.DrawString("NO", drawFont, drawBrush, 10F, line);
        }
        if (ans1 == "0" && ans2 == "0" && ans3 == "1")
        {
```

Energy Analysis Plug in Codes:

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Data.SqlServerCe;
using System.Drawing;
using System.Drawing.Imaging;
using System.IO;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;
using System.Windows.Forms.DataVisualization.Charting;

namespace VafaRostamiAslUottawa
{
    public partial class EaWWR : Form
    {
        int cont = 1;

        public EaWWR()
        {
            InitializeComponent();
        }

        private void label3_Click(object sender, EventArgs e)
        {
            chart.Visible = false;
            this.Hide();
        }

        private void button1_Click_1(object sender, EventArgs e)
        {
            chart.Series[1].Points.Clear();

            double wallw,
                wallh,
                m2,
                result,
                win;

            win = Double.Parse(res.Text);

            wallw = Double.Parse(WallW.Text);
            wallw = wallw / 100;
            wallh = Double.Parse(WallH.Text);
            wallh = wallh / 100;
            m2 = wallw * wallh;
            result = win / m2 * 100;

            float f = (float)result;
            int N = 0;
            double f2 = Math.Round(f * Math.Pow(10, N)) / Math.Pow(10, N);

            if (f2 <= 22)
            {
                la.Text = "20";
                lb.Text = dataGridView1.Rows[0].Cells[1].Value.ToString();
                chart.Series[1].Points.AddXY(20, dataGridView1.Rows[0].Cells[1].Value);
            }
            if (f2 >= 23 && f2 < 28)
```

```
{
    la.Text = "25";
    lb.Text = dataGridView1.Rows[1].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(25, dataGridView1.Rows[1].Cells[1].Value);
}
if (f2 >= 28 && f2 < 33)
{
    la.Text = "30";
    lb.Text = dataGridView1.Rows[2].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(30, dataGridView1.Rows[2].Cells[1].Value);
}
if (f2 >= 33 && f2 < 38)
{
    la.Text = "35";
    lb.Text = dataGridView1.Rows[3].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(35, dataGridView1.Rows[3].Cells[1].Value);
}
if (f2 >= 38 && f2 < 43)
{
    la.Text = "40";
    lb.Text = dataGridView1.Rows[4].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(40, dataGridView1.Rows[4].Cells[1].Value);
}
if (f2 >= 43 && f2 < 48)
{
    la.Text = "45";
    lb.Text = dataGridView1.Rows[5].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(45, dataGridView1.Rows[5].Cells[1].Value);
}
if (f2 >= 48 && f2 < 53)
{
    la.Text = "50";
    lb.Text = dataGridView1.Rows[6].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(50, dataGridView1.Rows[6].Cells[1].Value);
}
if (f2 >= 53 && f2 < 58)
{
    la.Text = "55";
    lb.Text = dataGridView1.Rows[7].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(55, dataGridView1.Rows[7].Cells[1].Value);
}
if (f2 >= 58 && f2 < 63)
{
    la.Text = "60";
    lb.Text = dataGridView1.Rows[8].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(60, dataGridView1.Rows[8].Cells[1].Value);
}
if (f2 >= 63 && f2 < 68)
{
    la.Text = "65";
    lb.Text = dataGridView1.Rows[9].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(65, dataGridView1.Rows[9].Cells[1].Value);
}
if (f2 >= 68 && f2 < 73)
{
    la.Text = "70";
    lb.Text = dataGridView1.Rows[10].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(70, dataGridView1.Rows[10].Cells[1].Value);
}
if (f2 >= 73 && f2 < 78)
{
    la.Text = "75";
    lb.Text = dataGridView1.Rows[11].Cells[1].Value.ToString();
    chart.Series[1].Points.AddXY(75, dataGridView1.Rows[11].Cells[1].Value);
```

LCA Plug-in Codes:

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Data.SqlServerCe;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;
using MySqlX.XDevAPI.Relational;

namespace VafaRostamiAslUottawa
{
    public partial class LCA : Form
    {
        public LCA()
        {
            InitializeComponent();
        }

        private void button5_Click(object sender, EventArgs e)
        {
            comboBox1.SelectedIndex = 1;
            comboBox2.SelectedIndex = 2;
            comboBox3.SelectedIndex = 2;
            comboBox4.SelectedIndex = 6;
            comboBox5.SelectedIndex = 0;
            resl.ForeColor = Color.Green;
            SqlCeConnection myconnection = new SqlCeConnection();
            myconnection.ConnectionString =
                "Data Source = C:\\VafaRostamiAslUottawa\\dl\\VafaRostamiAslUottawa\\RevitSta.sdf;Persist Security Info=False";
            SqlCeCommand mycommand = new SqlCeCommand();
            mycommand.Connection = myconnection;
            mycommand.CommandText =
                "SELECT LCA FROM [LCA] WHERE EWC ='"
                + comboBox1.Text
                + "' AND WWR ='"
                + comboBox4.Text
                + "' AND GT ='"
                + comboBox3.Text
                + "' AND WFT ='"
                + comboBox2.Text
                + "' AND PRC ='"
                + comboBox5.Text
                + "' ";

