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A Building Information Modeling-Life Cycle Cost Analysis Integrated Model to Enhance Decisions Related to the Selection of Construction Methods at the Conceptual Design Stage of Buildings

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Abstract

Life Cycle Cost Analysis (LCCA) provides a systematic approach to assess the total cost associated with owning, operating, and maintaining assets throughout their entire life. BIM empowers architects and designers to perform real-time evaluations to explore various design options. However, when integrated with LCCA, BIM provides a comprehensive economic perspective that helps stakeholders understand the long-term financial implications of design decisions. This study presents a methodology for developing a model that seamlessly integrates BIM and LCCA during the conceptual design stage of buildings. This integration allows for a comprehensive evaluation and analysis of the design process, ensuring that the development aligns with the principles of low carbon emissions by employing modular construction, 3D concrete printing methods, and different building design alternatives. The model considers the initial construction costs in addition to all the long-term operational, maintenance, and salvage values. It combines various tools and data through different modules, including energy analysis, Life Cycle Assessment (LCA), and Life Cycle Cost Analysis (LCCA) to execute a comprehensive assessment of the financial implications of a specific design option throughout the lifecycle of building projects. The development of the said model and its implementation involves the creation of a new plug-in for the BIM tool (*i.e.*, Autodesk Revit) to enhance its functionalities and capabilities in forecasting the life-cycle costs of buildings in addition to generating associated cash flows, creating scenarios, and sensitivity analyses in an automatic manner. This model empowers designers to evaluate and justify their initial investments while designing and selecting potential construction methods for buildings, and enabling stakeholders to make informed decisions by assessing different design alternatives based on long-term financial considerations during the early stages of design.

Keywords

Life Cycle Cost Analysis (LCCA), Building Information Modeling (BIM), Cost Decision, Modular Construction and 3D Concrete Printing

1. Introduction

Making informed cost decisions at the conceptual design stage is essential for ensuring project's feasibility and overall success throughout its lifecycle. Therefore, LCCA should be employed early during the design process to refine its economic feasibility, ultimately reducing the future costs of proposed projects. Construction practitioners often face pressure to reduce the costs to satisfy owners and then, focus on the initial construction expenses rather than future operating costs [1]. Commonly, this approach results in an increase in the operational and maintenance expenses over the project's life cycle.

The construction industry uses LCCA to compare different construction or design alternatives for any building or system by considering their costs and associated revenues over its life [2] [3]. However, the adoption of LCCA by the owners of residential buildings remains uncommon due to the lack of quantifiable data, deficiency in actual performance measurements, and uncertainty about potential future savings, despite the numerous benefits that LCCA offers to the construction industry [3].

Adopting innovative design and construction methods can enhance data quantification, specify potential future savings, and benchmark LCCA performance in buildings. These innovations may include new technologies like Building Information Modeling (BIM). BIM stands as a sustainable technology that offers comprehensive contributions to the design and construction processes of environmentally responsible and resource-efficient buildings, with the primary goal of creating a detailed multi-disciplinary 3D digital design model. Through BIM-powered robotic layout systems, prefabricated construction and 3D concrete printing methods are introduced to expedite the construction of projects. Notably, the critical areas with significant potential to enhance efficiency and advancements in low-carbon construction are modular off-site prefabrication and 3D concrete printing through BIM implementation. Additionally, BIM has proven to be effective in facilitating the design integration of 3D concrete printing into construction practices, adaptable to both small and large-scale building projects. Consequently, the adoption of modular prefabrication and 3D printing in construction holds the potential to transform the current conventional and fragmented built environment [4].

According to [5], various techniques are employed to reduce the total Life Cycle Cost (LCC) of a construction project and to increase revenue. Some of the mathematical approaches and theories used to evaluate the life cycle cost of buildings include Net Present Value (NPV), Mixed Integer Linear Programming (MILP), Monte Carlo Simulation, the Markov Method, and multi-objective optimization using Neural Networks [6].

The life cycle cost analysis concept is integral to the design, implementation and management of projects, emphasizing the comprehensive and long-term costs associated with assets such as buildings. However, the impact of LCCA on cost related decisions has not been considered while selecting various construction methods for buildings, and yet, the authors are not able to find established models for using LCCA to select suitable construction methods at the conceptual design stage of buildings.

Therefore, this study presents a methodology to develop a model that seamlessly integrates BIM and LCCA during the conceptual design stage to supply project teams with detailed information on how different design options would impact the long-term costs. The integration allows for a comprehensive evaluation and analysis of the design by employing conventional, modular and 3D concrete printing as alternative design methods. The model will combine various tools and data through different modules that include energy analysis, Life-Cycle Assessment (LCA), and Life-Cycle Cost Analysis (LCCA) to facilitate the execution of a comprehensive assessment of the financial implications of a design option throughout its life cycle.

2. Literature Review

According to [7], the LCCA technique is one of the practical tools used to incorporate economic feasibility in construction projects. Dhillon (2010) [8] emphasized that the knowledge of economics and economics-related information and approaches are required in life cycle cost calculation since all potential costs are calculated by considering the time value of money. Kirk and Dell'Isola (1995) [9] described LCCA as a management tool for forecasting the total expenses incurred during a building's life, while [10] described it as a decision-making tool for selecting alternative projects. The primary purpose of LCCA is to enhance the decision-making's process to form reasonable judgments on the economic performance of a building through its useful life cycle [11]. Whereas its main objective is to assess the comprehensive economic impact, including the costs associated with various alternatives and, notably, the initial capital investment costs, which significantly influence the overall expenses throughout a project's life cycle [6]. Nonetheless, the ISO 15686-5:2017 methodology for life-cycle costing (LCC) sustainability framework was developed for buildings and construction assets (ISO 15686-5:2017). LCCA is divided into four typical elements to cover the overall projected costs of the building throughout its life-cycle: 1) initial cost (construction cost); 2) operation and maintenance costs; 3) replacement costs; and 4) end-of-life costs, which include revenues and residual value [12]. The lowest life-cycle cost (lowest LCC) method is the easiest and most interpreted measure of economic evaluation for construction projects. The other common methods used for the economic evaluation include: Net Savings (or Net Benefits); Savings-to-Investment Ratio (or Benefit-to-Cost Ratio); Payback Period (PP); and Internal Rate of Return (IRR). These are consistent with the lowest possible LCC measure of the evaluation method, where the same parameters and length of the study period are used [13]. The LCCA method converts all cash flows to the present values (PV) by discounting them to a common time horizon, usually the base date.

Generally, the main focus on costs tends to center around the initial construction cost. However, it is crucial to acknowledge that, in many instances, the operations and maintenance (O&M) cost surpasses the initial construction cost, particularly the operational costs of buildings, which is recognized for consuming roughly 40% of the total global energy [14] [15]. According to [14] [16], the high building operating cost is linked to the energy consumption necessary to sustain thermal comfort within the building, which is affected by several factors, including climate, occupant behaviour, and heating and cooling system. The energy utilized for heating and cooling constitutes a significant portion, ranging from 17% to 73% of the total energy consumption for the building. However, the most challenging factor in using LCCA as an economic evaluation method is to understand the economic implications of the different design alternatives for a building, including the energy performance and associated environmental impacts. These challenges arise from the limited access to reliable cost data, disparities in life cycle cost standards, accessibility of design information, and other important attributes of the design stage [6]. Additionally, complexities extend in quantifying these impacts and expressing them in monetary terms that can be easily understood by investors at the design stage [13]. Considering these challenges, research gravitates to using LCCA integrated with BIM during the conceptual design phase to identify a project's optimized Life Cycle Cost (LCC), as the integration of BIM and LCCA has been acknowledged for enhancing the execution of more economical and sustainable buildings [14] [17].

BIM can be leveraged to develop virtual intelligent models that are capable of integrating with other construction management tools, such as cost estimating at the early design stage of building to promote collaboration, visualization and constructability reviews to benefit investors throughout the building's life-cycle [18].

