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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 of integrating Building Information Modeling (BIM) and Life Cycle Cost Analysis (LCCA) to evaluate the economic implications of designing aging-in-place (AIP) homes at the conceptual stage. With the rising global aging population, there is a growing demand for housing tailored to elderly needs. This study emphasizes the importance of early design phases, offering a semi-automated model to estimate life cycle costs from design to disposal. The model enables comprehensive economic assessments, highlighting the long-term feasibility of design decisions by considering life cycle costs early in the process. Investing in accessible and universal design features upfront can lead to long-term savings by reducing the need for extensive future retrofits. The model allows for comparisons among different design alternatives, assessing the financial impact of features such as wider doorways, accessible bathrooms, and elevators. This study provides valuable insights for designers and homeowners, supporting efficient decision-making during the early design stages of AIP homes.

Keywords: Building Information Modeling (BIM); Life Cycle Cost Analysis (LCCA); aging in place (AIP); computer integration and automation

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1. Introduction

Presently, Canada is navigating through a profound demographic transition, and it is anticipated 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 already represent 19% of the population and account for almost half (47%) of healthcare spending [1]. A national survey conducted by the National Institute on Ageing (NIA) in collaboration with TELUS Health in the year 2020 reveals 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 [2]. AIP is emphasized for its benefits in providing comfort, familiarity, and enhanced well-being for seniors, minimizing the stress associated with major life changes [3]. Housing plays a pivotal role in AIP, as architectural space is intimately connected to human existence [4]. 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, widening doorways would cost between CAD 20,000 and CAD 40,000, depending on the home's architecture, the cost of installing an elevator ranges from CAD 45,000 to CAD 100,000, bathroom refurbishments would cost from around CAD 20,000 to CAD 40,000, and the cost of a kitchen overhaul is between CAD 40,000 and CAD 80,000. These costs underscore the financial impact of retrofitting. It is important to note that these costs are based on the year 2022 and could be much higher in future years. Proactively integrating these considerations during the

conceptual design phase can substantially mitigate these costs [5]. Conceptual design is increasingly crucial in addressing the specialized demands of customers. The influence of design decisions is greatest at this stage and diminishes significantly as the design progresses [6]. The strategic integration of AIP requirements during the conceptual design stage holds the potential to significantly reduce the costs associated with retrofitting and modifying 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 a 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 in the overall cost estimation helps in selecting the best option among projects with similar applications but with varying cost parameters throughout their life cycle [7,8]. 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 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. [7] emphasized the importance of employing LCCA during the initial phases of design. This early application allows for refinement and improvement in a design, ultimately aiming to minimize the 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 plug-in developed and inherited into Autodesk Revit 2022 as a BIM tool. This integrated approach offers architects and stakeholders a robust analytical tool that can 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 plug-in, 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 (plug-in) allows for holistic assessments of the construction costs and the long-term financial implications of design decisions. This approach considers numerous factors, such as maintenance, adaptability, and energy efficiency, and redefines the design of AIPH by merging economic sustainability with advanced digital modeling. The integration of LCCA and BIM supports real-time design adjustments, making homes more adaptable as residents age; therefore, it reduces the need for expensive future modifications and offers 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 the authors' prior research, i.e., Rostamiasl and Jrade [9], 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 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.

To achieve the objectives of this study, this manuscript is structured as follows: Section 2, Literature Review, identifies research gaps and the need for integrated approaches; Section 3, Methodology, details the development of a semi-automated economic evaluation model; Section 4, Model Development and Testing, explains the model through a case study demonstrating its application in evaluating the life cycle costs of different design

alternatives; Section 5, Results, Limitations, and Future Works, analyzes the economic implications and benefits of the model, research limitations, and future research directions; and Section 6, Conclusions, summarizes our key findings.

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 [10]. The BIM concept serves as a valuable method for managing a project's information, which facilitates the evaluation of the life cycle cost (LCC) while creating project models at the various stages of its design. BIM speeds up the process of estimating costs with fewer mistakes, fewer errors, and simplified decision-making procedures. This streamlined approach contributes to improving a structure's performance over its lifespan. Moreover, BIM, as a visual and generative programming tool [11], offers incredible opportunities to facilitate the utilization of visual tools and specific information about various components and activities, enhancing LCC results for effective use by decision-makers [12]. One of the most significant tasks facilitated by BIM is the execution of the quantity take-off (QTO) process [13], which is one of the most important items needed to conduct an LCCA.

According to Altaf et al. [14], the integration of LCC and BIM mitigates potential conflicts and errors in the cost-estimating process. Early integration of BIM and LCCA during a project's design has the potential to minimize the operation, repair, and maintenance costs [14] as the early design stage has a significant impact on the performance of a building during its life span [15]. 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 [16,17]. Various studies have explored the integration of LCCA with Building Information Modeling (BIM) and have demonstrated promising outcomes. For instance, Kehily et al. [18] investigated the feasibility of utilizing 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. [19] 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. [20] assessed the benefits of integrating BIM and LCC by incorporating an external database for LCCA into a BIM environment. Their findings indicated that this integration played a significant role in promoting sustainability during the initial stages of projects. Ansah et al. [21] 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. [22] introduced an LCCA framework that was designed for use during the conceptual design stage of buildings. The framework aimed to enhance resilience and optimize construction costs by developing a plug-in within BIM tools. The plug-in facilitated the selection of resilient components at the early stages of design. Viscuso et al. [23] devised a model framework that integrated 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 could

be spanned over various stages of a project aiming to deliver more sustainable designs aligned with LEED protocols. The framework extended its consideration to economic aspects by employing LCCA to attain optimal cost solutions at every stage of a project. Shin and Cho [24] 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 [25] developed three design proposals that targeted 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. [26] developed a BIM-integrated RDBMS (Relational Database Management System) for compiling and organizing the required data and information from BIM models to compute buildings' LCCs. The system integrated a BIM authoring program (tool), a database management system, a spreadsheet system, and a visual programming interface to perform building LCCA. Lee et al. [27] proposed a method for preparing preliminary cost estimates based on BIM levels 1 and 2 of details and the actual construction cost data to support decision-making early in the design phase. Rashed et al. [28] 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 a building's envelope.

Furthermore, building upon this 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 [29] and Yang et al. [30], this phase offers the greatest flexibility for improvements, whereas the opportunities for changes diminish and the costs of implementing alterations escalate rapidly as projects progress. Therefore, a strategic approach to making efficient design decisions during the initial stages is imperative for achieving sustainability outcomes.

Estimating the cost of embodied carbon emissions in buildings primarily focuses on assessing carbon outputs across all the stages of a building's life, including material extraction, processing, construction, operation, and end-of-life phases [31]. The primary aim is to quantify carbon emissions in carbon equivalent units to measure the building's total environmental impact. The process comprises the calculation of embodied carbon, which includes emissions from material production to construction, and 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 [32,33]. A study by Schmidt et al. [34] 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, 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 life cycle. 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 and Park [35] used BIM to estimate the cost of embodied carbon emissions for tunnel construction by integrating CO_2 emission factors of materials and equipment into a 3D model in Autodesk Revit. These emissions were converted to costs using 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. [36] employed a Carbon Value Engineering (CO2VE) framework for estimating the cost of embodied carbon emissions during the design of buildings. The approach integrated a reduction in 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-story building in Sydney, where significant savings in carbon emissions and construction costs were attained by optimizing the design and material selection. Langston et al. [37] 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 with new-builds. Their study highlighted the economic and environmental advantages of refurbishment over new construction.