            SqlCeDataAdapter myDataAdapter = new SqlCeDataAdapter(mycommand);
            myDataAdapter.SelectCommand = mycommand;

            DataSet ds = new DataSet();
            myDataAdapter.Fill(ds);

            resl.Text = ds.Tables[0].Rows[0][0].ToString();
        }

        private void button1_Click(object sender, EventArgs e) { }

        private void updateReportLCA()
        {
            string connectionString =
```

```
                "Data Source = C:\\VafaRostamiAslUottawa\\dl\\VafaRostamiAslUottawa\\RevitSta.sdf;Persist Security Info=False";
            using (SqlCeConnection connection = new SqlCeConnection(connectionString))
            {
                connection.Open();

                using (
                    SqlCeCommand deleteAllCommand = new SqlCeCommand(
                        "DELETE FROM ReportLCA",
                        connection
                    )
                )
                {
                    deleteAllCommand.ExecuteNonQuery();
                }

                string column1Value = comboBox1.Text;
                string column2Value = comboBox2.Text;
                string column3Value = comboBox3.Text;
                string column4Value = comboBox4.Text;
                string column5Value = comboBox5.Text;
                string column6Value = resl.Text;

                using (
                    SqlCeCommand insertCommand = new SqlCeCommand(
                        "INSERT INTO ReportLCA (wall, window, glazing, wwr, roof, ce) VALUES (@Column1, @Column2, @Column3,
@Column4, @Column5, @Column6)",
                        connection
                    )
                )
                {
                    insertCommand.Parameters.AddWithValue("@Column1", column1Value);
                    insertCommand.Parameters.AddWithValue("@Column2", column2Value);
                    insertCommand.Parameters.AddWithValue("@Column3", column3Value);
                    insertCommand.Parameters.AddWithValue("@Column4", column4Value);
                    insertCommand.Parameters.AddWithValue("@Column5", column5Value);
                    insertCommand.Parameters.AddWithValue("@Column6", column6Value);

                    insertCommand.ExecuteNonQuery();
                }
            }
        }

        private void label3_Click(object sender, EventArgs e)
        {
            updateReportLCA();
            System.Windows.Forms.Application.Exit();
        }

        private void pictureBox1_Click(object sender, EventArgs e)
        {
            EaWWR frm = new EaWWR();
            frm.Show();
        }

        private void pictureBox3_Click(object sender, EventArgs e)
        {
            lbTitle.Text = "External Wall Type";
            pbox1.Image = VafaRostamiAslUottawa
                .Properties
                .Resources
                .WhatsApp_Image_2023_08_01_at_11_23_36_PM;
            radPanel1.Visible = true;
        }
```

LCCA Plug in Codes:

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Data.SqlServerCe;
using System.Drawing;
using System.IO;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;

namespace VafaRostamiAslUottawa
{
    public partial class LCC : Form
    {
        private Dictionary<DataGridViewCell, object> previousCellValues =
            new Dictionary<DataGridViewCell, object>();

        public LCC()
        {
            InitializeComponent();
        }

        private void label3_Click(object sender, EventArgs e)
        {
            System.Windows.Forms.Application.Exit();
        }

        private void pictureBox2_Click(object sender, EventArgs e)
        {
            VS form = new VS();

            form.Show();
        }

        private void pictureBox3_Click(object sender, EventArgs e)
        {
            graph form = new graph();

            CopyData(DGVR, form.DGVRR);

            form.Show();
        }

        private void comboBox1_SelectedIndexChanged(object sender, EventArgs e)
        {
            SqlCeConnection myconnection = new SqlCeConnection();
            myconnection.ConnectionString =
                "Data Source = C:\\VafaRostamiAslUottawa\\dl\\VafaRostamiAslUottawa\\RevitSta.sdf;Persist Security Info=False";
            SqlCeCommand mycommand = new SqlCeCommand();
            mycommand.Connection = myconnection;
            mycommand.CommandText =
                "SELECT * FROM [Canada] WHERE Province ='" + comboBox1.Text + "'";

            SqlCeDataAdapter myDataAdapter = new SqlCeDataAdapter(mycommand);
            myDataAdapter.SelectCommand = mycommand;

            DataSet ds = new DataSet();
            myDataAdapter.Fill(ds);
```

```
    comboBox2.Items.Clear();
    for (int i = 0; i < ds.Tables[0].Rows.Count; i++)
        comboBox2.Items.Add(ds.Tables[0].Rows[i][2].ToString());
    comboBox2.Text = ds.Tables[0].Rows[0][2].ToString();
}

private void textBox1_TextChanged(object sender, EventArgs e) { }

private void comboBox4_SelectedIndexChanged(object sender, EventArgs e) { }

private void button1_Click(object sender, EventArgs e)
{
    if (t4.Text == "")
    {
        t4.Text = "0";
    }
    int xx1 = Convert.ToInt32(t1.Text);
    int xx2 = Convert.ToInt32(t2.Text);
    double xx3 = Convert.ToInt32(t3.Text);
    xx3 = xx3 * 0.01;
    xx3 = xx3 * xx2;
    int xx4 = Convert.ToInt32(t4.Text);
    double xxs = xx1 + xx2 + xx3 + xx4;
    xxs = -xxs;
    rs.Text = string.Format("{0:n0}", xxs);

    tabPage2.Enabled = true;
    tabControl1.SelectedTab = tabPage2;
}

private void button5_Click(object sender, EventArgs e)
{
    if (bo.Text == "")
        bo.Text = "0";
    if (bou.Text == "")
        bou.Text = "0";
    if (gas.Text == "")
        gas.Text = "0";
    if (gasu.Text == "")
        gasu.Text = "0";
    if (water.Text == "")
        water.Text = "0";
    if (wateru.Text == "")
        wateru.Text = "0";
    if (iii.Text == "")
    {
        string message = "please fill Interest rate fild";
        MessageBox.Show(message);
    }

    double ee = Convert.ToDouble(bo.Text);
    double g = Convert.ToDouble(gas.Text);
    double w = Convert.ToDouble(water.Text);
    double eeu = Convert.ToDouble(bou.Text);
    double gu = Convert.ToDouble(gasu.Text);
    double wu = Convert.ToDouble(wateru.Text);
    ee = ee * eeu;
    g = g * gu;
    w = w * wu;
    double tot2 = ee + g + w;

    double mino = Convert.ToDouble(minor.Text);
    double con = Convert.ToDouble(t2.Text);
    mino = mino / 100;
```