Furthermore, BIM has positively impacted the way the construction industry designs, builds and manages urban spaces as it contains sufficient information about building's performance analysis, evaluation, and assessments as it easily captures data to support various design options [4] [19]. As a digital process, it also creates and uses a 3D design model of an asset to manage critical data to form a reliable basis for the decision-making through its life cycle [20], thereby empowering architects and designers to perform real-time evaluations to achieve low-carbon buildings and explore various design options. Altaf *et al.*, (2023) [14] developed a model that considers the life cycle cost and energy efficiency by utilizing BIM-based LCCA integration to assess the building's envelope in an attempt to optimize energy demand and reduce associated costs. Rad *et al.*, (2021) [6] adopted a comprehensive LCC methodology during the early design phase to integrate a model that combines LCC and BIM in order to support the design of resilient buildings and to improve the accuracy of cost indicators for better cost optimization. The study developed a plug-in in a BIM tool to estimate the overall cost of a building project, assisting designers in choosing cost-efficient and resilient design alternatives. The idea behind the LCCA method is to support designers in quantifying the relevant long-term investment decisions on the cost of an asset over its life cycle early during the design stage. Its integration with various tools and data through energy analysis and Life-cycle Assessment (LCA) within BIM tool aids in facilitating the execution of a comprehensive assessment of the financial implications of a design option throughout the life-cycle of these structures. Hence, this study will develop a methodology that integrates BIM with lifecycle cost analysis at the conceptual design stage by using conventional, modular prefabrication and 3D concrete printing construction methods to evaluate all the relevant costs and to precisely predict the lifecycle costs. The study considers initial construction costs and accounts for long-term operational, maintenance, and salvage values. The development and implementation of the integrated model involves the creation of a new plug-in in BIM tool (Autodesk Revit). This plug-in will enhance the tool's capabilities by enabling it to forecast the life-cycle costs of buildings, generate cash flows, and perform scenario and sensitivity analyses in an automatic manner.

3. Development Methodology

The objective of the development's methodology is to automate the evaluation of the total project costs for all design alternatives and to select the one that ensures the building will provide the lowest overall cost of ownership coherent with its overall functionality within BIM environment at the conceptual design stage by using the three construction methods. The goal is to identify the most cost-efficient building's design associated with a construction method over the life cycle of a building. The methodology will use the capabilities of BIM tool (*i.e.*, Autodesk Revit) to perform a comprehensive LCCA. That analysis involves establishing design alternatives, determining the study period, estimating costs, computing life-cycle costs and analyzing results following the construction industry's classification of monetary expenses such as initial costs, running costs (utility, operation, and maintenance), revenues and salvage value. This would help stakeholders evaluate and justify their initial investments and enable them to make informed decisions by assessing different design alternatives based on long-term financial considerations during the early design stages in a timely manner. This is achieved by following five essential steps, as illustrated in **Figure 1**.

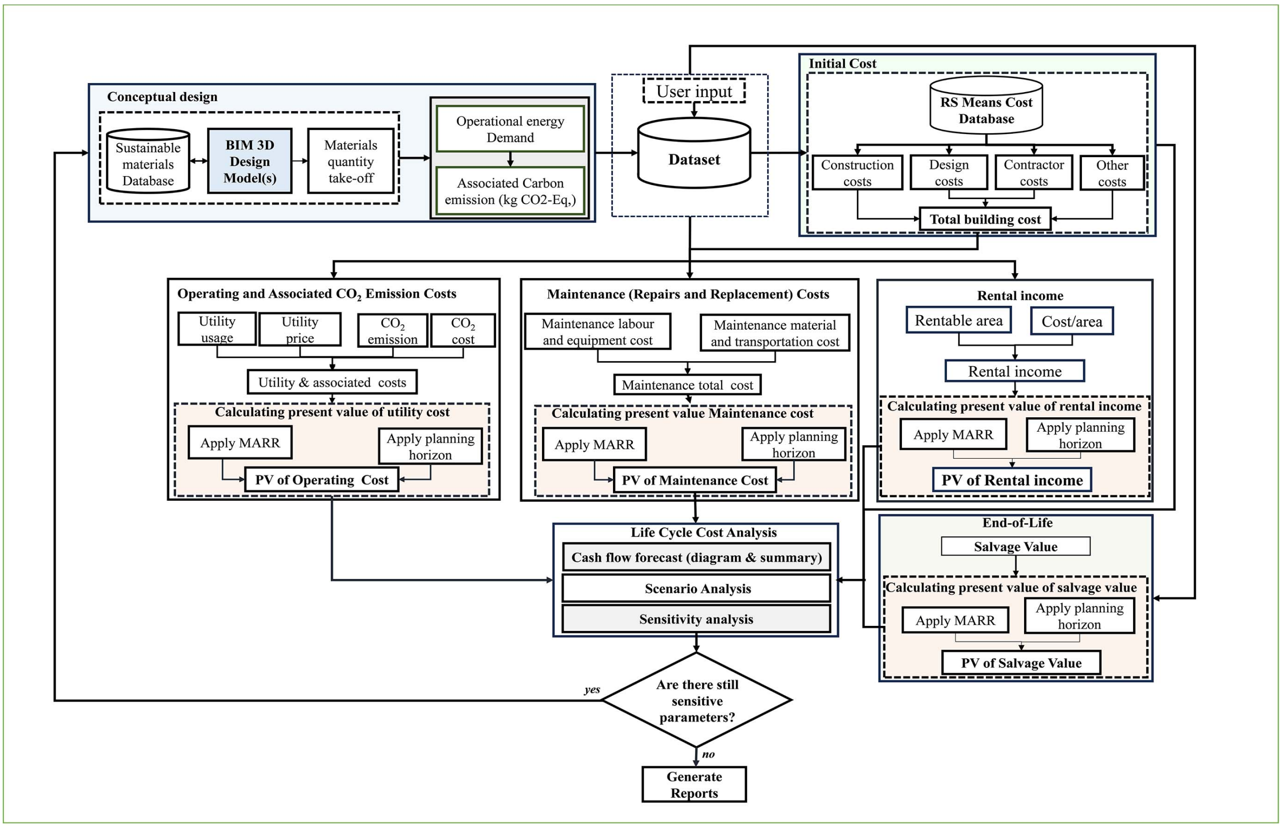

Figure 1. BIM-LCCA model's integration process.

The first step of the process starts by creating and exploring design options where the conventional construction is set as the baseline design to compare the other two design's alternatives. The associated process involves estimating and analyzing the costs related to the three options, incorporating the initial construction cost, operational utility cost, and maintenance costs that include the minor repair and major replacement. **Table 1** provides a comprehensive overview of the cost components, along with the pertinent information and data sources for facilitating the development process and estimating the costs.

Table 1. Cost components and data sources for the BIM-LCCA model.

Cost Components	Data Definition Source	Cost Data Source
Construction Initial capital required for construction project	▪ BIM model (Autodesk Revit) ▪ Material quantity take-off ▪ Material specification	▪ Detailed cost estimate ▪ Industry guidelines (e.g., RS Means) ▪ Related literature
Operating Utilities Energy consumption for electricity, natural gas and water	▪ BIM Model (Autodesk Revit) ▪ Energy simulation result (Design Builder tool)	▪ Industry guidelines (e.g., utility rates)

Continued

Carbon Embodied carbon associated with project materials and processes. Operational GHG emissions from utilities	▪ BIM Model (Autodesk Revit) ▪ Energy Simulation result (Design Builder tool) ▪ LCA result (open LCA) ▪ Emission factors	▪ Carbon tax ▪ Government guidelines (e.g., Intergovernmental Panel on Climate Change (IPCC)) ▪ GHG protocol
Maintenance (Repair and Replacement) Annual repairs and periodic replacement of major building components reaching their end of life	▪ Industry organizations (BOMA) ▪ BIM Model (Autodesk Revit) ▪ Material quantity take-off ▪ Material specification	▪ Industry guidelines (e.g., RS Means) ▪ Related literature
Rental Income Using a rentable area measurement, a basis for a tenant's rental payments	▪ BIM Model (Autodesk Revit) ▪ Rental Market Report (CMH)	▪ Industry guidelines (e.g., Canada Mortgage and Housing Corporation (CMH)) ▪ Related literature
Salvage Value Value of an asset after it has fully depreciated or has reached/beyond its useful life	▪ Industry guidelines and practices	▪ Industry guidelines ▪ Related literature

Following that, the quantity take-off of the 3D model's materials is generated and exported to a functional database that will be used in other phases for additional calculations and analysis. Furthermore, BIM tool will be integrated with energy analysis tool for simulation and to determine the operational energy of the building by using the materials quantity take-off and building parameters to determine the energy consumption for utilities (such as electricity, heating and cooling) at the operation stage. Finally, life cycle assessment (LCA) will be used to determine the carbon emissions of the designed model. Life cycle carbon emission calculations (LCCE) will be based on the study conducted by [21] and integrated within BIM workflow that comprises the material production, construction, operation, and demolition stages. The created 3D BIM model will be the basis for all the calculations and analysis of results, including the integration with LCCA.

Step two, focuses on calculating the initial costs, including construction costs, design and contractor fees, materials, and other costs for the building's project by using the generated QTO and the unit costs retrieved from RSM eans cost database for conventional and modular building's elements. The literature will be used to gain insight into the building elements and construction processes related to 3D concrete printing.