Several studies, such as those by Llatas et al. [38] and Nwodo and Anumba [39], have been proposed to assess the environmental impact and cost of construction projects by translating embodied carbon into a monetary value. Schmidt et al. [34] advocated for the implementation of a carbon tax applied to the life cycle carbon emissions of buildings. This strategy aimed to communicate greenhouse gas (GHG) emissions to stakeholders effectively and provide incentives for reducing emissions.

Despite 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, thus guiding efforts to reduce carbon footprints in the construction industry. The main challenges include the standardization of measurement methods and improvement in data 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 to optimize 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.

3. 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 a 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 at the initial costs, moving through operational, repairs and maintenance, major replacements, and ending at 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. These data are 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 energy consumption and associated costs, and conducting an LCA to calculate embodied carbon. These results are subsequently integrated into the LCCA module to contribute to the calculation of both the initial and operational costs. Finally, Phase 4 focuses on developing the LCCA plug-in, which autonomously receives data from the energy analysis and LCA plug-ins, RSMeans cost data, and user inputs. The sophisticated design of this plug-in facilitates the implementation of scenario and sensitivity analysis and therefore generates 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. Figure 1 illustrates the framework of the integrated model.

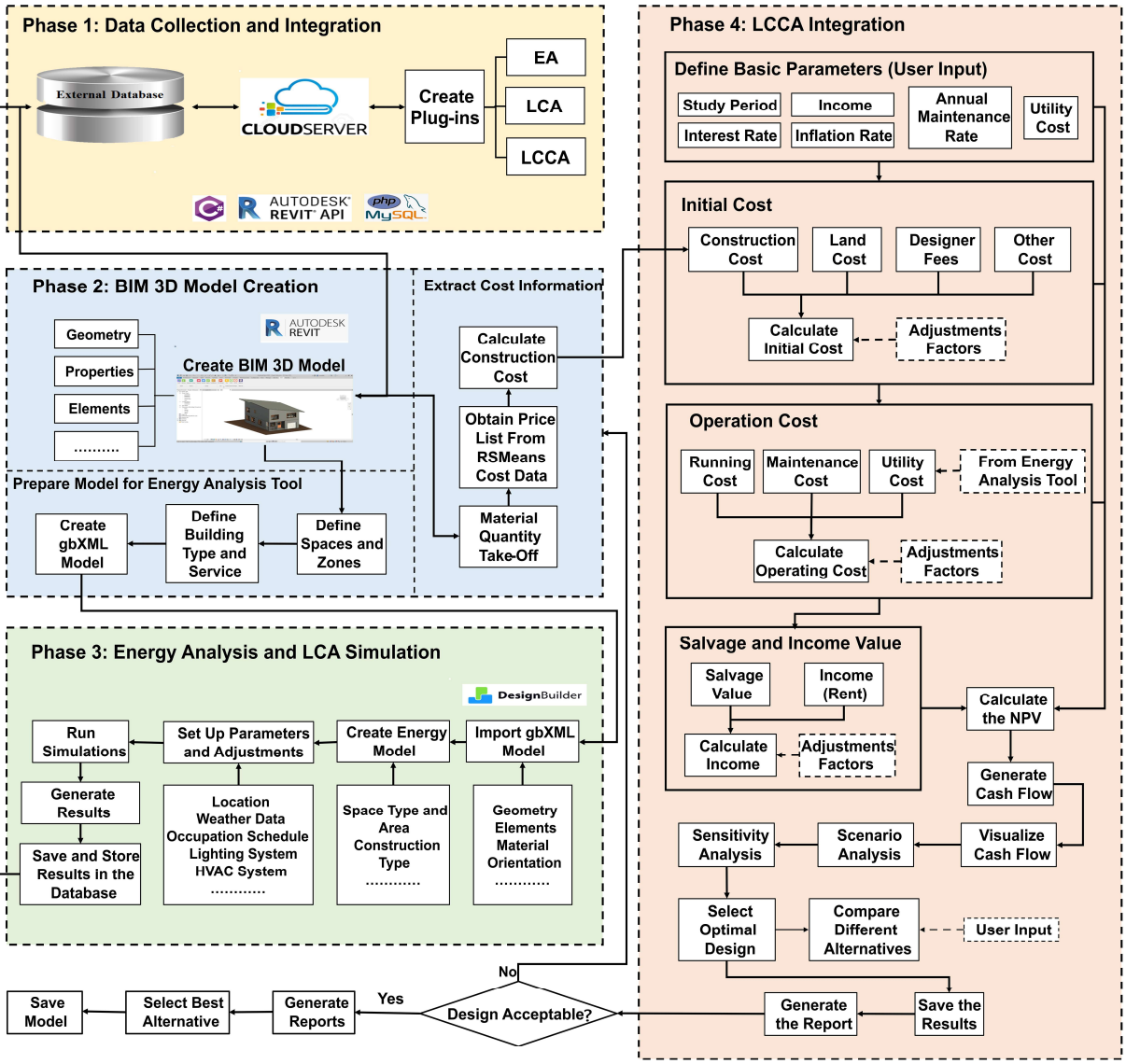


Figure 1. Framework for the integration of BIM and LCCA.

3.1. Phase 1—Data Collection and Integration

During the 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 plug-ins are developed in this phase, which include the following: (1) an AIP requirements plug-in, to facilitate the integration of specific design considerations into the BIM model; (2) an energy analysis plug-in that extracts detailed energy consumption data with cost implications and seamlessly transfers this information to the LCCA plug-in; (3) an LCA plug-in that calculates the model's embodied carbon and transfers it to the LCCA plug-in along with the associated carbon cost; and (4) an LCCA plug-in, 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.

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 identified in Phase 1 to ensure a holistic representation. The BIM 3D model is the basis for all the subsequent calculations, analyses, and integration of LCCA. Concurrently, a detailed material quantity take-off is executed. Quantity can be measured from BIM models by extracting geometric data and semantic properties of each building element, which is called BIM-based quantity take-off (QTO) [13]. This phase also incorporates RSMeans cost data to estimate the construction costs, encompassing the costs of materials, equipment, and labor, contractor costs, and O and P (overhead and profit), establishing the initial cost based on the MasterFormat and Uniformat divisions for all the building elements. Upon performing a detailed QTO from BIM model, RSMeans cost data are utilized to acquire unit costs for materials, labor, and equipment outlined in the quantity take-off. Next, the total cost for each construction item is ascertained by multiplying the quantities derived from the QTO by the respective unit costs from RSMeans, as shown in Equation (1).

$$C_{total} = \sum_{i=1}^{n} (Q_i \times U_i) \quad (1)$$

where (C_{total}) is the total construction cost; (Q_i) is the quantity of item i from the QTO; (U_i) is the unit cost of item i from RSMeans; and (n) is the number of different construction items.

During this stage, the cloud server engages in a bidirectional 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 and exported to DesignBuilder v6 as an 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 performed in two ways as follows: (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 homes, where design, cost, LCA, and energy considerations are intricately interwoven to enhance the overall project outcomes.