LEED Plug in Codes:

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;
using System.Net.Http;
using HtmlAgilityPack;
using HtmlDocument = HtmlAgilityPack.HtmlDocument;
using Microsoft.Web.WebView2.Core;
using Newtonsoft.Json.Linq;
using GoogleMapsApi.Entities.Directions.Response;
using GoogleMapsApi.Entities.Directions.Request;
using GoogleMapsApi;
using GoogleMapsApi.Entities.Common;
using Newtonsoft.Json;
using System.Net;
using System.Reflection.Emit;
using System.Security.Cryptography;
using System.Xml.Linq;
using System.Xml;
using Telerik.WinControls;
using static System.Windows.Forms.VisualStyles.VisualStyleElement;
using DevExpress.XtraBars.Docking2010.Views.WindowsUI;
using DevExpress.XtraEditors;
using static Stimulsoft.Report.StiOptions.Designer;
using Telerik.WinControls.UI;
using System.IO;

namespace VafaRostamiAslUottawa
{
    public partial class Leed : Form
    {
        private const string GoogleMapsApiKey = "-------";
        private const string GoogleMapsBaseUrl = "https:
        private static readonly HttpClient _httpClient = new HttpClient();

        public Leed()
        {
            this.AutoScaleMode = AutoScaleMode.Dpi;

            this.AutoScaleMode = AutoScaleMode.Dpi;

            float scaleFactor = DpiHelper.ScaleFactor();
            this.Font = new Font("Arial", 10 * scaleFactor);

            InitializeComponent();

        }

        public static class DpiHelper
        {
            public static float ScaleFactor()
            {
                using (Graphics graphics = Graphics.FromHwnd(IntPtr.Zero))
                {
                    float dpiX = graphics.DpiX;
                    return dpiX / 96f;
```

```
        }
    }
}

private async Task<(double Latitude, double Longitude)> GetLatLongFromAddressAsync(string address)
{
    try
    {
        string apiUrl = $"https:

        using (HttpClient httpClient = new HttpClient())
        {
            HttpResponseMessage response = await httpClient.GetAsync(apiUrl);
            response.EnsureSuccessStatusCode();

            string responseBody = await response.Content.ReadAsStringAsync();
            JObject jsonResponse = JObject.Parse(responseBody);
            JToken results = jsonResponse["results"];
            if (results != null && results.HasValues)
            {
                JToken location = results[0]["geometry"]["location"];
                double latitude = (double)location["lat"];
                double longitude = (double)location["lng"];
                return (latitude, longitude);
            }
        }
    }
    catch (HttpRequestException ex)
    {

        Console.WriteLine($"Error: {ex.Message}");
    }
    catch (Exception ex)
    {
        Console.WriteLine($"Unexpected error: {ex.Message}");
    }

    return (0, 0);
}

private async void score()
{

    string url = "https:


    using (HttpClient httpClient = new HttpClient())
    {
        try
        {

            HttpResponseMessage response = await httpClient.GetAsync(url);

            if (response.IsSuccessStatusCode)
            {

                string htmlContent = await response.Content.ReadAsStringAsync();

                HtmlDocument htmlDocument = new HtmlDocument();
                htmlDocument.LoadHtml(htmlContent);

                HtmlNode walkDivNode = htmlDocument.DocumentNode.SelectSingleNode("

                if (walkDivNode != null
```