Step three, consists of the future costs and revenue associated with the operational stage. Utility and carbon emission costs will include the energy consumption, which will be analyzed by using a BIM-based energy simulation tool (Design builder) to generate the consumption rate as previously mentioned. The associated energy consumption prices will be collected from sources that are specified in **Table 1**. The utility annual usage and associated unit prices are then computed via the developed plug-in and stored in the functional database as energy cost information to be utilized for evaluating the life cycle cost of the building. Furthermore, the CO_2 emissions' estimation method will be applied to quantify the cost associated with the impact of energy consumption.

Maintenance costs are categorized into minor repairs and major replacements. Minor repairs are small-scale building maintenance tasks and fixes that address specific issues. Regular building maintenance costs, including repairs, management, and associated fees, will be considered as a percentage of the initial costs and will be charged annually when obtained from the historical data and expert's opinions. Replacement costs are anticipated to be future expenses for major building components required to maintain a facility in good operational condition. Examples of replacement costs considered in this study are flooring, painting, windows, roof covering, and HVAC systems incurred when the components reach the end of their useful life. This study will adopt the life expectancy of components based on the study done by [22], while the associated cost will adopted from R. S. Means cost data.

Rental revenue refers to the inclusion of rental income as a component in the analysis to attain the financial feasibility of a building over its life-cycle, particularly when the asset is intended for rental purposes, such as residential buildings and commercial spaces. The expected and estimated rental income is retrieved from rental guidelines for this study and the projected rental revenue is then integrated into the cost analysis to assess the project's financial feasibility.

Step four, focuses on the salvage value toward the end-of-life, the study considers and implements two types end-of-life salvage. Salvage value represents the estimated worth of an asset at the end of its designated service period. Since this study considers different design alternatives and associated construction methods, each of those has a predetermined structure based on its particular type and construction characteristics. Therefore, the salvage value will be based on those considerations. For example, conventional buildings will have a zero salvage value at the end of the building's lifetime, while modular and 3D concrete printing buildings will be deconstructed.

The deconstruction cost includes the disposal of waste generated by the building, labour cost, and equipment and/or machinery cost for disassembled building materials for the purpose of reusing, refurbishing, or recycling. Equipment owning costs for deconstruction will be estimated through several components: depreciation using the straight-line method, investment cost based on the average investment value over the equipment's life, insurance covering fire, theft, accident, and liability, ownership tax and equipment licenses, and rent and maintenance costs for equipment storage. These costs can be calculated on an annual or hourly basis, but in this study, they will be expressed as an hourly cost. Operating costs, incurred while the equipment is in use, may vary depending on equipment usage and job operating conditions. Major elements of operating costs include fuel, service, repair, tires, special items, labor, and logistics. All associated costs will be retrieved from historical data or equipment manufacturer recommendations, such as the Caterpillar Performance Handbook [23]. Hence, the user has the flexibility to enter those costs as required.

Quantifying and Normalizing the Life Cycle Costs

To calculate the LCC, all the annual and one-time incurred costs, along with revenue income at various periods throughout a building's life cycle, are adjusted to the initial values by using the present value (*PV*) method, which can be computed via Equation (1), while for uniform annual payments calculation is done via Equation (2) that considers annual payments associated with constant percentage increases or decreases, whereas Equation (3) is used for single payments occurrence.

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

$$PV = A\left[\frac{1-(1+j)^n (1+i)^{-n}}{i-j}\right] \quad \text{Equation (2)}$$

$$PV = \frac{F}{(1+i)^n} \quad \text{Equation (3)}$$

where *PV*: present value, *A*: annual value, *F*: future value, *i*: *MARR*, *n*: planning horizon, *j*: annual constant percentage increase or decrease.

LCCA's calculation will employ the Net Present Value (NPV) method to aggregate the present values (*PV*) of the series of payments and future cash flows. Therefore, the total LCCA of the building involves the integration of all costs associated with the life cycle process using the NPV method within a specified time horizon and a discount rate using Equation (4).

$$\text{LCCA} = \text{initial cost} - \sum(\text{O\&M}) + \text{rental icome} + \text{salvage value} \quad \text{Equation (4)}$$

Notably, the equations used in this study for quantifying and normalizing the life cycle costs, labeled as Equations (1) through (4), were adapted from reference [8]. Additionally, uncertainty associated with LCCA results will be tackled by utilizing the sensitivity analysis, as suggested in a study by [24], to test the sensitivity of NPV for all the cost parameters. In this process, the parameters will be changed one at a time while the other parameters are fixed. Hence, variation in the output is a direct measure of the effect caused by varying a single input.

4. Model's Development

The five phases in developing the integrated model as described in **Figure 1** are executed by customizing and extending the APIs' capabilities of BIM tool using its development kits, which serve as the building blocks for any application. APs allow writing additional programming code to create new functionality to fulfill the needs of the model's integration. The challenges associated with interoperability related to data exchange for the integrated model from one phase to another through specific formats like IFC, gbXML, IDM, etc, are over passed by developing a new plug-in by using the API's of Autodesk Revit© and C# the programming language. The newly created plug-in facilitates the use of essential LCCA data for all quantification, simulation, evaluation and analyses, and the resulting outcomes are displayed in a text-based cost data format.

The integrated model is functional through a user interface within the plug-in, which is designed and developed with utmost user-friendliness, offering an intuitive and seamless collaboration that facilitates user interaction with the underlying model, as shown in **Figure 2**. The model is designed to consider two main building design options (1 to 3 floors and above 3 floors building), three construction methods (conventional, modular and 3D concrete printing) and is developed to execute various actions for life-cycle costing using the embedded data and associated cost evaluation and result simulations. **Figure 3** shows the comprehensive layout of the developed model. The model permits users to access individual buildings' LCC information through various sections such as basic information, cost and revenue (initial, operation, maintenance, rental income and salvage value) and analysis (LCC cash flow, scenario and sensitivity) as shown in **Figure 2**.

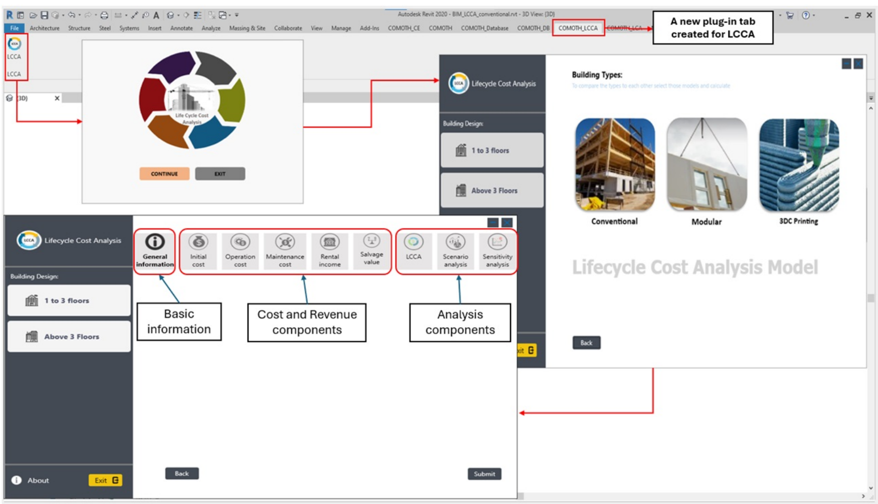

Figure 2. Snapshot of the developed LCCA design model.

Users are required to enter specific information that is essential for conducting the LCCA within BIM environment. This information encompasses the time horizon for each building's type expressed in years, the organization's Minimum Attractive Rate of Return (MARR) as a percentage, contractor's fees as a percentage, monthly utility operating costs, rent costs per unit area, annual cost fluctuations as a percentage, and the type of building's structure, among other parameters. Furthermore, users must complete all the mandatory fields within the user interface (UI). In case the model identifies any missing information in the data entry process, it will trigger a warning to users to enter the missing information, and yet users are prevented from moving forward with the process; hence, the transition of values from that section into the functional database will be disabled until all required fields are appropriately populated.

The model prompts users to first choose the number of floors out of two options (1 - 3 floors and above three floors) and one of the three construction methods (conventional, modular, and 3D concrete printing). The subsequent step involves inputting data into the general information page. While the plug-in automatically populates information such as the gross floor area and perimeter of the building, users are required to specify the time horizon by selecting from the dropdown list, assign a value for the Minimum Attractive Rate of Return (MARR), and designate the cash flow pattern for the analysis. It is essential to note that this plug-in is accurately designed to perform LCCA for two distinct cash flow patterns: uniform and geometric series.

The construction cost of the asset is estimated by generating and exporting the material quantities take-off from the BIM 3D design model. This data is then integrated with R. S. Means cost information to formulate the unit costs followed by the precise project's budget. However, the material and equipment costs for the 3D concrete printed walls are estimated by using data from published studies [25]. Users are expected to input the contractor's fees as a percentage of the construction and other necessary costs, as shown in **Figure 3**.