3.3. Phase 3—Energy Analysis, LCA, and Simulation

In the 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 integration into the designated tool. This study elected to use DesignBuilder as the energy analysis and LCA tool because of 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 [40]. In this investigation, the successful exportation of the house geometry is evidenced in Figure 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. The heating and cooling setpoint temperatures are configured at 18 °C and 25 °C, respectively. For additional accuracy, the walls and roofs are restructured similarly to the 3D BIM model's wall and roof properties. The windows are centrally positioned on each façade, and the properties of these selected windows are detailed in Table 1. Furthermore, shading is not considered in the base model, and, for simplicity, the influence of window frames is excluded from consideration in this study.

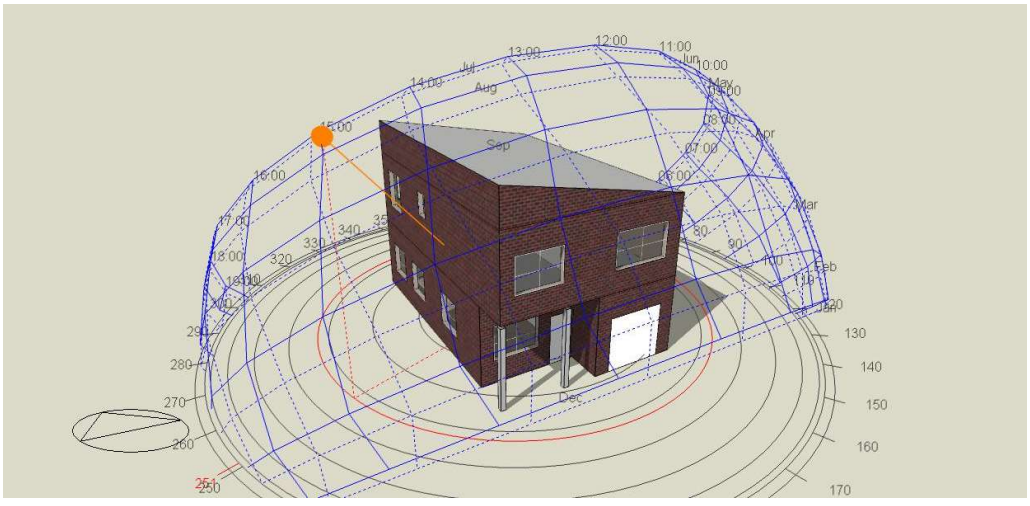


Figure 2. House geometry and zones in DesignBuilder.

Table 1. Window properties in base model.

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 are 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 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 embodied carbon within this scope involves the quantification of the embodied carbon associated with the extracting, processing, and manufacturing processes. By analyzing 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 envelopes and supports the decision-making process aimed at mitigating carbon emissions and promoting the adoption of low-carbon building materials and construction practices. This 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 the variables shown in Table 2. Figures 3 and 4 show the selected walls and roofs, respectively.

Table 2. List of optimization parameters.

Design Variables	Objective
Wall materials (three alternatives) Roof materials (three alternatives) Window-to-wall ratio (ranging from 20% to 80%) Window glazing types (single, doubled, and tripled) Window frame materials (three alternatives)	Embodied carbon total energy consumption



Figure 3. Different wall options selected for the optimization analysis.

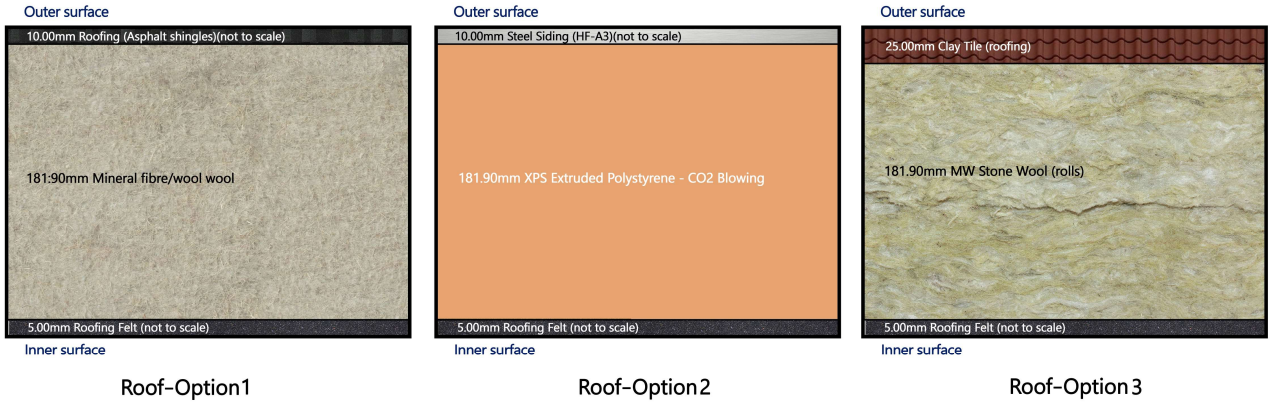


Figure 4. Different roof options selected for the optimization analysis.

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, 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. The maximum population size is set at 50, the tournament size at 2, the crossover rate at 1, and the individual mutation probability at 0.4. Upon generating the optimization analysis and the results, all data are stored in the external database that is used later in the 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 plug-in. The plug-in is able to recommend the best and worst combination of variables in terms of embodied carbon emissions.

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 CAD 20 per tonne of carbon dioxide equivalent emissions (tCO2e) in 2019 and rising to CAD 80 per tonne as of 1 April 2024. All provinces and territories in Canada must maintain a carbon price of at least CAD 80 per tCO2e in 2024 [41]. Equation (2) is used to calculate the embodied carbon cost.

$$\textit{Carbon Emission Cost} = \textit{Carbon Emission} \times \textit{Cost per unit of carbon emission} \quad (2)$$

where carbon emission represents the amount of carbon dioxide (CO_2) or other greenhouse gases emitted and cost per unit of carbon emission denotes the monetary value assigned to each unit of carbon emission, typically based on carbon pricing mechanisms.

3.4. Phase 4—LCCA Integration

In this phase, the developed LCCA plug-in automatically receives data inputs from the AIP, LCA, and energy analysis plug-ins, ensuring real-time and accurate integration. It also brings in RSMeans cost data and user inputs, forming a complete dataset for thorough LCCA. The plug-in 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 option, empowering designers and owners to make informed decisions. Ultimately, the plug-in 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 costs are retrieved from the database that is established in Phase 2. With the model's flexibility, users can change the input values. Equation (3) is used to calculate the initial cost.

$$C_{initial} = C_{land} + C_{construction} + C_{design} + C_{carbon} + C_{other} \quad (3)$$

where C_{land} is the land cost; $C_{construction}$ is the construction cost calculated by using QTO and RSMeans; C_{design} is the design cost; C_{carbon} is embodied carbon emission cost; and C_{other} is any other cost that the user can add.

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. 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 life cycle 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 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, the relevant literature was thoroughly reviewed [5,42]. The findings of reviewing the literature, including cost breakdowns, are presented in Table 3, which shed light on the financial implications of incorporating aging-in-place features into residential designs. Certain prices were initially denominated in U.S. 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 perform 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 (4).

$$F = P(1+i)^t \quad (4)$$

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.

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 of 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.

Table 3. Modification and remodeling costs [5,42].