The operation cost consists of the building's annual energy usage cost for electricity and fuel, as well as for water consumption, besides the associated carbon emission tax. Energy costs are calculated through the integration of the Design Builder tool with BIM tool (Autodesk Revit). The architectural elements and building envelopes are modeled in Autodesk Revit by incorporating the necessary construction data and parameters required to fulfill the performance simulation for the Building Energy Modeling (BEM) workflow. The new plug-in created for the energy modeling helps users to accurately integrate the analysis process of the Design Builder within BIM environment for review and simulation, as shown in **Figure 4**.

To quantify the maintenance costs, users need to enter two separate values. The first value relates to the annual repairs cost, which is calculated using the equal maintenance method. However, the model also allows users to input a specific percentage of the total project cost based on the maintenance rule, while the second is the replacement. For the replacement costs, users can select up to five replacement cycles throughout the entire duration of the study for the major replacement cost. Each selected year is linked to various replaceable building's components, where users have the flexibility to select one or multiple components to be replaced based on the service life of each component. The replacement cost is derived by using R. S. Means online cost data and is escalated to

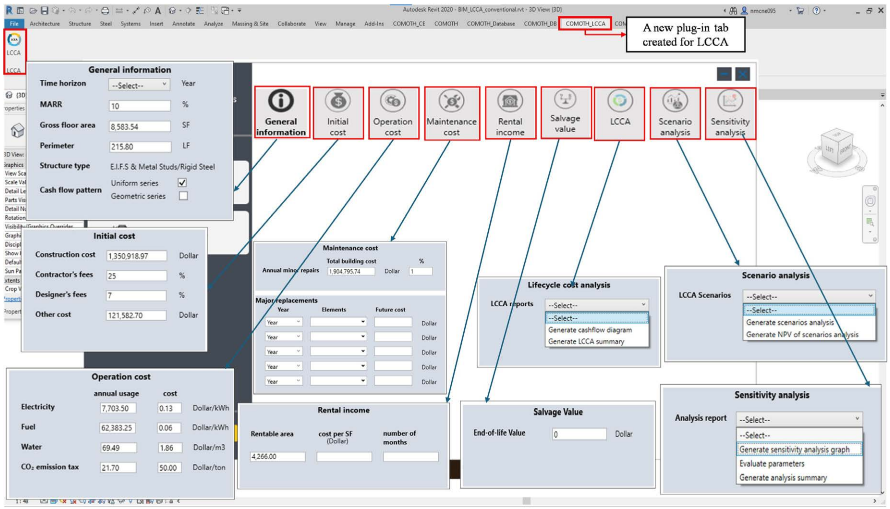

Figure 3. Model's general information, cost, and revenue analysis structure.

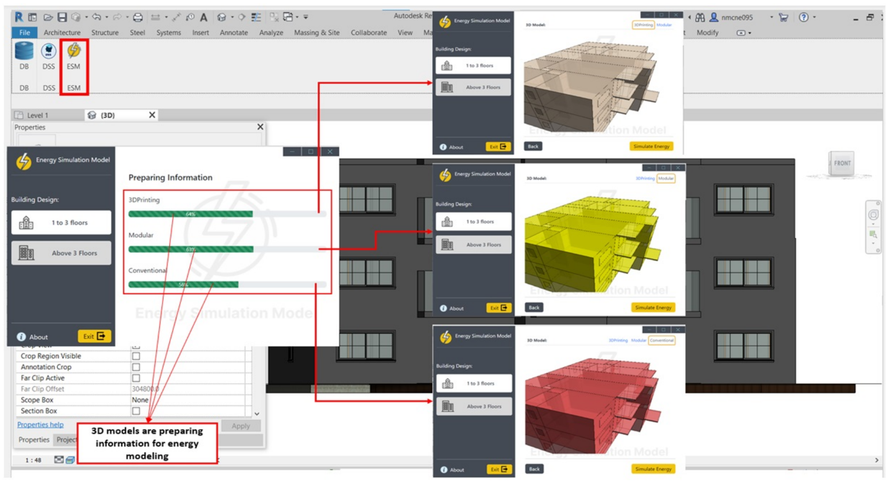

Figure 4. Operational energy analysis for BIM-LCCA model.

base-year costs to their future time of occurrence, as suggested by [13] and linked to the LCCA model from the functional database.

In computing the rental income, the integrated model automatically generates the rentable area from the 3D design model, the generated value is then multiplied by the cost per rentable area and the total number of months, as illustrated in Figure 3. Additionally, users have the option to specify a dollar cost for the salvage value at the end of the asset's life. Nevertheless, in this study, the end-of-life value was assumed to be zero in line with the linear depreciation method that considers the building's salvage value will be zero after its useful life [6]. After entering each cost, users must click the submit button to transmit the provided information and to complete all the associated analyses. The model computes the lifecycle costs at the back end to generate various analyses and reports for users, as shown in Figure 3, which include: 1) LCC report—cash flow diagram and LCCA summary; 2) LCCA scenarios—scenario analysis and NPV of scenario; and 3) Sensitivity analysis—sensitivity graph, sensitive parameters, and sensitivity summary.

5. Model's Testing

The developed model is tested to verify its functionalities and capabilities for the evaluation and selection of associated construction methods (*i.e.*, conventional, modular, and 3D printing) at the conceptual design stage through three identical 3D BIM design models for three-story residential building created by using Autodesk Revit 2020, as shown in **Figure 5**. These 3D design models aim to test and verify the workability, functionality, and performance of the developed model. The buildings are intended to be constructed in Ottawa, ON, Canada, with a total gross area of 8584 ft^2 and a perimeter of 216 lft, and are currently under design. To accurately represent each building's characteristics, its associated materials are customized with additional parameters that define their identity, appearance, graphics, as well as physical and thermal properties. Finally, this study assumes that the three designs have a similar foundation; therefore, all substructural elements and associated materials for works below the floor slab are excluded.

The conventional design of the building consists of a brick veneer/wood frame and is assumed to comprise the wall assembly from exterior to interior brick veneer cladding, drainage cavity, water barriers, Oriented Strand Board (OSB), stud cavity insulation, vapour barrier, and gypsum panel where the inner structure is composed of wood studs that provide structural support. The wood frame allows for adaptability in design, making it easier to customize and modify the structure as needed.

The modular prefabrication design consists of metal studs/rigid steel frame structure designed using Cold-formed Steel (CFS), following BS 5950-1:2000 guidelines and the process outlined in [26]. The floor slab configuration is assumed to be a composite steel corrugated deck, supported by purlins spaced at 1-meter center-to-center, while the external components are considered as thermally insulated sandwich walls and fire-resistant gypsum and insulation for the internal walls. Overall, the modular frame system is designed to meet the range between 35 to 50 kg/m^2, as suggested by [25], for low-rise steel buildings within two to six stories.

The 3D concrete printing method adopted in this study follows the approach proposed by [27]. The building is assumed to be printed by an Ontario-based company called Nidus3D, which utilizes COBOD's BOD 2 gantry system printer and a low-carbon cement, OneCem concrete paste from Lafarge Canada. The 3D concrete printer is transported from Kingston, Ontario, and the technique involves printing concrete without incorporating steel reinforcement. However, the only printed components of the structure will be the interior and exterior walls, as they serve as effective load-bearing walls without requiring additional reinforcement. Additionally, precast hollow-core panels will be used for slabs, as they are subjected to bending, eliminating the need for formwork.

Users can initiate the Life Cycle Cost Analysis for the project using the developed model by accessing it from COMOTH_LCCA tab in Autodesk Revit and following the sequence of commands sequence. The first step in testing the developed model involves populating the general information with all required data. The detailed considerations and assumptions made and used to test the BIM-LCCA model are provided in Table 2.

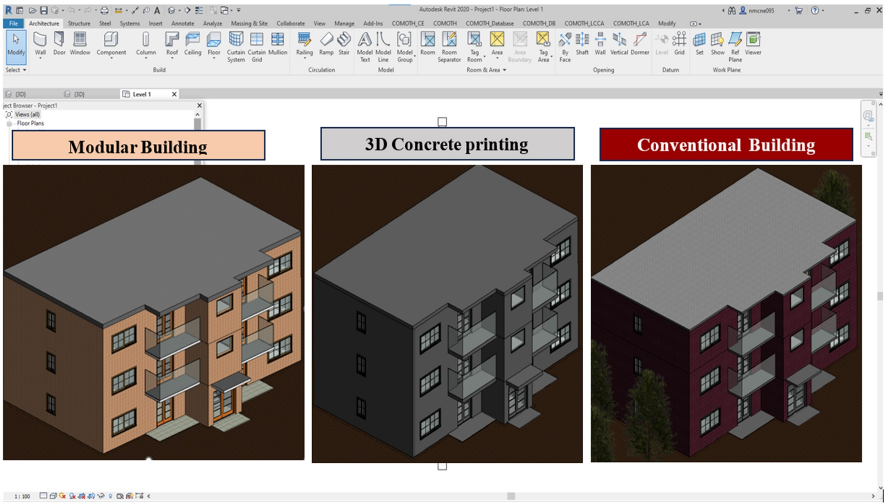

Figure 5. 3D BIM design model(s) used for testing.