Project Work Item (s)	Price Range to Install *	Average Cost *
Walk-in tub or shower	CAD 5000 to CAD 20,000	CAD 12,500
Ramp installation at entrance	CAD 1200 to CAD 2500	CAD 1850
Widen an entry door	CAD 300 to CAD 10,000	CAD 5150
Stairlift installation	CAD 4000 to CAD 27,000	CAD 15,500
Install entry handrails	CAD 1000 to CAD 1600	CAD 1300
Install an elevator	CAD 45,000 to CAD 100,000	CAD 72,500
Install lever taps on faucets	CAD 250 to CAD 500	CAD 375
Widen hallways w/out structural changes	CAD 1100 to CAD 2000	CAD 1550
Widen hallways with structural changes	CAD 41,000 to CAD 55,000	CAD 48,000
Replace 10 windows	CAD 7500 to CAD 14,500	CAD 11,000
Remodel bathroom	CAD 20,000 to CAD 38,500	CAD 29,250
Kitchen countertop height adjustment	CAD 20,000 to CAD 27,500	CAD 23,750
Replace the bathroom floor with a nonslip surface	CAD 9000 to CAD 37,500	CAD 46,500
Through-the-floor lift (only links two floors)	CAD 30,000	CAD 30,000
Porch lift	CAD 9000	CAD 9000
Kitchen renovation	CAD 40,000 to CAD 80,000	CAD 60,000

* Prices vary by location.

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 is made by using different equations. For recurrent costs such as annual operating costs and minor maintenance costs, Equation (5) is incorporated in the developed model. These recurring costs are treated as a uniform series in the cash flows, ensuring a comprehensive assessment of their present value over the building's life cycle.

$$PW = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \quad (5)$$

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 n 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 (6) is incorporated into the developed model.

$$PW = F(1+i)^{-t} \quad (6)$$

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 cash flow diagram formats for use in comparative analysis. The alternative with the highest present worth serves as the favored 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 life cycle.

To ensure clarity in the selection process, Table 4 presents the criteria and assumptions used for determining the optimal design.

Table 4. Criteria and assumptions used for determining the optimal design.

Criterion	Description	Assumption
Net present value (NPV)	Calculation of the total value of the design over a specified period.	Study period of 25 years; MARR/interest rate of 5%.
Initial cost	Initial investment required for construction and setup.	Based on RSMeans data and QTO from the BIM model.
Operational cost	Costs associated with running and maintaining the house, including energy consumption and minor repairs.	Assumes standard energy rates and maintenance schedules.
Maintenance/replacement cost	Costs for regular upkeep and any required modifications over the life cycle of the house.	Considers proactive integration of AIP features vs. retrofitting costs.
Resale value	Potential future market value of the property.	Assumes growing demand for accessible and adaptable housing options.

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 because of their influence on 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 compare options easily during the conceptual design stage, which is a novel feature of the developed model. In this study, the primary objective is to compare various design alternatives and illustrate that integrating aging-in-place (AIP) requirements at the conceptual stage yields a higher net present value (NPV), emphasizing the economic advantages and long-term value of the early integration of AIP requirements in the design process. This approach offers a clear, quantitative basis for recommending the incorporation of AIP features in future housing designs.

4. Model Development and Testing

To assess the capability and functionality of the developed model, encompassing input parameters, pertinent criteria, subsequent analytical processes, and output generation, testing was conducted using a case study of a two-story residential structure located in Ottawa, Ontario, Canada, as depicted in Figure 5. This approach aimed to test the model's effectiveness in integrating LCCA and BIM and served as a foundational step in validating the model's predictive accuracy and usability. Future efforts will focus on broader validation across multiple case studies and stakeholder feedback, providing a comprehensive roadmap for enhancing its applicability and reliability in diverse architectural contexts. 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. In contrast, Alternative 2 maintains the same size and exterior elements and design as Alternative 1 but incorporates aging-in-place features, such as wider doors and hallways, an elevator, and modifications to the bathroom and kitchen for enhanced accessibility. Both alternatives include 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 m. 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. Figure 6 shows the developed LCA plug-in and associated features. In this plug-in, the 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 for use by the LCCA plug-in.

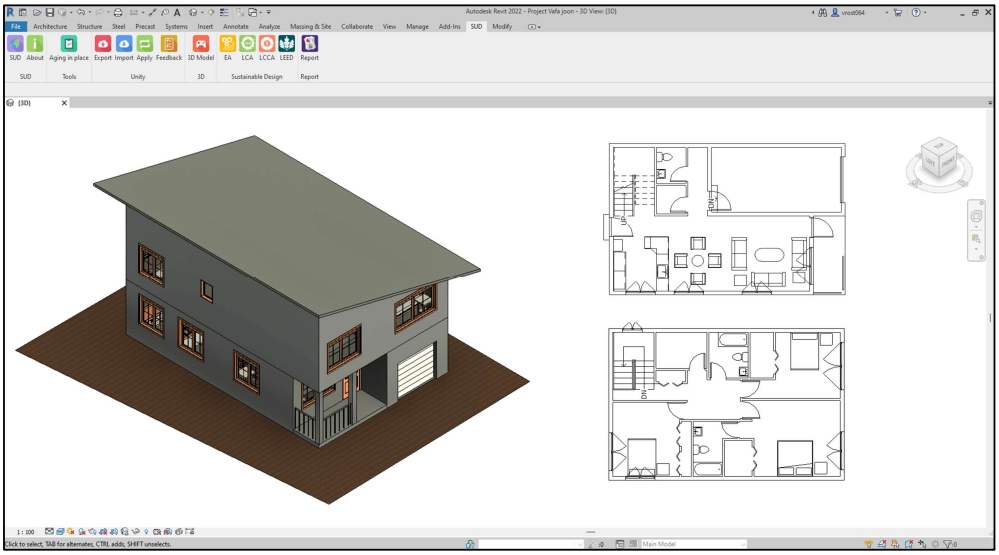


Figure 5. Proposed 3D BIM model (alternative 1, conventional design).

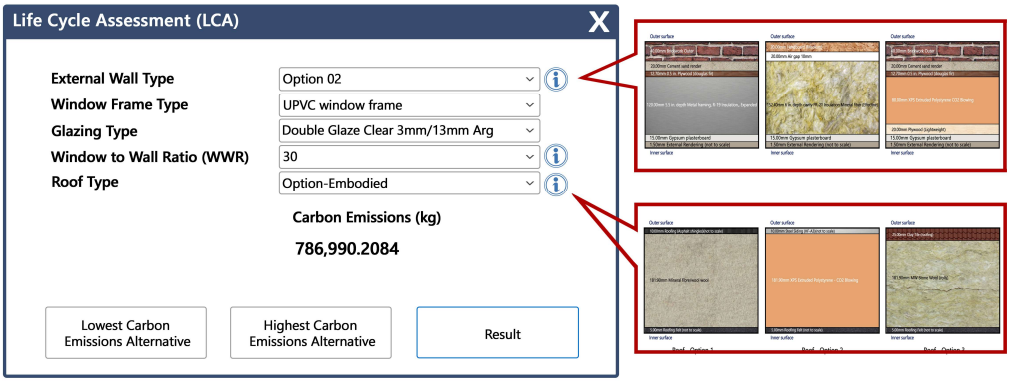


Figure 6. Life cycle assessment plug-in.