Table 2. LCCA input data consideration and assumptions.

Analysis Inputs	Assumed Values	LCCA Considerations
Analysis Period ▪ Expected lifetime of a project or standardized period for LCCA review and assessment	25 year	Residential housing
Discount Rate ▪ Opportunity cost of money for the capital investment	Default value: 10%	Minimum Attractive Rate of Return (MARR)
General Inflation ▪ Increase in overall costs of goods and services	Default value: 4.06%	Based on Canada's current inflation rates
Construction Escalation ▪ Increase in costs of construction materials and labor	Default value: 7.0%	Based on current construction costs increase in Canada

Continued

O&M Escalation ▪ Increase in costs to operate and maintain buildings	Default value: 3.0%	Based on a set rate to align with general inflation.
Rental Escalation ▪ Increase in rental charged to tenants	Default value: 2.5%	Based on the rent increment guideline

First, users specify the planning horizon of 25 years by selecting it from the dropdown list. The MARR is set at 10%, based on Canada's current discount and inflation rates, and representing an average rate over the last ten years [6]. Moreover, 10% serves as a target rate for evaluating the project investment, suitable for average risk, with residential buildings falling under normal risk investments [28]. Next, is the building's total gross area and perimeter, which are automatically populated by the model. Finally, users select a cash flow pattern as required for their LCCA by choosing between uniform and geometric gradient series cash flow, and then to proceed, they click on the submit button, as depicted in **Figure 6**.

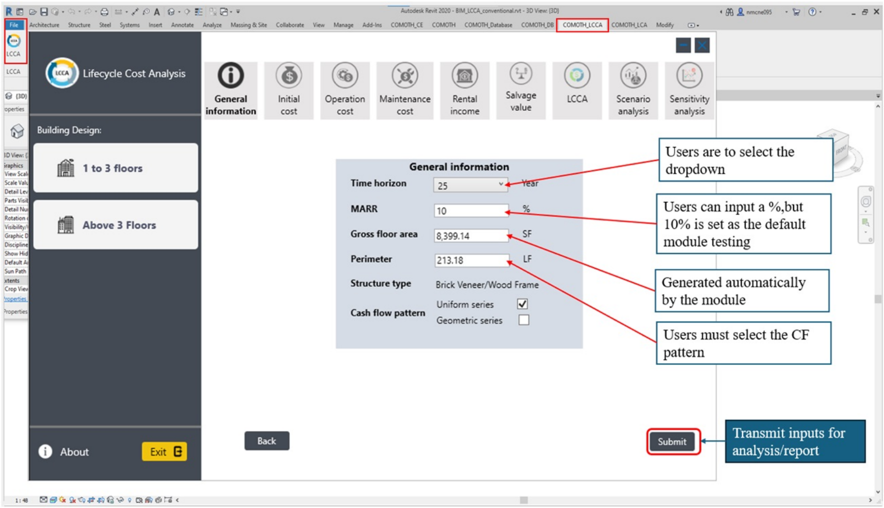

Figure 6. LCCA model general information.

The developed model integrates a cost database to populate the associated initial cost, as shown in **Figure 7**. **Table 3** outlines the total initial costs for each construction type, including construction costs, contractors, and design fees. While conventional construction incurs no additional costs beyond these parameters, modular construction and 3D concrete printing involve additional expenses such as transportation, handling, storage, and rigging of prefabricated components and the cost of the 3D concrete printer. Estimating the costs for conventional and modular construction is relatively straightforward by using R. S. Means cost data. However, calculating the costs for 3D concrete printing walls is difficult because there is no single source for the data. This study adopted an estimate that used an average cost of 920 CAD/m^3 for a gantry system 3D concrete printer, considering labour, material, and equipment expenses, with material constituting approximately 45% (\$414/m^3), labour 35% (\$322/m^3), and equipment 20% (184 CAD/m^3), based on the information adopted from the studies conducted by Batikha *et al.*, (2022) and Holt *et al.* (2019).

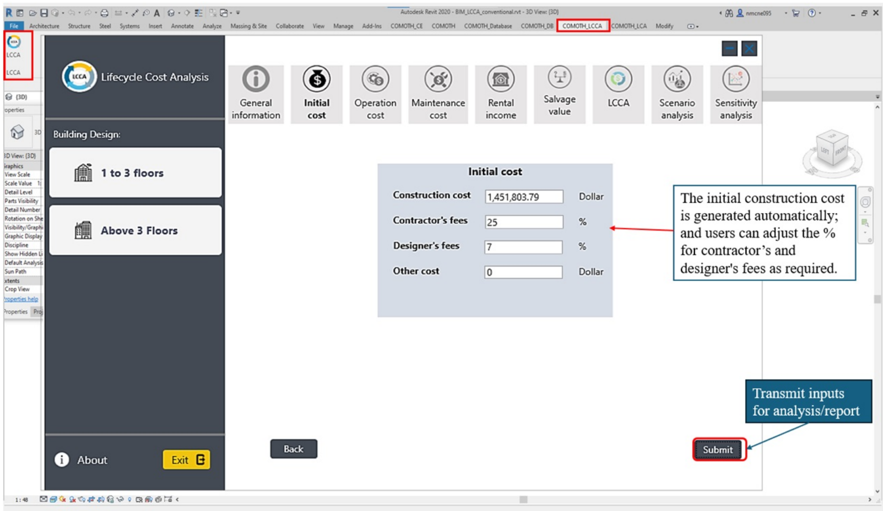

Figure 7. Modeling initial costs in the developed model.

Table 3. Summary of total initial cost.

Construction method	Project cost (CAD)	Other costs (CAD)	Total cost (CAD)
Conventional construction	1916381.03	0	1916381.03
Modular construction	1783213.04	121582.71	1904795.75
3D concrete printing	1566778.49	59568.00	1626346.49

Operation cost is calculated as the annual future cost of energy that will be utilized to operate the building efficiently. This study provides users with two cashflow patterns for calculating all annual costs: uniform and geometric gradient series of future payments, the resulting values for the two options are based on their initial cost values and are shown in Table 4. The HVAC system is considered to be operated in kWh and is calculated by adding the monthly usage and multiplying the total annual energy demand in kWh by the unit price for electricity and fuel, respectively. Water usage is calculated in m^3, and the associated CO_2 emission from the operating energy is priced in dollars/ton, as discussed previously in the development and illustrated in Figure 8. Hence, the total annual operating cost for the construction method was calculated based on the operating energy demand simulation by Design Builder.

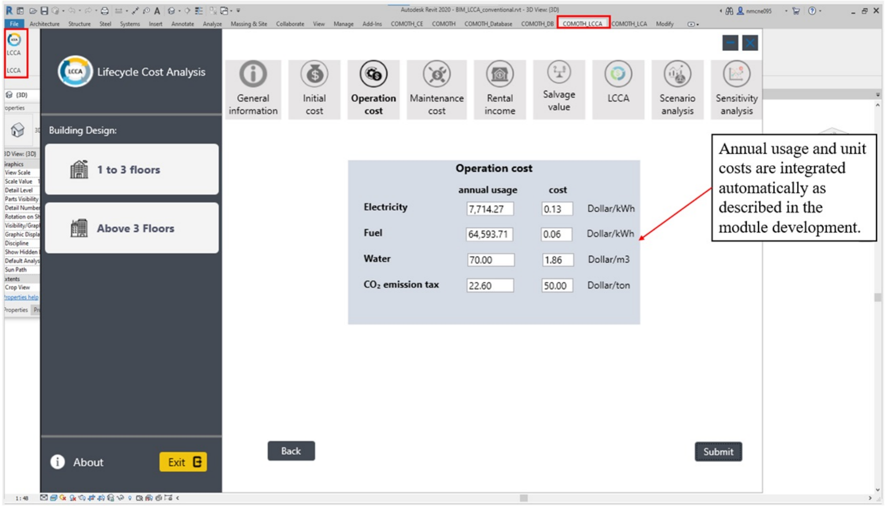

Figure 8. Modeling the operating costs.

Table 4. Summary of the operating costs.

Operating cost	Conventional construction (CAD)	Modular construction (CAD)	3D concrete printing (CAD)
Initial value	6229.30	6087.69	6330.07
Uniform series value	79631.38	77821.15	80919.50
Geometric series value	106345.10	103927.60	108065.35

Maintenance costs consist of annual minor repairs and major replacements. Minor repairs covers the administrative routine maintenance and are calculated based on one percent of the total project cost, as shown in Table 5. Hence, it is worth emphasizing that this cost is influenced by various factors, including material, labour, and equipment, and is also subject to change based on user input. For the replacement of major building's components, five replacement cycles for the three construction methods within 25 years of study period as follows: year 5 (painting), year 10 (painting and flooring), year 15 (painting roof shingles/ membrane, HVAC system and windows), year 20 (painting, flooring and external doors), and year 25 (painting) considered in testing the model, however, users can select the replacement cycle and the components from the dropdown list that meets their design need. The summary of the replacement costs for the three construction methods is shown in Table 6. It is evident that conventional construction and 3D concrete printing have similar replacement costs, which may be because most of their components are similar apart from their interior and exterior walls. Users are required to select the replacement cycle and the components to be replaced, and the associated cost will be generated and populated in the required cells of the UI as provided in the developed model and shown in Figure 9.

Table 5. Summary of minor repair costs.

Minor Repairs	Conventional construction (CAD)	Modular Construction (CAD)	3D concrete printing (CAD)
Initial value	19076.77	19047.96	16263.46
Uniform series value	173160.63	172899.07	147624.12
Geometric series value	327159.85	325182.04	277645.87

Table 6. Summary of major replacement cost.

Replacement Cycles	Conventional construction (CAD)	Modular prefabrication (CAD)	3D concrete printing (CAD)
Year 05	21066.05	14865.19	21065.05
Year 10	111128.43	102432.80	111128.43
Year 15	531079.26	508241.24	579856.01
Year 20	481102.59	463996.97	481102.59
Year 25	81515.11	57523.60	81515.11

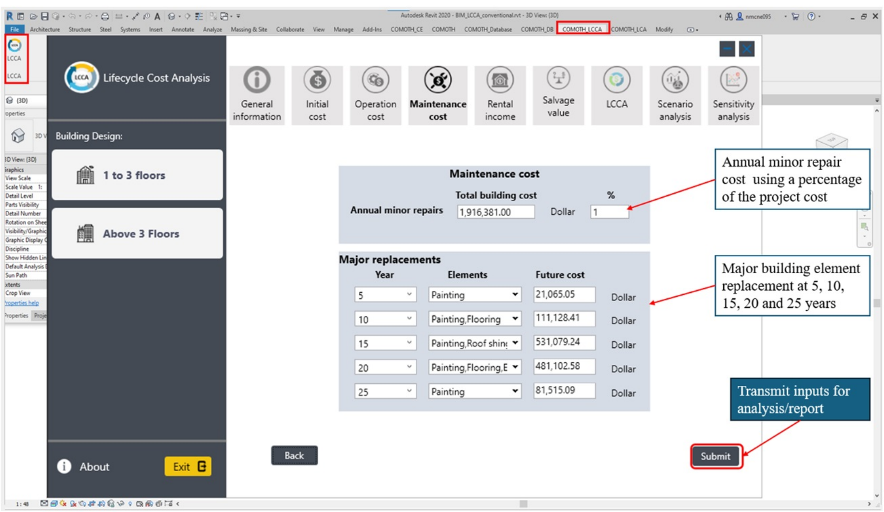

Figure 9. Modeling maintenance costs.

For the rental income, the rentable area is automatically generated from the design model, while \$17.20/ft^2 is the cost per rentable area and the total number of months is 12, which are used to multiply the generated value, as shown in Figure 10. Salvage value, also known as scrap value, refers to the residual worth of an asset once its usable life has been exhausted. This measurement technique plays a crucial role in computing the average depreciation cost of the asset. In the context of this study, the straight line depreciation method is employed. According to this method, the building under consideration reaches a salvage value of zero after completing its useful life. As a result, the salvage value becomes zero, indicating the completion of the building's depreciation under the chosen depreciation method. However, this model also allows users to input a salvage value or a salvage cost in the provided user interface (UI), as shown in Figure 11.

Once all the life cycle cost's components have been modeled and submitted, including the initial cost, operating cost, minor repair cost, major replacement cost, rental income, and salvage value, users can proceed to generate various types of reports, starts with LCCA reports, accessed by selecting the dropdown list as shown in Figure 12, to generate the cash flow diagram as shown in Figure 13. Table 7 illustrates the life cycle cost summary using the inputs and assumptions.

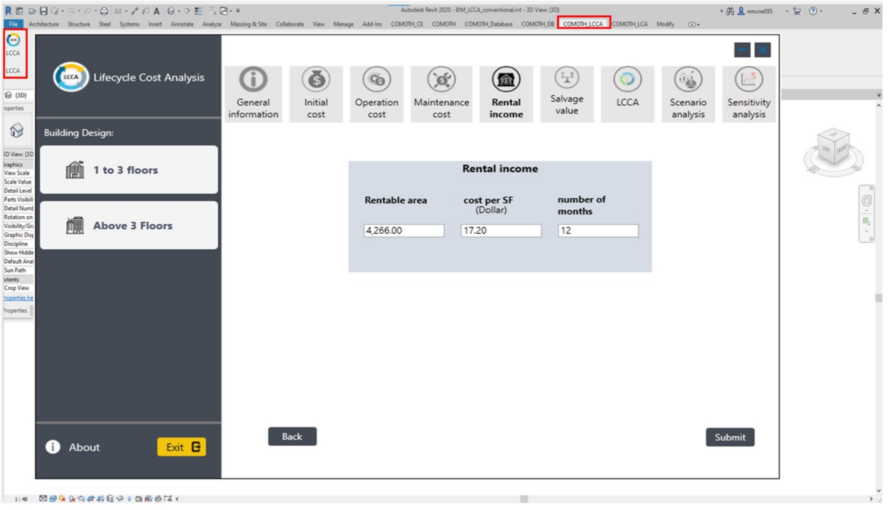

Figure 10. Modeling rental income.

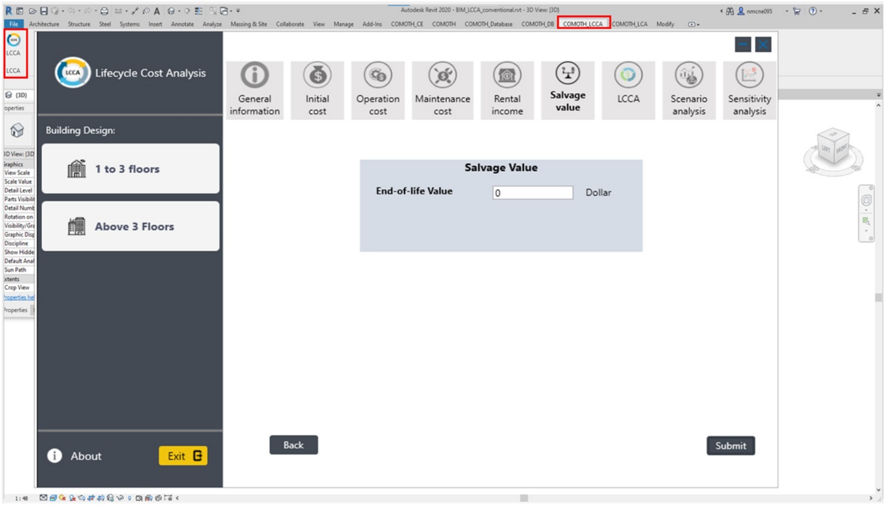

Figure 11. Modeling salvage value/cost.

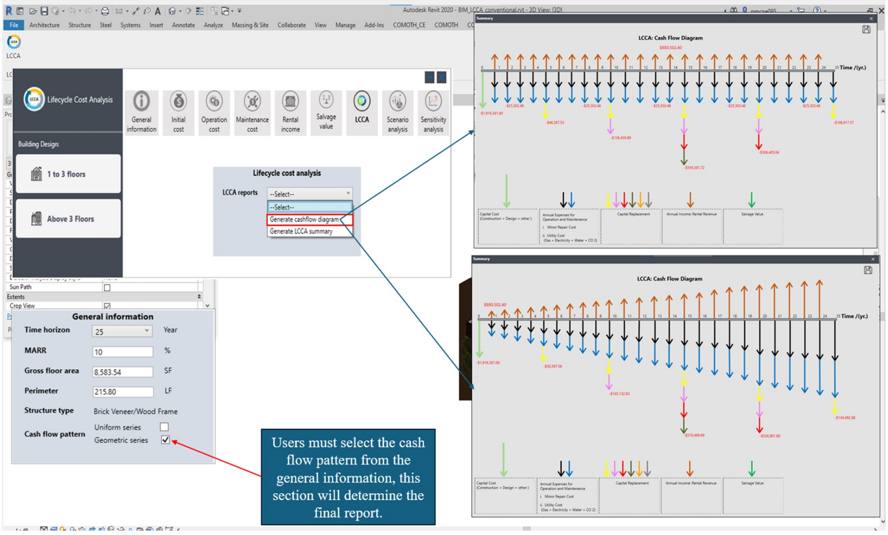

Figure 12. Uniform and Geometric series cash flow patterns.