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 study period is assumed to be 25 years, aligning with the typical lifespan of major building components and systems, which provides a meaningful timeframe for evaluating long-term costs and benefits. The MARR rate is assumed to be 5%. These values serve as baseline assumptions for this study; however, they may vary based on specific project contexts and regional differences. Importantly, the model is flexible, allowing users to input their own values for these parameters to suit their specific project needs. End-users are encouraged to adjust these parameters to reflect their unique circumstances and project requirements. 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, associated costs, and more. Microsoft Excel and MySQL were utilized as external databases to store and manage these data effectively. 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 the 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 Figure 7.

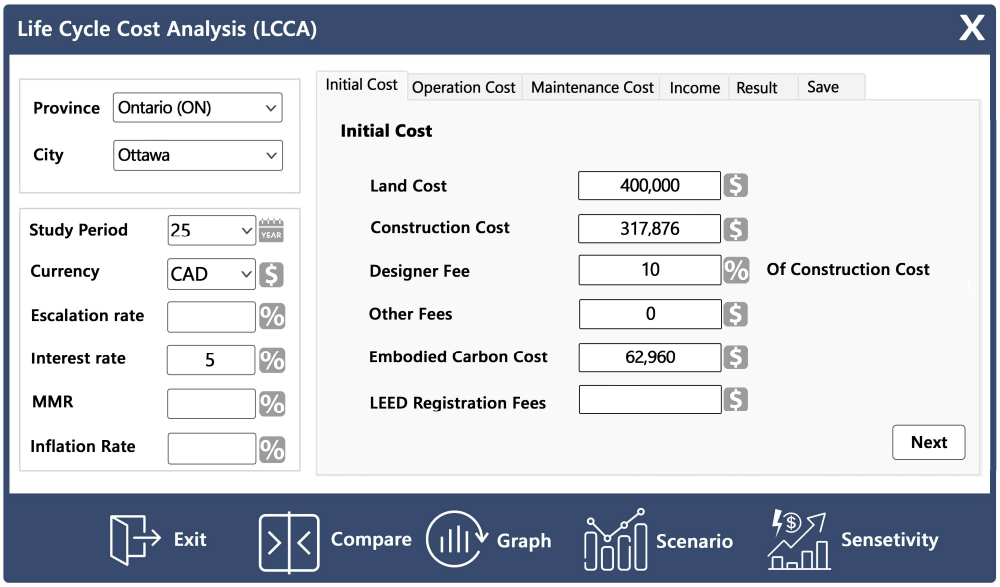


Figure 7. Initial cost and other entries.

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 CAD 317,876 for Alternative 1 and CAD 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 in Alternative 2 as being part of the AIP requirements. Additionally, the designer fee was assumed to be 10% of the construction cost derived from standard fee structures in architectural and engineering practices, such as those outlined in the "A GUIDE TO Determining Appropriate Fees for the Services of an Architect" published by the Royal Architectural Institute of Canada (RAIC). In addition, the carbon cost was calculated and incorporated into the plug-in automatically.

Moving to the next step, which is dedicated to calculating the operating costs, data are 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 to simulate 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 parameter input, including energy unit cost and annual minor maintenance or repair costs as percentages, as shown in Figure 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. The subsequent step delves into the major replacement costs. Over the project's

life cycle, components may require replacement or significant repairs because of 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. The associated costs are sourced from the 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 are not considered in either alternative since they are assumed to be the same. For Alternative 1, which lacks the aging-in-place requirements, future modifications are accounted for, as shown in Figure 9.

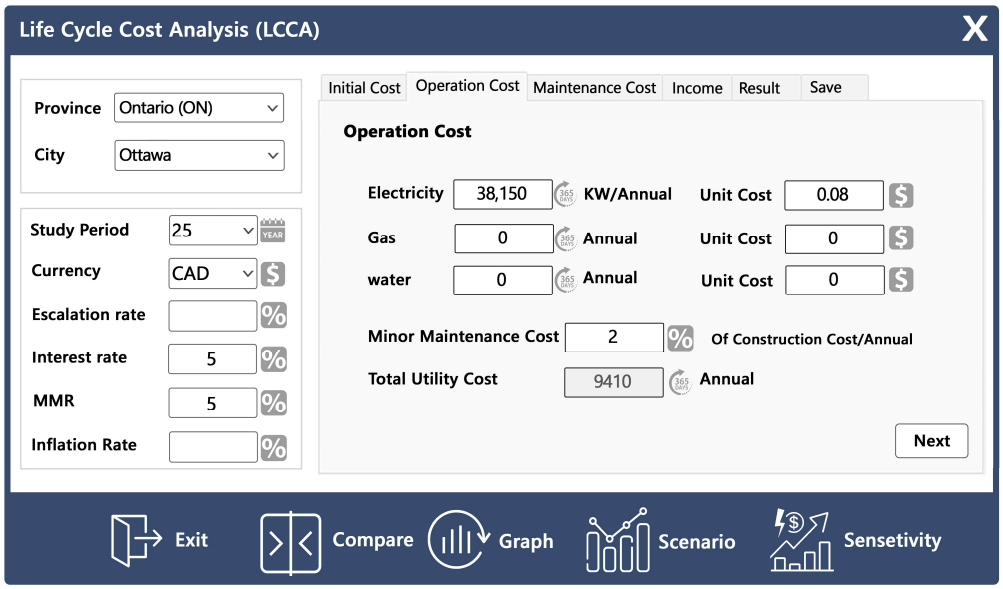


Figure 8. Operational cost data entry.

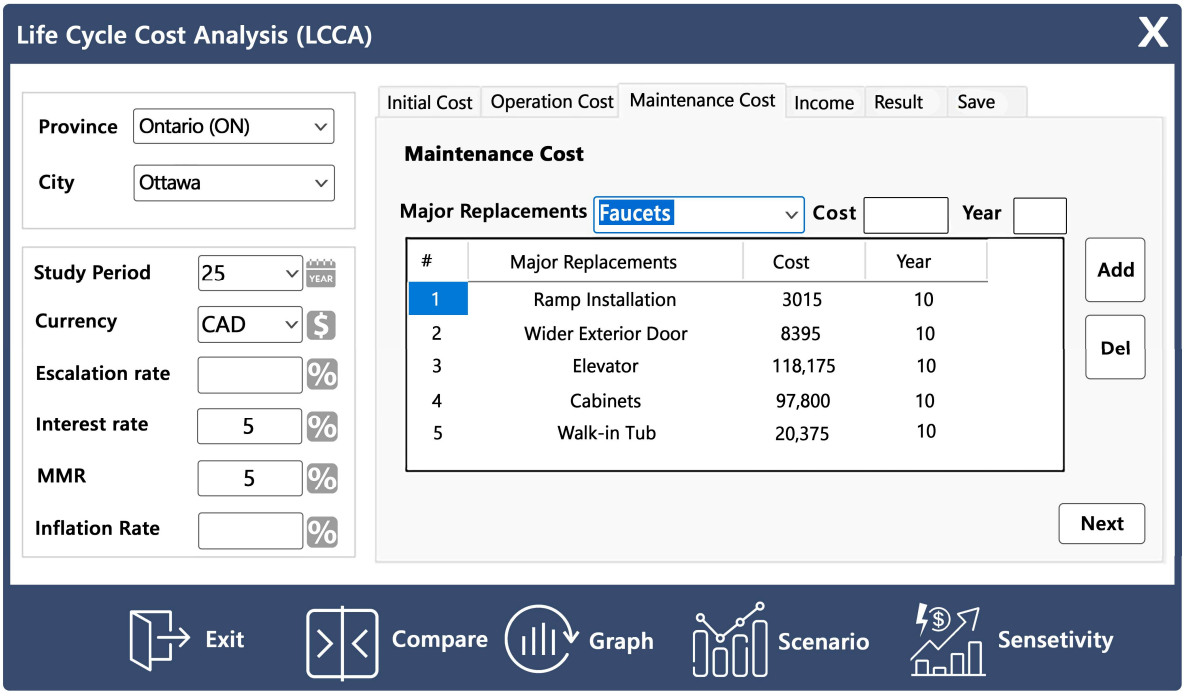


Figure 9. Major replacement cost data entry.