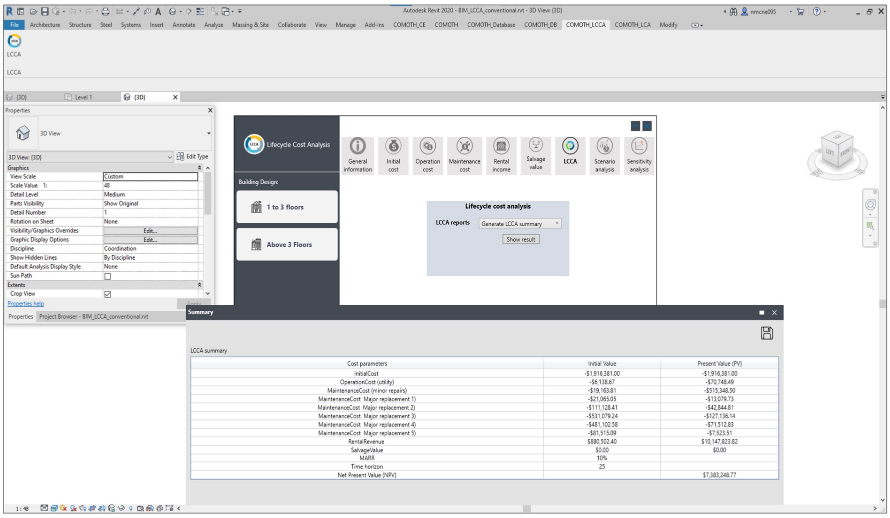

Figure 13. Life cycle cost summary conventional method (using geometric series).

Table 7. Summary of LCC.

Life Cycle Cost	Conventional Construction (CAD)	Modular Prefabrication (CAD)	3D Concrete Printing (CAD)
Uniform series	5584205.78	5615902.66	5903301.45
Geometric series	7383248.77	7710154.71	8003803.30

The cash flow diagram and the NPV are developed for a 25-year analysis period for the uniform and geometric series, as shown in Figure 12, with the same process applied to the three construction methods. As previously described, the present value is used to convert the current value of the cash flow stream given a specific rate of return. Although the developed LCCA model uses a defaut value of 10% for MARR but users have the flexibility to input an alternative discount value that aligns with their project requirements and objectives. Moreover, while the NPV evaluation raises uncertainty for most parameters, the influence of certain parameters or decisions on LCCA outcomes is better to be analyzed through individual scenarios. In this testing, three scenarios are created based on the combinations of the eleven parameters for worst-case scenarios (pessimistic) and best-case scenarios (optimistic), with the NPV result being the most likely case scenario. Consequently, the developed model can aid users in implementing these assessments by selecting the scenarios analysis from the dropdown list to generate the LCCA scenarios and their corresponding NPV reports, as shown in **Figure 14**.

The LCCA model used the sensitivity analysis method to evaluate the sensitivity of all parameters using a range of error based on a ±25 percent range of the baseline net present value (NPV). **Figure 15** shows the sensitivity analysis graph for the NPV of the rental revenue, MARR, and initial construction cost as the most sensitive parameters. Therefore, decision-makers must recognize that these parameters can significantly influence the project's outcomes. Moreover, users can set the sensitivity margin of errors to suit their evaluation needs, evaluate each parameter separately by specifying the parameter from the analysis dropdown button, and generate the sensitivity analysis summary, as shown in **Figure 16**. It should be emphasized that analyzing the life cycle cost using the developed model demonstrated in the testing section is applied to conventional, modular, and 3D concrete printing construction methods. Therefore, users must choose their construction method at the start and the cash flow pattern to obtain the appropriate results.

6. Discussion

6.1. Model Evaluation and Comparative Analysis

This study introduces the development of an automated model intended to provide designers with comprehensive access to evaluate and analyze various design options and construction methods, to enhance effective cost decisions by employing modular prefabrication and 3D concrete printing construction methods by considering their initial construction costs in addition to long-term operational and maintenance costs, rental income and salvage value. The goal is to empower designers to perform real-time evaluations, expand their exploration of design options, provide a comprehensive economic viewpoint on a proposed building asset investment and help stakeholders comprehend the enduring financial implications of design decisions. The integrating platform includes BIM tool, which is a sustainable mechanism for adequately optimizing the life cycle building performance involving data flow from energy simulation and LCA that helps achieve LCCA at the conceptional design stage of buildings.

Comparing the outcome of the developed model to an actual project values is challenging due to the scarcity of data on real projects that have utilized 3D

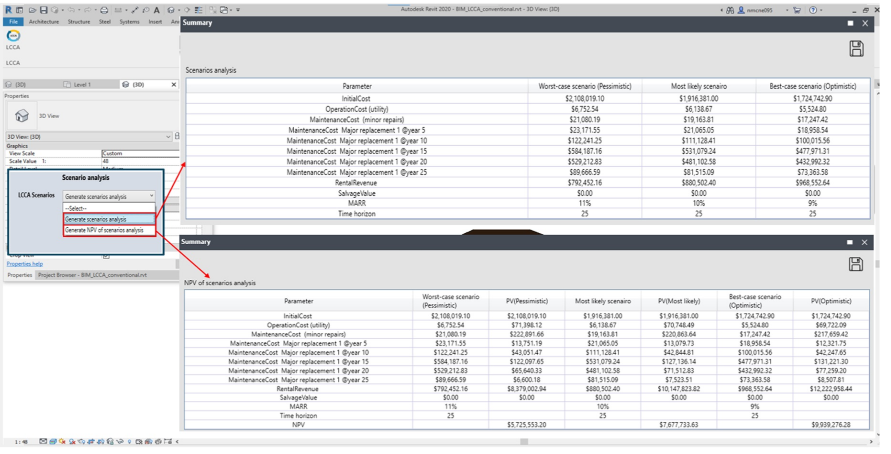

Figure 14. LCC scenarios and their corresponding NPV reports.

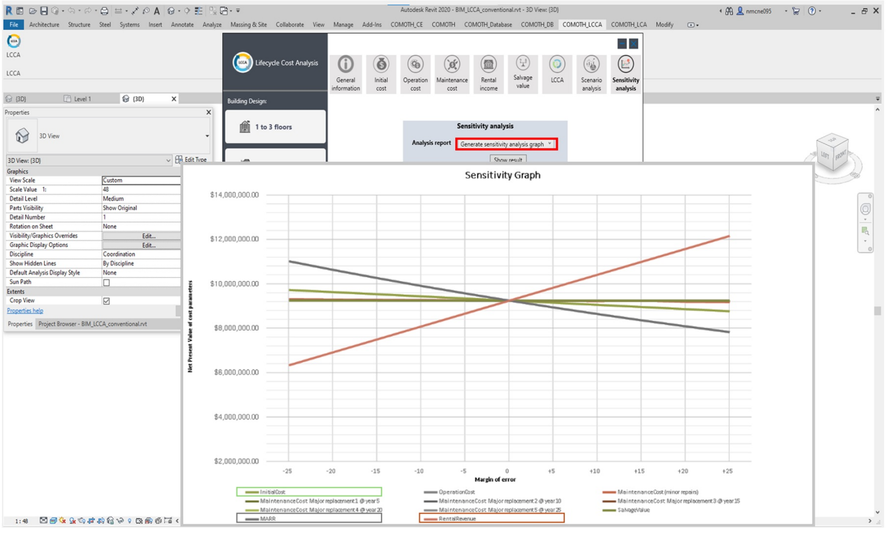

Figure 15. Sensitivity analysis graph highlighting rental revenue, MARR, and initial project cost.