The subsequent step is dedicated to entering the revenue, encompassing details such as potential rent value, salvage value, or resale value, as shown in Figure 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 costs, operational costs, and salvage/resale value. The summation is presented in detailed tables, encapsulating the project's life cycle cost. The plug-in generates a comprehensive cash flow in a tabulated format delineating all the parameters, their respective present worth, and the net present value (NPV), as shown in Figure 11. For additional clarity, users can visualize the cash flow diagram, enhancing their understanding of the financial implications, as shown in Figure 12. Figures 13 and 14 showcase the plug-in's 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 Figure 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 decision-making and knowledge sharing among stakeholders.

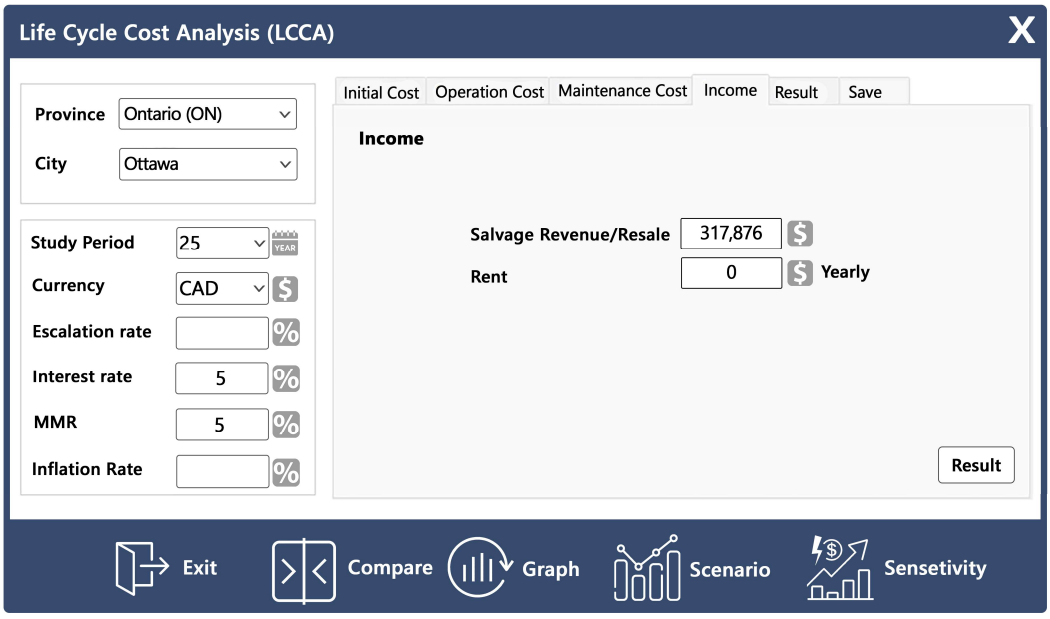


Figure 10. Income revenue data entry.

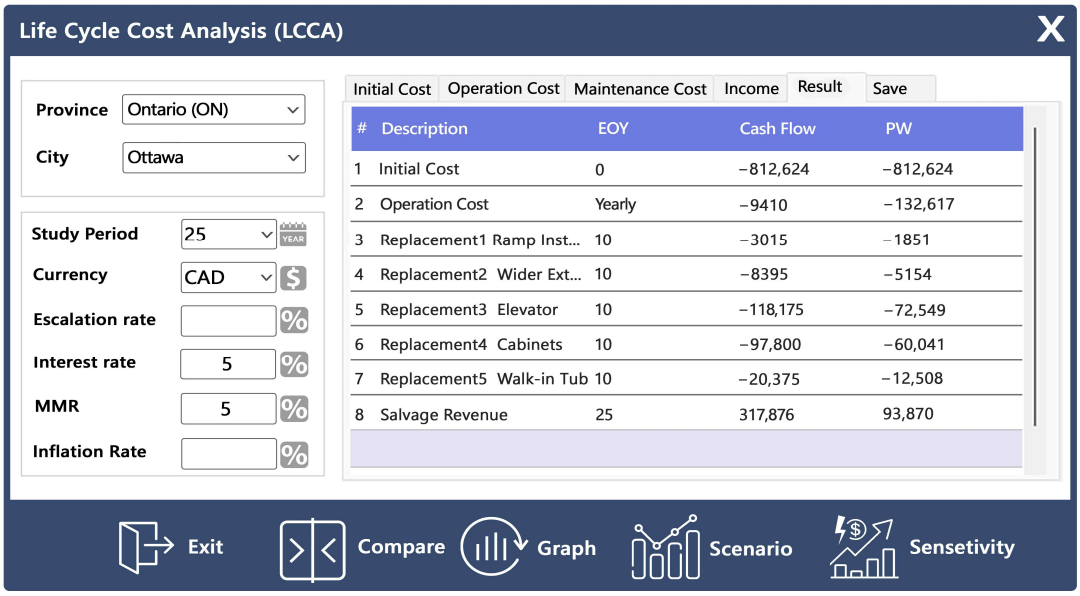


Figure 11. LCCA results.