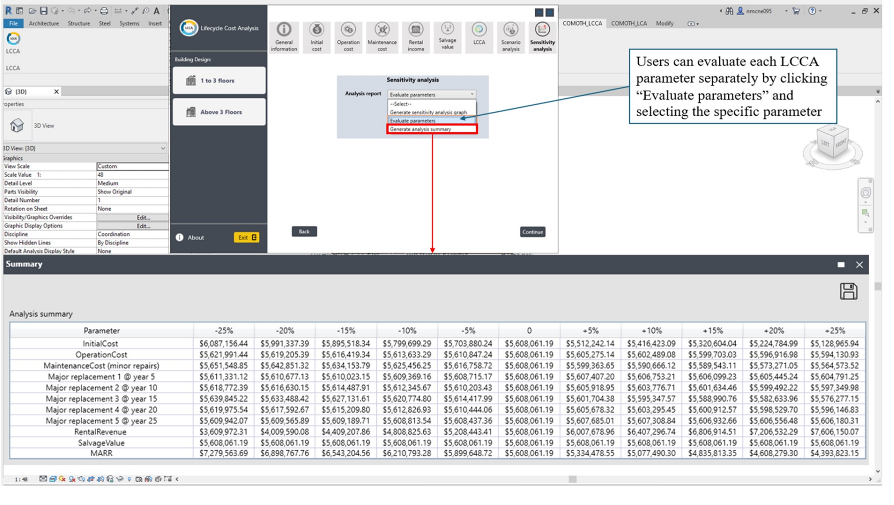

Figure 16. Summary of sensitivity analysis.

concrete printing techniques and modular prefabrication. Additionally, many existing models are primarily based on conventional design and on-site construction methods. Moreover, similar models that integrate BIM with off-site prefabrication (including modular and 3D printing) often focus primarily on comparing modular and conventional construction or 3D printing with conventional methods to validate their sustainability through some selected design criteria or by simply highlighting the advantages of BIM for off-site construction.

Consequently, the developed model has been tested to verify its functionality and workability in terms of input, relevant criteria, subsequent analysis, and the generated output. Additionally, the evaluation of the model, along with a review of relevant literature integrating BIM and LCCA, demonstrates its comprehensiveness. When compared to existing BIM-LCCA integration models or traditional decision-making approaches, the developed model effectively incorporates diverse construction methods and provides designers with easily accessible predefined data, enabling prompt decision-making during the early design process. Moreover, the developed model performs total LCCA using two different cash flow patterns: a uniform series of equal payments and a geometric series of payments, thereby offering investors enhanced insights.

Some related studies on BIM-LCCA model development are limited to evaluating the LCCA for a single building element. For instance, the study of [14] utilized a BIM approach for optimizing energy, and LCCA focused on three different insulated wall elements. Notably, the LCCA results of these walls are limited to a uniform series of equal payments cash flow patterns. Rad *et al.*, (2021) [6] developed a plug in within the BIM tool, integrating cost and resiliency factors to forecast the LCC of building projects. Their findings indicated that a 4.6% increase in initial costs corresponded to a 35.4% decrease in annual expected failure costs, ultimately resulting in an overall reduction of nearly 10.4% in total life-cycle costs.

6.2. Evaluation of Cost Components

In the current study, the developed model offers a distinct advantage by furnishing designers with enhanced cost data for three construction methods based on their life cycle information, facilitating a comprehensive LCCA result, which includes assessing various scenarios of the net present value and evaluating the sensitivity of cost parameters employed in LCCA. Leveraging a BIM environment proves to be a suitable approach for determining and executing all the essential modeling, integration simulations, evaluations, and computations. This concept ensured a reliable, practical outcome that enhanced decision-making regarding optimal alternatives.

An evaluation of the model's cost components shows that the outcome of the life cycle cost will vary based on the user input and assumptions. However, based on the input used for the model's testing, the initial project costs for modular prefabrication and conventional construction were similar, while 3DCP had an overall lower cost, about 14.7% lower than modular and conventional construction. The other cost components that resulted in an increase in modular construction were the transportation, storage and cranage costs. These results are comparable with those proposed by [25] for material, labour and equipment cost factors for 3D concrete printing.

In terms of operating costs, modular construction presents a 2.27% energy savings compared to traditional buildings and a 3.83% reduction compared to 3D concrete printing (3DCP). Minor maintenance costs align proportionally with overall construction costs, indicating that higher construction costs lead to increased routine maintenance expenses and vice versa. However, modular prefabrication also exhibits a cost advantage during major component replacement compared to conventional and 3D concrete printing structures. A comprehensive analysis of life cycle costs (LCC), as depicted in **Figure 12**, utilizes both uniform and geometric payment series consecutively to illustrate the comparison of different construction methods and their respective systems and envelopes. Results reveal that conventional construction incurs the highest total construction cost in terms of capital investment, followed by modular prefabrication, while 3D concrete printing boasts the lowest initial cost.

Modular prefabrication demonstrates the most economical expenditure during the operational and major replacement maintenance phases, followed by 3D concrete printing and conventional construction.

Employing the (LCCA) approach, all future project-related costs are discounted to present value using the (MARR) to facilitate a comprehensive comparison of alternatives and identify the optimal choice. Upon discounting all alternatives to present values, the assessment reveals that conventional buildings exhibit the lowest present value at $5584205.78, followed by modular buildings at $5615902.66 and 3D concrete printing with the highest present worth calculated at $5903301.45 based on a uniform series of equal payments. Similarly, the net present value using the geometric series of payments for conventional buildings is $7383248.77; for modular buildings, it stands at $7710154.71 and for 3D concrete printing, it amounts to $8003803.30, as shown in **Table 7**. The Life Cycle Cost Analysis (LCCA) results indicate that 3D concrete printing is the optimal alternative. A sensitivity analysis, at a variation of ±25%, identified initial construction cost, rental income, and MARR to be the parameters with significant influence on the LCCA, as shown in **Figure 15**. Consequently, project decision-makers should closely monitor these parameters, as even a slight change could potentially affect investment.

7. Conclusions

The development of an integrated model that couples BIM to conduct the Life Cycle Cost Analysis (LCCA) of three construction methods, namely conventional, modular prefabrication and 3D concrete printing (3DCP), was described and achieved in this study.

Integrating LCCA with BIM during the conceptual design stage has been shown to help designers and investors make efficient decisions to optimize the life cycle cost, which ultimately reduces total project costs. The integrated BIM-LCCA model was developed by using Autodesk Revit design environment as a plug-in enhancing existing and creating new functionality. The model's development can be summarized in three systematic steps. The initial step focuses on utilizing pre-existing data from external material databases to create three identical BIM 3D design models. Concurrently, material quantity take-offs were generated from the model to facilitate energy consumption simulations in Design Builder and Life Cycle Assessments in open LCA. The resulting datasets were systematically stored in a functional database. The second step involves developing new plug-ins within BIM tool (Autodesk Revit). These plug-ins link the functional database and Revit using its API and C#. The primary objective was to automate the calculation and analysis processes for all associated cost components extracted from the database. A comprehensive Life Cycle Cost Analysis (LCCA) was executed in the final step, which involved discounting all associated costs to their present values. This process included exploring various cost scenarios and identifying the impact of cost parameters on the Net Present Value (NPV) through sensitivity analysis. The analytical framework was tested by using a three-story residential building with three different construction methods, using data from various sources to establish initial, operating, and maintenance costs, as well as rental revenue and salvage value.

Hence, one of the novelties highlighted in the developed BIM-LCCA model is the development of an automated model that employs a newly created plug-in to provide designers with instant access to comprehensive cost data and information in an effective manner. Second, the model's capability to integrate various construction methods, including conventional, modular, and 3D concrete printing, as well as design options, enables efficient execution of building designs for both 1 - 3 floors and structures with more than 3 floors using these three construction methods. Third, the developed model can potentially conduct life cycle cost analysis using two different cash flow models: a uniform series of equal payments and a geometric series of payments, which would provide investors with improved insight.

While various tools have been utilized to tackle the economic assessment within the AEC industry, many of them only account for future expenses as uniform equal payments. None have been specifically tailored to incorporate the geometric series of payments with consistent increments. Consequently, the present study aims to bridge this gap by integrating BIM to execute a comprehensive LCCA to enhance cost decisions. One notable novelty highlighted in this study is the capability of the developed BIM-LCCA plug-in to generate cash flows using two distinct patterns: a uniform series of equal payments and a geometric series of payments. This feature serves as a valuable tool for investors seeking efficiency in financial planning.

The current study focuses on the conceptual design stage of buildings, where designers need comprehensive cost data from reliable sources to make an informed decision that will benefit all stakeholders with limited information. Therefore, the developed model did not account for certain complex factors influencing construction costs, such as market fluctuations, unforeseen project delays, and regulatory changes. Additionally, the study did not include examples from actual construction projects for validating modular and 3D concrete printing methods, as these construction techniques are still in the early stages of adaptation in the industry. Consequently, finding real project data that can be used for evaluation and comparison is challenging.

Although the results from this study demonstrate that 3D concrete printed construction is more cost-efficient compared to modular prefabricated and conventional construction, it's important to note that the latter methods have been established for decades with existing standards, codes, and specifications, ensuring their quality and functionality. In contrast, there is currently no regulation governing the construction of buildings using 3D concrete printing. While there is no doubt that 3D printing is an evolving technology with the potential to revolutionize, the process of establishing its associated regulations is still under discussion and may require some time before 3D concrete printing becomes properly regulated and widely adopted in the AEC industry. Hence, the implementation of 3D concrete printing is limited to three floors in this study, and should the designer select three floors and above as a design option, the model will show an error message that reads "not compatible."

Conflicts of Interest

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

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