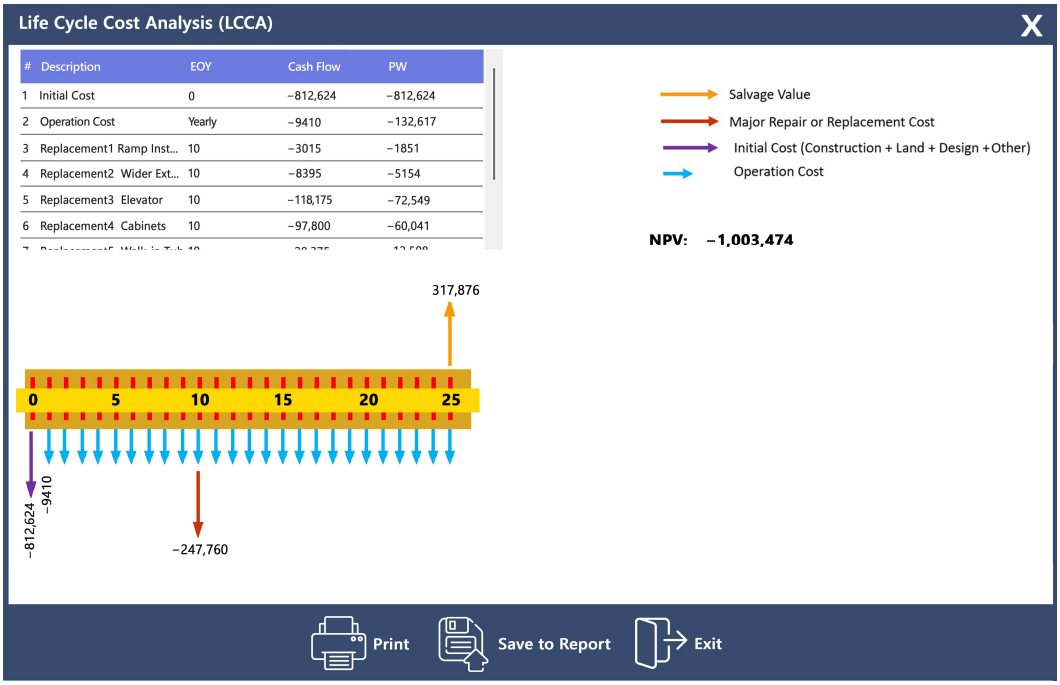
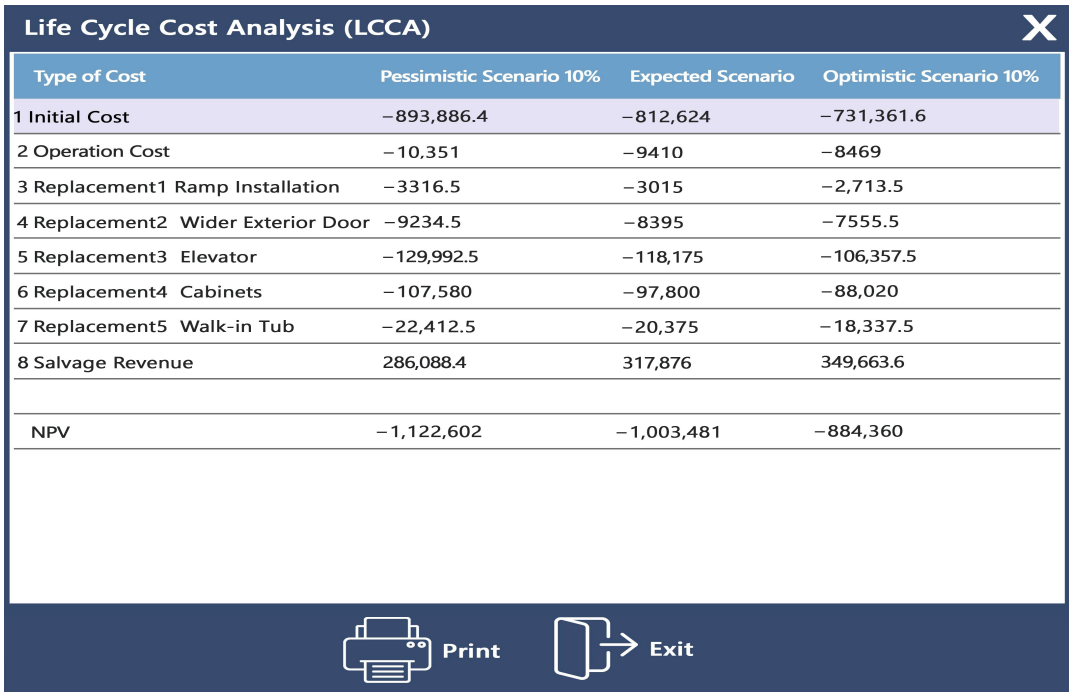
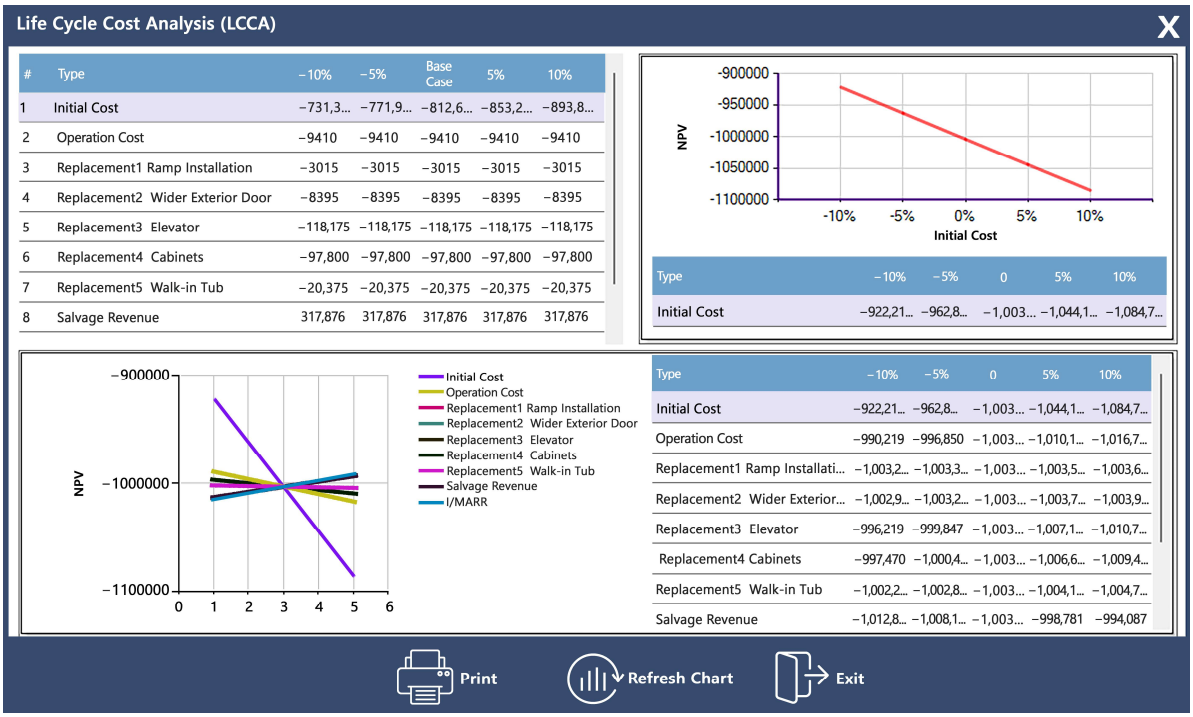


Figure 12. LCCA results (cash flow and NPV).



Type of Cost	Pessimistic Scenario 10%	Expected Scenario	Optimistic Scenario 10%
1 Initial Cost	−893,886.4	−812,624	−731,361.6
2 Operation Cost	−10,351	−9410	−8469
3 Replacement1 Ramp Installation	−3316.5	−3015	−2,713.5
4 Replacement2 Wider Exterior Door	−9234.5	−8395	−7555.5
5 Replacement3 Elevator	−129,992.5	−118,175	−106,357.5
6 Replacement4 Cabinets	−107,580	−97,800	−88,020
7 Replacement5 Walk-in Tub	−22,412.5	−20,375	−18,337.5
8 Salvage Revenue	286,088.4	317,876	349,663.6
NPV	−1,122,602	−1,003,481	−884,360

Figure 13. Scenario analysis example.



#	Type	−10%	−5%	Base Case	5%	10%
1	Initial Cost	−731,3...	−771,9...	−812,6...	−853,2...	−893,8...
2	Operation Cost	−9410	−9410	−9410	−9410	−9410
3	Replacement1 Ramp Installation	−3015	−3015	−3015	−3015	−3015
4	Replacement2 Wider Exterior Door	−8395	−8395	−8395	−8395	−8395
5	Replacement3 Elevator	−118,175	−118,175	−118,175	−118,175	−118,175
6	Replacement4 Cabinets	−97,800	−97,800	−97,800	−97,800	−97,800
7	Replacement5 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	−922,21...	−962,8...	−1,003...	−1,044,1...	−1,084,7...

Type	−10%	−5%	0	5%	10%
Initial Cost	−922,21...	−962,8...	−1,003...	−1,044,1...	−1,084,7...
Operation Cost	−990,219	−996,850	−1,003...	−1,010,1...	−1,016,7...
Replacement1 Ramp Installati...	−1,003,2...	−1,003,3...	−1,003...	−1,003,5...	−1,003,6...
Replacement2 Wider Exterior...	−1,002,9...	−1,003,2...	−1,003...	−1,003,7...	−1,003,9...
Replacement3 Elevator	−996,219	−999,847	−1,003...	−1,007,1...	−1,010,7...
Replacement4 Cabinets	−997,470	−1,000,4...	−1,003...	−1,006,6...	−1,009,4...
Replacement5 Walk-in Tub	−1,002,2...	−1,002,8...	−1,003...	−1,004,1...	−1,004,7...
Salvage Revenue	−1,012,8...	−1,008,1...	−1,003...	−998,781	−994,087

Figure 14. Complete sensitivity analysis.

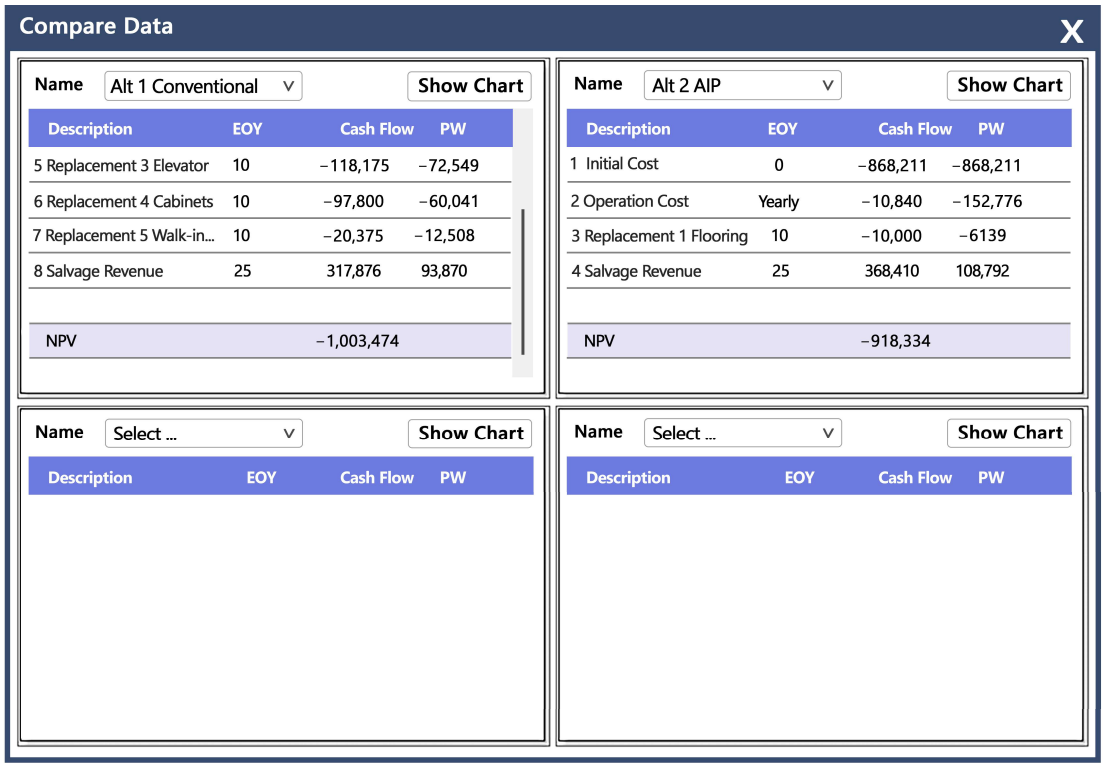


Figure 15. Comparison of different alternatives.

5. Results, 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. The recent advancements in BIM and LCCA integration demonstrate the increasing relevance and application of these methodologies in the architectural and construction industries. Research by Altaf et al. [43] highlights the potential of BIM in optimizing design processes, reducing life cycle costs, and enhancing energy efficiency through early-stage decision-making, aligning with the findings of this study. Additionally, the work by Lu et al. [44] on the integration of BIM and LCCA demonstrates the essential role of this integration in the economic sustainability assessment of buildings, further supporting the approach adopted in this research. Moreover, recent developments in BIM technology in promoting intelligent construction by He [45], proposing an engineering safety accident prediction model for the construction of age-friendly houses, underscore the significance of proactive design interventions. These studies collectively reinforce the value of integrating BIM, LCCA, and AIP principles, providing a robust framework for addressing the needs of the aging population while ensuring long-term economic viability and sustainability.

This study focuses on the early stage of design, because of its importance, with the aim to provide architects and stakeholders with valuable insights into the economic implications of designing AIP homes. It also 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 plug-ins 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 for 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 consists of a two-story house to be built in Ottawa, Ontario, Canada, and the results yielded 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 with 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 requires extensive retrofitting and alterations. These post-construction modifications can result in substantially higher costs compared with 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 because of 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 with 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 Figure 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, as shown in Table 5. 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 the 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.

Table 5. Comparison of economic costs for Alternatives 1 and 2.

Cost Category	Alternative 1	Alternative 2
Initial cost	CAD 812,624	CAD 868,211
Operation cost (Yearly)	CAD 9410	CAD 10,840
Replacement cost (for AIP items only; assumed at year 10)	CAD 247,760	CAD 0
Salvage/resale value	CAD 317,876	CAD 368,410
Net present value (PV)	CAD −1,003,474	CAD −918,334

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 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 plug-ins 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. Furthermore, testing the model on a single case limits the generalizability of our findings. Future research should include multiple case studies to validate the robustness and applicability of the proposed model across different contexts. Incorporating a broader range of case studies would provide a more comprehensive evaluation of the model's performance and reliability, further establishing its utility in facilitating decision-making processes during the early stages of design. In addition, future research could benefit from more extensive validation efforts. This includes conducting usability evaluations with potential end users to assess the practical application and user-friendliness of the integrated model.

6. Conclusions

In conclusion, this paper presented a comprehensive methodology for integrating BIM and LCCA to support the design of AIP homes. The four-phase approach starts with data collection and integration, progresses through 3D modeling, quantity take-off, energy analysis, and LCA simulation, and results in an automated LCCA, establishing a robust framework for designers and stakeholders. The integration of real-time data from aging-in-place requirements, LCA, and energy analysis plug-ins ensures accuracy and immediacy in design-related decisions. The LCCA plug-in, 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 can 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 plug-in 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.

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